M. Tech (Power System) CHIRAG KAUSHIK 2022

COMPARITIVE STUDY OF TRADITIONAL AND INTELLIGENT MPPT TECHNIQUES FOR PHOTOVOLTAIC SYSTEMS

A DISSERTATION SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF

MASTER OF TECHNOLOGY
IN
POWER SYSTEMS

SUBMITTED BY:

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(2K20/PSY/06)

UNDER THE SUPERVISION OF

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2022

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CANDIDATE'S DECLARATION

I, Chirag Kaushik, 2K20/PSY/06 student of M.Tech(Power System),hereby declare that the project Dissertation titled "Comparative study of traditional and intelligent techniques for Photovoltaic Systems" which is submitted by me to the Department of Electrical Engineering ,Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of Master of Technology ,is original and not copied from any without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

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CERTIFICATE

I hereby certify that the Project Dissertation titled "Comparative Study of Traditional and Intelligent techniques for Photovoltaic Systems" which is submitted by Chirag Kaushik, Roll No. 2K20/PSY/06 Department of Electrical Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the students under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

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Date: **SUPERVISOR**

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CO-SUPERVISOR

ABSTRACT

Electricity has become a basic necessity for humans in day-to-day life to fuel all kinds of industries, agriculture, households etc. In India, major portion of electricity is generated using fossil fuels like coal, oil and natural gas. As the fossil fuels are depleting at a fast pace, there is an urgent need of switching to renewable resources for power generation. Solar energy is seen as one of the most promising renewable energy source. Presently, in India 13.5% of electricity is generated from solar energy whereas 59.1% of it is generated from fossil fuels[1]. A lot of research is going on related to Solar Photovoltaic(SPV) systems to enhance its efficiency with higher affordability which can make it much more feasible and sustainable for human needs. SPV converts the solar energy from sunlight to electrical energy using photovoltaic effect. The DC power is efficiently extracted by the solar PV array using the optimum firing of the MOSFET/IGBT switch of the converter using Maximum Power Point Tracking (MPPT) techniques. The various MPPT techniques being compared in the project are 'Perturb & Observe Algorithm', 'Incremental Conductance Algorithm', 'Type-1 Fuzzy Logic Controller' and Artificial neural Network. The photovoltaic array of 13.68kW of SunPower SPR-76R-BLK-U module with 45 series connected modules in 4 parallel strings is used for the present studies. The MATLAB Simulink Model for standalone SPV system using boost converter is developed and validated under uniformly varying atmospheric conditions. Comparative analysis between MPPT techniques has been carried out based on fill factor, power loss, power extracted and ripples.

ACKNOWLEDGEMENT

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I would like to express my sincere gratitude to Prof. RACHANA GARG, Department of Electrical Engineering, my project guide, for support, motivation and encouragement throughout the period this work was carried out. Their readiness for consultation at all times and their educative comments have been invaluable. I am also grateful to my co-supervisor Prof. Priya Mahajan who helped me selflessly throughout my project work which made things even simpler.

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Date: **(Chirag Kaushik)**

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LIST OF ABBREVIATIONS

PV	Photovoltaic
MPPT	Maximum power point tracking
P-V	Power vs Voltage
I-V	Current vs Voltage
P&O	Perturb and Observe
INC	Incremental Conductance
FLC	Fuzzy Logic Controller
ANN	Artificial Neural Network
AC	Alternating Current
DC	Direct Current
Temp.	Temperature
T1-FLC	Type-1 Fuzzy Logic Controller

CHAPTER 1 INTRODUCTION

1.1 General

Electrical Energy plays a vital role in overall growth of the country. It helps in the development of all essential services like healthcare, banking etc. Electrical energy demand has also increased rapidly with the growing population and modernization of society. Total installed capacity of electrical energy generation in India is around 399,497MW [1]. Fossil fuels like coal, oil and natural gas are mostly used as raw material in production of electrical energy from thermal powerplant. Installed generation Capacity Percentage wise share of all the sources is shown in table 1.1[1]. Almost 59.1% of electrical energy is generated from fossil fuels whereas 13.5% of electrical energy is generated from solar energy. Due the high maintenance cost, pollution concerns and depletion of major reserves of these fossil fuels, it is the need of the hour to switch from conventional resources to renewable resources like solar, ocean, wave and wind. Renewable resources are more sustainable and eco-friendlier than non-renewable resources.

Table 1.1 Installed Generation Capacity of Electrical Energy in India

Category	**Installed Generation Capacity (MW)**	**%SHARE In Total**
Fossil Fuel		
Coal	2,04,080	51.1
Lignite	6,620	1.7
Gas	24,900	6.3
Diesel	510	0.1
Renewable Resources		
Hydro	46,723	11.7
Solar	53,997	13.5
Wind	40,358	10.1
Waste to energy	447	0.1
Small Hydro	4,849	1.2
BM Power/Cogen	10,206	2.6

1.2 Solar Energy

All the stake holders are working hard on exploring renewable resources to bring it out into mainstream for electrical energy generation. In India, Solar energy is at the advantageous position due to its geographical location as the tropic of Cancer passes through middle of the country. Government of India has launched multiple schemes to promote electricity generation from solar energy. National solar mission is one of the most famous initiatives taken by the Indian government which targets to setup 100GW of solar PV by the end of 2022. India is ranked fifth in solar power deployment across the globe [2]. In India, most of the solar projects are based on the photovoltaic systems. Photovoltaic systems have less maintenance cost and can be set up at any remote location very easily. This system directly converts the light energy into electrical energy when sunlight falls on the solar panels. There has been an extraordinary work going on in research and development in field of PV which has helped to enhance its efficiency.

1.3 Purpose of the project

The main objective of this thesis is to understand the designing, simulation and comparison of PV system using different MPPT techniques under uniformly varying atmospheric conditions. A standalone PV system is considered which uses boost converter as an interface between load and PV array. Figure 1.1 shows the pictorial representation of standalone PV systems.

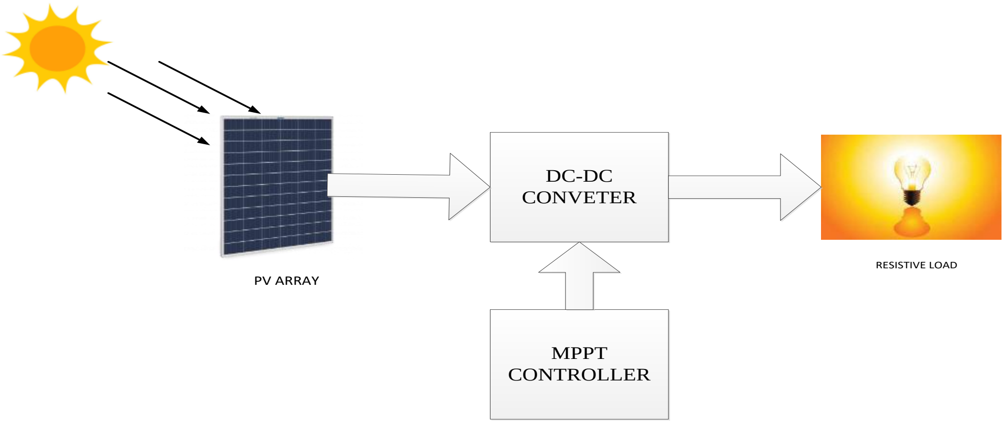

Figure 1.1 Standalone PV system

Due to the nonlinear characteristics of PV array, there is only one operating point at which maximum power can be extracted. The characteristics of PV arrays also get affected by the variation of atmospheric conditions. This peculiar behavior of PV arrays resulted in development of maximum power point tracking techniques. The purpose of the thesis is to establish the comparison of extracted power from PV array using different Maximum Power Point Techniques like Perturb & Observation algorithm, Incremental conductance algorithm, Type-1 Fuzzy Logic Controller and Artificial neural network. The comparison is done on the basis of fill factor , power loss , ripples and power extracted from PV array under uniformly varying atmospheric conditions i.e., varying ambient temperature at constant solar irradiations and varying solar irradiations at constant ambient temperature.

1.4 Outline of thesis

The report consists of flowing chapters:

Chapter 1: This chapter provides the brief overview on current scenario on generation of electrical energy, need for solar energy and purpose of this project.

Chapter2: This chapter gives the literature review done to get through the working of Photovoltaic systems, modelling of boost converter, different MPPT techniques adopted in PV systems.

Chapter 3: This chapter describes the working of photovoltaic System and its electrical modelling to obtain the I-V and P-V curve. It highlights the different type of equivalent electrical models of PV cell. It further gives the overview on dependence of Photovoltaic system on solar Irradiance and ambient Temperature. This chapter also provides detailed description of working and designing of Boost converter and its application in the present work

Chapter 4: This chapter explains the concepts of conventional MPPT techniques which are generally used to improve the efficiency of Photovoltaic Systems. The MPPT techniques employed are ‘Perturb and Observe’ and ‘Incremental Conductance’.

Chapter 5: This chapter explains the concepts of intelligent MPPT techniques which are generally used to improve the efficiency of Photovoltaic Systems. The MPPT techniques employed are ’Type-1 Fuzzy Logic Controller’ and ‘Artificial Neural Network ‘.

Chapter 6: This chapter highlights the comparative analysis of performance of four techniques mentioned i.e., Perturb and Observe, Incremental Conductance, Type-1 Fuzzy Logic Controller and Artificial Neural Network is described.

Chapter 7: This chapter gives the main conclusion of the work done and also includes the scope of future work.

CHAPTER 2 LITERATURE REVIEW

2.1 General

This chapter highlights the literature review done in order to understand the working of photovoltaic systems A lot of research work carried out in past to acknowledge the concept of MPPT using different techniques and complex behavior of PV arrays under various atmospheric conditions. The main focus of literature review is on the following topics:

i) Modelling of Solar PV array

ii) Maximum Power Point tracking

iii) Modelling of Boost Converter

2.2 Modelling of Solar PV Array

Solar PV cell is the fundamental component of solar PV array. Solar PV cell is a semiconductor device which generates DC voltage when photons with appropriate energy level falls on the surface of panel. Villalva et al. (2009) [6] has proposed modelling of PV arrays. The authors described the parameters of the I-V equation of solar by modifying the curve with respect to the open circuit voltage, short circuit current and maximum power. These three has been useful for providing datasheets for all industrial array, the authors have proposed the best I-V equation for the single diode PV model considering the effect of parallel and series resistance. With the three parameters of the modified I-V equation one can build a PV module with any simulator by using different math blocks. The authors initially presented the basic tutorials of PV and different parameters that can compose single diode PV model. Sinha et al. (2014) [7] has demonstrated that PV array exhibits the nonlinear characteristics of voltage and current this characteristic directly depend on the solar irradiation and some environmental factors. The author discussed the equivalent configuration of PV cells with respect to environmental conditions and from the observations the I-V characteristics has been plotted. The author has analysed the performance for accomplishing the maximum power. Nguyen Binh Nam et al[8] has depicted improvement in the power generation from a PV array in any weather condition, and also help to reduce the impact of rapid change of solar irradiation on the output power variation within the time duration of change. Hyeonah Park and Hyosung Kim[9] proposed a novel PV modelling algorithm which can be used for different types of PV cells such as thin-film type and Cr-Si type Pv cells. The authors have analyzed three representative PV modelling. H. Andrei et al [10] gives a detailed study of sensitivity of PV cell under standard test conditions and different atmospheric conditions i.e., varying solar irradiations and ambient temperature. G. Bhuvaneswari and R. Annamalai [11] has proposed an new model of PV cell in MATLAB/SIMULINK and compared it with two existing models of PV cell. The author has validated the results by obtaining the I-V and P-V characteristics of all three models. P. K. Pandey and K. S. Sandhu[12] presents performance analysis of PV cell using single diode, double diode and triple diode configuration using MATLAB programming.

2.3 Maximum PowerPoint Tracking

Beriber et al[13] gives a detailed comparative survey of four maximum power tracking techniques: Perturb and Observe (P&O), Incremental Conductance (INC), fuzzy logic based tracking technique and a, less known, method using only the photovoltaic current measurement. Karami et al. [14] explains and classifies 40 different MPPT techniques. The author has explained the working principle of the 40 different MPPT techniques and theoretical comparative analysis is also done for the same. Liu et al [15] show that the INC based MPPT controller has good dynamic performance even when irradiance changes sharply. Gundogdu et al [16] gives a brief overview of improved performance of ANN based MPPT over INC and P&O algorithm. Singh et al[17] gives the basic review of grid integration of PV system with grid using ANN and Fuzzy based MPPT. R.Chafle & B Vadiya (2013) [18] explained the importance of solar energy and problem facing in using solar energy and the authors has also explained the INC algorithm used for Maximum power point tracking. S. Kumar Roy et al[19] proposed two ways of implementing perturb &Observe algorithm using MATLAB/SIMULINK. One of the ways is using MATLAB function block and the other one is using artificial neural network. Zhanghong et al[20] has given detailed description of designing of fuzzy logic controller using MATLAB/SIMULINK software.

2.4 Modelling of Boost Converter

Mohan et al. [21] has explained working and design of DC-DC converters and magnetic components used for the same. Simoiu et al [22] has described the BOOST converter modelling as a subsystem of a photovoltaic panel control system. Operation of BOOST converter is explained in detail by author. Choi et al [23] aims at modelling boost converter having fairly large equivalent series resistance (ESR) of input reservoir capacitor by state-space-averaging method and Pulse width modulating switch model and compares both mentioned methods using Bode plots. M. Nasiri et al[24] has highlighted the effect of input capacitor on stability MPPT of PV array, the performance of PV system has been compared with different input capacitors of boost converter. O. K. Islam[25] has depicted the comparison of performance of designing of PV system using boost and buck-boost converter

2.5 Conclusion

In this chapter the literature review is done in the required is detailed. The literature review is done to understand the scope of solar energy in future, electrical modelling of photovoltaics, traditional and intelligent MPPT techniques PV system. It helps to implement the learning more effectively and gain adequate knowledge about latest trends

CHAPTER 3:DESIGN OF PHOTOVOLTAIC SYSTEM

3.1 General

With the lot of research going on, many developments have been made in photovoltaic systems which has resulted in its reduced cost and enhanced efficiency. In order to understand the working and designing of PV system it is very important to understand the electrical modelling of photovoltaic systems and its output characteristics. This chapter gives a brief overview of the Photovoltaic system, its modelling and behavior under different working conditions like varying solar irradiance, varying ambient temperature. All the equations are mentioned in this chapter associated to electrical modelling of the Photovoltaics.

3.2 Photovoltaic Systems

Photovoltaic system is an energy system which converts the solar energy into electrical energy. It may comprise of Solar array, DC-DC converters, inverters, battery, controllers etc. Solar array consists of multiple solar cells connected in parallel and series connection. When sunlight falls on solar array, electricity is produced using photovoltaic effect. The electricity generated is in the form of DC power. It is preferred to use inverters for AC loads. Controllers are also used to maintain the operating point of PV array at MPP so as to achieve maximum efficiency of the PV system. The basic block diagram of standalone PV system is shown in fig 3.1.DC-DC converter and controller are used to trace the maximum power point of solar array. Some of the examples of DC-DC converter are buck-boost, buck, flyback etc. Controllers generate duty cycle for DC-DC converters so as to achieve impedance matching which helps to trace maximum power point of solar array.

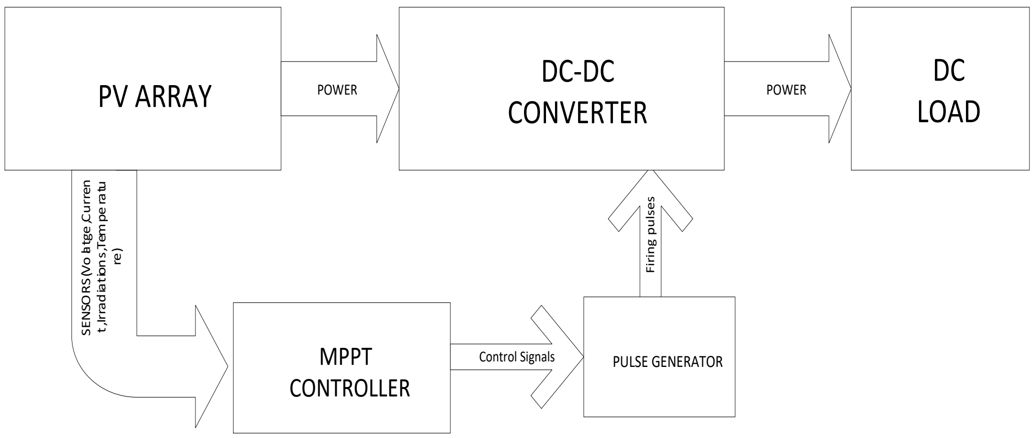

Figure 3.1 Basic block diagram of standalone PV system

3.3 Photovoltaic Cell

The fundamental unit of Photovoltaic system is Photovoltaic cell. It is a semiconductor p-n junction which generates DC voltage at its terminal when photons at a certain energy level strikes on its surface. The current generated when load is connected to PV cell depends on the solar irradiance. Multiple PV cells are connected in series to obtain the higher voltage rating and can also be connected in parallel to obtain higher current rating. Open circuit voltage of solar cell is approximately around 0.6V with appropriate amount of insolation. Figure 3.2 shows structure of PV array composed of PV modules which in turn are composed of PV cells.

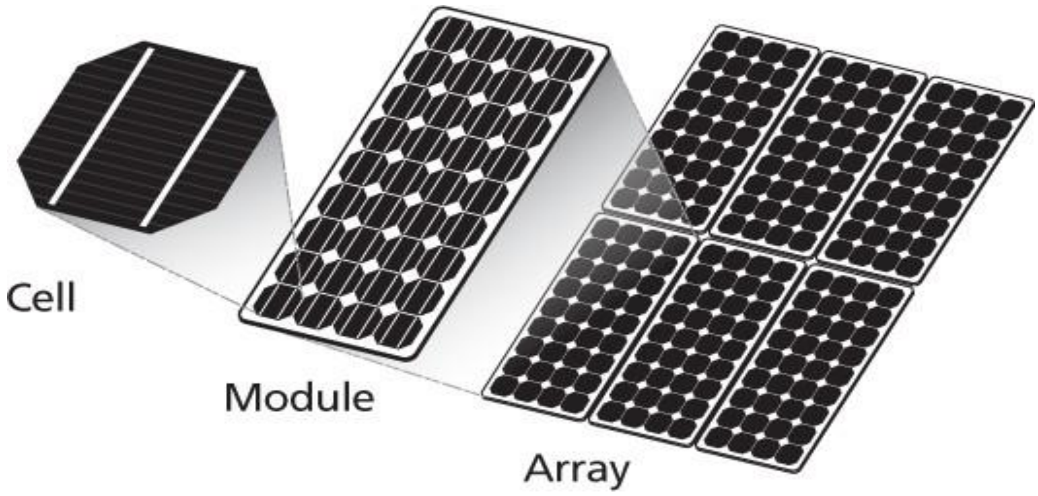

Figure 3.2. Structure of PV array

3.3.1 Electrical Model of a Photovoltaic Cell

Equivalent electrical model plays a vital role in understanding the working and behavior of a PV cell. There are two types of equivalent electrical models for PV cell i.e. single-diode model and double-diode model. Double-diode model is more complex representation of PV cell but it provides accurate results. On the other hand, Single diode model is a simpler model which provides approximate results. The results obtained using single diode model has tolerable accuracy and mostly preferred for analysis and design purposes.

3.3.1.1 Single Diode Equivalent Electrical Model

Single-diode model is a simple equivalent electrical model in which junction recombination process is neglected. Single-diode model considers series and shunt resistance to consider the power losses in the practical operation of PV cell. Series resistance is used to depict the voltage drop. Shunt depicts the leakage current under reverse biased condition. This model is less accurate than double diode equivalent electrical model.

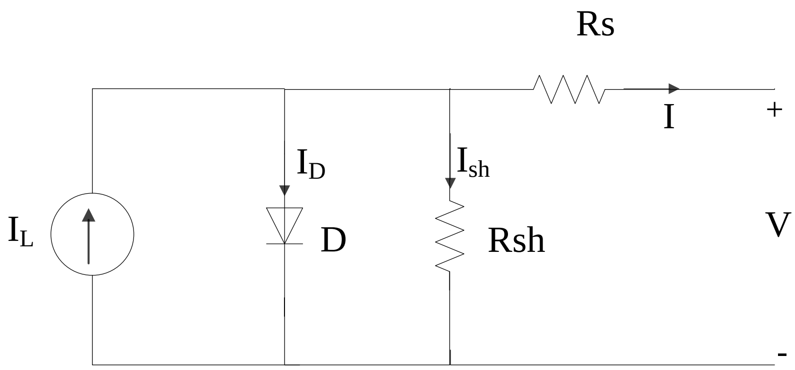

Figure 3.3. Single-diode model of a PV cell

In the present work, single diode is taken into account and the equations are explained below. Using Kirchhoff's current law, the output current I can be calculated as:

$$I = I_L - I_D - I_{sh} \qquad (3.1)$$

Here I is the output current from PV cell, I_L is the current generated by the incident light, I_D is the diode current which can be expressed as in equation 3.2. I_{sh} is the current through shunt resistance R_{sh} and can be expressed as shown in equation 3.8.

$$I_D = I_o[exp\,(\frac{V+IRs}{Vt})\ -1] \qquad (3.2)$$

$$I_{sh} = \frac{V+IRs}{Rsh} \qquad (3.3)$$

Here I_0 is the reverse saturation current for diode D. Rs is the effective series resistance, Vt is the thermal voltage which is given as:

$$Vt=KT/q \qquad (3.4)$$

Where T is cell temperature (K), q is change of an electron =1.6 *10^{-19} coulombs, K is the Boltzmann constant (J/K)

$$I = I_L - I_o[exp\,(\frac{V+IRs}{Vt})\ -1] - \frac{V+IRs}{Rsh} \qquad (3.5)$$

3.3.1.2 Double Diode Equivalent Electrical Model

This is more precise equivalent electrical model of PV cell in which recombination effect at junction is taken into account. This type of model works fine when ideality factor approaches two because it considers diffusion current as well as space charge recombination effect into account for analysis. Ideality factor of a PV cell is function of voltage across device. At higher voltages, the ideality factor is close to unity whereas at lower voltages, it reaches to two. At lower voltages, recombination at the junction is higher which makes ideality factor to approach towards two. Figure 3.2 shows the double diode equivalent electrical model of PV cell.

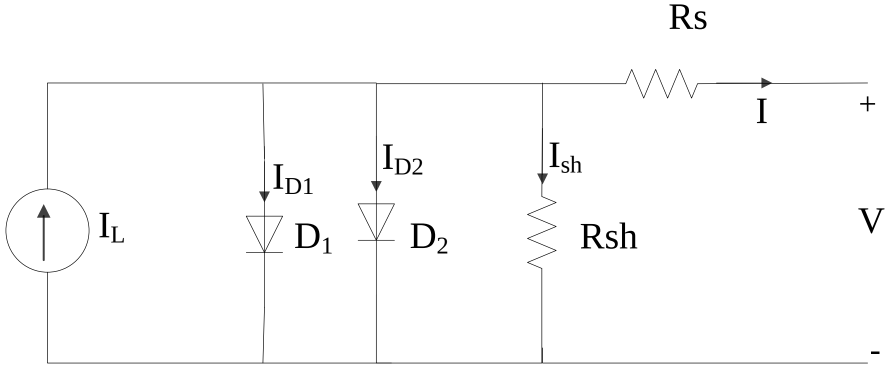

Figure 3.4. Double-diode model of a PV cell

The equations for double diode model is as follows:

$$I = I_L - I_{D1} - I_{D2} - I_{sh} \tag{3.6}$$

Here, I is the output current from PV cell, I_{D1} and I_{D2} are the diode currents from diode D1 and D2 respectively which are expressed in equation 3.7. and 3.8, also known as Shockley equation. I_L is the current generated by the incident light, I_{sh} is the current through shunt resistance R_{sh} and can be expressed as shown in equation 3.9.

$$I_{D1}=I_{o1}[exp\left(\frac{V+IRs}{\eta 1 * Vt}\right) -1] \tag{3.7}$$

$$I_{D2}=I_{o2}[exp\left(\frac{V+IRs}{\eta 2 * Vt}\right) -1] \tag{3.8}$$

$$I_{sh} = \frac{V+IRs}{Rsh} \tag{3.9}$$

Here I_{o1} and I_{02} is the reverse saturation current for diode D_1 and D_2. R_s is the effective series resistance, V_t is the thermal voltage which is given as:

V_t=KT/q (3.10)

Where T is cell temperature (K) , q is change of an electron =1.6 *10^{-19} coulombs, K is the Boltzmann constant (J/K)

$$I=I_L-I_{o1}[exp\left(\frac{V+IRs}{\eta1*Vt}\right) -1] - I_{o2}[exp\left(\frac{V+IRs}{\eta2*Vt}\right) -1] -\frac{V+IRs}{Rsh} \quad (3.11)$$

The recombination component also depends upon carrier concentration. At the rear end of surface, recombination varies dramatically with applied voltage. In such scenario, single diode equivalent model performs much better as compared to double diode model In the present work, we have considered an array consisting of module (SunPower SPR-76R-BLK-U) which are 45 series connected in each 4 parallel strings. The module parameters are shown in table 3.1.

Table 3.1 PV Module Parameters

Maximum Power	76 W
Cells per module	24
Open Circuit Voltage (V_{oc})	16.2V
Short Circuit Current (I_{sc})	6.02A
Voltage at Maximum Power Point	13.45V
Current at Maximum Power Point	5.65A
Temperature coefficient of V_{oc}(%/C)	-0.3791
Temperature coefficient of I_{sc}(%/C)	0.030797
Light generated current I_L	6.0238A
Diode saturation current	3.716*10^{-10}
Diode Ideality factor	1.1182
Shunt Resistance (R_{sh})	196.948 **Ω**
Series Resistance (R_s)	0.12312 **Ω**

Figure 3.5 and 3.6 shows the dependency of photovoltaic array on varying solar irradiance at constant ambient temperature of 25ºC. As the solar irradiance reduces, the current from PV array also reduces which ultimately reduces the power extracted from PV array. Fig 3.5 is the current vs voltage curve at uniformly varying solar irradiations. Fig 3.6 shows the Power vs voltage curve of PV array under uniformly varying solar irradiations. There is less effect on the voltage at MPP as compared to the current variation. The power extracted from PV array also reduces with reduction in irradiance.

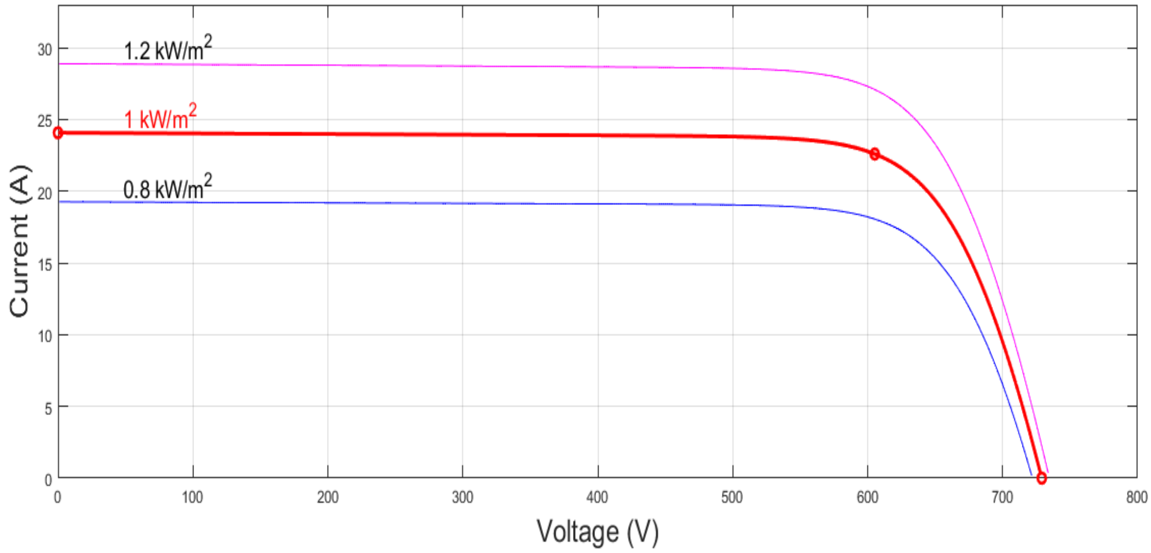

Figure3.5: Current vs Voltage curve of PV array under varying solar irradiations

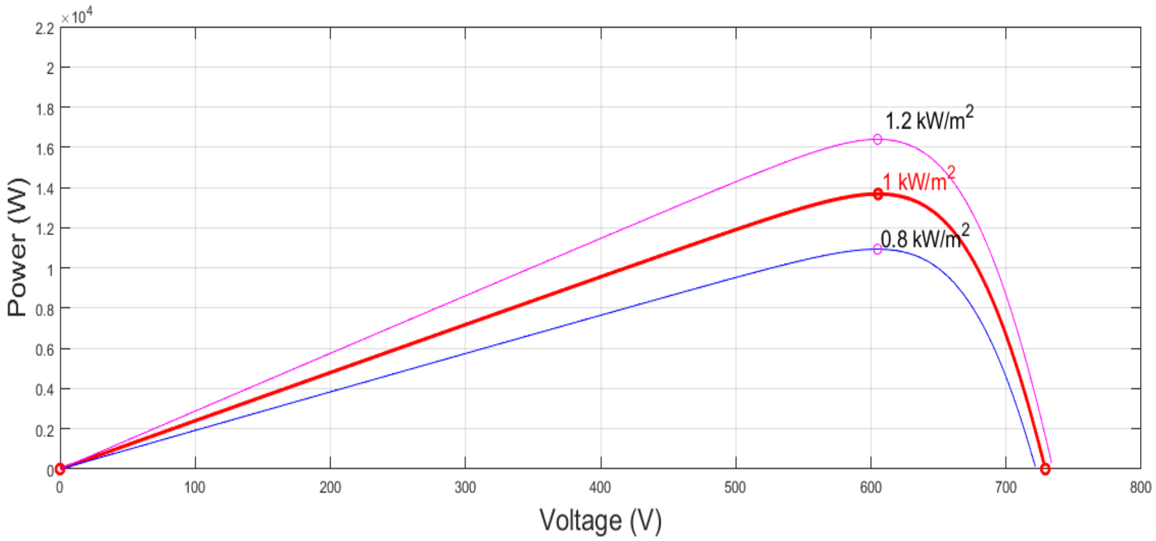

Figure3.6: Power vs Voltage curve of PV array under varying solar irradiations

Figure 3.7 and 3.8 depicts the dependency of photovoltaic array on varying ambient temperature. As the ambient temperature reduces the voltage at PV array also increases which ultimately increases the power extracted from PV array. Fig 3.7 is the current vs voltage curve at varying ambient temperature at constant solar irradiations. Fig 3.8 shows the Power vs voltage curve of PV array under uniformly varying ambient temperature at constant solar irradiations. There is less effect on the current at MPP as compared to the voltage variation. The power extracted from PV array also reduces with increase in the ambient temperature.

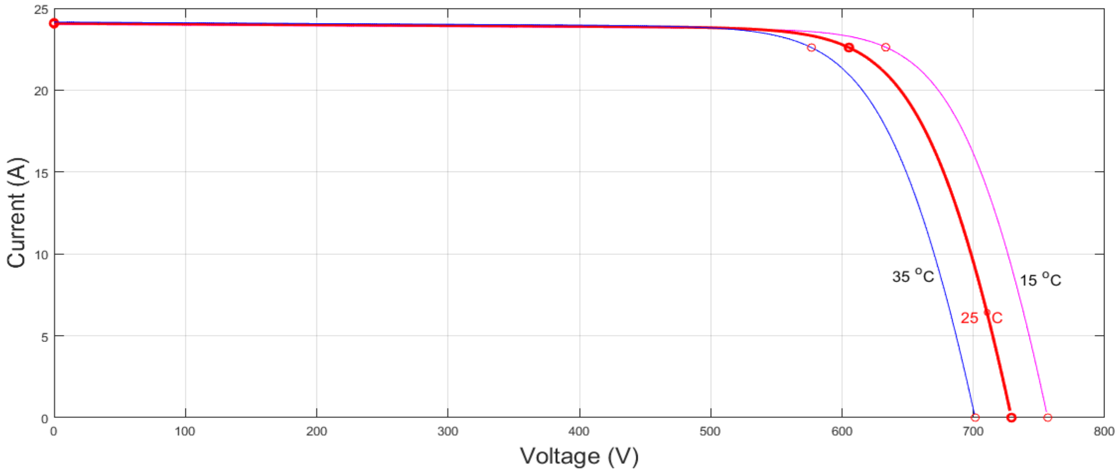

Figure3.7: Current vs Voltage curve of PV array under varying ambient temperature

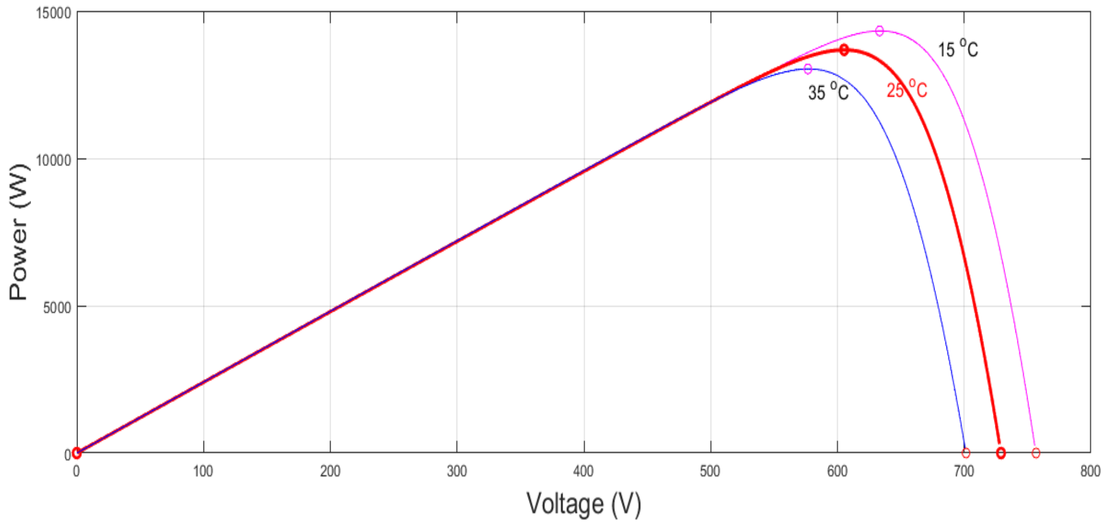

Figure3.8: Power vs Voltage curve of PV array under varying ambient temperature

3.4 DC-DC Converter

DC-DC converter is an electronic circuit which converts DC power from one voltage level to another voltage level. In PV systems DC-DC converters are used to maintain the operating point of PV array at MPP by using some controllers The firing pulses of DC-DC converter is generated by these controllers. Some of the DC-DC converters used in PV systems are boost, buck-boost, flyback converter etc. In the present work, boost converter is used as DC-DC converter. Boost converter is DC-DC power converter which provides output voltage greater than the input voltage. Boost converter consists of an inductor, a power electronic switch (MOSFET/IGBT), diode and a capacitor as shown in figure 3.9. Power electronic switch is selected based on the power rating and switching frequency. The operation of boost converter can be divided into two modes, Mode 1 and Mode 2. Mode1 begins when transistor M1 is switched on at time t=0. The input current rises and flows through inductor L and transistor M1. Mode 2 begins when transistor M1 is switched off at time t=t1. The input current now flows through L, C, load, and diode Dm. The inductor current falls until the next cycle. The energy stored in inductor L flows through the load. The circuits for the two modes of operation are shown in figure 3.10 and figure 3.11. The current and voltage waveforms are shown in fig 3.12.

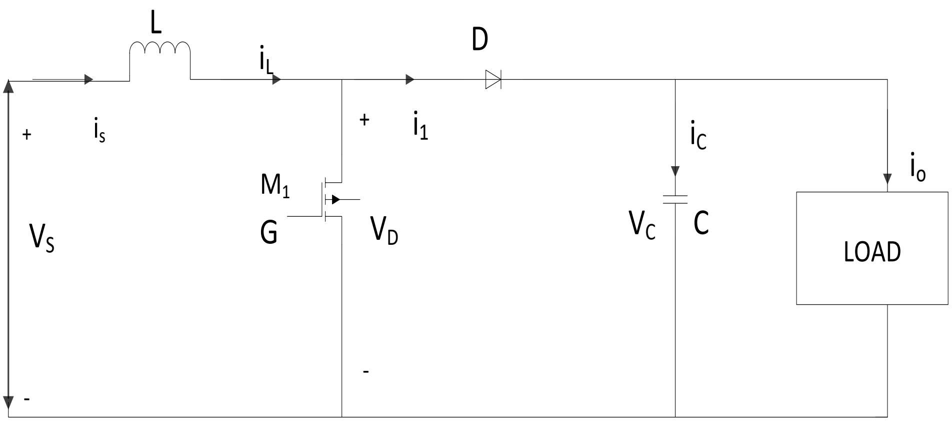

Figure 3.9: Boost Converter

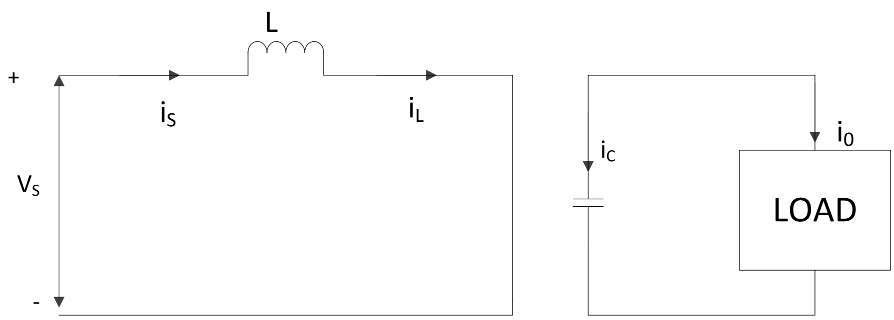

Figure 3.10: Mode 1 operation of Boost Converter

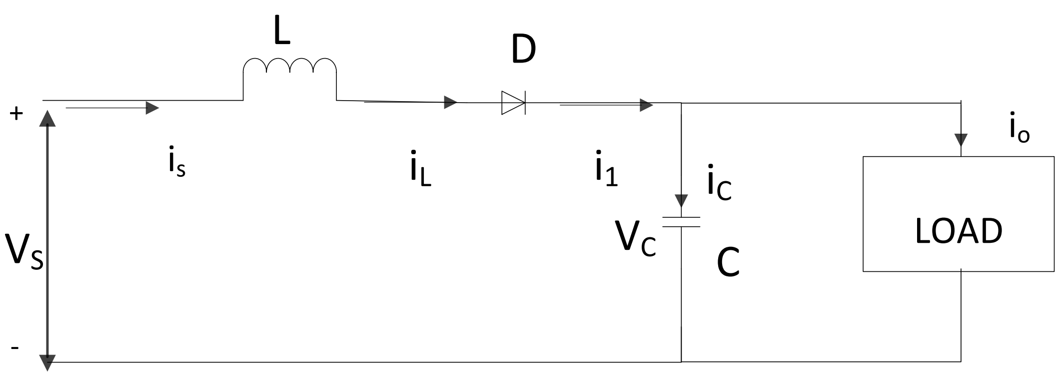

Figure 3.11: Mode 2 operation of Boost Converter

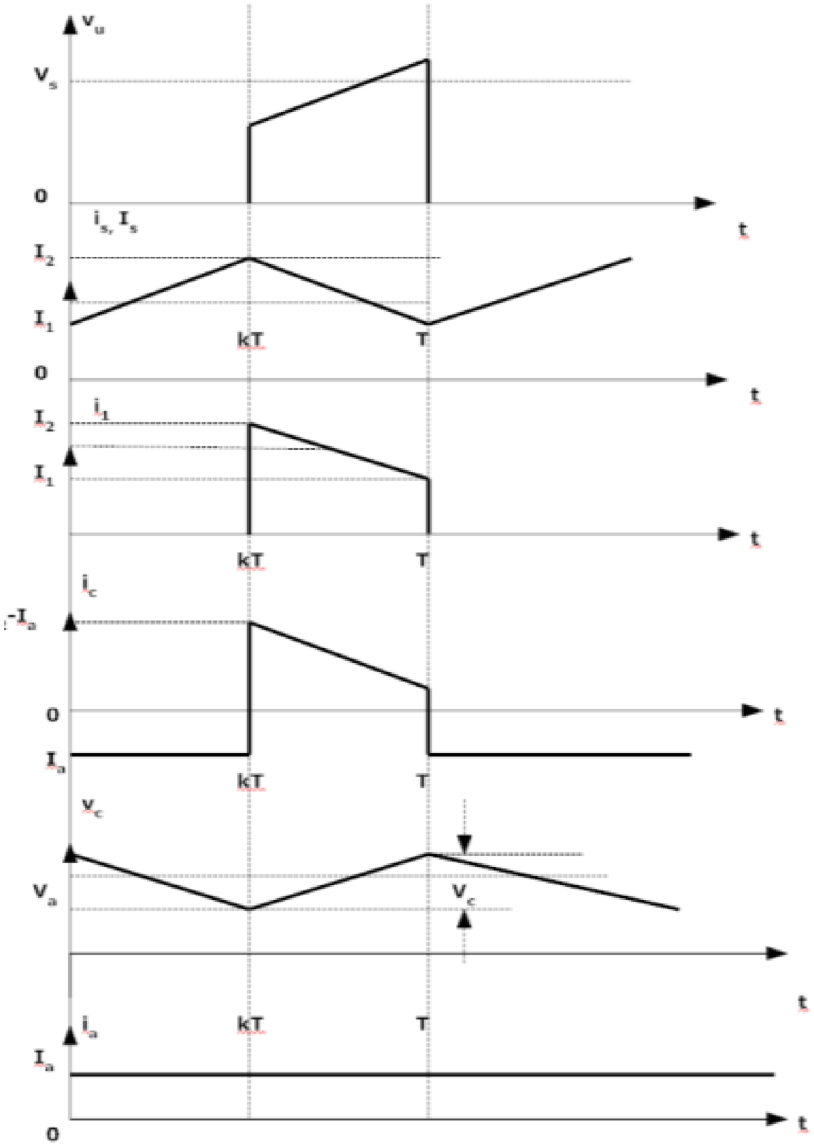

Figure 3.12 Current and Voltage waveforms of Boost converter

3.4.1 Designing of Boost Converter

i) Inductor Design

The inductor used in the boost converter can be calculated using equation 3.12

$$L = \frac{V_S D}{\Delta I f} \tag{3.12}$$

Where V_s is the input supply voltage at MPP; D is the duty cycle of converter; f is frequency at which converter is working; ΔI is 5% of the input current at MPP.

After calculation, the values are: ΔI =1.13A, ,f=20000Hz, Vs=605.25V and D is taken as 0.5 so as to obtain the inductor value for maximum ripple. The calculated value of inductance is 6.3mH. To ensure safe operation a higher value of 7mH is selected.

ii) Capacitor Design

The capacitor used can be calculated using equation 3.13

$$C = \frac{I_{\circ} D}{f \Delta V_c} \tag{3.13}$$

Where ΔVc is kept less than 5% of load voltage. after substituting the values in above equation, a relational equation is obtained which is as follows:

RC>5*10-4. The value of capacitance is assumed to be 33 µF. Hence the Resistance value must be greater than 15.15 Ω, In the project we have considered 90Ω.

3.5 Concept of Maximum PowerPoint Tracking

Power output from PV array is maximum at a certain operating point called maximum power point (MPP) which can be obtained by plotting Power vs Voltage curve. The voltage at MPP is denoted as V_{mp} and current at MPP is denoted as I_{mp}. Maximum Power can be calculated using equation 3.14:

$$P_m = V_m * I_m \tag{3.14}$$

As the power from PV array depends on ambient temperature and solar irradiations, the MPP also varies accordingly. On variation of the environmental conditions, it becomes difficult to trace the MPP as a particular load will provide maximum power at a fixed environmental condition only. When the environmental conditions will change, maximum power cannot be extracted from PV array which will make the system less efficient. Hence Maximum Power Point techniques were developed to enhance the efficiency of complete system under varying atmospheric conditions. Main goal of Maximum Power Point technique (MPPT) is to maintain the operating point of PV at its

MPP irrespective of the load and varying atmospheric conditions. The MPPT is achieved using DC-DC converters as an interface between PV array and load. However, boost converter is mostly preferred over other converters as it provides high efficiency over wide power range. These DC-DC converters helps to maintain the operating point at MPP by controlling the its duty cycle using different techniques. In the present work, boost converter is considered as DC-DC converter to achieve the objective.

3.6 Conclusion

In this chapter basic idea of photovoltaic system is given using block diagram. Different equivalent models of a PV cell and its characteristics are studied. The concept of maximum PowerPoint tracking is discussed. MPPT in PV system is using boost converter is discussed along with the its operation and designing required in the present work.

CHAPTER 4 CONVENTIONAL TECHNIQUES FOR MPPT

4.1 General

Photovoltaic cells exhibit non-linear P-V characteristics which are highly dependent on atmospheric conditions. To extract maximum power from PV array, different MPPT techniques are used. This chapter contains description of conventional techniques like Perturbation & Observation (P&O) and Incremental Conductance. These algorithms are easy to implement and less complex which makes it economical as compared to artificial intelligent techniques. These MPPT algorithms works on the logic of true or false. Different conditions are established for each algorithm and checked after each computation and then the signals are fed into the system to control the duty cycle of converter through which MPP is achieved.

4.2 Perturb & Observe Algorithm

It is one of the most widely used conventional algorithm to trace the Maximum Power Point. The main concept behind this MPPT algorithm is to perturb the PV output voltage and observe the change in Power. The duty cycle of the boost converter is changed in small steps depending upon the difference the operating and previous voltage and power of PV system. Figure 4.1 shows the graphical description of this technique., it is observed that from P-V characteristics that on the left of MPP, dP/dV is positive and on the right side dP/dV is negative and at MPP, dP/dV =0. When dP/dV is positive, MPPT algorithm tries to increase the voltage. When dP/dV is negative, MPPT algorithm tries to reduce the voltage. The flowchart of the algorithm is shown in figure4.2.

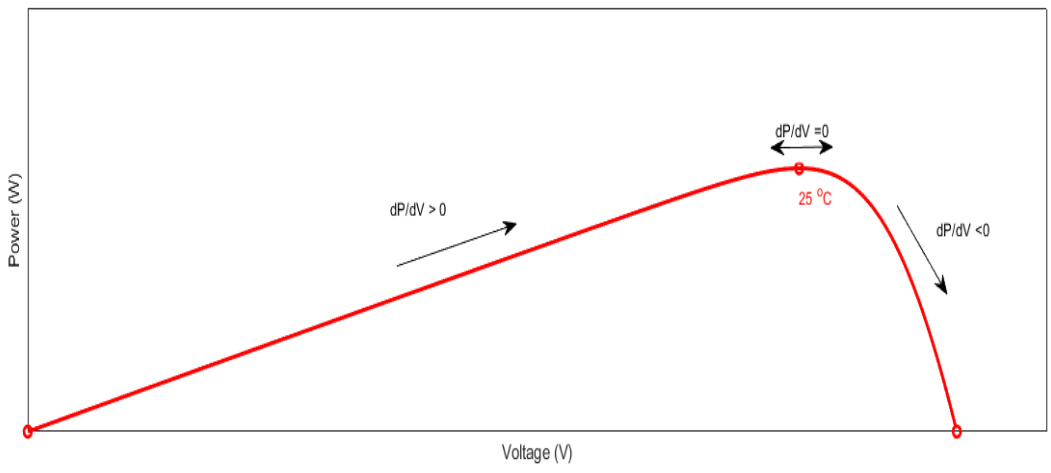

Figure 4.1 P-V characteristics of PV array explaining P&O technique

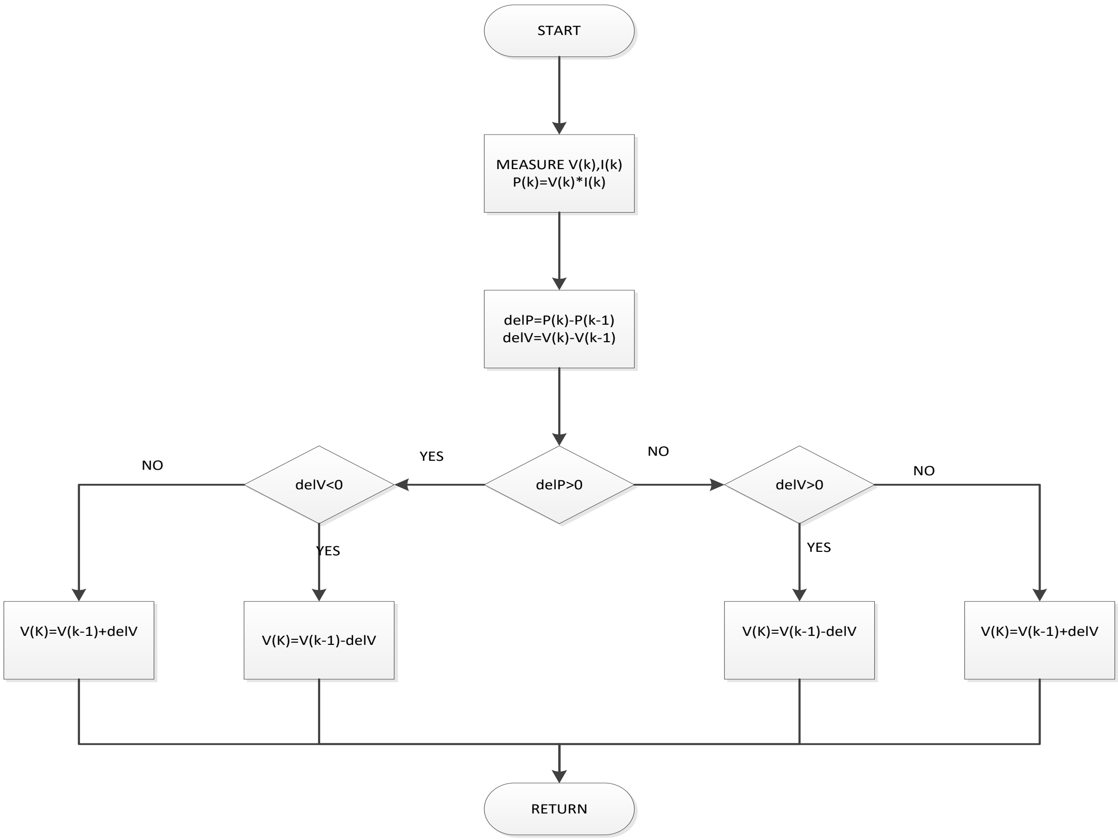

Figure 4.2 Flow chart of P&O algorithm

A MATLAB-SIMULINK model for PV system using Perturb & Observe algorithm is shown in figure 4.3. The specification of the developed MATLAB -SIMULINK model is shown in table 4.1.

The simulation results are obtained for two different cases which are mentioned below:

i) Uniformly varying solar irradiations at constant ambient temperature.

ii) Uniformly varying ambient temperature at constant solar irradiations.

Table 4.1 Specification of MATLAB/SIMULINK model in PV system using Boost Converter

Maximum Power of PV array at STC	13.68kW
Inductor (L)	7mH
Capacitor (C)	33 µF
Switching Frequency	20KHz
Load Resistance	90 Ω

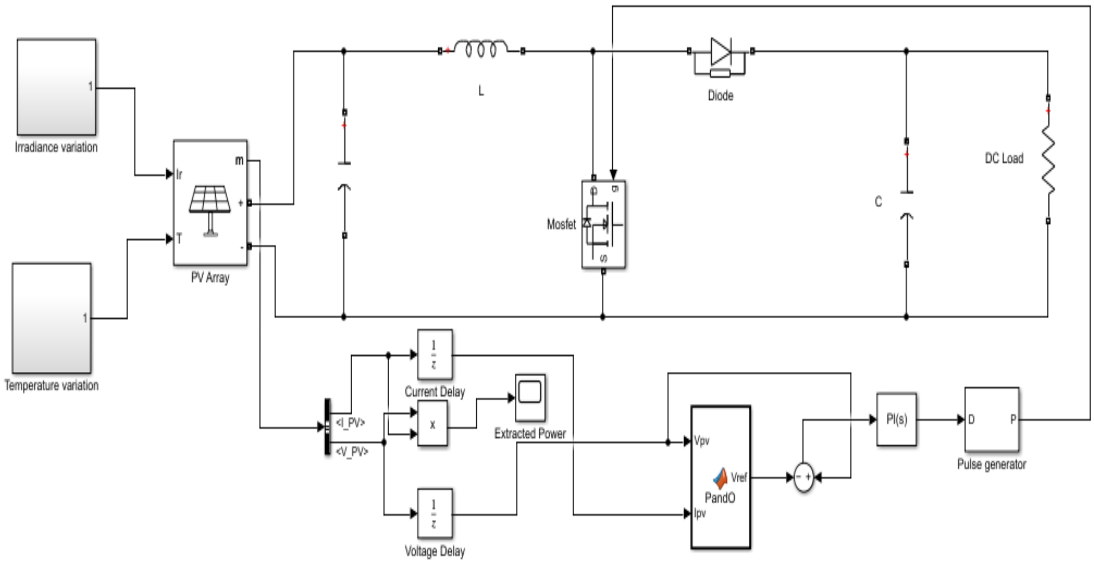

Figure4.3 MATLAB/SIMULINK model of PV system using P&O algorithm

4.2.1 MATLAB Simulation results

4.2.1.1 Uniformly varying solar irradiations at constant ambient temp.

The proposed PV system using P&O algorithm has been tested under varying solar irradiation at constant ambient temperature i.e. 25^{o}C . The proposed PV system is tested under 800W/m^{2,} 1000W/m^2 and 1200W/m^2. The extracted power from PV array under these condition is plotted in figure 4.4. Initially, solar irradiance is kept at 800 W/m^2 then it is changed to 1000 W/m^2 at time instant t=0.5 sec. Furthermore, solar irradiance is changed to 1200 W/m^2 at time instant t=1 sec.

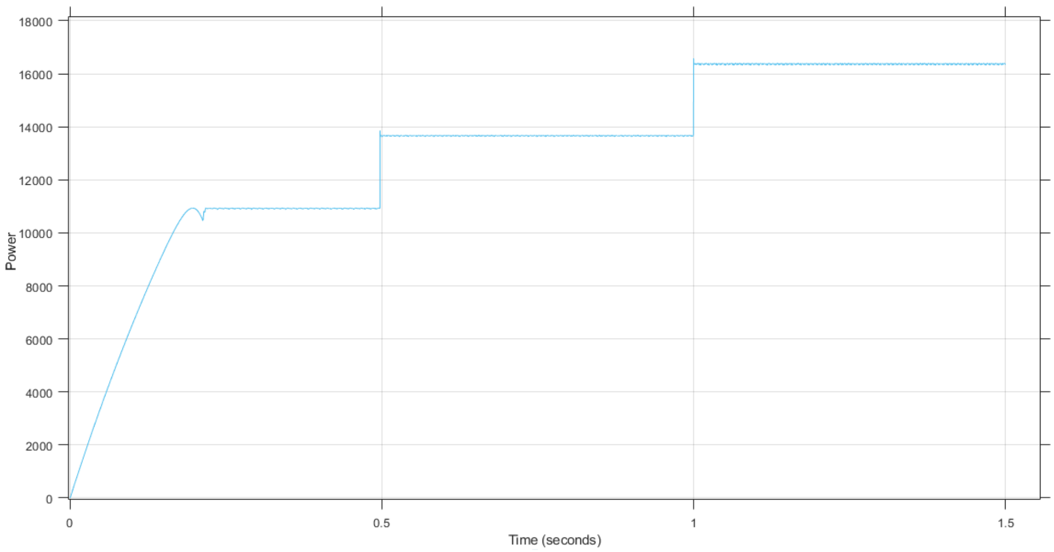

Figure 4.4 Power extracted under varying solar irradiations using P&O algorithm

Figure 4.5,4,.6 and4.7 shows the zoomed in view of extracted power from PV array at 800 W/m$^{2.}$,1000W/m^{2} and 1200W/m^{2} respectively. When PV system is operating at 800 W/m^{2} the extracted power oscillates between 10931.9W to 10883.9W which gives a ripple of around 48W. When PV system is operating at 1000 W/m$^{2.}$ extracted power oscillates between 13678W to 13628.7W which gives a ripple of around 50W. When PV system is operating at 1200 W/m$^{2.}$ extracted power oscillates between 16394.1W to 16321.3W which gives a ripple of around 72.8W.

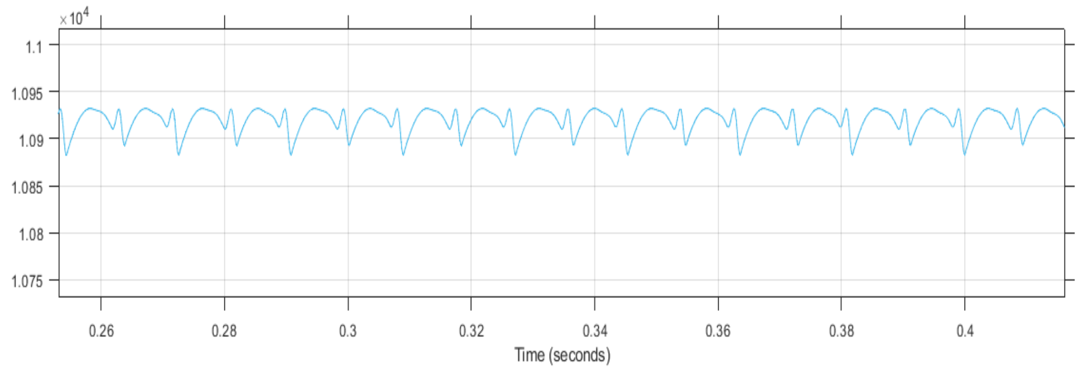

Figure 4.5 Power extracted from PV system at 800W/m^{2} using P&O algorithm

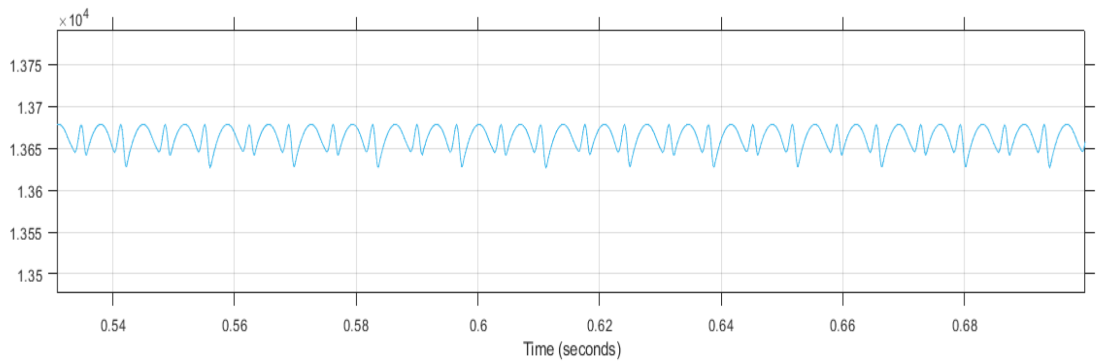

Figure 4.6 Power extracted from PV system at 1000W/m^{2} using P&O algorithm

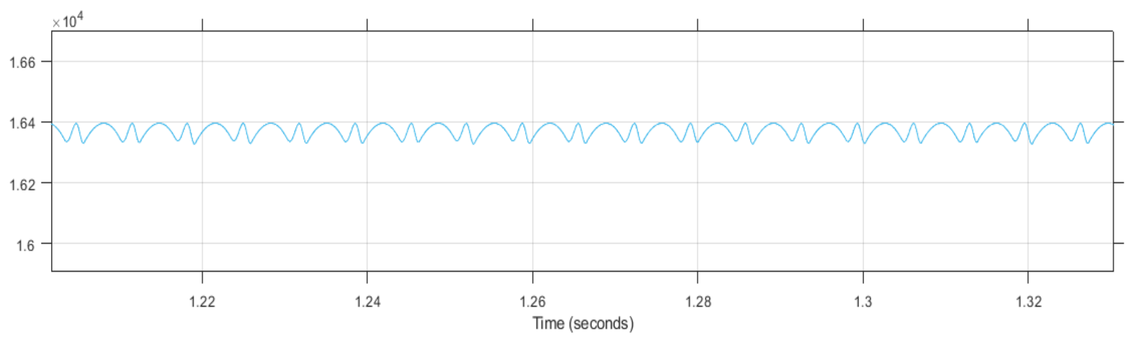

Figure 4.7 Power extracted from PV system at 1200W/m^{2} using P&O algorithm

4.2.1.2 Uniformly varying ambient temperature at constant solar irradiations

The proposed PV system using P&O algorithm has been tested under varying ambient temperature at constant solar irradiations i.e., 1000W/m^2. The proposed PV system is tested under 35°C, 25°C, and 15°C. The extracted power from PV array under this condition is plotted in figure 4.8. Initially, ambient temperature is kept at 35°C then it is changed to 25°C at time instant t=0.5 sec. Furthermore, ambient temperature is changed to 15°C at time instant t=1 sec.

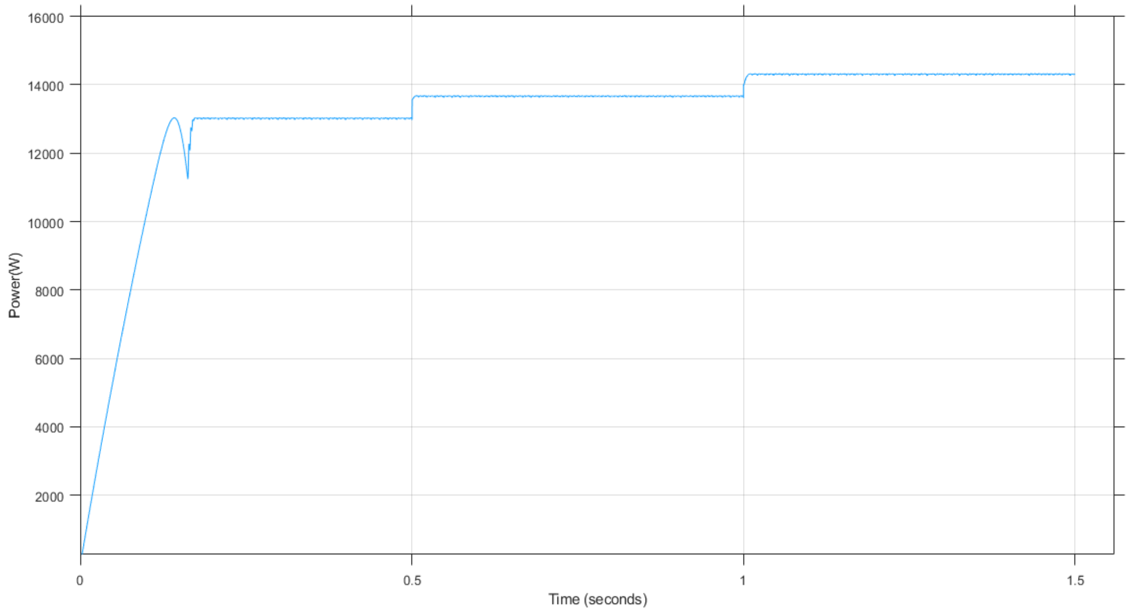

Figure 4.8 Power extracted under varying ambient temperature using P&O algorithm

Figure 4.9,4.10 and4.11 shows the zoomed in view of extracted power from PV array at 35°C, 25°C and 15°C respectively. When PV system is operating at 35°C the extracted power oscillates between 13031.4W to 12980.9W which gives a ripple of around 50.5W. When PV system is operating at 25°C extracted power oscillates between 13678.2W to 13628.7W which gives a ripple of around 50W. When PV system is operating at 15°C extracted power oscillates between 14322.3W to 14265.7W which gives a ripple of around 56.6W.

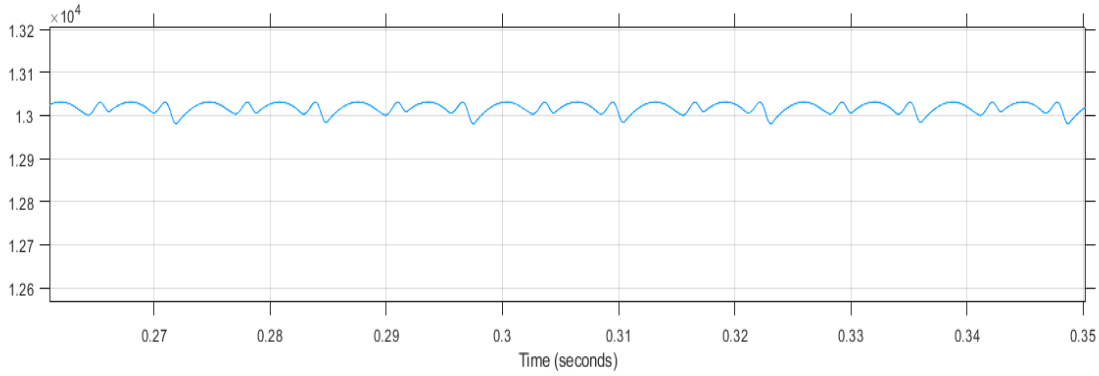

Figure 4.9 Power extracted from PV system at 35^{0}C using P&O algorithm

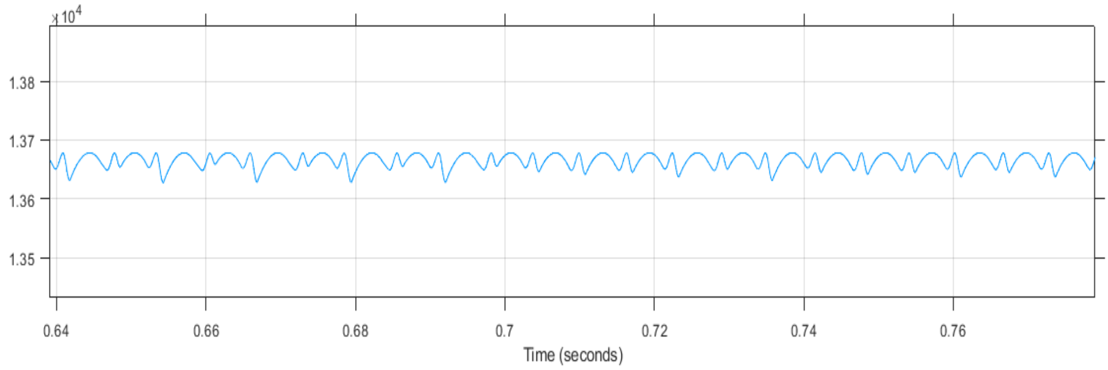

Figure 4.10 Power extracted from PV system at 25^{0}C using P&O algorithm

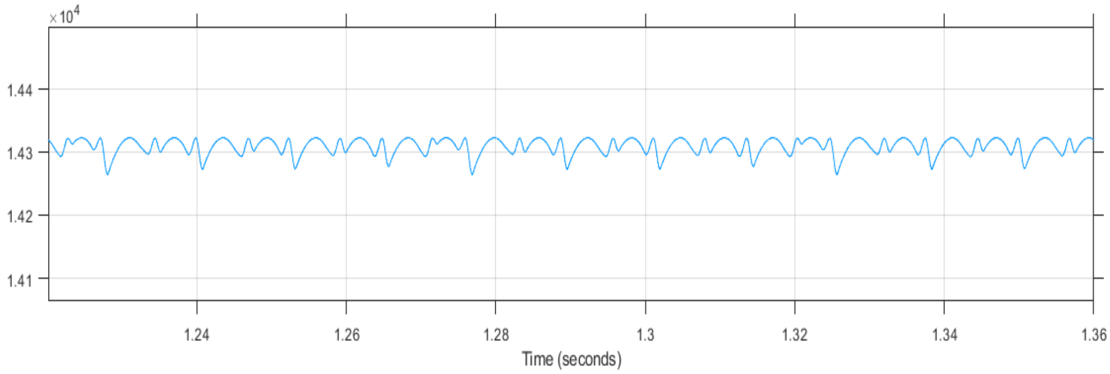

Figure 4.11 Power extracted from PV system at 15^{0}C using P&O algorithm

4.3 Incremental Conductance Algorithm

Incremental Conductance algorithm is one of the most widely used conventional MPPT techniques. It takes advantages of both the P-V curve and I-V curve of PV array which helps it to track MPP much better than perturb &Observe algorithm. The equation 4.1 is differentiated with respect to voltage and then equation 4.2 is obtained for maximum power output from PV array.

$$P = V.I \qquad (4.1)$$

$$\partial P / \partial V = I + V.\ \partial I / \partial V \qquad (4.2)$$

Equation 4.2 is equated to zero. Hence, we get equation (4.3) at MPP.

$$\partial I / \partial V = -I/V \qquad (4.3)$$

On further analysis of MPP on PV , following equations were observed:

$$\partial I / \partial V > -I/V \text{ , left of MPP} \qquad (4.4)$$

$$\partial I / \partial V < -I/V \text{ , right of MPP} \qquad (4.5)$$

Equation 4.4 and 4.5 are main concepts around which INC algorithm revolves The duty cycle of the converter is adjusted in such a way that the condition $\partial I / \partial V = -I/V$ is satisfied. Figure 4.12 shows the graphical description of this technique. The flowchart of the algorithm is shown in figure 4.13.

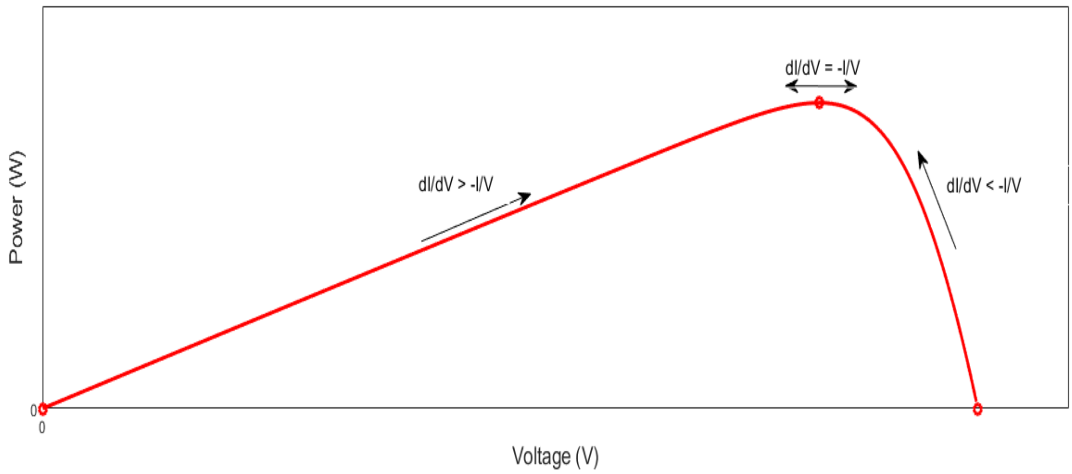

Figure 4.12 P-V characteristics of PV array explaining INC algorithm

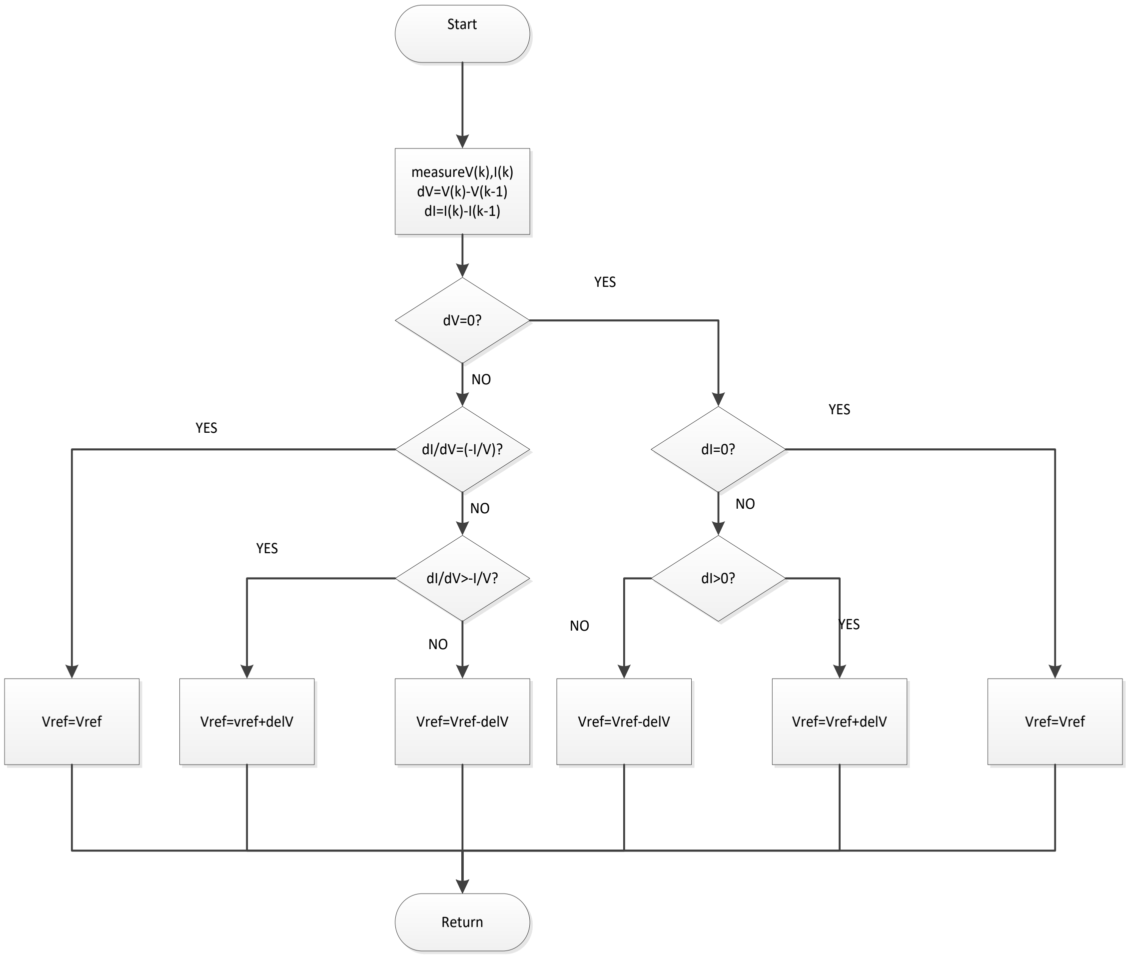

Figure 4.13 Flowchart of INC algorithm

A MATLAB-SIMULINK model for PV system using Incremental Conductance algorithm is shown in figure 4.14. The specification of the developed MATLAB - SIMULINK model is shown in table 4.1.

The simulation results are obtained for two different cases which are mentioned below:

i) Uniformly varying solar irradiations at constant ambient temperature.

ii) Uniformly varying ambient temperature at constant solar irradiations.

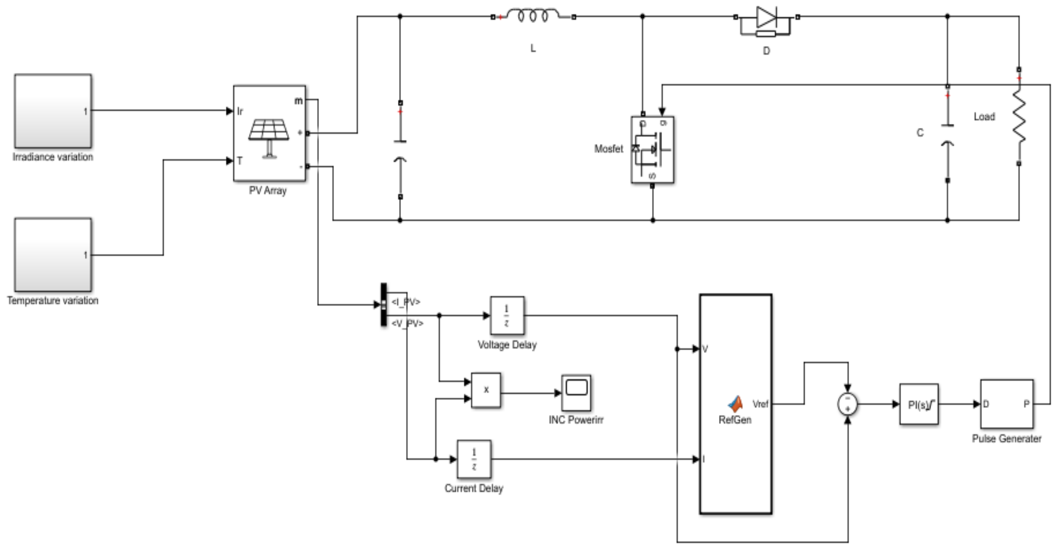

Figure4.14 MATLAB/SIMULINK model of PV system using INC algorithm

4.3.1 MATLAB Simulation results

4.3.1.1 Uniformly varying solar irradiations at constant ambient temperature

The proposed PV system using INC algorithm has been tested under varying solar irradiation at constant ambient temperature i.e. 25ºC . The proposed PV system is tested under 800W/m^{2,} 1000W/m^2 and 1200W/m^2. The extracted power from PV array under these conditions is plotted in figure 4.15. Initially, solar irradiance is kept at 800 W/m^2 then it is changed to 1000 W/m^2 at time instant t=0.5 sec. Furthermore, solar irradiance is changed to 1200 W/m^2 at time instant t=1 sec.

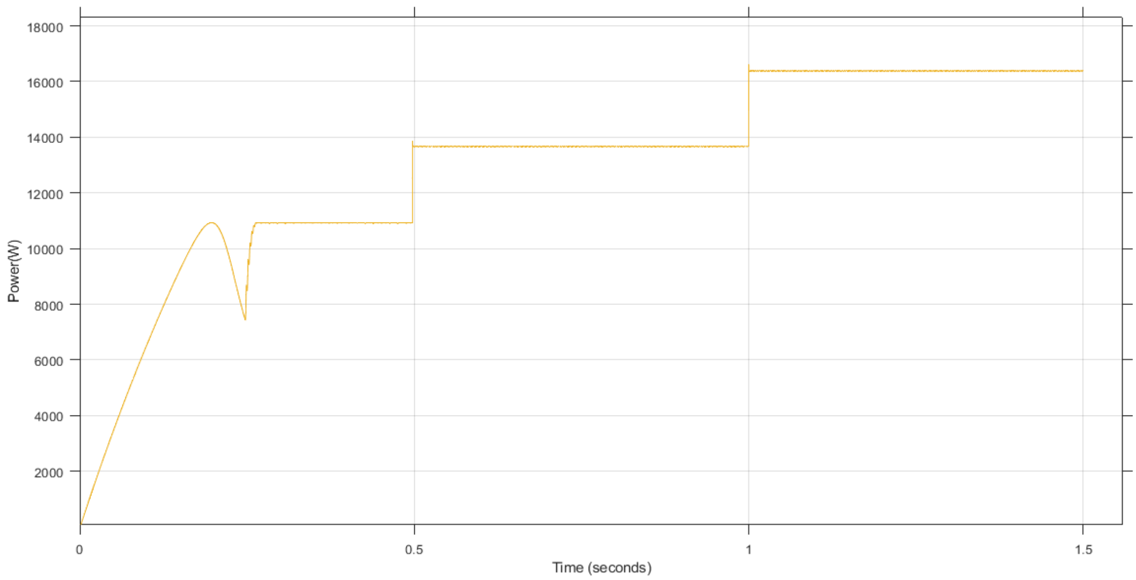

Figure 4.15 Power extracted under varying solar irradiations using INC algorithm

Figure 4.16,4.17 and4.18 shows the zoomed in view of extracted power from PV array using INC algorithm at 800 W/m^{2}.,1000W/m^{2} and 1200W/m^{2} respectively. When PV system is operating at 800 W/m^{2} the extracted power oscillates between 10931.9W to 10903W which gives a ripple of around 28.7W. When PV system is operating at 1000W/m^{2}. extracted power oscillates between 13678.2W to 13645.4W which gives a ripple of around 32.8W. When PV system is operating at 1200 W/m^{2}. extracted power oscillates between 16395.8W to 16356.1W which gives a ripple of around 39.7W.

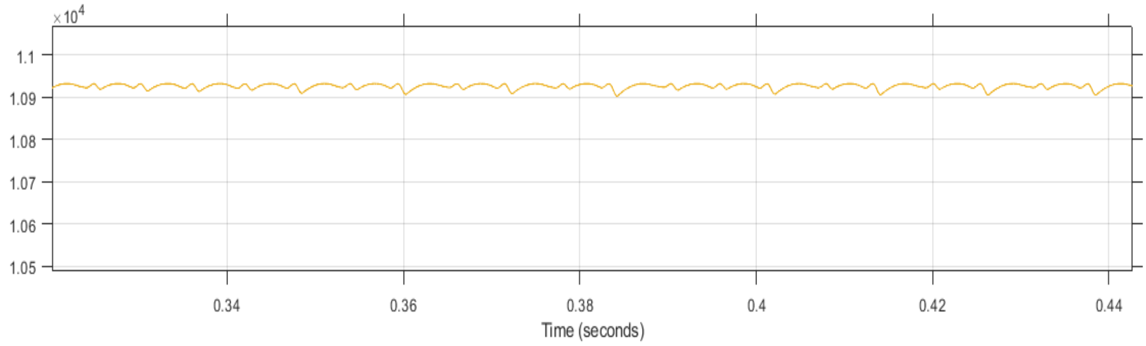

Figure 4.16 Power extracted from PV system at 800W/m^{2} using INC algorithm

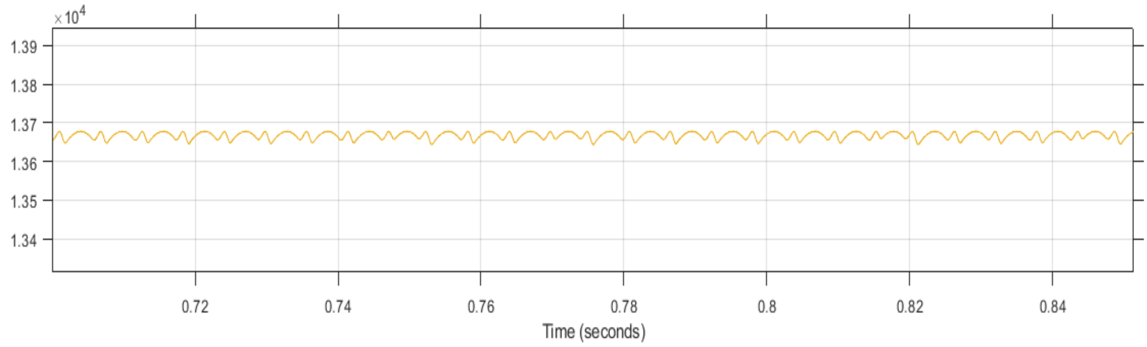

Figure 4.17 Power extracted from PV system at 1000W/m^{2} using INC algorithm

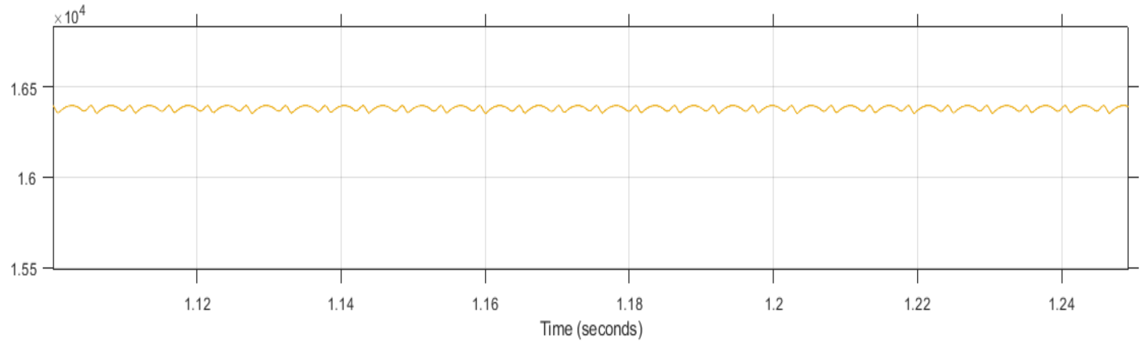

Figure 4.18 Power extracted from PV system at 1200W/m^{2} using INC algorithm

4.3.1.2 Uniformly varying ambient temperature at constant solar irradiations

The proposed PV system using INC algorithm has been tested under varying ambient temperature at constant solar irradiations i.e., 1000W/m^2. The proposed PV system is tested under 35ºC, 25ºC and 15ºC. The extracted power from PV array under this condition is plotted in figure 4.19. Initially, ambient temperature is kept at 35ºC then it is changed to 25ºC at time instant t=0.5 sec. Furthermore, ambient temperature is changed to 15ºC at time instant t=1 sec.

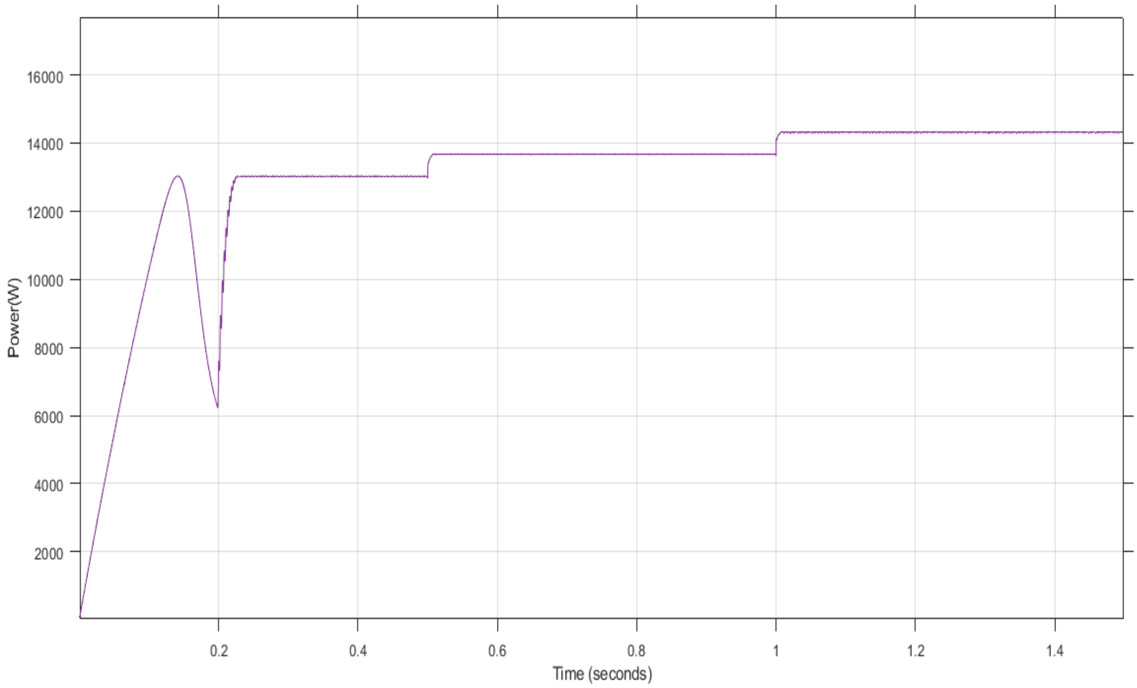

Figure 4.19 Power extracted under varying ambient temperature using INC algorithm

Figure 4.20,4.21 and4.22 shows the zoomed in view of extracted power from PV array using INC algorithm at 35ºC, 25ºC and 15ºC respectively. When PV system is operating at 35ºC the extracted power oscillates between 13031.4W to 13007.9W which gives a ripple of around 23.5W. When PV system is operating at 25ºC extracted power oscillates between 13678.2W to 13645.7W which gives a ripple of around 32.8W. When PV system is operating at 15ºC extracted power oscillates between 14322.3W to 14299.7W which gives a ripple of around 22.6W.

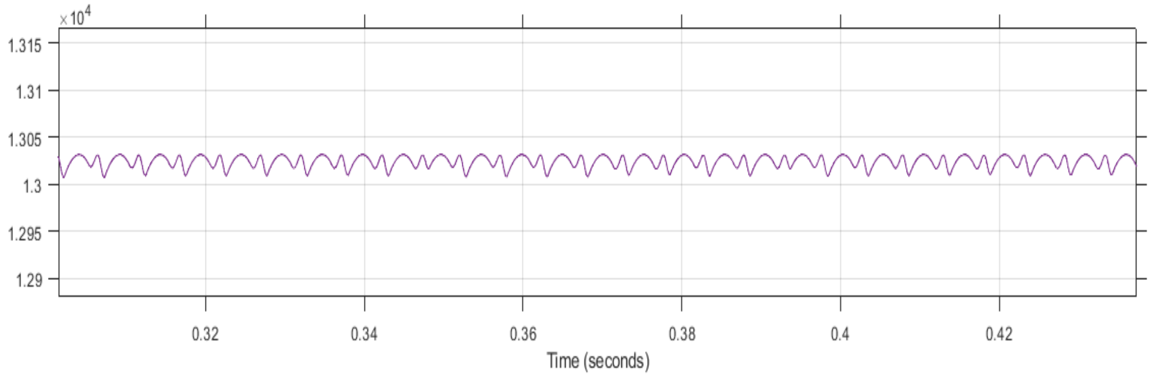

Figure 4.20 Power extracted from PV system at 35ºC using INC algorithm

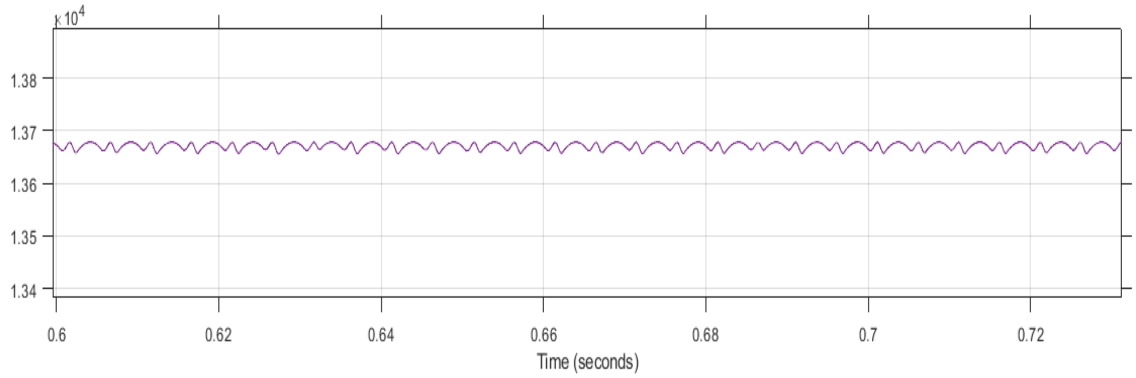

Figure 4.21 Power extracted from PV system at 25ºC using INC algorithm

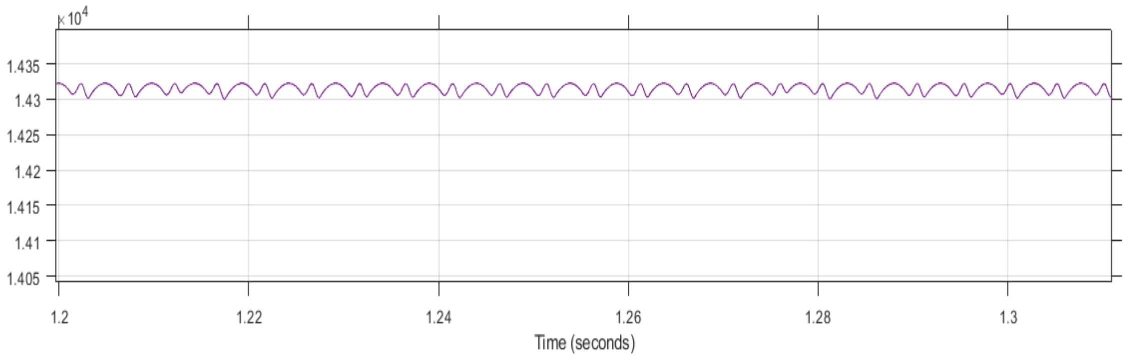

Figure 4.22 Power extracted from PV system at 15ºC using INC algorithm

4.4 Conclusion

In this chapter conventional algorithms i.e. perturb & observe and incremental conductance are described which are used as MPPT techniques. Flowchart and graphical representations are used to highlight the detailed study of both the algorithms .The MATLAB/SIMULINK model has been developed for both the algorithms and simulation results are discussed under uniformly varying atmospheric conditions i.e. varying solar irradiations at constant ambient temperature and varying ambient temperature at constant solar irradiations. It is observed that both conventional algorithms were able to trace the maximum power from PV under all the testing conditions.

CHAPTER 5 INTELLIGENT TECHNIQUES FOR MPPT

5.1 General

With the advancement of PV systems, multiple intelligent MPPT techniques have been introduced like fuzzy logic controller, genetic algorithms, artificial neural network etc. They are more complex and advanced in terms of computation which helps to generate more precise results. Intelligent techniques overcome the drawbacks of conventional techniques as it performs much better in terms of tracking speed and less oscillations under various operating conditions. These techniques perform brilliantly under varying atmospheric conditions and partial shading. The overall efficiency of PV system is also improved using these algorithms.

5.2 Type-1 fuzzy Logic Controller

Fuzzy logic controller works on fuzzy logic theory which helps to incorporate the diverse values of a variable instead exact or fixed vales. Fuzzy logic theory helps to reduce the effects of uncertainties.

Fuzzy controller comprises of four parts which are as follows:

i) Fuzzification: It is a process by which crisp inputs are converted into fuzzy sets based on membership function. The crisp inputs are provided by the sensor to the controller. The crisp inputs depend on the application of controller.

ii) Inference Engine: Based on the fuzzy inputs provided in the form of fuzzy sets, inference engine takes the decision of which rule is to be implemented. There are two types of fuzzy inference system defined which are as follows:

1. Mamdani Inference system: In this fuzzy inference system, rules are defined based on the required behavior of the controller and consequent output is defined for every possible case in terms of fuzzy logic set.
2. Sugeno Inference System: In this type of inference system, the output is generated using a fuzzy rule which can be defined as:

   IF a is X and b is Y THEN z = f(a, b)

   Here, X and Y are fuzzy sets in antecedent whereas f(a,b) is a crisp function in the consequent.

iii) Rule Base: It contains all the rules provided by the designer to be incorporated in the controller. It contains rules in the form of IF-THEN which helps to make efficient decision-making system.

iv) Defuzzification: This process helps in converting the fuzzy sets back to the crisp value which is understood by external system. The input to defuzzifier is provided from inference system.

In the present work , mamdani inference system is considered for implementation of the controller. Five fuzzy levels are defined i.e. NB(Negative Big), NS(Negative Small), ZE (Zero), PS(Positive Small) and PB(Positive Big). The inputs of controller are change in the voltage at PV array and change in power extracted by PV array. The output from controller is the required change in the duty cycle of Boost converter Figure 5.1 ,5.2 and 5.3 shows the membership functions of change in voltage, change in power and change in duty cycle respectively. Table 5.1 shows the rule base used by the inference system to take decisions.

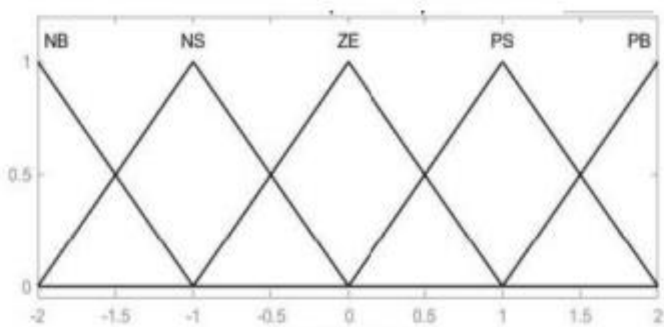

Figure 5.1 Membership function for change in PV array output Voltage

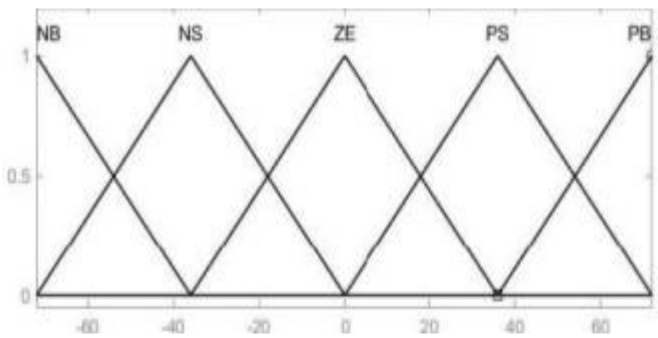

Figure 5.2 Membership function for change in PV array output Power

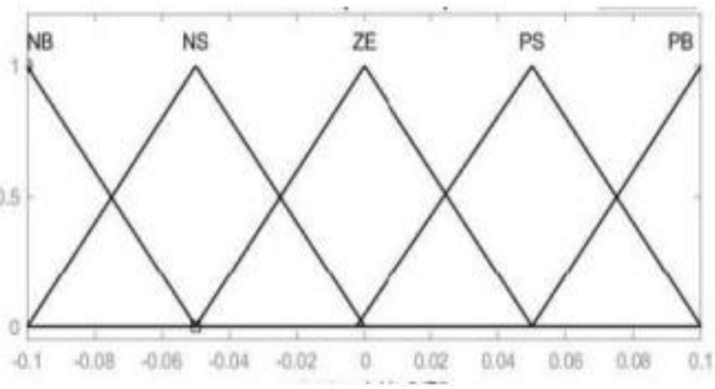

Figure 5.3 Membership function for change in Duty cycle

Table 5.1 Fuzzy rule base

dP \ dV	NB	NS	ZE	PS	PB
NB	NS	NB	PB	PB	PS
NS	ZE	NS	PS	PS	ZE
ZE	ZE	ZE	ZE	ZE	ZE
PS	ZE	PS	NS	NS	ZE
PB	PS	PB	NB	NB	NS

A MATLAB-SIMULINK model for PV system using Type -1 Fuzzy Logic Controller is shown in figure 5.4. The specification of the developed MATLAB -SIMULINK model is shown in table 4.1.The designing of controller is discussed in previous section.

The simulation results are obtained for two different cases which are mentioned below:

iii) Uniformly varying solar irradiations at constant ambient temperature.

iv) Uniformly varying ambient temperature at constant solar irradiations.

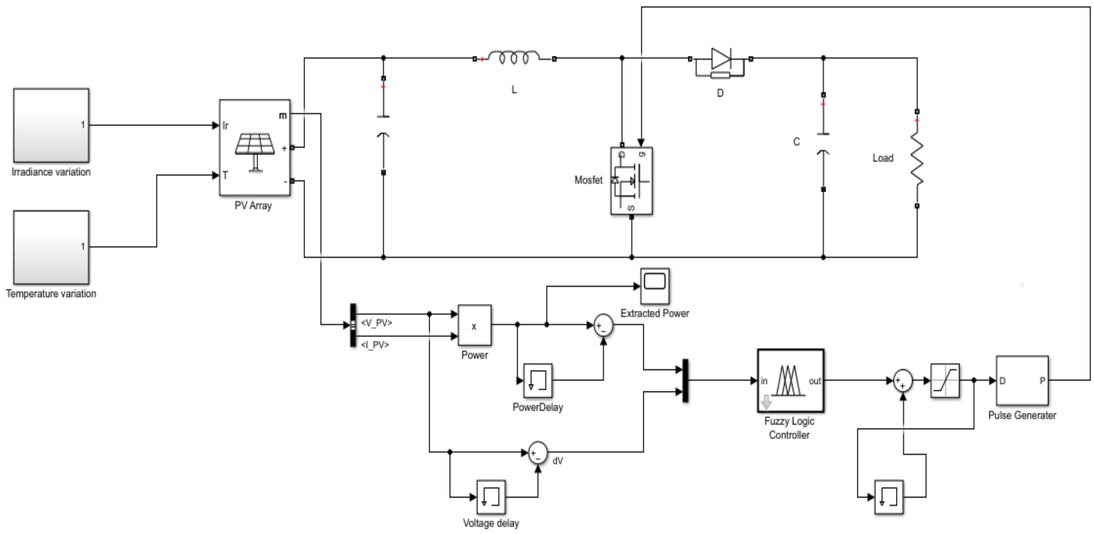

Figure5.4 MATLAB/SIMULINK model of PV system using Type-1 Fuzzy Logic Controller

5.2.1 MATLAB Simulation results

5.2.1.1 Uniformly varying solar irradiations at constant ambient temperature

The proposed PV system using type-1 fuzzy logic controller has been tested under varying solar irradiation at constant ambient temperature i.e. 25ºC . The proposed PV system is tested under 800W/m^{2,} 1000W/m^2 and 1200W/m^2. The extracted power from PV array under these conditions is plotted in figure 5.5. Initially, solar irradiance is kept at 800 W/m^2 then it is changed to 1000 W/m^2 at time instant t=0.5 sec. Furthermore, solar irradiance is changed to 1200 W/m^2 at time instant t=1 sec.

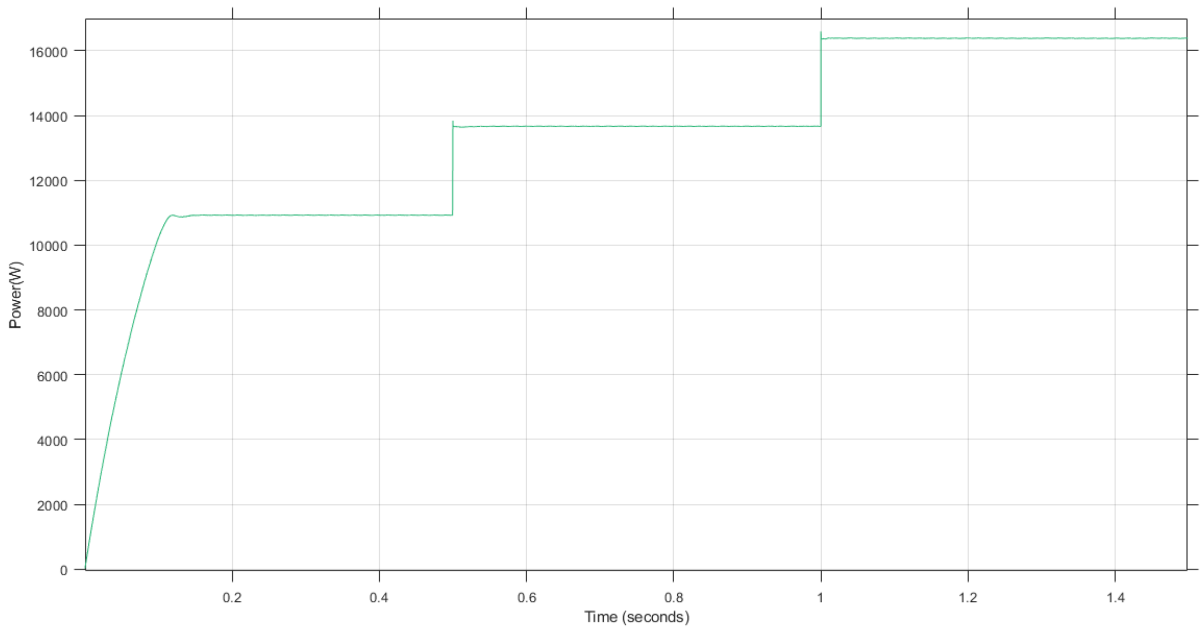

Figure 5.5 Power extracted under varying solar irradiations using Type-1 FLC

Figure 5.6,5.7 and 5.8 shows the zoomed in view of extracted power from PV array at 800 W/m^2.,1000W/m^2 and 1200W/m^2 respectively. When PV system is operating at 800W/m^2 the extracted power oscillates between 10931.9W to 10922.9W which gives a ripple of around 9.1W. When PV system is operating at 1000 W/m^2. extracted power oscillates between 13678W to 13666.7W which gives a ripple of around 10.88W. When PV system is operating at 1200 W/m^2. extracted power oscillates between 16392.8W to 16378.9W which gives a ripple of around 13.9W.

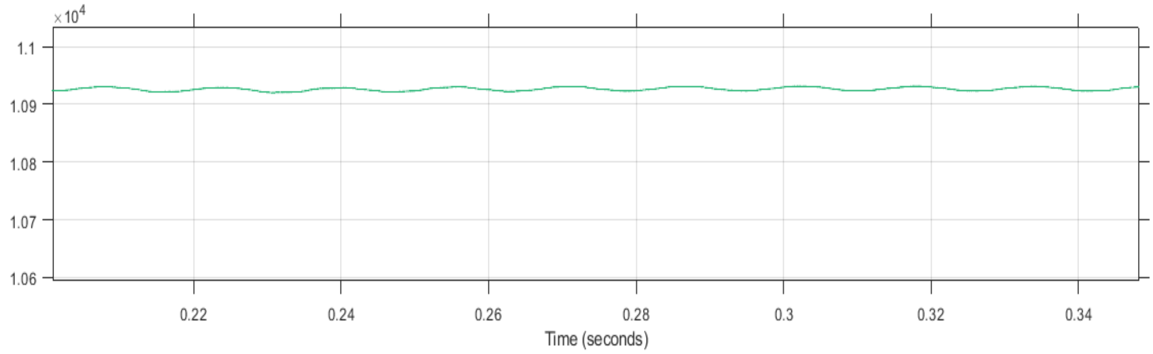

Figure 5.6 Power extracted from PV system at 800W/m^2 using Type-1 FLC

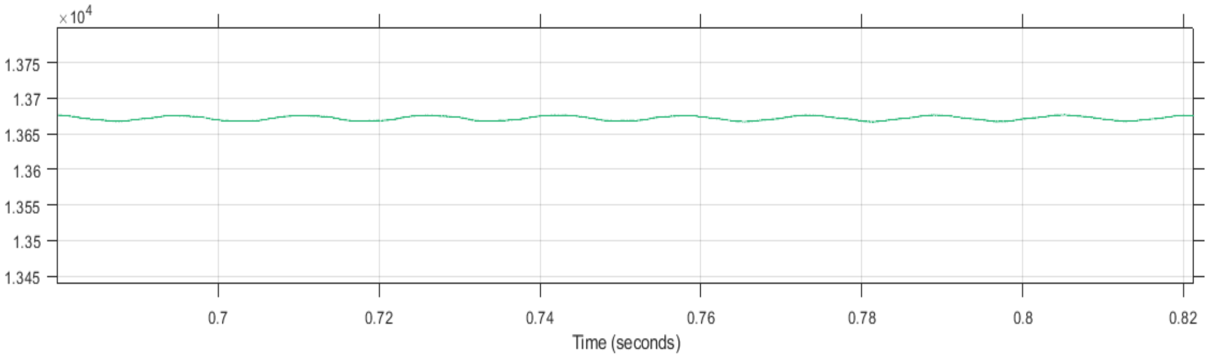

Figure 5.7 Power extracted from PV system at 1000W/m^2 using Type-1 FLC

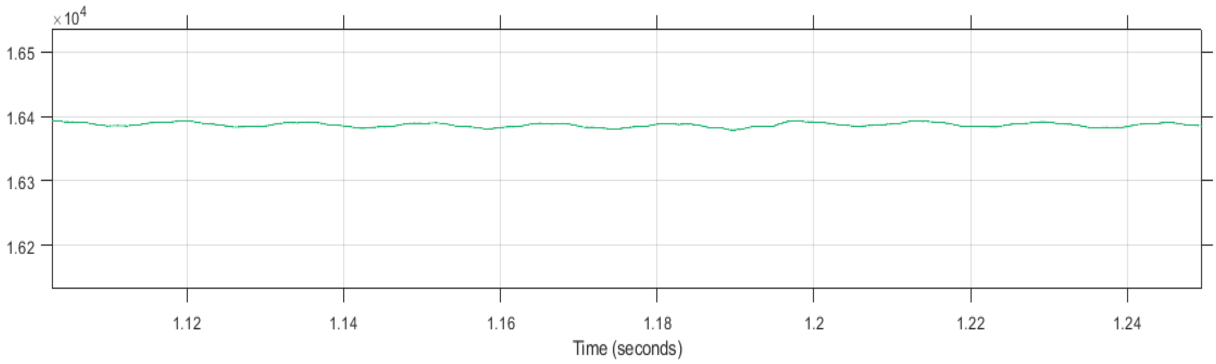

Figure 5.8 Power extracted from PV system at 1200W/m^2 using Type-1 FLC

5.2.1.2 Uniformly varying ambient temperature at constant solar irradiations

The proposed PV system using type-1 fuzzy logic controller has been tested under varying ambient temperature at constant solar irradiations i.e., 1000W/m^2. The proposed PV system is tested under 35ºC, 25ºC, and 15ºC. The extracted power from PV array under this condition is plotted in figure 5.7. Initially, ambient temperature is kept at 35ºC then it is changed to 25ºC at time instant t=0.5 sec. Furthermore, ambient temperature is changed to 15ºC at time instant t=1 sec.

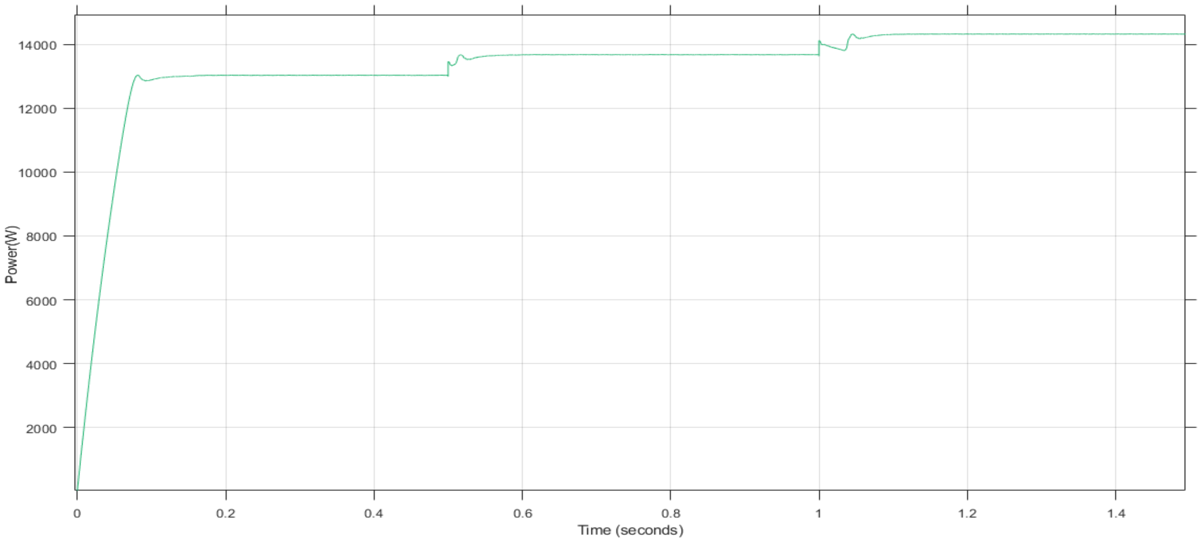

Figure 5.7 Power extracted under varying ambient temperature using type-1 FLC

Figure 5.8, 5.9 and 5.10 shows the zoomed in view of extracted power from PV array using Incremental Conductance algorithm at 35ºC, 25ºC and 15ºC respectively. When PV system is operating at 35ºC the extracted power oscillates between 13031.4W to 13025.2W which gives a ripple of around 6W. When PV system is operating at 25ºC extracted power oscillates between 13678.2W to 13670.7W which gives a ripple of around 7.26W. When PV system is operating at 15ºC extracted power oscillates between 14321.9W to 14316.56W which gives a ripple of around 5.34W.

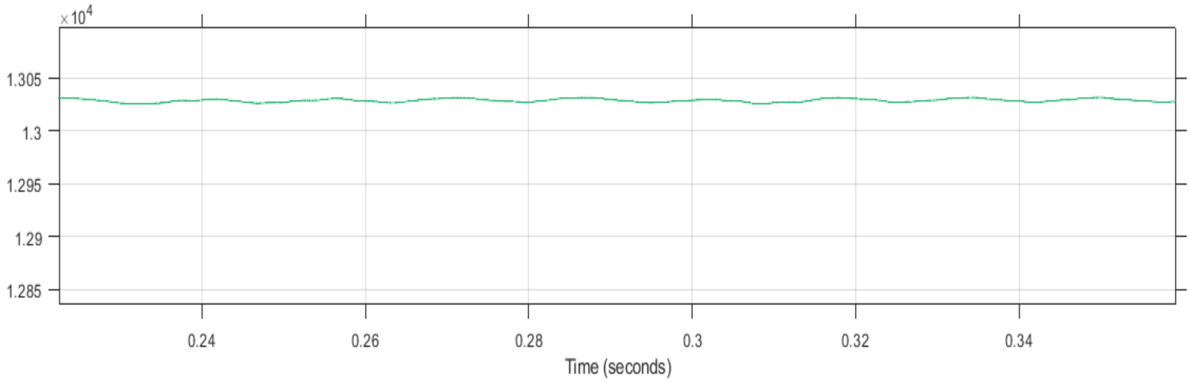

Figure 5.8 Power extracted from PV system at 15ºC using type-1 FLC

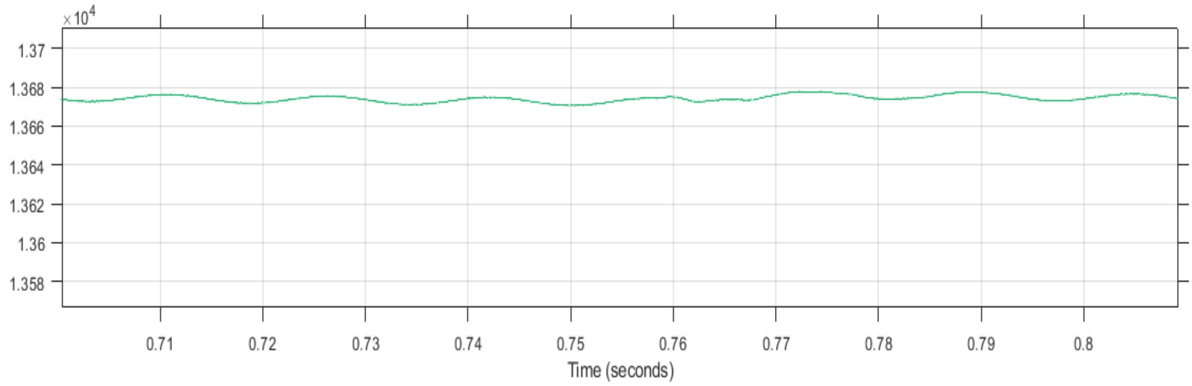

Figure 5.9 Power extracted from PV system at 25ºC using type-1 FLC

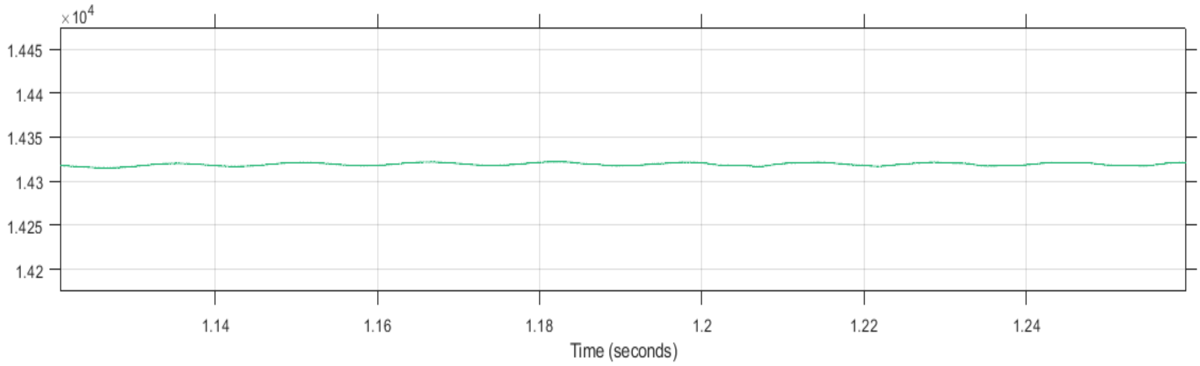

Figure 5.10 Power extracted from PV system at 35ºC using type-1 FLC

5.3 Artificial Neural Network

Artificial neural network (ANN) is a type of machine learning model inspired by human brain, which are generally used to perform tasks like clustering, classification and pattern recognition. ANN consists of different layers i.e. Input layer, output layer and hidden layers. Input layer accepts the input from several different formats provided by the designer. Hidden layer is present in between input layer and output layer. Most of the time, performance of ANN depends on the complexity of the hidden layer. More the number of neurons are present in hidden layer , better it will perform but it might take more time to train the model. Output layer conveys the output computed by trained ANN based on the inputs provided to ANN. The neurons of different layers are connected to each other so as to send signals to each other. Each neuron computes the weighted sum of its input and includes bias to it. This computation is further passed through an activation function like relu , tanh, sigmoid etc. ANN provides the facility of parallel processing, storing data and having memory distribution. Figure 5.11 shows the basic architecture of artificial neural network.

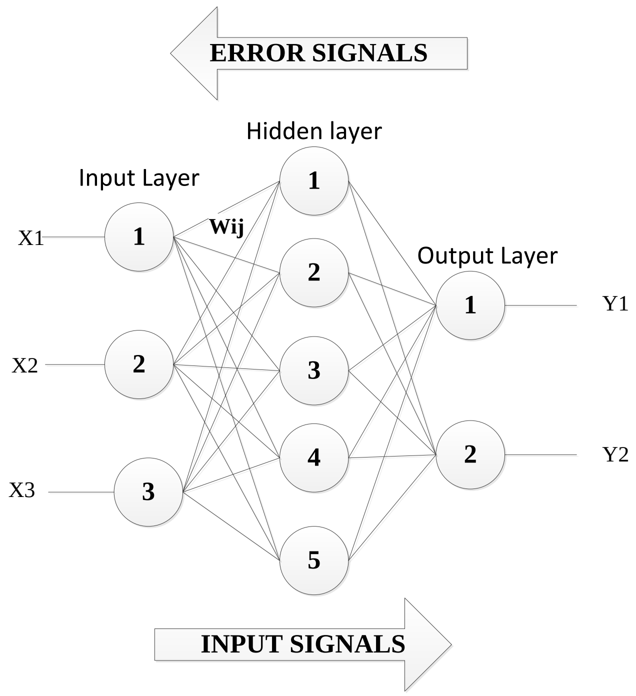

Figure 5.11 Basic architecture of Artificial neural network

The values of weights can be calculated based on three learning methods which are as follows:

i) Supervised learning: This type of learning requires a dataset comprising of set inputs and their desired outputs to train the network. The dataset is divided into three parts i.e., training dataset, validation dataset and test dataset. It is advised to keep the training data set 70% of whole dataset. During each epoch, mean square error is calculated and weights are modified to get minimum error for test dataset.

ii) Unsupervised Learning: This type of learning requires dataset which does not have output dataset. The datasets of similar type are combined in the form of clusters and when a new input is applied, the output response indicates the class to which input pattern belongs.

iii) Reinforcement learning: In this type of learning, during training the network receives the feedback from the environment in the form of rewards and based on the rewards the action are taken by the network to provide output from output layer.

Multilayer perceptron model with inputs as ambient temperature and solar irradiance and the output is the reference voltage at which the PV array exhibits maximum power. Weighted linear sum is considered as basis function for hidden layer and output layer. Transig is considered as activation function for hidden layer whereas output layer has linear activation function. The algorithm used to train the ANN is Levenberg-Marquardt which requires more memory but takes less time compared to other algorithms. This algorithm takes advantage of gauss newton algorithm and gradient descent. Levenberg - Marquardt algorithm consist of solving the equation 5.1

$$(J^T J + \lambda I)\ \delta = J^T E \qquad (5.1)$$

Here, J is the Jacobian matrix for the system, λ is the Levenberg's damping factor, **δ** is the weight update vector and **E** is the error vector containing the output errors for each input vector used on training the network. **δ** is the change to be made in the weight after each iteration to achieve better solution. The $\mathbf{J^t J}$ matrix can also be known as the approximated Hessian. λ is know as damping factor which is adjusted to guide the optimization process. Higher value of damping factor inclines it towards gradient descent algorithm and smaller value of damping factor incline the algorithm towards gauss-Newton algorithm. Jacobian matrix can be calculated using equation 5.2 .

$$J = \begin{bmatrix} \frac{\partial F(x_1, w)}{\partial w_1} & \cdots & \frac{\partial F(x_1, w)}{\partial w_W} \\ \vdots & \ddots & \vdots \\ \frac{\partial F(x_N, w)}{\partial w_1} & \cdots & \frac{\partial F(x_N, w)}{\partial w_W} \end{bmatrix}. \quad (5.2)$$

Here, $F(x_i,w)$ is the network function for ith input vector of training set and w is weight vector of the network.

Mean square error is considered as the parameter to determine the performance of the proposed ANN, training of the ANN stops when there is no improvement in mean square error. Feedforward based neural network is constructed as shown in fig 5.12.

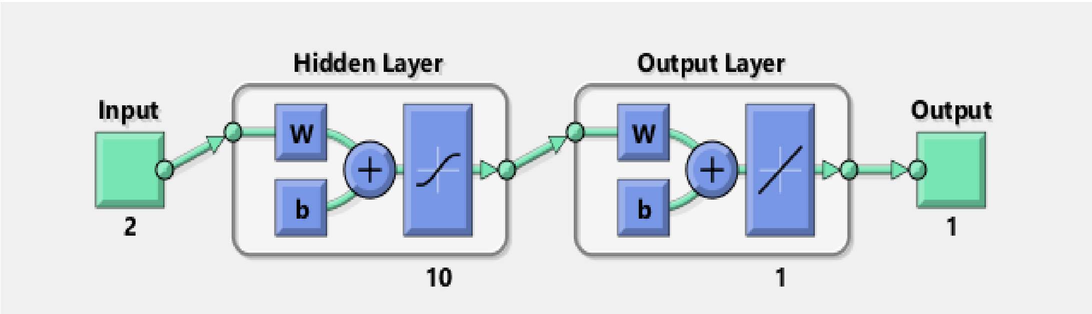

Figure 5.12 Feedforward Based Neural Network

The training data is generated using MATLAB script program which produces matrix for solar irradiation varying from 0 to1000 and ambient temperature varying from 15°C to 35°C. Among 1000 data sets 700 data sets are used for training, 150data sets for validating and 150 for testing. The hidden layer consists of 10 neurons. The neural network was created using neural network wizard provided by MATLAB/Simulink. The error histogram is shown in fig. 5.13. Also, the performance curve of trained ANN is shown in fig. 5.14 which shows Mean squared error of order 10^{-8} was attained after 1000 epoch.

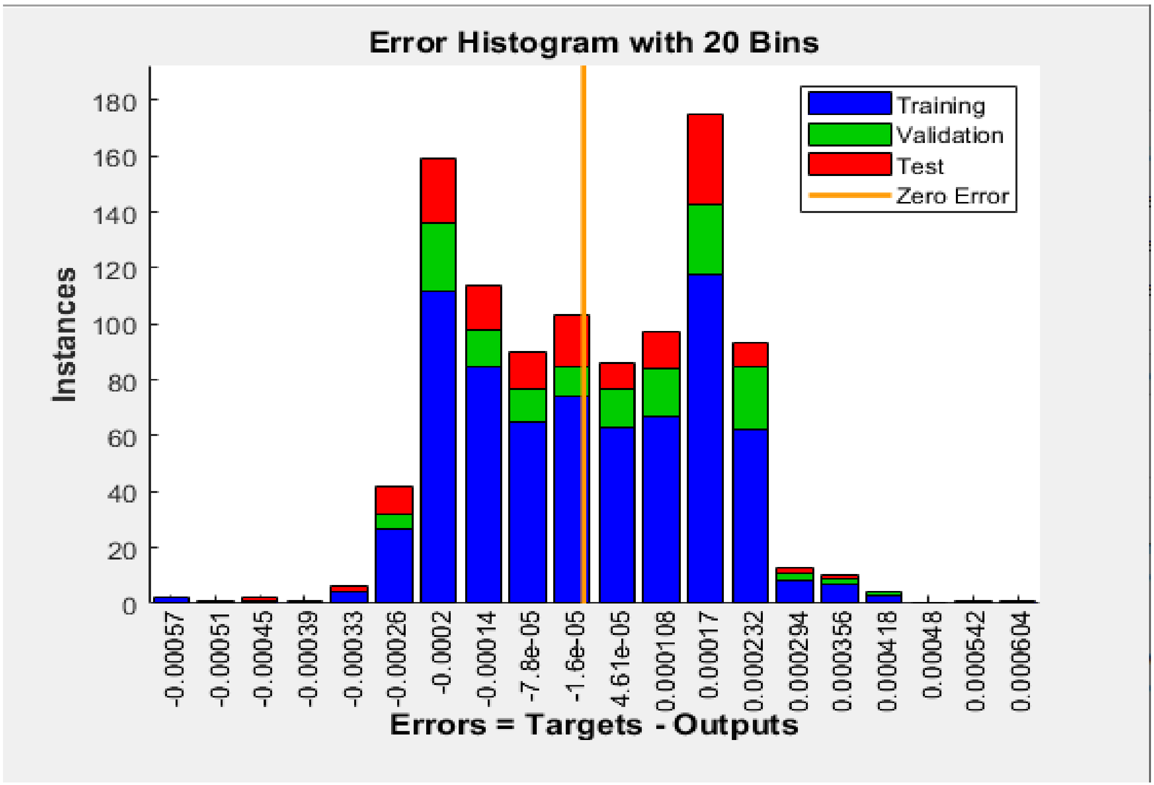

Figure 5.13 Error histogram of trained artificial neural network

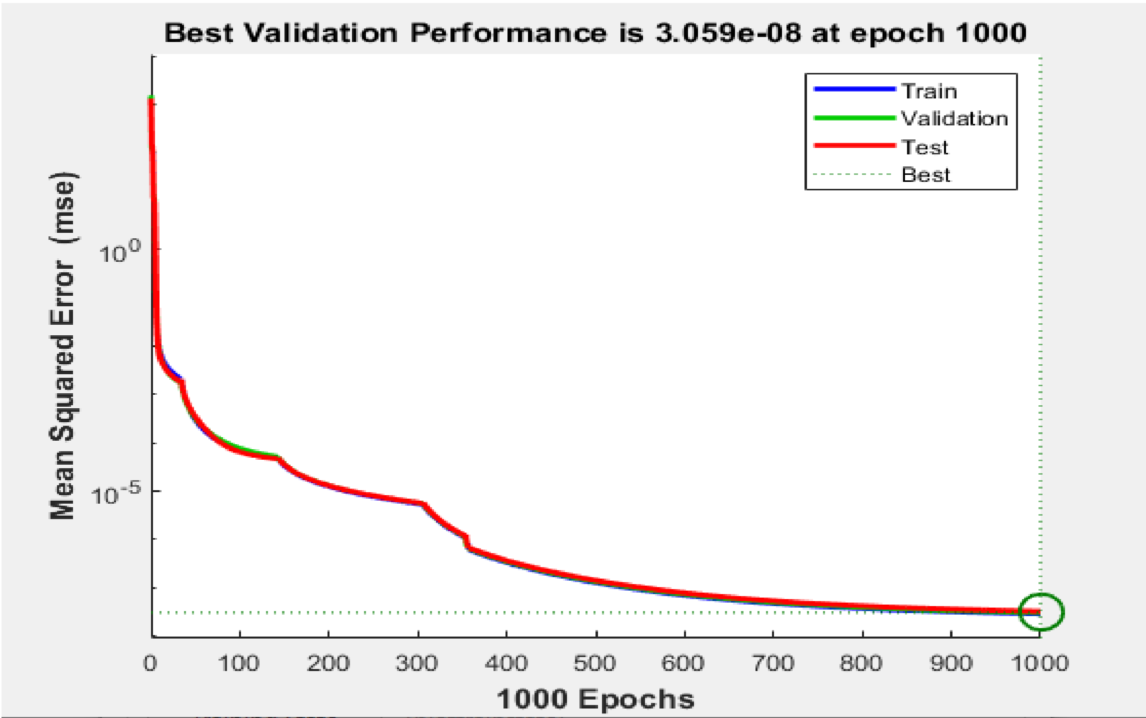

Figure 5.14 Performance Curve Of The Artificial Neural Network

A MATLAB-SIMULINK model for PV system using artificial neural network is shown in figure 5.15. The specification of the developed MATLAB -SIMULINK model is shown in table 4.1. The designing of controller is discussed above.

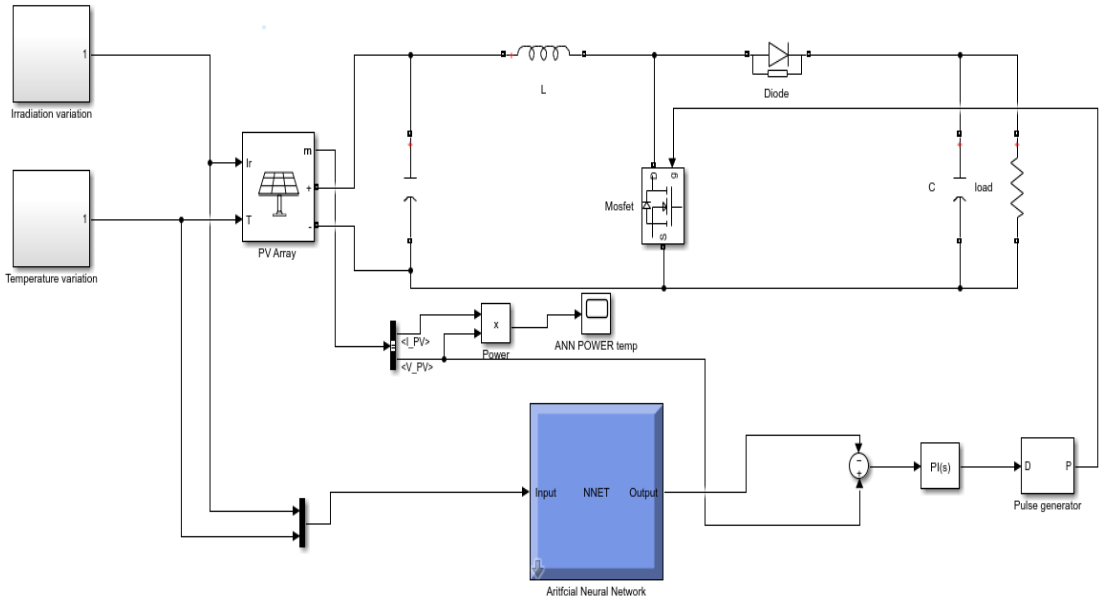

Figure 5.15 MATLAB/SIMULINK model of PV system using ANN

The simulation results are obtained for two different cases which are mentioned below:

1. Uniformly varying solar irradiations at constant ambient temperature.
2. Uniformly varying ambient temperature at constant solar irradiations

5.3.1 MATLAB Simulation results

5.3.1.1 Uniformly varying solar irradiations at constant ambient temp.

The proposed PV system using Artificial Neural Network has been tested under varying solar irradiation at constant ambient temperature i.e., 25ºC. The proposed PV system is tested under 800W/$m^{2,}$ 1000W/m^2 and 1200W/m^2. The extracted power from PV array under these conditions is plotted in figure 5.16. Initially, solar irradiance is kept at 800 W/m^2 then it is changed to 1000 W/m^2 at time instant t=0.5 sec. Furthermore, solar irradiance is changed to 1200 W/m^2 at time instant t=1 sec.

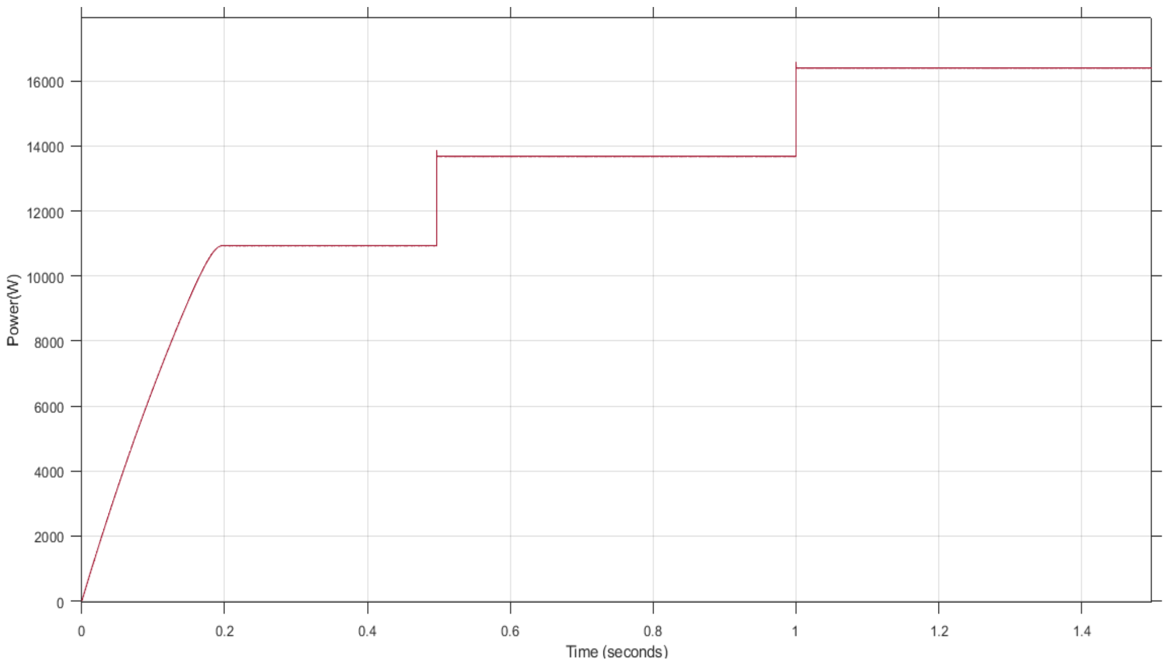

Figure 5.16 Power extracted under varying solar irradiations using ANN

Figure 5.17,5.18 and 5.19 shows the zoomed in view of extracted power from PV array at 800 W/m^2.,1000W/m^2 and 1200W/m^2 respectively. When PV system is operating at 800 W/m2 the extracted power oscillates between 10931.9W to 10929.9W which gives a ripple of around 2W. When PV system is operating at 1000 W/m^2. extracted power oscillates between 13678W to 13676.43W which gives a ripple of around 1.57W. When PV system is operating at 1200 W/m^2. extracted power oscillates between 16395.72W to 16392.9W which gives a ripple of around 2.84W.

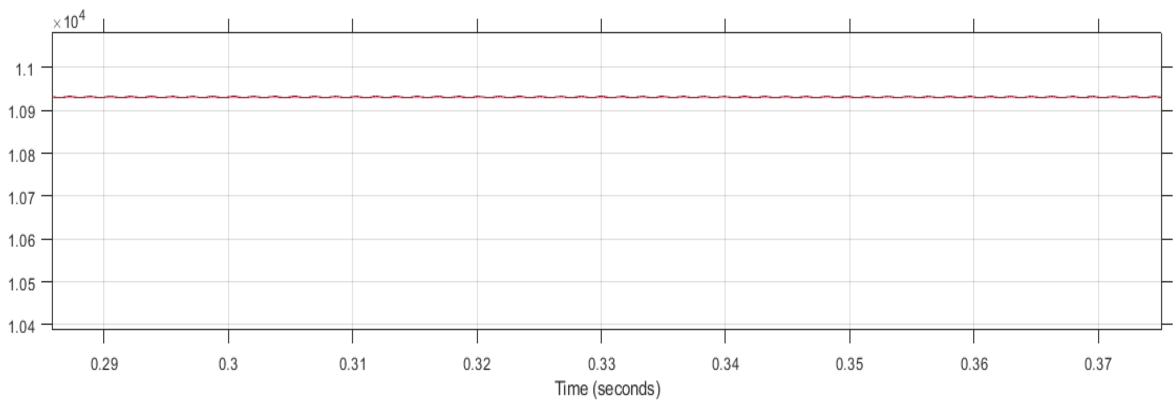

Figure 5.17 Power extracted from PV system at 800W/m^2 using ANN

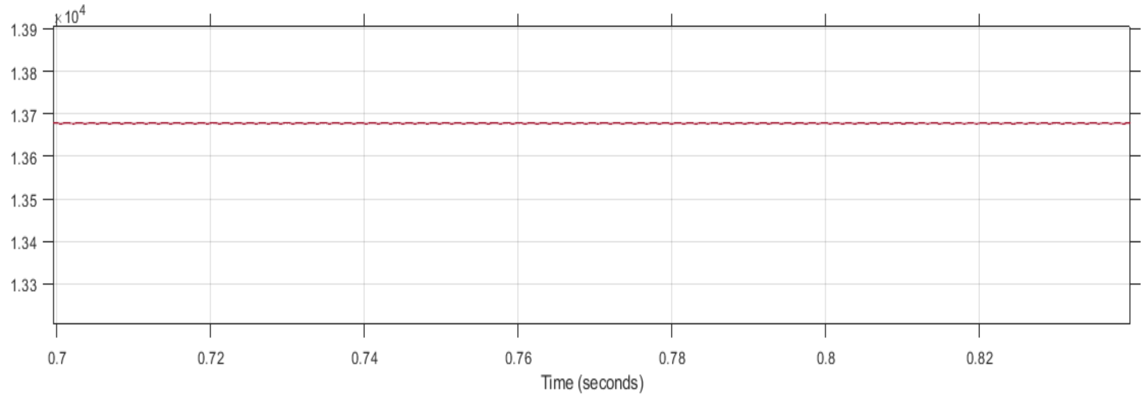

Figure 5.18 Power extracted from PV system at 1000W/m^2 using ANN

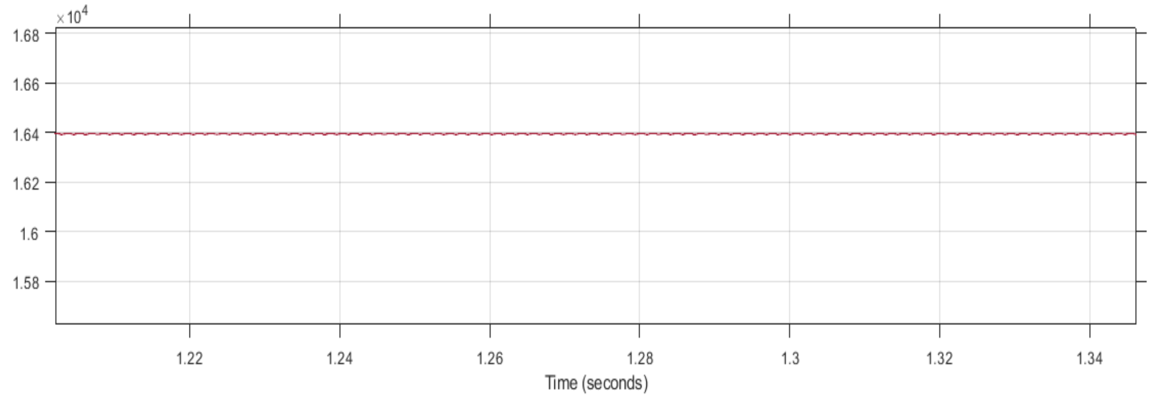

Figure 5.19 Power extracted from PV system at 1200W/m^2 using ANN

5.3.1.2 Uniformly varying ambient temperature at constant solar irradiations

The proposed PV system using artificial neural network has been tested under varying ambient temperature at constant solar irradiations i.e., 1000W/m^2. The proposed PV system is tested under 35^{o}C, 25^{o}C, and 15^{o}C. The extracted power from PV array under this condition is plotted in figure 5.20. Initially, ambient temperature is kept at 35^{o}C then it is changed to 25^{o}C at time instant t=0.5 sec. Furthermore, ambient temperature is changed to 15^{o}C at time instant t=1 sec.

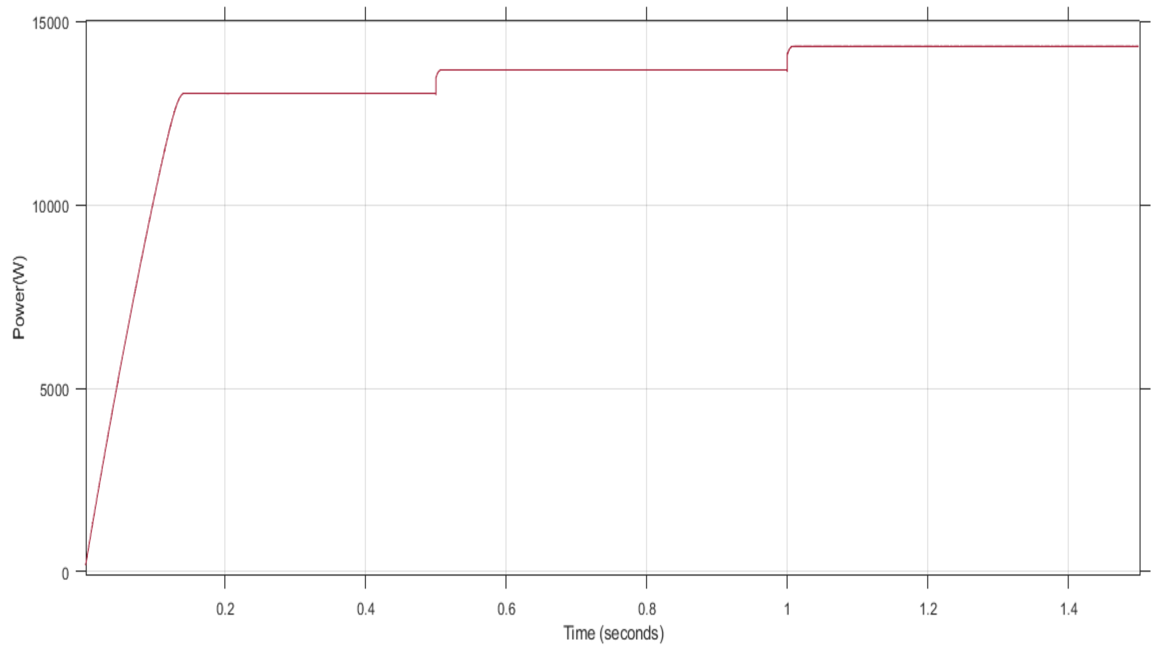

Figure 5.20 Power extracted under varying ambient temperature using ANN

Figure 5.21, 5.22 and 5.23 shows the zoomed in view of extracted power from PV array using Artificial neural network at 35ºC, 25ºC and 15ºC respectively. When PV system is operating at 35ºC the extracted power oscillates between 13031.4W to 13030.185W which gives a ripple of around 1.23W. When PV system is operating at 25ºC extracted power oscillates between 13678.2W to 13676.54W which gives a ripple of around 1.57W. When PV system is operating at 15ºC extracted power oscillates between 14322.4W to 14320.6W which gives a ripple of around 1.82W.

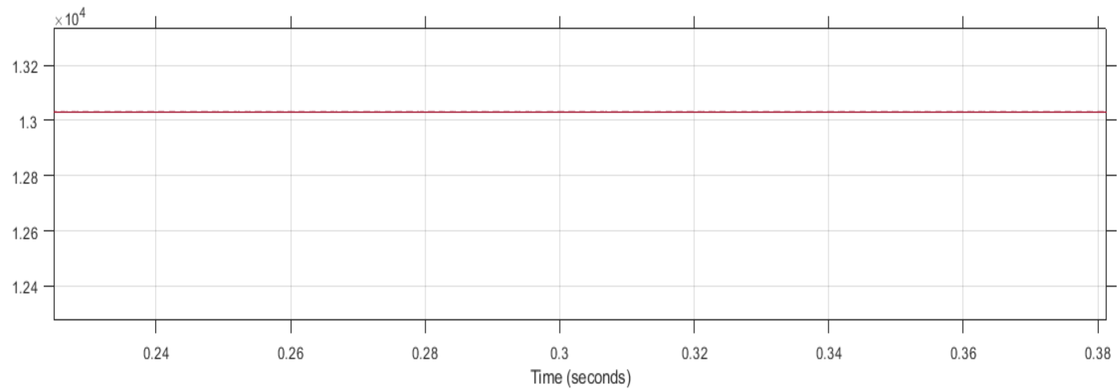

Figure 5.21 Power extracted from PV system at 15ºC using ANN

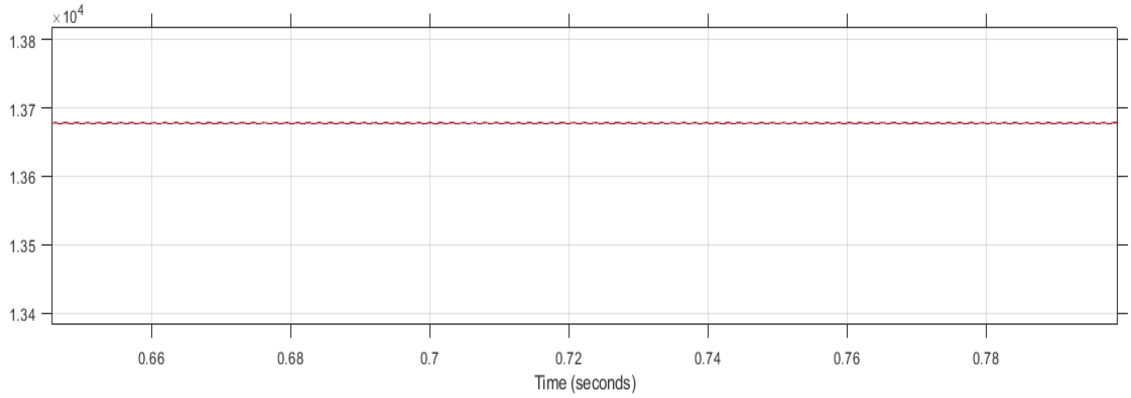

Figure 5.22 Power extracted from PV system at 25^{0}C using ANN

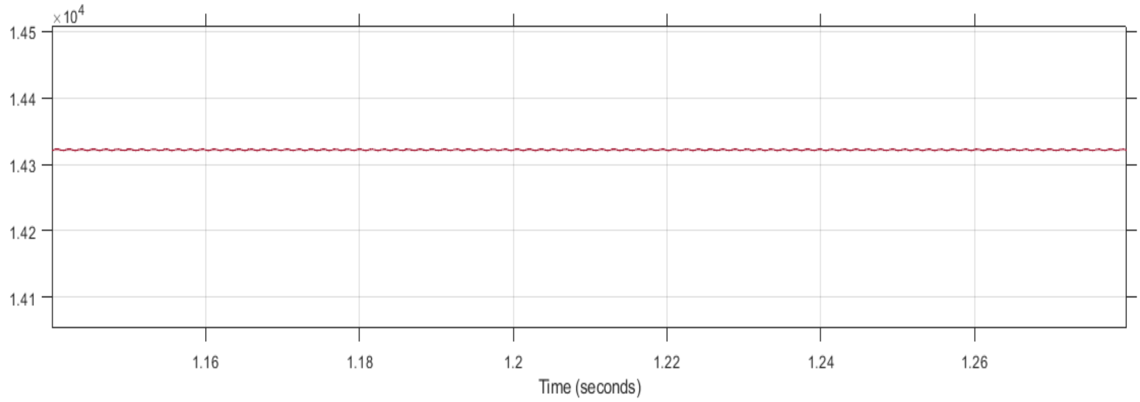

Figure 5.23 Power extracted from PV system at 35^{0}C using ANN

5.4 Conclusion

In this chapter intelligent control techniques i.e. Type1 fuzzy logic controller and artificial neural network based MPPT are described. Membership functions of input and output of FLC along the rule based has been discussed. The detailed working of artificial neural networks has also been discussed in this chapter. The MATLAB/SIMULINK model has been developed for both the techniques and simulation results are discussed under uniformly varying atmospheric conditions i.e., varying solar irradiations at constant ambient temperature and varying ambient temperature at constant solar irradiations. It is observed that both intelligent techniques were able to trace the maximum power from PV under all the testing conditions.

CHAPTER 6 COMPARATIVE ANALYSIS OF MPPT ALGORITHMS

6.1 General

In this chapter comparative analysis has been done between all the MPPT techniques i.e. Perturb & Observe algorithm, Incremental Conductance algorithm, Type -1 Fuzzy logic controller and Artificial neural Network under uniformly varying atmospheric conditions. The dependency of PV array on solar irradiations and ambient temperature is highlighted in this chapter. The comparison has been done on the basis of fill factor, power loss and ripples in the extracted power from PV array. The theoretical maximum power which can be extracted from PV array under different atmospheric conditions is shown in table 6.1. The power extracted using all the algorithms are overlapped on the same graph to get the better understanding of the performance of all the algorithms.

Table 6.1. Theoretical maximum Power of PV array

Ambient Temperature (^{0}C)	Solar Irradiations (W/m^2)	Theoretical Maximum Power (W)
25	800	10931.9
25	1000	13678.7
25	1200	16395.6
15	1000	14322.3
35	1000	13031.3

6.2 Power Extracted and Ripples

The power extracted from the PV array majorly depends upon the algorithms used to generate the firing pulses for boost converter which acts as an impedance matching interface. The extracted power oscillates near theoretical maximum power of PV array. It is advised to get minimum oscillation to improve performance of system. These oscillations in the extracted power has been discussed in this section. The comparison of all the MPPT algorithms is done under two conditions i.e., varying solar irradiations at constant ambient temperature and varying ambient temperature at constant solar irradiations which is discussed further.

6.2.1 Uniformly varying solar Irradiations at constant ambient temperature

Fig 6.1 shows the power extracted under varying solar irradiations at constant ambient temperature using all the MPPT algorithms The solar radiations for testing are considered as 800 W/m^2 ,1000W/m^2 and 1200 W/m^2 at constant ambient temperature i.e. 25^{o}C. The waveforms for all the MPPT techniques are highlighted using different colours as shown in legend.

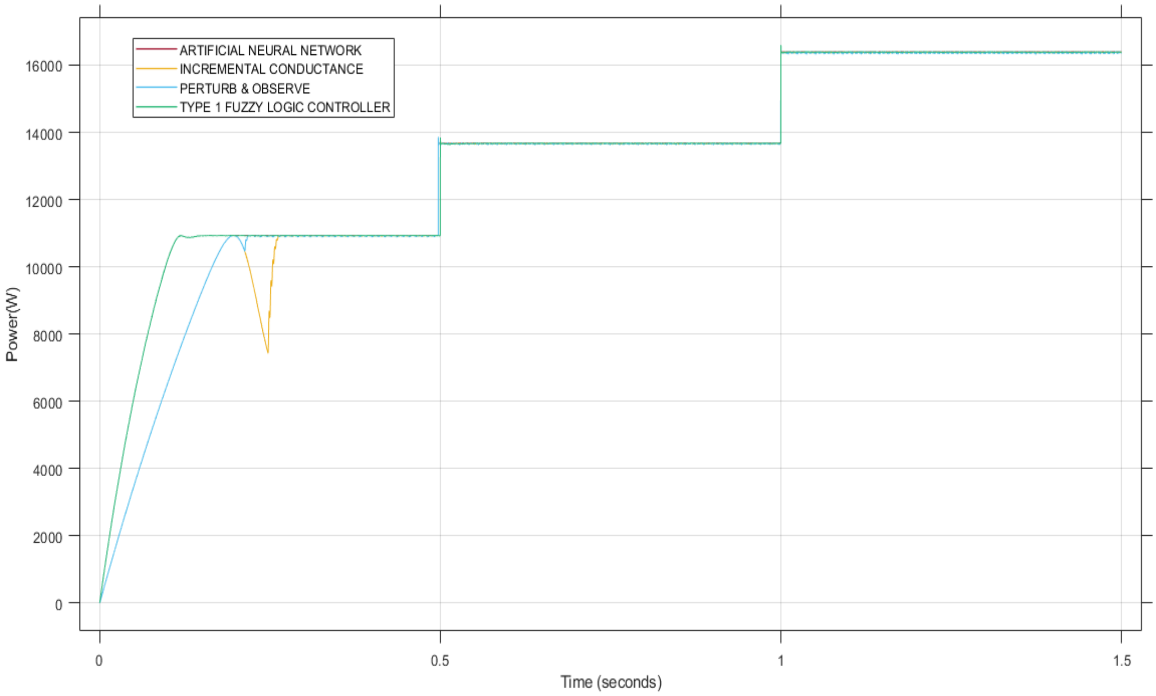

Figure 6.1 Power output from PV array for various MPPT techniques under uniformly varying solar irradiations

It is quite evident from fig 6.2 ,6.3 and 6.4 that the power extracted from PV array under all the cases is maximum when controller is designed using artificial neural network. When the PV array was operating at 800 W/m^2, it has extracted maximum power of 10390.8W with ripple of 2W. When the PV array was operating at 1000(W/m^2), it has extracted maximum power of 13677.33W from PV array with ripple of around 1.57W. When the PV array was operating at 1200(W/m^2), it has extracted maximum power from PV array i.e. 16394.3W with ripple of around 2.84W.

Furthermore, it has been found out that T1-FLC based MPPT controller has performed better than P&O and INC based MPPT controllers as T1-FLC generated ripples of around 8.14W whereas INC based MPPT controller has generated ripples of around 26.3W and P&O based MPPT controller has generated ripples of around 54W. It can also be noted that lesser ripples were produced under standard test conditions as compared to other testing conditions mentioned above.

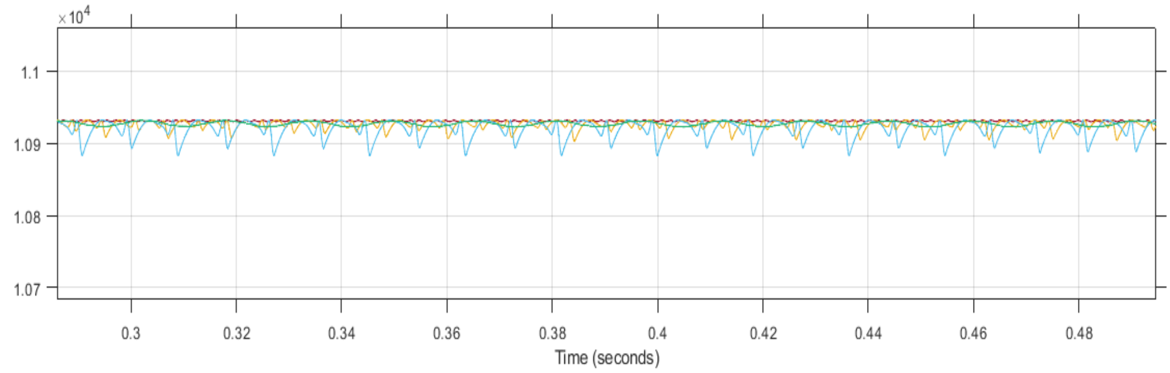

Figure 6.2 Power output from PV array for various MPPT techniques at 800W/m^2

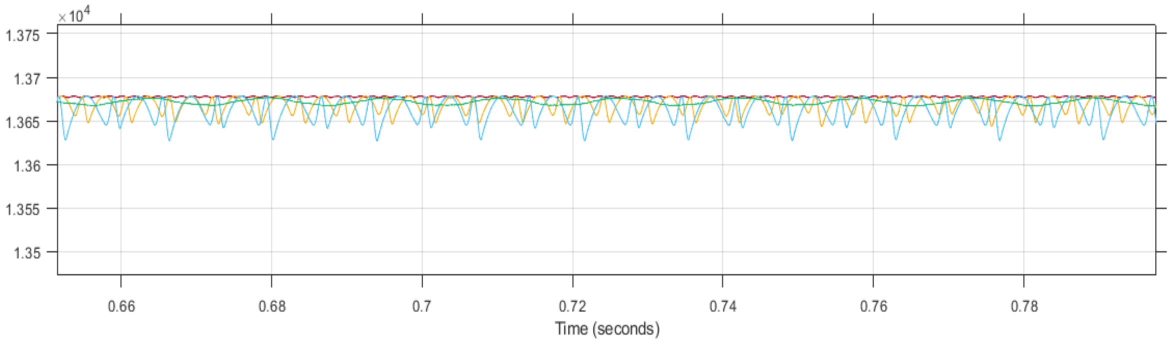

Figure 6.3 Power output from PV array for various MPPT techniques at 1000W/m^2

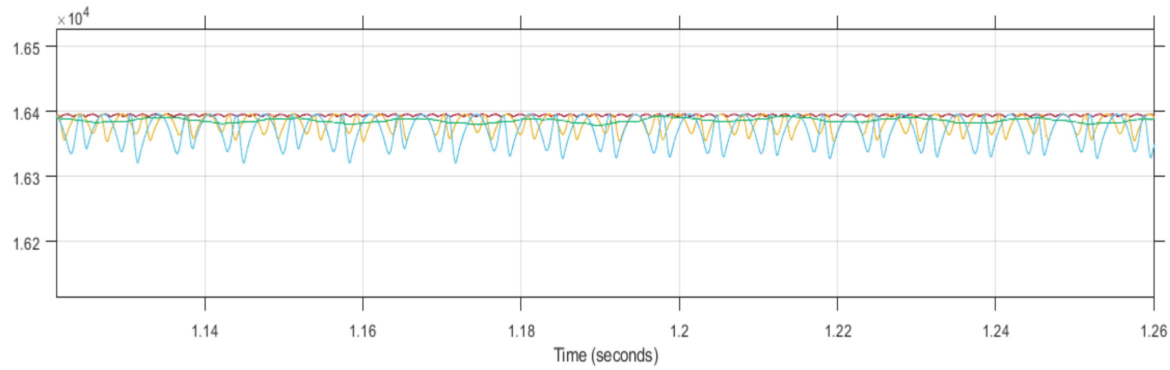

Figure 6.4 Power output from PV array for various MPPT techniques at 1200W/m^2

Table 6.2 Extracted Power for various MPPT techniques under varying solar irradiations

Testing conditions		Power Extracted from PV array (W)			
Ambient Temperature (°C)	Irradiance (W/m^2)	P&O	INC	T1-FLC	ANN
25	800	10907.9	10917.65	10928.95	10930.8
25	1000	13653.7	13667.3	13674.3	13677.33
25	1200	16357.7	16375.7	16385.85	16394.3

Table 6.3 Ripples in Power for various MPPT techniques under varying solar irradiations

Testing conditions		Ripples (W)			
Ambient Temperature (ºC)	Irradiance (W/m^2)	P&O	INC	T1-FLC	ANN
25	800	48	28.7	9.1	2
25	1000	50	21.7	7.26	1.57
25	1200	72.8	39.7	13.9	2.84

6.2.2 Uniformly varying ambient temperature at constant solar irradiations

Fig 6.5 shows the power extracted under varying ambient temperature at constant solar irradiations using all the MPPT algorithms The ambient temperature for testing are considered as 35ºC, 25ºC and 15ºC at constant solar irradiation i.e. 1000 W/m^2. The waveforms for all the MPPT techniques are highlighted using different colours as shown in legend.

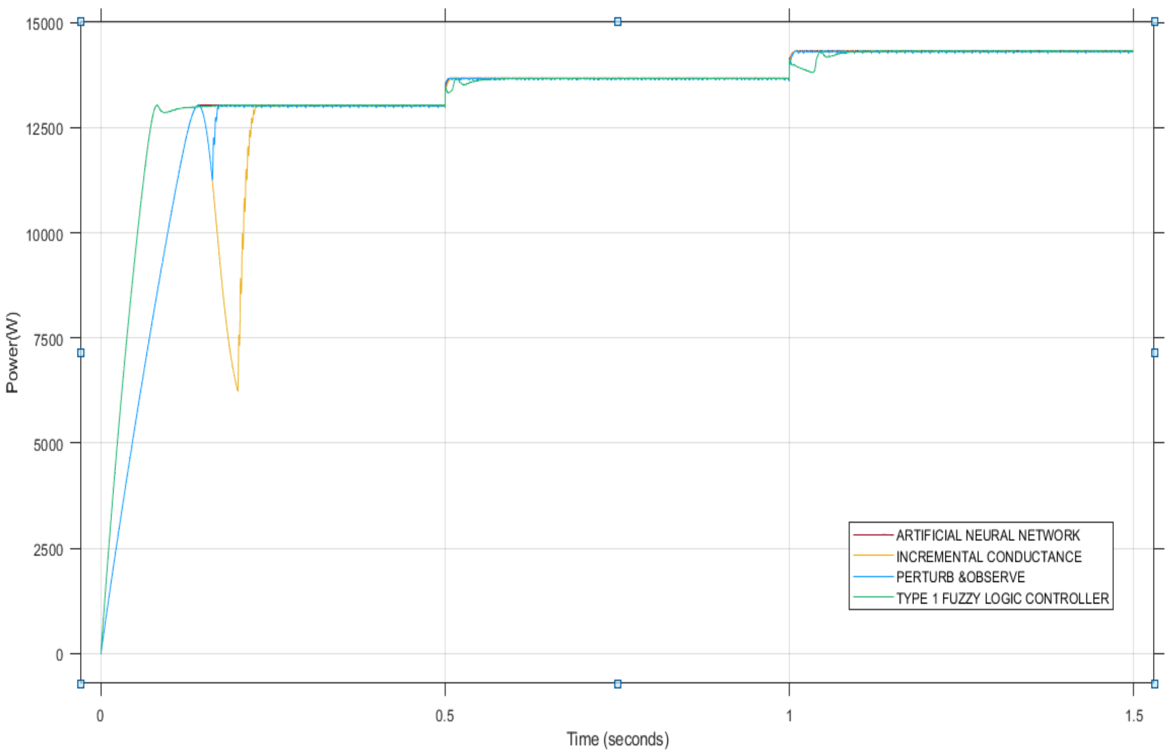

Figure 6.5 Power output from PV array for various MPPT techniques under uniformly varying atmospheric conditions

It is quite evident from fig 6.6 ,6.7 and 6.8 that the power extracted from PV array under all the cases is maximum when controller is designed using artificial neural network. When the PV array was operating at 35 °C, it has extracted maximum power of 13030.8W with ripple of 1.23W. When the PV array was operating at 25 °C, it has extracted maximum power of 13677.33W from PV array with ripple of around 1.57W. When the PV array was operating at 15 °C, it has extracted maximum power from PV array i.e. 14321.5W with ripple of around 1.82W.

Furthermore,, it has been found out that T1-FLC based MPPT controller has performed better than P&O and INC based MPPT controllers as T1-FLC generated ripples of around 6.2W whereas INC based MPPT controller has generated ripples of around 22.6W and P&O based MPPT controller has generated ripples of around 52.3W. It can also be noted that lesser ripples were produced under standard test conditions as compared to other testing conditions mentioned above.

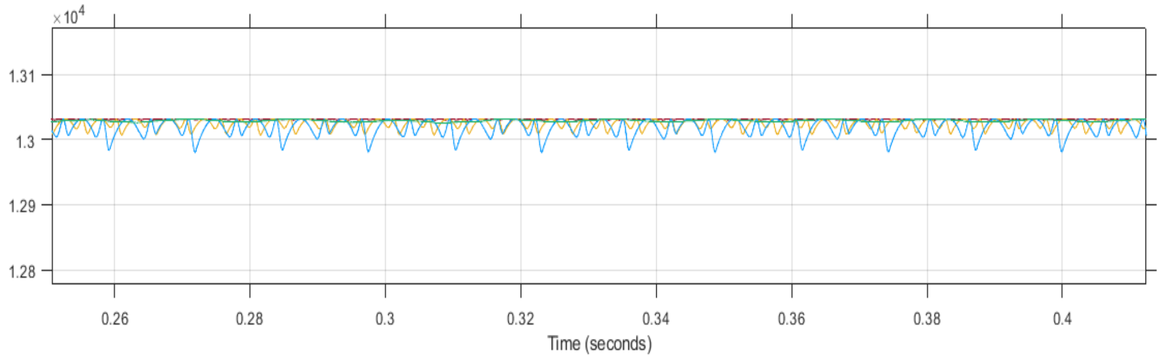

Figure 6.6 Power output from PV array for various MPPT techniques at 35 °C

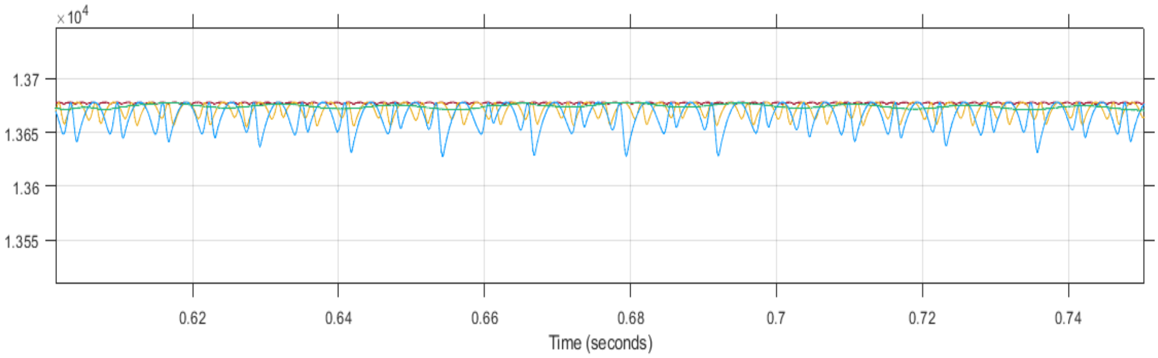

Figure 6.7 Power output from PV array for various MPPT techniques at 25 °C

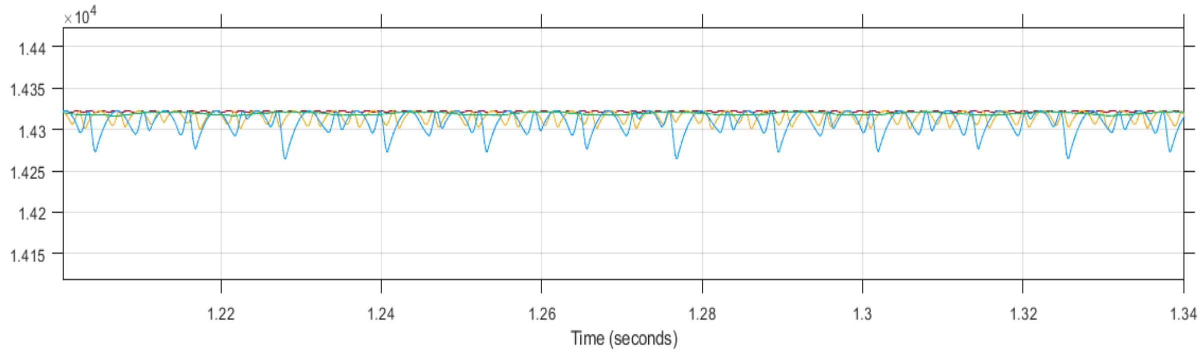

Figure 6.8 Power output from PV array for various MPPT techniques at 15 ºC

Table 6.4 Extracted Power for various MPPT techniques under varying ambient temperature

Testing conditions		Power Extracted from PV array (W)			
Ambient Temperature (ºC)	Irradiance (W/m^2)	P&O	INC	T1-FLC	ANN
35	1000	13006.15	13019.65	13028.23	13030.8
25	1000	13653.25	13667.3	13674.3	13677.33
15	1000	14294	14311	14319.92	14321.5

Table 6.5 Ripples in Power for various MPPT techniques under varying ambient temperature

Testing conditions		Ripples (W)			
Ambient Temperature (ºC)	Irradiance (W/m^2)	P&O	INC	T1-FLC	ANN
35	1000	50.5	23.5	6	1.23
25	1000	49.7	21.7	7.26	1.57
15	1000	56.6	22.6	5.34	1.82

6.3 Fill factor

Fill Factor is defined as the percentage of maximum Power output from PV array (Pm) to the product of open circuit voltage (Voc) and short circuit current (Isc) of the PV array at given atmospheric conditions. As the fill factor moves closer to unity, the more efficient is the system.

Fill factor can be calculated using equation 6.1

$$FF = \frac{Pm}{Voc*Isc} * 100 \qquad (6.1)$$

6.3.1 Uniformly Varying solar Irradiations at constant ambient temperature

Table 6.6 gives the detailed description of fill factor under uniformly varying solar irradiations at constant ambient temperature. It can be summarised that artificial neural network-based controller has performed better than other techniques. When the PV array is operating at 800 W/m^2, fill factor is 78.62%. When the PV array is operating at 1000(W/m^2), fill factor is 77.91%. When the PV array is operating at 1200W/m^2, fill factor is 77.34%.

Table 6.6. Fill Factor Under Uniformly Varying Solar Irradiations

Testing Conditions		P&O	INC	T1-FLC	ANN
Temperature(C)	Irradiance (W/ m^2)				
25	800	78.45	78.54	78.6	78.62
25	1000	77.77	77.82	77.88	77.91
25	1200	77.16	77.25	77.29	77.34

Furthermore, it has been found out that T1-FLC based MPPT controller has performed better than P&O and INC based MPPT controllers as T1-FLC has fill factor of around 77.92% whereas INC based MPPT controller has fill factor of around 77.87% and P&O based MPPT controller has fill factor of around 77.79%.

6.3.2 Uniformly varying ambient temperature at constant solar irradiation

Table 6.7 gives the detailed description of fill factor under uniformly varying ambient temperature at constant solar irradiations. It can be summarised that artificial neural network-based controller has performed better than other techniques. When the PV array is operating at 15ºC, fill factor is 78.37%. When the PV array is operating at 25ºC, fill factor is 77.91%. When the PV array is operating at 35ºC, fill factor is 76.92%.

Table 6.7 Fill Factor Under Uniformly Varying Ambient Temperature

Testing Conditions		P&O	INC	T1-FLC	ANN
Temperature(C)	Irradiance (W/ m^2)				
15	1000	78.21	78.3	78.34	78.37
25	1000	77.77	77.82	77.88	77.91
35	1000	76.77	76.85	76.9	76.92

Furthermore, it has been found out that T1-FLC based MPPT controller has performed better than P&O and INC based MPPT controllers as T1-FLC has fill factor of around 77.7% whereas INC based MPPT controller has fill factor of around 77.65% and P&O based MPPT controller has fill factor of around 77.58%. It can also be noted that fill factor is directly proportional to ambient temperature and inversely proportional to solar irradiations.

6.4 Power Loss

Power loss is calculated as difference between theoretical maximum power output from PV array and maximum power output from PV array. It is preferred to have minimum power loss to make full utilisation of the PV array. Power loss can be calculated using equation 6.2.

$$\text{Power Loss} = P_{theo.\ max} - P_{o/p\ pv} \quad (6.2)$$

6.4.1 Uniformly varying solar Irradiations at constant ambient temperature

Table 6.8 gives the detailed description of power loss under uniformly varying solar irradiations at constant ambient temperature. It can be summarised that artificial neural network-based controller has performed better than other techniques. When the PV array is operating at 800 W/m^2, power loss is 1W. When the PV array is operating at 1000(W/m^2), power loss is 0.78W. When the PV array is operating at 1200(W/m^2), power loss is 1.42W.

Table 6.8 Power Loss Under Uniformly Varying Solar Irradiations

Testing Conditions		P&O	INC	T1-FLC	ANN
Temperature(C)	Irradiance (W/ m^2)				
25	800	24	14.3	4.6	1
25	1000	24.8	10.85	3.63	0.78
25	1200	36.4	19.85	6.95	1.42

Furthermore, it has been found out that T1-FLC based MPPT controller has performed better than P&O and INC based MPPT controllers as T1-FLC has power loss of around 5.06W whereas INC based MPPT controller has power loss of around 15W and P&O based MPPT controller has 28.4W.

6.4.2 Uniformly varying ambient temperature at constant solar irradiations

Table 6.9 gives the detailed description of power loss under uniformly varying ambient temperature at constant solar irradiations. It can be summarised that artificial neural network-based controller has performed better than other techniques. When the PV array is operating at 15ºC, power loss is 0.91W. When the PV array is operating at 25ºC, power loss is 0.78W. When the PV array is operating at 35ºC, power loss is 0.6W.

Table 6.9 Power Loss Under Uniformly Varying ambient temperature

Testing Conditions		P&O	INC	T1-FLC	ANN
Temperature(C)	Irradiance (W/ m^2)				
35	1000	24.25	11.75	3	0.6
25	1000	24.8	10.85	3.63	0.78
15	1000	28.3	11.3	2.67	0.91

Furthermore, it has been found out that T1-FLC based MPPT controller has performed better than P&O and INC based MPPT controllers as T1-FLC has power loss of around 3.1W whereas INC based MPPT controller has power loss of around 11.3W and P&O based MPPT controller has power loss of around 26.11W.

6.5 Conclusion

In this chapter comparative analysis has been done between all the MPPT techniques based on the extracted power, fill factor and power loss. It has been observed that under uniformly varying atmospheric conditions artificial neural network has outperformed all other techniques. ANN based MPPT extracted maximum with minimum ripple from PV array, also the fill factor and power loss was minimum. It has also been observed that Type-1 fuzzy logic controller has performed better than conventional MPPT techniques.

CHAPTER 7 CONCLUSION AND FUTURE WORK

7.1 Main Conclusion

The main objective of this work is to have detailed knowledge of working of PV systems, DC-DC converters and MPPT controllers. The electrical equivalent model of photovoltaic is studied to get the detailed idea of its characteristics under uniformly varying atmospheric conditions. Boost converter is also designed and its application in PV system is also studied. Conventional and intelligent Maximum Power Point techniques are compared in the present work. Comparison of following MPPT techniques is done:

i) Conventional MPPT Techniques

1. Perturb &Observe
2. Incremental Conductance

ii) Intelligent MPPT Techniques

1. Type-1 Fuzzy Logic Controller
2. Artificial Neural Network

MATLAB/SIMULINK model for all four MPPT techniques are developed and simulation results are presented. All MPPT techniques are able to trace the maximum Power point under following two conditions:

i) Varying solar irradiations at constant ambient temperature.

ii) Varying ambient temperature at constant solar irradiations.

The power extracted using ANN based MPPT controller has minimum ripples and highest fill factor. On the other hand, it is observed that Type-1 Fuzzy logic controller has performed better than conventional MPPT techniques.

7.2 Future Work

The future work is to study and implement the following:

- Grid integration of PV system.
- Battery charging using PV system
- Hardware implementation of PV system
- Study hybrid renewable energy system

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