FPGA Implementation of Maximum Power Point Tracking Algorithm for PV System

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May 25, 2013

Certificate

This is to certify that the work in the thesis entitled *FPGA Implementation of Maximum Power Point Tracking Algorithm for PV system* by *Jadhav Pankaj Shankarrao*, bearing roll number 211EC3318, is a record of an original research work carried out by him under my supervision and guidance in partial fulfillment of the requirements for the award of the degree of *Master of Technology* in *Electronics and Communication Engineering*. Neither this thesis nor any part of it has been submitted for any degree or academic award elsewhere.

Kamalakanta Mahapatra

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Many thanks to my comrades and fellow research colleagues. It gives me a sense of happiness to be with you all.

Finally, my heartfelt thanks to my family for their unconditional love and support. Words fail me to express my gratitude to my beloved parents, who sacrificed their comfort for my betterment.

Jadhav Pankaj Shankarrao

Abstract

Photovoltaic power generation has two major problems: the conversion efficiency of existing PV modules is less and amount of power generated by PV system changes with weather conditions. Also, the PV cell I-V characteristics are non-linear due to complex relationship of voltage and current and varies with change in temperature or insolation. There is only one point on P-V or I-V curve called Maximum Power Point at which PV system operates at maximum efficiency and produces maximum output power. Failure to track MPP causes significant power loss. So, Maximum Power Point Tracking $MPPT$ are required to operate PV system at MPP. The P&O algorithm and INC algorithm are commonly used methods to track MPP by adjusting duty cycle of DC-DC converter.

The existing methods use microcontroller or DSP controller to implement MPPT algorithm.FPGA provides number of advantages over sequential machine microcontroller as FPGA does concurrent operation i.e. instructions executed continuously and simultaneously. DSP does DSP related calculation only so, with FPGA numbers number of components required are less. Also, FPGA is faster than DSP. Thus, the size of components required for power converter decreases. The MPPT algorithm is implemented on FPGA and programmed through LabVIEW. The programmed FPGA track MPP continuously.

***Keywords*:** Photovoltaic System, MPPT, P&O Algorithm, Incremental Conductance Algorithm, DC-DC Converter, FPGA

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Chapter 1

Introduction

1.1 Renewable Energy & Solar Energy

Energy is required for our life and economy.As the country develops it needs more energy.Nowadys energy is supplied by burning fossil fuels such as coal,diesel.Increased energy demand results in two problems:energy crisis and climate change(global warming).The worldwide energy demand increases ,the energy related green house gases emission increases.It is global challenge to reduce the CO_2 emission and provide clean,sustainable and affordable energy.

Energy saving is one cost effective solution but does not tackle the worldwide increasing energy demand.Using Renewable energy is good option because it provides clean and green enrgy,with little or no CO_2 emission.Renewable energy is generated from renewable energy sources such as Solar emission,Wind ,Tides,geothermal etc.The major renewable energy technologies are Hydropower,wind power generation ,biomass and ocean energy.This energy is used in Power Generation,Rural electrification (off-grid) and as transport fuels. Compared to fossil fuels Renewable energy has many advantages.firstly,the Renewable energy obtained from natural sources so it is sustainable and it will not emit CO_2 gas.So renewable energies tackle the green house effect and also provides sustainable energy.To achieve the renewable energy target,more funds will be provided in research and development of renewable energy .

1.2 Solar Energy

Solar energy is one of the important source of renewable energy.The sun radiates large amount of energy which is enough to satisfy the need of whole world.Solar energy is used for providing heating,cooling,light and for electricity.One of the important technology is Photovoltaic (PV),by photoelectric effect the sunlight is directly converted into electricity.In 1839 the Edmond Bequerel found the photoelectric effect accidently while working on solid-state physics.1n 1883 Fxitz fabricated the first thin film solar cell. In 1941 ohl fabricated silicon PV cell but that was very inefficient. In 1954 Bell labs Chopin, Fuller, Pearson fabricated PV cell with efficiency of 6%. In 1958 PV cell was used as a backup power source in satellite Vanguard-1. This extended the life of satellite for about 6 years.
PV generation has following main advantages:

(i) It is abundunt and sustainable.

(ii) It is green and clean.The production of PV energy does not produces green house gases hence it is safe.It is pollution free,since manufacturer of PV are commited to minimize pollution during production.

(iii) Pv energy is reliable,since power generation using PV has no moving parts hence it has less maintainance.When PV is used as distributed energy source it reduces the cost of transmission lines and improve grid reliabilty. .

(iv) It has longer life than other renewable technologies.

However there are few problems when using PV energy:
PV energy is dependent on weather condition.It is not availabe at night.during

cloudy weather its efficiency becomes less.Hence PV energy generation is intermittent and variable.
The cost of large scale PV system installation is high compared to conventional energy systems for same enegy production.
The research is going on to reduce the installation cost of large scale power generation and to increase the efficiency of PV system.

1.3 Literature Review

[1, 2] In this author presented an accurate PV module electrical model based on Shockley diode equation. The method of parameter extraction and model extraction and model evaluation is demonstrated in MATLAB for 60W solar panel. This model is used to investigate the variation of MPP with insolation levels and temperature. The author has made comparison between buck and boost converter topology for MPPT, connected to battery.
[3]In this paper the matlab model for patial shading condition is proposed.which is useful in large scle PV installlation.Also it is useful for interfacing PV module to model of power converter.
[4]The comparative study of widely adopted MPPT algorithms is done on the basis of simplicity, convergence speed, cost, digital or analogical implementation, sensors required and in other aspects. Their performance is evaluated on the energy point of view.
[5]In this paper, different mppt methods are discussed from various literature dating back to present days. At least nineteen methods are introduced in this literature survey. This paper is useful for people who wish to work in the field of photovoltaic power generation. Author has done comparison of various mppt techniques based on implementation, cost and parameters to be sensed for particular mppt.
[6]A drawback of Pertub & Observe is that, in steady state, the operating point of PV oscillates around the MPP giving rise to the loss of some amount of available power;

also it is known that P&O algorithm can be jumbled during those time intervals characterized by rapidly changing the environmental conditions. This paper it is shown that, to limit the negative effects related to above drawbacks, the P&O MPPT parameters must be modified to the dynamic behavior of specific converter adopted. A theoretical analysis permitting optimal choice of such parameters is carried out.
[7]For large Power Generation System, probability for partially shaded condition to occur is high. Under Partially shaded condition(PSC), the P-V curve of PV system has multiple peaks, which reduces effectiveness of conventional maximum power point tracking methods. In this paper, particle swarm optimization (PSO) based MPPT algorithm for PV system operating under PSC is proposed. Standard version of PSO is modified to meet practical consideration of PGS operating under PSC. Problem formulation, design method and parameter setting method which takes hardware limitation into account are styled and explained in detail. The proposed method claims the advantages such as very easy to implement, pv system independent and has high maximum power point tracking efficiency. To confirm correctness of the proposed method simulation results, and experimental results of 500W PV system will be provided to demonstrate effectiveness of proposed technique.
[8] In this paper author has discussed the conversion efficiencies of different converter topologies using various control techniqus. MPPT algorithm is implemented in DSP processor. The control strategy is to control DC-DC converter using discrete PI controller.
[9] The author has implemented P&O algorithm and INC algorithm on dSPACE controller platform and compared their response. The various control algorithms can be simulated via MATLAB/SIMULINK and then downloaded onto dSPACE card for practical experimentation.
[10]In this paper information of detailed work done to optimize and implement fuzzy logic controller (FLC) used as maximum power point tracker for standalone PV system, are presented. Near optimum design for the membership functions and

control rules were found simultaneously by the genetic algorithms (GAs) which are evolutionary search algorithms based on mechanism of natural selection and genetics. These methods are easy to implement and efficient for multivariable optimization problems such as in fuzzy controller design. The FLC thus designed and components of the PV system control , were implemented on Xilinx reconfigurable field-programmable gate array (FPGA) chip using VHDL Hardware Description Language. The obtained simulation results shows good tracking efficiency and fast response to changes in the environmental parameters.

[11] The author has presented modified P&O algorithm. An improved variable step size P&O algorithm is realized and implemented using very high speed hardware description language VHDL. The proposed algorithm outperforms the conventional controller in terms of tracking speed and mitigation of output power in steady state operation.

[12] Author has presented MPPT algorithms for space application using FPGA platform. Since MPPT implementation are part of larger systems containing DC-DC converter considerable amount of noise can be picked up. The author has demonstrated noise cancellation and reduction techniques for MPPT algorithms.

[13] The hardware implementation of P&O algorithm in FPGA is presented. The author has given the list of various components required for PV system. The author has briefly described the interconnection of different components in photovoltaic system.

1.4 PV Basic Terminology

Figure 1.1: Solar Panel Basics

PV Cell:The smallest,basic photovoltaic device that converts radiation directly into elecrticity. Each PV cell is rated for 0.5 0.7 volt and a current of $30mA/cm^2$. Based on the manufacturing process they are classified as:

Mono crystalline: efficiency of 12-14 %. This are now predominantly available in market

Poly crystalline: efficiency of 12%

Amorphous: efficiency of 6-8%

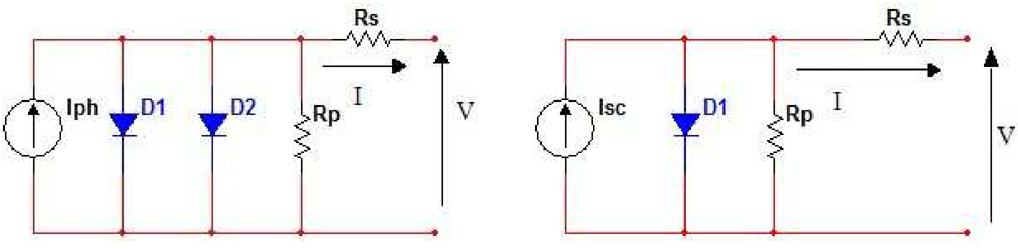
Life of crystalline cells is in the range of 25 years where as for amorphous cells it is in the range of 5 years.

PV Module: Series and parallel connected solar cells (normally of 36Wp rating).

PV Array: Series and parallel connected PV modules (generally consisting of 5 modules).

1.4.1 I-V Characteristics of PV Cell

fig 1.2 shows two electrical equivalent models of PV cell derived from the physical mechanism of PV cell.The first model contains two diodes that reflect diffusion and carrier recombination. The second model is a simplified providing similar characteristic for the representation of PV cell.



(a) Doble Exponential Model (b) Single Exponential Model

Figure 1.2: Electrical Equivalent Circuits of PV Cell

$$I = I_{ph} - I_{o1}(e^{\frac{q(V+IR_s)}{kT}} - 1) - I_{o2}(e^{\frac{q(V+IR_s)}{nkT}} - 1) - \frac{V + IR_s}{R_p} \tag{1.1}$$

$$I = I_{ph} - I_0(e^{\frac{q(V+IR_s)}{\eta kT}} - 1) - \frac{V + IR_s}{R_p} \tag{1.2}$$

The I-V characteristics of PVcell shown in fig1.3.The double exponential model eqn1.1 and single exponential model eqn1.2 are used to characterise the PV cell. [1–3] A PV cell behaves differently depending on the size/type of load connected to it. This behaviour is called the PV cell 'characteristics'. The characteristic of a PV cell is described by the current and voltage levels when different loads are connected.

where

V =PV cell terminal voltage (V)

I = PV cell terminal current (A)

I_{ph} = photocurrent (A)

I_{01} =saturation current due to diffusion mechanism (A)

I_{o2} = saturation current due to carrier recombination in space-charge region (A)

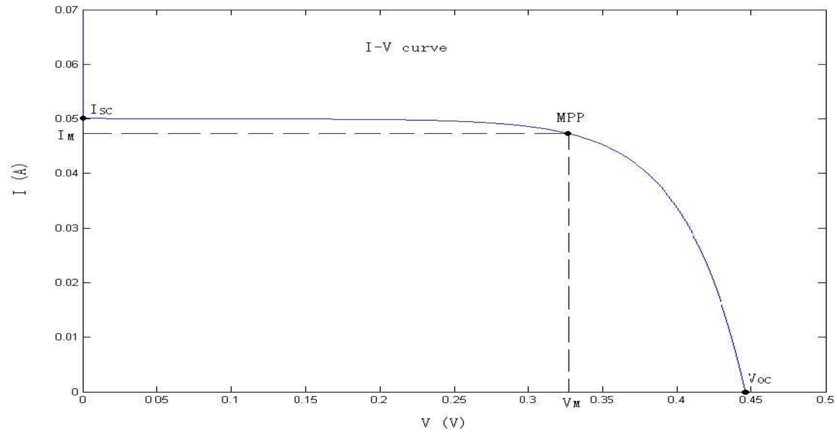


Figure 1.3: Typicel I-V characteristics of PV Cell

I_o = saturation current (A)

R_p = cell shunt resistance (Ω)

R_s = cell series resistance (Ω)

η= p-n junction ideality factor

q = electronic charge =1.6×10^{-19}C

k = Boltzmann's constant =1.38×10^{-23} J / K

T = junction temperature K

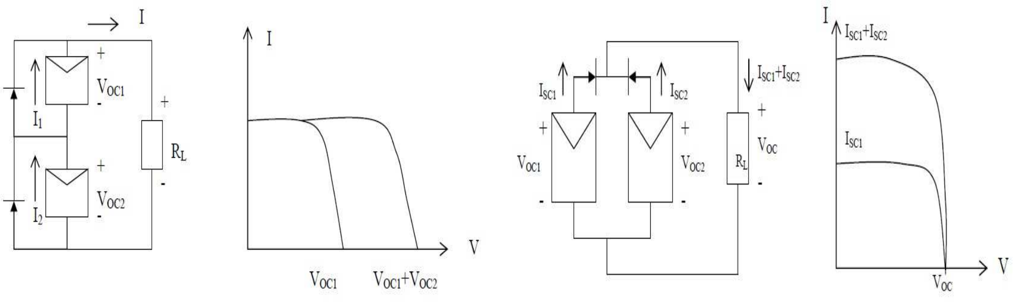
1.4.2 Series and Parallel combination of cells

Series Connection of Cells

If two identical cells are connected in series the V_{oc} of cells doubles while the I_{sc} remains same . But, practically two identical cells is not possible.When to dissimilar cells are connected in series the weaker cell behaves as sink.In this case the Voc of two cells adds up but the I_{sc} of system is in between the I_{sc}'s of two cell. Hence, if a diode is connected in parallel, then the weaker cell is bypassed,the current exceeds the short circuit current of the weaker cell. The system would look as if a single cell is connected across the load. The diode is called a bypass diode /series protection diode.

Parallel Conection of Cells

when two identical cells are connected in parallel, the V_{oc} remains sane but I_{sc} doubles. But, if cells are mismatched the current circulation takes place. The result is decrease in net current. This situation avoided by putting diode in series of each cell.The diode is called Reverse Blocking Diode.



(a) Cells in Series (b) Cells in Parallel

Figure 1.4: Series and Parallel Combination of Cell

1.5 Parameters of Solar Cell

1.5.1 Short Circuit Current (I_{sc})

The current is maximum when the two terminals are directly connected with each other and the voltage is zero. The current in this case is called 'short circuit' current. The short-circuit current is due to the genereation and collection of light generated carriers.

1.5.2 Open Circuit Voltage(V_{oc})

When the cell is not connected to any load there is no current flowing and the voltage across the PV cell reaches its maximum. This is called 'open circuit voltage'. When load is connected to the PV cell current flows through the circuit and the voltage goes down.

1.5.3 Maximum Power(P_m)

We Get DC power from solar cell.Power out of solar cell increases with voltage, reaches maximum (P_m) and decreases again.

$$P_m = V_{mpp} \times I_{mpp}$$

1.5.4 Fill Factor(FF)

The FF is defined as the maximum power from actual solar cell to the maximum power from ideal solar cell.

As time goes the PV curve degrades .It is essential to check quality of cell periodically. Quality of cell is determined by fill factor.For a good panel FF is between 0.7 to 0.8 while for bad panel it may be 0.4.

$$FF = \frac{V_{mpp} I_{mpp}}{V_{oc} I_{sc}}$$

1.5.5 Efiiciecy(η)

Efficiency is defined as ratio of energy output from solar cell to input energy from sun.

$$\eta = \frac{Max \quad cell \quad power}{Incident \quad light \quad intensity} = \frac{V_m I_m}{P_{in}} = \frac{V_{oc} I_{sc} FF}{P_{in}}$$

The efficiency is most commonly used parameter to compare the performance of one solar cell to another.Efficiency depend on solar spectrum,intensity of sunlight and the temprature of solar cell.

1.6 PV System

1.6.1 PV Modules and Array

PV source is scalable means it can be used from mW for solar watches, solar calculators to MW in large plants to provide power to utility grid. Depending on the cell area, the output current from a single PV cell can be used directly.However, its output voltage is usually too small for most application hence to produce useful DC voltage, a number of PV cells are connected in series and mounted in a support frame, which forms a PV module (or a PV panel).

To generate higher currents and/or voltages, PV modules can be connected in series and/or in parallel to form a PV array for higher power applications. Bypass and/or blocking diodes are often used in a PV array to reduce power loss when one PV module generates less photocurrent.

Suppose PV array in which the number of cells connected in series is N_s and that in parallel is N_p. Assuming that each cell has identical parameters, the electricalcharacteristic of the array can then be expressed as Eqn 1.3 or Eqn1.4, which is more useful in practical applications.PV cells, strings, modules, panels or arrays will be generally called PV sources.

$$I = N_p \left[I_{ph} - I_{o1}(e^{\frac{q(\frac{V}{N_s} + \frac{I}{N_p} R_s)}{kT}} - 1) - I_{o2}(e^{\frac{q(\frac{V}{N_s} + \frac{I}{N_p} R_s)}{\eta kT}} - 1) - \frac{\frac{V}{N_s} + \frac{I}{N_p}}{R_p} \right] \tag{1.3}$$

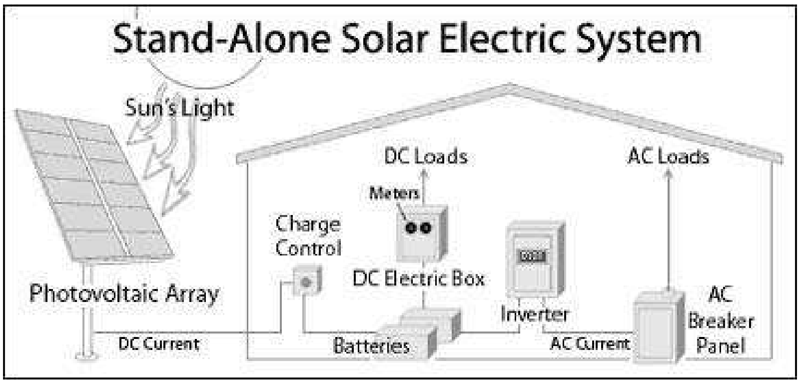
$$I = N_p \left[I_{ph} - I_o(e^{\frac{q(\frac{V}{N_s} + \frac{I}{N_p} R_s)}{\eta kT}} - 1) - \frac{\frac{V}{N_s} + \frac{I}{N_p}}{R_p} \right] \tag{1.4}$$

1.6.2 PV system topologies

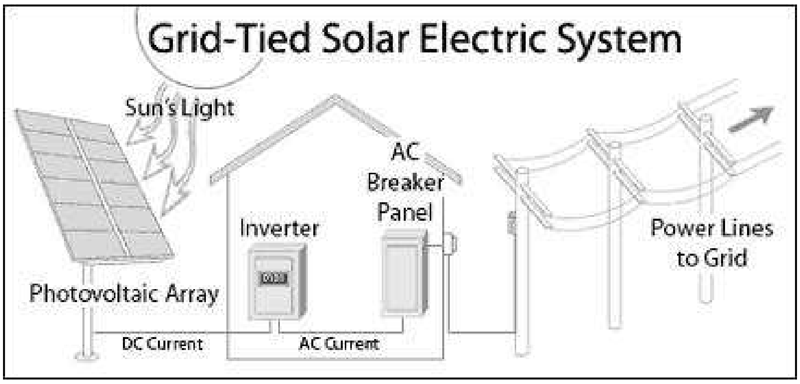
There are 3 types of PV systems :

1. stand-alone system
2. Grid connected systems
3. Hybrid systems

In Grid connected PV topology, the PV system provides power to grid. The PV system provides DC output hence Inverter is used to connect the PV system to grid. For grid connected PV system synchronisation with grid is necessary. In stand-alone PV topology the batteries store PV energy which are connected to inverter. In hybrid system along with PV another source such as fuel cell, wind generator is used to generate power. Hybrid systems are ideal for remote applications such as military installations, communications stations, and rural villages.



(a) Off-Grid PV system



(b) Grid Connected PV system

Figure 1.5: PV system topologies

1.7 Matlab Simulation of PV module MSX60

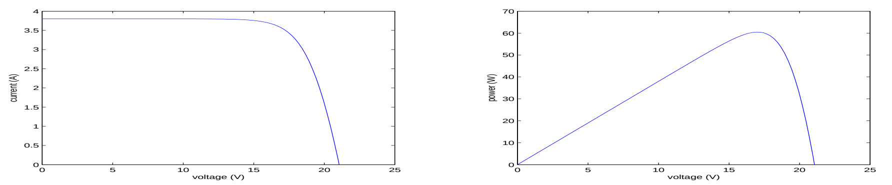
The PV cell/module characteristics depends on Insolation, Temparature of cell and area of cell. For evaluating the effect of temperature and insolation we have used MSX60 PV module.The PV model is presented in MATLAB used to check how MPP changes with insolation and temperature.

Table 1.1: Electrical Characteristics of MSX60

Open Ckt Voltage	V_{oc}	21.0 V
Short Ckt Current	I_{sc}	3.74 A
Voltage max power	V_{mpp}	17.1 V
Current max power	I_{mpp}	3.5 A
Maximum Power	P_m	59.9 W

1.7.1 I-V and P-V curves of PV module

- I-V curve of MSX60 module.
- I-V curve of PV module has two region one is constant current region and other is constant voltage region.
- power is increases with an increase in voltage, reaches a maximum and decreasing rapidly in near open circuit voltage V_{oc}.

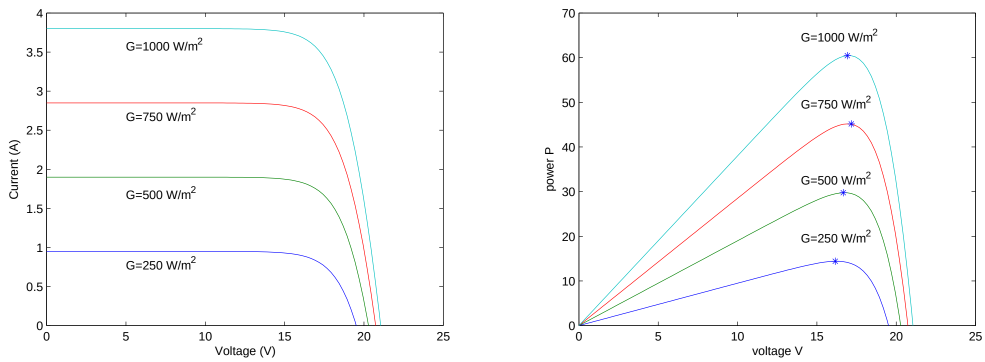


(a) I-V char of MSX60 (b) P-V char of MSX60

Figure 1.6: I-V and P-V Curves of MSX60,$T = 25^0C$,$G = 1000W/m^2$

1.7.2 Effect of Solar Irradiation

- Solar irradiation varies throughout the day.
- Photo current I_{ph} is directly proportional to the insolation.
- Voltage of module is logarithmic function of radiation intensity,hence it is almost constant.
- Power of module decreases linerarly with decrease in intensity of insolaton.
- Power output changes as irradiation changes.

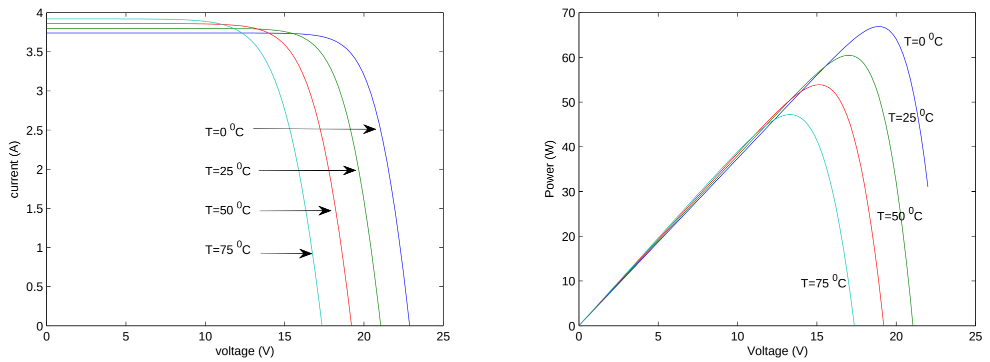


(a) I-V char,$T = 25^0C$ (b) P-V char,$T = 25^0C$

Figure 1.7: Matlab model I-V and P-V Curves for various irradiation levels

1.7.3 Effect of Temprature

- The output power of PV module also depends on temprature at which module is operating.
- Temperature has a strong effect on the saturation current I_o while slightly affects I_{ph}.
- As cell temprature increases the reverse saturation current increases that results in decrease of open circuit voltage.
- As temparature increases peak power decreases.



(a) I-V char, $G = 1000W/m^2$ (b) I-V char, $G = 1000W/m^2$

Figure 1.8: Matlab model VI curve for various tempratures

Chapter 2

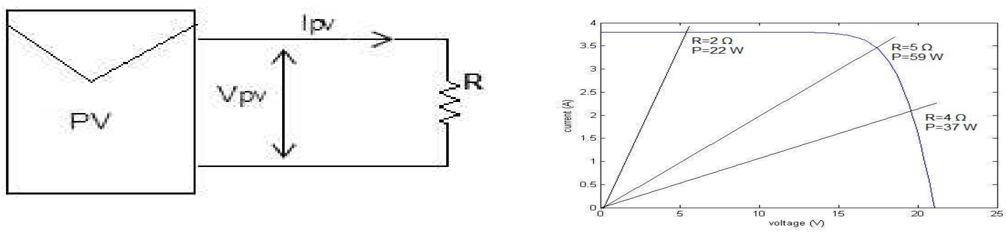
Power Evacuation Statergies From PV System

2.1 Interaction of PV array with Load

From PV module P-V characteristics we have seen there is only one point where power is maximum, the corresponding voltage is V_{mpp} and current is I_{mpp}. If load line crosses this point the maximum power is transferred to load. This value of load resistance is given by:

$$R_{mpp} = \frac{V_{mpp}}{I_{mpp}} \tag{2.1}$$

A PV cell behaves differently depending on the size/type of load connected to it.The behaviour of PV cell with diffrent load is shown in following fig 2.1

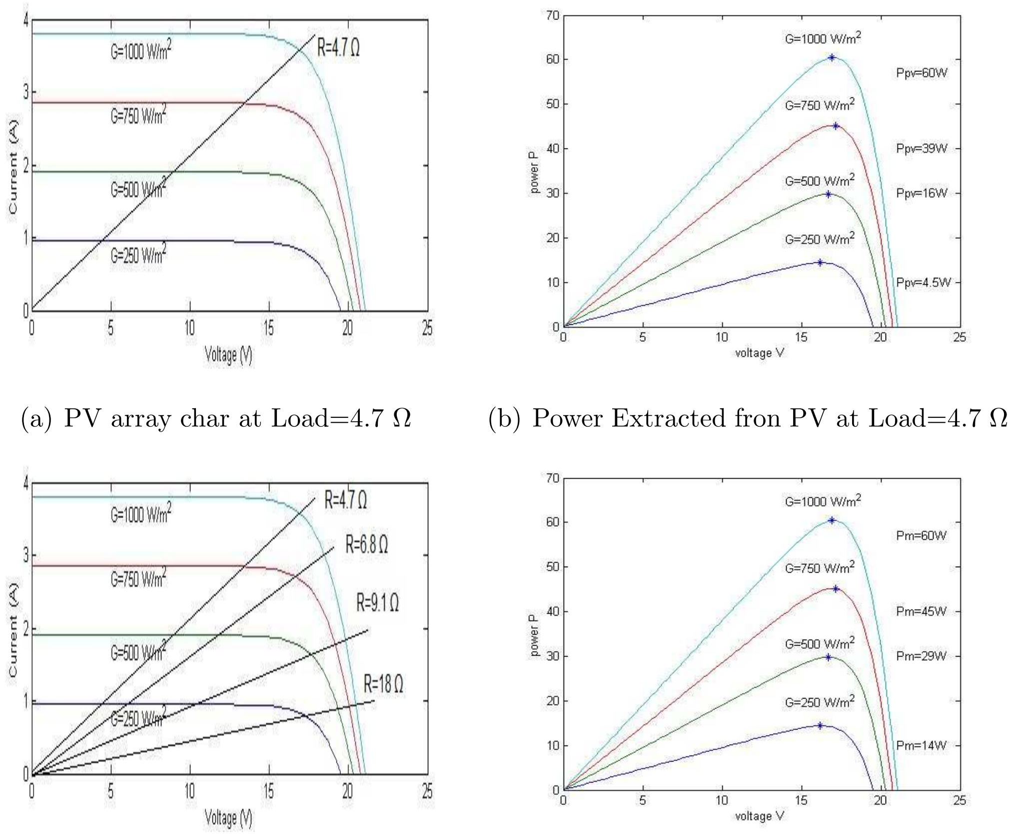


(a) PV interfacing to Load (b) PV Characteristics with different load

Figure 2.1: Interaction of PV array with load

2.2 MPPT Motivation

[21] This R_{mpp} changes with solar insolation and temparature.Our aim to extract maximum power from PV system irrespective of variation in load, insolation or temprature.The power exracted from PV shown for different load resistace infollowing fig 2.2



(a) PV array char at Load=4.7 Ω

(b) Power Extracted fron PV at Load=4.7 Ω

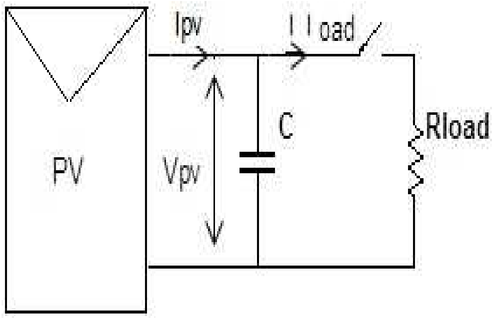
(c) PV array with varying Load

(d) Pmax at different irradiation

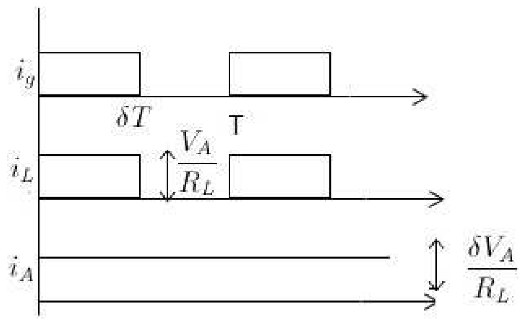
Figure 2.2: Motivation for MPPT

What should we need to do such that PV system always sees this constant load resistance?

MPPT Implementation In following figure fig2.3 the PV module is connected to load via high frequency switch.The average voltage and average current from PV is calculated.The R_{in} is PV effective resistance which is matched to load via high frequency switch.



(a) MPPT Strategy for PV



(b) Average PV current

Figure 2.3: MPPT Opeartion By High Frequency Switching

$$i_A = \bar{i_L} = \frac{1}{T}\frac{V_A}{R_L}\delta T \tag{2.2}$$

$$i_A = \frac{\delta V_A}{R_L} \tag{2.3}$$

$$\Rightarrow R_{in} = \frac{R_L}{\delta} \tag{2.4}$$

Let us consider DC-DC converter [18–20]

Buck Converter

In this converter output voltage is smaller than input voltage and output current is greater than input current.The Circuit diagram shown in fig2.4 The conversion ratio is given by

$$\frac{V_o}{V_{in}} = \frac{I_{in}}{I_o} = D \tag{2.5}$$

Where,D is duty cycle of converter.

$$V_{in} = \frac{V_o}{D} \tag{2.6}$$

$$I_{in} = DI_o \tag{2.7}$$

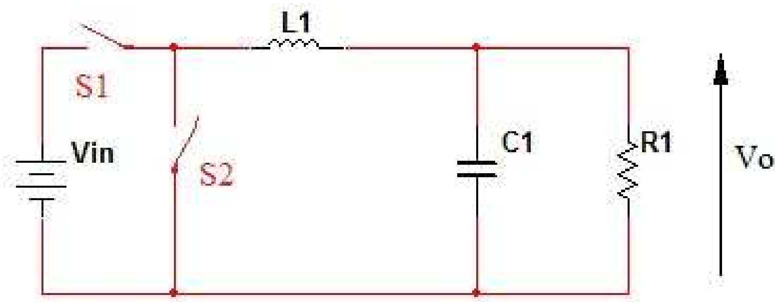


Figure 2.4: Buck Converter

By knowing V_{in} and I_{in} ,input resistance of converter can be found.

$$R_{in} = \frac{V_{in}}{I_{in}} = \frac{V_o/D}{I_o D} = \frac{V_o/I_o}{D^2} = \frac{R_o}{D^2} \tag{2.8}$$

Where R_o is load resistance of converter.

We know that duty ratio D varies from 0 to 1. **Hence R_{in} varies from ∞ to R_o when D varies from 0 to 1.**

Boost Converter

In this converter output voltage is greater than input voltage and output current is smaller than input current.The Circuit diagram shown in fig 2.5 The conversion

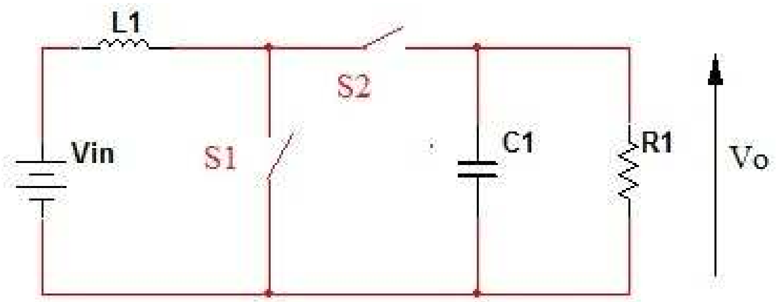


Figure 2.5: Boost Converter

ratio is given by

$$\frac{V_o}{V_{in}} = \frac{I_{in}}{I_o} = \frac{1}{1-D} \tag{2.9}$$

Where,D is duty cycle of converter.

$$V_{in} = V_o(1-D) \tag{2.10}$$

$$I_{in} = \frac{I_o}{1-D} \tag{2.11}$$

By knowing V_{in} and I_{in} ,input resistance of converter can be found.

$$R_{in} = \frac{V_{in}}{I_{in}} = \frac{V_o(1-D)}{I_o/1-D} = \frac{V_o(1-D)^2/I_o}{=} R_o(1-D)^2 \tag{2.12}$$

Here R_{in} **varies from** R_o **to 0 when D varies from 0 to 1.**

Buck-Boost Converter

It is combination of buck and boost converter.The output voltage can be increased or decreased depending on duty ratio.The Circuit diagram shown in fig 2.6 The

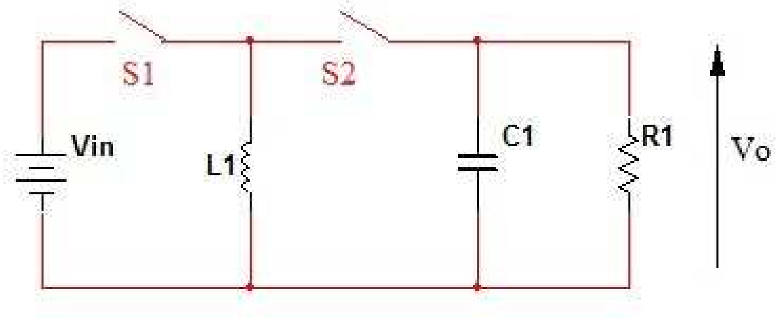


Figure 2.6: Buck-Boost Converter

conversion ratio is given by

$$\frac{V_o}{V_{in}} = \frac{I_{in}}{I_o} = \frac{D}{1-D} \tag{2.13}$$

Where,D is duty cycle of converter.

$$V_{in} = \frac{V_o(1-D)}{D} \tag{2.14}$$

$$I_{in} = \frac{I_o D}{1-D} \tag{2.15}$$

By knowing V_{in} and I_{in} ,input resistance of converter can be found.

$$R_{in} = \frac{V_{in}}{I_{in}} = \frac{(1-D)V_o/D}{DI_o/(1-D)} = \frac{V_o(1-D)^2}{I_o D^2} = R_o \left(\frac{1-D}{D}\right)^2 \tag{2.16}$$

Here R_{in} **varies from ∞ to 0 when D varies from 0 to 1.**
Maximum Power is trasferred to load if load line lies on point corresponding to V_{mpp} and I_{mpp} on I-V characreristics of PV cell/module/array.There is always intermediate subsystem that interfaces PV cell/module to load as shown in figure2.7

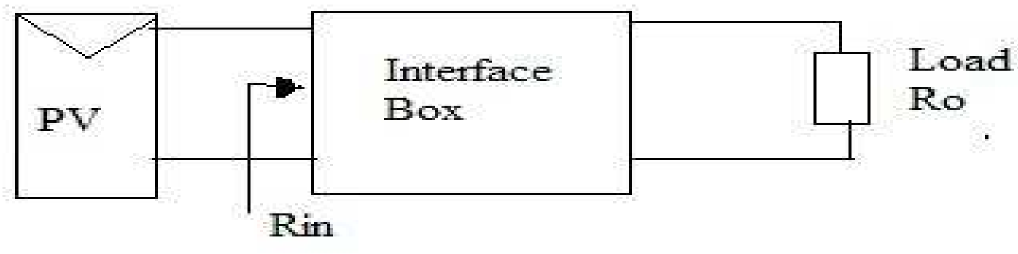


Figure 2.7: PV module interface to load

From above equations we seen that, the input resistance of converter is dependent on load resistance and duty cycle of converter.So DC-DC converter can be one such subsystem.Hence For the PV cell/module, the DC-DC converter acts as a load and hence we are interested in the input resistance of the converter. If the R_{in} of the converter lies on the V_{mpp}- I_{mpp} point, maximum power can be transferred to the converter and in turn to the load.

Hence Maximum Power Point Tracker or MPPT is a DC-DC converter which is used to interface PV system with load such as batteries, DC pump and DC motor. MPPT are power trackers not to be compared with panel trackers which track the sun. A capacitor is connected at output of PV module to remove the ripple or noise present.The high value of capacitor is chosen to do this task.The capacitor provides constant DC voltage to DC-DC converter.

Following figure gives a general block diagram of the whole system incorporating $DCDC$ converter:2.8

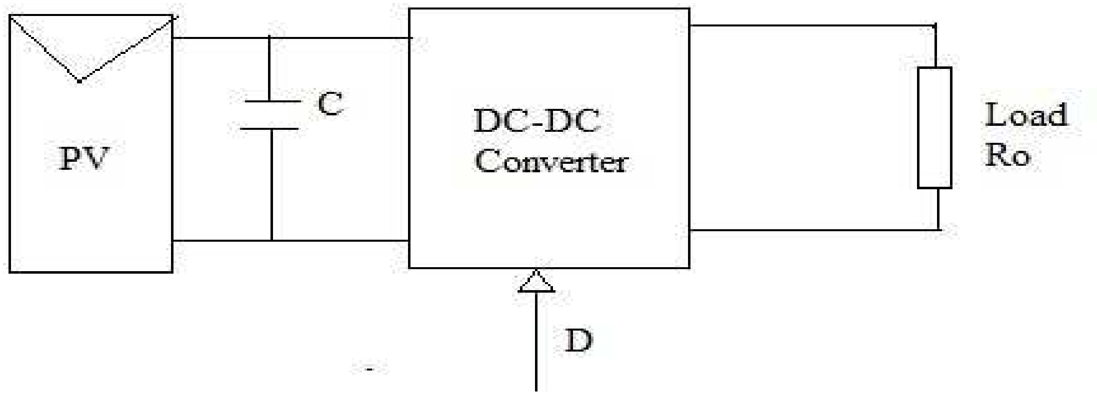
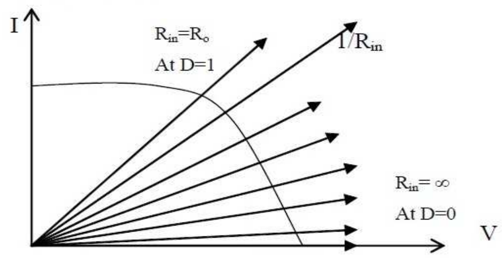
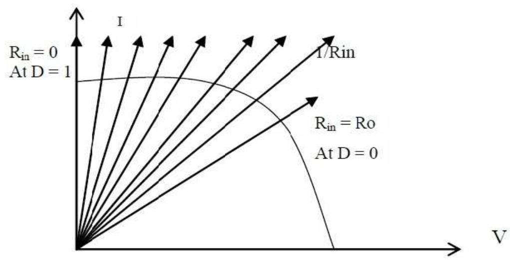


Figure 2.8: PV module interface DC DC Converter

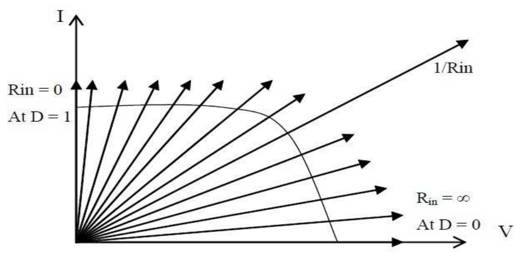
The range of R_{in} values for different converters are as shown in the following figures 2.9.



(a) Buck



(b) Boost



(c) Buck Boost

Figure 2.9: Variation R_{in} with D

This implies the range of load, that PV cell/panel can deliver maximum power.Hence, we need to look at the following requirements from an application:

a Range of load variation.

b Maximum power point Pmp (Vmp, Imp).

c Converter type that satisfies the range.

2.3 DC-DC Converter Analysis

2.3.1 Boost Converter

A boost converter is switch mode power supply which has an output voltage greater than its input voltage. MOSFET or IGBT are used for switching in boost converter. When the switch S1 is closed the current flows in first loop and the current through the inductor increases. When the switch opens, the voltage across inductor and input voltage combine in series and charges up the output capacitor to higher voltage than the input voltage. The duty ratio of the switching signal determines output voltage. The longer switch is closed, higher output voltage is expected. [5] A boost converter is a DC-to-DC power converter with an output voltage greater than its input voltage. It is a class of switched-mode power supply (SMPS) containing at least two semiconductor switches (a diode and a transistor) and atleast one energy storage element, a capacitor, inductor, or the two in combination. Filters is used to reduce the output voltage ripple. Fig below show the circuit diagram of a boost converter.

2.3.2 Working of the boost converter

The energy is transferred from input voltage source to output load. The output voltage is higher than the input voltage. There is a switch which is closed then the inductor will get energized and store the energy during on time period of

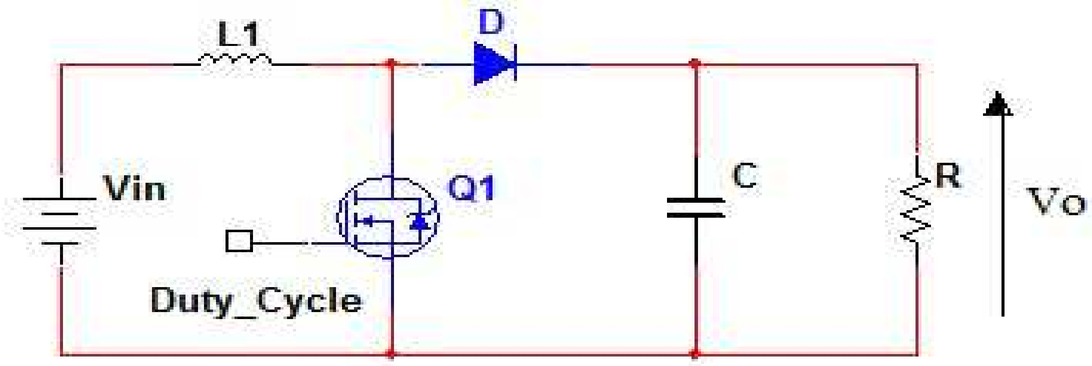
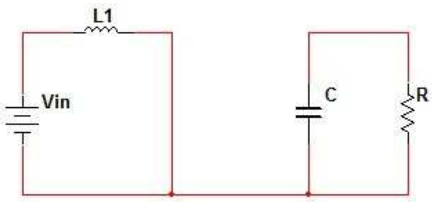


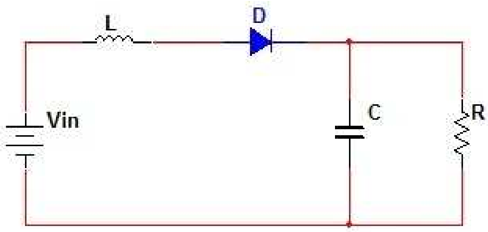
Figure 2.10: Circuit Diagram of Boost Converter

the switching signal, and diode will be open circuited. So output circuit will be disconnected.

When the switch is open diode will forward biased and the current will flow in load. Current will be summation of the supply current and stored in inductor during the on period of switching signal. During the on period when switch is close inductor



(a) Equivalent Circuit for Mode 1



(b) Equivalent Circuit for Mode 2

current will increase linearly, and the voltage across the inductor will be

$$V_{in} = L\frac{di}{dt} \tag{2.17}$$

Assuming that inductor current rise linearly from I_1 to I_2 in time t_1

$$V_{in} = L\frac{(I_2 - I_1)}{t_1} \tag{2.18}$$

$$t_1 = \frac{L\Delta I}{V_{in}} \tag{2.19}$$

When the switch will be open voltage across inductor will be theldifference of source voltage and the output voltage

$$V_L = V_{in} - V_o \tag{2.20}$$

$$L\frac{di}{dt} = V_{in} - V_o \tag{2.21}$$

$$L\frac{(I_2 - I_1)}{t_2} = V_{in} - V_o \tag{2.22}$$

$$t_2 = \frac{L\Delta I}{V_o - V_{in}} \tag{2.23}$$

Where $\Delta I = I_2$-I_1 is the peak ripple current of inductor L.
from eq 2.19 and eq 2.23

$$\Delta I = \frac{t_1 V_{in}}{L} = \frac{(V_o - V_{in})t_2}{L} \tag{2.24}$$

Substituting $t_1 = DT$ and $t_2 = (1 - D)T$ the average output voltage,

$$V_o = \frac{V_{in}}{1 - D} \tag{2.25}$$

for lossless converter,$V_o I_o = V_{in} I_{in}$,hence

$$I_{in} = \frac{I_o}{1 - D} \tag{2.26}$$

The switching period T is

$$T = t_1 + t_2 = \frac{\Delta IL}{V_{in}} + \frac{\Delta IL}{V_o - V_{in}} \tag{2.27}$$

The peak to peak ripple current can be found from above eq 2.27

$$\Delta I = \frac{V_{in}(V_o - V_{in})}{fLV_o} \tag{2.28}$$

$$\Delta I = \frac{DV_{in}}{fL} \tag{2.29}$$

When the capacitor is on,the transistor supplies the load current for $t = t_1$,The average capacitor current during time t_1 is $I_c = I_o$ and peak-to-peak ripple voltage of capacitor is

$$\Delta V_c = V_c - V_c(t = 0) = \frac{1}{C}\int_0^{t_1} I_c \, dt$$

$$= \frac{1}{C}\int_0^{t_1} I_o \, dt = \frac{I_o}{C} t_1 \tag{2.30}$$

$$L_c = L = \frac{D(1 - D)R}{2f} \tag{2.31}$$

$$C_c = C = \frac{D}{2fR} \tag{2.32}$$

2.4 Modelling of DC-DC converter in Matlab

For simulating boost converter in MATLAB ,the state space model of boost converter is used.The state space equations are obtained from On and Off state voltage and current relationship. Then these ordinary differential equations are solved to find input current I_L and output voltage V_c using trapezoidal method of integration. The MATLAB program used to observe the input and output current and voltage change with duty cycle. subsectionstate space modelling of Boost Converter The circuit diagram of boost converter shown in fig 2.12 and fig 2.3.2 shows the circuit diagram for ON and OFF state.

The general form of state space matrix is given by,

$$\dot{x} = Ax(t) + Bu(t) \tag{2.33}$$

$$y = Cx(t) + Du(t) \tag{2.34}$$

where,

A=System Matrix

B=Input Matrix

C=Output Matrix

D=feed-through matrix

x=state vector

u=input vector

y=output vector

The state variables for the system are inductor current i_L and capacitor voltage v_c.The Kirchoff's current and voltage equations are solved to get state matrix.

when switch is ON,

By KVL,

$$V_{in} - L\frac{di_L}{dt} = 0 \tag{2.35}$$

$$\dot{i_L} = \frac{V_{in}}{L} \tag{2.36}$$

By KCL,

$$ \tag{2.37}$$

$$\frac{V_c}{R} + C\frac{dv_c}{dt} = 0 \tag{2.38}$$

$$\dot{v_c} = -\frac{v_c}{RC} \tag{2.39}$$

$$\begin{bmatrix} \dot{i_L} \\ \dot{v_c} \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{RC} \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} Vin \tag{2.40}$$

When switch is OFF.by KVL

$$V_{in} - L\frac{di_L}{dt} - v_c = 0 \tag{2.41}$$

$$\dot{i_L} = \frac{V_{in} - v_c}{L} \tag{2.42}$$

By KCL,

$$ \tag{2.43} $$

$$ i_L = c\frac{dv_c}{dt} + \frac{v_c}{R} \tag{2.44} $$

$$ \dot{v_c} = \frac{1}{C}\left(i_L - \frac{v_c}{R}\right) \tag{2.45} $$

$$ \begin{bmatrix} \dot{i_L} \\ \dot{v_c} \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} Vin \tag{2.46} $$

$$ V_o = v_c \tag{2.47} $$

$$ v_o = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} i_L \\ v_c \end{bmatrix} \tag{2.48} $$

2.4.1 Simulation of Boost Converter in Matlab

The above state space matrices are solved by using trapezoidal metod of integration.

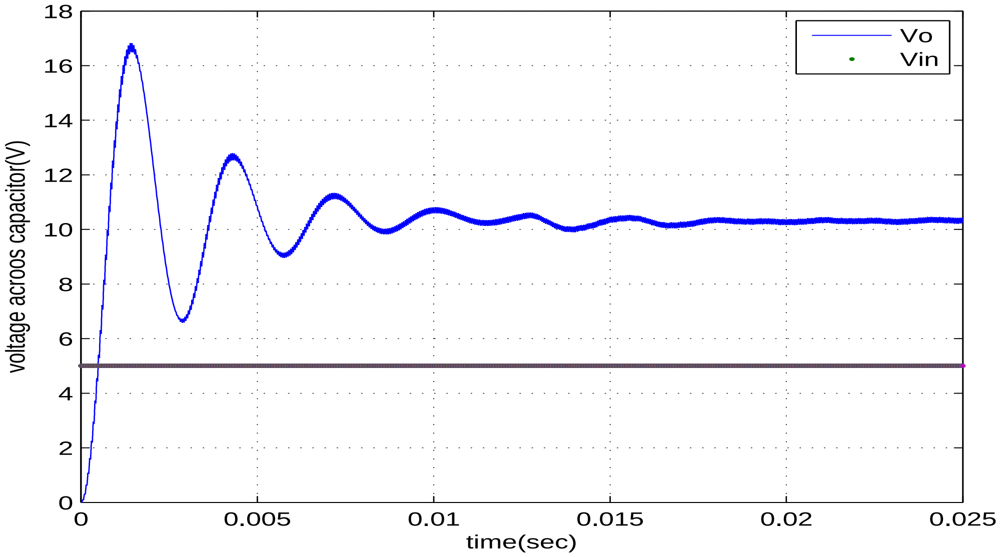


Figure 2.11: Input Voltage and Capacitor voltage of Boost Converter

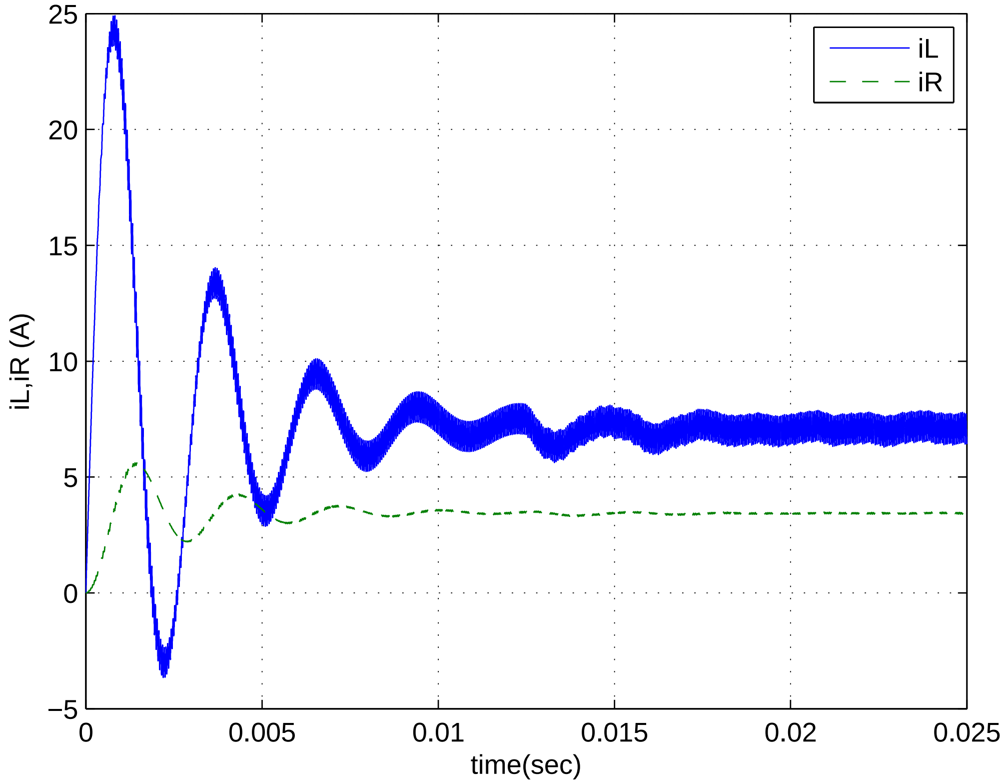


Figure 2.12: Inductor Current and Output Current of Boost Converter

Chapter 3

MPPT Algorithms

PV module would have a maximum power point for given temperature and insolation. If a load line crosses at this point, maximum power would be transferred to the load. When temperature /insolation changes, maximum power point changes. Since the load line does not change, it does not pass through the maximum power point and hence maximum power cannot be transferred to the load. To achieve the transfer of maximum power, it requires that the load follows the maximum power point and this is achieved by translating the actual load line point to maximum power point by varying the duty cycle of DC-DC converter. We can vary the

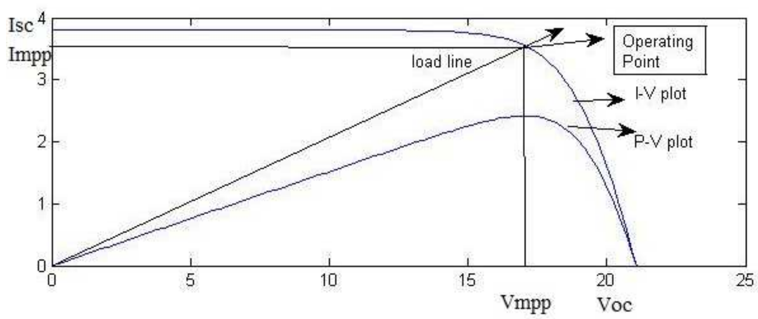


Figure 3.1: Load Line and Operating Point

DC-DC converter duty cycle(D) manually to operate PV system at maximum power point(Vmpp, Impp) .As the temperature and incident solar radiation changes throughout the day we should have to set duty cycle(D) automatically to track the maximum power point automatically. There are various techniques which adjust duty cycle (D) automatically which can be implemented in analog or digital mehod [5].

3.1 Maximum Power Point Techniques

Broadly the MPPT methods are classified in two types
Indirect metod: Maximum power point is estimated from various parameters such as voltage,current,irradiance temperature, using empirical data or using mathematical expression. This estimation is carried for specific PV system. Some of these techniques are:

- Curve fitting method
- Lookup table method
- Fractional OC method
- Fractional SC method

Direct methods: These techniques does not require any prior knowledge about PV panel and are independent of temperature ,insolation or degradation levels. They use voltage and/or current information about PV to track MPP. These techniques are computationaly intensive. Some of these techniques are:

- Pertub and Observe /Hill climbing Method
- Incremental Conductance Method
- Fuzzy Logic Control
- Sliding Mode Control Method

3.1.1 Constant voltage Method

This is also called as fractional open-circuit voltage method. MPP voltages is fractional of open-circuit voltage of PV system, that can be described as following equation,

$$V_{mpp} \approx k_1 V_{oc} \tag{3.1}$$

where k is between 0.71 to 0.78.

Under different irradiance condition, this coefficientk_1 will not change much. The MPP voltage decreases slightly when sunlight is reducing.Similarly the open-circuit voltage also decreases accordingly, the ratio between MPP voltage and open-circuit voltage on each curve is kept at k_1. The Vmpp and Voc for a specific PV array is computed beforehand empirically at different temratures and insolation levels. When the k_1 is known for specific PV array it needs to open circuit the PV array periodically to measure V_oc hence there is power loss occurs.The PV array operates at MPP (approximately).This method has low power generation efficiency. Frctional short circuit current method is there but generally it is not used because voltage measurement is simpler than current measurent.

3.1.2 Look Up Table Method

Look up table methods are relatively fast techniques that are able to directly provide the duty cycle to the suitable value . In this techniques, for a known characteristic of PV array, we need to store a duty cycle value for each temperature and insolation. Thus by measuring temperature and irradiance, a duty cycle is directly related with them. These techniques consume lot of memory and do not serve as a real searching algorithms, although the results obtained are satisfactory.

3.1.3 Pertub & Observe Algorithm

Perturb and Observe is most widely used MPPT method. It is based on Hill Climbing concept.

From the P-V charactistics of soalar array the power increases with voltage upto MPP and then power decreases as volatage increases further.Hence,Increasing the voltage increases the power when operating point is on the left of MPP and decreases the power when operating point is on the right of MPP. The controller adjusts the voltage by a small amount from the array and measures power; if the power increases, then further adjustments in that direction are tried until power no longer increases. Hill climbing method involve a perturbation in duty cycle .While P&O method involve the perturbation in operating voltage of PV array.

Perturb and Observe introduces an initial perturbation to the voltage by changing duty cycle of converter and then observations are made using sensing circuitry. P&O algorithm uses voltage and current measurements to calculate change in power over a change in time ΔP and change in the duty cycle ΔD of the signal sent to the gate of the switch in the boost converter. Given that ΔP and ΔD can be each either positive or negative, so there are four cases. To determine whether the duty cycle of the gate signal should be increased or decreased. The four cases are shown in Table 1. The first case, when both power and the duty cycle has increased, the duty cycle should continue to increase toward the MPP. Second Case is similar except the duty cycle should continue to decrease toward the MPP. Cases three and four occur when the power has decreased, so the duty cycle has moved the PV voltage away from the MPP. The duty cycle is reversed. It is decreased in case three and increased in case four.

Table 3.1: Summary of Hill Climbing and P&O Algorithm

Perturbation	Change in Power	Next Perturbation
Positive	Positive	Positive
Positive	Negative	Negative
Negative	Positive	Negative
Negative	Negative	Positive

The P&O algorithm can be implementaed using digital/analog circuitary.Voltage and current sensor required to implement.

The system oscillates around MPP. The oscillations are minimised by decreasing perturbation step size. But decreasing perturbation step size slows down MPPT algorithm. Variable pertubation step size gets small time to track MPP. Reference [14] [23] toggles between traditional hill-climbing algorithm and modified adaptive hill-climbing method to avoid deviation from the MPP. P&O method may result in top-level efficiency, when a proper predictive and adaptive hill climbing strategy is implemented. [6, 24]

Hill-climbing and P&O method can fail under rapidly changing atmospheric conditions [22] fig 3.2. Starting from an operating point A, if the atmospheric conditions remains approximately constant, a perturbation ΔV in the PV voltage V will bring operating point to B and perturbation will be reversed due to decrease in thepower. But, if the irradiance increases and shift the power curve from P1 to P2 within one sampling period, the operating point will move from point A to point C. This represents increase in power and perturbation is kept same. Subsequently, operating point will diverges from the MPP and will keep diverging if irradiance is steadily increases. To guarantee that the MPP is tracked even under the sudden changes in the irradiance, [15] uses three-point weight comparison P&O method that compares actual power point to two preceding ones before a decision is made about the perturbation sign. Reference [16] optimizes sampling rate while [17] simply uses high sampling rate.

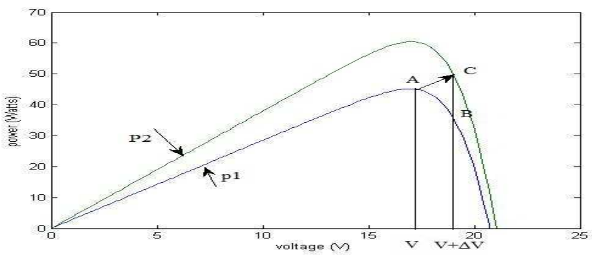
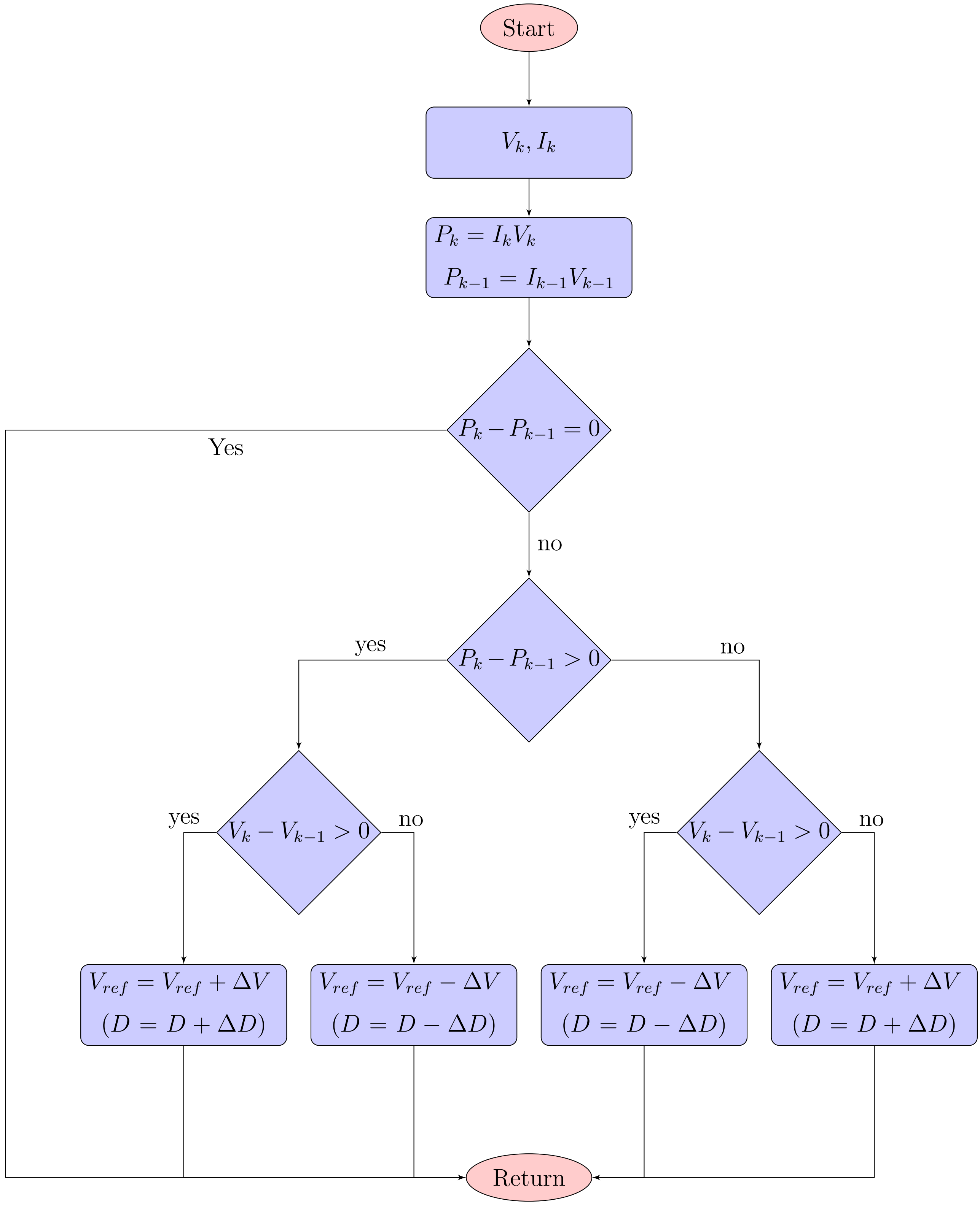


Figure 3.2: Divergence of hill climbing or P&O from MPP

Flowchart of P&0 / Hill Climbing Algorithm



Matlab Simulation Results of P&O Algorithm

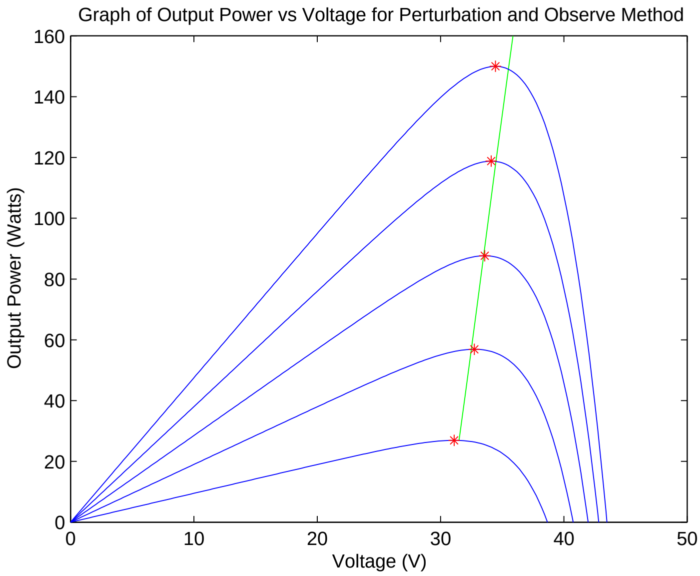


Figure 3.3: Matlab Simulation of P&O Algorithm

3.1.4 Incremental Conductance Algorithm

Incremental Conductance (INC) is the second MPPT algorithm possibility for this project. In cases of rapidly changing atmospheric conditions, as a result of moving clouds, it was noted that the P&O MPPT algorithm deviates from the MPP. Avoiding the P&O algorithm drawbacks formed the basis of the INC Conduction algorithm in which the array terminal voltage is always adjusted according to its value relative to the MPP voltage. At the MPP the derivative of the power with respect to the voltage is zero because the MPP is the maximum of the power curve(i.e slope of P-V curve at MPP is zero). we note that to the left of the MPP the power is increasing with the voltage, i.e. $dP/dV > 0$(slope is positive), and it is decreasing to the right of the MPP, i.e. $dP/dV < 0$(slope is negative).
Slope of PV Curve is

- Zero at Maximum power Point

- Negative on right of of Maximum power Point
- Positive on left of Maximum power Point

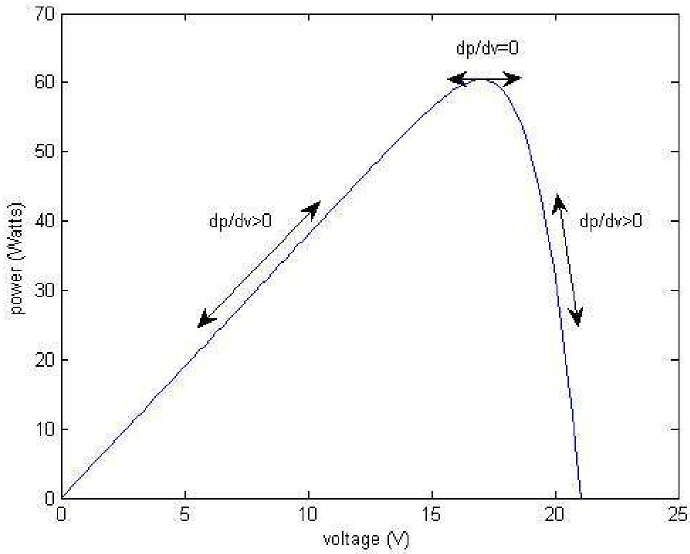


Figure 3.4: INC Algorithm

We know that

$$P = VI \tag{3.2}$$

$$\frac{dP}{dV} = \frac{d(IV)}{dV} = I + V\frac{dI}{dV} \cong I + V\frac{\Delta I}{\Delta V} \tag{3.3}$$

So,

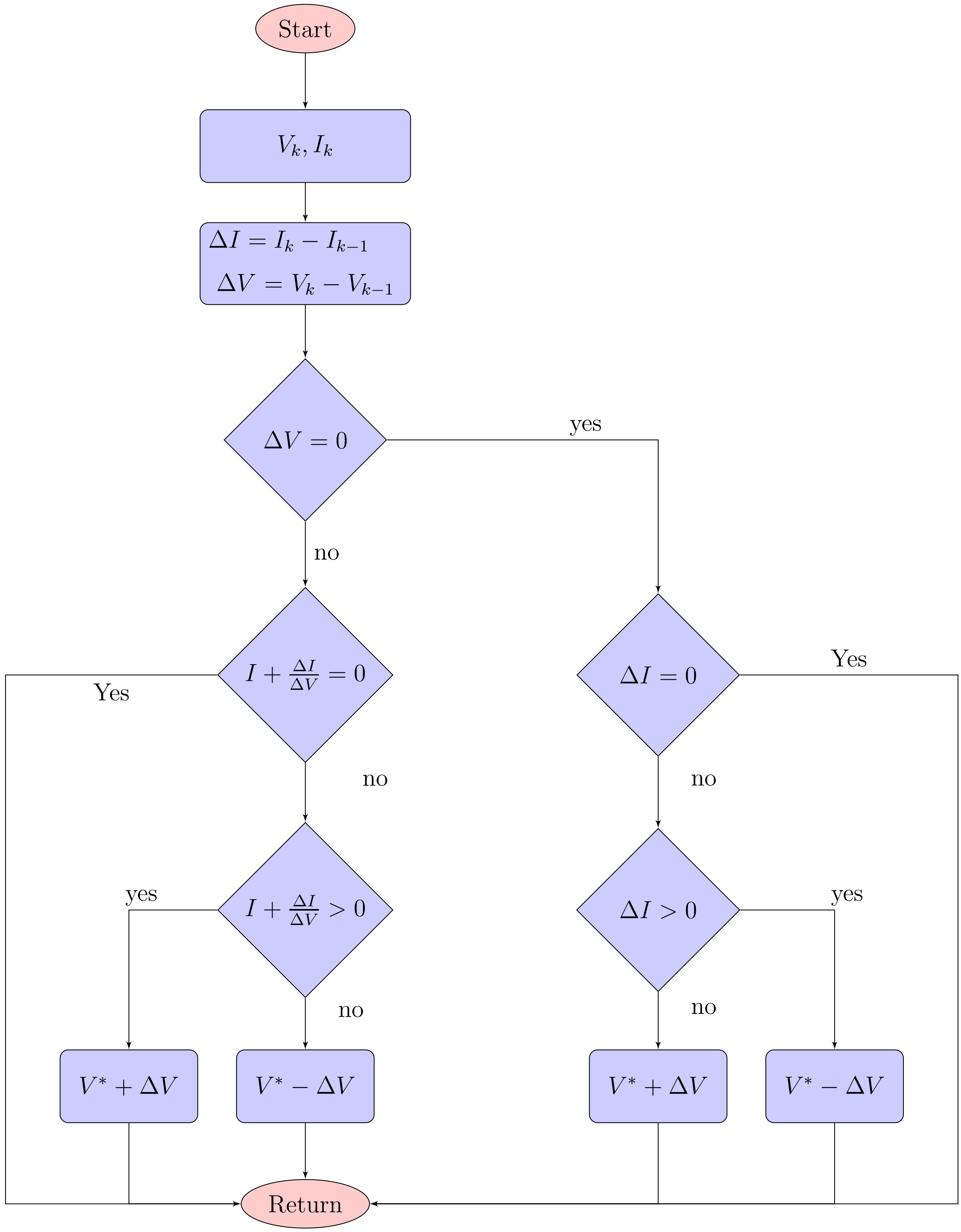
$$\frac{\Delta I}{\Delta V} = -\frac{I}{V},\ at\ MPP \tag{3.4}$$

$$\frac{\Delta I}{\Delta V} > -\frac{I}{V},\ left\ of\ MPP \tag{3.5}$$

$$\frac{\Delta I}{\Delta V} < -\frac{I}{V},\ right\ of\ MPP \tag{3.6}$$

Hence, the PV array terminal voltage can be adjusted relative to the MPP voltage by calculating the incremental conductance$\Delta I/\Delta V$ and instantaneous array conductance I/V and making use of above eqns.

Flowchart of Incremenatal Conductance Algorithm



Matlab Simulation Results of Incrremental Conductance Algorithm

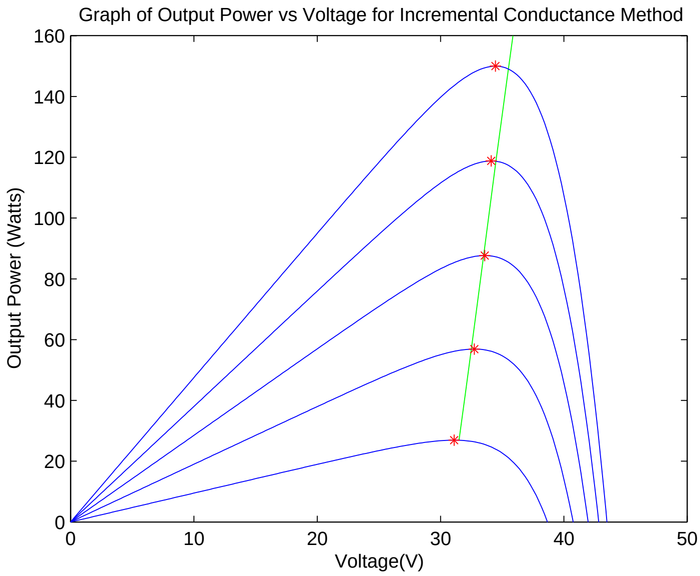


Figure 3.5: Matlab Simulation of INC Algorithm

3.1.5 Comparison of P&O and INC Algorithm

- Unlike P&O, Increamental Conductance algorithm is able to track a MPP in rapidly changing environment.
- However Increamental Conductance algorithm has increased susceptibility to noise and has increased complexity compared to P&O.
- In INC Power loss occurs since it oscillates around MPP like P&O.
- Tracking step size is value has significant effect on effectiveness of MPPT. When tracking step is chosen correctly, P&O will give performance equivalent to INC.
- P&O is a very popular and widely accepted MPPT algorithm and simpler to implement than INC.

3.2 Major Characteristics and Comparison of Various MPPT Techniques

Table 3.2: Major Characteristics of differernt MPPT Techniques

MPPT Technique	PV array Dependent?	True MPPT?	Analog or Digital?	Periodic Tuning?	Convergence speed	Implementation Complexity	Sensed Parameters
Hill Climbing/ P& O	No	Yes	Both	No	Varies	Low	Voltage,Current
Incremental Conductance	No	Yes	Digital	No	Varies	Medium	Voltage,Current
Fractional Voltage Voc	Yes	No	Both	Yes	Medium	Low	Voltage
Fractional Current Isc	Yes	No	Both	Yes	Medium	Medium	current
Fuzzy Logic Control	Yes	Yes	Digital	Yes	Fast	High	Varies
Neural Network	Yes	Yes	Digital	Yes	Fast	High	Varies
Lookup Table Method	Yes	Yes	Digital	Yes	Fast	Medium	Voltage,Current, Temparature, Irradiance
Online MPP Search Algorithm	No	Yes	Digital	No	Fast	High	Voltage,Current
Slide Control	No	Yes	Digital	No	Fast	Medium	Voltage,Current
Temprature Method	No	Yes	Digital	Yes	Medium	High	Voltage, Temparature, Irradiance
Three Point Weight Chasing	No	Yes	Digital	No	Varies	Low	Voltage,Current,
Biological Swarm Chasing MPPT	NO	Yes	Digital	No	Varies	High	Voltage,Current, Temparature, Irradiance

Chapter 4

System Design and Implementation

4.1 Proposed System

The main purpose of this project is to implement Maximum power point algorithm in FPGA which will provide more advantage than DSP processor or microcontroller. This algorithm will be installed on a controller. The controller will be implemented on an FPGA (Field Programmable Gate Arrays) and designed through a computer using graphical programming language called LabVIEW. The programmed FPGA will be able to automatically control the whole power system operation without the need of any user intervention.

The sampling Circuitary is used to convert voltage and current from analog to digital. The proposed system consists of Boost type DC/DC power converter, which is controlled by an FPGA-based unit using the Pulse Width Modulation (PWM) principle.

The advantage of this project is to give access to an everlasting and pollution free source. of energy. And give the user the option to use the system in two possible operating modes; the stand alone mode which is used to satisfy his needs, and the

grid connected mode which used to sell electricity to utility when in excess; thus eliminating the need of battery storage.
The overall system is shown in following fig 4.1

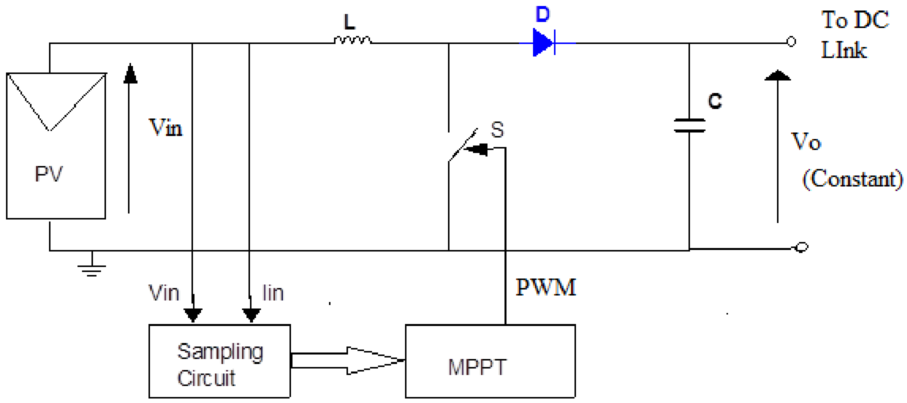


Figure 4.1: Block Diagram of Photovoltaic System

4.2 PV Simulator

To check MPPT Algorithm we need solar panel array. But for offline testing of MPPT Algorithm the solar panels are costly and we can't replicate the actual environment in laboratory .Most people use solar emulator to emulate PV array characteristics for a given temperature and irradiance . For simulating PV array characteristics we used simple circuit to be used as PV simulator. Solar panel is mainly a current source. In designing a solar panel simulator, our aim was to replicate a solar panel as current source to provide power the circuit. The main advantage of using solar panel simulator is that we can control the output of the solar array directly, than to deal with the changes that occur due to change in operating condition when testing PV MPPT outdoors. This design does not require power from artificial light source on a solar panel that is used for indoor testing. Following figure fig:pvsimulatorshows the schematic of the solar panel simulator that is used in testing and design of MPPT.

Table 4.1: I-V characteristics of PV simulator

Resistance (Ω)	Voltage(V)	Current(mA)	Voltage(V)	Current(mA)	Voltage(V)	Current(mA)
1	772.203(mV)	772.203	578.151(mV)	578.151	327.613(mV)	327.613
2	1.541	770.569	1.115	577.496	654.985(mV)	327.492
3	2.307	768.927	1.731	576.838	982.113(mV)	327.371
4	3.069	767.277	2.305	576.176	1.309	327.25
5	3.828	765.619	2.878	575.511	1.636	327.127
10	7.572	757.219	5.721	572.134	3.265	326.511
15	10.958	730.525	8.53	568.67	4.888	325.883
20	11.226	561.322	11.042	552.182	6.505	325.245
25	11.37	454.813	11.249	449.978	8.115	324.594
30	11.467	382.222	11.369	378.886	9.718	323.931
35	11.536	329.603	11.449	327.127	11.151	318.609
40	11.589	289.713	11.512	287.791	11.284	282.1
45	11.63	258.439	11.56	256.897	11.36	252.454
50	11.663	233.259	11.599	231.99	11.419	228.376
75	11.764	156.851	11.718	156.243	11.59	154.534
100	11.815	118.151	11.779	117.787	11.676	116.758
125	11.846	94.769	11.815	94.52	11.728	93.28
150	11.867	79.114	11.84	78.931	11.762	78.415
175	11.882	67.898	11.857	67.756	11.787	67.354
200	11.894	59.467	11.871	59.353	11.806	59.03
250	11.909	47.637	11.889	57.557	11.832	47.329
300	11.92	39.734	11.902	39.673	11.85	39.501

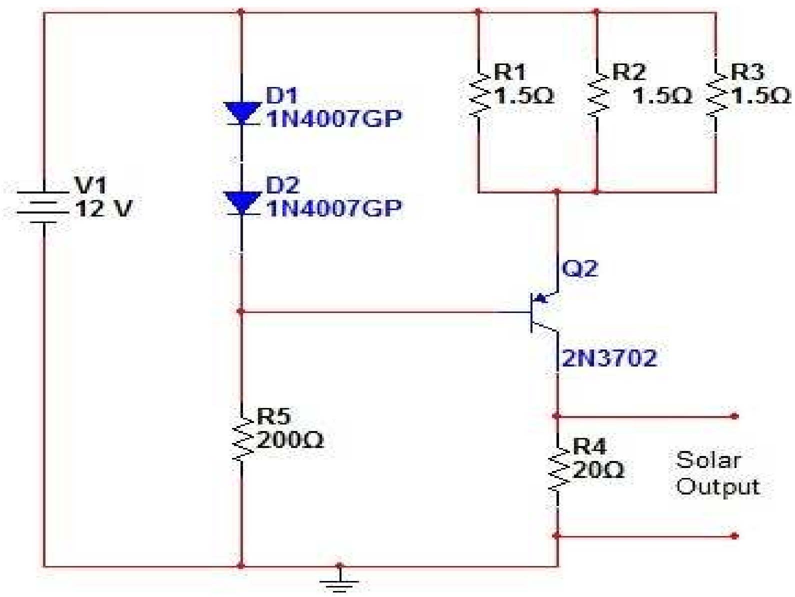


Figure 4.2: Schematic of Solar Panel Simulator

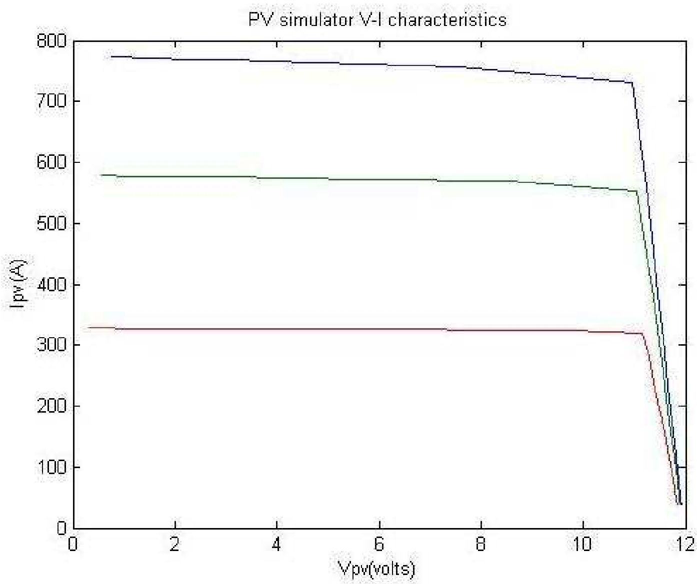


Figure 4.3: I-V characteristics of Solar Panel Simulator

4.3 Boost Converter

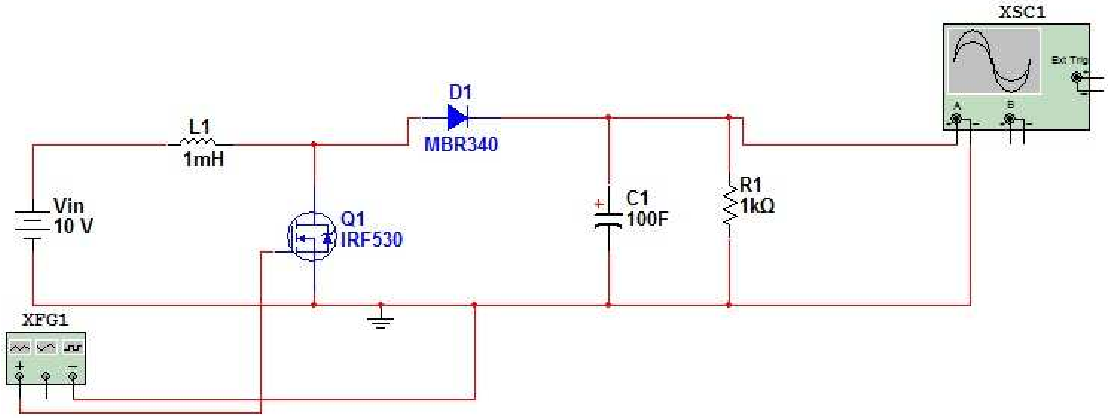


Figure 4.4: Multisim Simulation of Boost converter

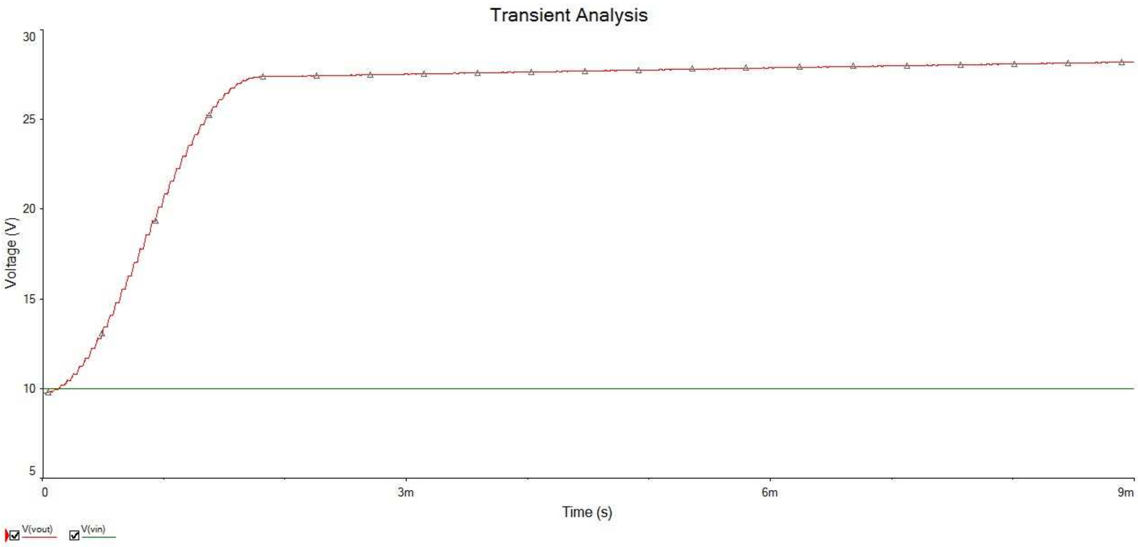


Figure 4.5: Transient Response of Boost converter

4.4 MPPT Implementation

To implement the Perturb & Observe MPPT method, software method chosen for controlling the duty cycle of converter, and the voltage and current sensing circuits were designed. Using Labview environment the MPPT algorithm is programmed .The NI compactRIO FPGA is chosen for real time implementation.

4.4.1 FPGA Based Real Time Controller

The controller is one of the important parts of the project. It controls various components of our design in order to achieve the required function. This controller will be responsible for the operation of the system at maximum efficiency. The controller will implement the MPPT algorithm.A digital controller is better suited for these operations schemes. Also, the digital controller operates at a frequency of several MHz which is much larger than that of our system, and can easily meet any design constraints imposed on it. The digital controller we will be an FPGA, and we will be using the compactRIO card from National Instruments to program the FPGA. The program will be directly installed using the LABVIEW software.The controller will have to control the driver circuits of the switch in the DC-DC converter.

The inputs of the controller are

1. Voltage from the PV panel:
   This voltage will not be provided directly. It will be stepped down by a voltage divider circuitry to be inputted into the NI cRIO device whose inputs cannot receive voltages beyond 10V.

2. Current from the PV panel
   This current cannot be provided directly since the NI cRIO cannot read current values. We are going to use current sensor that provides a mapped voltage level of the current which can be read easily by NI cRIO.The hall effect current

transducer is used for measurement of current.

Using the voltage and current signals, the controller can determine the power supplied by the PV panel and accordingly implement the MPPT algorithm installed on it.

The outputs of the controller are:

1. Control signals for the driver circuit in the DC-DC converter These signals will provide the right switching square-waveforms with the appropriate duty cycle and frequency to drive the boost converter according to the results of the MPPT algorithm.

4.4.2 Implementation Process

The first tests we did were conducted on the compactRIO card (FPGA) and LABVIEW to get aware with this tool. We were able to make a VI and download it on the FPGA. When we became used to programming in LABVIEW we tested a VI that generates a Square wave form. It worked exactly as planed. After wards we started building each block (DC-DC converter).

Tools Used:

- Computer used to write theLABVIEW program anddownload it on the FPGA
- FPGA (NI compactRIO 9014)
- Analog Input Module(NI 9201)
- Analog Output Module(NI 9263)

4.4.3 MPPT Implementation

The Mppt algorithm implemented on the FPGA controller to control the duty cycle of the boost converter is based on the P&O (Perturb and Observe) algorithm.The program is written and LABVIEW VI is built and downloaded on the FPGA.

The designed VI starts the infinite WHILE loop by initializing three values ("$Old\ \ power$" $= 0$, "$Initial\ \ Duty\ \ Cycle = 30$", "$Sign\ \ Duty\ \ Cycle = 1$"). Inside the WHILE loop there is a sequence of four steps.

The simplified algorithm states:

{

P=0, D=0, SignD=1;

Sense V_k and I_k;

Calculate $P_k = V_k * I_k$;

If $P_k > P_k - 1$

$SignD_k = SignD_{k-1} * 1$

$D_k = D_{k-1} + SignD_k$

elseif $Pk < P_{k-1}$

$SignD_k = SignD_{k-1} * -1$

$D_k = D_k - 1 + SignD_k$

else

$D_k = D_{k-1}$

end

}

The first step is the WAIT 500 ms, this step is needed when we change the duty cycle the power will change so we are introducing a delay so the power level settles and does not affect the accuracy of the sensing of the power. This is because the FPGA run this loop in microseconds and the power need about half a second to reach a steady level.

The second step initiates two FOR loops one inside the other. The inner loop runs for 10 iterations and it senses the highest Current level inputted in the FPGA from the Current sensing device so to eliminate any sensing error. The outer FOR loop runs for 100 iterations and it calculates the average levels of Current and Voltage values. While the two values are ready they multiplied with each other and a "New Power" value is obtained.

The third step initiates the cases of the algorithm;If "$NewPower$" is greater then "Old Power" (stored in a shift register in the previous iteration) then "New Sign Duty Cycle" = "Old Sign Duty Cycle" * 1 and "New Duty cycle" = "Old Duty Cycle" + "New Sign Duty Cycle", other wise if "New Power" is less then "Old Power" then "New Sign Duty Cycle" = "Old Sign Duty Cycle" * -1 and "New Duty cycle" = "Old Duty Cycle" + "New Sign Duty Cycle", else "New Duty cycle" = "Old Duty Cycle".

The fourth and final step gets the calculated "New Sign Duty Cycle" from step three and stores its value on the Flash Memory on a specified address of the FPGA in order to be used in the loop which generates the square waveform to control the Boost Converter. Before the present iteration of the WHILE loop end, all the newly calculated values ("New Power", "New Duty cycle", "New Sign Duty Cycle") are stored in shift registers to be used in the following iteration.

PWM Generation

WHILE loop generates the square waveform which controls the Boost Converter. The loop is made of a sequence of four steps. Before the sequence starts the "New Duty cycle" is obtained from the FPGA's MEMORY. This duty cycle will "ON time" and "OFF time" = "Time Period" - "ON time". First step outputs from the chosen terminal of the FPGA a voltage level around 4V, the second step is a WAIT which keeps the previous voltage level for "ON Cycle" time. Third step outputs a voltage level equal to 0V. The fourth step is a WAIT which keeps the previous voltage level for the "OFF Cycle" time. The resulting square wave outputted from the FPGA is shown in fig 4.7

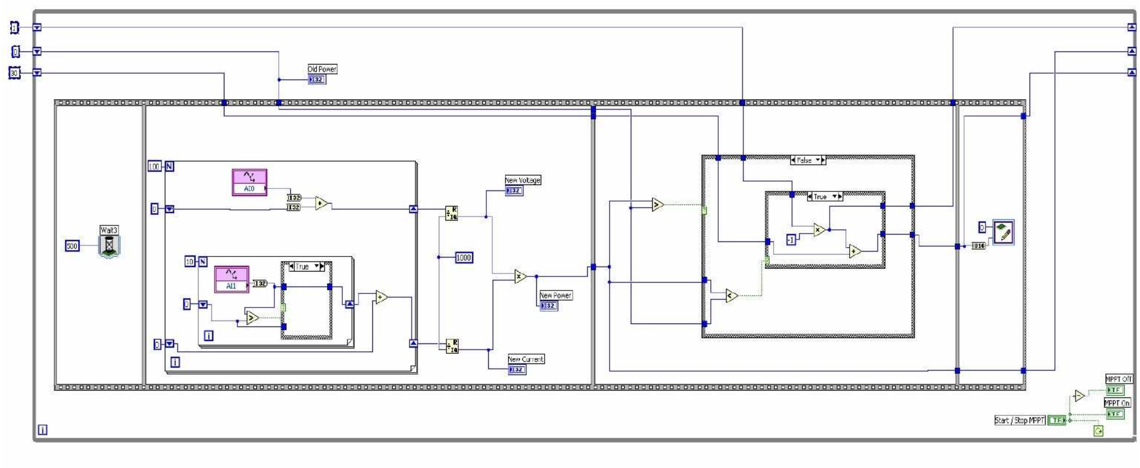


Figure 4.6: MPPT Algorithm in FPGA

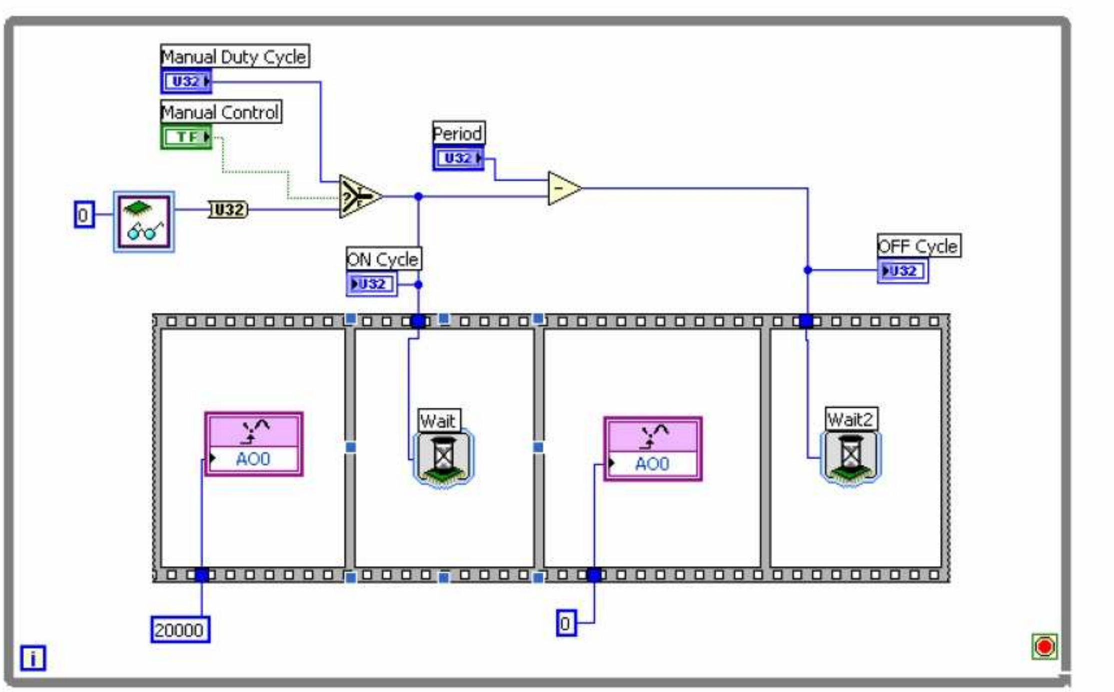


Figure 4.7: Labview Code for PWM Generation

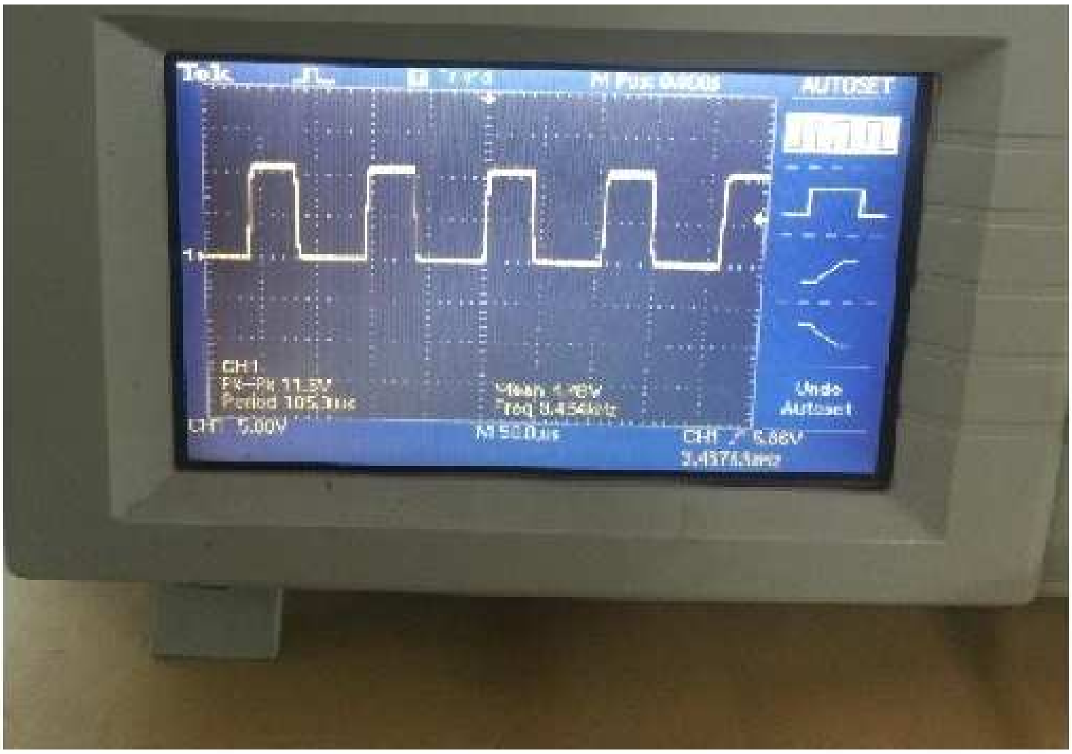


Figure 4.8: PWM waveform

4.5 Results

The following open loop results are obtained by using a function generator as PV source(thevenion equivalent) and pulse-width modulated signal from oscilloscope in combination with DC-DC converter in designed circuit.

Table 4.2: MPPT from Thevenion Equivalent circuit

Duty Cycle	Voltage(Volts)	Current(Amp)	Power(watts)
10	12.26	0.064	0.784
15	12.25	0.076	0.931
20	12.22	0.0948	1.158
25	12.20	0.1140	1.3968
30	12.16	0.1372	1.6683
35	12.11	0.165	1.998
40	12.05	0.2018	2.4316
45	12	0.2292	2.75
50	11.93	0.2628	3.147
55	11.73	0.335	3.9287
60	11.71	0.3355	3.93
65	11.33	0.4217	4.777
70	7.79	0.385	2.999
75	4.86	0.33	1.60
80	2.94	0.293	0.8614

4.6 Conclusion

Solar power continues to prove its potential as revolution for renewable energy. As companies continue research into the solar power, technology for them is becoming more and more useful. One of the main concerns for fixing problems involved with solar panel is of solar panel efficiency. A major goal for this solar panel application design was to optimize efficiency whenever possible. This was done through careful examination of product datasheets to obtain most desirable part, mainly with least amount of associated power loss. Continuous effort to maximize the efficiency should always be taken when we designing solar power applications to increase the solar energies usability and value.

The design of maximum power point tracking system proved to be serious design challenge. There are so many factors involved when designing circuit that depends on both digital and analog aspects of the circuitry. There are inherently many problems when designing system that relies heavily on digital circuitry. Errant code writing is one such problem, and can only be remedied through trial and experience. Overall, the digital portion of the circuit was performing as it should, however the interface between the analog and digital portion was found difficult.

There were many problems in design of maximum power point tracking for PV system but this project has given invaluable experience for future. It is useful for addressing different issues of system design in future. The experience was a valuable lesson in the problems that may occur when designing, ordering, assembling, and testing parts. We would have preferred to have a working prototype at the end of the design process, however the experience was enlightening and challenging at the same time.

Bibliography

[1] Geoff Walker. Evaluating mppt converter topologies using a matlab pv model. *Journal of Electrical & Electronics Engineering*, 21(1):49–56, 2001.

[2] Francisco M González-Longatt. Model of photovoltaic module in matlab. *II CIBELEC*, 2005:1–5, 2005.

[3] Hiren Patel and Vivek Agarwal. Matlab-based modeling to study the effects of partial shading on pv array characteristics. *Energy Conversion, IEEE Transactions on*, 23(1):302–310, 2008.

[4] Roberto Faranda and Sonia Leva. Energy comparison of mppt techniques for pv systems. *WSEAS transactions on power systems*, 3(6):446–455, 2008.

[5] Trishan Esram and Patrick L Chapman. Comparison of photovoltaic array maximum power point tracking techniques. *Energy conversion, IEEE transactions on*, 22(2):439–449, 2007.

[6] Nicola Femia, Giovanni Petrone, Giovanni Spagnuolo, and Massimo Vitelli. Optimization of perturb and observe maximum power point tracking method. *Power Electronics, IEEE Transactions on*, 20(4):963–973, 2005.

[7] Y-H Liu, S-C Huang, J-W Huang, and W-C Liang. A particle swarm optimization-based maximum power point tracking algorithm for pv systems operating under partially shaded conditions. 2012.

[8] Chihchiang Hua and Chihming Shen. Study of maximum power tracking techniques and control of dc/dc converters for photovoltaic power system. In *Power Electronics Specialists Conference, 1998. PESC 98 Record. 29th Annual IEEE*, volume 1, pages 86–93. IEEE, 1998.

[9] YM Tung, Aiguo Patrick Hu, and Nirmal-Kumar Nair. Evaluation of micro controller based maximum power point tracking methods using dspace platform. In *Australian University, Power Engineering Conference*, 2006.

[10] A Messai, A Mellit, A Guessoum, and SA Kalogirou. Maximum power point tracking using a ga optimized fuzzy logic controller and its fpga implementation. *Solar energy*, 85(2):265–277, 2011.

[11] Noppadol Khaehintung, Theerayod Wiangtong, and Phaophak Sirisuk. Fpga implementation of mppt using variable step-size p&o algorithm for pv applications. In *Communications and Information Technologies, 2006. ISCIT'06. International Symposium on*, pages 212–215. IEEE, 2006.

[12] Eftichios Koutroulis, Kostas Kalaitzakis, and Vasileios Tzitzilonis. Development of an fpga-based system for real-time simulation of photovoltaic modules. *Microelectronics Journal*, 40(7):1094–1102, 2009.

[13] A Mellit, H Rezzouk, A Messai, and B Medjahed. Fpga-based real time implementation of mppt-controller for photovoltaic systems. *Renewable energy*, 36(5):1652–1661, 2011.

[14] Weidong Xiao and William G Dunford. A modified adaptive hill climbing mppt method for photovoltaic power systems. In *Power Electronics Specialists Conference, 2004. PESC 04. 2004 IEEE 35th Annual*, volume 3, pages 1957–1963. IEEE, 2004.

[15] Tu A Nguyen, Xin Qiu, Thoshitha T Gamage, Mariesa L Crow, Bruce M McMillin, and AC Elmore. Microgrid application with computer models and power management integrated using pscad/emtdc. In *North American Power Symposium (NAPS), 2011*, pages 1–7. IEEE, 2011.

[16] Nicola Femia, Giovanni Petrone, Giovanni Spagnuolo, and Massimo Vitelli. Optimization of perturb and observe maximum power point tracking method. *Power Electronics, IEEE Transactions on*, 20(4):963–973, 2005.

[17] N.S. D'Souza, L. A C Lopes, and X. Liu. An intelligent maximum power point tracker using peak current control. In *Power Electronics Specialists Conference, 2005. PESC '05. IEEE 36th*, pages 172–, 2005.

[18] Paresh Chandra Sen. *Power electronics*. Tata McGraw-Hill Education, 1987.

[19] Muhammad H Rashid, Muhammad Harunur Rashid, and Muhammad Harunur Rashid. *Power electronics: circuits, devices, and applications*, volume 2. Prentice Hall NJ, 1988.

[20] Muhammad H Rashid. *Power electronics handbook*. Academic Pr, 2001.

[21] Chetan Singh Solanki. *Solar Photovaltaics*. PHI Learning Pvt. Ltd., 2011.

[22] KH Hussein, I Muta, T Hoshino, and Ml Osakada. Maximum photovoltaic power tracking: an algorithm for rapidly changing atmospheric conditions. In *Generation, Transmission and Distribution, IEE Proceedings-*, volume 142, pages 59–64. IET, 1995.

[23] Weidong Xiao and William G Dunford. A modified adaptive hill climbing mppt method for photovoltaic power systems. In *Power Electronics Specialists Conference, 2004. PESC 04. 2004 IEEE 35th Annual*, volume 3, pages 1957–1963. IEEE, 2004.

[24] Panagiotis E Kakosimos and Antonios G Kladas. Implementation of photovoltaic array mppt through fixed step predictive control technique. *Renewable energy*, 36(9):2508–2514, 2011.

[25] N Patcharaprakiti, K Kirtikara, D Chenvidhya, V Monyakul, and B Muenpinij. Modeling of single phase inverter of photovoltaic system using system identification. In *Computer and Network Technology (ICCNT), 2010 Second International Conference on*, pages 462–466. IEEE, 2010.

[26] Chihchiang Hua and Chihming Shen. Comparative study of peak power tracking techniques for solar storage system. In *Applied Power Electronics Conference and Exposition, 1998. APEC'98. Conference Proceedings 1998., Thirteenth Annual*, volume 2, pages 679–685. IEEE, 1998.

[27] N Patcharaprakiti, K Kirtikara, D Chenvidhya, V Monyakul, and B Muenpinij. Modeling of single phase inverter of photovoltaic system using system identification. In *Computer and Network Technology (ICCNT), 2010 Second International Conference on*, pages 462–466. IEEE, 2010.

[28] Wang Yi-bin, Bao-liang QI, and Yong-jian SUN. Research of photovoltaic inverter based on labview and dsp [j]. *Construction Conserves Energy*, 2:014, 2007.

[29] Kapil Bhise, Nataraj Pragallapati, Sushil Thale, and Vivek Agarwal. Labview based emulation of photovoltaic array to study maximum power point tracking algorithms. In *Photovoltaic Specialists Conference (PVSC), 2012 38th IEEE*, pages 002961–002966. IEEE, 2012.

[30] Massimo Valentini, Alin Raducu, Dezso Sera, and Remus Teodorescu. Pv inverter test setup for european efficiency, static and dynamic mppt efficiency evaluation. In *Optimization of Electrical and Electronic Equipment, 2008. OPTIM 2008. 11th International Conference on*, pages 433–438. IEEE, 2008.

[31] Ke DU, Shan-xu DUAN, and Fei LIU. Reserch on the photovoltaic array simulator based on matlab [j]. *Telecom Power Technologies*, 3:003, 2006.

[32] Li-bo Wu, Zheng-ming Zhao, Jian-zheng Liu, Jian Wamg, and Shu Liu. Research on the stability of mppt strategy applied in single-stage grid-connected photovoltaic system. *PROCEEDINGS-CHINESE SOCIETY OF ELECTRICAL ENGINEERING*, 26(6):73, 2006.