COMPARISON BETWEEN PERTURB AND OBSERVE AND INCREMENTAL CONDUCTANCE ALGORITHMS FOR PHOTOVOLTAIC SYSTEMS USING BUCK CONVERTER

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A project report submitted in partial fulfilment of the requirements for the award of Master of Electronic System

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April 2019

DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **"COMPARISON BETWEEN PERTURB AND OBSERVE AND INCREMENTAL CONDUCTANCE ALGORITHMS FOR PHOTOVOLTAIC SYSTEMS USING BUCK CONVERTER"** was prepared by **MALVEENDERJIT SINGH HULLON** has met the required standard for submission in partial fulfilment of the requirements for the award of Master of Electronic System at Universiti Tunku Abdul Rahman.

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ABSTRACT

Photovoltaic (PV) module is a very popular choice for renewable energy source globally. PV cells in general are harvesting light energy from the sun or any light source to produce electricity for consumption by humans in their daily life. However in today's implementation of PV module for energy harvesting has introduced several challenges.

The main challenges faced is the ability to ensure the PV module is performing well at all times with highest efficiency. This is to ensure no energy is wasted or under-utilized. In this research a simple buck converter for open loop PV application is designed with two different maximum power point tracking (MPPT) algorithms which are the Incremental Conductance (IC) and Perturb and Observe (P&O).

The buck converter is used in order to perform load matching to track the maximum power point. The duty cycle is controlled through the MPPT algorithm. The approach of this study is to compare the difference in terms of duty cycle step size, resultant power with the IC and P&O MPPT algorithms and performance of buck converter when using the IC and P&O algorithm.

The buck converter performs well with minimum efficiency 94 percent and maximum of 98.9 percent with both MPPT algorithms. The difference in efficiency of the buck converter when implementing both algorithms are about 1 percent at low irradiance levels of 200 to 800 W/m^2.

The MPPT algorithm of P&O has lesser accuracy due to oscillation about the maximum power point compared to the IC algorithm which has more accuracy with lesser oscillation about the maximum power point. However, the implementation of the IC method is more complex with more calculation needed to be performed to decide on the direction to perform the duty cycle change.

In conclusion, for easier and hassle free implementation, the best choice is the P&O algorithm. However for more accurate MPPT tracking, the designers should choose the incremental conductance technique.

For the future works, the comparison should be done in the form of hardware implementation with more accurate weather and shading conditions.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS / ABBREVIATIONS

MPPT	maximum power point tracker/tracking
MPP	maximum power point
PV	photovoltaic
P&O	perturb and observe
IC	incremental conductance
LIR	inductor current ripple
CVR	capacitor voltage ripple
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
ΔI	change of current
ΔV	change of voltage
η	Efficiency

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 General Introduction

The depletion of natural resources on a worldwide basis has necessitated an urgent search for alternative energy to meet present energy demands. In recent decades, researchers have been developing the photovoltaic panels as an alternative source of electrical energy. Photovoltaic (PV) module is made up of solar cells being connected together either in parallel or in series to form a module. Several PV modules can be connected together to produce an even higher output power. The surface area of a cell and the intensity of the light hitting the panel determines the amount of current produced (Gaur, Verma and Singh, 2015).

In order to ensure that the PV module always achieve maximum power as possible, that is the maximum power point tracker (MPPT) and a suitable converter need to be chosen. In most common applications, the MPPT is a DC-DC converter controlled through a strategy that allows the photovoltaic module operation point to be on the Maximum Power Point (MPP) or close to it. MPPT's are commonly used in charge controllers to charge power storage batteries. Due to the PV system is high in cost, it is necessary to extract all available output power generated. There are several kinds of MPPT technique that have been developed over time such as perturb and observe (P&O), incremental conductance (IC), short circuit current technique, ripple correlation technique and open circuit voltage technique. These techniques have their own variation in complexity to implement, cost, amount of sensors required, effectiveness, and convergence of speed.

There are many types of topology of converters that can be implemented in the design and development of the DC-DC converter for photovoltaic applications. The topology that is chosen is based on the type of load that this system is to be used in. Since the type of load that will be used is with high current demand instead of voltage. The proposed topology to be used is the DC-DC buck converter. The common use for this type of system is DC motors. DC motors is widely used in water pumps, electric golf carts, and etc. The DC-DC buck converter is used mainly as an interface between the load and the PV module as it serves the purpose of transferring maximum power from solar PV module to the load (Subudhi and Pradhan, 2013). By changing the duty cycle, the load impedance is matched with the source impedance to attain the maximum power from the PV panel (Masri, Norizah and Hariri, 2012)(Pradhan and Panda, 2005). The PV module voltage output depends on the amount of irradiance it gets. Thus, the input voltage will fluctuate according to the amount of sunlight energy it gets. Therefore the adjustment of the duty cycle seems like an appropriate way to extract the maximum power from the PV module.

1.2 Problem Statement

The harnessing of solar energy using PV modules comes hand in hand with problems from change in insolation and temperature conditions (Meksarik *et al.*, 2004). The main problem for PV modules are the operating efficiency of 30 to 40 percent without a maximum power point tracker. Due to the changes in insolation condition, the efficiency and output power of the PV module is affected. This as a result causes the PV module to have power wastage and under-utilization for energy harnessing. PV systems in general are expensive to implement. Due to the high cost of PV system implementation, the extraction of maximum power at all times is important. Since there are various MPPT techniques available, the selection of suitable MPPT for specific application is difficult. The problem designers for low power application face are which of this two algorithms helps in extracting the maximum power from the PV panel more efficiently.

1.3 Aims and Objectives

The objectives of this project are

- To compare efficiency of PV panel using P&O and IC algorithms in MATLAB Simulink.
- Design buck converter as medium to transfer maximum power to load from PV panel.
- To analyse the performance of the DC-DC buck converter at different insolation levels for each MPPT algorithm presented.

1.4 Scope and Limitation of the Study

The scopes of this project is to design a buck converter and also provide control methods to attain maximum power from the PV module. The project is to be simulated with the MATLAB software and the output resulting waveform and values need to be tabulated and analysed.

In this project, there will be comparison of the two famous MPPT tracking algorithm which is the Perturb & Observe and Incremental Conductance method in terms of tracking efficiencies and performance during real world scenarios. The buck converter is used as a medium to transfer maximum power from the PV module to the load and also due to the load specification which is high efficiency and lower voltage. The buck converter allows for maximum power through the control of the duty cycle to suit the load and also the insolation condition of the PV module. In designing the buck converter, the specific components such as the LC filter, Load resistance and also the duty cycle operation range for the MPPT operation.

The approach of this research is to evaluate the methods in terms of tracking capability during changes in solar insolation levels and temperature variation, time taken for solar panel to reach maximum operating power and effect of the duty cycle delta adjustment on the tracking efficiency.

1.5 Outline of the Report

This report has 5 chapters which is the introduction, literature review, methodology, result and discussion and lastly the conclusion. In the introduction, a general overview of the project, problem statements, aims and objective and the scope is discussed. The next chapter is the literature review which consist of the PV model modelling, buck converter design and MPPT algorithm descriptions. The report then continues with the critical analysis on past research done by several researchers. The third chapter is the methodology which discuss how the procedure of the experiment and simulation was done. The target specifications of the buck converter is also presented. The fourth chapter shows the result and discussion from the simulations done based on the methodology stated in chapter 3. Lastly, the conclusion is drawn and necessary appendix is attached.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this era of technology, solar energy is one of the energies used due to its clean and pollution-free sustainable energy (Ali *et al.*, 2014). Due to an increase in cost of electricity solar energy has high demand among household and public infrastructure. The initial approach to usage of solar energy is by storing energy into battery via photovoltaic (PV) panels with a suitable charge controller. However, PV panels do not perform well without any controller to track its maximum power. Therefore the use of maximum power-point tracking (MPPT) is needed in order to ensure the PV module is functioning at its highest efficiency possible. There are many different types of MPPT have been developed and implemented by many research studies. In order to implement MPPT, there is a need to integrate a DC-DC converter to transfer the maximum power to the load efficiently (Choudhary and Saxena, 2014) and aid the PV module to track its MPPT by varying the duty cycle.

This literature review aims to provide an overview of two different kind of MPPT algorithm widely used with buck converters which is the Perturb and Observe (P&O) and Incremental Conductance (IC). The outline of this literature review is started with the modelling of the PV Array and then followed by the modelling of the DC-DC Buck converter for PV system. After the fundamental portion, the review will continue with the MPPT algorithms analysed in this dissertation. The last portion will address issues, solutions, and discussion of papers from several researchers.

2.2 Solar PV Cell Modelling

A solar cell is the single unit of the solar PV module, the cells are combined in series and parallel to achieve a desired voltage and current level. A PV cell is a semiconductor diode which generates current when the cell is exposed to light. The mathematical model of the PV cell is used in this study to model a PV array of 230W from Accu-Solar. There are two types of model present in several type of research which is used to predict the energy production in a solar cell modelling is the single diode circuit model (Kashif Ishaque, 2011; Pandiarajan and Muthu, 2011; Rahmani, 2012). The single diode connected in parallel with the light generated current source (I_{SC}) as shown in Figure 2-1 below is the ideal photovoltaic module.

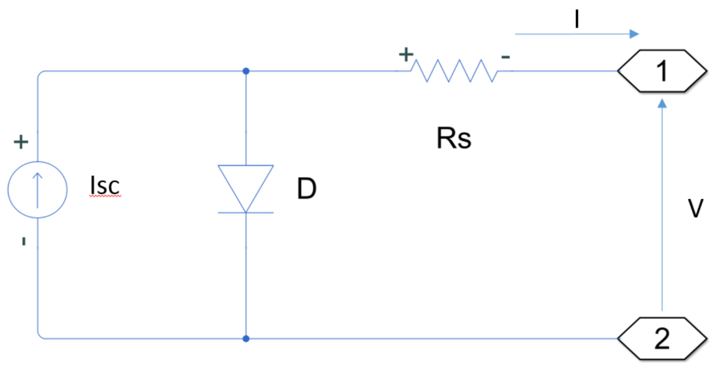

Figure 2-1 Single Diode Solar Cell Model

From the figure above, output current is formulated as:

$$I = I_{SC} - I_D \tag{2.2.1}$$

Whereby

$$I = I_{SC(ref)} \left[e^{\frac{qVoc}{kAT}}\right] - 1 \tag{2.2.2}$$

I_{SC} depends on the irradiance and temperature. They are measured to reference conditions as equation below.

$$I_{SC} = [I_{SC(ref)} + K_i(T_k - T_{ref})] \times \frac{\sigma}{1000} \tag{2.2.3}$$

Whereby I is the solar cell current (A), I_D is the module diode saturation current, $I_{SC(ref)}$ is the module short circuit current at 25°C, q is the electron charge which is 1.61 x 10^{-19} coloumbs, V_{oc} is the module open circuit voltage, σ is the irradiation on the device surface in W/m^2, A is the ideality factor, T is the module operating temperature in Kelvin, T_k is the actual temperature in Kelvin, T_{ref} is the reference temperature (25°C) in Kelvin, I_{SC} is the photocurrent in Ampere and k is the Boltzmann constant which is $1.38 \times 10^{-23} JK^{-1}$

According to (Pandiarajan and Muthu, 2011; Zegaoui *et al.*, 2011; Abdulkadir *et al.*, 2013), equation (2.2.2) does not represent the behaviour of the cell adequately when subjected to environmental variations, at low voltages. Due to this, a more practical model is the solar cell model using single diode with R_s and

R_p as shown in Figure 2-2. R_s represent the series resistance and R_p represent the equivalent parallel resistance.

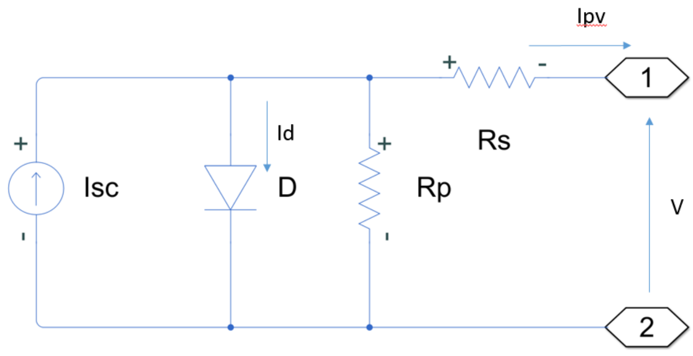

Figure 2-2 Solar cell model using single diode with R_s and R_p

For the model in Figure 2-2, the addition of R_p is to ensure the resistive losses was considered. The equations that describe the, I-V and P-V characteristics of the equivalent circuit in Figure 2-2 is given by;

$$I_{SC} - I_D - \frac{v_D}{Rp} - I_{pv} = 0 \tag{2.2.4}$$

Hence,

$$I_{pv} = I_{SC} - I_D - \frac{v_D}{Rp} \tag{2.2.5}$$

Reverse saturation current, I_{rs} is given as;

$$I_{rs} = I_{SC(ref)} \left[e^{\frac{qVoc}{N_S kAT}} \right] - 1 \tag{2.2.6}$$

Module saturation current, I_D is given as;

$$I_D = I_{rs} \cdot \left[\left(\frac{T}{T_{ref}} \right)^3 \cdot e^{\frac{qEg\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)}{Ak}} \right] \tag{2.2.7}$$

The current output of PV module, I_{pv} for Figure 2-2 is given in equation (2.2.8).

$$I_{pv} = N_p I_{sc} - N_s I_D \left\{ e^{\left(\frac{q(V_{pv} + I_{pv} R_S)}{N_S AkT}\right)} - 1 \right\} - V_{pv} + \left(\frac{I_{pv} R_s}{R_p} \right) \tag{2.2.8}$$

Where the number of cells connected in series is N_s, the number of cells connected in parallel is N_p, the resistance in parallel is R_p (Ω), and the resistance in series is R_s (Ω).

Equation (2.2.4) is highly dependent on the incident solar irradiance, cell temperature, and their respective reference values of the PV module (Abdullah *et al.*, 2012; Abdulkadir *et al.*, 2013). The reference values will be provided in the product datasheet from the respective module manufacturer for specified conditions. For an example STC (Standard Test Conditions) where the irradiance is at 1000 W/m^2 with cell temperature at 25℃. However, the real operating condition are always different from the STC, this could cause mismatch effects which affects the real values of these mean parameters (da Silva, 2010; Dell'Aquila, R V Balboni, L Morici, 2010; Rahmani, 2012). Table 2-1 below shows specification of the Accu-Solar Power ASP610-B230. Figures 2-4 to 2-9 shows the PV characteristics for fixed irradiance and temperature and varying irradiance at fixed temperature and varying temperature at fixed irradiance.

Table 2-1 Accu-Solar Power ASP610-B230 Module Parameters

Maximum Power	P_{mpp}	230.02W
Voltage at Maximum Power	V_{mpp}	29.68 V
Current at Maximum Power	I_{mpp}	7.75 A
Open Circuit Voltage	V_{oc}	37.19 V
Short circuit current	I_{sc}	8.69 A
Total No. of cells in series	N_s	60
Total No. of cells in parallel	N_p	1
Parallel resistance	R_p	57.6597 Ω
Series Resistance	R_S	0.36797 Ω

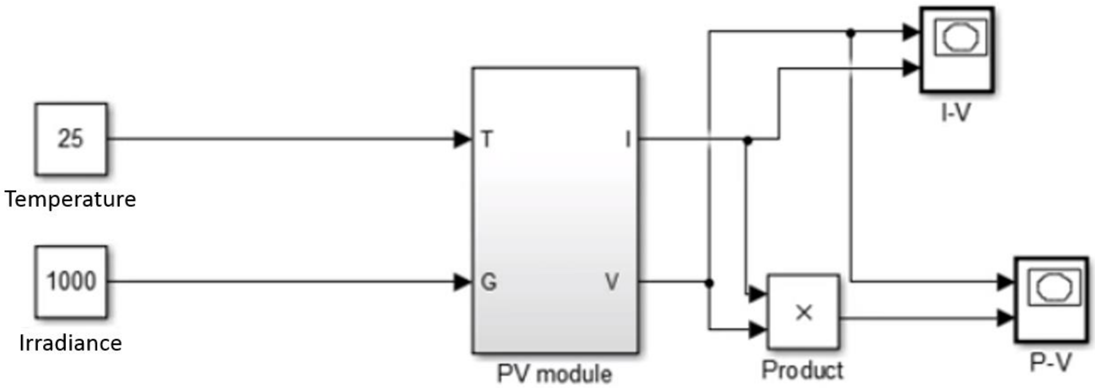

Figure 2-3 Simulink simulation schematic of PV model.

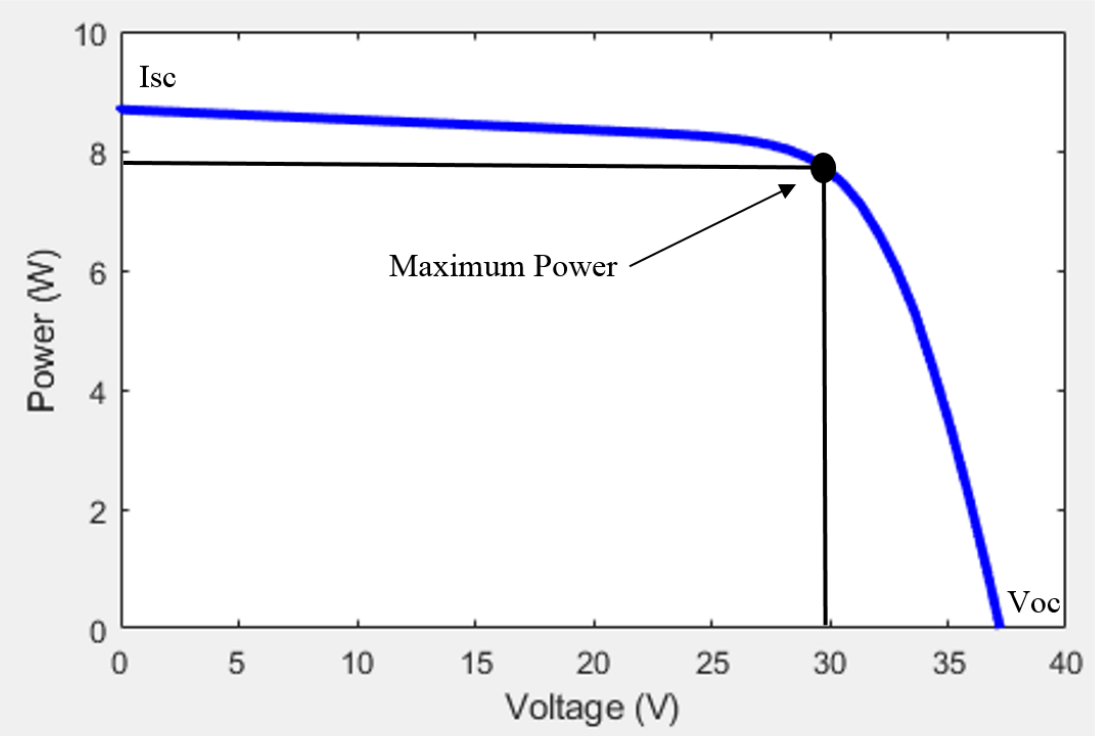

Figure 2-4 I-V Characteristic curve of PV model at 1000 W/m^2 constant irradiance and ambient temperature of 25℃

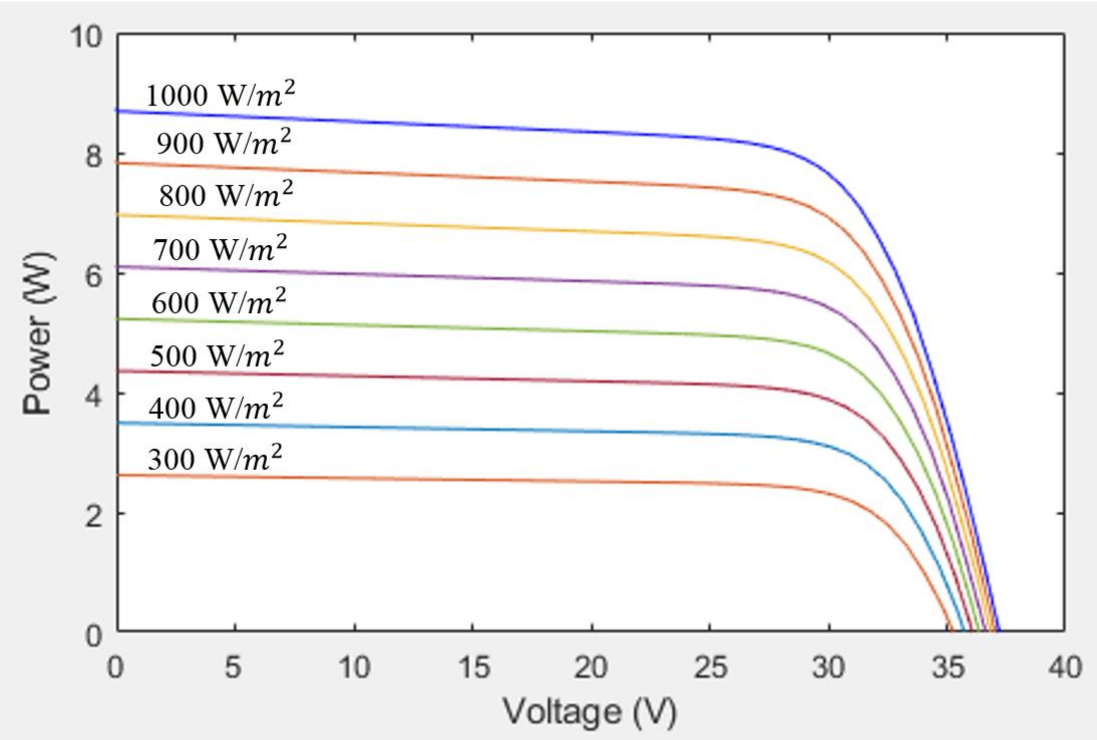

Figure 2-5 I-V Characteristic curve of PV model at varying irradiance at ambient temperature of 25℃

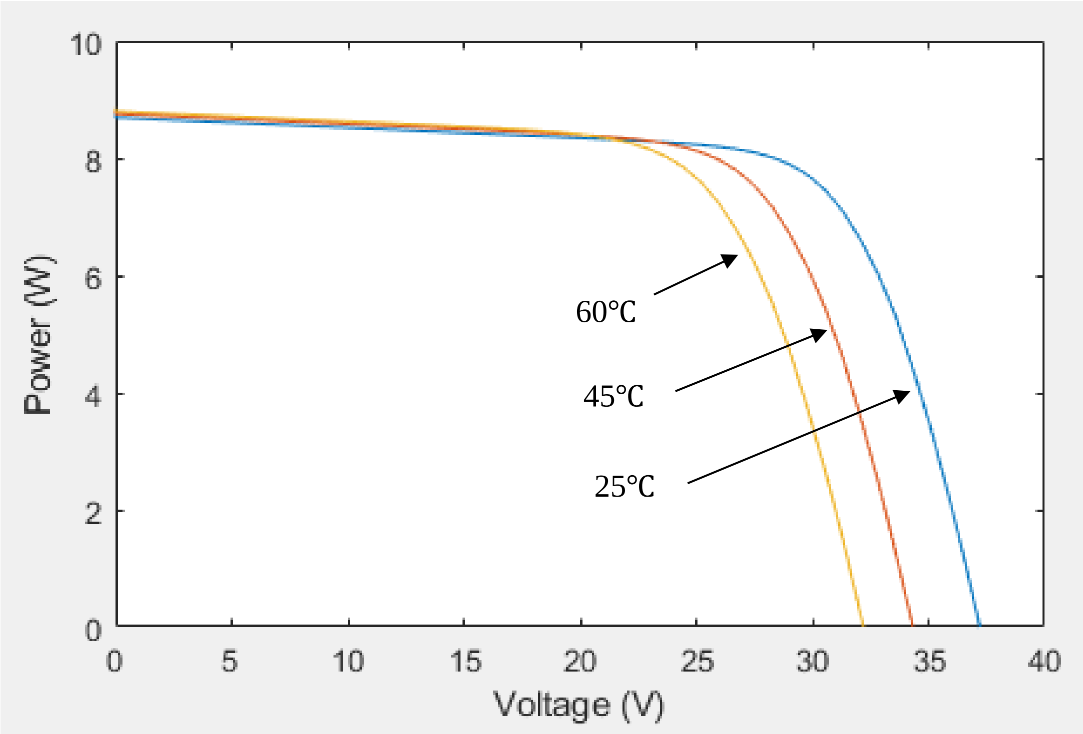

Figure 2-6 I-V Characteristic curve of PV model at varying temperature at constant irradiance of 1000 W/m^2

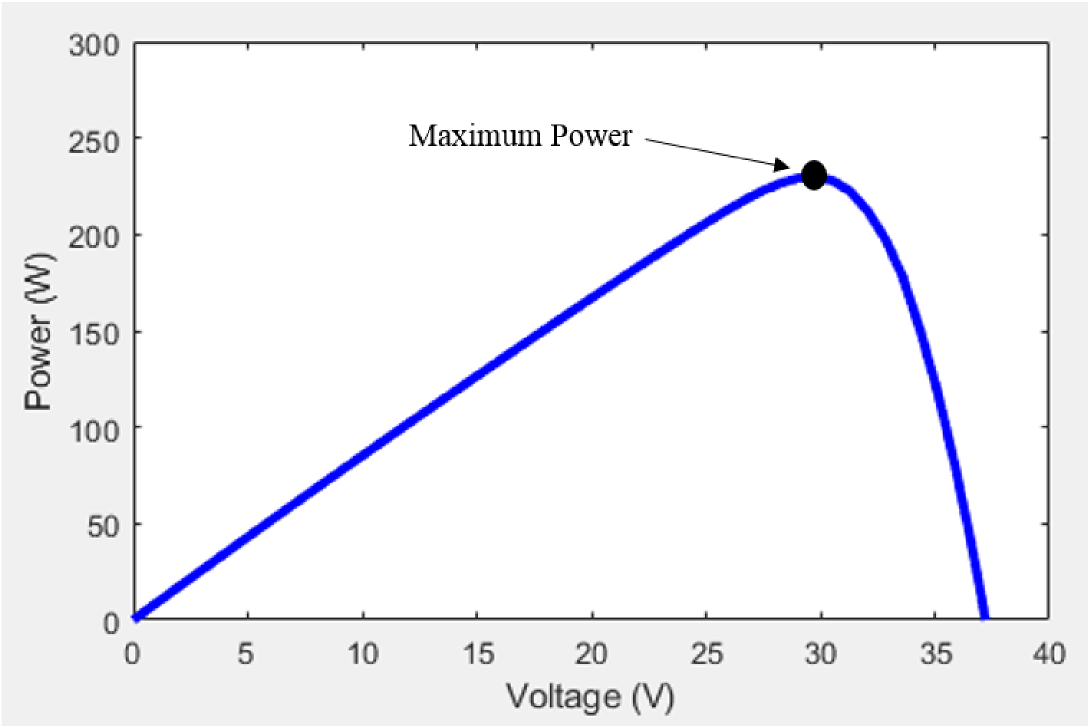

Figure 2-7 P-V Characteristic curve of PV model at 1000 W/m^2 constant irradiance and ambient temperature of 25℃

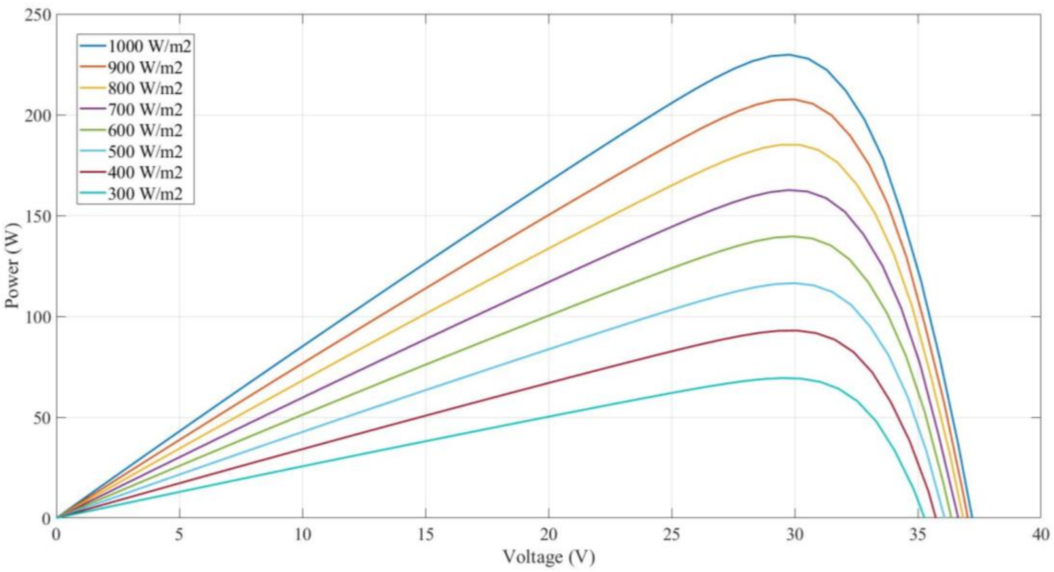

Figure 2-8 P-V Characteristics curve for PV model at varying irradiance and fixed 25℃

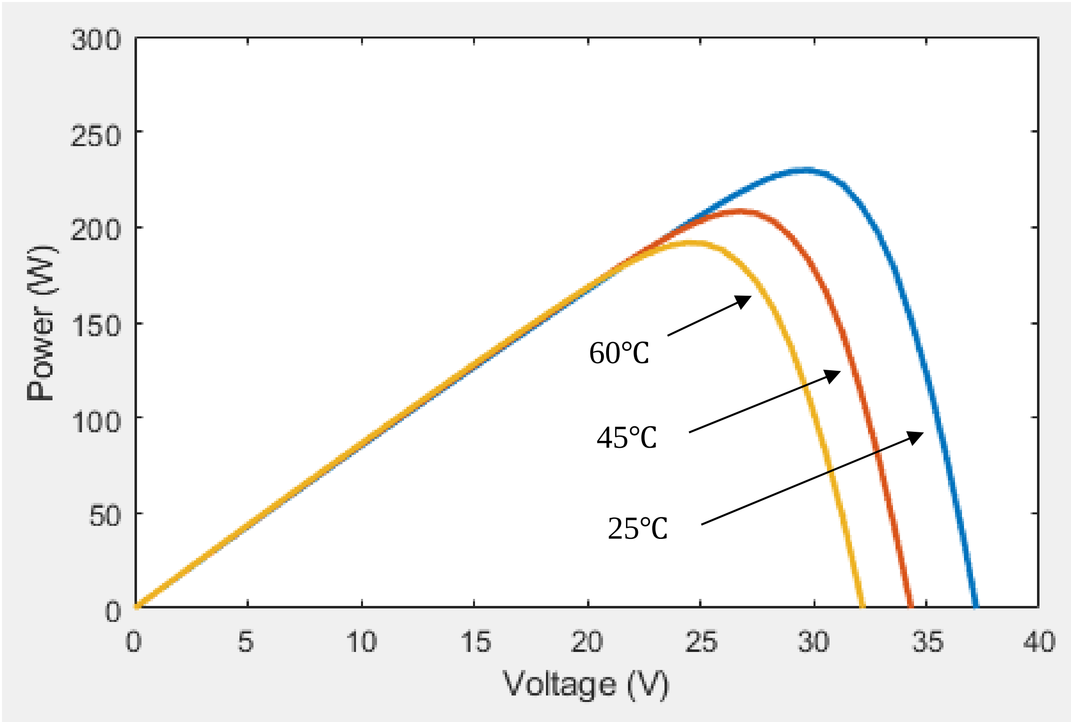

Figure 2-9 P-V Characteristics curve for PV model at varying temperature with fixed irradiance of 1000 W/m^2

2.3 Maximum Power Point Tracking Method

Maximum Power Point Tracking (MPPT) is used as an electronic system which alters the operation of the PV to gain a maximum power. The MPPT is 100 percent on software tracking instead of a mechanical tracking method. However, a mechanical method can be implemented together with the MPPT in order to further increase the PV module efficiency in producing maximum power at all times and for different load levels. There several kinds of maximum power point tracking techniques available. The most common techniques are perturb and observe (P&O), Incremental Conductance (IC), fractional open-circuit voltage (Voc), fractional short-circuit current control (Isc), ripple correlation control, forced oscillation, beta method and dc link capacitor droop control.

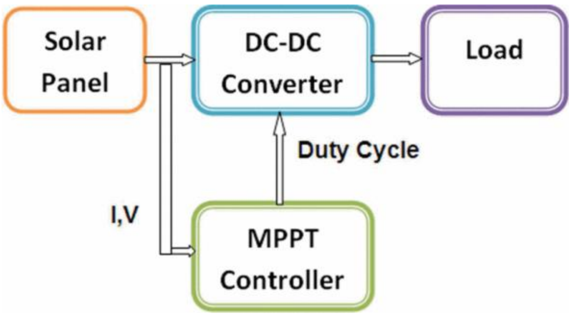

Figure 2-10 PV Panel system with MPPT and DC-DC Converter system block

2.3.1 Perturb and Observe (P&O) Algorithm

P&O algorithm is one of the most famous method of MPPT used in many applications. This is because it is simple and does not need the previous PV generator characteristics or cell temperature and insolation levels. The flowchart of the algorithm is shown in Figure 2-11 below.

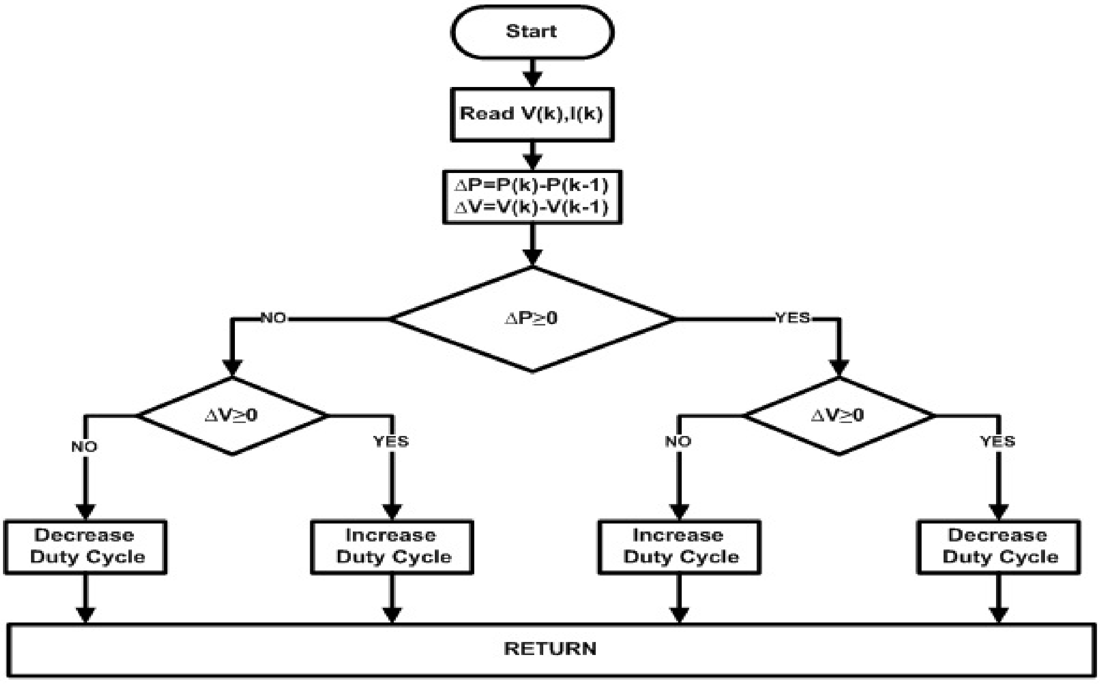

Figure 2-11 P&O algorithm flowchart

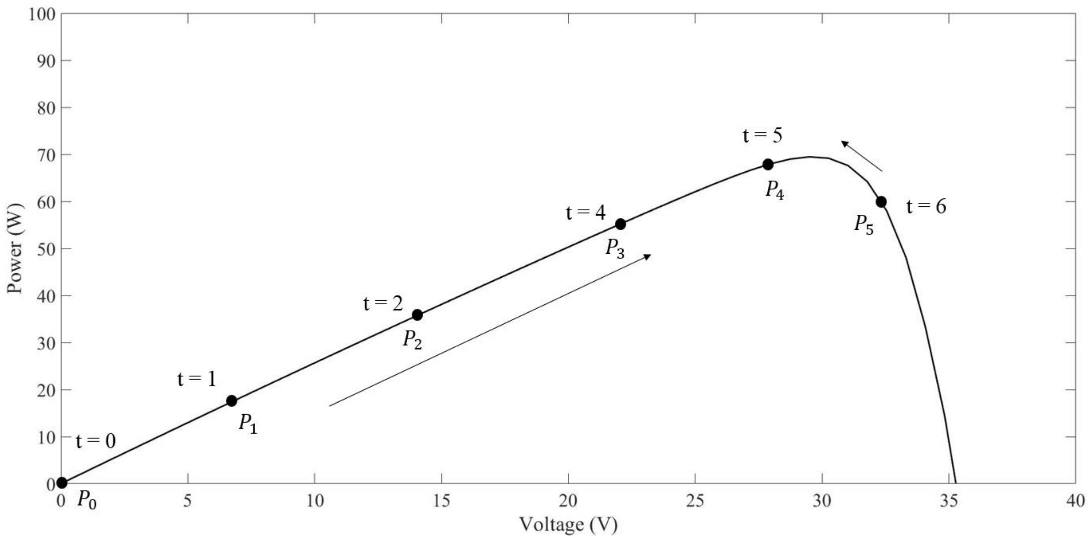

Figure 2-12 Perturb and Observe Tracking steps

The algorithm starts by measuring the voltage and current from the PV module .Based on Figure 2-12, assuming power at initial state is P_0, the corresponding power P_1 is calculated with voltage and current values obtained at start of the algorithm. The difference between P_0 and P_1 is calculated. If the difference is a positive value, then the following step will be to find the change in voltage of the module between point P_1 and P_0. If the voltage difference is found to be positive, the duty cycle will be reduced by 0.01 in accordance to the equation (2.4.11) for load matching purpose. This steps are repeated until point P_5. At point P_5 the power is lesser than the power at point P_4. Hence the power difference will be negative and the voltage difference will be positive. As a result the duty cycle will be increased by 0.01 until it reached back to point P_4. This will keep on repeating and the power point will be oscillating back and forth between point P_4 and P_5. The main drawback of this algorithm is during the steady state which causes the PV operating point to oscillation about the maximum power of the PV module as claimed by (Pakkiraiah and Sukumar, 2016).

Table 2-2 Summary of P&O Algorithm

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

2.3.2 Incremental Conductance (IC) Algorithm

For an IC method, the slope of the PV array power curve is zero at the maximum power point (MPP). The MPP can be tracked by comparing the instantaneous conductance (I/V) to the incremental conductance (ΔI/ΔV)

$\Delta I/\Delta V = -I/V$, means the PV panel is at MPP on PV curve.

$\Delta I/\Delta V > -I/V$, means the PV panel is at left of MPP on PV curve.

$\Delta I/\Delta V < -I/V$, means the PV panel is at right of MPP on PV curve.

At MPP, the reference voltage is equal to the MPP voltage. The reference voltage is at which the PV panel is forced to operate. Table 2-3 and Figure 2-13 summarizes the IC technique used for MPPT as reported in literature.

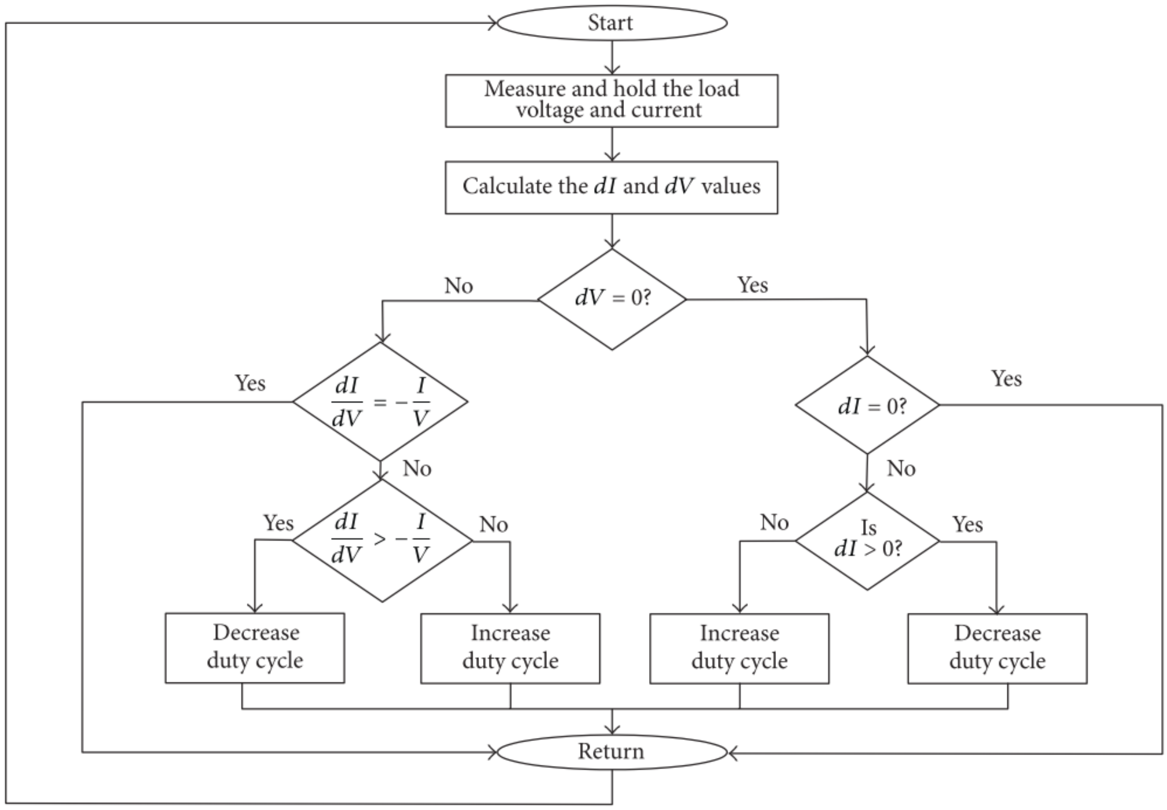

Figure 2-13 Incremental Conductance flowchart (Pakkiraiah and Sukumar, 2016)

Based on Figure 2-13 above, the incremental conductance algorithm starts by sensing the voltage and current values using appropriate sensors. The change in voltage is then calculated. If the voltage change is zero, then the algorithm will proceed to check on the change in current. If the current change is zero, then the algorithm will remain the same duty cycle. If this is not the case, then the algorithm will perform calculation to see if the change of current is positive or negative, if the positive is obtained then the duty cycle will be reduced by 0.01, else the duty cycle will be increased by 0.01. The next case will be if the voltage change is not zero, then the algorithm will have to perform computation for the instantaneous conductance and incremental conductance. Then it will perform comparison to see if they are equal, more or less. If it's equal, the duty cycle will remain the same. If they are different, then if the incremental conductance is more than the instantaneous conductance, the duty cycle will be reduced by 0.01, else it will be increased by 0.01.

(Gaur, Verma and Singh, 2015) claims that the incremental conductance algorithm has good yields during rapidly changing environmental condition as compared to the P&O algorithm. (Irisawa *et al.*, 2000; Kobayashi, Takano and Sawada, 2006), proposes a two-stage method, to assure that the real MPP is tracked in case of multiple local maxima because the operating point of PV array close to the MPP, then by using IC method to track the MPP.

Table 2-3 Incremental Conductance algorithm summary

$\frac{dP}{dV} = 0$	True Maximum Power Point	Duty Cycle unchanged
$\frac{dP}{dV} > 0$	Left of Maximum Power Point	Increase duty cycle until $V_{pv} = V_{mpp}$
$\frac{dP}{dV} < 0$	Right of Maximum Power Point	Decrease duty cycle until $V_{pv} = V_{mpp}$

2.4 Buck Converter for PV applications

The buck converter is a DC-DC converter used to produce a regulated and lower output voltage than the input voltage. The equivalent circuit diagram and the switch states are shown in Figure 2-14 and Figure 2-15, respectively.V_s, V_o and R are respectively the source voltage (PV output voltage, V =V_s), the output voltage of the buck converter (load voltage,V_o) and the load resistance.

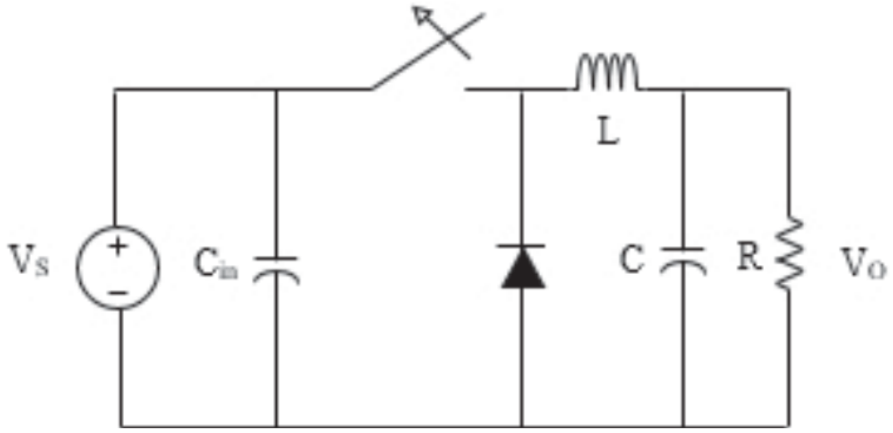

Figure 2-14 Buck Converter schematic

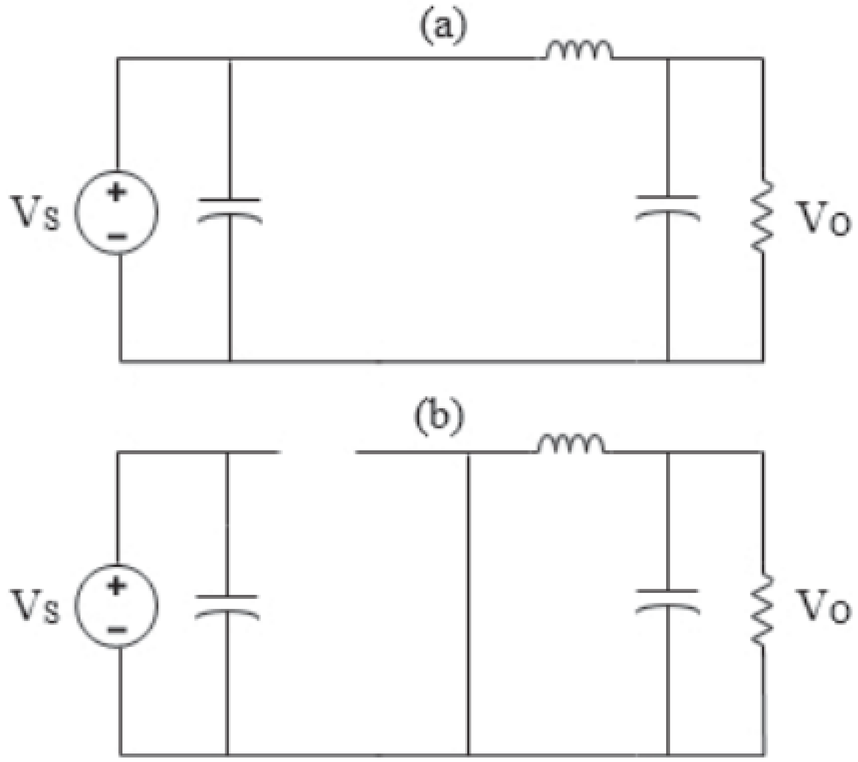

Figure 2-15 (a) Buck Converter during switch turned ON and (b) Buck Converter during switch turned OFF

When the switch is ON, the diode becomes reverse biased and the input voltage appears across the inductor causing a linear increase in the inductor current and the capacitor is also charged at the same time. When the MOSFET switch is OFF, the diode becomes forward biased and because of the inductor energy storage, it discharges through the diode. The buck converter is used in a PV system due to its ability to perform MPPT and impedance matching between the input and output load resistance (Pradhan and Panda, 2005). The formula's for the calculation of duty cycle is given as in equation (2.4.9). Load voltage is based on the desired output voltage needed by the user and module voltage refers to the maximum power of PV module from the manufacturer datasheet. Once duty cycle is calculated, the load resistance given by equation (2.4.11) can be calculated. Generally in the design of a buck converter, the inductance is 125% more than the minimum inductance calculated to ensure the converter always functions at continuous current mode. The formula to calculate the inductance minimum value is given by equation (2.4.12) whereby LIR refers to the inductor ripple current. The maximum allowed ripple current should be 20 to 40 percent for best design(Hauke, 2015).

$$D = \frac{V_{load}}{V_{module}} \tag{2.4.9}$$

$$I_{load} = \frac{I_{module}}{D} \tag{2.4.10}$$

$$\frac{R_{load}}{D^2} = R_{pv} = \frac{V_{mpp}}{I_{mpp}} \tag{2.4.11}$$

$$L_{min} = \frac{(V_{module} - V_{load})(D)}{(LIR)(I_{load})(f_{sw})} \tag{2.4.12}$$

$$C = \frac{(LIR)(I_{load})}{8(f_{sw})(CVR)(V_{load})} \tag{2.4.11}$$

Where D is the duty cycle, V_{load} is the load voltage of buck converter, V_{module} is the module voltage, I_{load} is the load current of the buck converter, I_{module} is the module current, R_{load} is the load resistance of the buck converter, R_{pv} is the resistance seen at the output of the PV module, V_{mpp} is the maximum power point voltage, I_{mpp} is the maximum power point current, L_{min} is the minimum inductance for the buck converter, LIR is the inductor ripple current percentage, f_{sw} is the MOSFET switch frequency, C is the minimum capacitance value for the buck converter, CVR is the capacitor voltage ripple percentage.

2.4 Critical Analysis

(Masri, Norizah and Hariri, 2012) have brought about the implementation of buck converters in the photovoltaic system which uses a microcontroller to generate a PWM signal to control the MOSFET in the buck converter circuit. From this article, there is a disadvantage in the method the experiment was conducted because the author only performs analysis of the output of buck converter for each state of fixed input. However, in real time application, the PV module provides varying voltage to the input of the converter. Therefore in this project, the system is integrated with two different MPPT controllers which will ensure the PV module operating point is near to the maximum operating power.

(Pradhan and Panda, 2005) discussed about the implementation of dc-dc converters in terms of load matching. The author explains in detail how the load matching can be done with a DC-DC converter. This particular method will be used in order to track the maximum power point of the PV module together with a Buck Converter. The author shows a brief explanation on the theory of load matching based on the IV curve which corresponds to the initial claim by the author which states that connecting the PV module directly to a resistive load, the module's operating point intersects the IC curve and the load line as shown in the Figure 2-16 below. The method of design which is explained in this research is used in order to design a buck converter to perform the MPPT process and load matching.

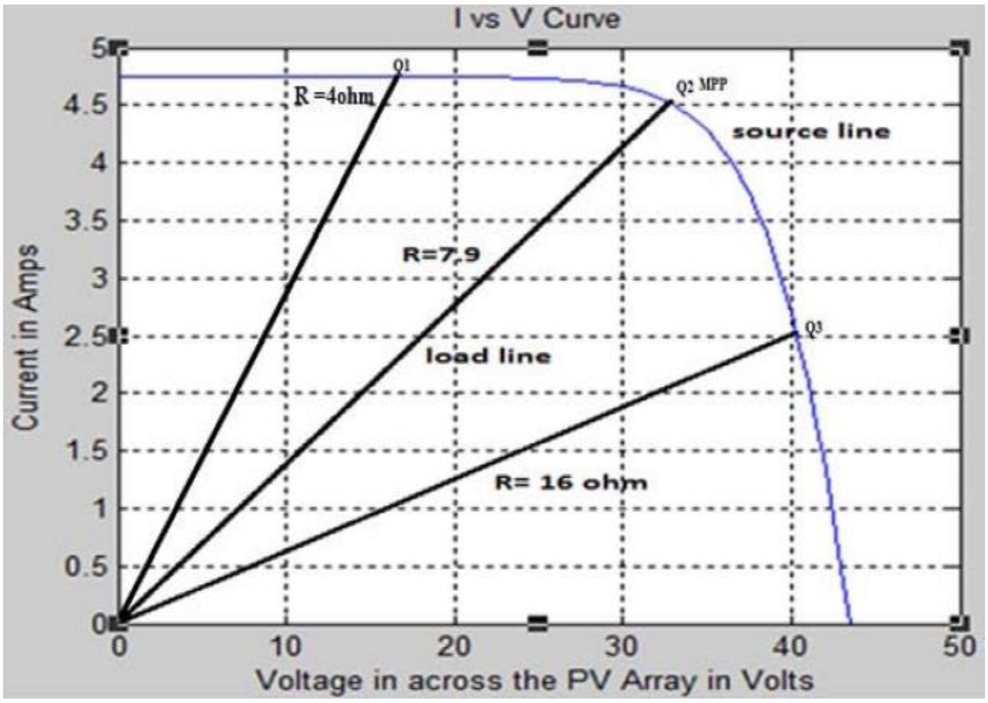

Figure 2-16 IV Curve and load line for solar module at various loads. (Pradhan and Panda, 2005)

(Coelho, Concer and Martins, 2009, 2010) studies about the different types of dc-dc converter used to implement the maximum power point tracking. Coelho used similar theory to control the maximum power point tracking which is using load matching as discussed by (Pradhan and Panda, 2005). However, the author provides more in depth explanation by testing out the minimum and maximum duty cycle that is able to be used by each DC-DC converter in the journal. This article shows the operational and non-operational region for each of the dc-dc converter through a calculation. The author concludes that the best converters to be used for MPPT applications are Buck-Boost, Cuk, SEPIC and Zeta as their operation region for duty cycle is very wide and has no limitation as that of the Buck and Boost converters. This analysis will also be performed in this research study to check on whether there is any difference in operation region with different MPPT algorithm implementation.

(Richard and Brian, 2006) showed the effects of dc-dc converter switching frequencies. This literature is used in this research as a guide in the design of a buck converter to select the appropriate switching frequency to obtain maximum efficiency and also balance the size of components. The author performed several experiments with an IC that has a programmable switching frequency at 3 different frequencies which is 1.6 MHz, 700 kHz and 350 kHz. The result shows that lowest frequency of 350 kHz has better efficiency rating compared to the other two higher frequencies for the DC-DC converter. In the end of the article, the author also mentioned that the higher switching frequencies will provide to higher head dissipation due to rapid switching. In the application of PV modules, there is no need for such high frequency as the selected tracking algorithms in this paper do not need such high tracking speeds. This is because the MPPT usually operate at very high audio frequencies in the 20-80 kHz range('All About Maximum Power Point Tracking (MPPT) Solar Charge Controllers', 2019).

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

In this section, the methodology of the project is being discussed. The methodology will cover on how the simulation was performed, the project work flow and overall work plan. Figure 3-1 shows block diagram of MPPT controller for this project. The analogue signal output from the PV module will be stepped down using buck converter. The MPPT controller will analyse the collected data/ maximum power curve and send signal to adjust buck converter output being sent to the load. Hypothesis that is intended to be proved will be buck converter has higher and more stable load performance.

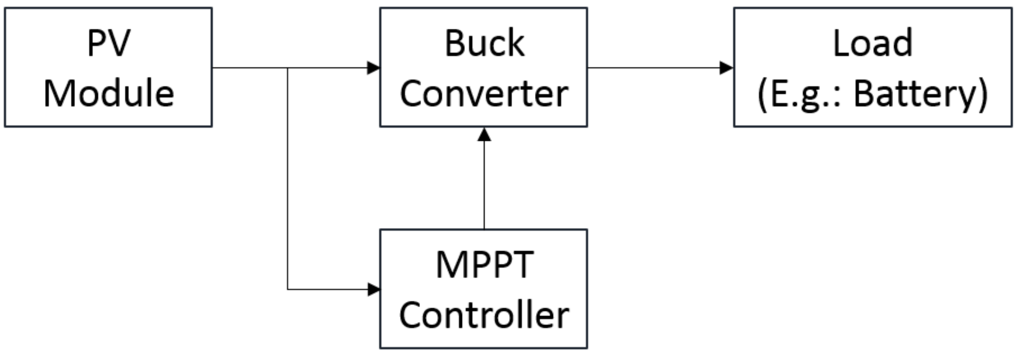

Figure 3-1 Block diagram of MPPT controller

There are 2 system block diagram for the MPPT controller. The first block is the buck converter which consists of the LC filter, load resistance and the second system block which formed the MPPT controller. MPPT tracking algorithm will be simulated using the MATLAB software.

3.2 Design Flow/Project Development

methodology of this project started with circuit design of buck converter. Calculation is done to identify component value inside the converter circuit. Simulation is done using MATLAB software. Performance of the Perturb & Observe and Incremental Conductance MPPT controller are being compared on MATLAB software. If the results obtained after from both MPPT controller are distinctive, design of the controller is considered successful. However, if results are almost similar, design of MPPT controller will be reconsidered. The flowchart summary is shown in Figure 3-2 below.

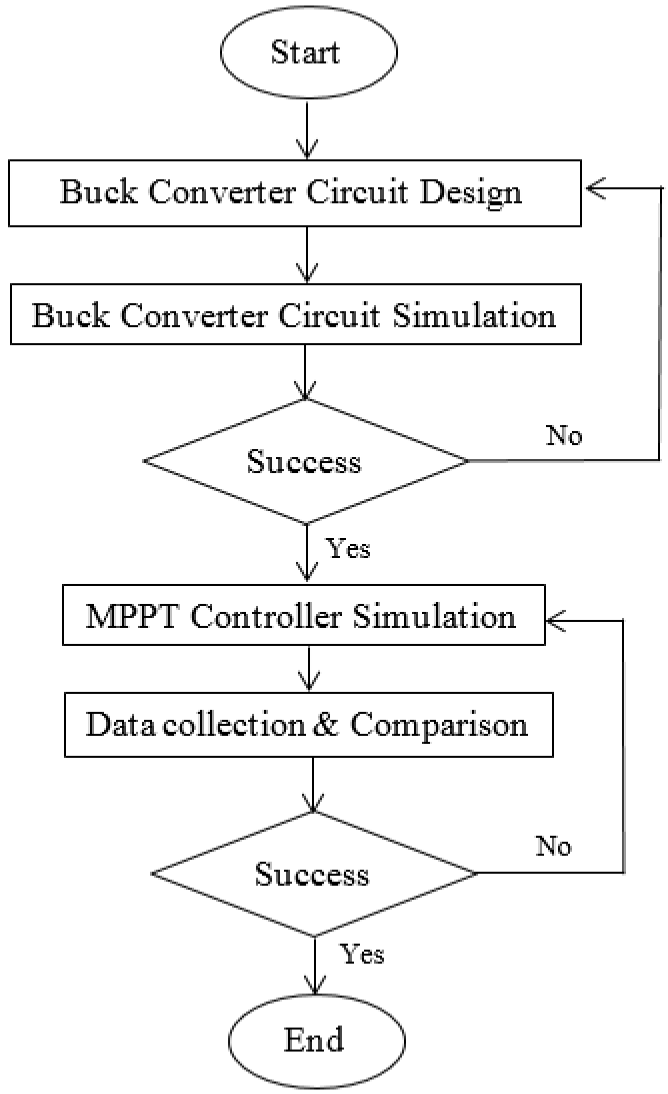

Figure 3-2 Project development of MPPT controller

3.3 Target Specification

Before begin to design the schematic, the specification of designed MPPT system must be present. There are 2 blocks in the MPPT system namely buck converter and MPPT controller block. The PV module chosen in this project are rated 230Watt. V_{load} is output from buck converter and act as input voltage to the load. Thus, it is important to maintain value of V_{load} in input voltage range of the load. V_{module} defines output voltage level of PV module. Output from PV module will be monitor and regulated by buck converter based on signal from MPPT controller. Summary of target specification of the designed MPPT system is shown in Table 3-1.

Table 3-1 Target specification of designed MPPT System (Rashid, 2011)

Parameter	Value
Max Rated output power of Accu-Solar ASP610-B230	230 Watt
Buck Converter desired load voltage, V_{load}	$0\sim24V$
Accu-Solar ASP610-B230 output voltage at MPP, V_{module}	29.68V
Buck Converter calculated load current, I_{load}	9.58A
Ripple Current (Maximum)	30%
Ripple Voltage (Maximum)	2%
Desired Switching frequency (f_{sw})	100 kHz

3.4 Buck Converter Design

A buck converter is designed for PV application in this study, the buck converter is set to be able to generate load voltages between 1V and 24V. Figure 3-3 shows schematic of buck converter to generate load voltage of 24V. The optimum inductor, load resistor and output capacitor is designed with formulae from literature review section 2.4. The calculation for each component is discussed in the following parts of this section. The resultant duty cycle calculation is fed into the gate of the MOSFET with a PWM generator.

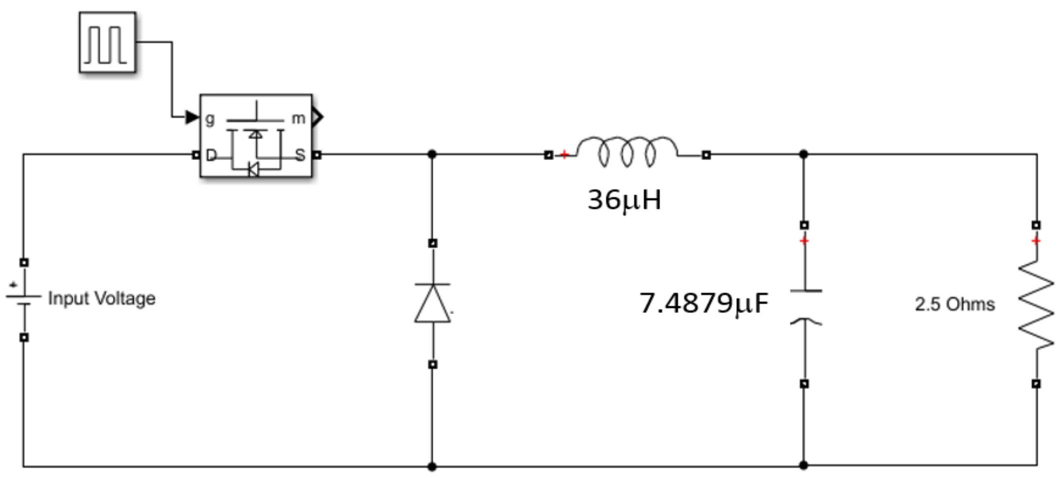

Figure 3-3 Buck Converter schematic to generate maximum load voltage of 24V

Proposed buck converter consists of 3 major parts which is load resistance for duty cycle adjustment, inductor for ripple current control and capacitor for output ripple voltage control. According to target specification in Table 3.1, duty cycle, D of the buck converter are calculated using equation (2.4.9)

$$D = \frac{24\,V}{29.68\,V}$$

$$D = 0.8086$$

Load resistance value is calculated using equation (2.4.11) which was referenced to (Pradhan and Panda, 2005; Coelho, Concer and Martins, 2009) to obtain duty cycle of 80.86% in the buck converter.

$$R_{load} = \frac{29.68}{7.75} \times (0.8086)^2 = 2.5\ \Omega$$

DC signal sent to load need to be clean and without noise. In practical, both current and voltage source has ripples. According to target specification in Table 3-1, maximum allowable ripple current is set to be 30 percent of the total rated current. Inductor value are calculated using equation (2.4.12) selected to be more than the minimum calculated inductance by 125 percent to ensure that the converter functions in Continuous Current Mode (Rashid, 2011).

$$L_{min} = \frac{(29.68 - 24)(0.8086)}{(0.3)(9.5845)(100k)} = 15.9731\mu H$$

$$L = 15.9731 + (1.25\ \times 15.9731\mu H) = 35.9394\mu H$$

$L = 36\mu H$ (Optimum Inductor selected)

According to target specification in Table 3.1, maximum allowable ripple voltage is set to be 2 percent of the buck converter output voltage (V_{load}). The optimum capacitor value are calculated using equation (2.4.13).

$$C = \frac{(0.3)(9.5845)}{8(100k)(0.02)(24)} = 7.4879\mu F$$

The buck converter that is designed will be simulated with a PV array at fixed temperature of 25℃ while varying the irradiance from 0 to 2000 W/m^2 with 100 W/m^2 step and followed with varying temperature from 0℃ to 100℃ while having fixed irradiance of 1000 W/m^2. This is done to check on the operating range of the designed converter. Buck converter efficiency is then calculated with equation (3.4.1) below.

$$Buck\ Converter\ Efficiency, \eta = \frac{Buck\ Converter\ Output\ Power}{PV\ Module\ Power} \times 100\% \quad (3.4.1)$$

3.5 MPPT Experiment Simulation method

The complete circuitry for the buck converter with the respective MPPT system is as in Figure 3-4 and Figure 3-5. The green and blue sub-system contains the MATLAB coding for the selected MPPT which is perturb and observe and incremental conductance algorithm. Buck converter that is designed in section 3.4 is the yellow sub-system in Figures 3-4 and Figure 3-5 below. Capacitor C1 is placed before the input of buck converter to ensure the ripple from PV module is minimal before being fed into the converter and act as a load seen from the PV module.

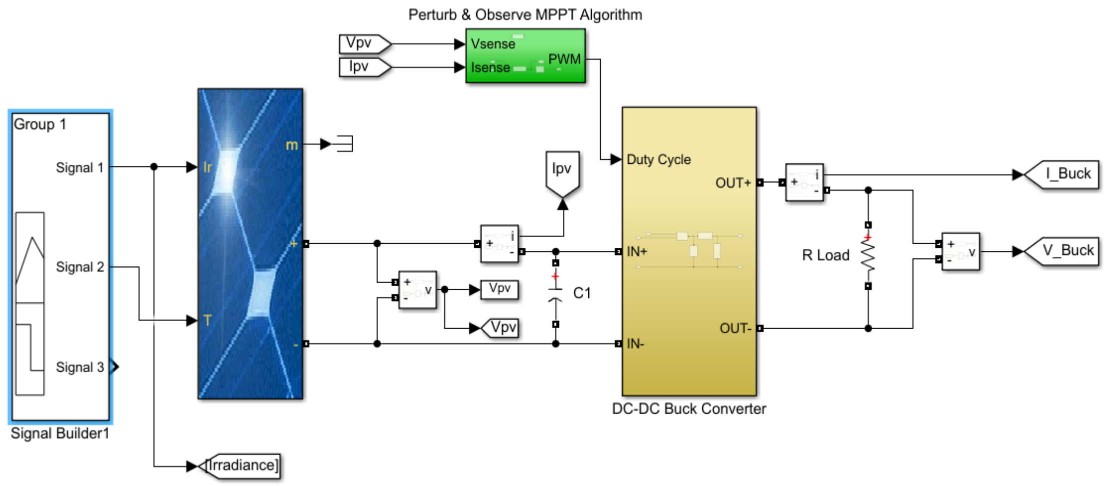

Figure 3-4 Perturb & Observe MPPT Algorithm with Buck Converter

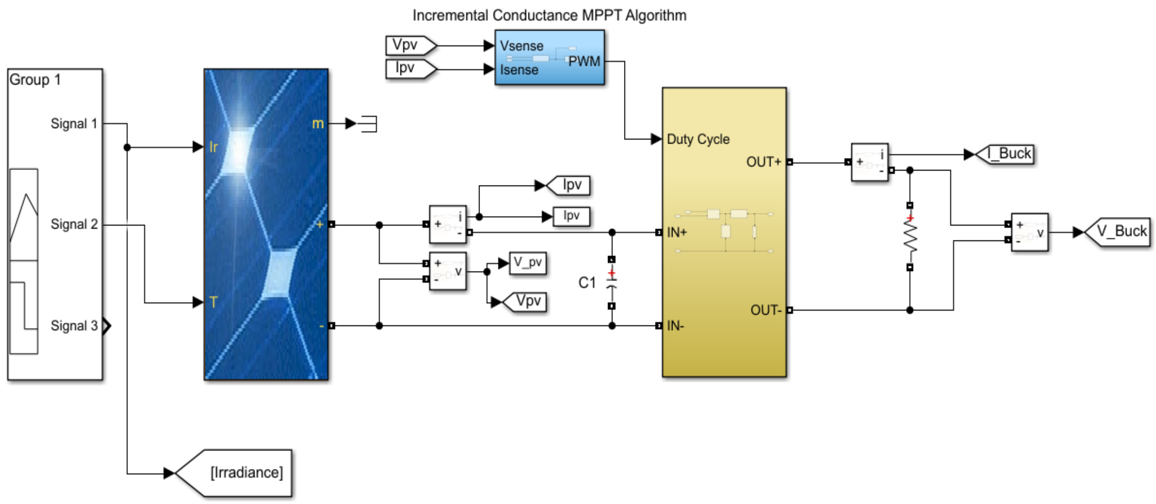

Figure 3-5 Incremental Conductance MPPT Algorithm with Buck Converter

The detailed coding for the MPPT algorithms are published in the **Appendix A** and **Appendix B** according to operation flowchart shown in the section 2.3.1 and 2.3.2. The MPPT are simulated to compare steady-state operation, duty cycle step size reduction and the performance of buck converter paired with the selected MPPT algorithms at different insolation and temperature levels. Firstly, the simulation is performed to see the difference of the whole system with the maximum power tracking and without the maximum power tracking. The voltage and current are measured through the voltage and current measurement block in MATLAB which is placed directly at the output of the PV module as shown in Figure 3-4 and Figure 3-5. The voltage and current will be fed into the MPPT block highlighted as green for Perturb and Observe and blue for incremental conductance. The voltage and current will then go through the respective MPPT algorithm and produce a value of duty cycle for example 0.8086 will display as a DC signal from the output of the algorithm. The duty cycle DC signal will then be fed to a comparator circuit to generate a Pulse Width Modulation (PWM) signal. Figure 3-6 and Figure 3-7 below shows the comparator block to generate PWM signal and waveform generated respectively.

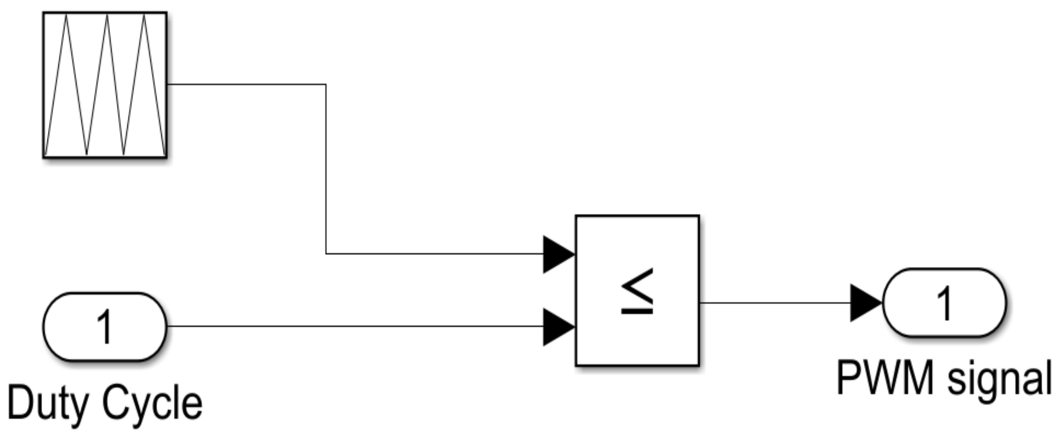

Figure 3-6 Comparator block to generate PWM signal for DC-DC Buck Converter

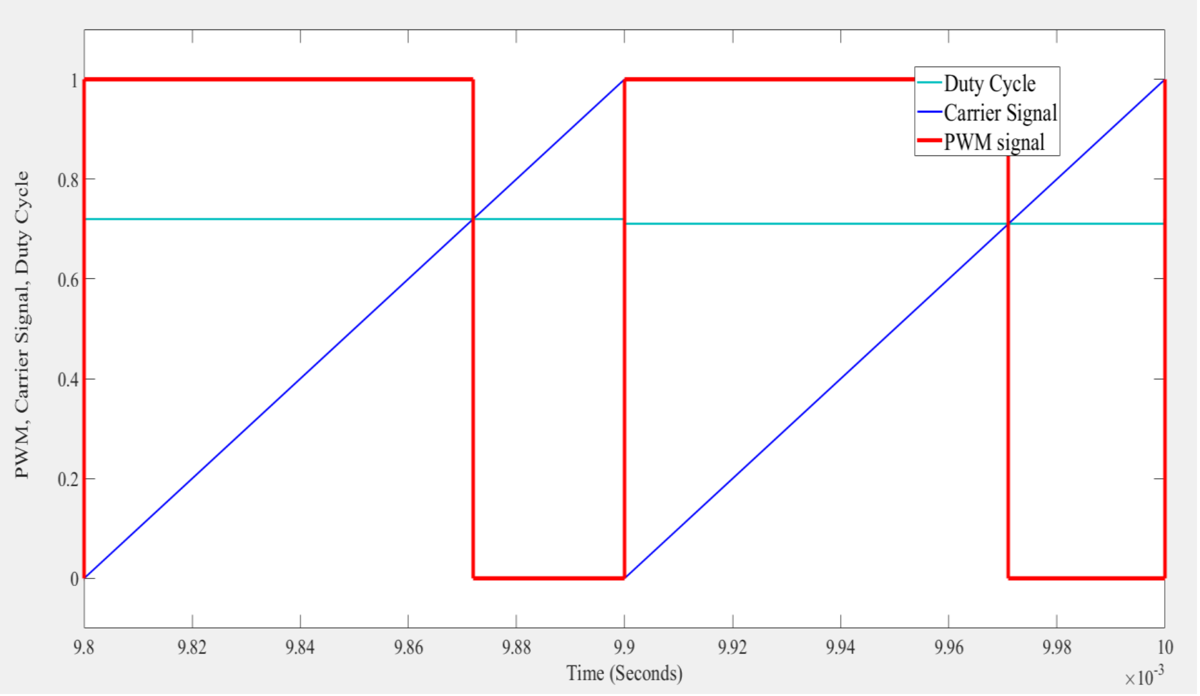

Figure 3-7 PWM Signal Generated from comparison of Triangle Signal and Duty Cycle

3.6 Work Schedule

Table 3-2 Work plan for the project

Research Stage	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12	Week 13
Literature Review Gathering and Reading													
Design and simulation for DC-DC Buck Converter													
Coding and simulation of MPPT Algorithm (P&O, Incremental Conductance in Simulink													
Implementation of MPPT Algorithm into Buck Converter													
Analysis of Algorithms													
Report writing and review													

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter the result from simulation will be displayed and analysed. The data and analysis of the proposed buck converter topology are attained via simulations. The simulation result of the buck converter paired with the MPPT system is from MATLAB Simulink software. The chapter starts with the evaluation of the buck converter designed and followed by simulation to compare perturb and observe and incremental conductance MPPT algorithm.

4.2 Maximum Power Tracking Results

The incremental conductance and perturb and observe method are simulated with input signal of constant solar irradiation and temperature of 1000 W/ m^2 and 25 $°C$ respectively. Figure 4-1 and Figure 4-2 shows the result of simulation to compare the output of the PV module with and without maximum power point tracking using P&O and IC algorithms.

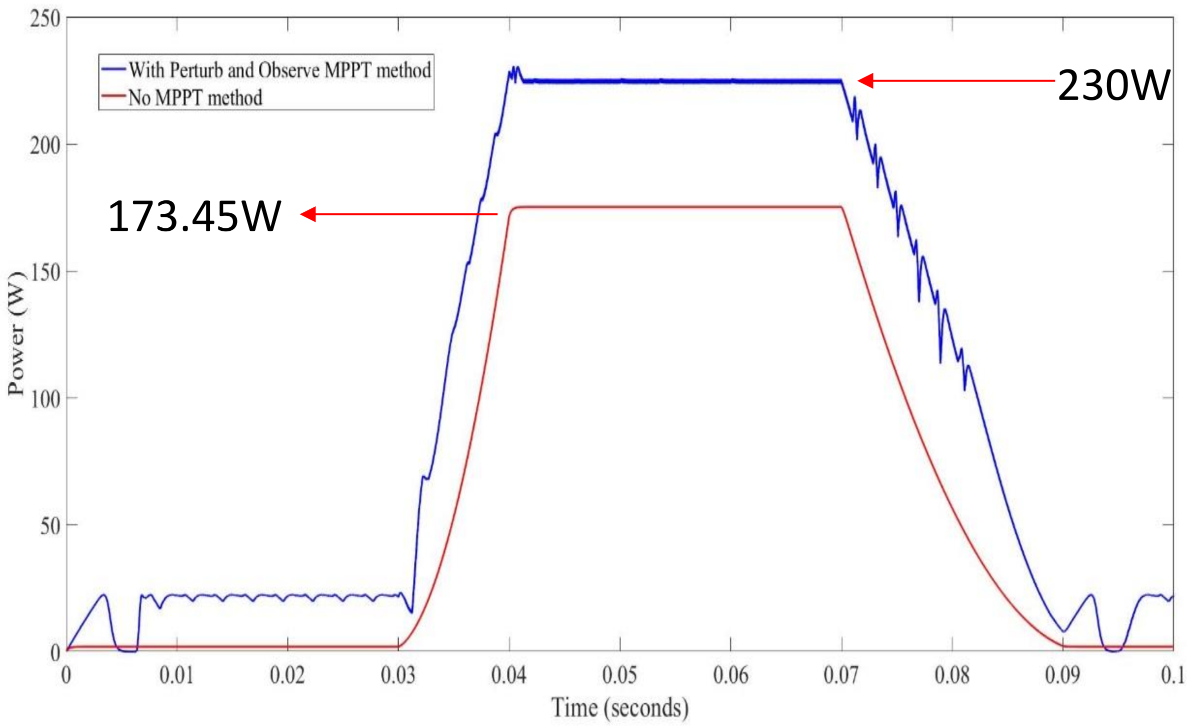

Figure 4-1 PV module power with P&O MPPT and without MPPT

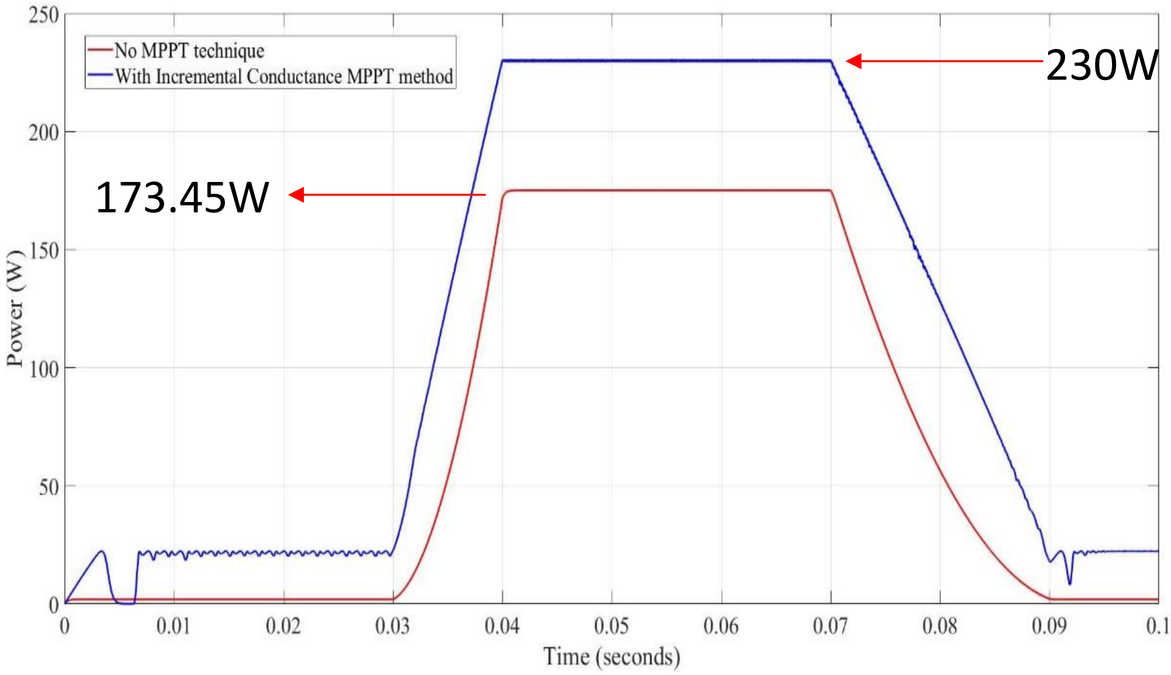

Figure 4-2 PV module power with Incremental Conductance MPPT and without MPPT

Based on Figure 4-1 and Figure 4-2, at irradiation of 1000 W/ m^2 and temperature at 25°C, the PV module is supposed to have a maximum power of 230W as stated in the datasheet specification of PV module in Table 2-1. However, without an MPPT tracker either the Incremental Conductance or the Perturb and Observe algorithm, the PV module is only able to output 173.45W. This shows that without an MPPT, the PV module efficiency is greatly affected. The efficiency was calculated using formulae (3.4.1). The efficiency of the PV module is more than 98% when using both the Perturb and Observe and Incremental Conductance algorithm, whereas the efficiency of the module without MPPT is less than 80% with a load of 2.5Ω.

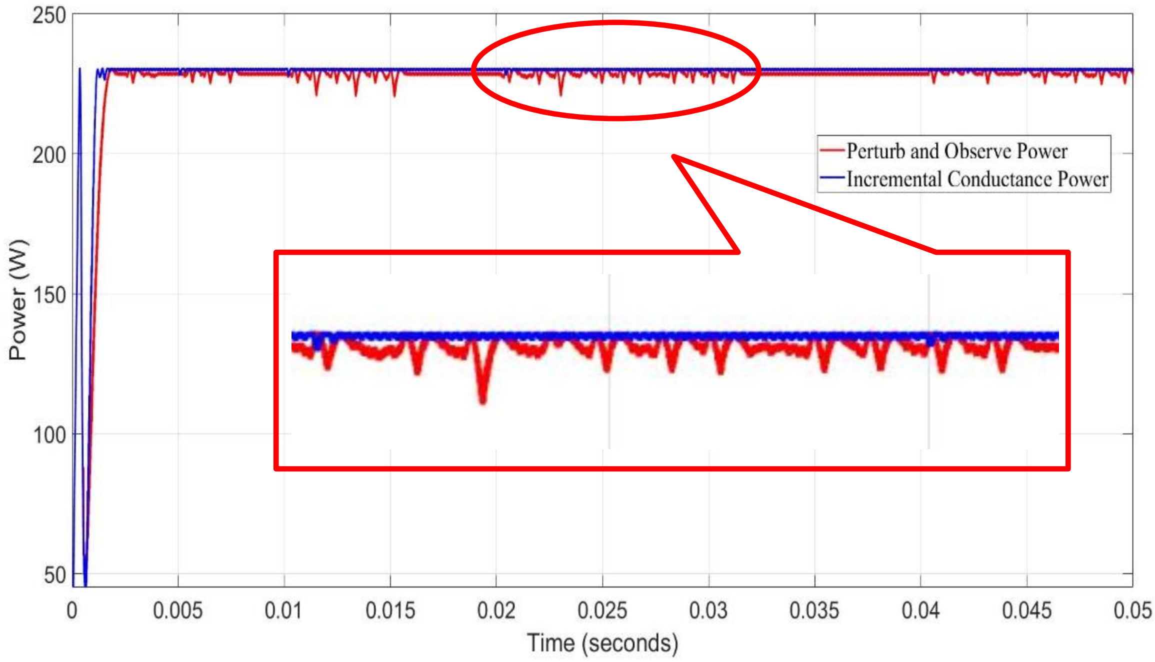

Figure 4-3 Power Output curve for Incremental Conductance and Perturb and Observe

Figure 4-3 shows the comparison in the power response at constant irradiation of 1000 W/m^2 and ambient temperature of 25℃ for both IC and P&O algorithms. There is distinctive difference between the two MPPT techniques. The incremental conductance has lesser oscillation once it reaches the module maximum operating point. Figure 4-4 below shows the average daily irradiance and temperature for 10 years between 1992 to 2002 from research done by (Hussin *et al.*, 2010).

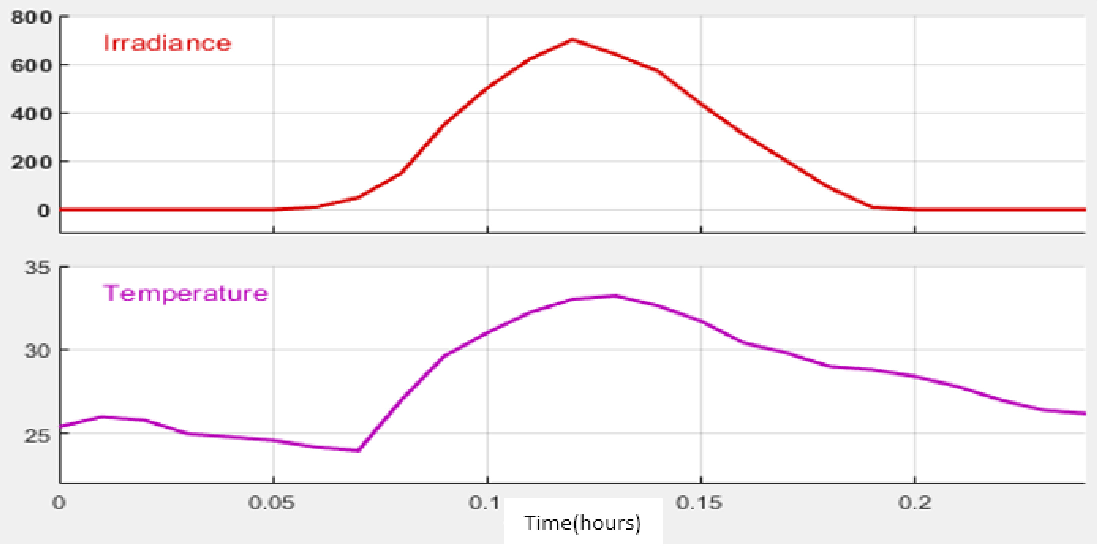

Figure 4-4 Average Irradiance and Temperature variation in Subang and Klang Valley area(Hussin *et al.*, 2010)

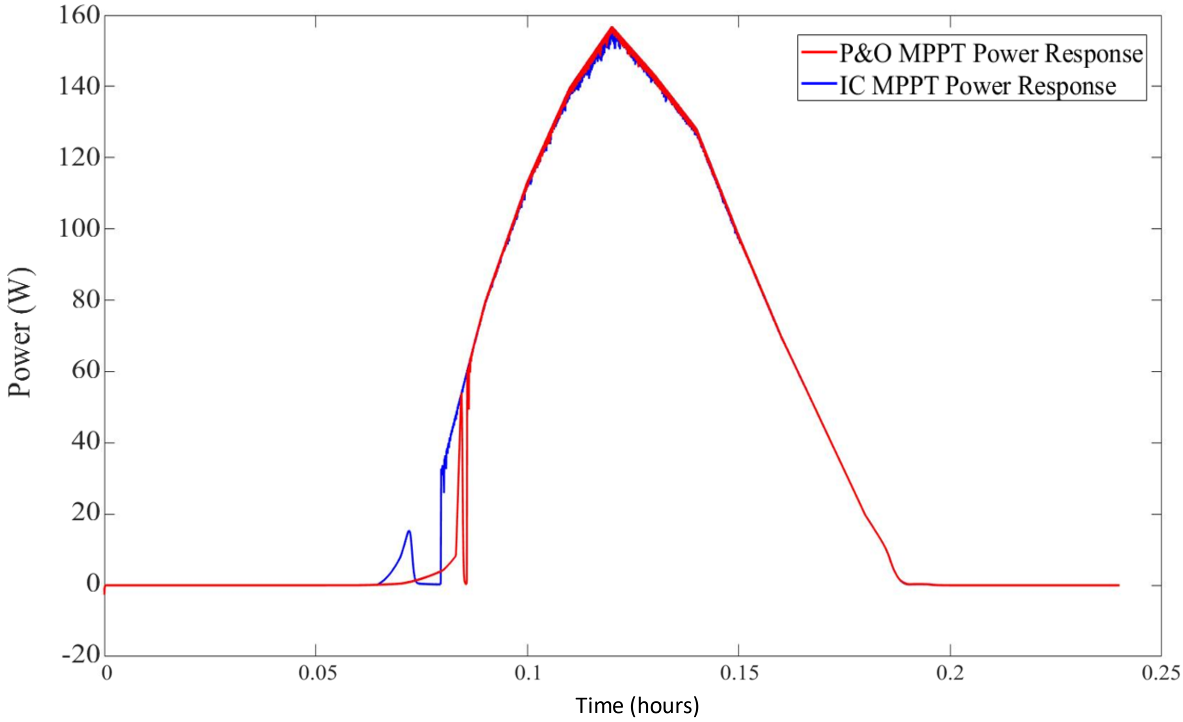

Figure 4-5 Real world irradiation and temperature testing for both MPPT algorithms

The simulation result for condition stated in Figure 4-4 is shown in Figure 4-5 above. Each time of day is 0.01 second. From the figure 4-5, it can be seen that both MPPT algorithm and PV system was unable to track the maximum power of the PV panel in the morning from 6am to 9am. However, the incremental conductance method took far lesser time to speed up and track the maximum operating power point of the PV module when compared to perturb and observe technique. The experiment was then carried out to reduce the step size of the duty cycle perturbation from 0.01 per step to 0.0001 per step. By changing the duty cycle step size to a smaller value, perturb and observe is ahead of the incremental conductance technique in tracking the maximum power of the PV module. Figure 4-6 shows the resulting waveform from the adjustment of duty cycle perturbation step size.

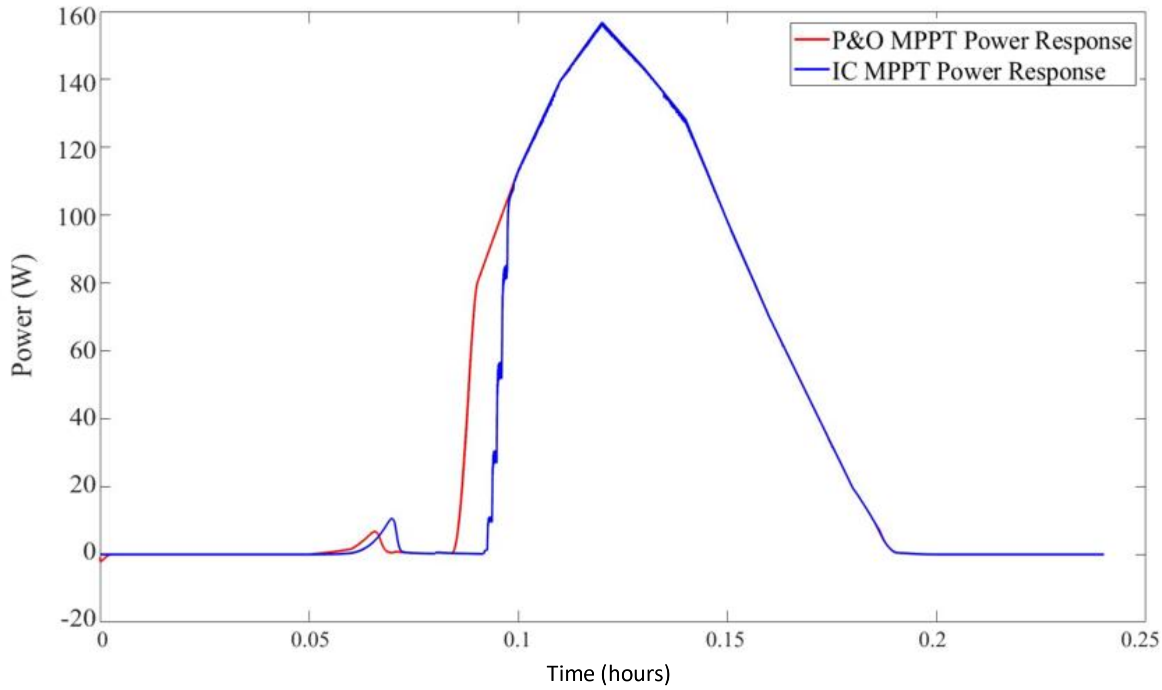

Figure 4-6 Power output curve for change in duty cycle perturbation step size for P&O and IC algorithm

Simulation was also performed at room temperature of $25°C$ with varying irradiance from 600 to 1000 W/m^2. Comparing both Figure 4-7 and Figure 4-8, it is seen that the P&O algorithm move more around the MPPT compared to the incremental conductance algorithm. This is denoted by the red line in both the figures mentioned below.

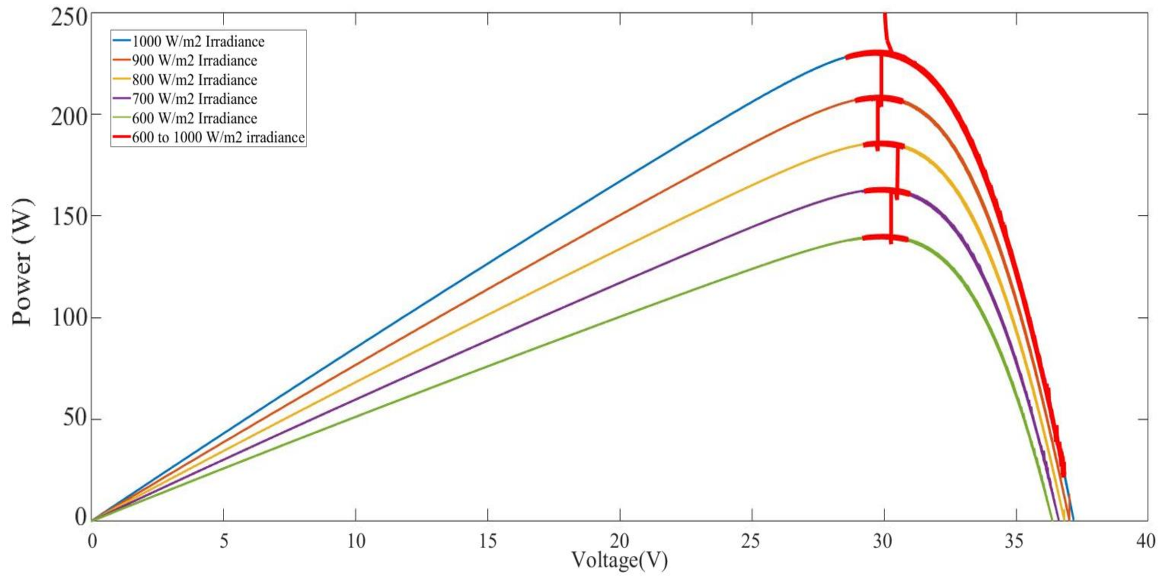

Figure 4-7 Incremental Conductance Algorithm tracking from 1000 W/m^2 to 600 W/m^2

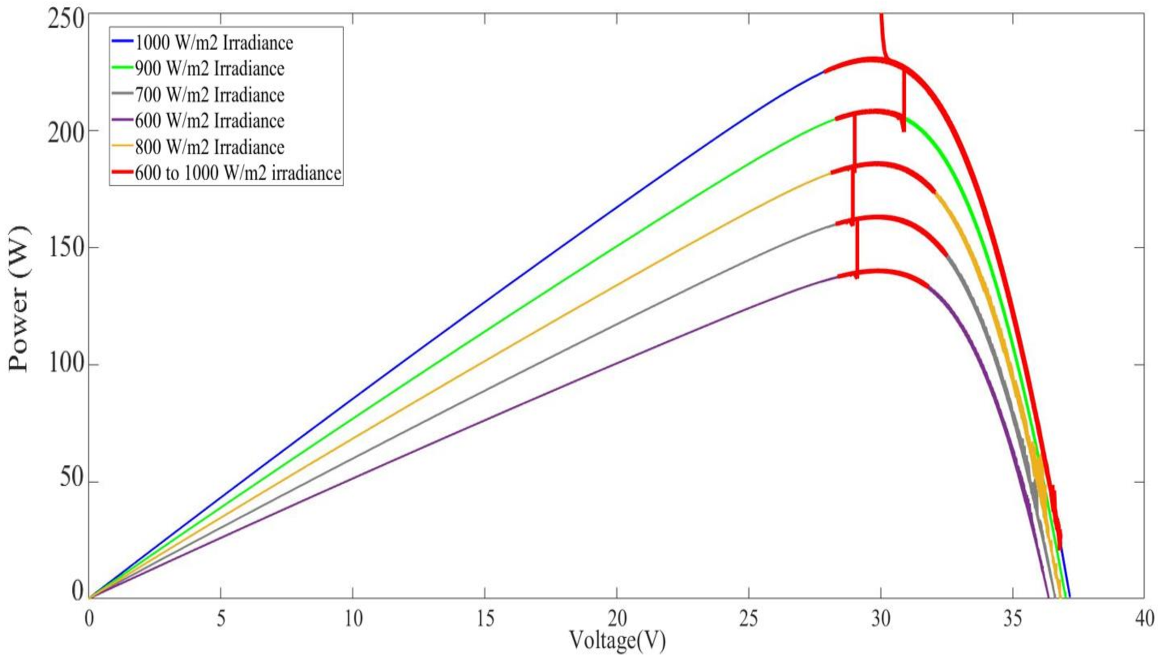

Figure 4-8 P&O Algorithm tracking from 1000 W/m^2 to 600 W/m^2

4.3 Buck Converter Simulation Results

The buck converter is simulated to check on the ability to function at which specific range of irradiance and temperature. The simulation methodology is specified in section 3.4. The MPPT technique used is the incremental conductance in this simulation due to it has better tracking efficiency without any modifications. Table 4-1 shows the result from the simulation with varying irradiation and Table 4-2 shows the simulation with varying temperature.

Table 4-1 Duty Cycle and Maximum Power of PV system with varying irradiance and fixed temperature of 25℃

Irradiance	MPP ,(W)	Ideal MPP, (W)	Duty Cycle	MPPT Efficiency (%)
200	45.5	45.84	0.36	99.26%
400	93.01	93.1	0.51	99.90%
600	139.6	139.8	0.62	99.86%
800	185.38	185.5	0.72	99.94%
1000	229.8	230	0.8	99.91%
1200	273.13	273.3	0.88	99.94%
1400	315	315.1	0.96	99.97%

Table 4-2 Duty Cycle and Maximum Power of PV system with varying temperature and fixed irradiance of 1000 W/m^2

Temperature, Celsius	MPP ,(W)	Ideal MPP, (W)	Duty Cycle	MPPT Efficiency (%)
0	256.1	256.3	0.76	99.92%
10	245.75	245.9	0.77	99.94%
20	235	235.3	0.79	99.87%
30	224.495	224.7	0.81	99.91%
40	213.7	213.9	0.83	99.91%
50	203	203.95	0.86	99.53%
60	191.275	192.1	0.885	99.57%
70	180.645	181	0.91	99.80%

From the table of results above, the buck converter is able to track over a wide range of temperature up to 70℃. The converter is able to track the maximum power through the variation of the duty cycle up to 1400 W/m^2. Based on Table 4-1, the buck converter design is able to match the theoretical duty cycle at 1000 W/m^2 and 25℃ at ~80 percent.

Table 4-3 and Table 4-4 shows the data tabulated from the simulation for the incremental conductance and perturb and observe MPPT algorithm respectively performed by varying the irradiance at a fixed temperature of $25°C$. The simulation is then performed at varying temperature from 0 to $70°C$. Table 4-5 and Table 4-6 shows the data collected from the simulation for the incremental conductance and perturb and observe MPPT algorithm respectively. The buck converter is simulated with varying temperature and irradiance as shown in Figure 4-1 and Figure 4-2. From these two graphs shown below, the buck converter has an average of 97 percent efficiency during varying irradiance at fixed temperature of $25°C$ and a 98 percent efficiency during varying temperature at fixed irradiance of 1000 W/m^2. The efficiency of the buck converter for both algorithm is comparable for all varying temperature conditions. However, during the variation of irradiance situation, as shown in Figure 4-1, the buck converter has slightly better efficiency when used with perturb & observe algorithm during low irradiance condition compared to incremental conductance algorithm. The difference in efficiency during low irradiance between 200 W/m^2 and 800 W/m^2 is 0.89 percent.

Table 4-3 Buck converter efficiency of Incremental Conductance MPPT algorithm with varying irradiance and fixed 25℃ operating temperature

Irradiance	Buck Output Power ,(W)	PV output Power, (W)	IC Duty Cycle, D	Buck Converter Efficiency (%)
200	43.47	45.85	33%	94.81%
400	90.08	93.14	46%	96.71%
600	136.01	139.39	59%	97.58%
800	180.64	184.97	69%	97.66%
1000	225.01	228.13	78%	98.63%
1200	268.44	273.13	88%	98.28%
1400	310.81	315.04	96%	98.66%

Table 4-4 Buck converter efficiency of Perturb and Observe MPPT algorithm with varying irradiance and fixed 25℃ operating temperature

Irradiance	Buck Output Power ,(W)	PV output Power, (W)	P&O Duty Cycle, D	Buck Converter Efficiency with P&O (%)
200	43.35	45.3	39%	95.70%
400	89.15	91.77	54%	97.15%
600	134.63	137.67	66%	97.79%
800	179.19	182.42	76%	98.23%
1000	221.17	224.48	86%	98.53%
1200	268.44	273.13	88%	98.28%
1400	310.95	314.36	96%	98.92%

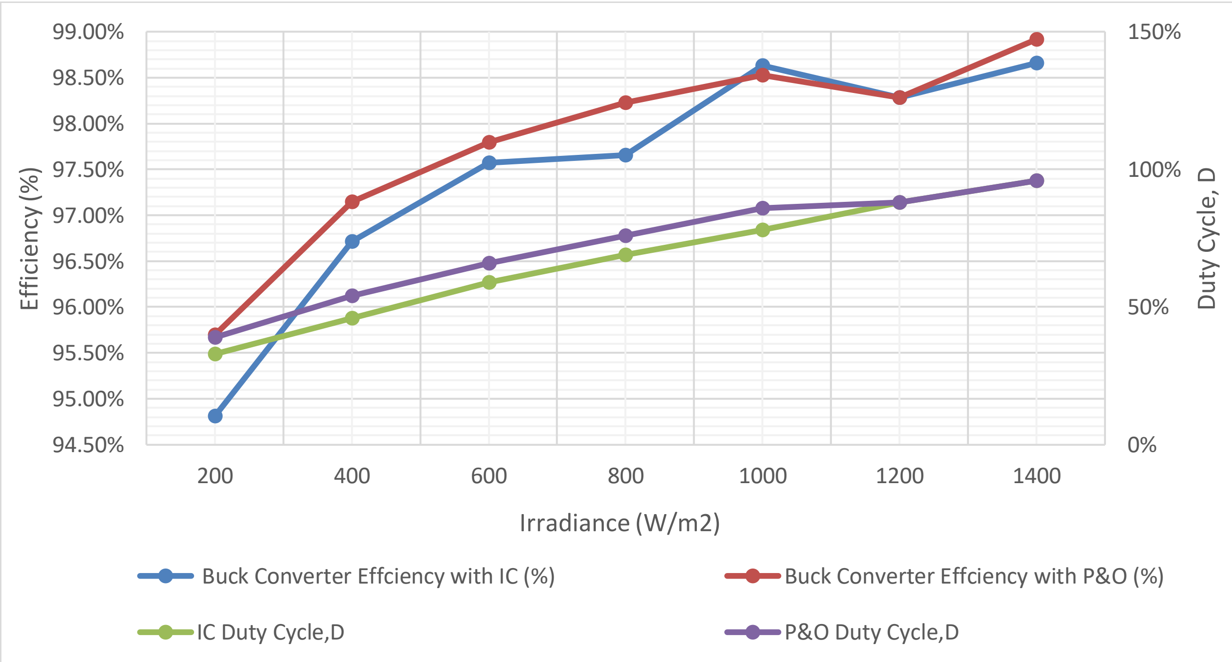

Figure 4-9 Comparison of buck converter efficiency of Incremental Conductance and Perturb and Observe MPPT algorithm with varying irradiance and fixed 25℃ operating temperature

Table 4-5 Buck converter efficiency and duty cycle of Incremental Conductance MPPT algorithm with varying temperature and fixed 1000 W/m^2 irradiance.

Temperature	Buck Output Power ,(W)	PV output Power, (W)	IC Duty Cycle, D	Buck Converter Efficiency with IC (%)
0	250.69	255.55	72%	98.10%
10	241.2	245.61	75%	98.20%
20	230.78	233.89	78%	98.67%
30	220.57	224.47	79%	98.26%
40	210.17	213.48	82%	98.45%
50	199.83	203	86%	98.44%
60	189.02	191.61	88%	98.65%
70	178.42	180.39	91%	98.91%

Table 4-6 Buck converter efficiency and duty cycle of Perturb and Observe MPPT algorithm with varying temperature and fixed 1000 W/m^2 irradiance.

Temperature	Buck Output Power ,(W)	PV output Power, (W)	P&O Duty Cycle, D	Buck Converter Efficiency with P&O (%)
0	250.2	254.7	78%	98.23%
10	239.52	244.14	80%	98.11%
20	229.52	233.41	83%	98.33%
30	219.66	222.9	82%	98.55%
40	208.82	212	85%	98.50%
50	198.97	202	87%	98.50%
60	187.36	189.81	90%	98.71%
70	176.13	178.47	94%	98.69%

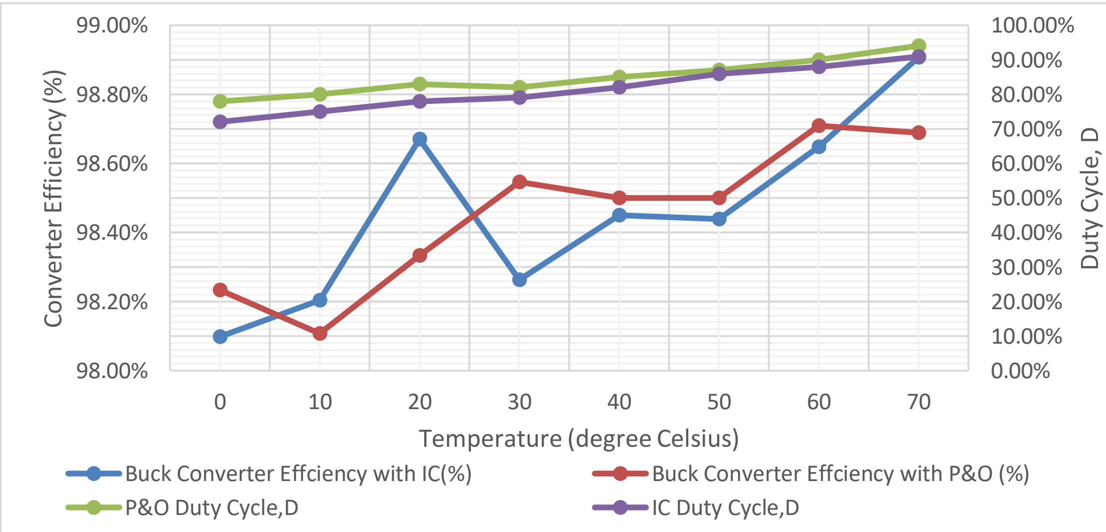

Figure 4-10 Comparison of buck converter efficiency and duty cycle of Incremental Conductance and Perturb and Observe MPPT algorithm with varying temperature and fixed 1000 W/m^2 irradiance.

4.4 Discussion

The simulation result shows that the incremental conductance has a lesser oscillation compared to perturb and observe MPPT algorithm as shown in result section Figure 4-3. This is due to the tracking methodology of the incremental conductance algorithm. The algorithm will not change the duty cycle very widely once the instantaneous conductance is equal to the incremental conductance and also when the current change is equal to zero. The power will still have oscillation but with lesser magnitude compared to perturb and observe method. This can be seen clearly from the duty cycle waveform comparison in Figure 4-11 between the incremental conductance tracking and perturb and observe method.

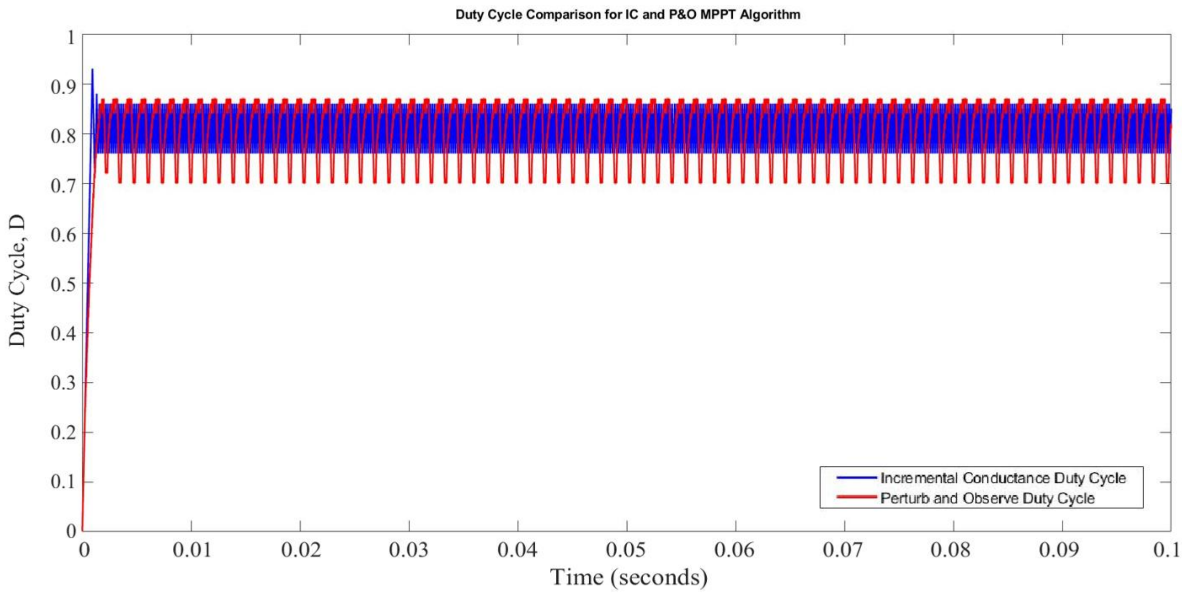

Figure 4-11 Duty cycle comparison between incremental conductance and perturb and observe

This however, can be overcome by adjusting the duty cycle adjustment delta from 0.01 to 0.0001 to increase the accuracy of perturb and observe algorithm and overcome the drawbacks of having oscillating power response. Figure 4-12 shows the comparison in the response of the power from both algorithm.

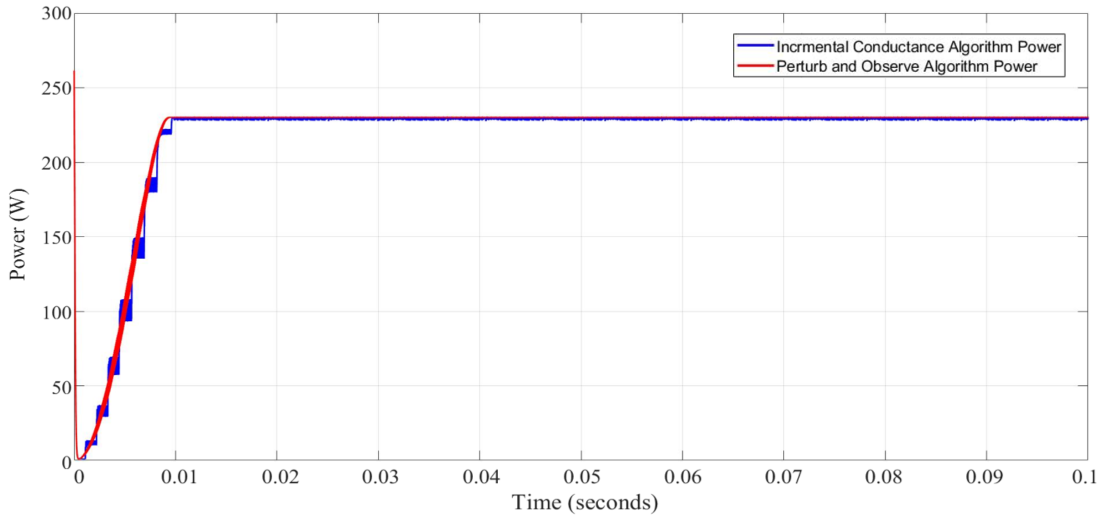

Figure 4-12 Power response comparison between incremental conductance and perturb and observe with smaller duty cycle perturbation step

It can be observed that perturb and observe achieve the maximum power faster than the incremental conductance algorithm with a smaller duty cycle perturbation. The oscillation is reduced because perturb and observe algorithm is highly influenced by the perturbation of the duty cycle to track the maximum power of the PV system. With a smaller power change, the system will oscillate lesser and attain maximum power in a shorter time due to lesser calculation need to be performed compared to incremental conductance algorithm. The incremental conductance algorithm does not depend solely on the delta of the duty cycle but it compares the instantaneous conductance and the incremental conductance. This method is more complex to be implement than perturb and observe method due to the slope calculation which needs to be performed by the algorithm before it can decide to change the duty cycle in which direction.

Next, the discussion about the converter efficiency for the use of MPPT power transfer medium. In this study, the converter used was the buck converter and two different MPPT algorithm which is perturb and observe and incremental conductance method. Based on simulation result shown in Figure 4-1 and Figure 4-2, the methods used has gave us a result which shows that at higher duty cycle close to 100 percent, the efficiency of buck converter for both algorithm are comparable and reach a maximum of 98.9 percent. This is due to when the switch is at or reaching maximum duty cycle, the MOSFET is not very frequently switched. This will result in the switching losses to be lower. However, there will still be parasitic losses from the inductor and the capacitor due to equivalent series resistance present at both components. The losses from this is minimal as the resistance is small with almost negligible effect.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This study had analysed two MPPT methods which allow for extraction of maximum power from PV modules. The project investigates the performance of the popular techniques that is the P&O and Incremental Conductance, while the simulation results considering the maximum power extracted from the PV array have been obtained.

From individual analysis of each technique, perturb and observe algorithm is the easiest to implement. This is because there is least amount of calculation to be done in order to track the MPP of the PV module. However, for incremental conductance, the implementation is complex with two types of calculation to be performed which is the instantaneous conductance and incremental conductance which is needed for accurate tracking and low steady-state error of calculation of the derivative of current with respect to voltage. The oscillations in perturb and observe algorithm could be reduced with smaller duty cycle step size from 0.01 to 0.0001 as demonstrated in chapter 4.

In this study, the buck converter was designed with optimum parameters for the selected PV module as a medium to transfer the maximum power from the PV module to the load without much power loss. The buck converter in this study was able to produce comparable efficiency when using two different MPPT algorithm to track the PV module maximum power. The maximum efficiency attained for the buck converter is from 94.8 percent to 98.9 percent. The buck converter was simulated with multiple level of irradiance from 100 W/m^2 to 1400 W/m^2 with 100 W/m^2 steps at 25°C. From the simulation results, the buck converter designed for PV application is able to convert maximum powers up to solar irradiance level of 1400 W/m^2. The converter is also able to perform well at wide range of temperature variation between 0°C and 70°C with average efficiency of 99.7 percent. Therefore in conclusion, all objective stated in section 1.3 were fulfilled in this study.

5.2 Recommendations for future work

To continue this study, researchers can continue to exploit the MPPT algorithm to track multiple peaks of the PV array during partial shading condition. Researches can also build the physical model of this buck converter and implement the two MPPT algorithm mentioned in this study that is the IC and P&O algorithm. The algorithm can further be tested to check for performance in real world condition with partial shading effect on PV array and sudden change in cloud covers.

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APPENDICES

APPENDIX A: MATLAB Coding of Incremental Conductance MPPT algorithm

```
function D = IncCond(Vpv,Ipv)

persistent Dprev Iprev Vprev

if isempty(Dprev)
    Dprev = 0;
    Vprev = 0;
    Iprev = 0;
end

deltaD = 0.01;
D = Dprev;
dV = Vpv - Vprev;
dI = Ipv - Iprev;

if (dV==0)
    if (dI==0)
        D = Dprev;
    end
    if (dI>0)
        D = Dprev - deltaD;
    end
    if (dI<0)
        D = Dprev + deltaD;
    end
else
    if((dI/dV)==(-Ipv/Vpv))
        D = Dprev;
    end
    if((dI/dV)>(-Ipv/Vpv))
        D = Dprev - deltaD;
    end
    if((dI/dV)<(-Ipv/Vpv))
        D = Dprev + deltaD;
    end
end

Dprev = D;
Vprev = Vpv;
Iprev = Ipv;
```

APPENDIX B: MATLAB Coding of Perturb and Observe MPPT algorithm

```
function D = PandO(Vpv,Ipv)

persistent Dprev Pprev Vprev

if isempty(Dprev)
    Dprev = 0;
    Vprev = 0;
    Pprev = 0;
end
D = Dprev;
deltaD = 0.01;

Ppv = Vpv*Ipv;

if(Ppv-Pprev)>=0
    if(Vpv-Vprev)>=0
        D = Dprev-deltaD;
    else
        D = Dprev+deltaD;
    end
else
    if(Vpv-Vprev)>=0
        D = Dprev+deltaD;
    else
        D = Dprev-deltaD;
    end
end

Dprev = D;
Vprev = Vpv;
Pprev = Ppv;
```