

**COMPARATIVE ANALYSIS OF VARIOUS MPPT
TECHNIQUES WITH DIFFERENT DC-DC
CONVERTERS ON SOLAR PHOTOVOLTAIC
SYSTEM**

DISSERTATION/THESIS

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Submitted by:

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I, Kshitijaa Ranjan, Roll No. 2k14/C&I/23 student of M. Tech. (Control & Instrumentation), hereby declare that the dissertation/project titled “Comparative Analysis Of Various MPPT Techniques With Different DC-DC Converters On Solar Photovoltaic System” under the supervision of Dr. Narendra Kumar of Electrical Engineering Department Delhi Technological University in partial fulfilment of the requirement for the award of the degree of Master of Technology has not been submitted elsewhere for the award of any Degree.

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ABSTRACT

The ever increasing demand of energy day by day due to increase in population, urbanization and industrialization requires research and development in the area of non-conventional sources of energy. Conventional sources are being depleted and are estimated to be finished by approximately next sixty years if consumed at the present rate. Therefore considering this point this project focuses on the photovoltaic panel which utilises solar energy to produce electricity and how to attain maximum power from it.

The aim of this project is to implement various maximum power point tracking (MPPT) techniques along with various DC-DC converters on a solar photovoltaic panel. The MPPT algorithms are used to control the duty ratio of DC-DC converters on the photovoltaic system in order to get the maximum power point which changes with changing irradiance and temperature. The different algorithms used are Perturb and Observe, Incremental Conductance and Fuzzy Logic Controller with different fuzzy input variables along with different DC-DC converters namely Buck, Boost and Buck-Boost. The power output across the load is compared for all the above cases for each type of DC-DC converter.

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LIST OF SYMBOLS, ABBREVIATIONS AND NOMENCLATURE

A	Amperes
α	Duty ratio
CE	Change in error
DC	Direct current
E	Error
E_g	Band gap for silicon = 1.1eV
eV	Electron volt
f	Switching frequency in Hz
FLC	Fuzzy logic control
G	Irradiance in W/m ²
G_{ref}	Reference irradiance at STC
I	Output current of PV module
INC	Incremental conductance
I_a	Diode current
I_m/I_{mpp}	Current at maximum power
I_o	Diode saturation current
I_{oref}	Diode saturation current during STC
I_{ph}	Photocurrent produced
I_{phref}	Photocurrent produced during STC
I_{sc}	Short-circuit current
I_{scref}	Short- circuit current at STC
I_{sh}	Shunt current
I-V	Current-Voltage
k	Boltzman constant = $1.3805 \cdot 10^{-23}$ J/K
K_i	Short-circuit current temperature coefficient
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
n	Diode ideality factor
N_p	Number of cells connected in parallel
N_s	Number of cell connected in series
P&O	Perturb & Observe

P_{max}	Maximum power
P-I	Power-Current
PV	Photovoltaic
P-V	Power-Voltage
q	Electron charge
R_L	Load resistance
R_s	Series resistance
R_{sh}	Shunt resistance
S(k)	Slope of P-V curve
STC	Standard Test Condition
T_c	Module operating temperature in Kelvin
T_{ref}	Reference temperature = 298 K
μ_{sc}	Temperature coefficient of short circuit current
V	Volt
V	Output voltage of PV module
V_m/V_{mpp}	Voltage at maximum power
V_o	Output voltage of converter
V_{oc}	Open-circuit voltage
V_{ref}	Reference voltage at which PV array is to be operated
V_t	Thermal voltage
ΔI	Change in current
ΔV	Change in voltage
ΔV_o/V_o	Ripple in output voltage of converter
ΔP	Change in power before steady state
ΔS(k)	Change in the slope of P-V curve
ΔT	Difference in actual and reference PV module temperature

CHAPTER 1

INTRODUCTION

1.1 GENERAL

Energy plays an important role in our daily activities. Energy demand is increasing day by day due to increase in population, urbanization and industrialization. At present, the total energy consumption in the world is fourteen terawatts (TW) at any given moment, and this consumption is estimated to be about two times higher by 2050. To meet this demand all forms of energy need to be increased rapidly in the coming years. The use of traditional energy resources such as fossil fuels is not justifiable, due to its pollution and greenhouse gas emission. For this reason, there has been rapid development of renewable energy technologies to meet the future energy demand and creates a sustainable free pollution energy economy. [1]

The demand of inexhaustible energy has experienced a noticeable rise in recent times because of the exhaustion of exhaustible sources used for power generation and increasing awareness of its detrimental effects over the environment. This demand has been bolstered by advancement in research and innovative technology which has been introduced until now to help in the productive utilization of these inexhaustible resources and it is estimated that renewable sources might contribute about 20% – 50% to the energy consumption up to the end of the 21st century. [2]

There are two main kinds of sources for electrical power production. One of them is exhaustible and the other is inexhaustible. Today, to generate most of electrical power conventional sources like coal, gas, nuclear power are used. Some of conventional sources are polluting the environment while generating electricity. And nuclear energy is not much preferable because of its harmful radiation effect on the mankind. After a period of time, these conventional sources will not be sufficient enough to fulfil the requirements of the mankind. So the focus has shifted towards non-conventional energy sources like solar, wind, tidal, etc and some of the electrical power is being generated by them. [2, 25-28]

Renewable or non-conventional energy resources exist over wide geographical areas, in contrast to other energy sources, which are concentrated in a limited number of countries. Rapid deployment of renewable energy and technological diversification of energy sources would result in significant energy security and economic benefits. It would also reduce environmental pollution such as air pollution which is caused by burning of fossil fuels and help in improving public health, reducing premature mortalities due to pollution thereby saving associated health costs. Among the different ways of extracting energy from our nature, solar energy is one of the most prominent one due to its availability. It is estimated that the renewable energy sources are capable of supplying energy for almost another 1 billion years. According to the International Energy Agency, solar energy may produce most of the world's electricity within 50 years, thereby reducing the production of greenhouse gases that harm our environment. [1]

1.2 ENERGY IN INDIA

Energy in India implies amount of production of energy and electricity, its consumption and import in India. The data concerning advancement in the energy sector is provided as annual report by The Ministry of New and Renewable Energy . India is the fourth largest country in terms of energy consumption after China, USA and Russia. As on 31 March 2015 the installed capacity of utility power plants is 267,637 MW and the gross electricity generated by utilities including the auxiliary power consumed by the power generating stations is 1106 billion kWh. The installed capacity of captive power plants in industries is 47,082 MW and generated 166.426 billion kWh in the financial year 2014-15. In addition, there are nearly 75,000 MW aggregate capacity diesel generator sets with unit sizes between 100 KVA and 1000 KVA. Hence during the financial year 2014-15 all India per capita Electricity consumed is nearly 1010 kWh. [1]

India has one of the world's fastest growing energy markets due to its rapid economic expansion and is likely to be the second-largest contributor to the rise in global energy demand by 2035, accounting for 18% of the rise in global energy consumption. Given India's growing energy demands and limited domestic fossil fuel reserves, the country has ambitious plans to expand its renewable and most worked

out nuclear power programme. India has the world's fifth largest wind power market and also plans to add about 100,000 MW of solar power capacity by 2020. India also envisages to increase the contribution of nuclear power to overall electricity generation capacity from 4.2% to 9% within 25 years. The country has five nuclear reactors under construction (third highest in the world) and is planning to construct 18 additional nuclear reactors (second highest in the world) by 2025. [1]

The Ministry of New and Renewable Energy is responsible for the renewable energy in India. In early 1980s, first ministry of non-conventional energy resources was set up in India in the world. As of 30th April 2016, India's cumulative grid interactive or grid tied renewable energy capacity (excluding large hydro) has reached about 42.85 GW, which for the first time in Indian history has surpassed the installed capacity of hydroelectric power in India. In India the renewable power contributed by wind is 62.7%, solar contributes nearly 15.8%, 11.3% comes from biomass, 10% from small hydro plants and remaining 0.3% is contributed by waste-to-power. [1]

1.2.1 Solar Potential in India

India is a thickly populated country and has high level of solar insolation which is an ideal combination for harnessing solar power in India. India has about 300 clear, sunny days in a year and hence theoretical solar power received only on its land area, is about 5000 Petawatt-hours per year. Most of the parts of our country on an average receives about 7000 MJ/m² of global solar radiant exposure in a year. The peninsular India receives about 7200 MJ/m² in a year over its major parts while the annual highest dosage is over the Rann of Kutch which receives over 8000 MJ/m² in a year or an average daily of 22 MJ/m². The Kashmir valley receives about 16.5 MJ/m² per day, whereas it is around 15 MJ/m² over North-East India. This the general picture of the solar insolation received all over the country. Hence the daily average solar energy incident over India ranges from 4 to 7 kWh/m² with about 1500–2000 sunshine hours per year (depending upon its location), which is far more than current total energy consumption. [1]

For the large solar projects proposed in the solar energy sector a 35,000 km² area of the Thar Desert has been allocated which is sufficient to generate power ranging from 700 GW to 2,100 GW. In terms of amount of production of electricity from solar

energy per watt installed, India is ranked number one, with solar irradiance of 1,700 to 1,900 kilowatt hours per kilowatt peak (kWh/KWp). The aggregate installed grid connected solar power capacity is 7.5 GW as of 31st May, 2016 and under the Jawaharlal Nehru National Solar Mission a total of 100,000 MW is to be installed by 2022. The Jawaharlal Nehru National (JNN) Solar Mission was launched on 11th January, 2010 with an aim to achieve 20GW power from solar energy which was later increased to 100GW in 2015. Out of the 100GW, 40,000MW is to be achieved through rooftop solar projects and the remaining 60,000MW through large and medium scale solar projects. Solar projects in pipeline have already surpassed 22 GW with 13 GW under construction and 9 GW proposed. [1]

1.3 ORGANIZATION OF DISSERTATION/THESIS

This thesis consists of five chapters. Chapter first is an introduction to energy in India. It deals with the various forms of energy used for production of electricity, need for shifting from conventional to non-conventional sources and potential of solar energy in India. Chapter two includes the Review of Literature of the work done in the field of MPPT Techniques. In Chapter three modelling of photovoltaic module in MATLAB/Simulink is discussed in detail. This modelling uses the physical equation governing the Photovoltaic Module and stepwise simulation for each equation is also presented. Chapter four deals with the different types of MPPT techniques used in this thesis and how they are implemented in the system. Chapter five discusses the designing of the different DC-DC Converters namely Buck, Boost and Buck-Boost in MATLAB/Simulink in detail. Chapter six deals with the results and analysis of presented study. The comparative study of all the different MPPT methods on different DC-DC Converter is discussed. Summary and Conclusion are made in chapter seven based on the information available in the literature and the work carried in this thesis.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

In this chapter various research papers on modelling, simulation of PV system and MPPT Techniques have been discussed. Maximum power point tracking (MPPT) techniques are employed in photovoltaic (PV) systems in order to make full utilization of the PV array output power which is dependent on solar irradiation and ambient temperature. Electricity has become one the most essential needs for humans at present. Conversion of solar energy into electricity not only improves generation of electricity but also reduces pollution due to fossil fuels. The output power of solar panel is dependent upon solar irradiance, temperature and the load impedance. As the load impedance is dependent on application, a dc-dc converter is used for improving the performance of solar panel.

The solar irradiance and temperature changes with time and are not constant. Hence an online algorithm which rapidly calculates the operating point for the solar panel at every change of solar irradiance or temperature is required. This efficient conversion of solar energy is possible with Maximum Power Point Tracking (MPPT) algorithm. There are different MPPT algorithms such as Perturb and Observe, Incremental Conductance, fuzzy logic etc.

2.2 LITERATURE REVIEW

Assaf, M. et al, 2005 [17] explains that the designing of the circuit of power electronic converters with the use of closed loop scheme requires modelling and simulation of the converter using those equations. This paper deals with modelling of all the basic non-isolated power converters with the help of state equations and they are simulated in MATLAB/Simulink. Hence these models can now be easily used for any closed loop design such as PI, fuzzy, sliding mode control, etc.

Esram, T. et al. 2007 [10] studied different techniques for MPPT of PV arrays. The techniques were taken from the literature dating back to the earliest methods. It

was shown that at least 19 distinct methods have been introduced in the literature, with many variations on implementation. The comparison among different MPPT techniques was also discussed on the basis of ease of implementation, types and number of sensors required to implement MPPT. Hence it can be said that this paper serves as a convenient reference for future work in solar power generation.

Hamed, B.M. et al. 2012 [11] developed a small photovoltaic system based upon fuzzy logic control for MPPT with FPGA technology design. In order to attain peak power from photovoltaic system it requires Maximum Power Point Tracking (MPPT) controller. The developed system consists of photovoltaic module, buck converter and the fuzzy logic controller which is implemented on FPGA for monitoring on/off time of MOSFET switch of the buck converter. The proposed maximum power point tracking controller based upon fuzzy logic is verified using model designed by MATLAB/Simulink. Simulation and experimental results show that the performance of the fuzzy controller with FPGA as a MPPT of a photovoltaic array can be used in several photovoltaic products and satisfactory result can be obtained.

Ramos-Hernanz, J.A. et al. 2012 [4] explains that in order to study photovoltaic systems in an efficient manner accurate knowledge of the I-V and P-V characteristics of the photovoltaic modules is required. Hence, the aim of this paper is to design two different computer models so as to simulate the behaviour of a photovoltaic cell and represent their I-V and P-V curves. Both these models are realized in MATLAB/Simulink. In order to prove the rationality of the I-V and P-V curves obtained from the models, they are compared with those provided by the manufacturer. To examine the process and the appropriateness of the model it is necessary to have accurate knowledge of these curves. With the help of experimental and practical data of the commercial panel these models will be validated.

Salmi, T. et al. 2012 [5] mainly describes how simulation and modelling of a PV cell is done and how does a photovoltaic cell behave on variation of various parameters. The parameters included are as temperature, solar radiation, series resistors and shunt resistors. It also includes the mathematical modelling of photovoltaic cell. In order to authenticate the designed model, an experimental test

bench was built and the obtained results exhibited a good agreement with the simulation ones.

Sridhar, T. *et al.* 2012 [7] discusses about the rise in the need for renewable energy sources because of the severe energy crisis in the World today. Solar energy is still a vital unexploited resource in a tropical country like ours. This paper examines a schematic model in order to extract maximum obtainable solar power by means of the idea of Maximum Power Point Tracking (MPPT) which considerably increases the efficiency of the solar photovoltaic system. A maximum power point tracker (MPPT) is a system that guides the converter to track the maximum power of a solar panel and supply it to load. This paper focuses on designing of a boost converter for photovoltaic system using microcontroller. As the insolation and temperature levels change frequently, the solar panel voltage fluctuates and becomes irregular. The converter is designed to step up solar panel voltage and produce a stable 24V output without any storage elements such as battery. Boost converter output is constantly tracked and calculated and the values are sent to the microcontroller unit to generate pulse-width-modulation (PWM) signal. These signals are used to regulate the duty cycle of the boost converter.

El-Moghany, M.S. *et al.* 2013 [12] developed two fuzzy logic controllers based upon modern FPGA card in order to raise the energy generation efficiency of solar cells. These controllers track the position of the sun and maximum power point. Sun tracking producing power system is designed and employed in real time. A tracking mechanism consists of photovoltaic module, stepper motor, sensors, input/output interface and expert FLC controller realized on FPGA so as to track the sun and keep the position of solar cells in the direction of sun for most of the time. The proposed sun tracking controller and MPPT controller are verified using MATLAB/Simulink. The results show that both controllers have a superior response as compared to the conventional controller when applied on the same system.

Kotak, V.C. *et al.* 2013 [15] explains that the DC-DC converters are extensively used in photovoltaic generating systems where they act as an interface between the photovoltaic panel and the load, thereby permitting the follow-up of the maximum power point (MPP). The paper describes that in order to extract maximum power, the load should be adjusted so as to match the current and voltage of the solar panel. The

converter must be developed in such a way that it connects directly to the photovoltaic panel and performs the process to hunt the maximum power point (MPPT). DC-DC converters are used along with maximum power point tracking systems (MPPT) in order to prevent losses.

Mahapatro, S.K. 2013 [20] developed a buck-boost converter in order to control of photovoltaic power using Maximum Power Point Tracking (MPPT) control mechanism. Initially the photovoltaic module is scrutinised using MATLAB/Simulink software. The main purpose of the paper is to use the buck-boost converter together with a MPPT control mechanism. The chief target will be to track the maximum power point of the photovoltaic module so as to extract the highest possible power from the photovoltaic deliver it to the load via buck-boost converter which increases or decreases it as required.

Bellia, H. et al. 2014 [6] presented a work on detailed modelling and simulation of the PV cell and module. It was implemented under MATLAB/Simulink environment. Modelling of the photovoltaic module, essentially requires taking weather data (solar insolation and temperature) as input variables. The output may be current, voltage or power. Hence, in this paper photovoltaic module parameters have been selected according to their variation with illumination and temperature. This model can be considered as a tool which can be used to study all types of PV modules available in markets, especially their behaviours under different weather data of standard test conditions (STC).

Gowda, M. et al. 2014 [18] developed a mathematical model of a Buck Converter and simulated it using MATLAB/Simulink without any Sim Power System. This paper also explain how Matlab's Tuning tools are used in order to attain better rise time, settling time and peak overshoot.

Kumar, A. 2014 [3] describes the various features of passive solar building design concept and design elements for residential buildings for temperate climate. Solar energy, together with secondary solar-powered resources such as wind and wave power, hydroelectricity and biomass accounts to maximum of the accessible renewable energy on earth. Solar technologies can be broadly classified as either passive or active depending upon the way they are captured, converted and distribute sunlight.

Kolsi, S. et al. 2014 [16] discusses the effect of climatic conditions on designing of the two main components (inductance, capacitance) for the three topologies of DC-DC converters which are usually used in photovoltaic systems. As climatic conditions varies, the margin of inductance and capacitance parameters of DC-DC converter will vary. These two parameters should be correctly sized in order to attain optimal efficiency for each converter. The design optimization is grounded on two principles: 1) for a steady-state operation in a continuous conduction mode, the value of inductor for all choppers should be more than the highest value of boundary inductance, and 2) to bound the output voltage ripple of DC-DC converter below a preferred value, the value of filter capacitance must be greater than the highest value of boundary capacitance.

Ojha, A.K. et al. 2014 [1] discusses about solar energy and economic development in India. It gives an outline of global solar energy, Indian solar energy, potential of solar energy and economic development in the field of solar energy. The paper emphasises on the importance and need of shifting our focus from conventional sources of energy to renewable sources of energy. Being a tropical country, India receives solar energy in large amount which can be easily harnessed to produce electricity. In fact some large scale solar projects are already proposed in the Thar Desert region. The paper brings to our attention the installed capacity of India, various operational solar projects and parks in India and how much more solar energy can be harnessed. It also discusses about the solar projects in other countries of the world such as Germany, California, Spain, China, etc. Moreover the effect of development in the field of solar energy on social and economic development of a country is also discussed in detail.

Sholapur, S. et al. 2014 [19] developed a boost converter in order to control of photovoltaic power using Maximum Power Point Tracking (MPPT) control mechanism. Initially the photovoltaic module is scrutinised using MATLAB/Simulink software. The main purpose of the paper is to use the boost converter together with a MPPT control mechanism. The chief target will be to track the maximum power point of the photovoltaic module so as to extract the highest possible power from the photovoltaic. In this paper the algorithm employed for MPPT is perturb and observe which is easy to model or use as a code. The MPPT algorithm is written in m file of MATLAB and operated in simulation. Both the

boost converter and the solar cell are modelled using SimPower Systems blocks.

Kumar, M. *et al.* 2015 [13] compared two intelligent control methods in order to optimize the efficiency of the solar photovoltaic system that are incremental conductance algorithm and fuzzy Logic controller algorithm which are further applied to a DC-DC Boost converter. The Boost converter raises the output voltage, depending upon its duty cycle. The proposed controllers are regulating the duty cycle of the DC-DC converter switch in order to attain the maximum power for a solar photovoltaic array. Lastly the performance of Incremental conductance and Fuzzy logic controller method are compared which show that the fuzzy logic controller are more effective as they produce less fluctuations and fast response when weather condition varies. Hence it can be concluded that the fuzzy logic controller displays a superior performance as compared to Incremental conductance.

Ranjan, K. *et al.* 2015 [2] describes the modelling and analysis of a photovoltaic cell and the effect of variation of different parameters using MATLAB/Simulink. The model is prepared on the basis of the mathematical equations and is represented with the help of an equivalent circuit which includes a photocurrent source, a diode, a series resistor and a shunt resistor. The model so developed helps in predicting the behaviour of photovoltaic cell when physical and environmental parameters are varied. The parameters that are varied in this paper are temperature, solar radiation, series resistor and shunt resistor. In addition to this, the paper also aims at forming the PV panel through the series and parallel combination of the photovoltaic cells.

Ravi, N. *et al.* 2015 [8] presented a comparative analysis of the available algorithms used to implement MPPT. It is seen that there is an increase in global energy demand every day and the most appropriate source of energy is renewable energy. Among all the available renewable sources solar energy is in most abundance. Electricity is generated from solar energy through photovoltaic system. The photovoltaic systems show non-linear characteristics and their energy conversion efficiency is very low. This paper discusses the non-linearity of these systems in detail. Hence Maximum Power Point Tracking (MPPT) is used in order to increment the efficiency of the system. It is used to guarantee that maximum available energy is extracted under fluctuating environmental conditions such as solar irradiation, temperature, load, etc.

Shiau, J. et al, 2015 [14] explored the design of fuzzy-logic-based MPPT algorithms using various fuzzy input variables. The paper explains six fuzzy MPPT algorithms, based on various input variables, viz. (i) slope (of solar power-*versus*-solar voltage) and changes in the slope; (ii) slope and variation in the power; (iii) variation in power and variation in voltage; (iv) variation in power and variation in current; (v) sum of conductance and increment in the conductance; and (vi) sum of angles of arctangent of the conductance and arctangent of increment in the conductance. The first four algorithms need two input variables each while last two algorithms need a single input variable. The fuzzy logic based MPPT is arranged using a buck-boost power converter. This paper explains the computation, consideration of the fuzzy rules, as well as benefits and drawbacks of each MPPT algorithm based upon photovoltaic cell properties in detail. Computer simulations are conducted in order to prove the designs in MATLAB/Simulink.

Joshi, S.K. et al. 2016 [9] presents an outline of the various types of MPPT techniques. The perturb and observe(P&O) or hill climbing , incremental conductance, fractional open circuit voltage, fractional open circuit current and neural network techniques of MPPT are extensively used techniques. Hence this paper estimates the performance of these methods from a dynamic and steady state viewpoint. Maximum power point tracking(MPPT) is a practice that grid connected inverters, solar battery chargers and similar devices use in order to get the maximum possible power from one or more photovoltaic devices.

CHAPTER 3

MODELLING OF PV SYSTEM

3.1 INTRODUCTION

The energy obtained from the sun in the form of heat and light is called solar energy. This energy has been harnessed by human beings since ancient times using a range of ever-evolving technologies. The technologies utilising solar energy are solar heating, solar photovoltaic, solar thermal electricity, solar architecture and artificial photosynthesis. These technologies can make considerable contributions to solve some of the most crucial energy problems that the world is facing. [3]

Solar technologies can be classified as passive solar and active solar depending upon the way they capture, convert and distribute solar energy. The active solar techniques include the use of photovoltaic panels and solar thermal collectors to harness the energy. The passive solar techniques include orienting a building to the Sun, selecting materials with favourable thermal mass or light dispersing properties, and designing spaces that naturally circulate air. [3]

The electrical device which converts the solar energy directly into electricity using photovoltaic effect is known as a solar cell or photovoltaic cell. The word “photovoltaic” consists of two words- photo which means “light” and voltaic which means “Voltage”. It is a form of cell in which its electrical characteristics i.e. current, voltage, or resistance change when light is incident upon it. These cells when exposed to light can produce an electric current without being connected to any voltage source externally. The voltage produced by a single photovoltaic cell is very small approximately 0.6 to 0.8. In order to get higher voltage a number of solar cells are interconnected and such an interconnection is called solar or photovoltaic module. When many such modules are interconnected, solar panel or array is obtained. [2]

3.2 WORKING PRINCIPLE

Photovoltaic cells are used to convert sunlight directly into electricity. They are primarily made up of a PN junction diode. A p-n junction is an interface which is formed when two types of semiconductor material, i.e. p-type and n-type, are joined together inside a single crystal of semiconductor. The photovoltaic cell works in three steps:

1. When the photons in sunlight hit the solar cell they are absorbed by semiconducting materials, such as silicon.
2. Electrons are knocked out from their atoms thereby developing an electric potential difference. This free electron moves through an external circuit towards the positive layer causing an electric current to flow from the positive layer to the negative layer. The electrons are allowed to move in only one direction because of their special composition.
3. Hence an array of solar cells is used to convert solar energy into a useable amount of direct current (DC) electricity. [2, 25-28]

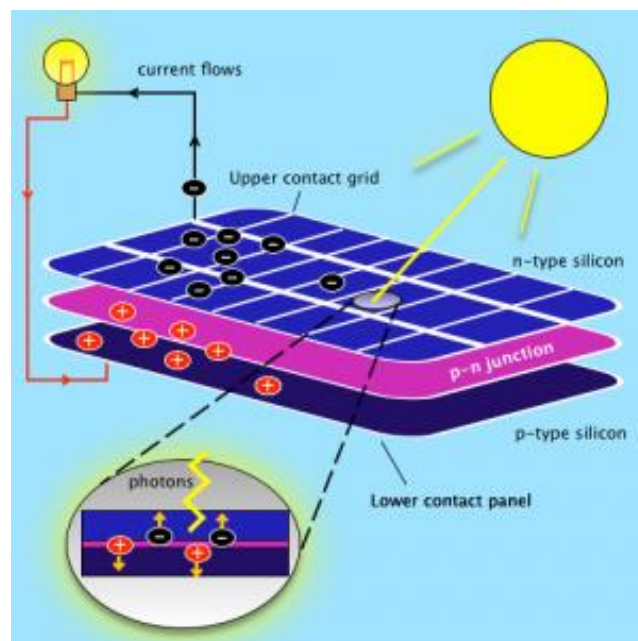


Figure 3.1: Photocurrent generation principle

The figure 3.1 above shows the generation of photocurrent in a photovoltaic cell when it is exposed to sunlight. When a photon hits a piece of silicon, one of the three things can happen:

1. The photon can pass through the silicon which generally happens when photons have low energy,
2. The photon is reflected by the surface,
3. The photon is absorbed by the silicon which happens when the photon energy is higher than the silicon band gap value. This produces an electron-hole pair or heat, depending on the band structure.

When a photon is absorbed, its energy is taken by the electron in the crystal lattice. Usually this electron is in the valence band tightly bounded in covalent bonds with its neighbouring atoms and hence is unable to move. The energy taken by it from the photon energizes it into the conduction band, where it becomes free to move around within the semiconductor. The covalent bond of which the electron was previously a part of now has one less electron which is known as a hole. The presence of this hole allows the bonded electrons of neighbouring atoms to move into it thereby leaving another hole behind, and in this way a hole moves along the lattice. Hence, it can be seen that photons absorbed by the semiconductor create mobile electron-hole pairs which causes conductivity and results in formation of electricity. [2, 25-28]

3.3 EQUIVALENT CIRCUIT DIAGRAM

The Photovoltaic cell can be interpreted as an electrical circuit as shown in figure 3.2 below.

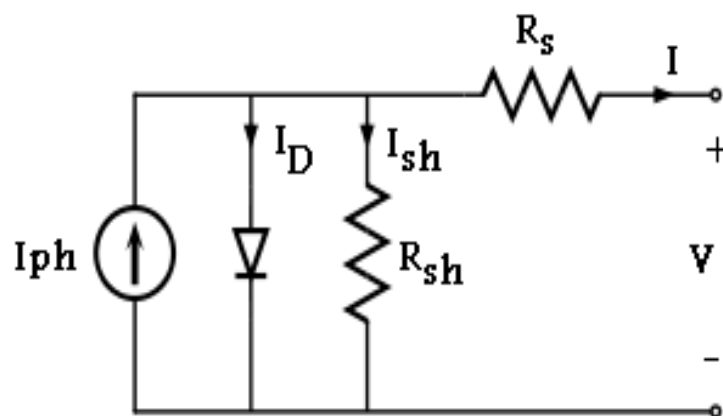


Figure 3.2: Equivalent Circuit Diagram

The PV cell is equivalent to a direct current source (I_{ph}), a diode, a series resistor (R_s) and a shunt resistor (R_{sh}). I_{ph} represents the current produced by the cell when it is exposed to the sun. Ideally the losses should be zero but practically it is not possible.

In order to consider these internal losses of the cell we connect a resistor in series and in shunt to the parallel combination of the current source, I_{ph} , and the diode. For an ideal cell the value of the shunt resistance is infinite and that of series resistance is zero. Hence in order to take into account the reduction in the efficiency of the cell due to dissipation of power across internal resistances the shunt resistor is not infinite and series resistor is non-zero. The schematic symbol of a photovoltaic cell is as shown in the figure 3.3 below [5]:

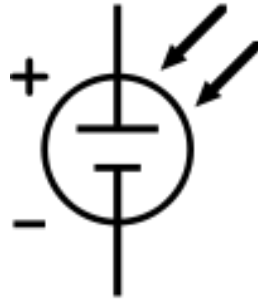


Figure 3.3 : Schematic symbol of a PV cell

3.4 MATHEMATICAL MODELLING

From the equivalent circuit it is evident that the current produced by the solar cell is equal to that produced by the current source, minus that which flows through the diode, minus that which flows through the shunt resistor [4, 24]:

$$I = I_{ph} - I_d - I_{sh} \quad (3.1)$$

Where,

I = output current (ampere)

I_{ph} = photocurrent produced (ampere)

I_d = diode current (ampere)

I_{sh} = shunt current (ampere).

By the Shockley diode equation, the current diverted through the diode is determined from the equation [4]:

$$I_d = I_o \left[\exp\left(\frac{V + I \cdot R_s}{a}\right) - 1 \right] \quad (3.2)$$

Where,

$$a = (N_s \cdot k \cdot n \cdot T_c) / q$$

$$V_t = kT/q$$

I_d = Diode current (ampere)

I_o = reverse saturation current (ampere)

V = output voltage (volt)

n = diode ideality factor

q = elementary charge = 1.6×10^{-19} C

k = Boltzmann's constant = 1.381×10^{-3} J/K

T_c = actual temperature ($^{\circ}$ K)

V_t = thermal voltage because of its exclusive dependence on temperature

R_s = series resistance (Ω).

N_s = no. of cells connected in series

$$I_{sh} = V + I * R_s / R_{sh} \quad (3.3)$$

Where,

R_{sh} = shunt resistance (Ω).

Substituting the above equations 3.2 and 3.3 into the first equation 3.1 gives the characteristic equation of a photovoltaic cell, which relates photovoltaic cell parameters to the output current and voltage as [4, 24]:

$$I = I_{ph} - I_o \left(\exp \left(\frac{V + I * R_s}{a} \right) - 1 \right) - \frac{V + I * R_s}{R_{sh}} \quad (3.4)$$

3.5 SIMULATION OF PV MODULE

The Solar Photovoltaic Module chosen to be simulated in MATLAB/Simulink is Vikram Solar Model: Eldora 40. It consists of 36 cells which are connected in series to produce a total power of 40 watt at normalized irradiance. The electrical characteristics of the solar photovoltaic module at 25° C and $1000\text{W}/\text{m}^2$ is as given in the Table 3.1 below.

CHARACTERISTICS	VALUES
Maximum Power (Pmax)	40W
Voltage at Maximum Power (Vm)	17.40V
Current at Maximum Power (Im)	2.30A
Open Circuit Voltage (Voc)	22.25V
Short Circuit Current (Isc)	2.53A
No. of cells in Series (Ns)	36
No. of cells in Parallel (Np)	1

Table 3.1: Electrical Characteristics of PV Module

The figure 3.4 shows the Simulink model for the above described solar photovoltaic module. It is obtained through the mathematical equations discussed in section 3.4. There are two inputs to the solar photovoltaic module i.e. temperature and irradiance.

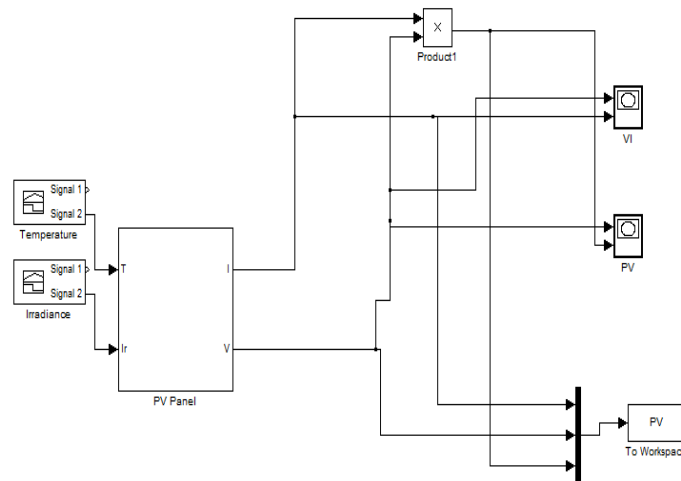


Figure 3.4: Simulation model of PV module

In order to simulate the photovoltaic module all the parameters mentioned in the equation 3.4 has to be calculated. The calculations of these parameters are discussed below:

3.5.1 Determination of I_{ph}

According to the equivalent circuit diagram as shown earlier in figure 3.2, the output current during standard test conditions (STC) is as follows [6, 28-29]:

$$I = I_{phref} - I_{oref} \left[\exp \left(\frac{V}{a_{ref}} \right) - 1 \right] \quad (3.5)$$

This equation allows computation of I_{phref} which is not possible otherwise but when PV module is short circuited, the equation becomes [6, 28-29]:

$$I_{scref} = I_{phref} - I_{oref} \left[\exp \left(\frac{0}{a_{ref}} \right) - 1 \right] \quad (3.6)$$

$$\text{Therefore, } I_{scref} \approx I_{phref} \quad (3.7)$$

The above relation is true for ideal case. So it is assumed that I_{phref} is approximately equal to I_{scref} . The photocurrent is dependent upon both the solar irradiance and temperature and is expressed as [6, 28-29]:

$$I_{ph} = \frac{G}{G_{ref}} (I_{phref} + \mu_{sc} * \Delta T) \quad (3.8)$$

Where,

G = Irradiance (w/m^2)

G_{ref} = Irradiance at STC=1000 w/m^2

ΔT = $T_c - T_{ref}$ (kelvin)

T_c = actual cell temperature (kelvin)

T_{ref} = cell temperature at STC = 25+273 K

μ_{sc} = temperature coefficient of short circuit current (A/K)

I_{phref} = photocurrent at STC (ampere)

The figure 3.5 below shows the simulation of photocurrent, I_{ph} , in MATLAB/Simulink.

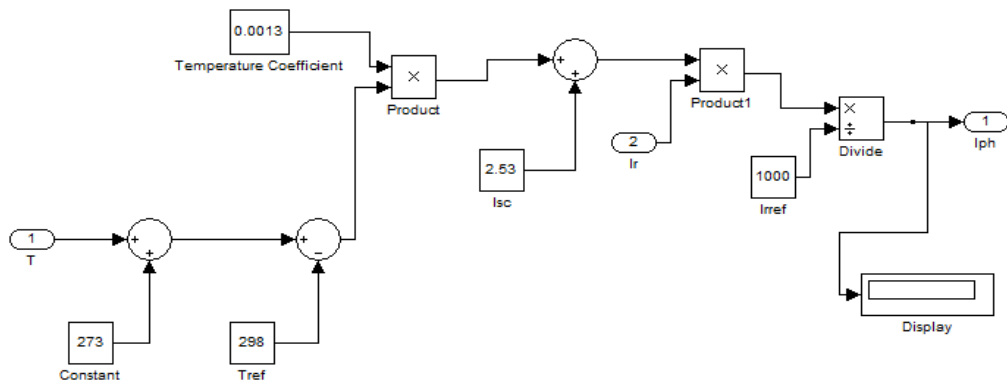


Figure 3.5: Simulation of I_{ph}

3.5.2 Determination of I_o

The value of diode reverse saturation current I_o is calculated by the following given equation [6, 28-29]:

$$I_o = I_{oref} \left(\frac{T_c}{T_{cref}} \right)^3 \exp \left[\left(\frac{q \cdot E_g}{A \cdot k} \right) \left(\frac{1}{T_{cref}} - \frac{1}{T_c} \right) \right] \quad (3.9)$$

The figure 3.6 below shows the simulation of diode saturation current, I_o, in MATLAB/Simulink.

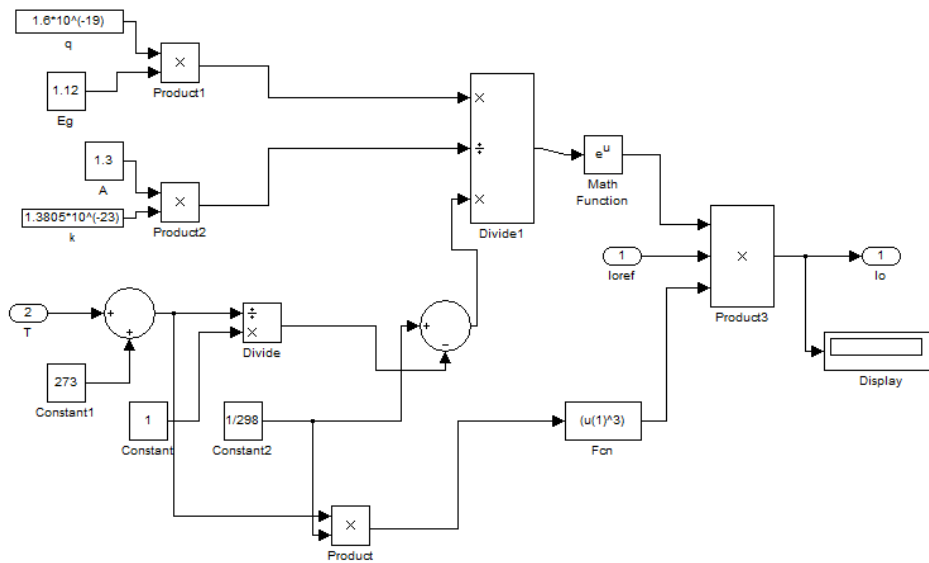


Figure 3.6: Simulation of I_o

3.5.3 Determination of I_{oref}

The value of the diode saturation current during standard test conditions (STC) is calculated by the following equation [6, 28-29]:

$$I_{scrf} = I_{oref} \left[\exp \left(\frac{V_{oc}}{a_{ref}} \right) - 1 \right] \quad (3.10)$$

The figure 3.7 shows the simulation of the diode saturation current during standard test conditions (STC), I_{oref}, in MATLAB/Simulink.

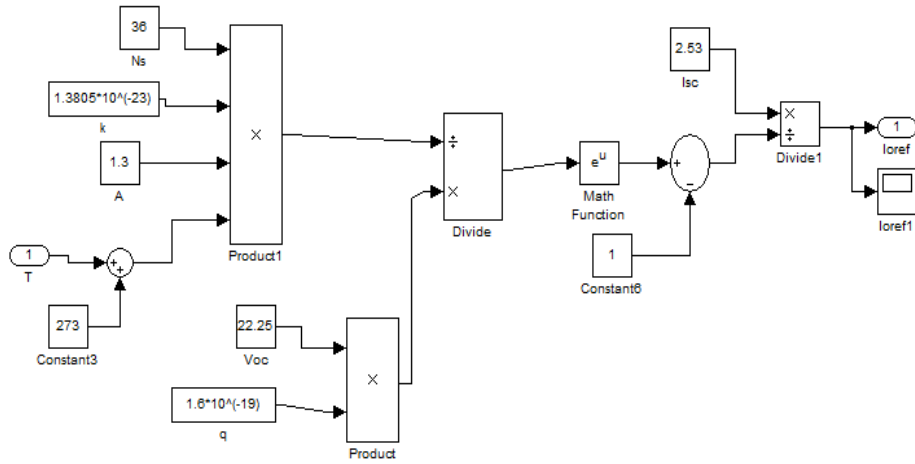


Figure 3.7: Simulation of Ioref

3.5.4 Determination of I

The figure 3.8 below shows the simulation of output current, I, in MATLAB/Simulink.

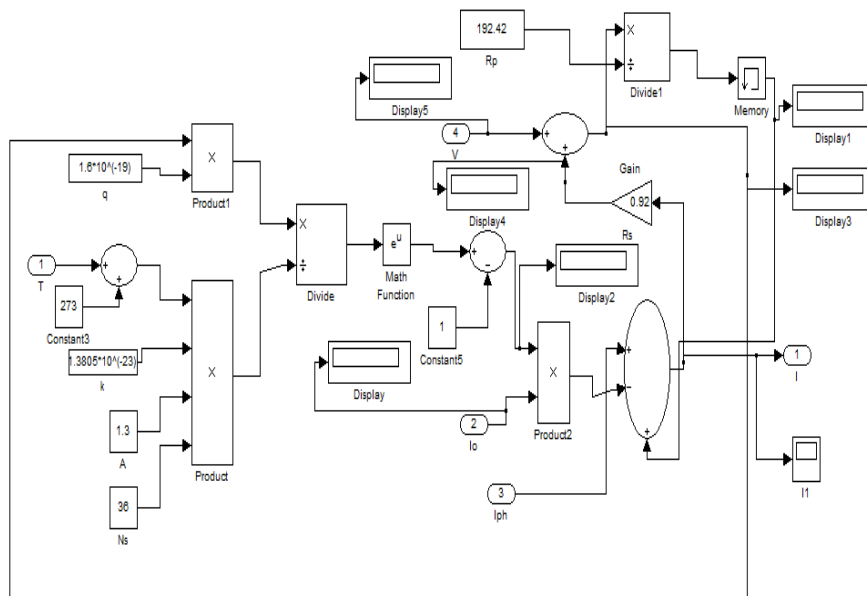


Figure 3.8: Simulation of I

CHAPTER 4

MAXIMUM POWER POINT TRACKING

4.1 INTRODUCTION

Maximum Power Point Tracking, also known as MPPT, is an electronic system that directs the Photovoltaic (PV) modules to work in such a manner that the modules produce all the power that they can. MPPT is not a mechanized tracking system that manually moves the modules in order to make them face the direction of the sun. MPPT is a fully automatic system that changes the electrical operating point of the modules so that the modules deliver maximum obtainable power at that irradiance and temperature. Additional power obtained from the modules becomes available in the form of increased battery charge current. MPPT can be used in combination with a mechanized tracking system, but the two systems are completely dissimilar [7].

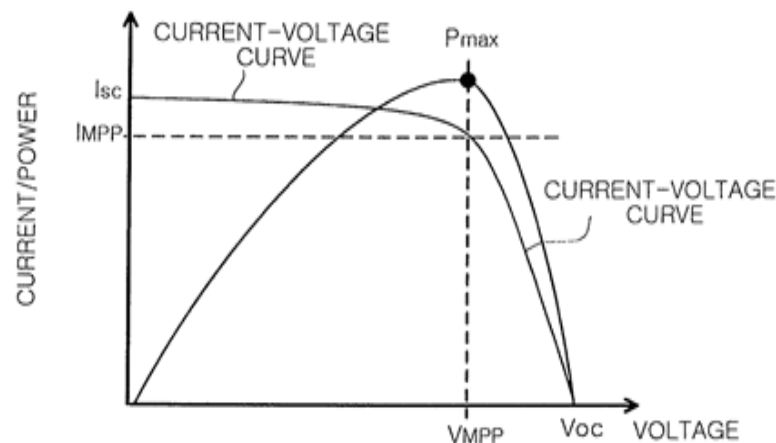


Figure 4.1: Power-Voltage and Current-Voltage Curve

The output current from the photovoltaic panels changes depending upon the condition of the load. Figure 4.1 above shows current (I)-voltage (V) and power (P)-voltage (V) characteristics of a photovoltaic panel respectively. Over a wide range of current and voltage, it is necessary to find a point where the output power is maximum. The power is determined by multiplying voltage and current. The point where the power maximizes allows the users to extract utmost power that the PV module can produce. For a specific value of irradiance and temperature there is only one single point. This point is called the Maximum Power Point (MPP) and determining this point is called Maximum

Power Point Tracking (MPPT) [7].

4.2 NEED OF MPPT

The power obtained at the output of a solar module varies as the direction of sun changes or solar irradiance changes or operating temperature varies. From the P-V curve of the module it can be seen that there is only one single maximum power point at a specific irradiance or temperature. It is known that the efficiency of the photovoltaic module is low. A typical solar panel transforms only 30 to 40 percent of the solar irradiation falling over it into electrical energy. In order to boost the efficiency of the solar panel maximum power tracking techniques are used. As the efficiency of the module is less, it is preferred to operate the module at its peak power point so as to deliver maximum power to the load for changing temperature and solar insolation conditions. Hence maximization of power helps in improving the utilization of the solar photovoltaic module. A maximum power point tracker (MPPT) is used for deriving maximum power from the solar photovoltaic module and delivering that power to the load [8, 21].

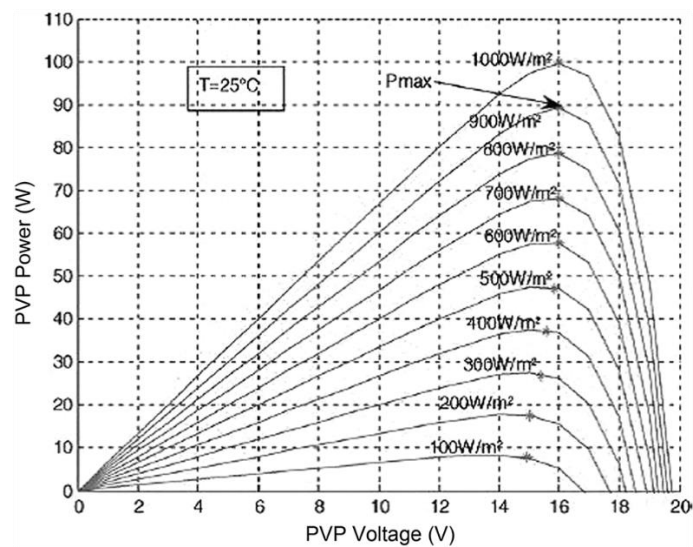


Figure 4.2: P-V curve for varying irradiance

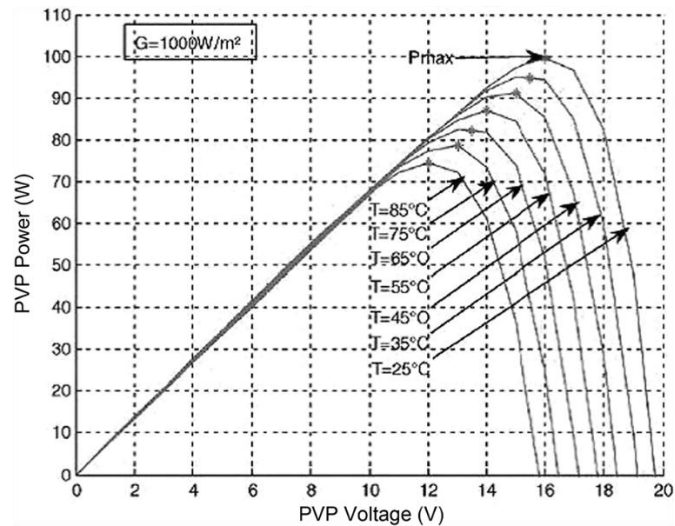


Figure 4.3: P-V curve for varying temperature

Figure 4.2 and 4.3 above shows different P-V characteristics of a certain solar panel at different irradiances and temperature respectively. The circles on the graph represent the single MPP on every characteristic curve. Since the characteristic of P-V curve is regularly changing as the irradiance and temperature changes, the MPP has to be determined at every changed moment in order to get maximum output power from the solar panel. Hence a photovoltaic system requires both a good tracking speed and accuracy. The performance of MPPT can be considered as an essential element for increasing the generation revenue [8].

The solar irradiation has sudden variations throughout the day. Under such conditions, the MPP of the photovoltaic array keeps changing regularly. Hence the photovoltaic system's operating point should be changed regularly in order to maximize the produced power. Therefore it can be said that an MPPT technique is required to maintain the operating point of photovoltaic array at its MPP.

There are several MPPT methods used and the most widely-used techniques are as follows:

- 1) Fractional open circuit voltage
- 2) Fractional short circuit current
- 3) Perturb and observe
- 4) Incremental Conductance method
- 5) Fuzzy logic
- 6) Neural Network

4.3 TYPES OF MPPT TECHNIQUES

As discussed in the previous section there are several methods of implementing MPPT techniques in a photovoltaic system. The MPPT methods used in this thesis are explained in detail as follows:

4.3.1 Perturb and Observe Method

In Perturb and Observe technique of maximum power point tracking, the operational voltage or current of the solar photovoltaic module is perturbed. By observing the power which is calculated by multiplying the voltage and current, the direction in which further changes in the voltage or current has to be made is decided. The direction of changing the voltage or current is kept same if the calculated power increases with perturbation until the power begins to fall [8-10].

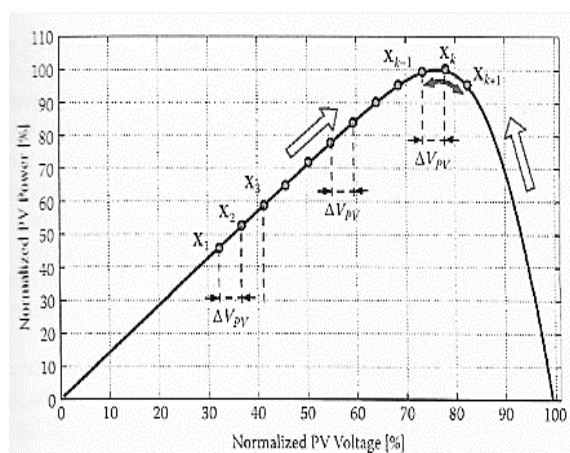


Figure 4.4: Perturb and Observe Algorithm

From the figure 4.4 shown above it can be seen that when operating on the left side of the maximum power point, on increasing the voltage the power increases while when operating on the right side it decreases the power. Similarly, when operating on the left side of maximum power point on decreasing the voltage the power decreases while when operating on the right side it increases the power. Hence, the successive perturbation is kept in the same direction if an increase in the power is there in order to reach the maximum power point but if there is a decrease in the power, the next perturbation should be reversed [8-10].

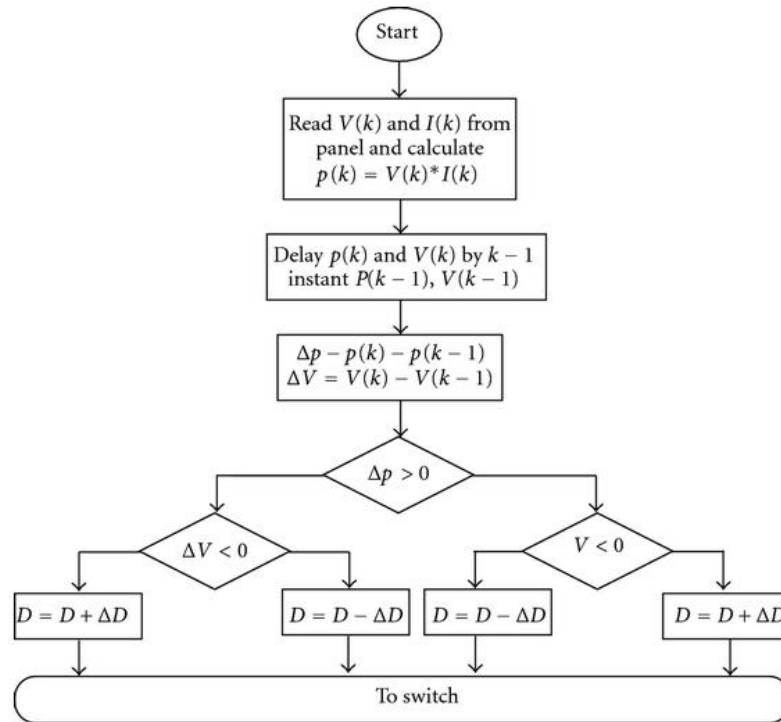


Figure 4.5: P&O Algorithm Flowchart

The figure 4.5 above shows the flowchart for the Perturb and Observe algorithm. The inputs to the algorithm are voltage and current of the solar photovoltaic module. As seen from the flowchart the instantaneous voltage, $V(k)$, and current, $I(k)$, are measured by the algorithm and the instantaneous power, $P(k)$, is calculated by multiplying them. The calculated power is then compared with the last calculated power, $P(k-1)$. The system is constantly perturbed by the algorithm if the variation in operational point is positive, or else the direction of perturbation is swapped. It can be seen from the flowchart that if both the change in power and change in voltage is positive or negative then the duty cycle is reduced by a factor of ΔD in order to produce the successive cycle of perturbation and to force the operational point to move towards the maximum power point. Similarly, if the change in the voltage is positive and the change in power is negative or vice-versa then the duty cycle is increased by a factor of ΔD for the next cycle of perturbation. The advantages of the Perturb and Observe algorithm are simple structure, easy implementation and less required parameters [21-22].

The figure 4.6 below shows the simulation diagram for the Perturb and Observe algorithm in MATLAB/Simulink. It can be seen that the model requires two inputs

that are voltage and current of the solar photovoltaic module and the output is duty cycle which is given to the gate of the converter. The factor ΔD by which the duty cycle is increased or decreased as required is taken as 0.001.

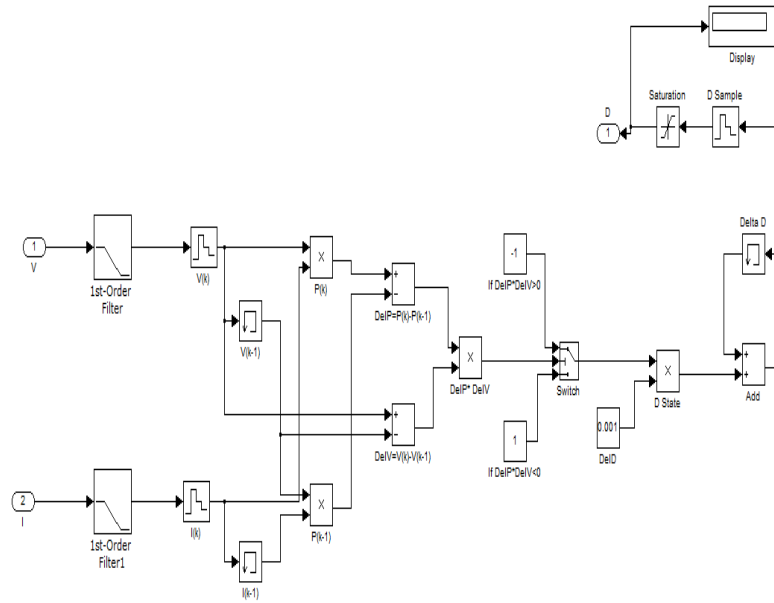


Figure 4.6: Simulation of P&O algorithm

4.3.2 Incremental Conductance Method

The Incremental conductance technique of maximum power point tracking is based upon the criteria that derivative of the photovoltaic module power with respect to voltage is zero at MPP, positive if on left side of MPP and negative if on the right side of MPP. This method depends on the sign of dP/dV without any perturbation which overpowers the shortcomings of P&O technique. The basic mathematical equations which govern this technique are as follows [9-10]:

$$\begin{aligned} \frac{dP}{dV} &= 0 \dots\dots\dots \text{at MPP} \\ \frac{dP}{dV} &> 0 \dots\dots\dots \text{when at left side of MPP} \\ \frac{dP}{dV} &< 0 \dots\dots\dots \text{when at right side of MPP} \end{aligned} \quad (4.1)$$

Now,

$$\frac{dP}{dV} = \frac{d(IV)}{dV} = I + V \frac{dI}{dV} \cong I + V \frac{\Delta I}{\Delta V} \quad (4.2)$$

Now for MPP $\frac{dP}{dV} = 0$. Putting this in equation 4.2 we get,

$$I + V \frac{\Delta I}{\Delta V} = 0$$

This implies,

$$\begin{aligned} \frac{\Delta I}{\Delta V} &= -\frac{I}{V} \dots\dots\dots \text{at MPP} \\ \frac{\Delta I}{\Delta V} &> -\frac{I}{V} \dots\dots\dots \text{when at left side of MPP} \\ \frac{\Delta I}{\Delta V} &< -\frac{I}{V} \dots\dots\dots \text{when at right side of MPP} \end{aligned} \quad (4.3)$$

Where,

$\frac{\Delta I}{\Delta V}$ is incremental conductance

$\frac{I}{V}$ is instantaneous conductance

From the above equations 4.1, 4.2 and 4.3 it can be seen that the maximum power point for a photovoltaic module can be determined by comparing the value of incremental conductance with instantaneous conductance. This can also be seen through a flowchart as shown in the figure 4.7 below.

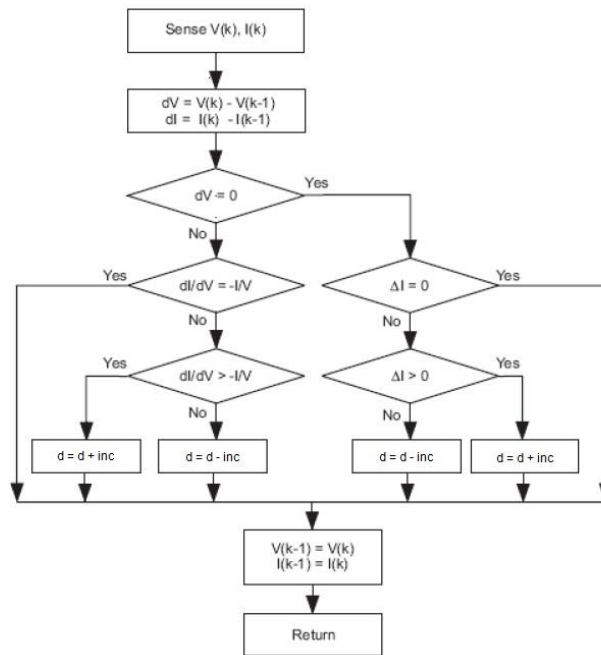


Figure 4.7: Flowchart of INC algorithm

The drawback of perturb and observe algorithm is that it is unable to track the peak power point when atmospheric condition is changing rapidly. This has been overcome by INC method. In INC method when the MPPT reaches the MPP it stops changing the operating point. But if the MPP is not reached, then the direction in which the MPPT operating point should be changed is computed using the relationship between the value of incremental conductance and instantaneous

conductance. This correlation is based on the fact that dP/dV is negative when the MPPT is on the right side of the MPP and positive when it is on the left side of the MPP. The advantage of INC algorithm over P&O algorithm is that it can calculate when the MPPT reaches the MPP while P&O algorithm fluctuates about the MPP. Moreover, INC can trace speedily increasing and decreasing solar irradiance conditions more accurately as compared to perturb and observe algorithm. The INC algorithm has one disadvantage of increased complexity as compared to P&O algorithm [9-10].

The figure 4.8 below shows the simulation diagram for the Incremental Conductance algorithm in MATLAB/Simulink. It can be seen that the model requires two inputs that are voltage and current of the solar photovoltaic module and the output is duty cycle which is given to the gate of the converter. The factor ΔD by which the duty cycle is increased or decreased as required is taken as 0.001.

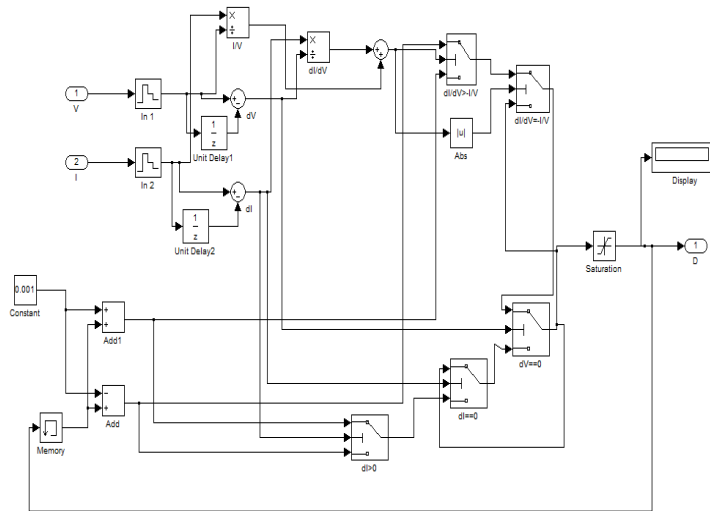


Figure 4.8: Simulation of INC algorithm

4.3.3 Fuzzy Logic Control (FLC)

The use of artificial intelligence in MPPT is the new development in the field of research. One of the artificial technique that can be used in MPPT is Fuzzy Logic Control. A conventional FLC used in MPPT has two inputs such as error, E , and change in error, CE , while the output is the duty cycle, D . The basic approach of fuzzy logic is that it uses linguistic variable which means a variable which uses words as values instead of numbers (like *small* and *large*) [23]. It is way to look at vagueness in a mathematical manner. The main aim of FLC is to make computers think as human

beings and to make computing with words possible. Fuzzy logic uses fuzzy sets which relate categories of objects with vaguely defined boundaries of which its membership is a matter of degree. The figure 4.9 below shows the block diagram of FLC. It can be seen that FLC is divided into four sections namely fuzzification, fuzzy inference, rule-base and defuzzification [11-12, 24].

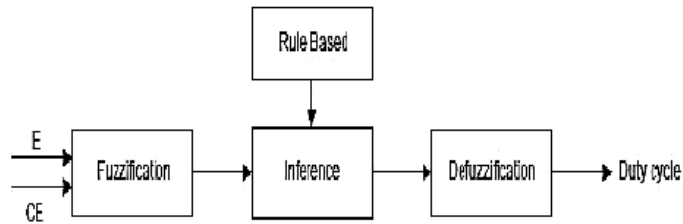


Figure 4.9: Block Diagram of FLC

Fuzzification is the first step in which the numerical values of input variables are transformed into linguistic variables depending upon the already decided membership functions. Numerous fuzzy levels can be used as input and output variables. For MPPT control to operate in a photovoltaic system, after error and change in error are calculated, they are transformed into linguistic variables then output is produced depending upon the rule base table. The rule base is a collection of rules formed on the basis of the linguistic variables. They are of the form ‘If X and Y then Z’. According to these rules the FLC tracks the MPP. Next step is the fuzzy inference engine. The fuzzy inference engine is used for formulating the mapping of a number of inputs to a single output using fuzzy logic. There are several methods for inference but the most popular one is Mamdani. Other techniques include Sugeno inference method, compositional rule of inference and generalized Modus Ponens. The fuzzy output obtained from fuzzy inference engine is transformed back to a mathematical variable from linguistic variable during defuzzification. The most common method used for defuzzification is the Centroid of Area (COA) as it generates accurate results and has good averaging properties. Other defuzzification methods include bisector and middle of maxima [13, 23-24].

In this thesis the focus is on designing of solar power MPPT algorithms with different fuzzy input variables. Special emphases is on the considerations for formulating desired fuzzy rules for various fuzzy input variables. Five fuzzy MPPT algorithms having different input variables are considered in the study which are (i)

P-V slope and changes in the slope; (ii) P-V slope and change in the output power; (iii) change in output power and change in voltage; (iv) change in output power and change in current; (v) sum of conductance and incremental conductance. The first four algorithms used have two input variables each whereas the last algorithm used has a single input variable. The five algorithms mentioned above are discussed in detail as:

4.3.3.1 P-V Slope and change in Slope as inputs

In this algorithm of the fuzzy logic MPPT system the fuzzy input variables taken are the slope of the Power-Voltage (P-V) curve of photovoltaic module ($S(k)$) and the variation in the slope ($\Delta S(k)$). The variables taken can be defined as [14, 30-37]:

$$\mathbf{S(k)} = \frac{\Delta P}{\Delta V} = \frac{I(k)*V(k)-I(k-1)*V(k-1)}{V(k)-V(k-1)} \quad (4.4)$$

$$\Delta \mathbf{S(k)} = \mathbf{S(k)} - \mathbf{S(k - 1)} \quad (4.5)$$

Fuzzy Rule		$S(k)$				
		NB	NS	ZE	PS	PB
$\Delta S(k)$	NB	ZE	PB	PS	ZE	NB
	NS	PB	PS	ZE	ZE	NB
	ZE	PB	PS	ZE	NS	NB
	PS	PB	ZE	ZE	NS	NB
	PB	PB	ZE	NS	NB	ZE

Region 1 **Region 2** **Region 3**

Table 4.1: Fuzzy Rules when $S(k)$ and $\Delta S(k)$ are inputs

The table 4.1 above the set of fuzzy rules designed for this algorithm depending the fuzzy input variables used. A five-term fuzzy set namely negative big (NB), negative small (NS), zero (ZE), positive small (PS) and positive big (PB) is used to represent each linguistic variable. Output of the fuzzy controller (which is change in duty ratio of the dc-dc converter) will alter the output voltage and current of the photovoltaic module. When the output of photovoltaic module alters, it influences the values of the fuzzy input variables of the successive cycle. The output commands are re-adjusted by the controller accordingly. The general guidelines for deciding the membership functions are as follows: (1) first determine the limits of the PB and NB regions based upon the characteristics of the input variables; (2) then decide the

spread of ZE based upon the predesigned MPPT target (efficiency criteria); (3) thereafter the limits of PM and NM determined [14, 30-37].

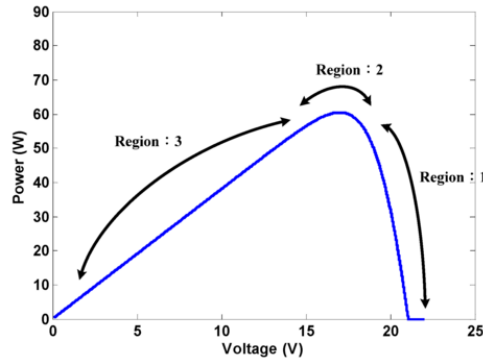


Figure 4.10: P-V curve with defined regions

The above figure 4.10 shows the regions in P-V curve which has been considered while designing the fuzzy rules. The detailed explanations for designing the rule database in each region is as follows:

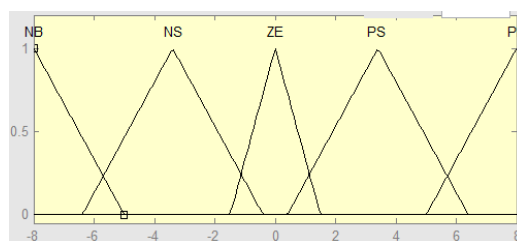
Region 1: In this region the slope is negative which means that the operating point of the photovoltaic module is on MPP's right. Hence the duty ratio has to be increased in order to reach the MPP. The second set of input variables i.e. the change in the slope is used to decide by how much the duty ratio has to be increased. However when both the slope and the changes in slope are NB, the calculations may result in wrong outputs as $S(k) = \Delta P / \Delta V$. When the value of change in both power and voltage are small and the operating point is close to the MPP then the output is set as ZE so as to avoid slope from becoming NB which will produce error output after division. When slope is NS and change in slope is either negative or zero then it means that the operating point is on the MPP's right and is likely to move further in that direction. Therefore the rule base is set such that the duty ratio increases under this condition. If slope is positive then it means that the operating point is advancing towards the MPP its right. At this point, the output is set as ZE so as to prevent excessive increase in the duty ratio and cause oscillations in the system.

Region 2: In this region, the slope is set as ZE. This means that the operating point is close to the MPP. Therefore, the aim will be to keep the value of the duty ratio constant under such conditions. If slope is NB then it means that the

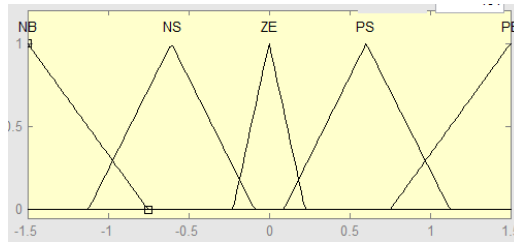
operating point is advancing towards the MPP rapidly from its left side. Now so to prevent the operating point from moving to the right of the MPP, the output is set as PS which subdues the change in value of the duty ratio in the reverse direction. When slope is PB then it means that the operating point is on MPP's right. Now so as to prevent sudden excessive increase in the duty ratio which would cause the operating point to cross its MPP and move to its left, the output is set as NS which subdues the value of the duty ratio in the reverse direction.

Region 3: In this region when the slope is positive then the operating point is on MPP's left. For such settings, the duty ratio has to be decreased in order to reach MPP. The second set of input variables i.e. the change in the slope is used to decide by how much the duty ratio has to be decreased. When both slope and the change in slope are PB then the controller would produce wrong outputs for the same reasons as that in Region 1. Therefore, to prevent such conditions the output is set as ZE. When the slope is PS and the change in slope is either positive or zero, the operating point is on MPP's left and is likely to move further in that direction. Hence the rule base is set such that the duty ratio decreases under such conditions. When slope is negative then it means that the operating point is advancing towards the MPP from its left. At this point, the output is set as ZE so as to prevent excessive decrease in the duty ratio and cause oscillations in the system [14, 30-37].

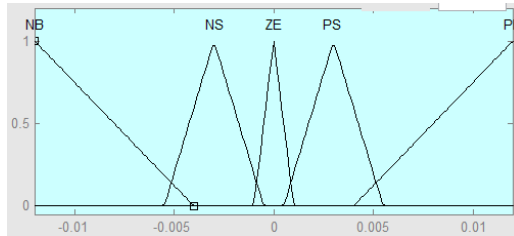
The figure 4.11a, b and c below shows the membership functions for the slope, changes in the slope and the change in duty ratio which is the output.



(a)



(b)



(c)

Figure 4.11: (a) Membership functions for the slope (b) Membership functions for the changes in slope (c) Membership functions for the change in duty ratio

4.3.3.2 P-V Slope and change in power as inputs

In this algorithm of the fuzzy logic MPPT system the fuzzy input variables taken are the slope $S(k)$ and the variation in power (ΔP). The table 4.2 below shows the rule base which is designed in accordance to the fuzzy input variables. The figure 4.12 below shows the regions of the P-V curve taken into consideration while designing the rules.

Fuzzy Rule		$S(k)$				
		NB	NS	ZE	PS	PB
ΔP	NB	PB	PB	ZE	NS	NB
	NS	PB	PS	ZE	NS	NB
	ZE	PS	PS	ZE	NS	NS
	PS	PB	PS	ZE	NS	NB
	PB	PB	PS	ZE	NB	NB

Region 1
Region 2
Region 3
Region 4

Table 4.2: Fuzzy Rules with $S(k)$ and ΔP as inputs

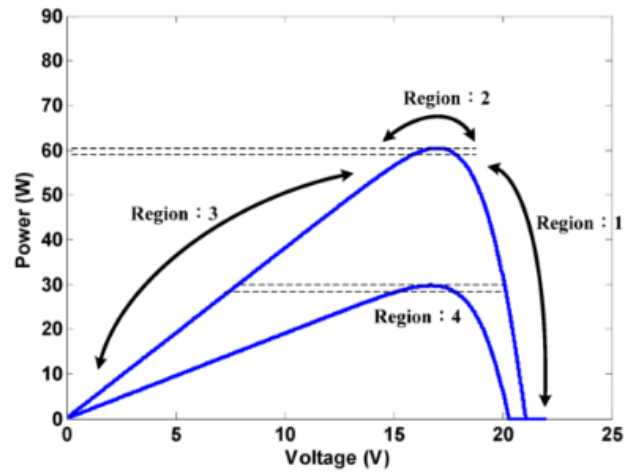


Figure 4.12: P-V curve with defined regions

The detailed explanations for designing the rule database in each region is as follows:

Region 1: The main criteria for determining the rule in this region is the negative slope of the P-V curve which means that the operating point is on MPP's right. Therefore, it can be concluded that the duty ratio has to be raised in order to reach the MPP. Change in the power output is used to achieve the value by which the duty ratio has to be increased.

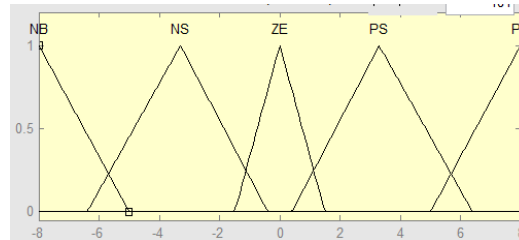
Region 2: In this region the slope is ZE which means that the operating point is close to MPP. So the duty ratio will hence remain constant.

Region 3: The main criteria for determining the rule in this region is the positive slope of the P-V curve which means that the operating point is on MPP's left. Therefore, it can be concluded that the duty ratio has to be reduced in order to reach the MPP. Change in the power output is used to achieve the value by which the duty ratio has to be reduced.

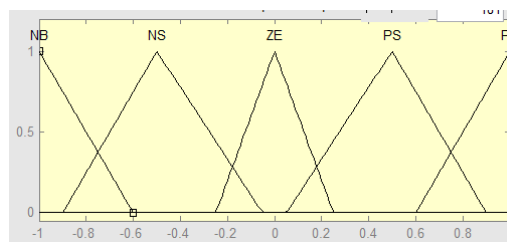
Region 4: This region is primarily used to determine the output when the variation in output power is in the range of ZE. This means that the operating point is very close to the MPP. At this point, the slope is used to adjust the correctness of the operating point. The use of slope exactly aims low insolation levels where the slope of P-V curve is of very low value and the system may be not be able perform MPPT precisely. Therefore it can be said that the slope is used to improve the accuracy and precision of the system algorithm. The increase or decrease of the duty ratio will be of small value so as to prevent addition or removal of too much duty ratio in one step and this could give rise to oscillations in the operating point [14,

30-37].

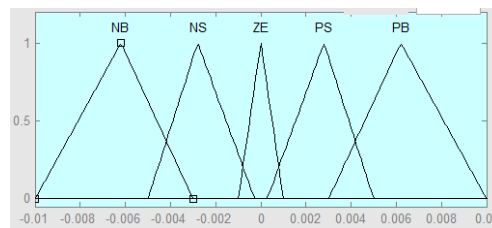
The figure 4.13a, b and c below shows the membership functions for the slope, changes in power and the change in duty ratio which is the output.



(a)



(b)



(c)

Figure 4.13: (a) Membership functions for the slope (b) Membership functions for the change in power (c) Membership functions for change in the duty ratio

4.3.3.3 Change in Power and change in Voltage as inputs

In this algorithm of the fuzzy logic MPPT system the fuzzy input variables taken are the change in power (ΔP) and the change in voltage (ΔV). The table 4.3 below shows the rule base which is designed in accordance to the fuzzy input variables. The figure 4.14 below shows the regions of the P-V curve taken into consideration while designing the rules.

Fuzzy Rule		Region 1		Region 2		Region 3	
		NB	NS	ZE	PS	PB	
ΔV	NB	NB	NS	ZE	PS	PB	
	NS	NS	NS	ZE	PS	PS	
	ZE	ZE	ZE	ZE	ZE	ZE	
	PS	PS	PS	ZE	NS	NS	
	PB	PB	PS	ZE	NS	NB	

Region 1 Region 2 Region 3
 Region 7 Region 8 Region 9
 Region 4 Region 5 Region 6

Table 4.3: Fuzzy Rules with ΔP and ΔV as inputs

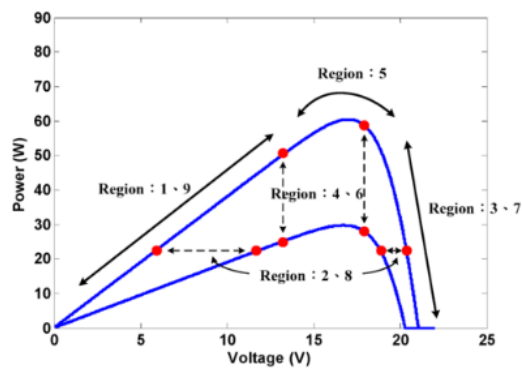


Figure 4.14: P-V curve with defined regions

The detailed explanations for designing the rule database in each region is as follows:

Region 1: In this region both power and voltage reduces at the same time with the same insolation which means that the operating point is on MPP's left. Changes in the power and the voltage are used to decide the amount by which the duty ratio has to be reduced.

Region 2: In this region the power remains constant but the voltage reduces. Under such circumstances, it is presumed that the operating point is at the MPP, hence the output is set as ZE. At this point, the algorithm will not be able to decide whether the insolation has been raised or reduced if insolation has altered. Therefore, the output is set as ZE so as to avoid contradictions.

Region 3: In this region where insolation remains constant, power increments and voltage decrements which implies that the operating point is on MPP's right. At this point, the changes in the power and voltage is used to decide the amount by which the duty ratio has to be incremented. But if there is

an excessive increment in the duty ratio then the operating point will go from the right of the MPP to its left resulting in issuing of a conflicting command. In such circumstances, the power has to be incremented and voltage has to be reduced. It can be seen that after the duty ratio command, the operating point is on MPP's left, which implies that the duty ratio has to be decreased in the MPPT process, thereby opposing the command for incrementing the duty ratio in the fuzzy rules base. This would result in generation of wrong outputs in the system and lead to oscillations. Hence the step size for changing the duty ratio should not be too large.

Region 4: In this region is the voltage remains constant but the power decreases. In such circumstances, if the insolation is not changing, the system is not able to decide whether the operating point is on MPP's left or right. Therefore, the output is set as ZE. If insolation varies then also the algorithm will not be able to decide whether the operating point is on MPP's left or right. Hence the output is set as ZE so as to avoid conflicts.

Region 5: In this region both the power and voltage are unchanged which implies that the system has achieved the MPP. So the duty ratio is not changed and the output is set as ZE.

Region 6: For this region, power increments whereas voltage remains constant. If the insolation is same, the system will not be able to decide whether the operating point is on MPP's left or right. Therefore, the output is set as ZE. Now if the insolation varies then also the algorithm will not be able to decide whether the operating point is on MPP's left or right. Hence the output is set as ZE so as to avoid conflicts.

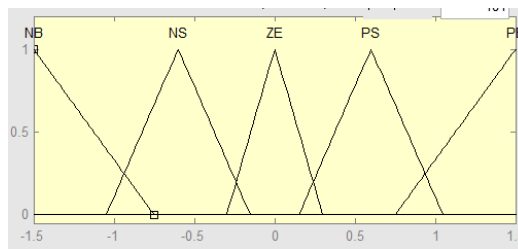
Region 7: In this region where the insolation is same, power reduces and voltage increments which implies that the operating point is on MPP's right. According to the changes in the power and voltage the duty ratio incremented.

Region 8: For this region, power is constant whereas voltage increments. When insolation is constant it is presumed that the operating point is at the MPP and therefore the output is set as ZE. If insolation varies then the algorithm will still not be able to decide whether the insolation is incremented or decremented. Hence the output will be set as ZE so as to

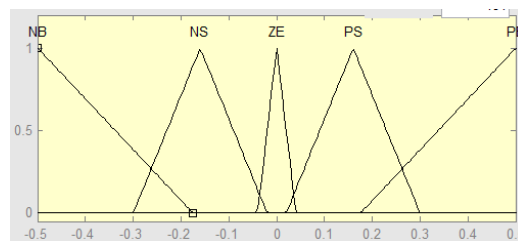
avoid conflicts.

Region 9: In this region both power and voltage increments at the same time with the same insolation which implies that the operating point is on MPP's left. The variations in the power and voltage are used to decide the amount by which the duty ratio has to be decremented. But if there is an excessive decrement in the duty ratio then the operating point will go from the left of the MPP to its right. After the shift the operating point is now on MPP's right which implies that the duty ratio has to be incremented in order to reach the MPP. This opposes the need to decrement the duty ratio command in the fuzzy rule base which would result in oscillations in the system. In order to prevent them the variation in the duty ratio should not be too great [14, 30-37].

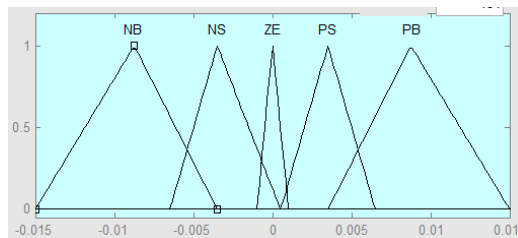
The figure 4.15a, b and c below shows the membership functions for the changes in power, changes in voltage and the change in duty ratio which is the output.



(a)



(b)



(c)

Figure 4.15: (a) Membership Functions for changes in power (b) Membership functions for changes in voltage (c) membership functions for change in the duty ratio

4.3.3.4 Change in Power and change in Current as inputs

In this algorithm of the fuzzy logic MPPT system the fuzzy input variables taken are the change in power (ΔP) and the change in current (ΔI). The table 4.4 below shows the rule base which is designed in accordance to the fuzzy input variables. The figure 4.16 below shows the regions of the P-I curve taken into consideration while designing the rules. From the figure 4.16 below it can be seen that the power versus current curve has the same shape as that of power versus voltage curve except that it exhibits a very sharp slope on the right side of the MPP. Hence it can be concluded that this side is very sensitive to the changes in the duty ratio.

Fuzzy Rule		ΔP				
		NB	NS	ZE	PS	PB
ΔI	NB	PB	PS	ZE	NS	NB
	NS	PS	PS	ZE	NS	NS
	ZE	ZE	ZE	ZE	ZE	ZE
	PS	NS	NS	ZE	PS	PS
	PB	NB	NS	ZE	PS	PB

Region 1 Region 2 Region 3
 Region 7 Region 8 Region 9
 Region 4 Region 5 Region 6

Table 4.4: Fuzzy Rules with ΔP and ΔI as inputs

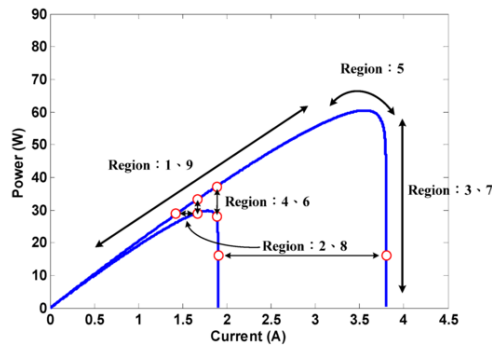


Figure 4.16: P-I curve with defined regions

In this algorithm the P-I curve is divided into 9 regions as in previous one. Since the current and voltage are inversely related the behaviour of the system is same with opposite increase or decrease results. The detailed explanations for designing the rule database in each region is as follows:

Region 1: In this region both power and current reduces at the same time with the same insolation which means that the operating point is on MPP's left. Changes in the power and the current are used to decide the amount by

which the duty ratio has to be incremented.

Region 2: In this region the power remains constant but the current reduces. Under such circumstances, it is presumed that the operating point is at the MPP, hence the output is set as ZE. At this point, the algorithm will not be able to decide whether the insolation has been raised or reduced if insolation has altered. Therefore, the output is set as ZE so as to avoid contradictions.

Region 3: In this region where insolation remains constant, power increments and current decrements which implies that the operating point is on MPP's right. At this point, the changes in the power and current is used to decide the amount by which the duty ratio has to be decremented. But if there is an excessive decrement in the duty ratio then the operating point will go from the right of the MPP to its left resulting in issuing of a conflicting command. In such circumstances, the power has to be incremented and current has to be reduced. It can be seen that after the duty ratio command, the operating point is on MPP's left, which implies that the duty ratio has to be increased in the MPPT process, thereby opposing the command for decrementing the duty ratio in the fuzzy rules base. This would result in generation of wrong outputs in the system and lead to oscillations. Hence the step size for changing the duty ratio should not be too large.

Region 4: In this region is the current remains constant but the power decreases. In such circumstances, if the insolation is not changing, the system is not able to decide whether the operating point is on MPP's left or right. Therefore, the output is set as ZE. If insolation varies then also the algorithm will not be able to decide whether the operating point is on MPP's left or right. Hence the output is set as ZE so as to avoid conflicts.

Region 5: In this region both the power and current are unchanged which implies that the system has achieved the MPP. So the duty ratio is not changed and the output is set as ZE.

Region 6: For this region, power increments whereas current remains constant. If the insolation is same, the system will not be able to decide whether the operating point is on MPP's left or right. Therefore, the output is set as ZE. Now if the insolation varies then also the algorithm will not be able

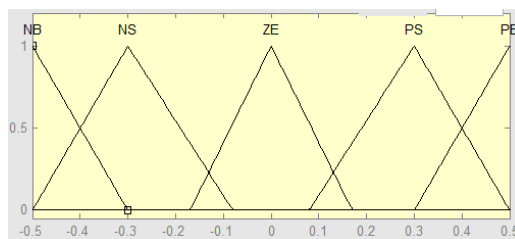
to decide whether the operating point is on MPP's left or right. Hence the output is set as ZE so as to avoid conflicts.

Region 7: In this region where the insolation is same, power reduces and current increments which implies that the operating point is on MPP's right. According to the changes in the power and voltage the duty ratio decremented.

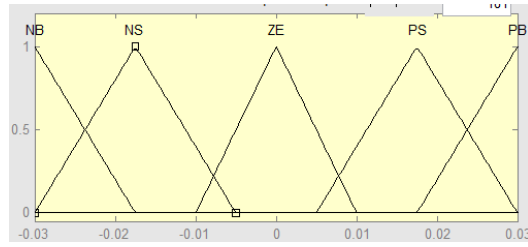
Region 8: For this region, power is constant whereas current increments. When insolation is constant it is presumed that the operating point is at the MPP and therefore the output is set as ZE. If insolation varies then the algorithm will still not be able to decide whether the insolation is incremented or decremented. Hence the output will be set as ZE so as to avoid conflicts.

Region 9: In this region both power and current increments at the same time with the same insolation which implies that the operating point is on MPP's left. The variations in the power and voltage are used to decide the amount by which the duty ratio has to be incremented. But if there is an excessive increment in the duty ratio then the operating point will go from the left of the MPP to its right. After the shift the operating point is now on MPP's right which implies that the duty ratio has to be decremented in order to reach the MPP. This opposes the need to increment the duty ratio command in the fuzzy rule base which would result in oscillations in the system. In order to prevent them the variation in the duty ratio should not be too great [14, 30-37].

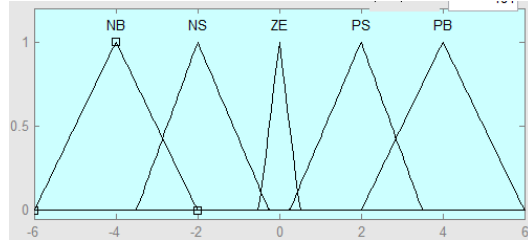
The figure 4.17a, b and c below shows the membership functions for the changes in power, changes in current and the change in duty ratio which is the output.



(a)



(b)



(c)

Figure 4.17: (a) Membership functions for changes in power (b) Membership functions for changes in current (c) Membership functions for change in the duty ratio

4.3.3.5 Sum of conductance and Incremental conductance as input

In this algorithm of the fuzzy logic MPPT system the fuzzy input variable taken is the sum of conductance and increment in conductance. As seen in the equations 4.2 and 4.3 before at MPP the power to voltage derivative is zero. This algorithm uses the characteristic that when the sum of conductance and increment in it is less than zero then the operating point is on MPP's right. It can be said that when output voltage of the photovoltaic module is very less, the duty ratio of the system should be decreased so as to increase the output voltage of photovoltaic module. Similarly when the sum of conductance and increment in it is more than zero then the operating point is on MPP's left. In this situation the output voltage is very high and hence the duty ratio of the system should be incremented so as to decrement the output voltage of the photovoltaic module. The table 4.5 below shows the rule base which is designed in accordance to the fuzzy input variables. The figure 4.18 below shows the regions of the I-V curve taken into consideration while designing the rules [14].

	$\frac{I}{V} + \frac{dI}{dV}$				
Fuzzy Rule	NB	NS	ZE	PS	PB
	PB	PS	ZE	NS	NB
	Region 1		Region 2	Region 3	

Table 4.5: Fuzzy Rules with $I/V + dI/dV$ as input

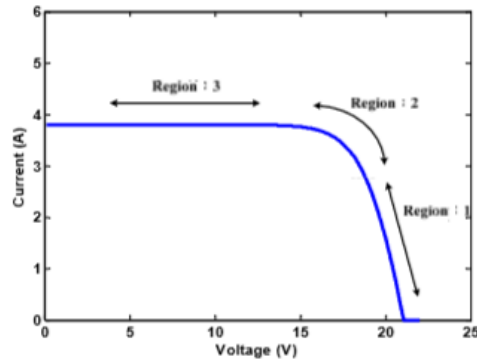


Figure 4.18: I-V curve with defined regions

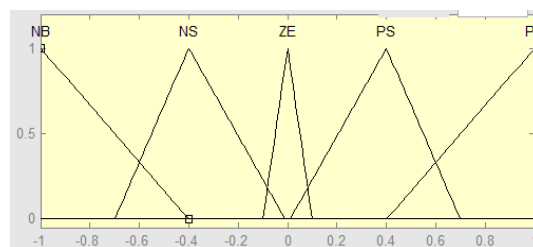
Through this algorithm the exact location of the operating point can be directly identified with respect to the MPP contrary to the earlier algorithms discussed in this thesis where changes are used to guess whether the system has reached MPP or not. Therefore, while using this algorithm the duty ratio can be increased or reduced with higher values so as to attain efficient MPPT. The other benefit of this algorithm is that it requires only one set of input variables resulting in a single-input and single-output system which further decreases calculation of loads. The detailed explanations for designing the rule database in each region is as follows:

Region 1: In this region the operating point is on MPP's right. The closeness of the operating point to the MPP is used to decide by how much amount the duty ratio of the system has to be incremented.

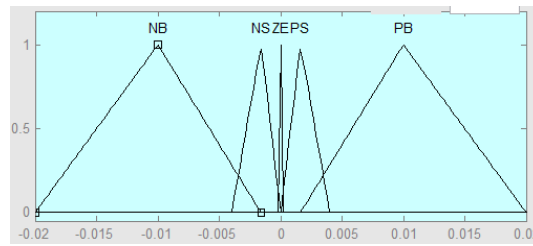
Region 2: In this region the operating point is close to the MPP. Hence the output is set as ZE for this region.

Region 3: In this region the operating point is on MPP's left. The closeness of the operating point to the MPP is used to decide by how much amount the duty ratio of the system has to be reduced [14, 30-37].

The figure 4.19a and b below shows the membership functions for the sum of conductance and incremental conductance and the change in duty ratio which is the output.



(a)



(b)

Figure 4.19: (a) Membership functions for $I/V + dI/dV$ (b) Membership functions for change in duty ratio

CHAPTER 5

DC-DC CONVERTERS

5.1 INTRODUCTION

The power electronics circuits which are used to transform a DC voltage into different levels of DC voltage are known as DC-DC converters. This can be done using different types of methods of conversion such as electronic, linear, switched mode. The circuits defined in this thesis work are categorised as switched mode dc-dc converters [15, 38-39].

The dc-dc converters takes in unregulated dc voltage and convert it into regulated dc voltage at its output. The switch in these circuits are turned 'ON' and 'OFF' (called as switching) at a high frequency. When the switch is 'ON', it enters saturation mode and the voltage drop across the collector and emitter terminals of the switch is negligible. While when the switch is 'OFF', it enters cutoff mode and the current through the collector and emitter terminals is negligible [15, 38-39].

The voltage regulating switch is a linear regulator which means that it is always in the active region. For the same circuit the switching regulator has higher efficiency than the linear regulator reaching as high as 80% to 95%. While the linear regulator generally shows only 50% to 60 % efficiency. As the efficiency increases heat sinks required are of smaller size as less heat is released. Another advantage of switching regulators is that the energy stored in inductor and capacitor can be transferred to output voltages such that they become greater than the input voltage (boost), or negative (inverter). Hence in contrast to the regulators, switched power supplies can increase i.e. step up or decrease i.e. step down the input voltage [15, 38-39].

5.2 NEED OF DC-DC CONVERTER

The purpose of a dc-dc converter whether step up or step down is to transfer maximum power from the solar photovoltaic module to the load. It is like an interface between the load and the photovoltaic module. With the variation in irradiance and

temperature the duty ratio for the dc-dc converter changes. On varying the duty cycle the load impedance seen by the input changes and is matched to the point of the highest power with the source in order to deliver the maximum power to the load. The duty cycle is kept on changing till the point of maximum power is obtained [15-16, 40].

Consider a step-up dc-dc converter. The relation between the input impedance and the output impedance is shown in equation 5.1 as follows:

$$R_i = (1-\alpha)^2 R_o \quad (5.1)$$

Where,

R_i = Input Impedance

R_o = Output Impedance

α = Duty Cycle

Hence it can be seen that the output resistance R_o remains unchanged and by varying the duty cycle the input resistance R_i as seen by the source can be changed. Thus it can be concluded that the resistance matching the maximum power point can be attained by varying the duty cycle [15-16, 40].

5.3 TYPES OF DC-DC CONVERTERS

There are a variety of dc-dc converters. At the basic level they can be categorised as follows:

5.3.1 Buck DC-DC Converter

A Buck DC-DC converter chops or attenuates the input voltage and a lower amplitude voltage is obtained at the output.

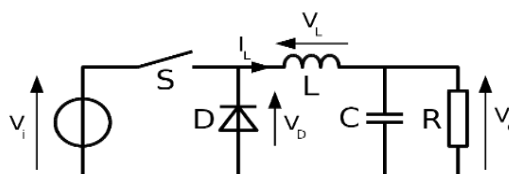


Figure 5.1: Buck DC-DC Converter

The figure 5.1 above shows the circuit of a Buck Converter which includes a switch, diode, inductor, capacitor and load. On tuning ON the switch, the voltage at

the input is applied to the load. During the ON period the diode becomes reverse biased and therefore it is off. The energy gets stored in the inductor during ON period. On turning OFF the switch, the output voltage becomes zero. The diode is forward biased i.e. it conducts in OFF period and hence the energy which was stored in the inductor during ON period discharges across it. The output voltage across the load is obtained by the following equation 5.2 [17, 18]:

$$V_o = \alpha V_{in} \quad (5.2)$$

Where,

V_o = Output Voltage in Volt

V_{in} = Input Voltage in Volt

α = Duty cycle = t_{on}/T

The value of inductor, L, and capacitor, C, are found with help of the following equations, 5.3 and 5.4:

$$L = \frac{(1-\alpha) \cdot R_o}{2 \cdot f} \quad (5.3)$$

$$C = \frac{(1-\alpha) \cdot V_o}{8 \cdot \Delta V_o \cdot L \cdot f^2} \quad (5.4)$$

Where,

f = Switching frequency in Hz

$\Delta V_o/V_o$ = Ripple in output voltage

In the simulation diagram of the Buck Converter used in this project the calculated value of inductor L is 0.459mH and capacitor C is 0.0844mF.

5.3.2 Boost DC-DC Converter

A Boost DC-DC Converter boosts or increases the input voltage to a higher value of voltage at the output.

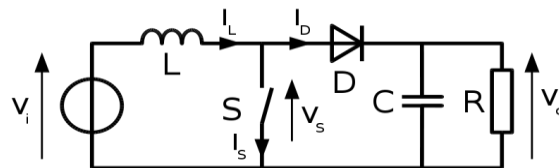


Figure 5.2: Boost Converter

The figure 5.2 above shows the circuit of a Boost converter which includes an inductor, switch, diode, capacitor and load. In this converter on turning ON the switch the inductor starts storing energy. As no current flows through the load, the output voltage is zero. On turning OFF the switch the voltage at the input gets applied to the load. In the OFF period the energy stored in inductor during the ON period also discharges through the load. Hence the output voltage becomes more than the input voltage. The output voltage across the load is obtained by the following equation 5.5 [17, 19]:

$$V_o = V_{in} / (1 - \alpha) \quad (5.5)$$

The value of inductor, L, and capacitor, C, are found with help of the following equations, 5.6 and 5.7:

$$L = \frac{(1-\alpha)^2 * \alpha * R_o}{2 * f} \quad (5.6)$$

$$C = \frac{\alpha * V_o}{\Delta V_o * R_o * f} \quad (5.7)$$

In the simulation diagram of the Boost converter used in this project, the value of calculated inductor L is 0.961mH and capacitor C is 0.19mF.

5.3.3 Buck-Boost DC-DC Converter

A Buck-Boost DC-DC converter can both increase and decrease the input voltage according to the duty cycle applied at its gate terminal.

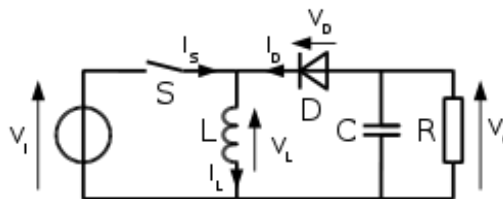


Figure 5.3: Buck-Boost Converter

The figure 5.3 above shows the circuit of a Buck-Boost converter which includes an inductor, switch, diode, capacitor and load. When the switch is in the On-state, the input voltage source is directly connected to the inductor (L). This results in accumulation of energy in L. In this stage, the capacitor which is already charged supplies energy to the output load. When the switch is in the Off-state, the inductor is

connected to the output load and capacitor, so energy is transferred from L to C and R. The output voltage across the load is obtained by the following equation 5.8 [17, 20]:

$$V_o = -\alpha V_{in} / (1 - \alpha) \quad (5.8)$$

The value of inductor, L, and capacitor, C, are found with help of the following equations, 5.9 and 5.10:

$$L = \frac{(1-\alpha)^2 * R_o}{2 * f} \quad (5.9)$$

$$C = \frac{\alpha * V_o}{\Delta V_o * R_o * f} \quad (5.10)$$

In the simulation diagram of the Buck-Boost Converter used in this project the value of calculated inductor L is 0.576mH and capacitor C is 4.31mF.

CHAPTER 6

RESULTS AND ANALYSIS

6.1 V-I AND P-V PLOTS OF PHOTOVOLTAIC SYSTEM

The Power Vs Voltage characteristics and Voltage Vs Current characteristics of the solar photovoltaic module is shown in the figures 6.1 and 6.2 respectively. The Power and Current are at Y-axis while Voltage is at X-Axis. The characteristics obtained are for 1000W/m^2 irradiance and 25°C of temperature. It can be seen that the maximum power obtained is 40W and the module has an open circuit voltage of 22.25V and short circuit current of 2.53A .

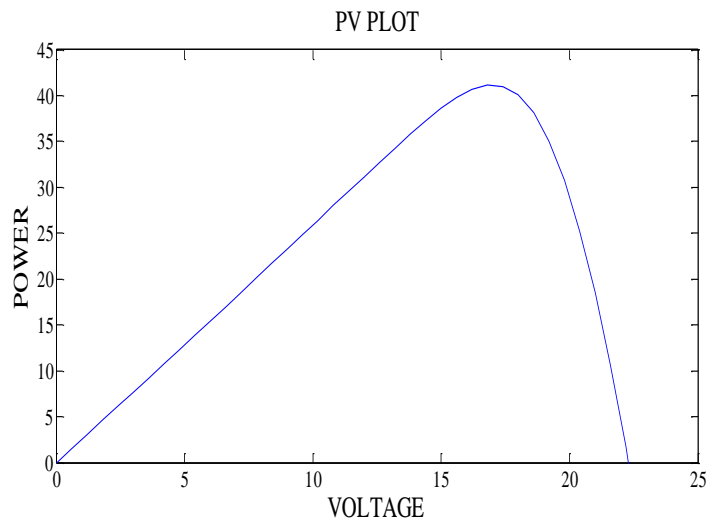


Figure 6.1: PV Plot for the PV Module

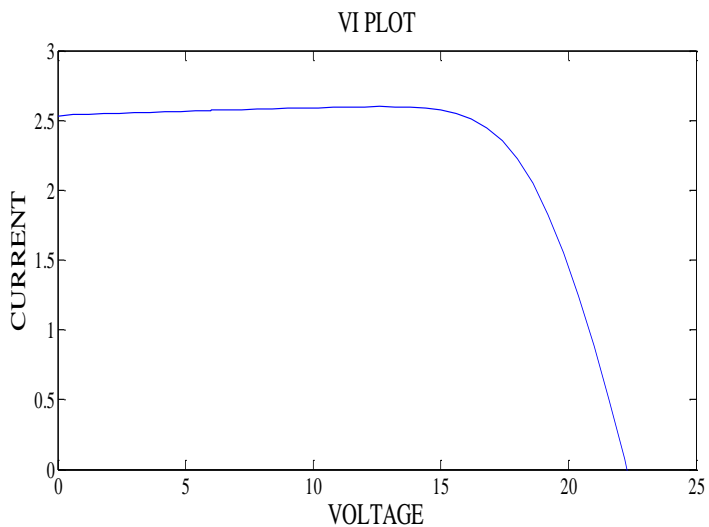


Figure 6.2: VI Plot for the PV Module.

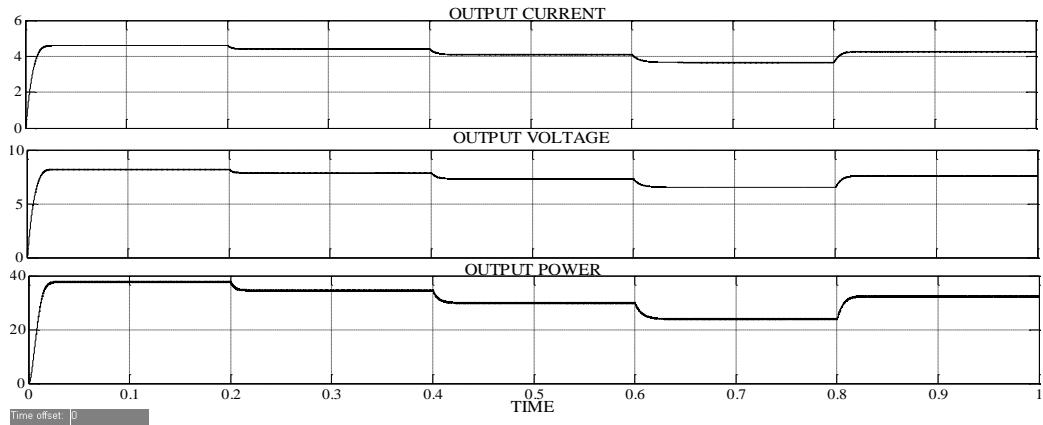


Figure 6.4: Output Current, Voltage and Power at 25°C Temperature and varying Irradiance

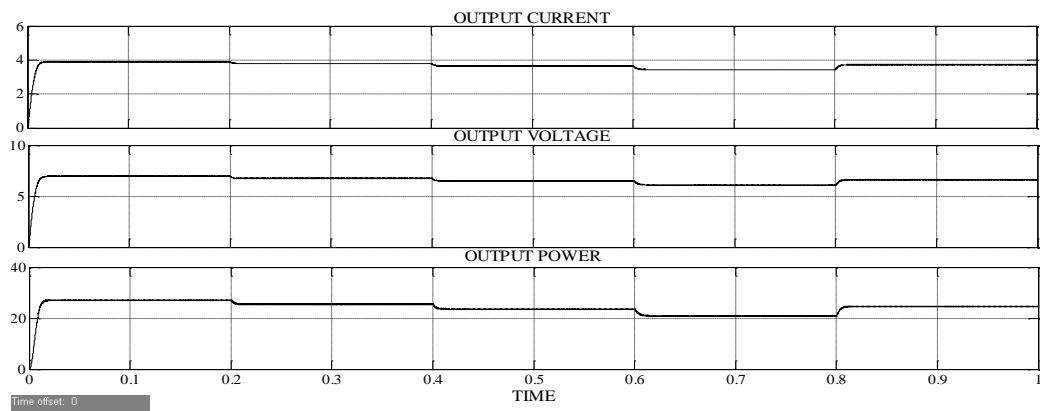


Figure 6.5: Output Current, Voltage and Power at 50°C Temperature and varying Irradiance

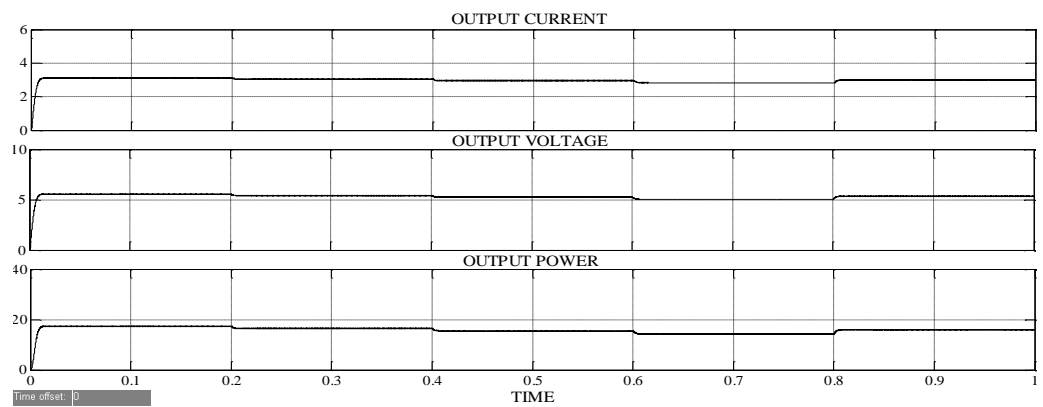


Figure 6.6: Output Current, Voltage and Power at 75°C Temperature and varying Irradiance

6.2.2 With Boost DC-DC Converter

The figure 6.7 below shows the simulation of MPPT of solar photovoltaic system with Boost DC-DC Converter using Perturb and Observe Algorithm for a resistive load.

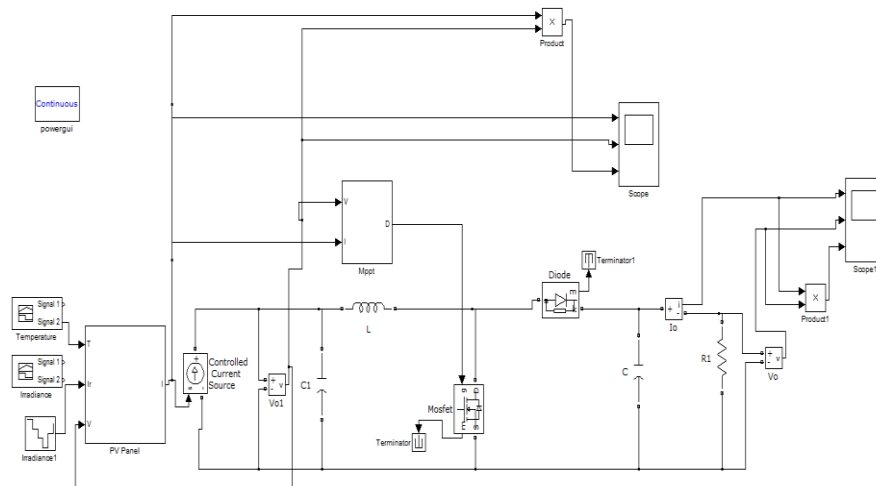


Figure 6.7: Simulation Diagram of PV system with P&O Algorithm and Boost Converter

The Boost Converter increases the input voltage to a greater value of output voltage according to the duty cycle applied to its gate input. It can be seen that the output of the Perturb and Observe algorithm is given to the gate of the Mosfet in the Boost converter so that whenever there is a change in the irradiance or temperature, the duty cycle of the converter can be adjusted in order to get maximum power at the load side. The simulation has been performed for a progressive change of solar irradiance between 500 and 1000W/m² for different values of temperature.

The figures 6.8, 6.9 and 6.10 below show the output current, voltage and power for irradiance varying between 500W/m² and 1000W/m² and temperature varying from 25°C to 75°C for a PV System working with a Boost Converter using Perturb and Observe Algorithm. The system has been designed for a duty cycle of 0.488. Hence, the input voltage of 17.4V has been boosted to 34V under standard conditions i.e. 1000w/m² irradiance and 25°C temperature. It can be noticed that the current, voltage and power are at their maximum at 1000W/m² and 25°C. They decrease as the value of irradiance decreases and increase as the value of irradiance increases between 500W/m² and 1000W/m². It can also be observed that as temperature increases from 25°C to 75°C, the current, voltage and power reduces.

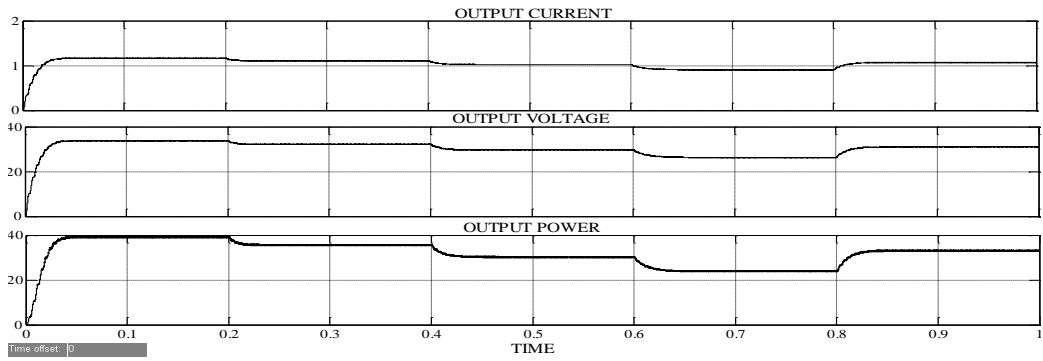


Figure 6.8: Output Current, Voltage and Power at 25°C Temperature and varying Irradiance

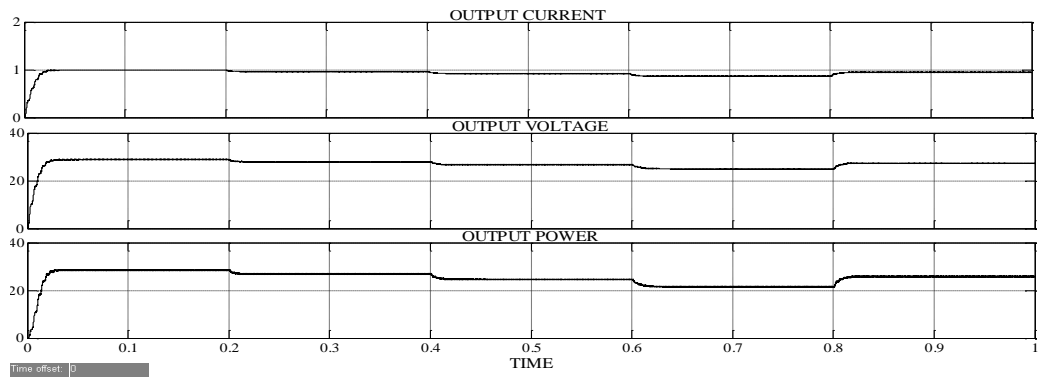


Figure 6.9: Output Current, Voltage and Power at 50°C Temperature and varying Irradiance

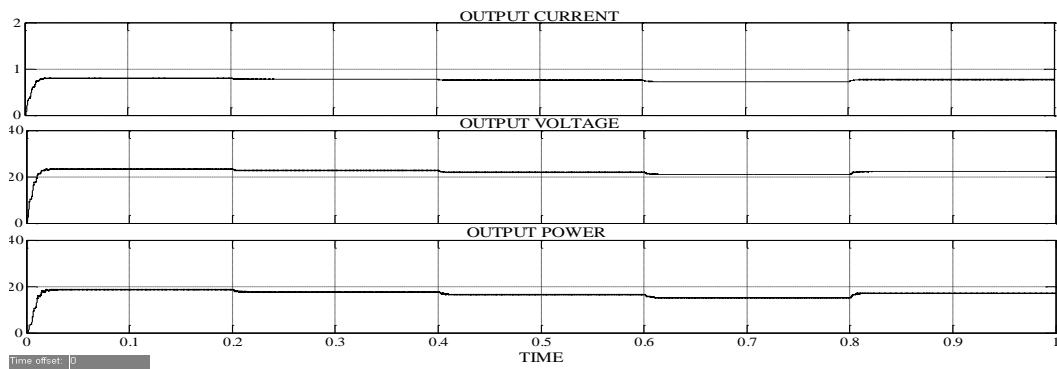


Figure 6.10: Output Current, Voltage and Power at 75°C Temperature and varying Irradiance

6.2.3 With Buck-Boost DC-DC Converter

The figure 6.11 below shows the simulation of MPPT of solar photovoltaic system with Buck-Boost DC-DC Converter using Perturb and Observe Algorithm for a resistive load. The Buck-Boost Converter reduces or boosts the input voltage to a lower value or a higher value of output voltage according to the duty cycle applied to its gate input. It can be seen that the output of the Perturb and Observe algorithm is

given to the gate of the Mosfet in the Buck-Boost converter so that whenever there is a change in the irradiance or temperature, the duty cycle of the converter can be adjusted in order to get maximum power at the load side. The simulation has been performed for a progressive change of solar irradiance between 500 and 1000W/m² for different values of temperature.

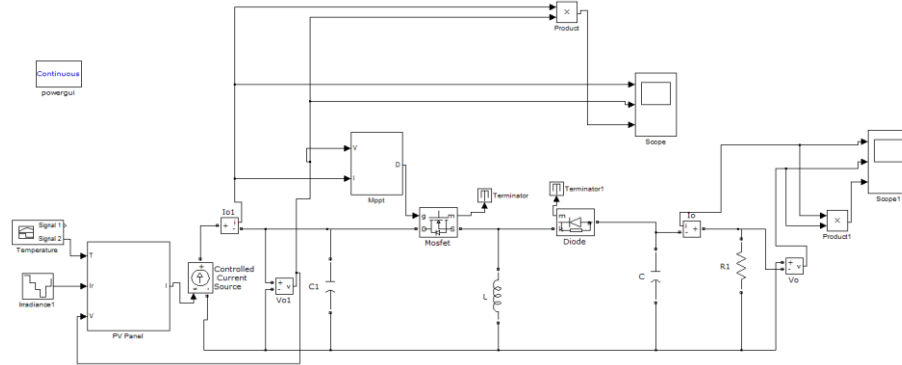


Figure 6.11: Simulation Diagram of PV system with P&O Algorithm and Buck-Boost Converter

The figures 6.12, 6.13 and 6.14 below show the output current, voltage and power for irradiance varying between 500W/m² and 1000W/m² and temperature varying from 25°C to 75°C for a PV System working with a Buck-Boost Converter using Perturb and Observe Algorithm. Since there are no variations in the input side we get output approximately equal to the input under standard conditions i.e. 1000w/m² irradiance and 25°C temperature. It can be noticed that the current, voltage and power are at their maximum at 1000W/m² and 25°C. They decrease as the value of irradiance decreases and increase as the value of irradiance increases between 500W/m² and 1000W/m². It can also be observed that as temperature increases from 25°C to 75°C, the current, voltage and power reduces.

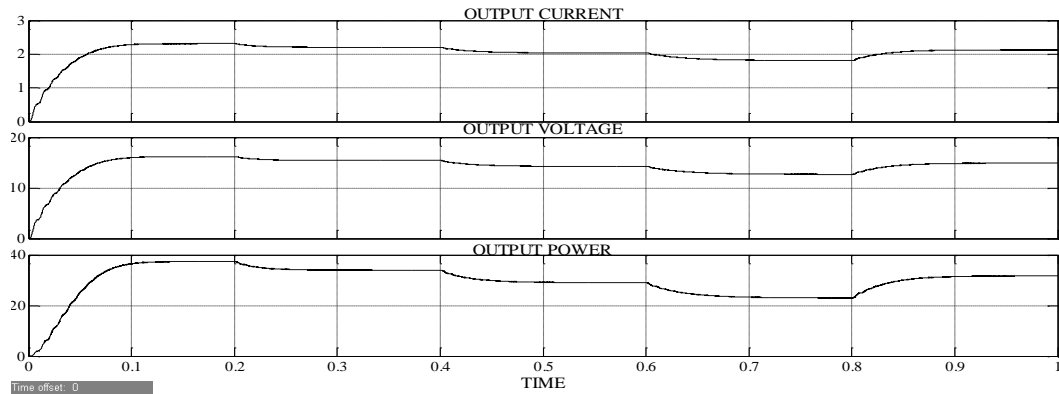


Figure 6.12: Output Current, Voltage and Power at 25°C Temperature and varying Irradiance

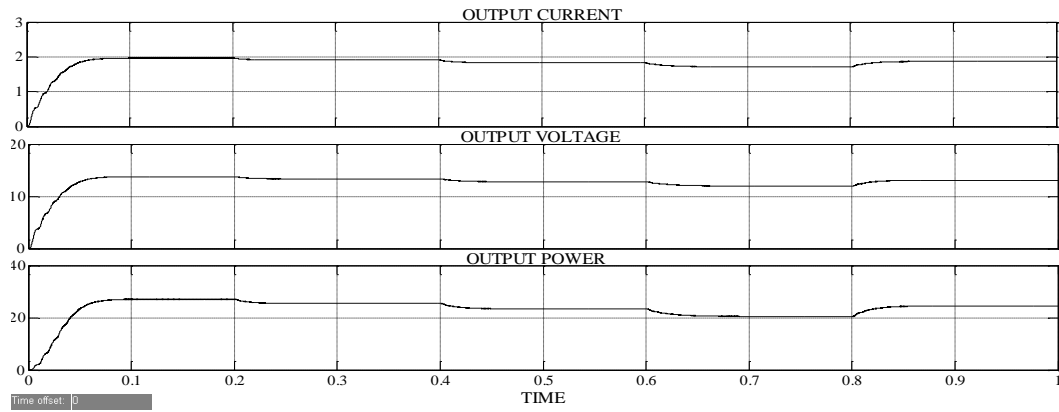


Figure 6.13: Output Current, Voltage and Power at 50°C Temperature and varying Irradiance

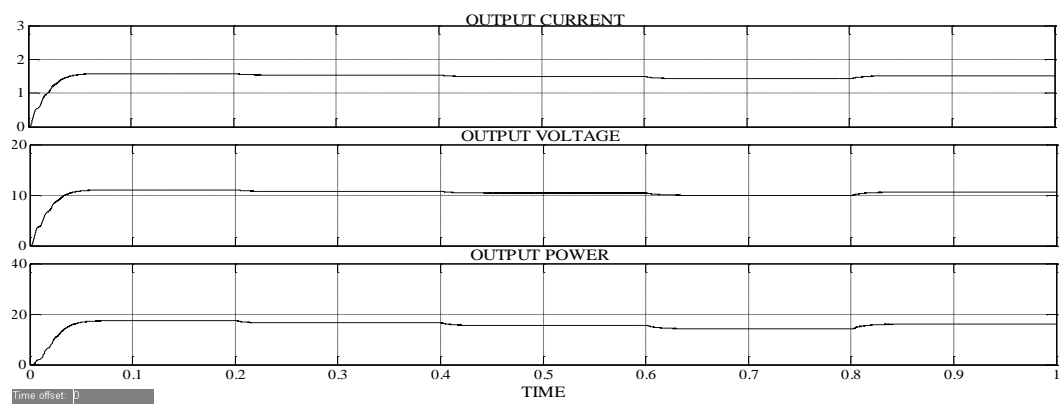


Figure 6.14: Output Current, Voltage and Power at 75°C Temperature and varying Irradiance

6.3 PHOTOVOLTAIC SYSTEM WITH INC ALGORITHM

6.3.1 With Buck DC-DC Converter

The figure 6.15 below shows the simulation of MPPT of solar photovoltaic system with Buck DC-DC Converter using Incremental Conductance Algorithm for a resistive load. The Buck Converter reduces the input voltage to a lower value of output voltage according to the duty cycle applied to its gate input. It can be seen that the output of the Incremental Conductance algorithm is given to the gate of the Mosfet in the Buck converter so that whenever there is a change in the irradiance or temperature, the duty cycle of the converter can be adjusted in order to get maximum power at the load side. The simulation has been performed for a variation of solar irradiance between 500 and 1000W/m² for different values of temperature.

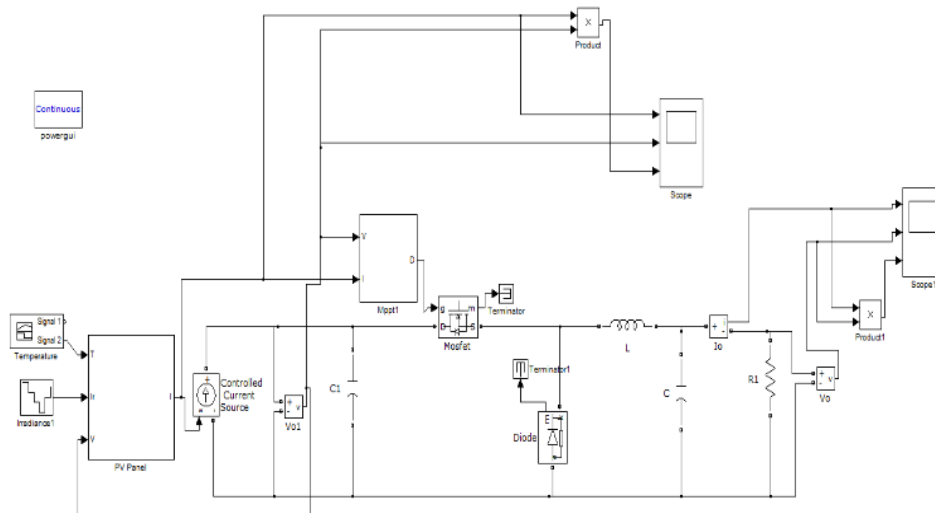


Figure 6.15: Simulation Diagram of PV system with INC Algorithm and Buck Converter

The figures 6.16, 6.17 and 6.18 below show the output current, voltage and power for irradiance varying between 500W/m^2 and 1000W/m^2 and temperature varying from 25°C to 75°C for a PV System working with a Buck Converter using Incremental Conductance Algorithm. The system has been designed for a duty cycle of 0.466. Hence, the input voltage of 17.4V has been reduced to 8.2V under standard conditions i.e. 1000W/m^2 irradiance and 25°C temperature. It can be noticed that the current, voltage and power are at their maximum at 1000W/m^2 and 25°C . They decrease as the value of irradiance decreases and increase as the value of irradiance increases between 500W/m^2 and 1000W/m^2 . It can also be observed that as temperature increases from 25°C to 75°C , the current, voltage and power reduces.

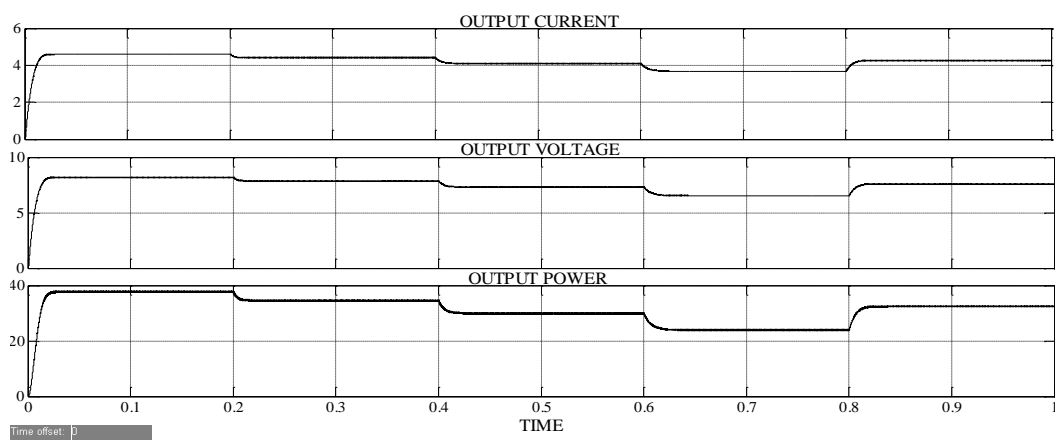


Figure 6.16: Output Current, Voltage and Power at 25°C Temperature and varying Irradiance

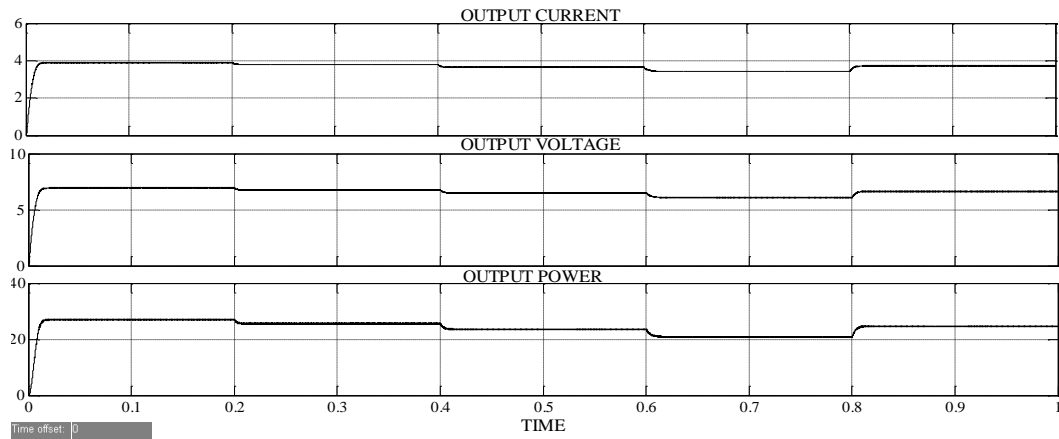


Figure 6.17: Output Current, Voltage and Power at 50°C Temperature and varying Irradiance

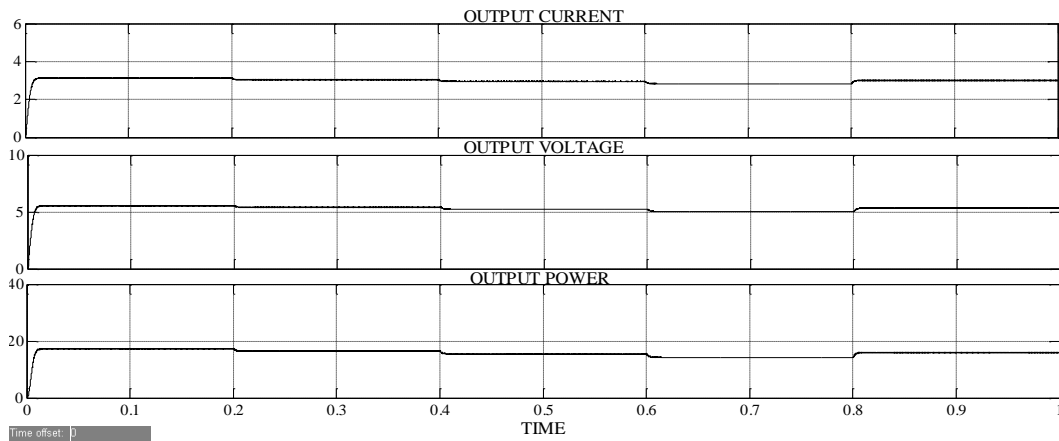


Figure 6.18: Output Current, Voltage and Power at 75°C Temperature and varying Irradiance

6.3.2 With Boost DC-DC Converter

The figure 6.19 below shows the simulation of MPPT of solar photovoltaic system with Boost DC-DC Converter using Incremental Conductance Algorithm for a resistive load. The Boost Converter increases the input voltage to a greater value of output voltage according to the duty cycle applied to its gate input. It can be seen that the output of the Incremental Conductance algorithm is given to the gate of the Mosfet in the Boost converter so that whenever there is a change in the irradiance or temperature, the duty cycle of the converter can be adjusted in order to get maximum power at the load side. The simulation has been performed for a progressive change of solar irradiance between 500 and 1000W/m² for different values of temperature.

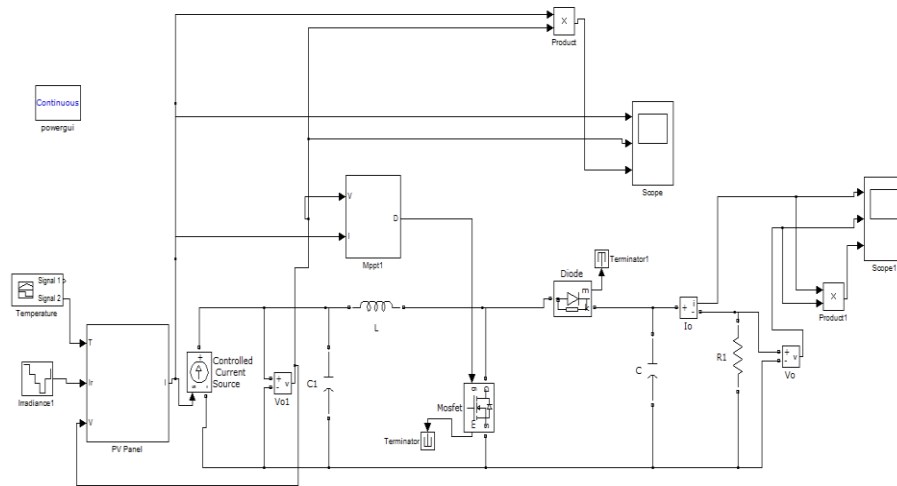


Figure 6.19: Simulation Diagram of PV system with INC Algorithm and Boost Converter

The figures 6.20, 6.21 and 6.22 below show the output current, voltage and power for irradiance varying between 500W/m^2 and 1000W/m^2 and temperature varying from 25°C to 75°C for a PV System working with a Boost Converter using Incremental Conductance Algorithm. The system has been designed for a duty cycle of 0.488. Hence, the input voltage of 17.4V has been boosted to 34V under standard conditions i.e. 1000W/m^2 irradiance and 25°C temperature. It can be noticed that the current, voltage and power are at their maximum at 1000W/m^2 and 25°C . They decrease as the value of irradiance decreases and increase as the value of irradiance increases between 500W/m^2 and 1000W/m^2 . It can also be observed that as temperature increases from 25°C to 75°C , the current, voltage and power reduces.

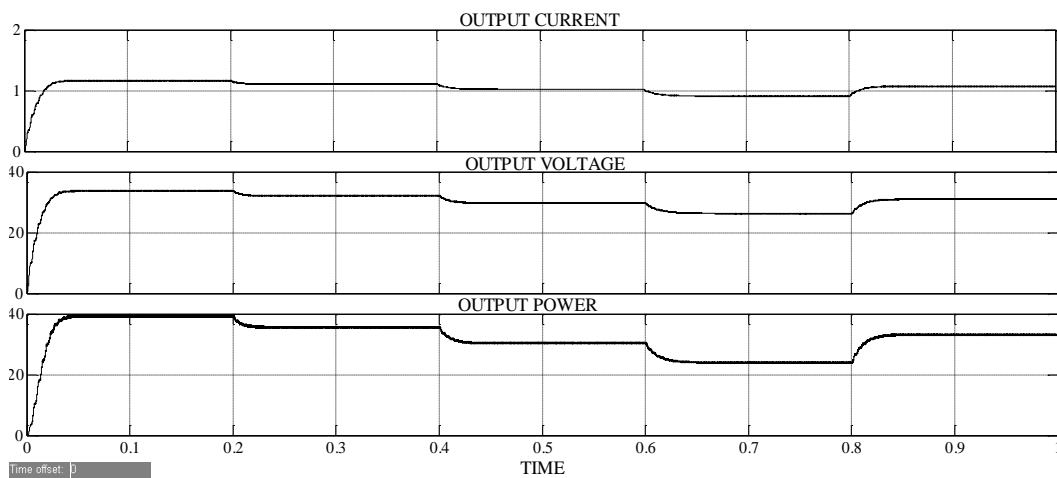


Figure 6.20: Output Current, Voltage and Power at 25°C Temperature and varying Irradiance

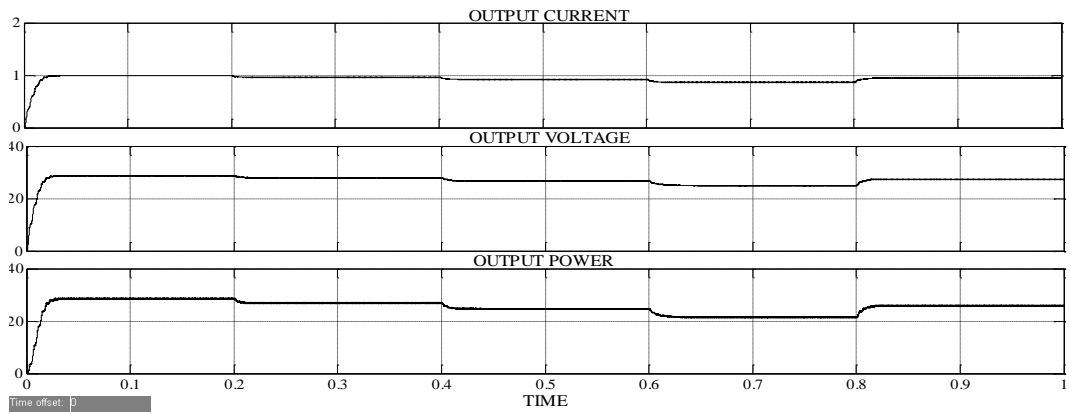


Figure 6.21: Output Current, Voltage and Power at 50°C Temperature and varying Irradiance

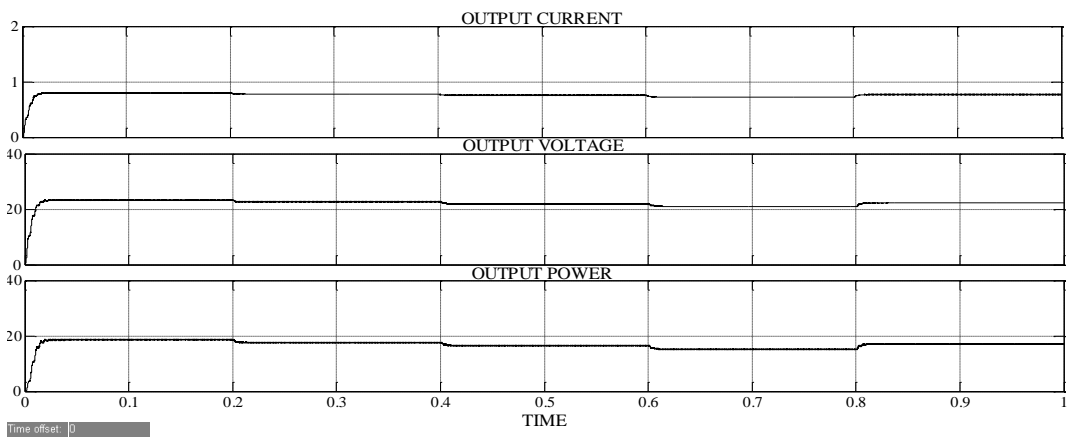


Figure 6.22: Output Current, Voltage and Power at 75°C Temperature and varying Irradiance

6.3.3 With Buck-Boost DC-DC Converter

The figure 6.23 below shows the simulation of MPPT of solar photovoltaic system with Buck-Boost DC-DC Converter using Incremental Conductance Algorithm for a resistive load. The Buck-Boost Converter reduces or boosts the input voltage to a lower value or a higher value of output voltage according to the duty cycle applied to its gate input. It can be seen that the output of the Incremental Conductance algorithm is given to the gate of the Mosfet in the Buck-Boost converter so that whenever there is a change in the irradiance or temperature, the duty cycle of the converter can be adjusted in order to get maximum power at the load side. The simulation has been performed for a progressive change of solar irradiance between 500 and 1000W/m² for different values of temperature.

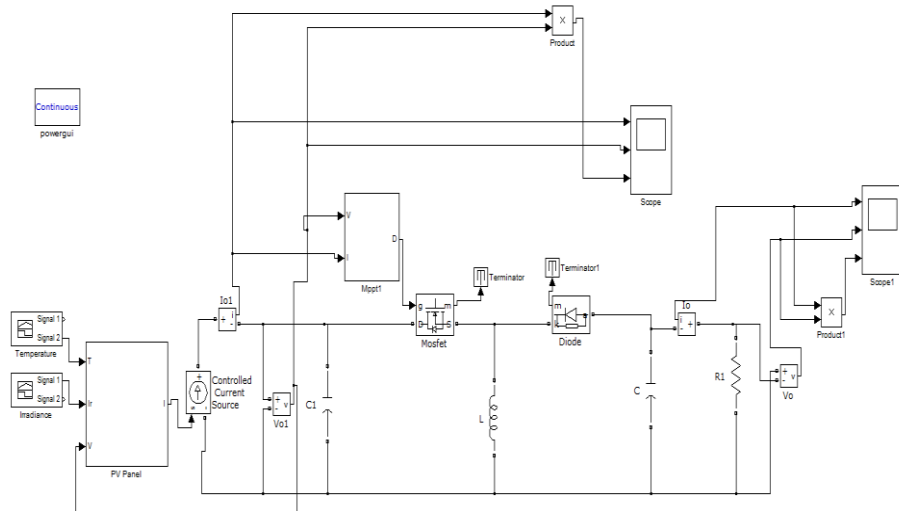


Figure 6.23: Simulation Diagram of PV system with INC Algorithm and Buck-Boost Converter

The figures 6.24, 6.25 and 6.26 below show the output current, voltage and power for irradiance varying between 500W/m^2 and 1000W/m^2 and temperature varying from 25°C to 75°C for a PV System working with a Buck-Boost Converter using Incremental Conductance Algorithm. Since there are no variations in the input side we get output approximately equal to the input under standard conditions i.e. 1000W/m^2 irradiance and 25°C temperature. It can be noticed that the current, voltage and power are at their maximum at 1000W/m^2 and 25°C . They decrease as the value of irradiance decreases and increase as the value of irradiance increases between 500W/m^2 and 1000W/m^2 . It can also be observed that as temperature increases from 25°C to 75°C , the current, voltage and power reduces.

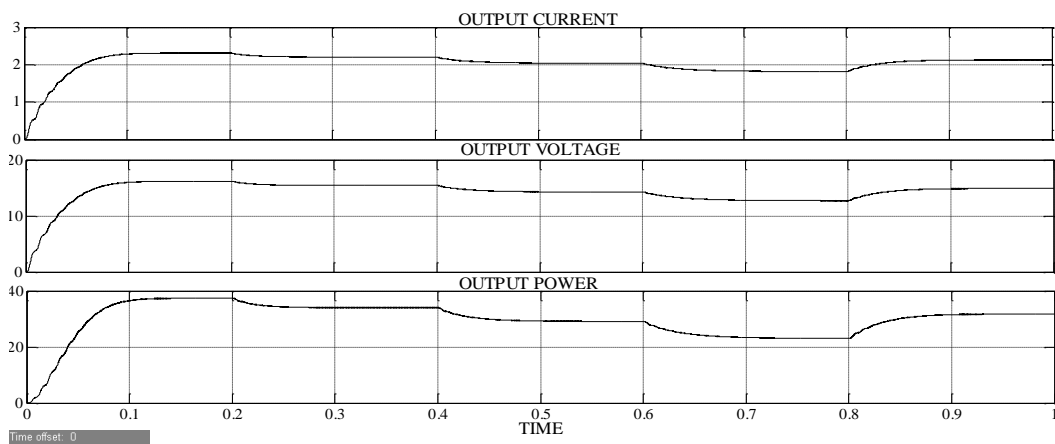


Figure 6.24: Output Current, Voltage and Power at 25°C Temperature and varying Irradiance

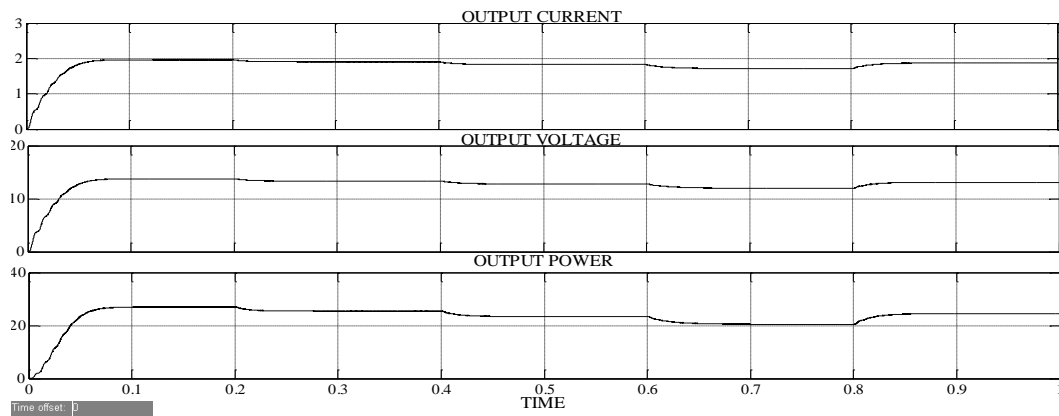


Figure 6.25: Output Current, Voltage and Power at 50°C Temperature and varying Irradiance

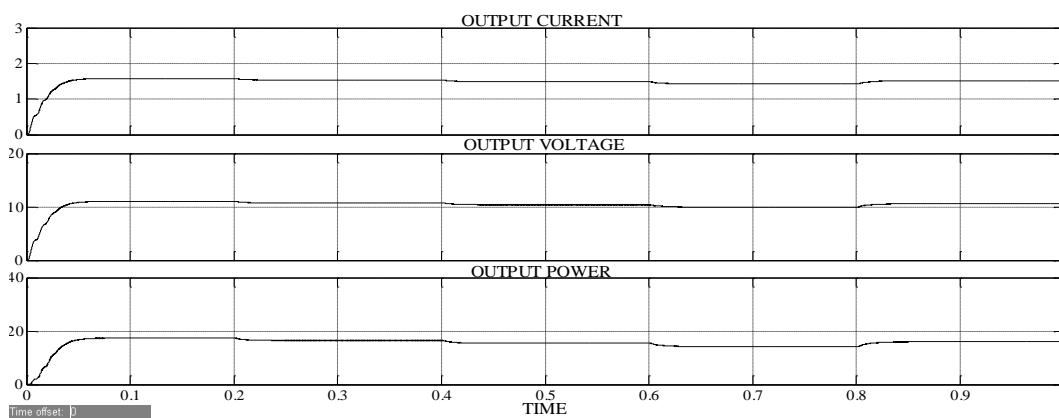


Figure 6.26: Output Current, Voltage and Power at 75°C Temperature and varying Irradiance

6.4 PHOTOVOLTAIC SYSTEM WITH FLC

6.4.1 P-V Slope and change in Slope as inputs

6.4.1.1 With Buck DC-DC Converter

The figure 6.27 below shows the simulation of MPPT of solar photovoltaic system with Buck DC-DC Converter using Fuzzy Logic Control with P-V slope and change in slope as inputs for a resistive load. The Buck Converter reduces the input voltage to a lower value of output voltage according to the duty cycle applied to its gate input. It can be seen that the output of the Fuzzy Logic Controller is given to the gate of the Mosfet in the Buck converter so that whenever there is a change in the irradiance or temperature, the duty cycle of the converter can be adjusted in order to get maximum power at the load side. The simulation has been performed for a

variation of solar irradiance between 500 and 1000W/m² for different values of temperature.

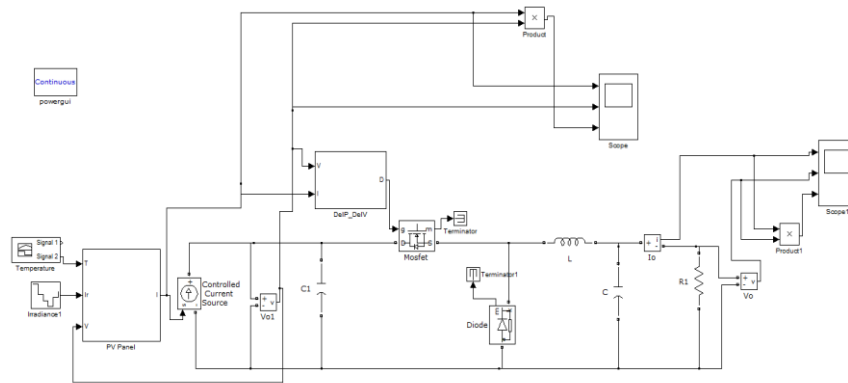


Figure 6.27: Simulation Diagram of PV system with FLC using $S(k)$ and $\Delta S(k)$ as inputs and Buck Converter

The figures 6.28, 6.29 and 6.30 below show the output current, voltage and power for irradiance varying between 500W/m² and 1000W/m² and temperature varying from 25°C to 75°C for a PV System working with a Buck Converter using Fuzzy Logic Control with P-V slope and change in slope as inputs . The system has been designed for a duty cycle of 0.466. Hence, the input voltage of 17.4V has been reduced to 8.2V under standard conditions i.e. 1000w/m² irradiance and 25°C temperature. It can be noticed that the current, voltage and power are at their maximum at 1000W/m² and 25°C. They decrease as the value of irradiance decreases and increase as the value of irradiance increases between 500W/m² and 1000W/m². It can also be observed that as temperature increases from 25°C to 75°C, the current, voltage and power reduces.

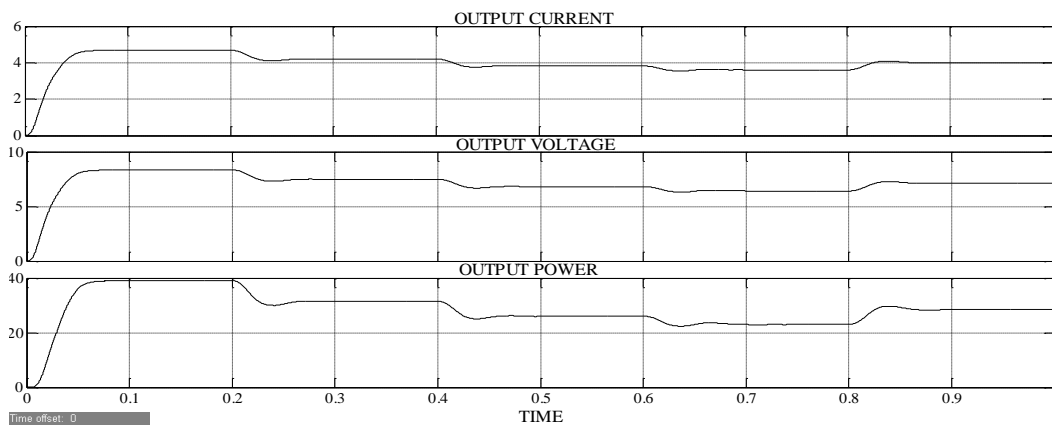


Figure 6.28: Output Current, Voltage and Power at 25°C Temperature and varying Irradiance

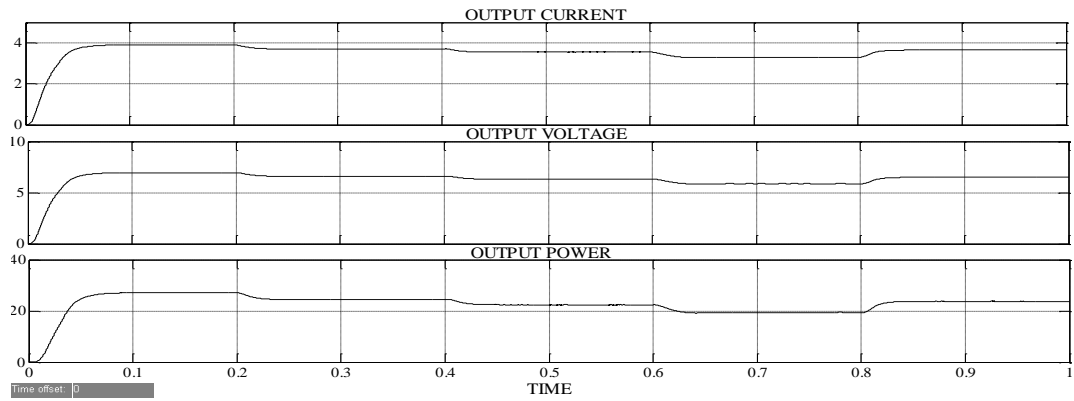


Figure 6.29: Output Current, Voltage and Power at 50°C Temperature and varying Irradiance

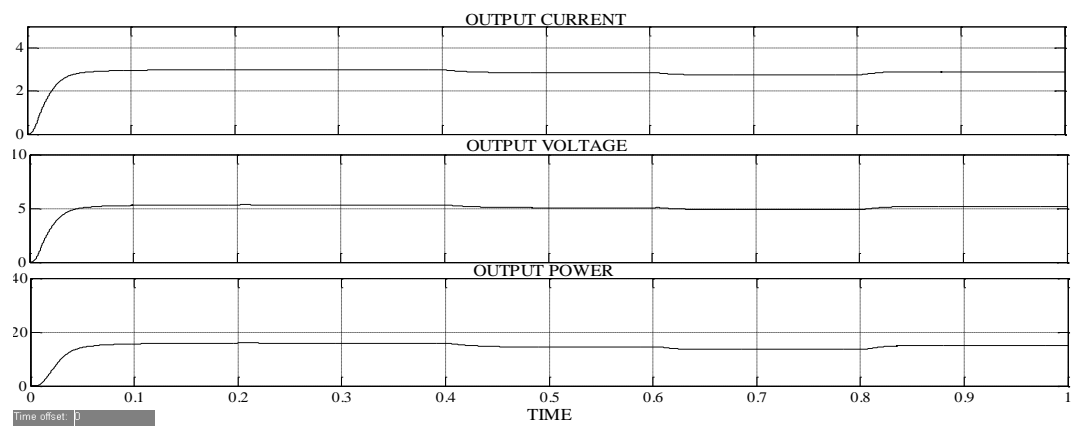


Figure 6.30: Output Current, Voltage and Power at 75°C Temperature and varying Irradiance

6.4.1.2 With Boost DC-DC Converter

The figure 6.31 below shows the simulation of MPPT of solar photovoltaic system with Boost DC-DC Converter using Fuzzy Logic Control with P-V slope and change in slope as inputs for a resistive load. The Boost Converter increases the input voltage to a greater value of output voltage according to the duty cycle applied to its gate input. It can be seen that the output of the Fuzzy Logic Controller is given to the gate of the Mosfet in the Boost converter so that whenever there is a change in the irradiance or temperature, the duty cycle of the converter can be adjusted in order to get maximum power at the load side. The simulation has been performed for a progressive change of solar irradiance between 500 and 1000W/m² for different values of temperature.

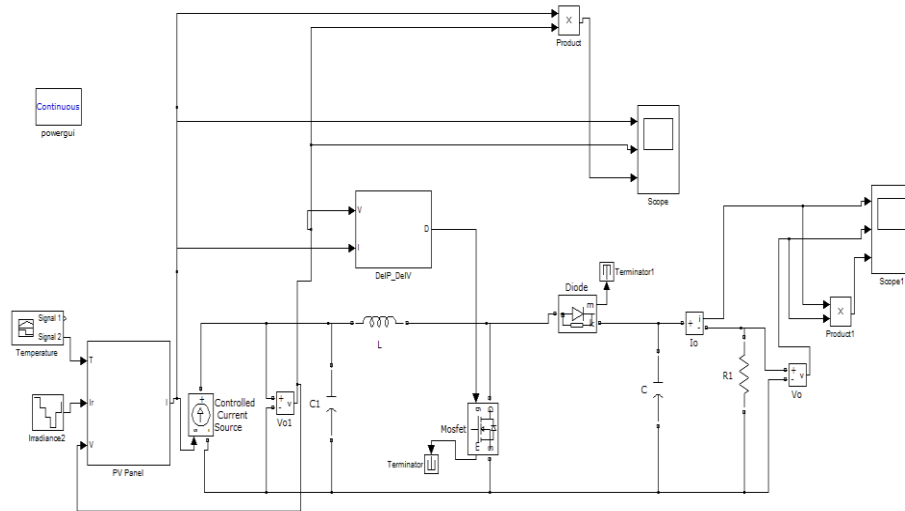


Figure 6.31: Simulation Diagram of PV system with FLC using $S(k)$ and $\Delta S(k)$ as inputs and Boost Converter

The figures 6.32, 6.33 and 6.34 below show the output current, voltage and power for irradiance varying between 500W/m^2 and 1000W/m^2 and temperature varying from 25°C to 75°C for a PV System working with a Boost Converter using Fuzzy Logic Control with P-V slope and change in slope as inputs. The system has been designed for a duty cycle of 0.488. Hence, the input voltage of 17.4V has been boosted to 34V under standard conditions i.e. 1000W/m^2 irradiance and 25°C temperature. It can be noticed that the current, voltage and power are at their maximum at 1000W/m^2 and 25°C . They decrease as the value of irradiance decreases and increase as the value of irradiance increases between 500W/m^2 and 1000W/m^2 . It can also be observed that as temperature increases from 25°C to 75°C , the current, voltage and power reduces.

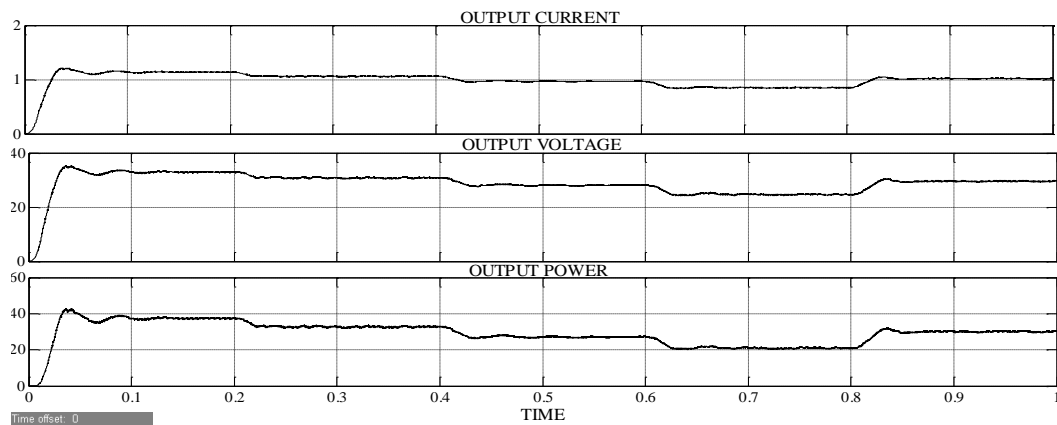


Figure 6.32: Output Current, Voltage and Power at 25°C Temperature and varying Irradiance

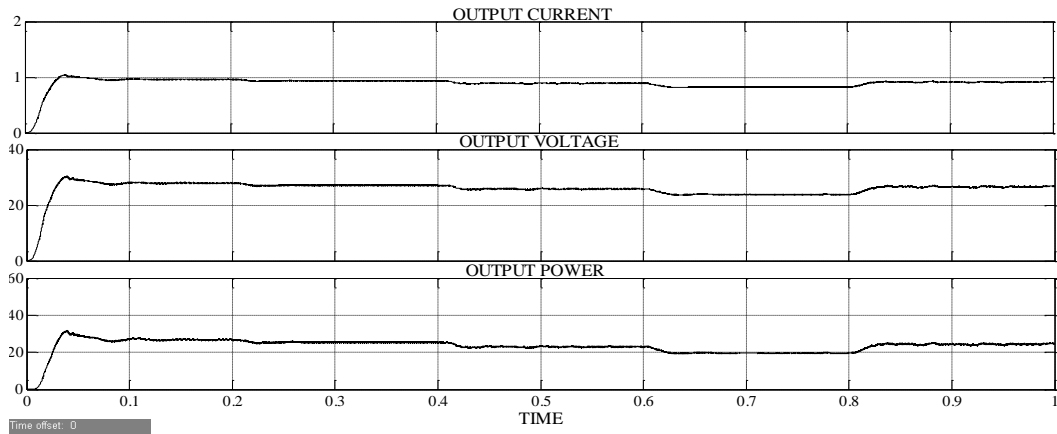


Figure 6.33: Output Current, Voltage and Power at 50°C Temperature and varying Irradiance

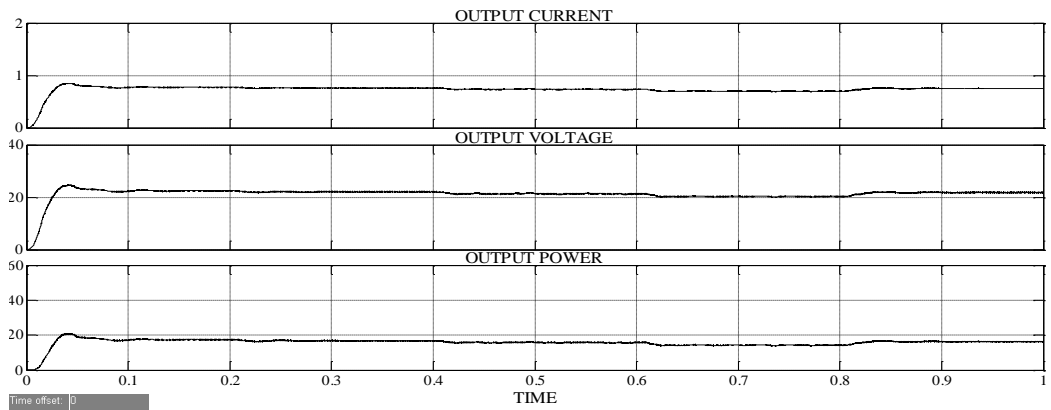


Figure 6.34: Output Current, Voltage and Power at 75°C Temperature and varying Irradiance

6.4.1.3 With Buck-Boost DC-DC Converter

The figure 6.35 below shows the simulation of MPPT of solar photovoltaic system with Buck-Boost DC-DC Converter Fuzzy Logic Control with P-V slope and change in slope as inputs for a resistive load. The Buck-Boost Converter reduces or boosts the input voltage to a lower value or a higher value of output voltage according to the duty cycle applied to its gate input. It can be seen that the output of the Fuzzy Logic Controller is given to the gate of the Mosfet in the Buck-Boost converter so that whenever there is a change in the irradiance or temperature, the duty cycle of the converter can be adjusted in order to get maximum power at the load side. The simulation has been performed for a progressive change of solar irradiance between 500 and 1000W/m² for different values of temperature.

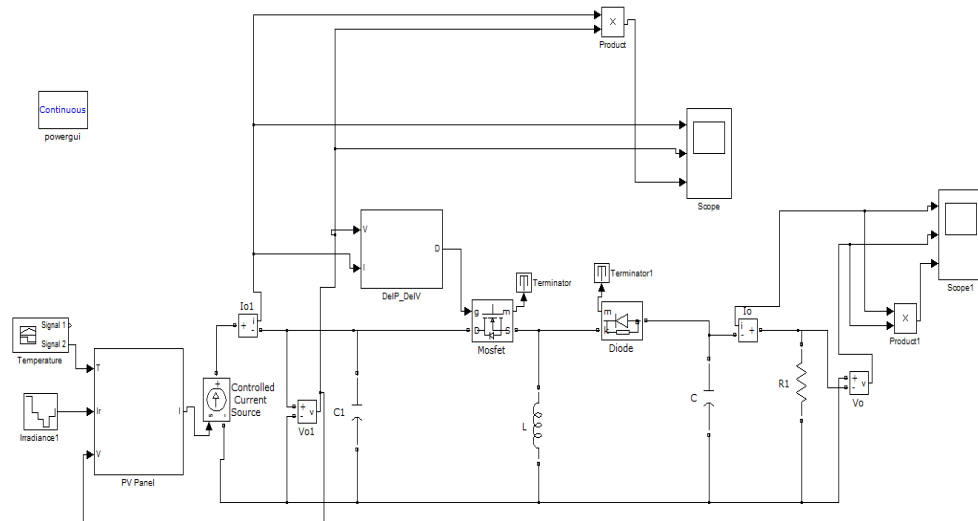


Figure 6.35: Simulation Diagram of PV system with FLC using $S(k)$ and $\Delta S(k)$ as inputs and Buck-Boost Converter

The figures 6.36, 6.37 and 6.38 below show the output current, voltage and power for irradiance varying between 500W/m^2 and 1000W/m^2 and temperature varying from 25°C to 75°C for a PV System working with a Buck-Boost Converter using Fuzzy Logic Control with P-V slope and change in slope as inputs. Since there are no variations in the input side we get output approximately equal to the input under standard conditions i.e. 1000W/m^2 irradiance and 25°C temperature. It can be noticed that the current, voltage and power are at their maximum at 1000W/m^2 and 25°C . They decrease as the value of irradiance decreases and increase as the value of irradiance increases between 500W/m^2 and 1000W/m^2 . It can also be observed that as temperature increases from 25°C to 75°C , the current, voltage and power reduces.

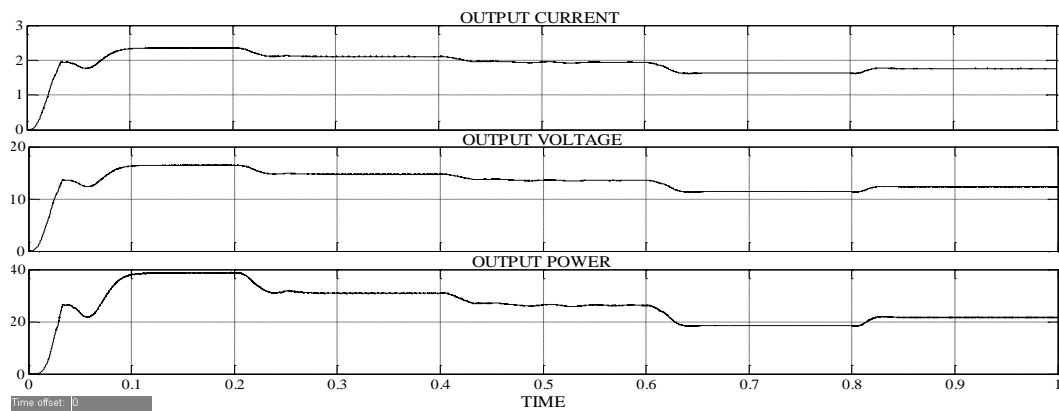


Figure 6.36: Output Current, Voltage and Power at 25°C Temperature and varying Irradiance

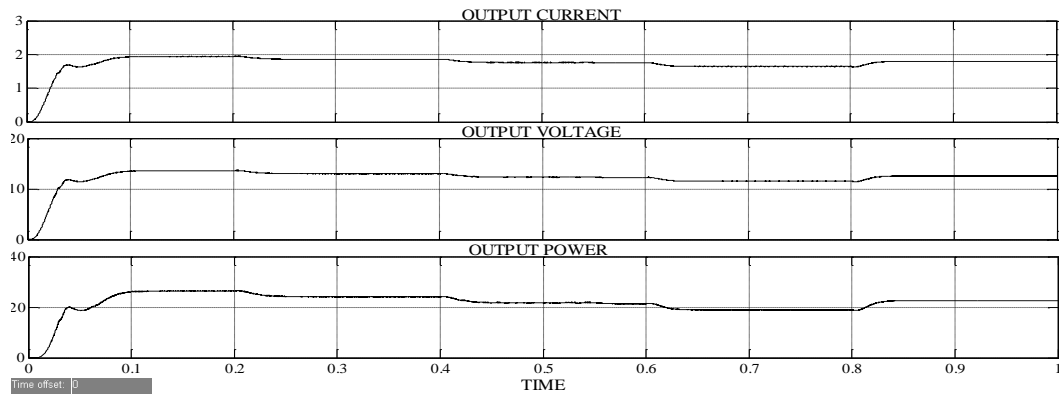


Figure 6.37: Output Current, Voltage and Power at 50°C Temperature and varying Irradiance

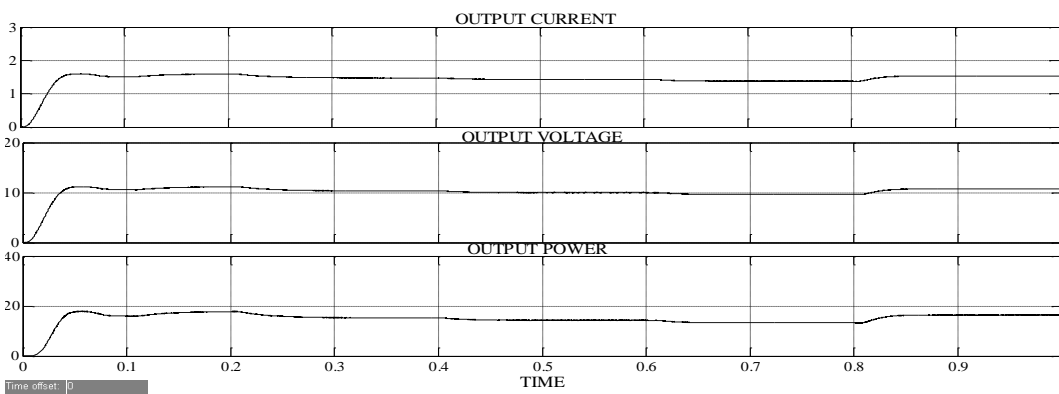


Figure 6.38: Output Current, Voltage and Power at 75°C Temperature and varying Irradiance

6.4.2 P-V Slope and change in power as inputs

6.4.2.1 With Buck DC-DC Converter

The figure 6.39 below shows the simulation of MPPT of solar photovoltaic system with Buck DC-DC Converter using Fuzzy Logic Control with P-V slope and change in power as inputs for a resistive load. The Buck Converter reduces the input voltage to a lower value of output voltage according to the duty cycle applied to its gate input. It can be seen that the output of the Fuzzy Logic Controller is given to the gate of the Mosfet in the Buck converter so that whenever there is a change in the irradiance or temperature, the duty cycle of the converter can be adjusted in order to get maximum power at the load side. The simulation has been performed for a variation of solar irradiance between 500 and 1000W/m² for different values of temperature.

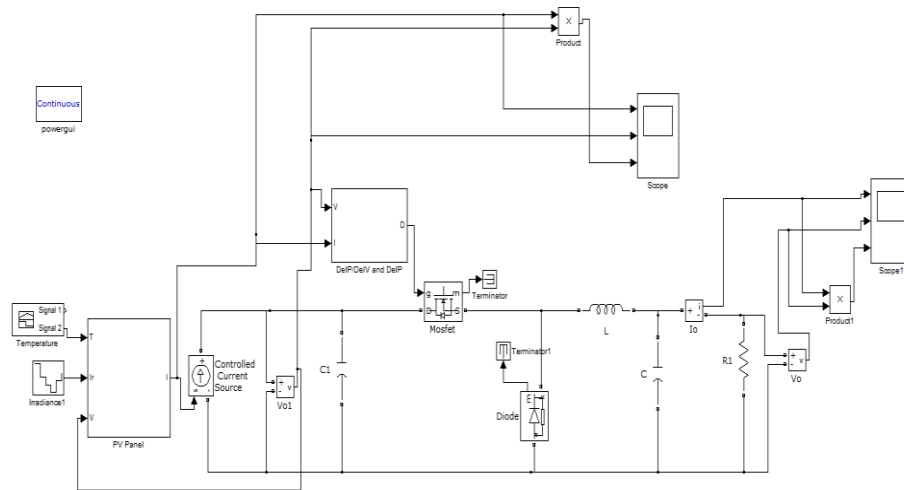


Figure 6.39: Simulation Diagram of PV system with FLC using $S(k)$ and ΔP as inputs and Buck Converter

The figures 6.40, 6.41 and 6.42 below show the output current, voltage and power for irradiance varying between 500W/m^2 and 1000W/m^2 and temperature varying from 25°C to 75°C for a PV System working with a Buck Converter using Fuzzy Logic Control with P-V slope and change in power as inputs. The system has been designed for a duty cycle of 0.466. Hence, the input voltage of 17.4V has been reduced to 8.2V under standard conditions i.e. 1000W/m^2 irradiance and 25°C temperature. It can be noticed that the current, voltage and power are at their maximum at 1000W/m^2 and 25°C . They decrease as the value of irradiance decreases and increase as the value of irradiance increases between 500W/m^2 and 1000W/m^2 . It can also be observed that as temperature increases from 25°C to 75°C , the current, voltage and power reduces.

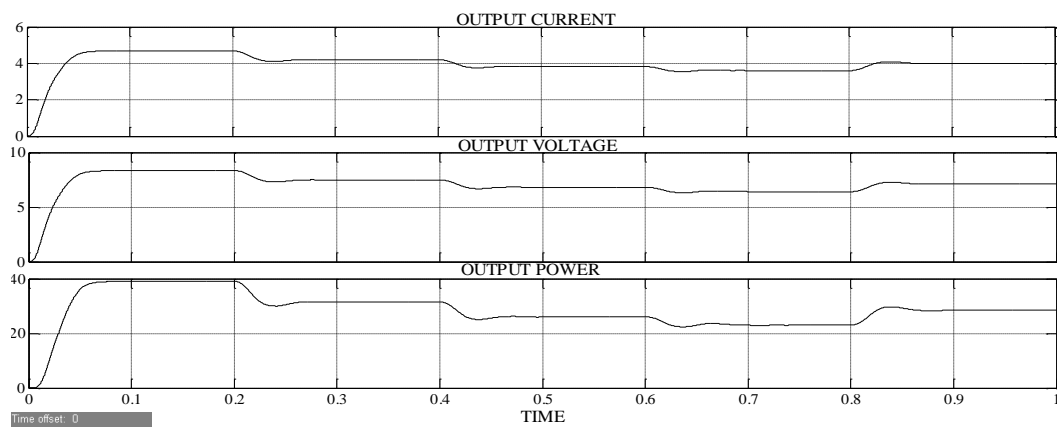


Figure 6.40: Output Current, Voltage and Power at 25°C Temperature and varying Irradiance

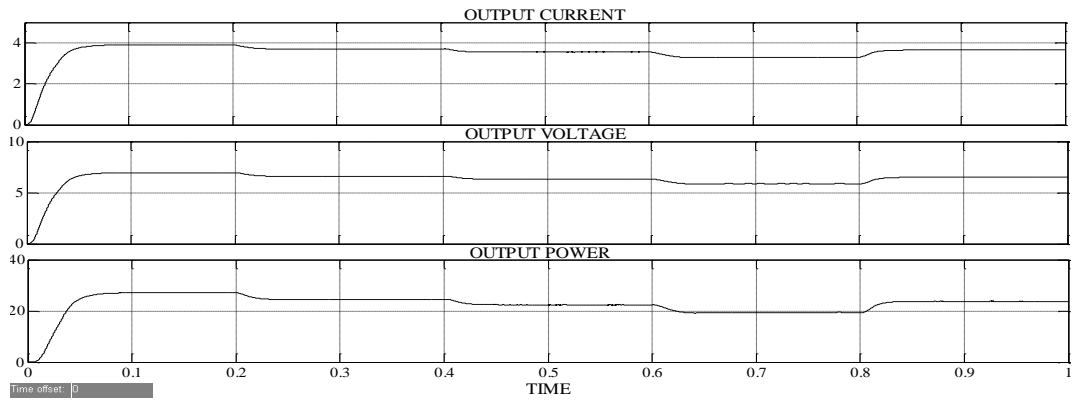


Figure 6.41: Output Current, Voltage and Power at 50°C Temperature and varying Irradiance

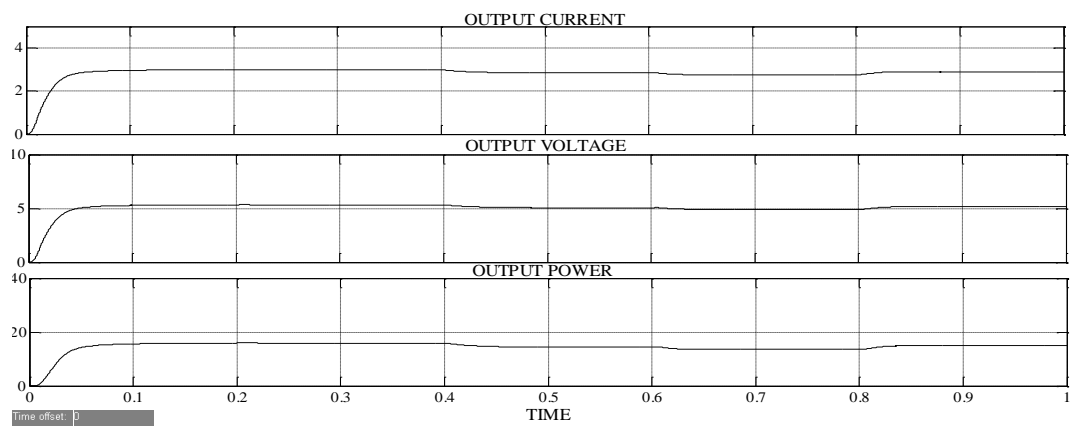


Figure 6.42: Output Current, Voltage and Power at 75°C Temperature and varying Irradiance

6.4.2.2 With Boost DC-DC Converter

The figure 6.43 below shows the simulation of MPPT of solar photovoltaic system with Boost DC-DC Converter using Fuzzy Logic Control with P-V slope and change in power as inputs for a resistive load. The Boost Converter increases the input voltage to a greater value of output voltage according to the duty cycle applied to its gate input. It can be seen that the output of the Fuzzy Logic Controller is given to the gate of the Mosfet in the Boost converter so that whenever there is a change in the irradiance or temperature, the duty cycle of the converter can be adjusted in order to get maximum power at the load side. The simulation has been performed for a progressive change of solar irradiance between 500 and 1000W/m² for different values of temperature.

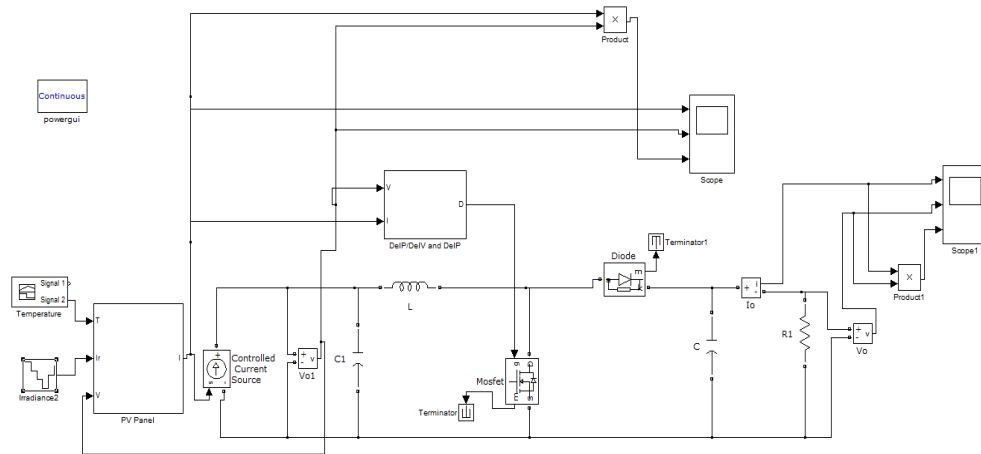


Figure 6.43: Simulation Diagram of PV system with FLC using $S(k)$ and ΔP as inputs and Boost Converter

The figures 6.44, 6.45 and 6.46 below show the output current, voltage and power for irradiance varying between 500W/m^2 and 1000W/m^2 and temperature varying from 25°C to 75°C for a PV System working with a Boost Converter using Fuzzy Logic Control with P-V slope and change in power as inputs. The system has been designed for a duty cycle of 0.488. Hence, the input voltage of 17.4V has been boosted to 34V under standard conditions i.e. 1000W/m^2 irradiance and 25°C temperature. It can be noticed that the current, voltage and power are at their maximum at 1000W/m^2 and 25°C . They decrease as the value of irradiance decreases and increase as the value of irradiance increases between 500W/m^2 and 1000W/m^2 . It can also be observed that as temperature increases from 25°C to 75°C , the current, voltage and power reduces.

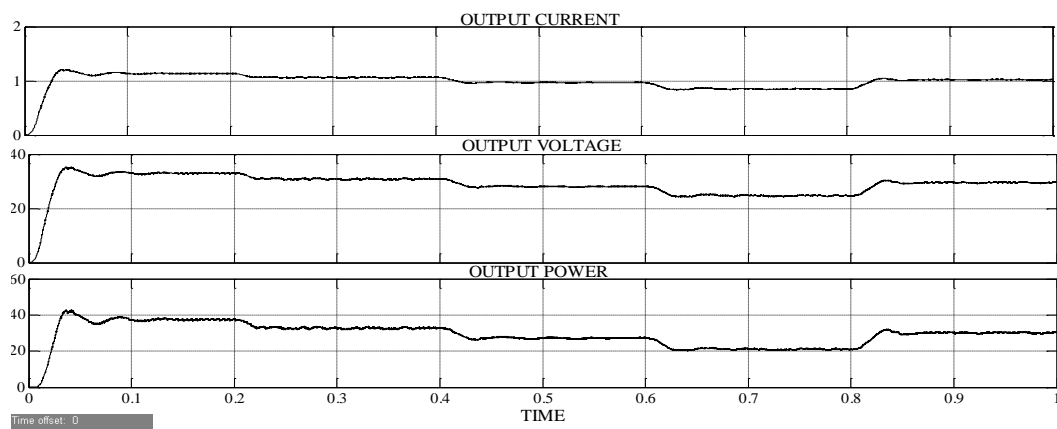


Figure 6.44: Output Current, Voltage and Power at 25°C Temperature and varying Irradiance

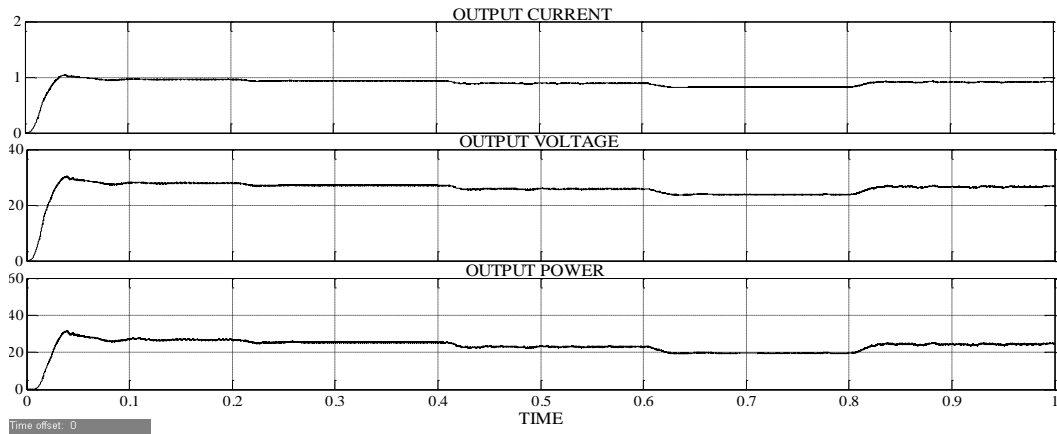


Figure 6.45: Output Current, Voltage and Power at 50°C Temperature and varying Irradiance

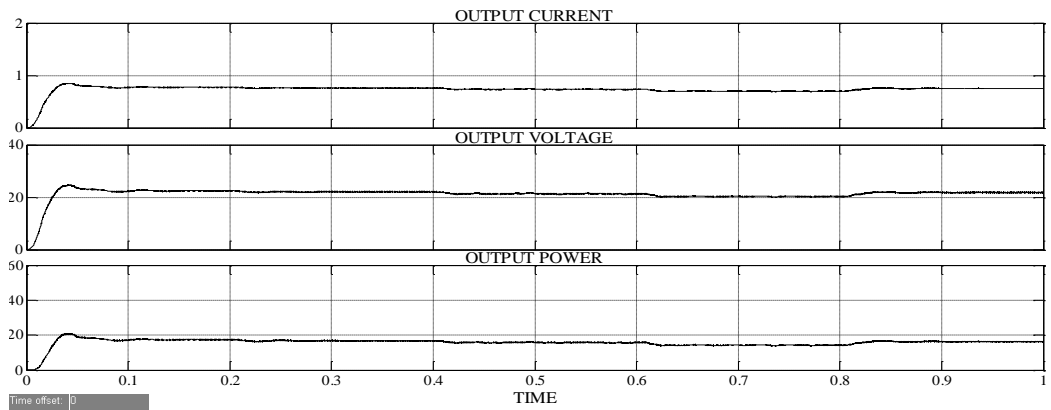


Figure 6.46: Output Current, Voltage and Power at 75°C Temperature and varying Irradiance

6.4.2.3 With Buck-Boost DC-DC Converter

The figure 6.47 below shows the simulation of MPPT of solar photovoltaic system with Buck-Boost DC-DC Converter Fuzzy Logic Control with P-V slope and change in power as inputs for a resistive load. The Buck-Boost Converter reduces or boosts the input voltage to a lower value or a higher value of output voltage according to the duty cycle applied to its gate input. It can be seen that the output of the Fuzzy Logic Controller is given to the gate of the Mosfet in the Buck-Boost converter so that whenever there is a change in the irradiance or temperature, the duty cycle of the converter can be adjusted in order to get maximum power at the load side. The simulation has been performed for a progressive change of solar irradiance between 500 and 1000W/m² for different values of temperature.

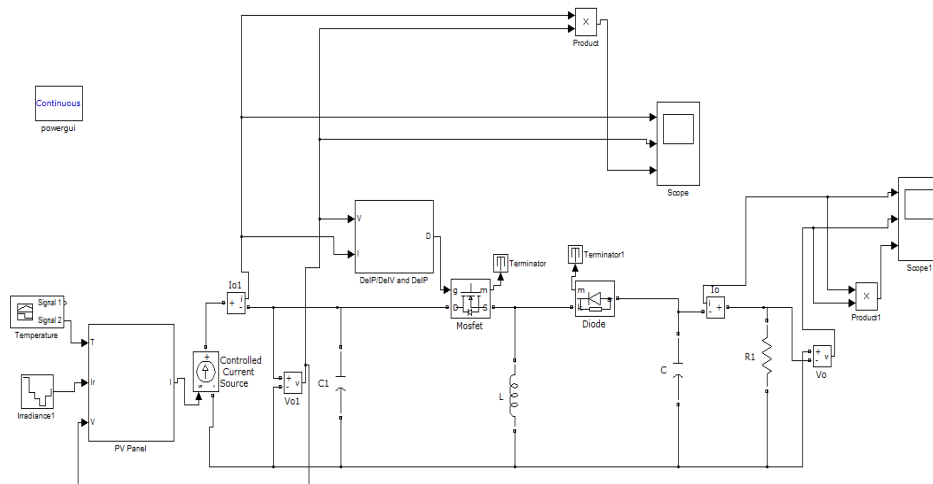


Figure 6.47: Simulation Diagram of PV system with FLC using $S(k)$ and ΔP as inputs and Buck-Boost Converter

The figures 6.48, 6.49 and 6.50 below show the output current, voltage and power for irradiance varying between 500W/m^2 and 1000W/m^2 and temperature varying from 25°C to 75°C for a PV System working with a Buck-Boost Converter using Fuzzy Logic Control with P-V slope and change in power as inputs. Since there are no variations in the input side we get output approximately equal to the input under standard conditions i.e. 1000W/m^2 irradiance and 25°C temperature. It can be noticed that the current, voltage and power are at their maximum at 1000W/m^2 and 25°C . They decrease as the value of irradiance decreases and increase as the value of irradiance increases between 500W/m^2 and 1000W/m^2 . It can also be observed that as temperature increases from 25°C to 75°C , the current, voltage and power reduces.

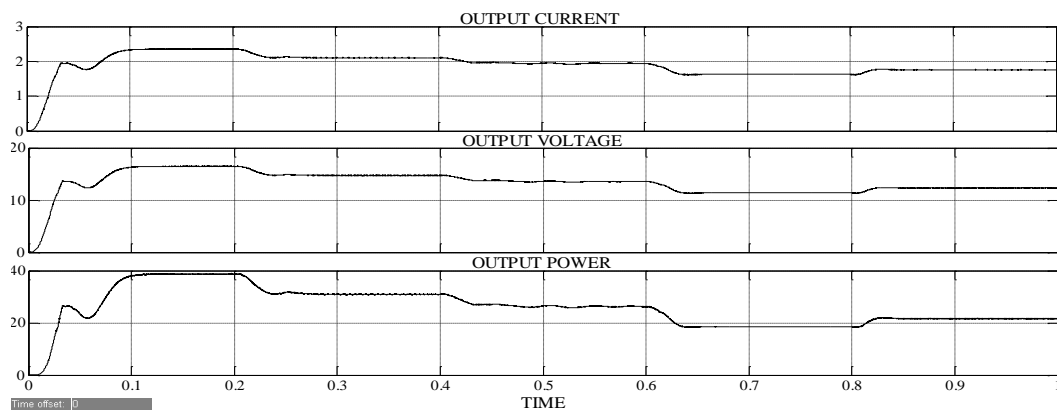


Figure 6.48: Output Current, Voltage and Power at 25°C Temperature and varying Irradiance

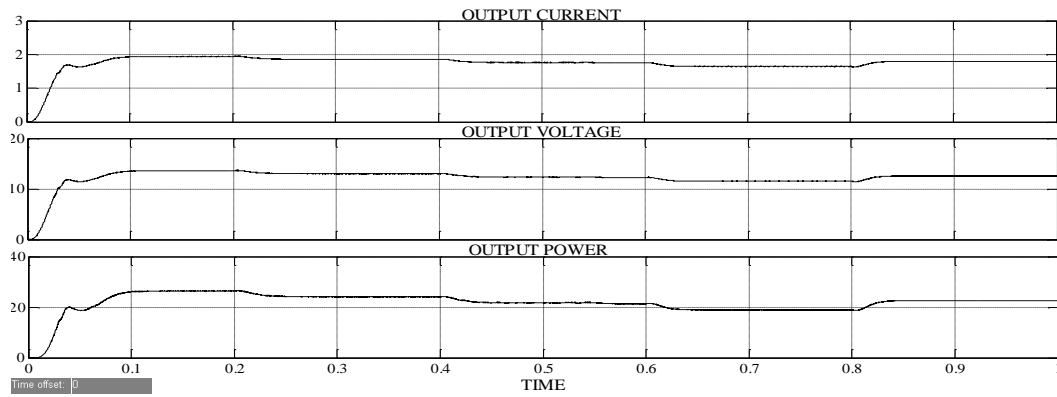


Figure 6.49: Output Current, Voltage and Power at 50°C Temperature and varying Irradiance

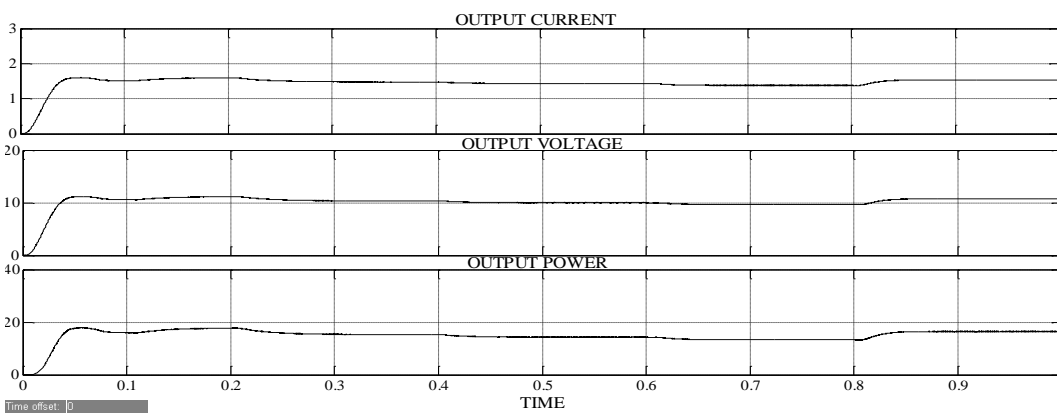


Figure 6.50: Output Current, Voltage and Power at 75°C Temperature and varying Irradiance

6.4.3 Change in Power and change in Voltage as inputs

6.4.3.1 With Buck DC-DC Converter

The figure 6.51 below shows the simulation of MPPT of solar photovoltaic system with Buck DC-DC Converter using Fuzzy Logic Control with change in power and change in voltage as inputs for a resistive load. The Buck Converter reduces the input voltage to a lower value of output voltage according to the duty cycle applied to its gate input. It can be seen that the output of the Fuzzy Logic Controller is given to the gate of the Mosfet in the Buck converter so that whenever there is a change in the irradiance or temperature, the duty cycle of the converter can be adjusted in order to get maximum power at the load side. The simulation has been performed for a variation of solar irradiance between 500 and 1000W/m² for different values of temperature.

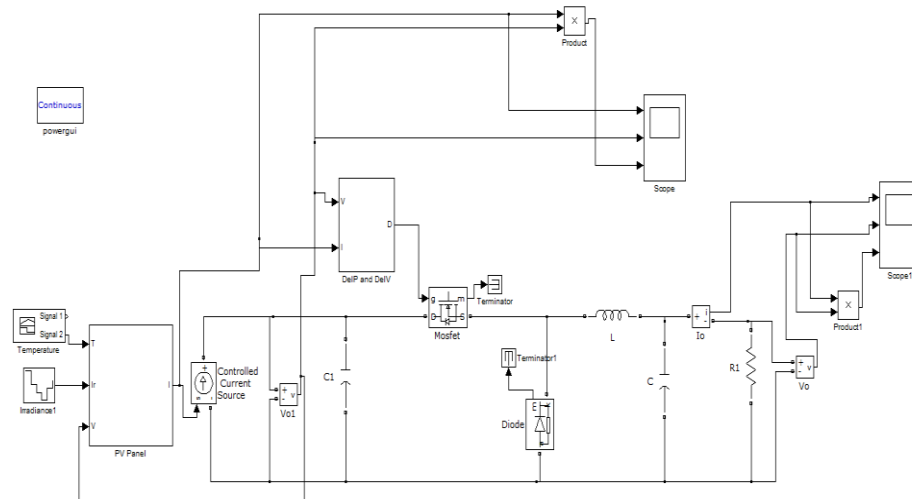


Figure 6.51: Simulation Diagram of PV system with FLC using ΔP and ΔV as inputs and Buck Converter

The figures 6.52, 6.53 and 6.54 below show the output current, voltage and power for irradiance varying between 500W/m^2 and 1000W/m^2 and temperature varying from 25°C to 75°C for a PV System working with a Buck Converter using Fuzzy Logic Control with change in power and change in voltage as inputs. The system has been designed for a duty cycle of 0.466. Hence, the input voltage of 17.4V has been reduced to 8.2V under standard conditions i.e. 1000W/m^2 irradiance and 25°C temperature. It can be noticed that the current, voltage and power are at their maximum at 1000W/m^2 and 25°C . They decrease as the value of irradiance decreases and increase as the value of irradiance increases between 500W/m^2 and 1000W/m^2 . It can also be observed that as temperature increases from 25°C to 75°C , the current, voltage and power reduces.

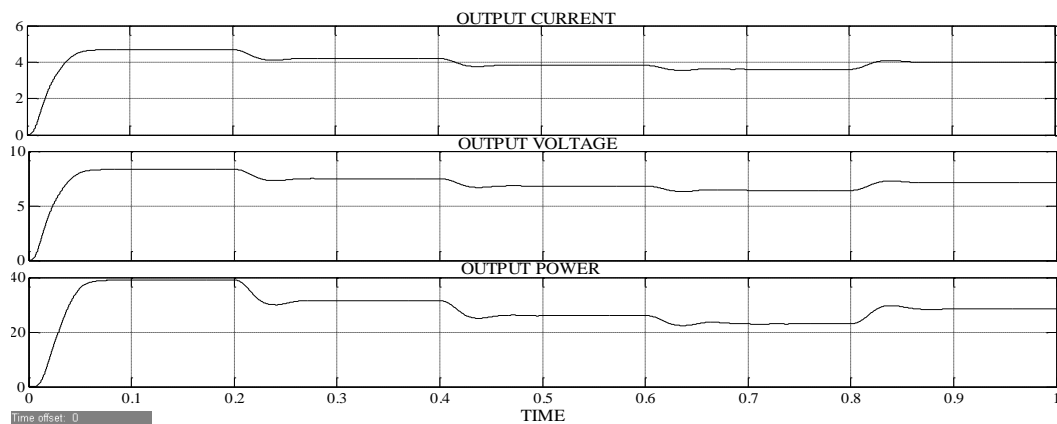


Figure 6.52: Output Current, Voltage and Power at 25°C Temperature and varying Irradiance

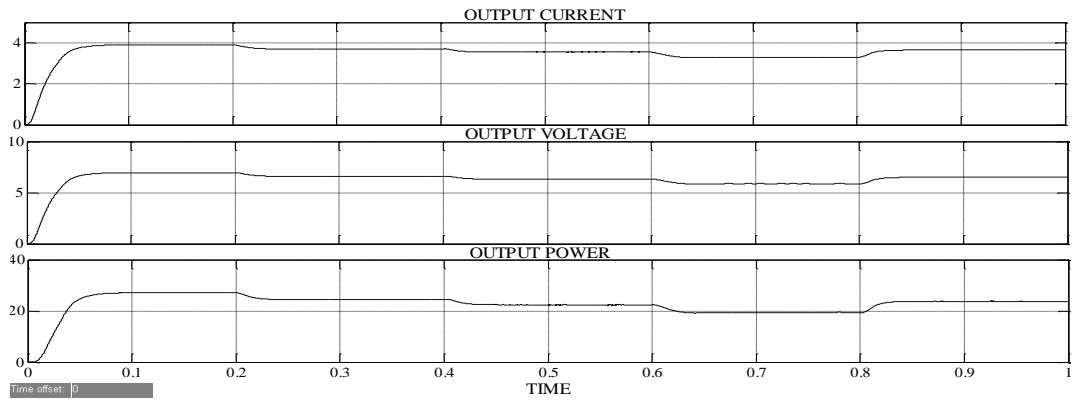


Figure 6.53: Output Current, Voltage and Power at 50°C Temperature and varying Irradiance

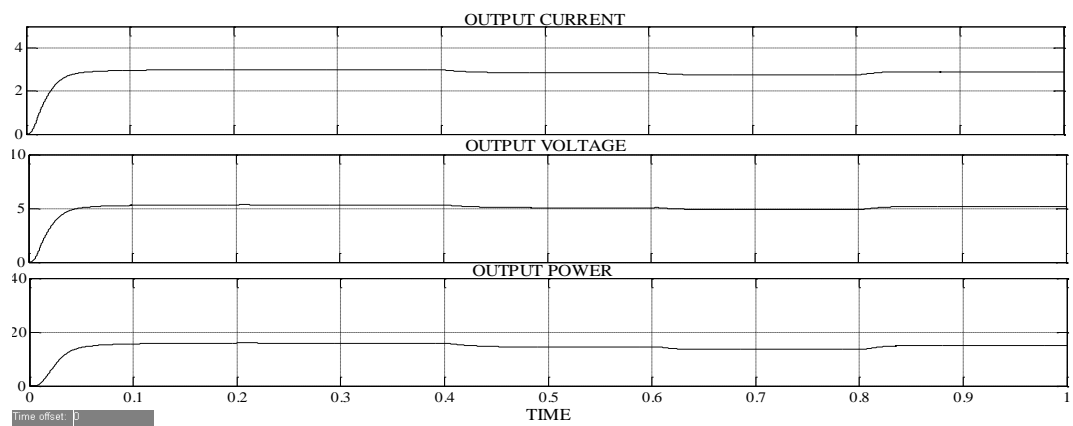


Figure 6.54: Output Current, Voltage and Power at 75°C Temperature and varying Irradiance

6.4.3.2 With Boost DC-DC Converter

The figure 6.55 below shows the simulation of MPPT of solar photovoltaic system with Boost DC-DC Converter using Fuzzy Logic Control with change in power and change in voltage as inputs for a resistive load. The Boost Converter increases the input voltage to a greater value of output voltage according to the duty cycle applied to its gate input. It can be seen that the output of the Fuzzy Logic Controller is given to the gate of the Mosfet in the Boost converter so that whenever there is a change in the irradiance or temperature, the duty cycle of the converter can be adjusted in order to get maximum power at the load side. The simulation has been performed for a progressive change of solar irradiance between 500 and 1000W/m² for different values of temperature.

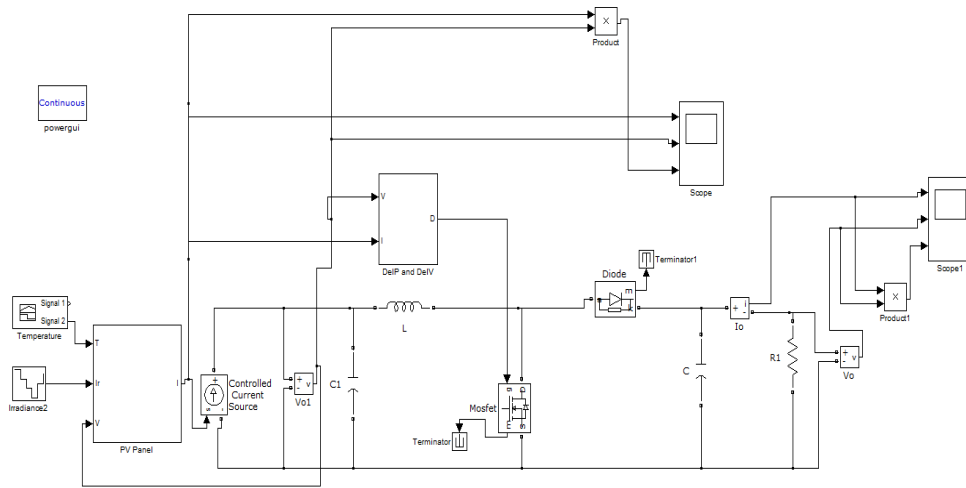


Figure 6.55: Simulation Diagram of PV system with FLC using ΔP and ΔV as inputs and Boost Converter

The figures 6.56, 6.57 and 6.58 below show the output current, voltage and power for irradiance varying between 500W/m^2 and 1000W/m^2 and temperature varying from 25°C to 75°C for a PV System working with a Boost Converter using Fuzzy Logic Control with change in power and change in voltage as inputs. The system has been designed for a duty cycle of 0.488. Hence, the input voltage of 17.4V has been boosted to 34V under standard conditions i.e. 1000W/m^2 irradiance and 25°C temperature. It can be noticed that the current, voltage and power are at their maximum at 1000W/m^2 and 25°C . They decrease as the value of irradiance decreases and increase as the value of irradiance increases between 500W/m^2 and 1000W/m^2 . It can also be observed that as temperature increases from 25°C to 75°C , the current, voltage and power reduces.

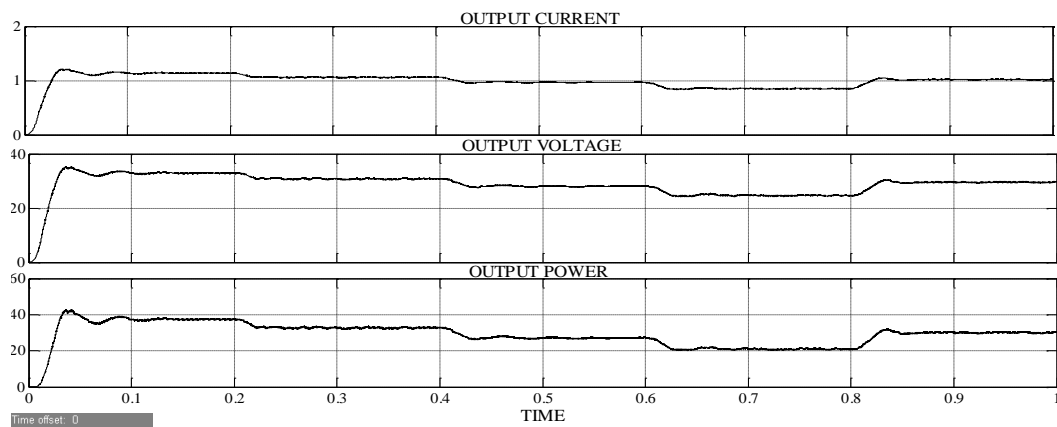


Figure 6.56: Output Current, Voltage and Power at 25°C Temperature and varying Irradiance

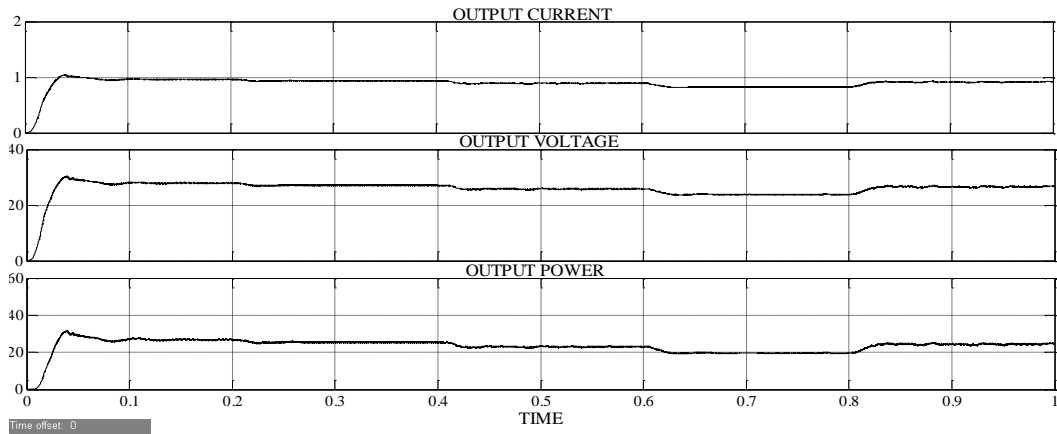


Figure 6.57: Output Current, Voltage and Power at 50°C Temperature and varying Irradiance

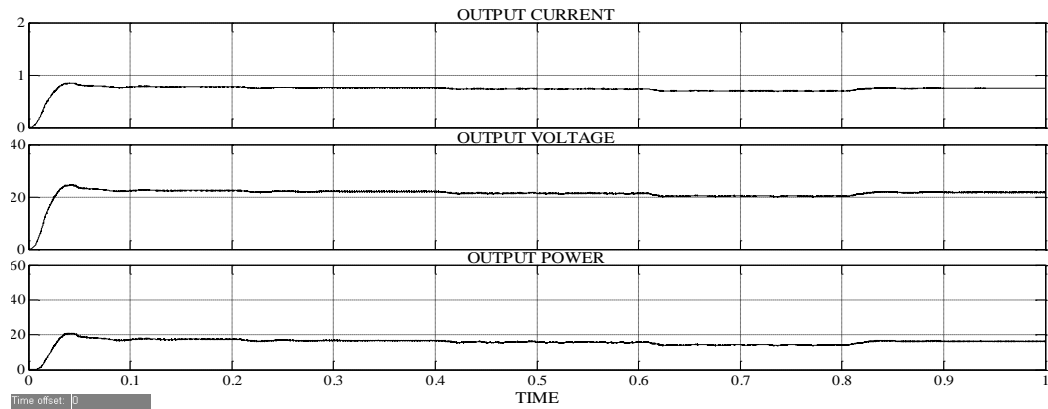


Figure 6.58: Output Current, Voltage and Power at 75°C Temperature and varying Irradiance

6.4.3.3 With Buck-Boost DC-DC Converter

The figure 6.59 below shows the simulation of MPPT of solar photovoltaic system with Buck-Boost DC-DC Converter Fuzzy Logic Control with change in power and change in voltage as inputs for a resistive load. The Buck-Boost Converter reduces or boosts the input voltage to a lower value or a higher value of output voltage according to the duty cycle applied to its gate input. It can be seen that the output of the Fuzzy Logic Controller is given to the gate of the Mosfet in the Buck-Boost converter so that whenever there is a change in the irradiance or temperature, the duty cycle of the converter can be adjusted in order to get maximum power at the load side. The simulation has been performed for a progressive change of solar irradiance between 500 and 1000W/m² for different values of temperature.

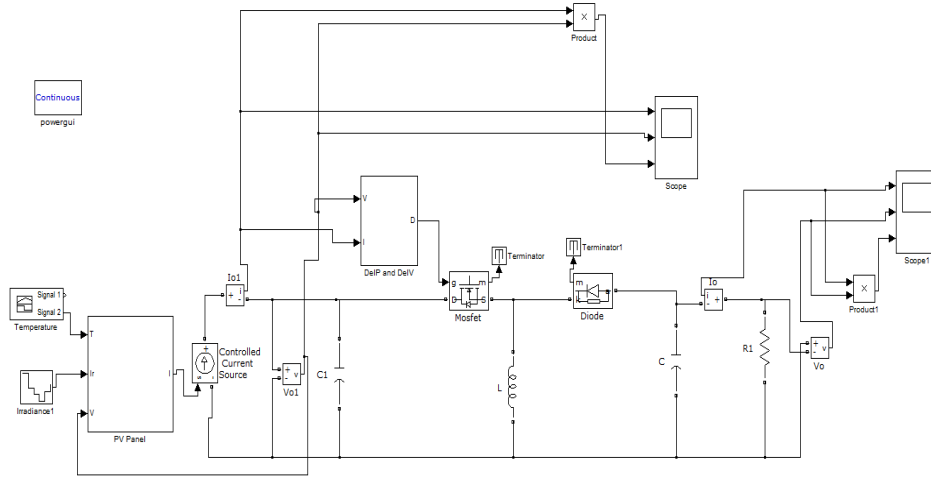


Figure 6.59: Simulation Diagram of PV system with FLC using ΔP and ΔV as inputs and Buck-Boost Converter

The figures 6.60, 6.61 and 6.62 below show the output current, voltage and power for irradiance varying between 500W/m^2 and 1000W/m^2 and temperature varying from 25°C to 75°C for a PV System working with a Buck-Boost Converter using Fuzzy Logic Control with change in power and change in voltage as inputs. Since there are no variations in the input side we get output approximately equal to the input under standard conditions i.e. 1000W/m^2 irradiance and 25°C temperature. It can be noticed that the current, voltage and power are at their maximum at 1000W/m^2 and 25°C . They decrease as the value of irradiance decreases and increase as the value of irradiance increases between 500W/m^2 and 1000W/m^2 . It can also be observed that as temperature increases from 25°C to 75°C , the current, voltage and power reduces.

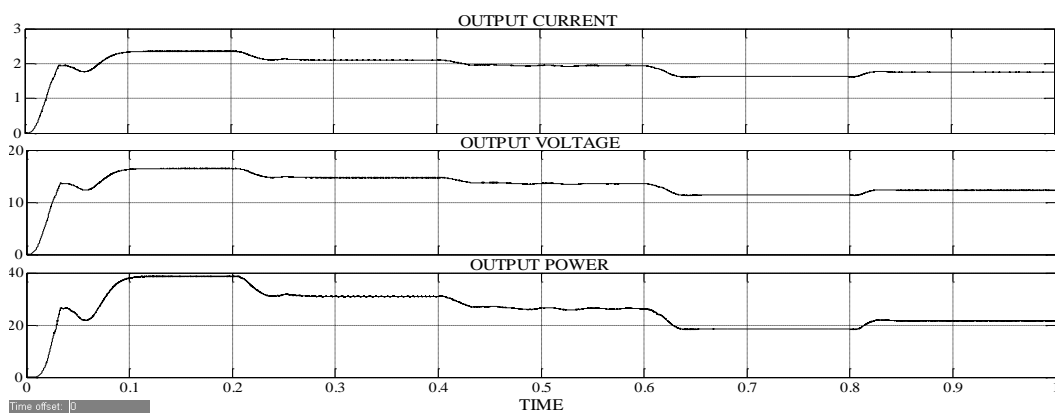


Figure 6.60: Output Current, Voltage and Power at 25°C Temperature and varying Irradiance

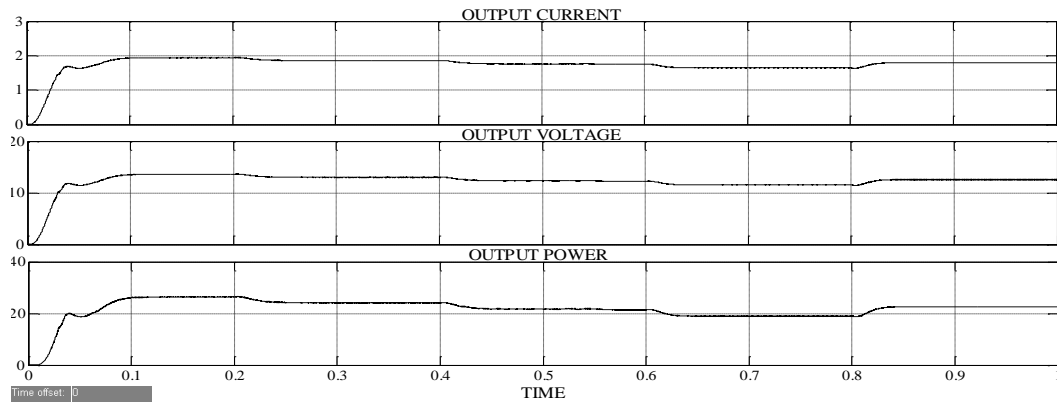


Figure 6.61: Output Current, Voltage and Power at 50°C Temperature and varying Irradiance

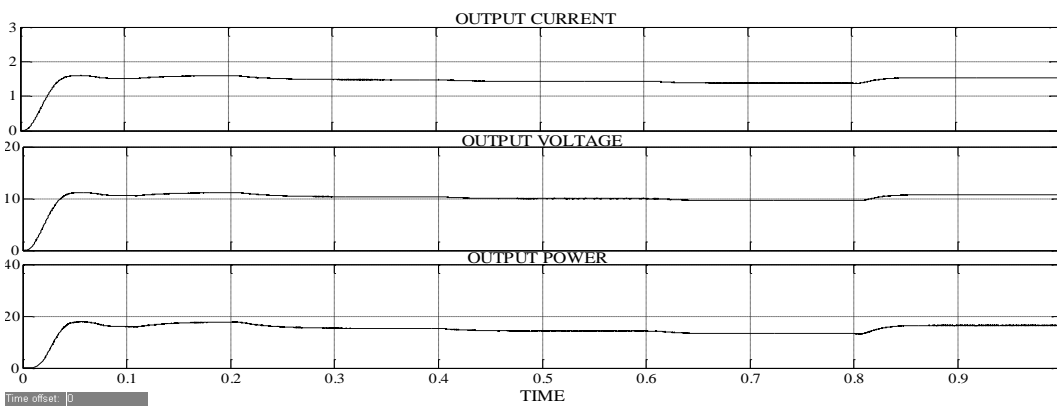


Figure 6.62: Output Current, Voltage and Power at 75°C Temperature and varying Irradiance

6.4.4 Change in Power and change in Current as inputs

6.4.4.1 With Buck DC-DC Converter

The figure 6.63 below shows the simulation of MPPT of solar photovoltaic system with Buck DC-DC Converter using Fuzzy Logic Control with change in power and change in current as inputs for a resistive load. The Buck Converter reduces the input voltage to a lower value of output voltage according to the duty cycle applied to its gate input. It can be seen that the output of the Fuzzy Logic Controller is given to the gate of the Mosfet in the Buck converter so that whenever there is a change in the irradiance or temperature, the duty cycle of the converter can be adjusted in order to get maximum power at the load side. The simulation has been performed for a variation of solar irradiance between 500 and 1000W/m² for different values of temperature.

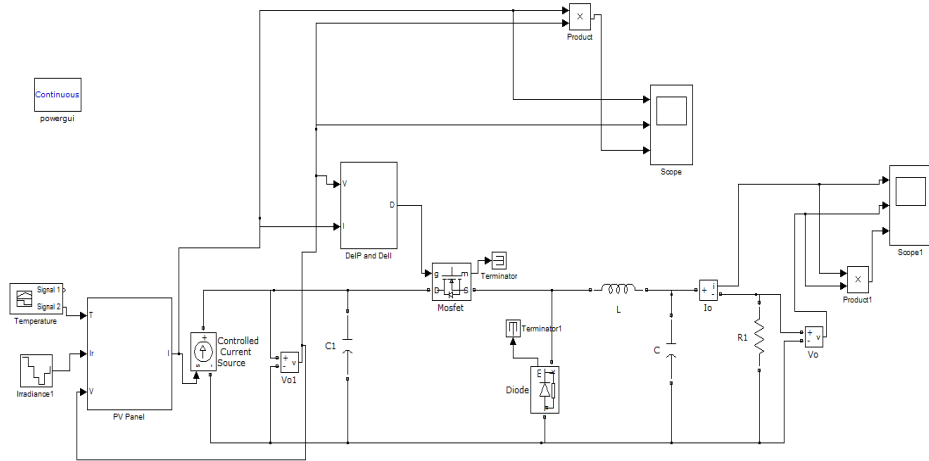


Figure 6.63: Simulation Diagram of PV system with FLC using ΔP and ΔI as inputs and Buck Converter

The figures 6.64, 6.65 and 6.66 below show the output current, voltage and power for irradiance varying between $500\text{W}/\text{m}^2$ and $1000\text{W}/\text{m}^2$ and temperature varying from 25°C to 75°C for a PV System working with a Buck Converter using Fuzzy Logic Control with change in power and change in current as inputs. The system has been designed for a duty cycle of 0.466. Hence, the input voltage of 17.4V has been reduced to 8.2V under standard conditions i.e. $1000\text{W}/\text{m}^2$ irradiance and 25°C temperature. It can be noticed that the current, voltage and power are at their maximum at $1000\text{W}/\text{m}^2$ and 25°C . They decrease as the value of irradiance decreases and increase as the value of irradiance increases between $500\text{W}/\text{m}^2$ and $1000\text{W}/\text{m}^2$. It can also be observed that as temperature increases from 25°C to 75°C , the current, voltage and power reduces.

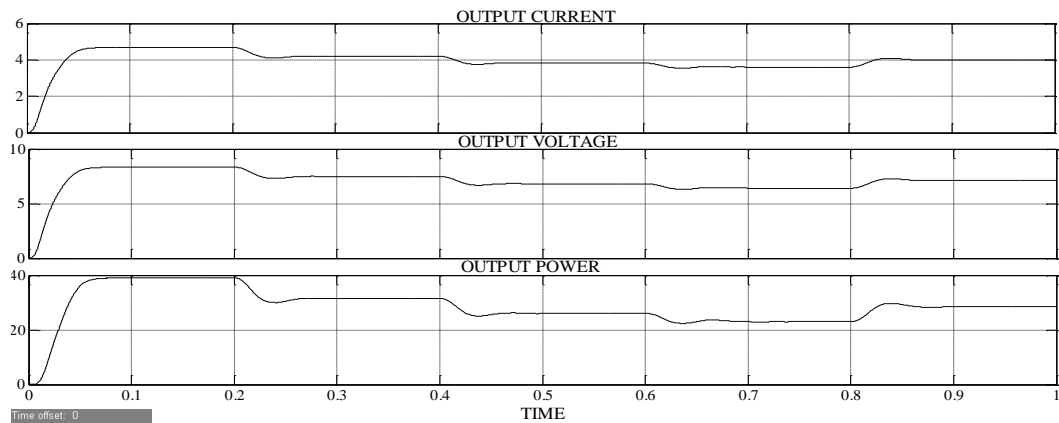


Figure 6.64: Output Current, Voltage and Power at 25°C Temperature and varying Irradiance

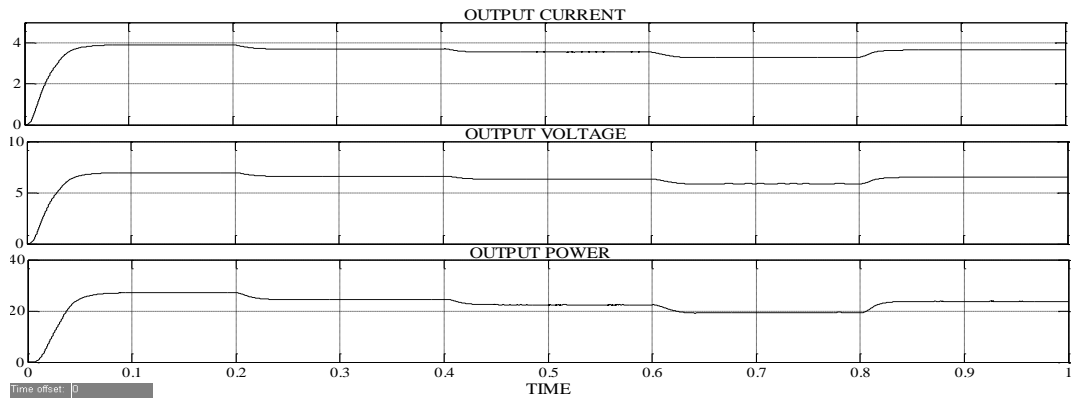


Figure 6.65: Output Current, Voltage and Power at 50°C Temperature and varying Irradiance

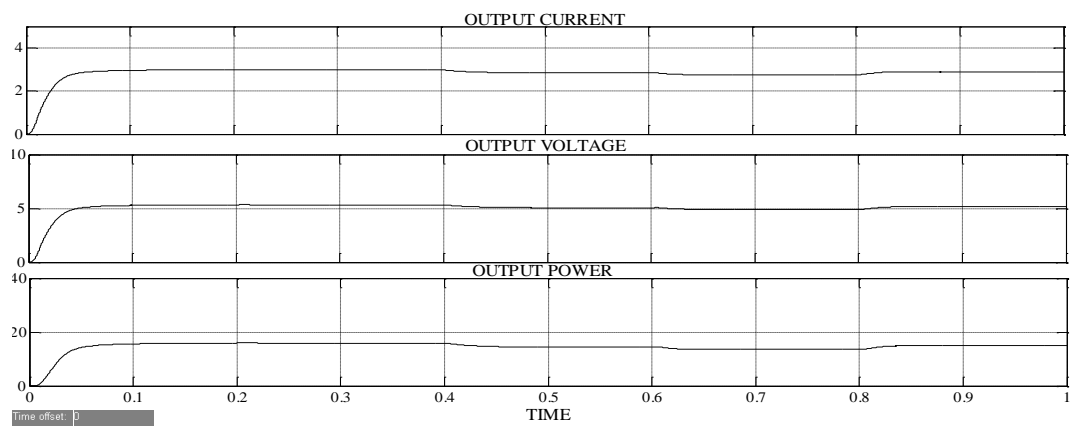


Figure 6.66: Output Current, Voltage and Power at 75°C Temperature and varying Irradiance

6.4.4.2 With Boost DC-DC Converter

The figure 6.67 below shows the simulation of MPPT of solar photovoltaic system with Boost DC-DC Converter using Fuzzy Logic Control with change in power and change in current as inputs for a resistive load. The Boost Converter increases the input voltage to a greater value of output voltage according to the duty cycle applied to its gate input. It can be seen that the output of the Fuzzy Logic Controller is given to the gate of the Mosfet in the Boost converter so that whenever there is a change in the irradiance or temperature, the duty cycle of the converter can be adjusted in order to get maximum power at the load side. The simulation has been performed for a progressive change of solar irradiance between 500 and 1000W/m² for different values of temperature.

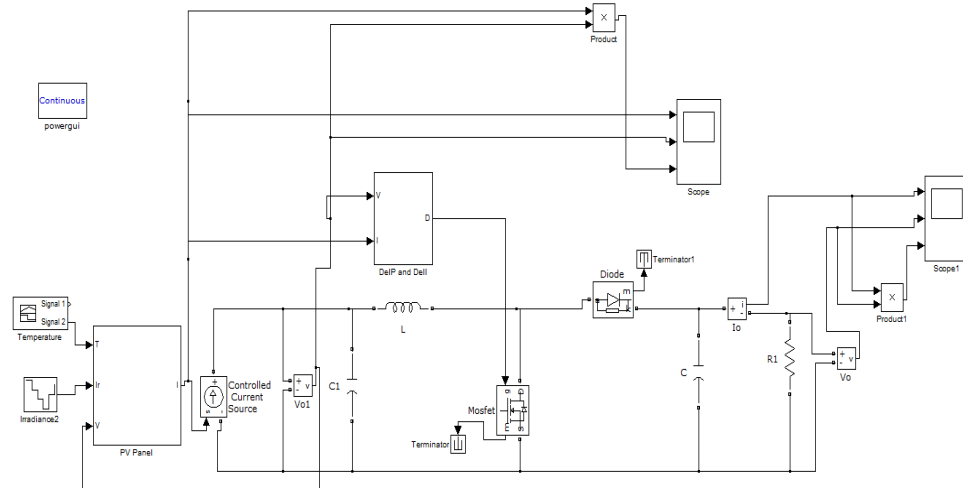


Figure 6.67: Simulation Diagram of PV system with FLC using ΔP and ΔI as inputs and Boost Converter

The figures 6.68, 6.69 and 6.70 below show the output current, voltage and power for irradiance varying between 500W/m^2 and 1000W/m^2 and temperature varying from 25°C to 75°C for a PV System working with a Boost Converter using Fuzzy Logic Control with change in power and change in current as inputs. The system has been designed for a duty cycle of 0.488. Hence, the input voltage of 17.4V has been boosted to 34V under standard conditions i.e. 1000W/m^2 irradiance and 25°C temperature. It can be noticed that the current, voltage and power are at their maximum at 1000W/m^2 and 25°C . They decrease as the value of irradiance decreases and increase as the value of irradiance increases between 500W/m^2 and 1000W/m^2 . It can also be observed that as temperature increases from 25°C to 75°C , the current, voltage and power reduces.

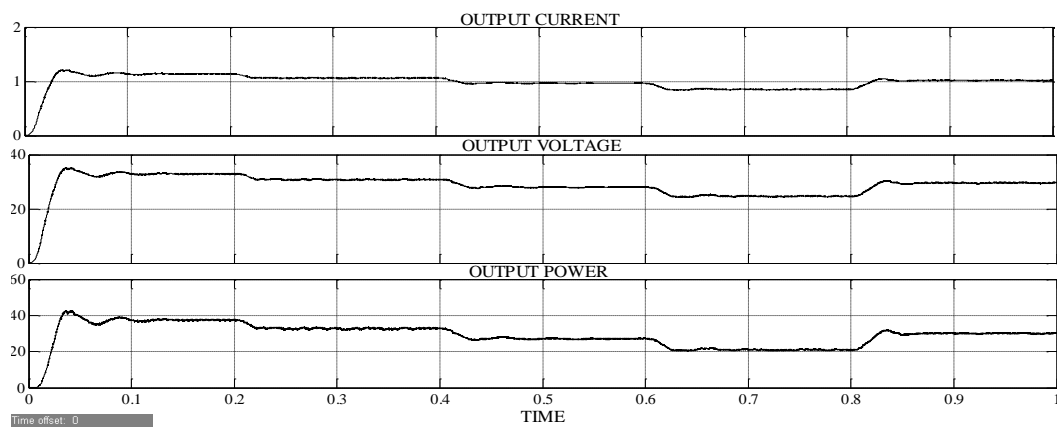


Figure 6.68: Output Current, Voltage and Power at 25°C Temperature and varying Irradiance

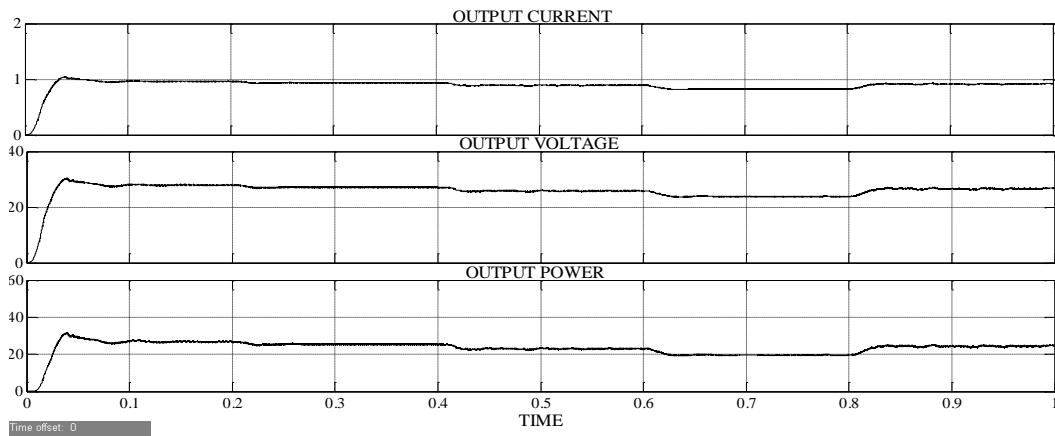


Figure 6.69: Output Current, Voltage and Power at 50°C Temperature and varying Irradiance

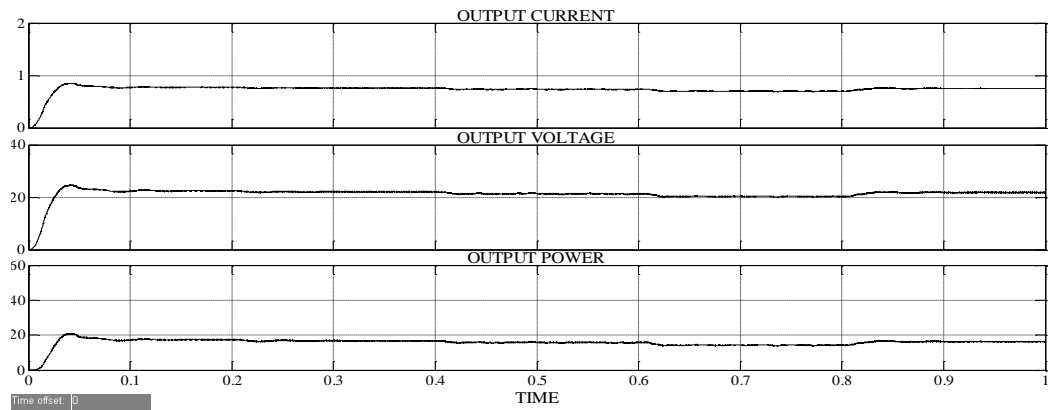


Figure 6.70: Output Current, Voltage and Power at 75°C Temperature and varying Irradiance

6.4.4.3 With Buck-Boost DC-DC Converter

The figure 6.71 below shows the simulation of MPPT of solar photovoltaic system with Buck-Boost DC-DC Converter Fuzzy Logic Control with change in power and change in current as inputs for a resistive load. The Buck-Boost Converter reduces or boosts the input voltage to a lower value or a higher value of output voltage according to the duty cycle applied to its gate input. It can be seen that the output of the Fuzzy Logic Controller is given to the gate of the Mosfet in the Buck-Boost converter so that whenever there is a change in the irradiance or temperature, the duty cycle of the converter can be adjusted in order to get maximum power at the load side. The simulation has been performed for a progressive change of solar irradiance between 500 and 1000W/m² for different values of temperature.

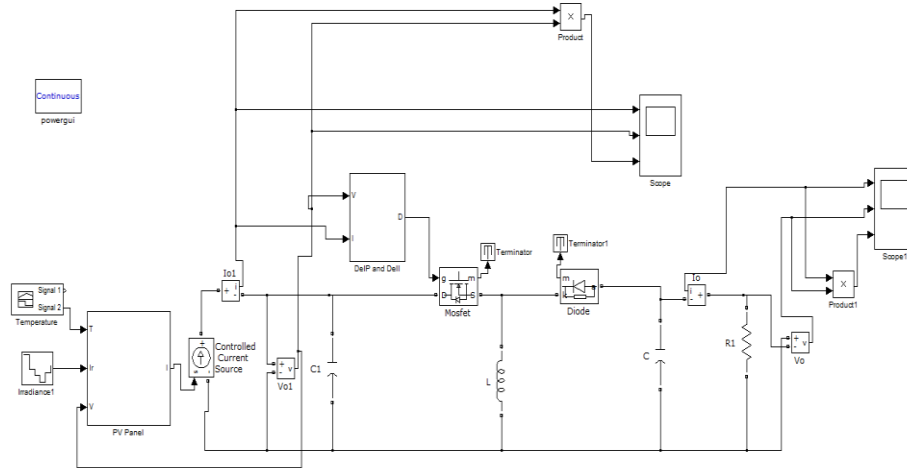


Figure 6.71: Simulation Diagram of PV system with FLC using ΔP and ΔI as inputs and Buck-Boost Converter

The figures 6.72, 6.73 and 6.74 below show the output current, voltage and power for irradiance varying between 500W/m^2 and 1000W/m^2 and temperature varying from 25°C to 75°C for a PV System working with a Buck-Boost Converter using Fuzzy Logic Control with change in power and change in current as inputs. Since there are no variations in the input side we get output approximately equal to the input under standard conditions i.e. 1000W/m^2 irradiance and 25°C temperature. It can be noticed that the current, voltage and power are at their maximum at 1000W/m^2 and 25°C . They decrease as the value of irradiance decreases and increase as the value of irradiance increases between 500W/m^2 and 1000W/m^2 . It can also be observed that as temperature increases from 25°C to 75°C , the current, voltage and power reduces.

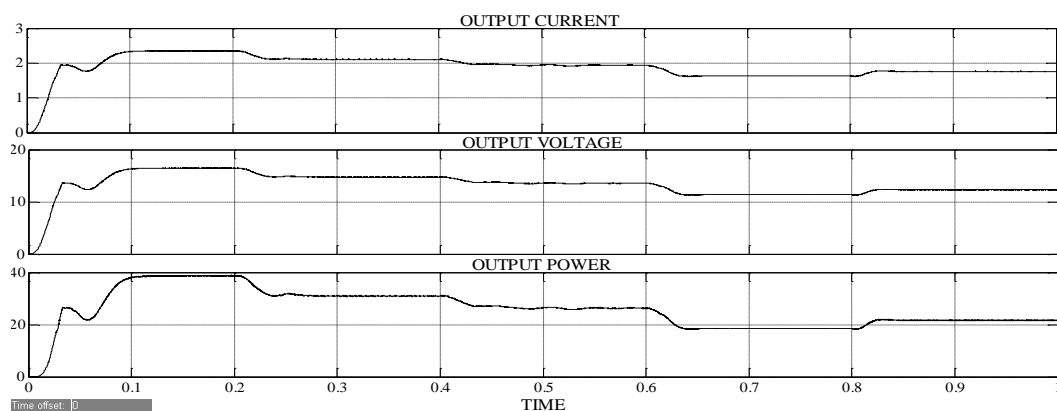


Figure 6.72: Output Current, Voltage and Power at 25°C Temperature and varying Irradiance

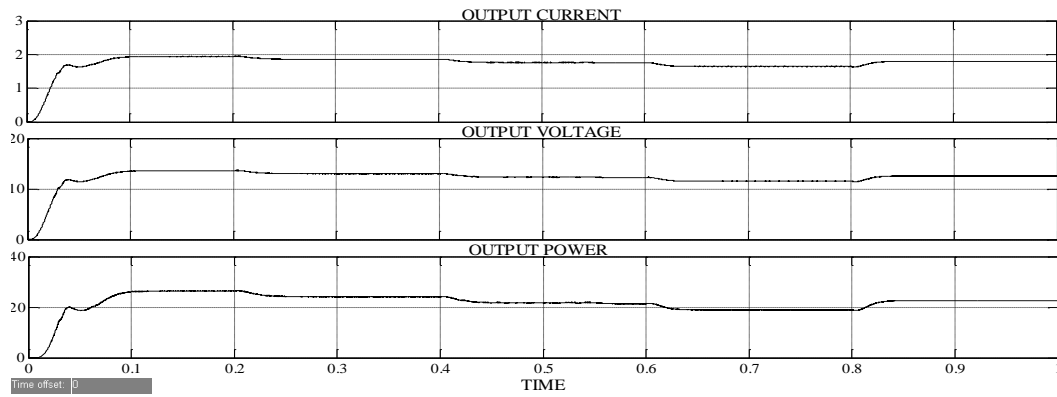


Figure 6.73: Output Current, Voltage and Power at 50°C Temperature and varying Irradiance

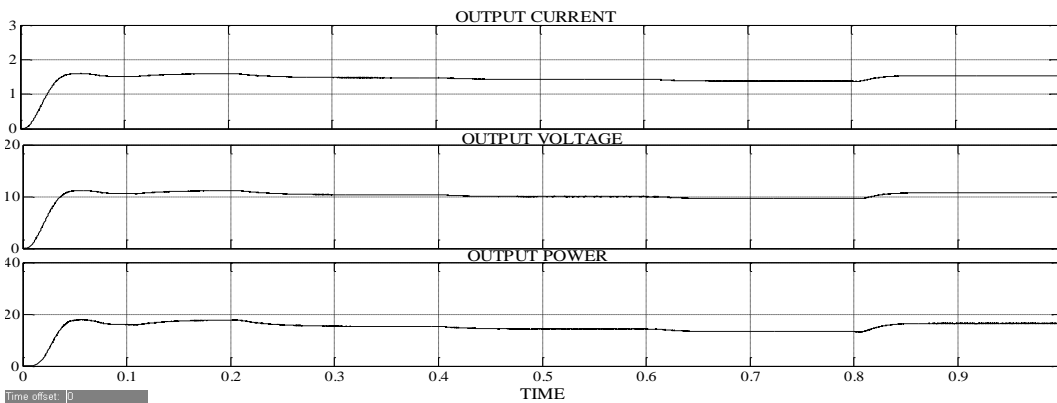


Figure 6.74: Output Current, Voltage and Power at 75°C Temperature and varying Irradiance

6.4.5 Sum of conductance and Incremental conductance as input

6.4.5.1 With Buck DC-DC Converter

The figure 6.75 below shows the simulation of MPPT of solar photovoltaic system with Buck DC-DC Converter using Fuzzy Logic Control with sum of conductance and incremental conductance as input for a resistive load. The Buck Converter reduces the input voltage to a lower value of output voltage according to the duty cycle applied to its gate input. It can be seen that the output of the Fuzzy Logic Controller is given to the gate of the Mosfet in the Buck converter so that whenever there is a change in the irradiance or temperature, the duty cycle of the converter can be adjusted in order to get maximum power at the load side. The simulation has been performed for a variation of solar irradiance between 500 and 1000W/m² for different values of temperature.

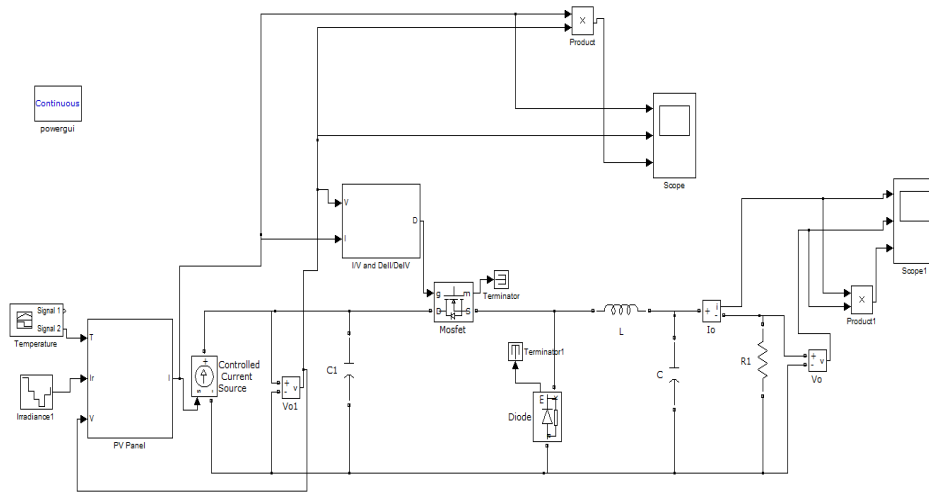


Figure 6.75: Simulation Diagram of PV system with FLC using $I/V + \Delta I / \Delta V$ as input and Buck Converter

The figures 6.76, 6.77 and 6.78 below show the output current, voltage and power for irradiance varying between 500W/m^2 and 1000W/m^2 and temperature varying from 25°C to 75°C for a PV System working with a Buck Converter using Fuzzy Logic Control with sum of conductance and incremental conductance as input. The system has been designed for a duty cycle of 0.466. Hence, the input voltage of 17.4V has been reduced to 8.2V under standard conditions i.e. 1000W/m^2 irradiance and 25°C temperature. It can be noticed that the current, voltage and power are at their maximum at 1000W/m^2 and 25°C . They decrease as the value of irradiance decreases and increase as the value of irradiance increases between 500W/m^2 and 1000W/m^2 . It can also be observed that as temperature increases from 25°C to 75°C , the current, voltage and power reduces.

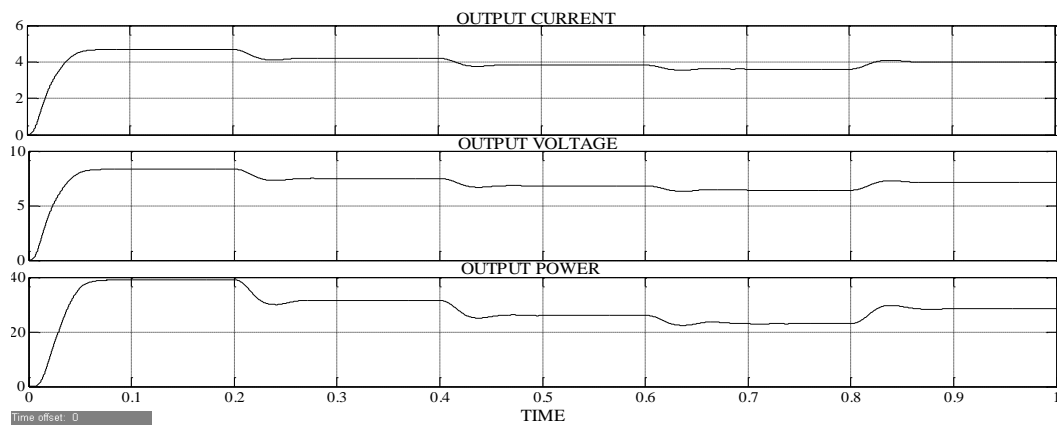


Figure 6.76: Output Current, Voltage and Power at 25°C Temperature and varying Irradiance

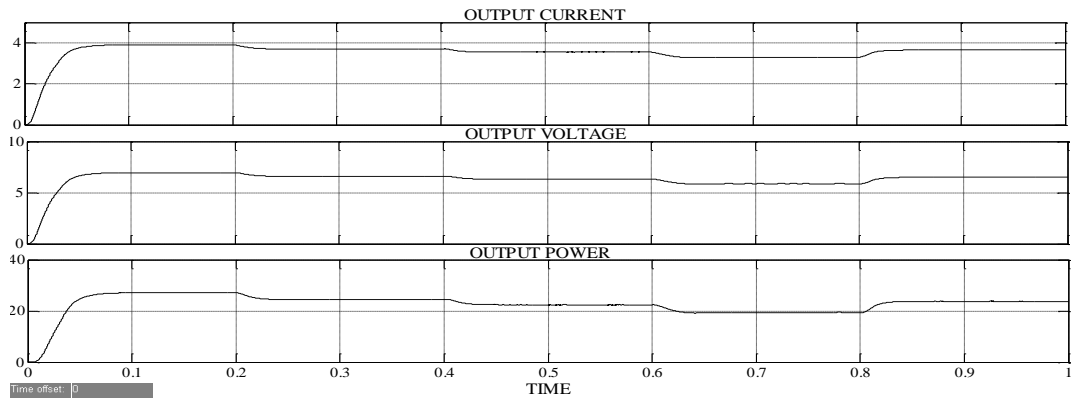


Figure 6.77: Output Current, Voltage and Power at 50°C Temperature and varying Irradiance

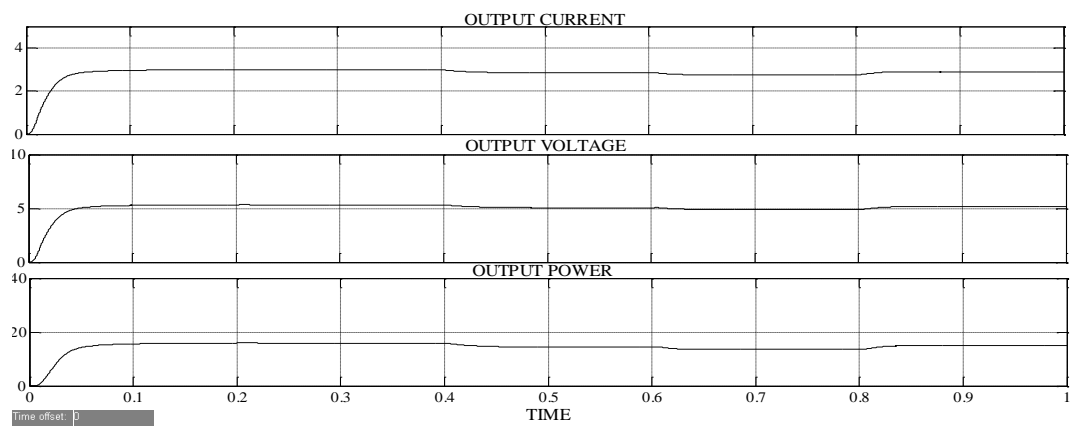


Figure 6.78: Output Current, Voltage and Power at 75°C Temperature and varying Irradiance

6.4.5.2 With Boost DC-DC Converter

The figure 6.79 below shows the simulation of MPPT of solar photovoltaic system with Boost DC-DC Converter using Fuzzy Logic Control with sum of conductance and incremental conductance as input for a resistive load. The Boost Converter increases the input voltage to a greater value of output voltage according to the duty cycle applied to its gate input. It can be seen that the output of the Fuzzy Logic Controller is given to the gate of the Mosfet in the Boost converter so that whenever there is a change in the irradiance or temperature, the duty cycle of the converter can be adjusted in order to get maximum power at the load side. The simulation has been performed for a progressive change of solar irradiance between 500 and 1000W/m² for different values of temperature.

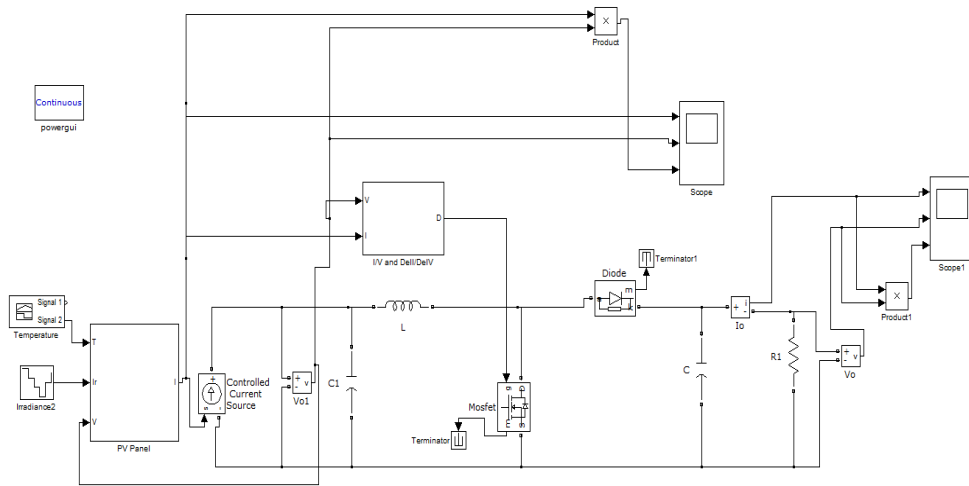


Figure 6.79: Simulation Diagram of PV system with FLC using $I/V + \Delta I / \Delta V$ as input and Boost Converter

The figures 6.80, 6.81 and 6.82 below show the output current, voltage and power for irradiance varying between 500W/m^2 and 1000W/m^2 and temperature varying from 25°C to 75°C for a PV System working with a Boost Converter using Fuzzy Logic Control with sum of conductance and incremental conductance as input. The system has been designed for a duty cycle of 0.488. Hence, the input voltage of 17.4V has been boosted to 34V under standard conditions i.e. 1000W/m^2 irradiance and 25°C temperature. It can be noticed that the current, voltage and power are at their maximum at 1000W/m^2 and 25°C . They decrease as the value of irradiance decreases and increase as the value of irradiance increases between 500W/m^2 and 1000W/m^2 . It can also be observed that as temperature increases from 25°C to 75°C , the current, voltage and power reduces.

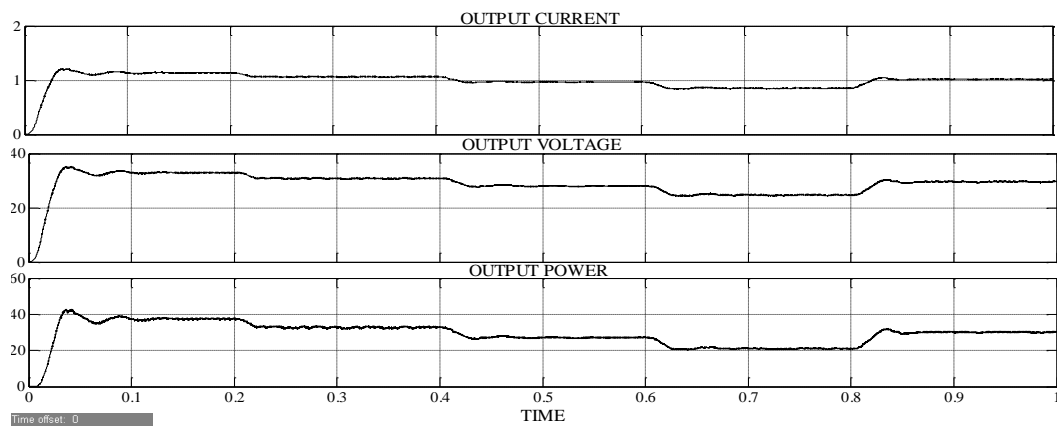


Figure 6.80: Output Current, Voltage and Power at 25°C Temperature and varying Irradiance

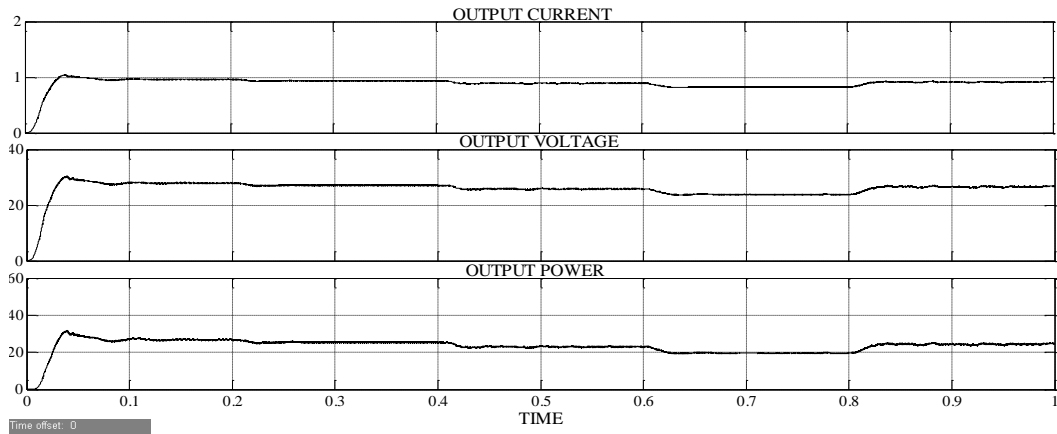


Figure 6.81: Output Current, Voltage and Power at 50°C Temperature and varying Irradiance

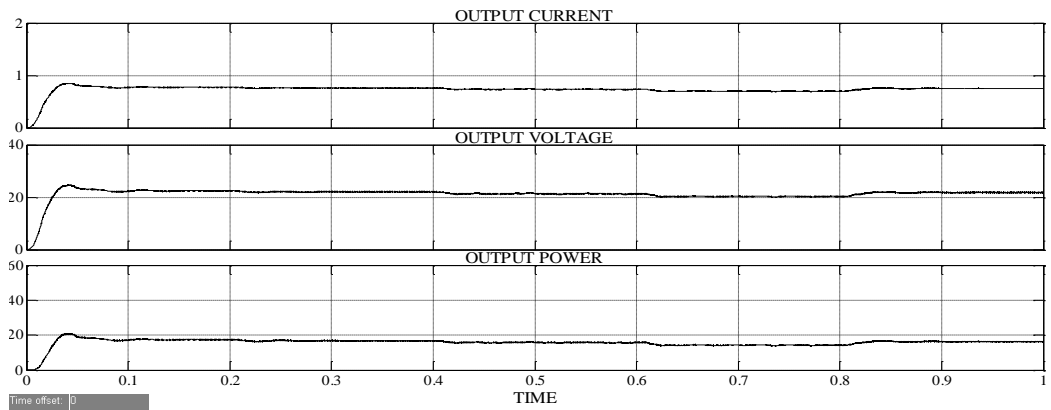


Figure 6.82: Output Current, Voltage and Power at 75°C Temperature and varying Irradiance

6.4.5.3 With Buck-Boost DC-DC Converter

The figure 6.83 below shows the simulation of MPPT of solar photovoltaic system with Buck-Boost DC-DC Converter Fuzzy Logic Control sum of conductance and incremental conductance as input for a resistive load. The Buck-Boost Converter reduces or boosts the input voltage to a lower value or a higher value of output voltage according to the duty cycle applied to its gate input. It can be seen that the output of the Fuzzy Logic Controller is given to the gate of the Mosfet in the Buck-Boost converter so that whenever there is a change in the irradiance or temperature, the duty cycle of the converter can be adjusted in order to get maximum power at the load side. The simulation has been performed for a progressive change of solar irradiance between 500 and 1000W/m² for different values of temperature.

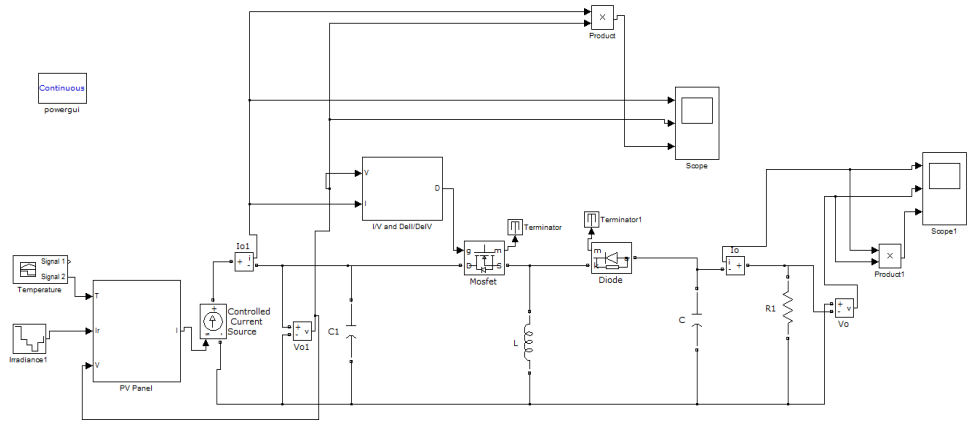


Figure 6.83: Simulation Diagram of PV system with FLC using $I/V + \Delta I / \Delta V$ as input and Buck-Boost Converter

The figures 6.84, 6.85 and 6.86 below show the output current, voltage and power for irradiance varying between 500W/m^2 and 1000W/m^2 and temperature varying from 25°C to 75°C for a PV System working with a Buck-Boost Converter using Fuzzy Logic Control with sum of conductance and incremental conductance as input. Since there are no variations in the input side we get output approximately equal to the input under standard conditions i.e. 1000W/m^2 irradiance and 25°C temperature. It can be noticed that the current, voltage and power are at their maximum at 1000W/m^2 and 25°C . They decrease as the value of irradiance decreases and increase as the value of irradiance increases between 500W/m^2 and 1000W/m^2 . It can also be observed that as temperature increases from 25°C to 75°C , the current, voltage and power reduces.

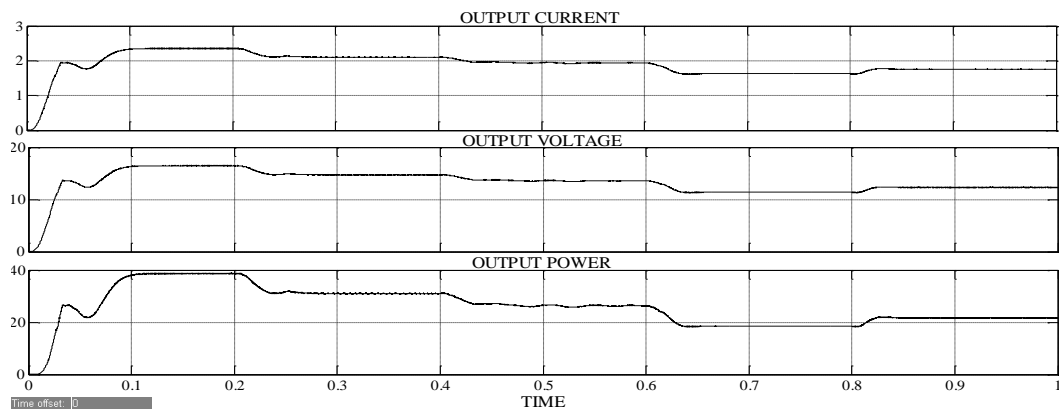


Figure 6.84: Output Current, Voltage and Power at 25°C Temperature and varying Irradiance

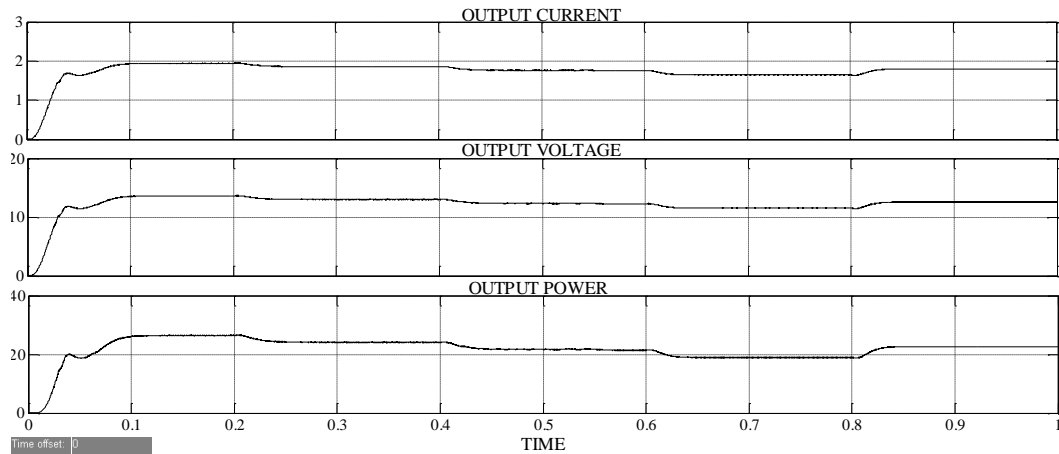


Figure 6.85: Output Current, Voltage and Power at 50°C Temperature and varying Irradiance

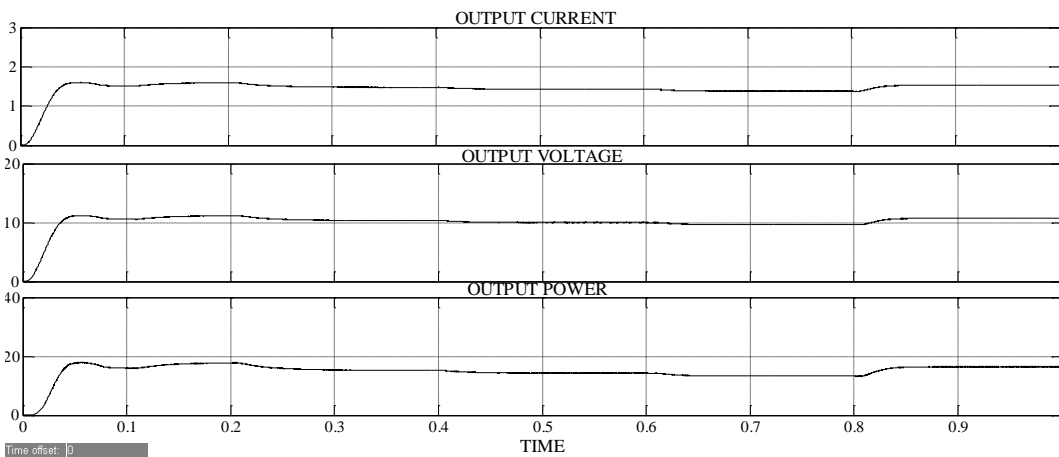


Figure 6.86: Output Current, Voltage and Power at 75°C Temperature and varying Irradiance

6.5 COMPARISON OF VARIOUS MPPT WITH VARIOUS CONVERTERS

The results obtained for various maximum power point tracking (MPPT) techniques are compiled together and compared with each other for the three types of DC-DC converters used. The comparison of the MPPT techniques for each DC-DC converter is done in terms of maximum power point (MPP) reached, settling time (T_s), tracking time (T_t), error in maximum power obtained (E), maximum power ratio (MPR) and complexity. Settling time is the time required by the MPPT technique to reach MPP. It is recorded in seconds. The lesser the settling time, more effective is the technique. Tracking time is the time taken by the MPPT technique to reach the next maximum power point when the solar insolation or temperature is changed. It is recorded in seconds. The lesser the tracking

time, more effective is the technique. The error is calculated as the difference in the maximum power obtained from the MPPT technique and the maximum power quoted by the manufacturer. The lesser the error, more effective is the technique. It is recorded in terms of Watt. Maximum power ratio is the ratio of the maximum power obtained and the desired value of maximum power. It is calculated in terms of percentage. Higher the value of maximum power ratio, more effective is the technique. The comparison of the different MPPT techniques in terms of the above defined parameters for each DC-DC converter is tabulated as follows:

6.5.1 Comparison of MPPT techniques for Buck DC-DC Converter

The comparison between various maximum power point tracking (MPPT) techniques for a Buck DC-DC converter for the parameters namely, maximum power point (MPP) reached, settling time (T_s), tracking time (T_t), error in maximum power obtained (E), maximum power ratio (MPR) and complexity are discussed in the table 6.1 below.

It can be seen from the below table 6.1 that the fuzzy logic control is the most effective maximum power point tracking (MPPT) techniques when compared to Perturb and Observe and Incremental Conductance Algorithm. Although it has the disadvantage of higher complexity over Perturb and Observe and Incremental Conductance Algorithm, it can be seen that the maximum power ratio is about 97.45% on an average for fuzzy logic control as compared to 93.75% for Perturb and Observe and 95 for Incremental Conductance. The tracking and settling time is also less than the other two algorithms. Hence it can be concluded that fuzzy logic control is better than Perturb and Observe and Incremental Conductance Algorithm in terms of performance. Now among the different ways in which fuzzy logic has been implemented, Fuzzy Logic with sum of conductance and incremental conductance as input has highest maximum power ratio minimum settling and tracking time. Hence this is the best method among the different fuzzy logic methods.

MPPT TECHNIQUE	MPP (Watts)	T_s (secs)	T_t (secs)	E (Watts)	MPR (%)	COMPLEXITY
P&O	37.5	0.08	0.035	2.5	93.75	Low
INC	38	0.07	0.03	2	95	Medium
FL with S(k) and $\Delta S(k)$	39	0.065	0.02	1	97.5	High
FL with S(k) and ΔP	39.1	0.07	0.025	0.9	97.75	High
FL with ΔP and ΔV	39	0.077	0.023	1	97.5	High
FL with ΔP and ΔI	38.5	0.065	0.022	1.5	96.25	High
FL with $I/V + \Delta I / \Delta V$	39.3	0.06	0.02	0.7	98.25	High

Table 6.1: Comparison of different MPPT techniques for Buck Converter

6.5.2 Comparison of MPPT techniques for Boost DC-DC Converter

The comparison between various maximum power point tracking (MPPT) techniques for a Boost DC-DC converter for the parameters namely, maximum power point (MPP) reached, settling time (T_s), tracking time (T_t), error in maximum power obtained (E), maximum power ratio (MPR) and complexity are discussed in the table 6.2 below.

It can be seen from the below table 6.2 that the fuzzy logic control is the most effective maximum power point tracking (MPPT) techniques when compared to Perturb and Observe and Incremental Conductance Algorithm. Although it has the disadvantage of higher complexity over Perturb and Observe and Incremental Conductance Algorithm, it can be seen that the maximum power ratio is about 98% on an average for fuzzy logic control as compared to 95% for Perturb and Observe

and 96.25% for Incremental Conductance. The tracking and settling time is also less than the other two algorithms. Hence it can be concluded that fuzzy logic control is better than Perturb and Observe and Incremental Conductance Algorithm in terms of performance. Now among the different ways in which fuzzy logic has been implemented, Fuzzy Logic with sum of conductance and incremental conductance as input has highest maximum power ratio minimum settling and tracking time. Hence this is the best method among the different fuzzy logic methods.

MPPT TECHNIQUE	MPP (Watts)	T_s (secs)	T_t (secs)	E (Watts)	MPR (%)	COMPLEXITY
P&O	38	0.05	0.04	2	95	Low
INC	38.5	0.04	0.03	1.5	96.25	Medium
FL with S(k) and $\Delta S(k)$	39.25	0.03	0.02	0.75	98.125	High
FL with S(k) and ΔP	39.3	0.04	0.03	0.7	98.25	High
FL with ΔP and ΔV	39.25	0.05	0.04	0.75	98.125	High
FL with ΔP and ΔI	39	0.04	0.03	1	97.5	High
FL with $I/V + \Delta I / \Delta V$	39.4	0.035	0.02	0.6	98.5	High

Table 6.2: Comparison of different MPPT techniques for Boost Converter

6.5.3 Comparison of MPPT techniques for Buck-Boost DC-DC Converter

The comparison between various maximum power point tracking (MPPT) techniques for a Buck-Boost DC-DC converter for the parameters namely, maximum power point (MPP) reached, settling time (T_s), tracking time (T_t), error in maximum

power obtained (E), maximum power ratio (MPR) and complexity are discussed in the table 6.3 below.

It can be seen from the below table 6.3 that the fuzzy logic control is the most effective maximum power point tracking (MPPT) techniques when compared to Perturb and Observe and Incremental Conductance Algorithm. Although it has the disadvantage of higher complexity over Perturb and Observe and Incremental Conductance Algorithm, it can be seen that the maximum power ratio is about 97.25% on an average for fuzzy logic control as compared to 93.25% for Perturb and Observe and 94% for Incremental Conductance. The tracking and settling time is also less than the other two algorithms.

MPPT TECHNIQUE	MPP (Watts)	T_s (secs)	T_t (secs)	E (Watts)	MPR (%)	COMPLEXITY
P&O	37.3	0.17	0.09	2.7	93.25	Low
INC	37.6	0.15	0.08	2.4	94	Medium
FL with S(k) and $\Delta S(k)$	38.7	0.1	0.05	1.3	96.75	High
FL with S(k) and ΔP	39	0.14	0.06	1	97.5	High
FL with ΔP and ΔV	38.8	0.15	0.06	1.2	97	High
FL with ΔP and ΔI	38.5	0.12	0.05	1.5	96.25	High
FL with $I/V + \Delta I / \Delta V$	39.5	0.11	0.05	0.5	98.75	High

Table 6.3: Comparison of different MPPT techniques for Buck-Boost Converter

Hence it can be concluded that fuzzy logic control is better than Perturb and Observe and Incremental Conductance Algorithm in terms of performance. Now

among the different ways in which fuzzy logic has been implemented, Fuzzy Logic with sum of conductance and incremental conductance as input has highest maximum power ratio minimum settling and tracking time. Hence this is the best method among the different fuzzy logic methods.

CHAPTER 7

CONCLUSION & FUTURE SCOPE

7.1 CONCLUSION

The main objective of this thesis work was to compare various maximum power point tracking (MPPT) methods namely, perturb and observe, incremental conductance and fuzzy logic control with five different fuzzy input variables, for different DC-DC converters viz., buck, boost and buck-boost. The five different fuzzy input variables used in this thesis were slope and change in slope, slope and change in power, change in power and change in voltage, change in power and change in current and sum of conductance and increment in it. The various MPPT methods and the various DC-DC converters were modelled and simulated in MATLAB/Simulink. For each DC-DC converter the comparison for different MPPT methods is done in terms of maximum power point (MPP) reached, settling time (T_s), tracking time (T_t), error in maximum power obtained (E), maximum power ratio (MPR) and complexity. From the comparison done above it is seen that fuzzy logic control is better than Perturb and Observe and Incremental Conductance Algorithm in terms of performance and effectiveness. Among the various ways in which the fuzzy logic control is implemented, the most promising one is the fuzzy logic control with the sum of conductance and incremental conductance as the input. This is because through this algorithm the exact location of the operating point can be directly identified with respect to the MPP contrary to the earlier algorithms discussed in this thesis where changes are used to guess whether the system has reached MPP or not. Therefore, while using this algorithm the duty ratio can be increased or reduced with higher values so as to attain efficient MPPT. The other benefit of this algorithm is that it requires only one set of input variables resulting in a single-input and single-output system which further decreases calculation of loads. Hence this algorithm will help in improving the efficiency of the solar photovoltaic system to its maximum extent.

Furthermore it is also seen that as the solar irradiation increases the output voltage, current and power increase and vice-versa and as the temperature increases

they decrease. Hence the solar irradiation should be as high as possible while the temperature should be maintained about 25°C for maximum power.

7.2 FUTURE SCOPE

These various MPPT controller results obtained can be compared to other methods of control such as the use of neural network controllers so as to optimize the PV System. Furthermore, the above MPPT techniques can also be implemented with other DC-DC Converters such as Cuk Converter, SEPIC Converter, Zeta Converter, etc. Hardware implementation of the proposed Fuzzy based MPPT control scheme using sum of conductance and incremental conductance as the fuzzy input variable on Solar PV Module can be applied by interfacing MATLAB with Solar PV Module using parallel ports. There could be one more idea of future work related to this study which is implementation of neuro-fuzzy based MPPT technique on a Solar PV Module. This is a combination of artificial neural networks and fuzzy logic resulting in formation of a hybrid intelligent system.

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LIST OF PUBLICATIONS

- [1] Ms. Kshitijaa Ranjan and Dr. Narendra Kumar, “Modelling and Simulation of Perturb and Observe Algorithm on Solar PV System using Different Converters in MATLAB/Simulink”, accepted in 1st IEEE International Conference on Power Electronics, Intelligent Control and Energy Systems, ICPEICES-2016, Delhi, to be published on IEEE Explore.