MODELING AND SIMULATION OF PV CONNECTED WITH STEP-UP CONVERTER BASED ON ANFIS MPPT CONTROLLER

MAJOR PROJECT 2 REPORT

SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS

FOR THE AWARD OF THE DEGREE OF

MASTER OF TECHNOLOGY

IN

CONTROL AND INSTRUMENTATION

Submitted by:

Adilson Bonifacio Donato Bumba Puna

2K19/C&I/20

Under the supervision of:

Dr. A.B.K Bhattacharya

DEPARTMENT OF ELECTRICAL ENGINEERING

DELHI TECHNOLOGICAL UNIVERSITY

(FORMERLY DELHI COLLEGE OF ENGINEERING)

Bawana road, Delhi-110042

July 2021

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

Bawana Road, Delhi-110042

CANDIDATE'S DECLARATION

I, Mr. Adilson Bonifacio Donato Bumba Puna, roll no: 20k19/C&I/19 student of M.Tech Control and Instrumentation, hereby declare that the Major project 2 titled (Modeling of PV connected with step-up converter based on ANFIS MPPT controller) which is submitted by me to the Department of electrical engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

Place: Delhi   Adilson Bonifacio Donato Bumba Puna

Date: 28/07/2021

ABSTRACT

Renewable energy are a key and powerful alternative sources widely used having many advantages comparing to the conventional power generation. Most known alternative power generation sources are solar, wind geothermal, hydro, and biomass. Therefore energy generated naturally from the sunlight as is it called solar energy in particular has been used now for years as an optional way to power multiple devices. However the energy generated depends proportionally on the amount of the radiation that varies constantly during the day because of the weather which influence negatively in voltage stability. Using a converter such as boost converter is an ideal option to step-up the power so that the usage requirement can be met. Hence ANFIS based MPPT controller is designed to control the duty cycle of the generated pulses and track the maximum power generated by the entire system plant.

ACKNOLEDGEMENT

I am highly grateful to the Department of Electrical Engineering, Delhi Technological University (DTU) for providing this opportunity to carry out this project work.

The constant guidance and encouragement received from my supervisor Prof. Dr. A.B.K Bhattacharya of Department of Electrical Engineering, DTU, has been of great help in carrying my present work and is acknowledged with reverential thanks.

Finally, I would like to expresses gratitude to all faculty members of Electrical Engineering Department, DTU for their intellectual support in my M.tech study at DTU as well as to ICCR whose financially supported my entire studies in India.

Adilson Bonifacio Donato Bumba Puna

2K19/C&I/20

M. Tech. (Control and Instrumentation)

Delhi Technological University

CONTENT

LIST OF FIGURES

LIST OF TABLES

<u>ABREVIATIONS</u>

PV: Photovoltaic

D: Duty cycle

ANFIS: Artificial Neuro Fuzzy Inference System

DC: direct current

P: Power

I: current

V: Voltage

L: Inductor

C: Capacitor

R: Resistance

MPPT: Maximum power point tracking

PWM : pulse width modulation

PID : Proportional Integral Controller

P&O: Perturb and Observer

IC: Incremental conductance

FIS: Fuzzy inference system

NB: Negative Big

PB: Positive Big

NS: Positive Small

PS: Positive small

FLC- Fuzzy logic controller

LIST OF SYMBOLS

V_D : is the voltage drop across the diode

V_{trans} : voltage drop across the transistor

I_0: saturation current

k: Boltzmann constant

T : operating temperature in Kelvin

V_T: diode thermal voltage

I_0: saturation current

R_P: parallel resistance

R_S: series resistance

q: electron charge

CHAPTER 1 : INTRODUCTION

1.1 Introduction

Much research has been undergoing on solar, wind, tidal, and so on to minimize the world energy crisis. Apart from available renewable sources, solar is one of the special alternative sources to meet the required power demand towards rural electrification of residences and industries. Photo-voltaic(PV) panel or the so called solar panel, is one of the many renewable energy sources, which is commonly use as its low price and relatively easy to maintain[1]. The solar power technology is mature enough for commercial use and does not involve any raw material, which makes it a highly attractive second option for large-scale electrification. Generally, photovoltaic (PV) systems are organized in strings. In order to attain a sufficiently high voltage, PV strings consist of 10 to 20 PV modules connected in series. At given insolation and temperature, the PV modules supply maximum power at a particular point-the maximum power point (MPP). If all modules were identical and evenly illuminated, they would have a common MPP. However, in practice, this is never the case. Shading by chimneys, trees, power lines, dust, and panel mismatch cause PV modules within a PV string to exhibit different I-V characteristics from one another. This makes it impossible to find an operation point at which all the modules in a string operate at the MPP, which results in a mismatch among the modules.

Switch-mode power conversion has been a column of modern electronics technology across a bunch of sectors including utility, industrial, commercial, and consumer markets for many years. In low-power DC/DC conversion applications, conversion is done using different types of converters such as boost converter, buck converter, or both together. These electrical devices work as step-up and step-down to supply regulated DC voltage offering a lower operating duty cycle and higher efficiency across a wide range of input and output voltages.

MPPT control technique that is widely used to be performed on the duty cycle automatically to place the PV module at its best and optimal output value whatever the differences of the weather conditions or the change in the value of loads which can happen at any moment

Generally direct and indirect methods are used for PV MPP. Constant Voltage Method: it is a direct method and focuses on PV voltage for controlling and maintaining the MPPT. This method is not very much efficient up to the benchmark on altering heather conditions[2]. Fractional Open Circuit Voltage : pinpoints to the fact that a maximum power point voltage is obtained by the product of constant K and open circuit voltage[2,3].

P&O is one of most used MPPT indirect method, which works by introducing small disturbance causing changes of power in PV array. then voltage is further gone on increasing in that direction or else the direction of voltage has to be changed in opposite direction (slope reference of P-v characteristics)[4]. Because of some disadvantages of P&O method, Incremental conductance is introduced to overcome these shortcomings by investigating the voltage operating point at which the conductance is equal to the IC. Fuzzy logic controller which is based on IF-THEN rules is as well one of techniques used for MPPT due to complexity and nonlinearity of the system. The Artificial Neural Network is designed by training it through data collected from FLC System [5,6]. A combination of these techniques, adaptive methods are also applied to improve performance response and overcome drawbacks of mentioned techniques. Therefore, a combination of neural network and fuzzy logic controller is the focus of this paper, aiming to improve certain limitation of prescribed methods.

1.2 BACK-GROUND OF THE PROJECT

The conventional power grid system generation aging and its generation is against environment laws causing known serious problems such as climate change. Due to that a lot of research has been carry out in the area of renewable energy mainly in solar photovoltaic system where energy is naturally generated from sun-light an ideal alternative for clean energy.

Energy generated from this source depends on the amount of sunlight that continuously varies during the day. Hence the use of buck-boost converter which has output voltage either greater or less than the input voltage magnitude to step up and down the voltage to desired output. They are used as switching regulators which use switching element typically one or two MOSFET and an energy storage

device such as inductor to efficiently regulate input voltage to lower or higher output voltage. .However many control techniques are developed in order to keep track of power generated such as MPPT, Perturb and Observer

1.3 PROBLEM DEFINITION

PV solar is one of the most reliable alternative source of power that the humanity have because of its great benefits mainly of emission free pollutants and no moving parts. This technology has been a focus of many scientist and many research has been carried out. Due to changes of the environment, the energy being generated decreases significantly. Moreover a need to track the sunlight is a must. Many MPPT controllers have been developed for its fine tracking but because of its non-linearity properties still a big challenge. This paper focus on designing an optimal controller ANFIS MPPT based solar power.

1.4 SCOPE OF THIS PROJECT

In real life design scenarios controllers are used to control and improve the performance of the plant. An ANFIS based MPPT controller is designed and implemented to PV system in order to track the power and control the output voltage.

A theoretical analysis about PV system design and DC-boost converter is provided as well as its working principles for better understanding of the system overall.

1.5 CONCLUSION

In this first chapter an introduction is given about solar system and step-up converter. Because of sunlight variations boost converter helps stepping-up the voltage at the desired output level required. In order to achieve that a controller is designed to control the duty cycle of the system.

CHAPTER 2 LITERATURE REVIEW OF PV MODULE AND STEP-UP
CONVERTER

2.1 INTRODUCTION

This chapters discusses a brief and general review about PV and step-up converter.
Renewable energy present a field of big research because of its advantages on
providing clean and green energy. Because of continuously varying sun-light
irradiation the amount of power generated is unstable. Therefore many control
techniques such as MPPT based PV controller, P&O based MPPT and so on are
applied to track the power and regulate the voltage.

2.2 PHOTOVOLTAIC MODULE

The PV cell is composed of semiconductor material. The exposure of
semiconductors in light, makes it absorb the light's energy and transfers it to
charged particles called electrons. Electrons flow through the material as electric
currents. By using conductive metal material, the current is extracted from solar
cells. The building blocks that compose an entire photovoltaic system are called
solar cells. A device that converts photons' energy into electricity is called a solar
cell

It operates silently and has no moving parts and is environmental emissions, solar
systems have developed from being niche market applications into a mature
technology used for mainstream electricity generation. A rooftop system recoups
the invested energy for its manufacturing and installation purpose within 0.7 to 2
years and produces approximately 95 percent of net clean renewable energy over
a 30-year service lifetime. Approximately 99 percent of all European countries and
most American solar power systems are connected to the electrical grid, while in
some cases off-grid systems are somewhat more common in some other countries
like Australia and South Korea.

2.3 ADVANTAGES OF PV

Some of advantages of this great resource can be cited here as it is today's most reliable and used second source of power generation. The energy can be used both to generate electricity and heat in the house, it is economy-friendly energy providing a great opportunity to create savings on electric bill, environmentally friendly energy and the discharge of waste and pollution is unavoidable in relation to the production of solar cells.[7]

Application	Operation
Solar Electric Power Generation	By means of photovoltaic cells the electricity can be produced
Solar Thermal Power Production	used to heat up a working fluid or any other volatile liquid
Solar Green Houses	acts as a solar collector and plants are grown by means of solar
Solar pumping	For water irrigation purpose
Solar cooling	Portable refrigeration system

Table.2.1: Application of PV

2.4 STEP-UP CONVERTER

A step-up converter is a DC-to-DC power converter that boosts the voltage from its low input value to high output voltage. It is a class of switched-mode power supply containing at least two different semiconductors such as a diode and a transistor and at least one energy source or storage element: a capacitor, inductor. Filters made of combination with inductor and capacitor are usually added together to these converters' output and input to reduce the voltage ripple.

DC generators, solar panels, batteries, and rectifiers are some of the DC sources of the boost converter. DC-to-DC conversion is a process of stepping up or down the voltage. A diode acts as a switch for current. It is basically a semiconductor device that allows the current to flow in one direction and restricting it from flowing in opposite direction.

To switch and amplify electronic signal devices a widely known semiconductor named Metal Oxide Semiconductor Field Effect is used which has three terminals: source, gate, and drain. An inductor is an important device that allows the current to flow during off switching periods. Whereas a capacitor stores the energy in form of an electric field.

2.5 ADVANTAGES OF STEP UP CONVERTERS

➢ Gives the high output voltage
➢ Low operating duty cycles
➢ Low voltage on MOSFET
➢ PV cells reduction

2.6 APPLICATIONS OF STEP-UP CONVERTERS

➢ Automotive applications
➢ Power amplifier applications
➢ Adaptive control applications
➢ Battery power systems
➢ Consumer Electronics
➢ Communication Applications

2.7 CONCLUSION

In this chapter an introduction of PV and buck boost converters is described, its advantages as well as its applications in many different conditions. Based on that it became clear how important is the PV together with boost converter. In the next chapter will be introduced the mathematical model of both PV and boost converter.

CHAPTER 3: MATHEMATICAL MODEL OF PV AND STEP-UP CONVERTER

3.1 INTRODUCTION

The PV cell is exposed to solar radiation and some of this radiation is absorbed by the junction creating pairs of electron-hole. The electric field separates these charges in E: the electrons migrate in the "n-type" area and the holes migrate in the "p-type" area and due to this effect electric current is generated. Considering a single-diode PV model with series resistance and a parallel resistance a practical PV cell can be investigated. Below in fig3.1 equivalent PV circuit is shown.
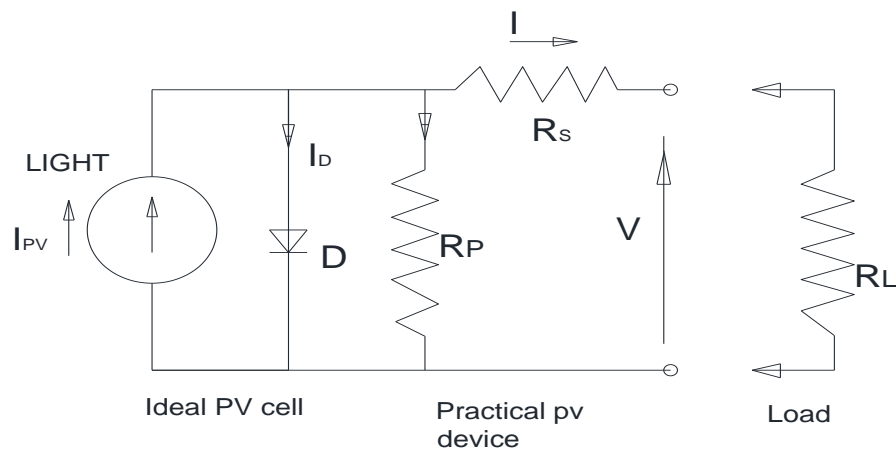
Fig.3.1: Equivalent electrical circuit of PV module.

Where:

Rs: cell series resistance

Rp: cell parallel resistance

RL : cell inductance

V: PV voltage

I: PV current

Ipv: Current developed from sun

Io: saturation current

The main equations to describe the I-V characteristics of an ideal PV cell are [8][9]

$$I = I_{pv} - I_D \tag{3.1}$$

$$I_D = I_0 \left[\exp \left(\frac{qV}{aKT} - 1 \right) \right] \tag{3.2}$$

$$I = I_{PV} - I_0 \left[\exp \left(\frac{qV}{aKT} \right) - 1 \right] \tag{3.3}$$

3.2 PV MODULE MODELLING

For analysis of PV cell researchers show that some supplementary parameters need to be used into equation(3.3)[8][10]

$$I = I_{PV} - I_0 \left[exp \left(\frac{V+R_S}{aV_T} \right) - 1 \right] - \frac{V+R_S I}{R_P} \tag{3.4}$$

$$V_T = \frac{kT}{q} \tag{3.5}$$

Where:

k: Boltzmann constant

T : operating temperature in Kelvin

V_T: diode thermal voltage

I_0: saturation current

R_P: parallel resistance

R_S: series resistance

q: electron charge

In order to assure the parameters required a photovoltaic system has to be made by a sufficient number of PV cells, connected in series or in parallel, usually called arrays.

The current generated by the photovoltaic panel depends directly on the solar irradiation and is influenced by the temperature according to the next relation [11]:

$$I_{PV} = (I_{pv,n} + K_I \Delta T) \frac{G}{G_n} \tag{3.6}$$

$$\Delta T = T - T_n \qquad (3.7)$$

The open voltage is as well influenced by the temperature

$$V_{0c} = V_{0c,n}(1 + K_V \Delta T) + V_T \ln\left(\frac{G}{G_n}\right) \qquad (3.8)$$

Where:

V_{0c}: open circuit voltage

n: ideality factor of the diode

The saturation current of the diode depends also on the temperature [12]

$$I_0 = I_{0,n}\left(\frac{T_n}{T}\right)1^3 exp\left[\frac{qE_g}{aK}\left(\frac{1}{T_n} - \frac{1}{T}\right)\right] \qquad (3.9)$$

Where E_g is the band gap energy of the semiconductor ($E_g = 1.2$)

The value of the saturated nominal current is given by [13]

$$I_{0,n} = \frac{I_{sc,n}}{\exp\left(\frac{V_{0c,n}}{aV_{T,n}}\right)-1} \qquad (3.10)$$

Efficiency of PV module is defined as the ratio of peak power to input solar power

$$\eta = \frac{V*I}{1\left(\frac{kw}{m^2}\right)A(m^2)} \qquad (3.11)$$

The efficiency will be maximum if the power is well tracked in different environment

3.2.1: BLOCK BUILDING DIAGRAM OF PHOTOVOLTAIC MODULE

In order to model a solar module basic parameters need to be determined and then the calculation of parameters such as photo-current, saturation current and so on. The bock diagram in fig.3.2 shows a basic parameters and steps to take into consideration while designing a PV module
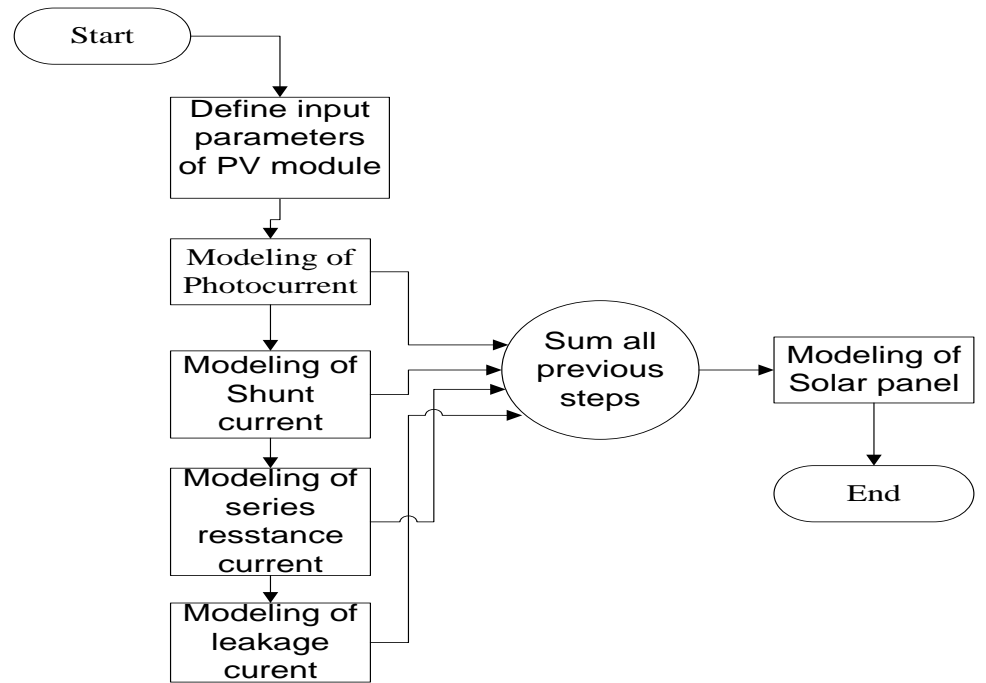
Fig. 3.2: Block diagram of PV module calculation

3.2.2 PV PARAMETERS

Maximum power	240W
Cells per module	60
Open circuit voltage Voc	36
Short-circuit current(Isc A)	9.2
Voltage at maximum power point Vmp (V)	30.72
Current at maximum power point Imp (A)	8.28
Temperature coefficient of Voc (%/deg.C)	-0.359
Temperature coefficient of Isc (%/deg.C)	0.102
Light-generated current IL (A)	9.20

Diode saturation current I0 (A)	3.387e-10
Diode ideality factor	0.982
Shunt resistance Rsh (ohms)	70.14
Series resistance Rs (ohms)	0.343

Table: 3.3: PV parameters

Simulink model based on numerical equations of PV model

Fig. 3.3: PV Module based on numerical equations

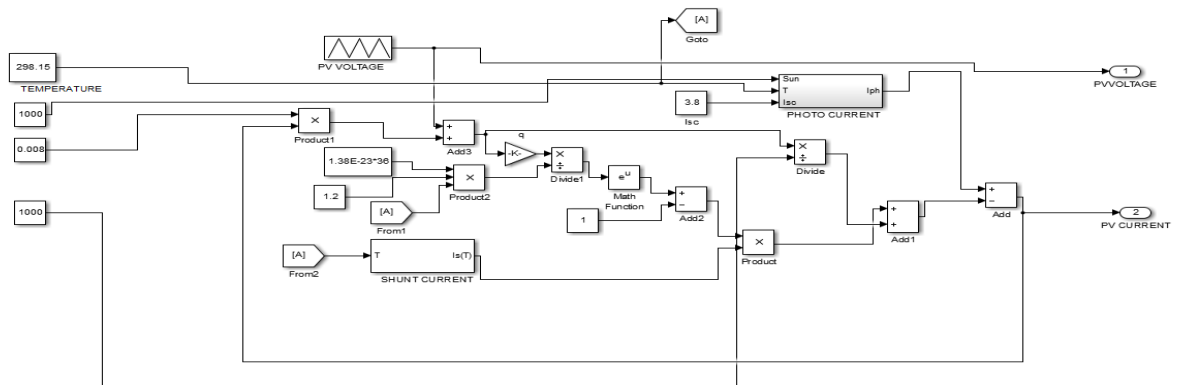Regardless that a Simulink Model for PV array can be designed based on the PV module equations MATLAB Simulink in its library has already an embedded PV module block, where parameters can be easily and with flexibility modified.
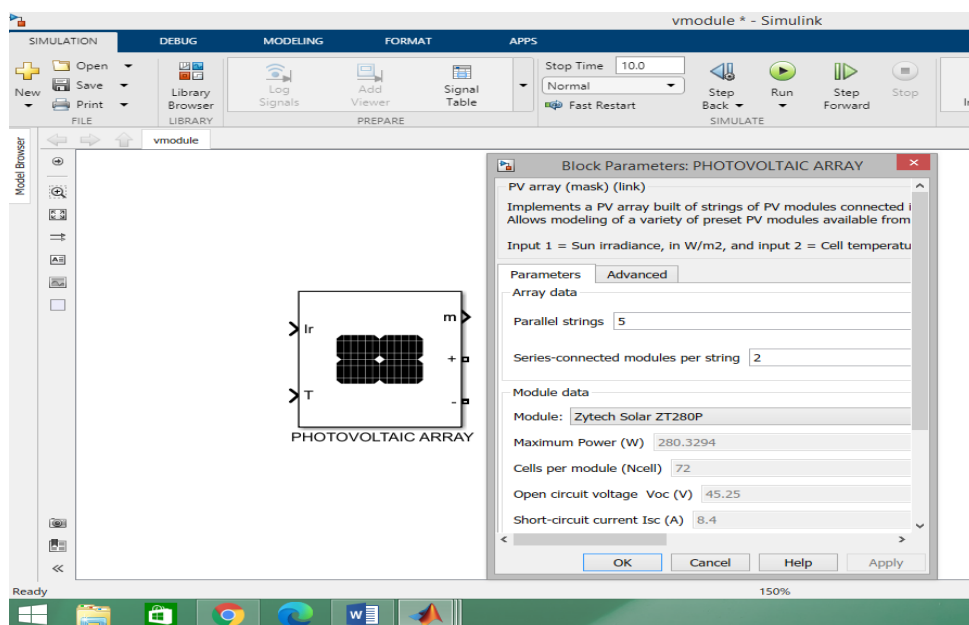
Fig. 3.4 : MATLAB Simulink block of PV array

3.2.3 PV MODULE CHARACTERISTICS CURVES

It is difficult to determine the maximum power point of solar PV because of its non-linearity characteristics. Below is shown the I-V and P-V characteristics of PV module in variables weather conditions.
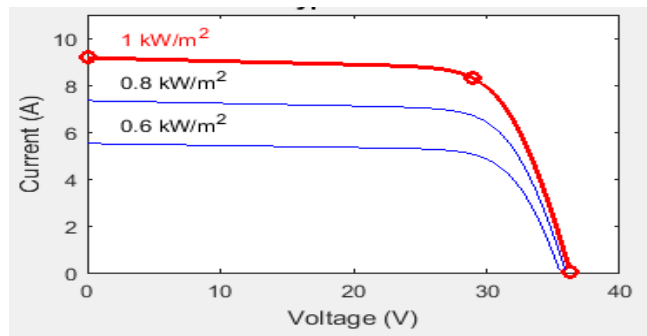
Fig.3.5: I-V characteristics of PV module at different irradiations and fixed temperature of 25 degree
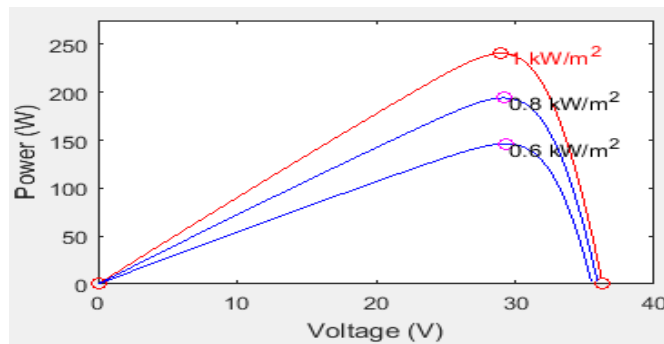
Fig.3.6: P-V characteristics of PV module at different irradiations and fixed temperature of 25 degree

3.3 WORKING PRINCIPLE OF STEP-UP OPERATION

The boost converter is one of the principal non-isolated converters. A boost converter is a power converter with an output dc voltage greater than its input dc voltage [14]. It is a class of switching-mode power supply composed of two semiconductor switches and one energy storage element. In order to improve the

performance of step-converters filters made of inductor and capacitor combinations are often added to a converter's output.

The circuit diagram of a step-up operation of the DC-DC converter is shown in Figure 3.4. When the switch 1 S is closed for time duration 1 t, the inductor current rises and the energy is stored in the inductor. If the switch 1 S is opened for time duration 2 t, the energy stored in the inductor is transferred to the load via the diode D1 and the inductor current falls.

Below is represented equivalent electric circuit of the step-up dc-dc converter.
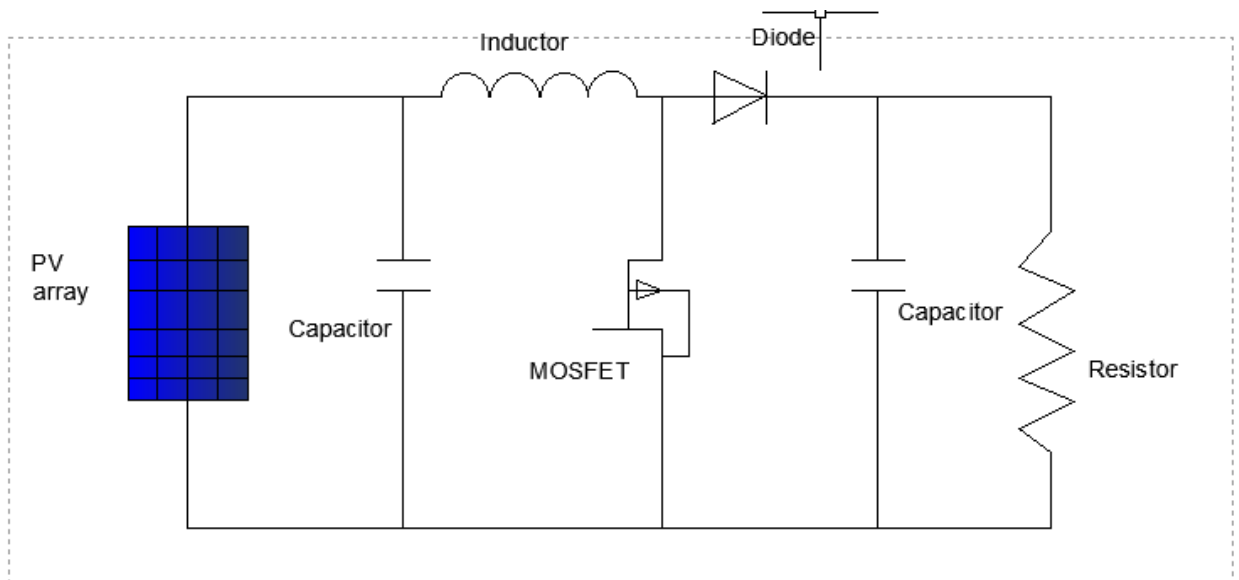
Fig. 3.7 Step up equivalent electric circuit

Based on fig.3.7 of the step-up converter, numerical equations can be derived as follows when the mosfet is turned on, the voltage across the inductor is

$$v_L = L \frac{di}{dt} \tag{3.12}$$

The peak to peak ripple current in the inductor is given by

$$\Delta I = \frac{V_S}{L} T_1 \tag{3.13}$$

The average output voltage is

$$v_0 = V_S + \frac{\Delta I}{T_2} = V_S \left(1 + \frac{T_1}{T_2}\right) = V_S \frac{1}{1-D} \tag{3.14}$$

3.3.1 Modes of operation of step-up converter

The function of boost converter can be divided into two modes:

In mode one (1) begins when transistor is switched on at time t equal zero. The input current rises and flows through inductor L and transistor

In mode two (2) the transistor is switched off at time t equal to t1. The input current now flows through L, C, load, and diode D. The inductor current falls until the next cycle. The energy stored in inductor L flows through the saturation current (Io)

The circuits for the two modes of operation are shown below:
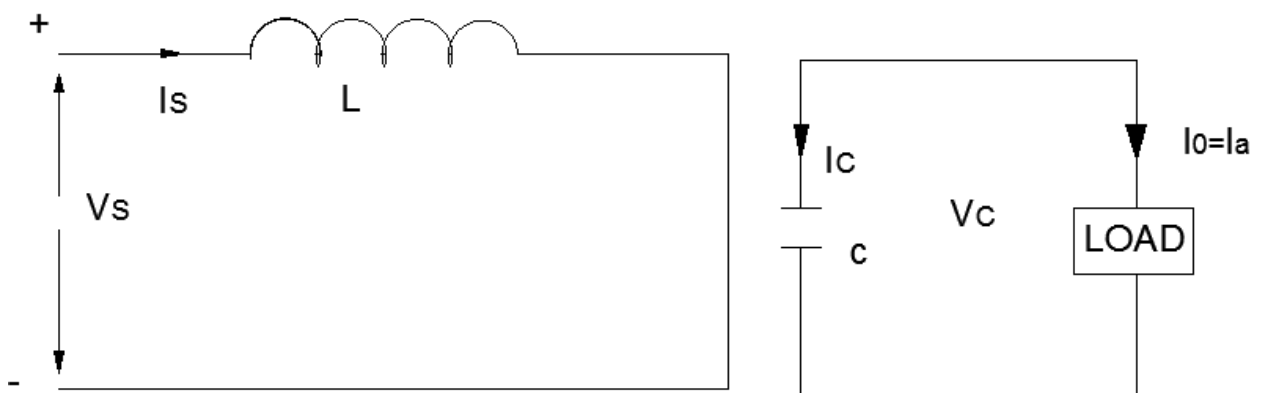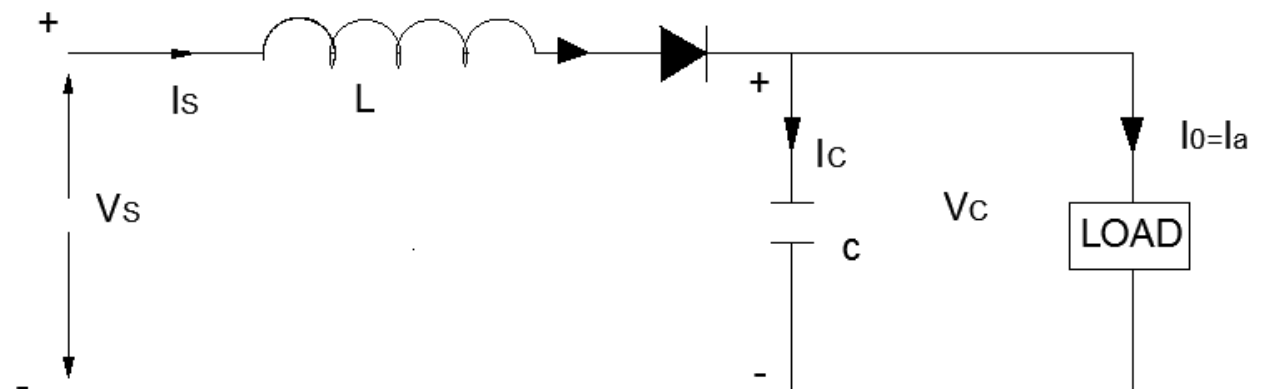
Fig.3.8: Mode operation 1 of step-up converter

Fig. 3.9: Mode operation 2 of step-up converter

For constant rectangular pulse

$$i = \frac{vt}{L} + i_0 \tag{3.15}$$

When the transistor is switched:

$$i_{pk} = \frac{(V_{in} - V_{trans})T_{on}}{L} + i_0 \tag{3.16}$$

And when the transistor is switched off the current is:

$$i_0 = i_{pk} - \frac{(V_{out} - V_{in} + V_D)T_{off}}{L} \tag{3.17}$$

Where:

V_D : is the voltage drop across the diode

V_{trans} : voltage drop across the transistor

Equating above equations, we can solve for V_{out} :

$$\frac{(V_{in} - V_{trans})T_{on}}{L} = \frac{(V_{out} - V_{in} + V_D)T_{off}}{L} \tag{3.18}$$

$$V_{in} - V_{trans}D = (V_{out} - V_D)(1 - D)$$

$$V_{out} = \frac{V_{in} - V_{trans}D}{(1 - D)} - V_D \tag{3.19}$$

Neglecting the voltage drops across the diode and the transistor:

$$V_{out} = \frac{V_{in}}{1 - D} \tag{3.20}$$

From Equation 3.13, the following observations can be made:

The voltage across the load may be boosted by varying the duty ratio (D)

The minimum voltage output is Vs and is acquired when duty cycle is equal to zero

The step-up converter cannot be switched on continuously such that duty ratio is equal to unity . For values of duty ratio tending to unity, the output becomes very sensitive to changes in D For values of duty ratio tending to unity, the output voltage becomes very sensitive to changes.

The biggest challenge when designing a converter is the type of inductor to be used. According to above mentioned equations, it can be noted that the inductance is inversely proportional to the ripple current. So in order to reduce the ripple a larger inductor must be used. Fig 3.10 shows representation diagram of a boost converter
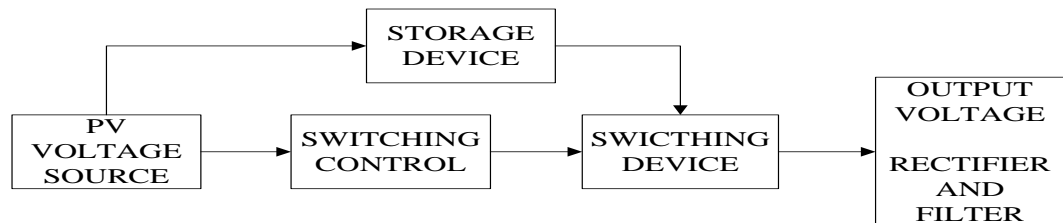
Fig.3.10: Block building diagram of a step-up

The PV acts as input DC voltage source providing to the switch control, and also to the magnetic field storage device(inductor or capacitor element). The block containing switch control directs the action of the switching device, whereas the output rectifier and filter deliver an acceptable DC voltage to the output.

3.4.CONCLUSION

Based on the design of PV array and design of step-up converter as shown above where different equations where derived from equivalent electric circuit, it can be summarized that the duty ratio plays an important role in increasing or decreasing of the output power and voltage. However, the next chapter will introduce controller design applying control techniques to track the maximum power point of our system.

CHAPTER 4: CONTROL TECHNIQUES FOR PV MPPT

4.1 INTRODUCTION

Designing a controller is an important and main step for any control system. However, two basic components are essential to know before designing it such as the system plant which describes the mathematical model behavior of the system and the output which is the target desired to reach.

Since photovoltaic systems exhibit nonlinear behavior, the maximum power point varies with solar insolation, and there is a unique solar panel operating point at which the power output is at a maximum. Therefore for maximum efficiency, MPPT algorithm technique are used to deliver optimal available solar output power at various different operating points to the load. Various are control techniques and much research has been carried out for solar optimization techniques. Most popular techniques include Perturbation and observation(P&O) and incremental conductance approaches.

4.2 TECHNIQUES USED FOR MAXIMUM POWER POINT TRACKING (MPPT)

A lot of MPPT algorithms have been introduced and proposed to overcome certain disadvantages that other techniques have. All the methods vary in complexity, number of sensors required, digital or analogue implementation, convergence speed, tracking ability, and cost effectiveness. Furthermore, the type of application can have a huge impact on the selection of MPPT technique. Tracking the maximum power point (MPP) of a photovoltaic array is an essential stage of a PV system [15] [16]

4.2.1 PERTURBATION AND OBSERVATION(P&O) TECHNIQUE

One of method used for tracking the maximum power point of solar array is the P&O. It consist of introducing a small disturbance causing variation of power in PV module. Its output is measured continuously and compared with the previous

status. If both power and voltage keep increasing the operating points are adjusted by control system. At each perturbation point, the algorithm continues to operate in the same manner [17] [18]. Because of solar irradiation not changing quickly hence it shows good performance and the oscillation of operating point of the MPP voltage at steady state normally fluctuates lightly. Moreover the perturbation frequency should be low enough at mentioned state in order to avoid negative effect of next perturbation. The step size of perturbation should be enough so that it is not affected by noise measurement which generates changes in PV module. These can be considered advantages of this technique. One of disadvantages of this technique which need to be highlighted here is the poor efficiency at low irradiation.

Fig.: 4.1 shows the flowchart of the P&O algorithm implementation. The sensor is used to perform voltage and current measurement and put in solar cells. Then the algorithm applied and performed calculations and comparisons with previous power. Settings done through the duty cycle using the new PV power voltage
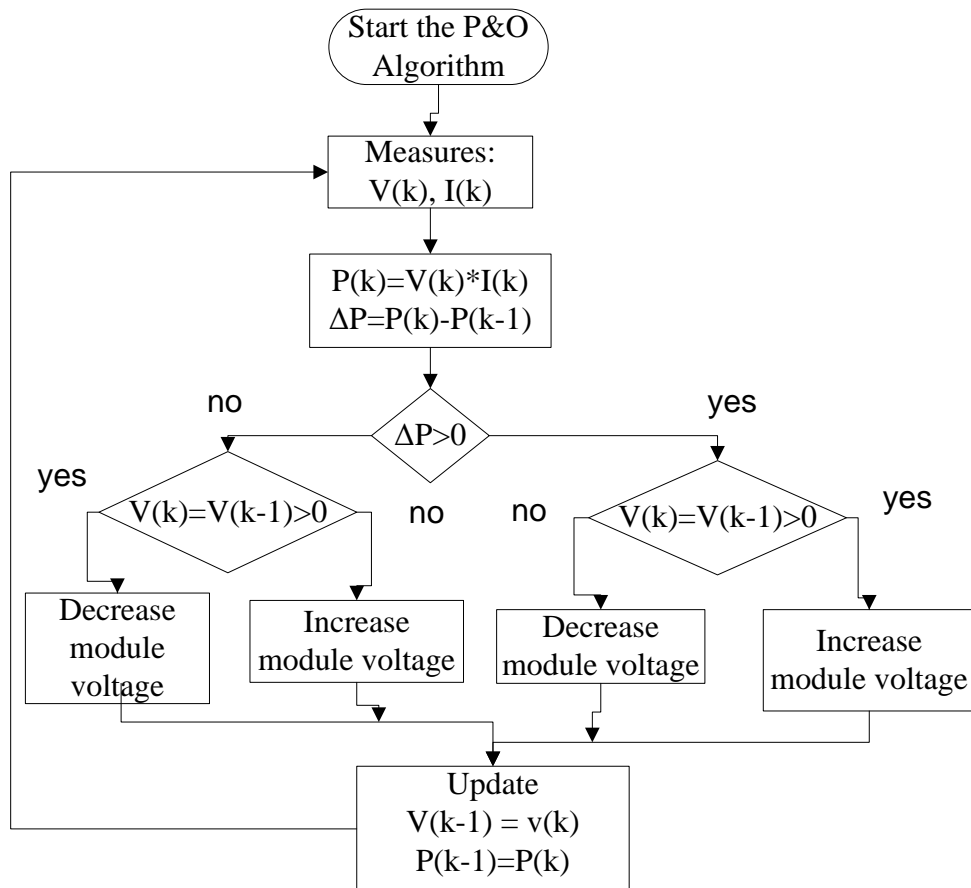
Fig. 4.1 : Flowchart of Perturb and Observer

As we can see from the flowchart, the process starts by measuring the solar voltage and rating PV current from the photovoltaic module so that its value will be obtained. According to the value acquired from the measurement of the current, the same is compared to the previous measurement value of power. If the difference between the two measurements values is equal to zero then the value of the PV voltage, current and power will be used as the value of the latest. But if the value of the difference between its different from zero then it will be given the addition and subtraction of voltage in accordance with the specified reference voltage. From this voltage value obtained perturb power latest. The block diagram for the P&O controller design is represented in fig. 4.2
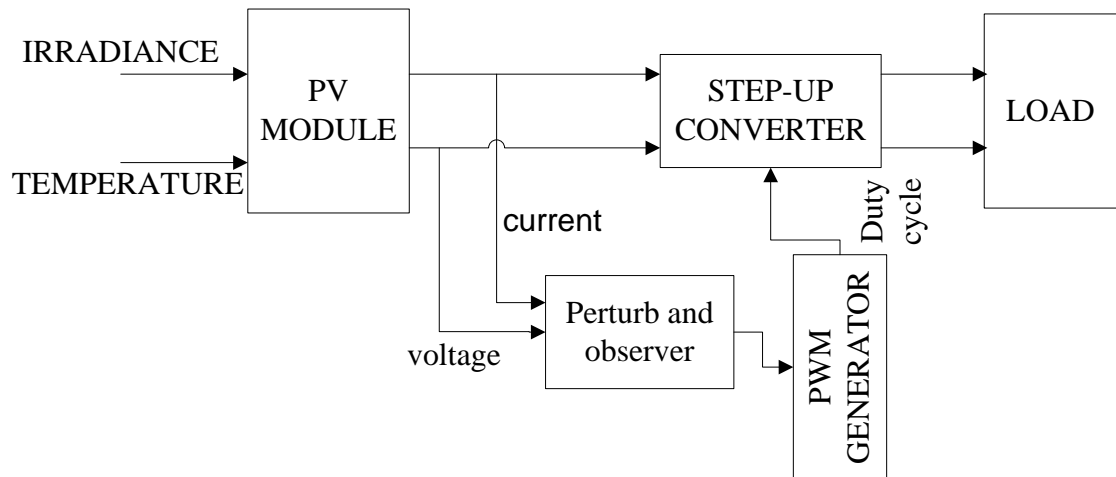
Fig.4.2: P&O based MPPT design

4.2.2 INCREMENTAL CONDUCTANCE ALGORITHM

Due to some disadvantages of P&O algorithm, the incremental conductance technique is used to overcome such limitations by using the incremental conductance of the photovoltaic. This technique works by investigating the voltage operating point at which the conductance is equal to the IC. Once that happens, the operating point is not perturbed anymore. The advantage of incremental conductance technique is the ability it has to ascertain the relative distance to the maximum power point, determining when the maximum power point has been reached. In variable weather conditions, this techniques tracks precisely the MPP, and exhibits less oscillatory behavior around the MPP compared to the P & O method, even when the P & O method is optimized [19]. Using a derivative operation in this technique tends to create instability of the system. This last is one of drawbacks of incremental conductance algorithm. Also under low levels of insolation, the differentiation process difficult and prone to measurement noise; and results can be unsatisfactory [20] .

```
                         ┌─────────────┐
                        (    START     )
                         └──────┬──────┘
                                │
                    ┌───────────┴───────────┐
                    │  Measures: V(k), I(k)  │
                    └───────────┬───────────┘
                                │
                    ┌───────────┴───────────┐
                    │  ΔI=I(k) - I(k - 1)    │
                    │  ΔV= V(k) -v(k - 1)    │
                    └───────────┬───────────┘
                                │
```

Fig.4.3 Incremental conductance method

4.2.3 FUZZY LOGIC CONTROLLER FOR MPPT BASED CONTROL

Fuzzy logic controller are specially used to deal with non-linear systems. Fuzzy by nature is non-linear controller as it is complex to describe mathematically when compared to proportional integral derivative controller which can be considered one of its disadvantage. The control strategy consists of IF-THEN rules which allow professional to deal with it in a very easy way.

This controller consists of fuzzification block, rule base, inference system and defuzzification block. It can be seen from fig.4.4 the basic building of fuzzy logic controller elements.

Fuzzification element investigates the membership function and drive as well the membership grades. Based on the learning rule it evaluates the input measurements. All collected rules is done by the rule base element which defines the output of the system. For the purpose of mapping the input windows to output the fuzzy inference engine is used. Finally follows the defuzzification block in which the control signal are to a non-fuzzy control signal.
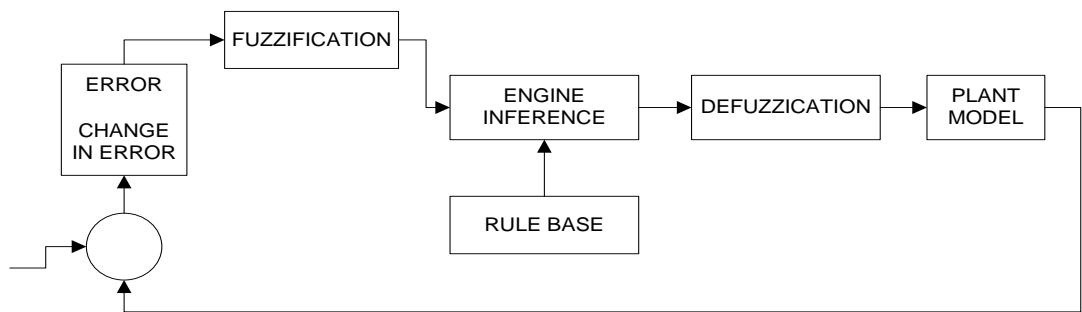
Fig.4.4 Block diagram of fuzzy logic controller

Error and change in error are called the inputs of the system and inside these elements are fuzzy variables. The input and output range built to track the maximum power point of our system are for error and change in error we have: (-1, -0.8. -0.6, -0.4, -0.2 0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8 1). Rule base table is shown in table 4.1.

ERROR	NB	NS	ZERO	PS	PB
CHANGE IN ERROR					
NB	PB	PS	NB	NS	NS

NS	PS	PS	NB	NS	NS
ZERO	NS	NS	PB	NB	PB
PS	NS	PB	PS	NB	PB
PB	NB	PB	PB	PS	PB

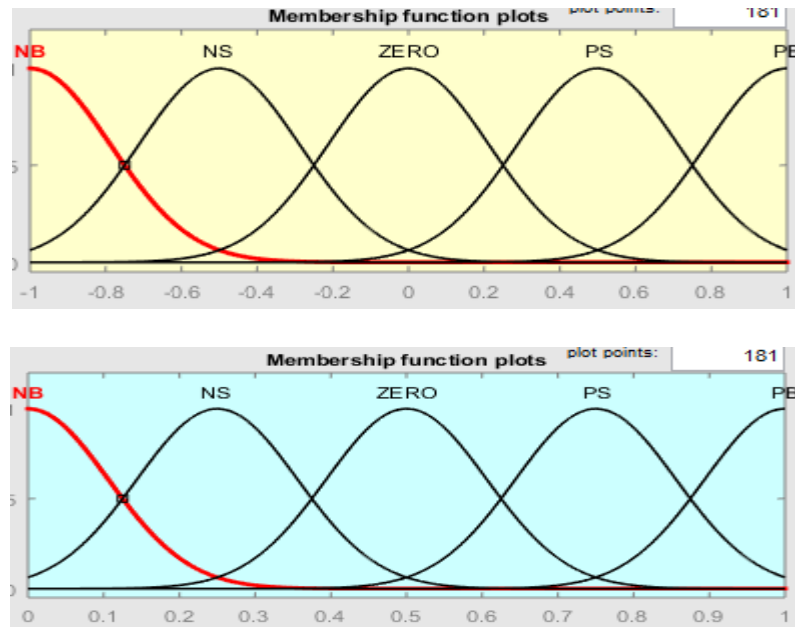Table. 4.1 Rule base for use in fuzzy controller

Fig.4.5: Membership function for input and output of the controller

4.2.3 ARTIFICIAL NEURO-FUZZY INFERENCE SYSTEM

Adaptive Network-based Fuzzy Inference System is a neuro-fuzzy algorithm where the combination of neural network and the fuzzy inference system is made. By using both mentioned techniques, the estimation of the parameters can be represented by the ANFIS architecture. Imprecision and uncertainty of the system being modeled are dealt with by the fuzzy logic whilst the neural network focuses on tuning the fuzzy rules so that the system can become adaptable. Data-driven series of steps for the synthesis of Adaptive Network-based Fuzzy Inference System networks are generally based on clustering a training group of numerical samples of the unknown function to be estimated. Since its introduction, ANFIS networks have been successfully applied to classification tasks, rule-based process control, pattern recognition, and similar problems.

4.2.3.1 ANFIS ARCHITECTURE

The ANFIS architecture is composed by five layers, having two inputs and one output. The rule base contains the fuzzy if-then rules of Takagi and Sugeno's type [21] as follows: If X is A and Y is B then z is f(X,Y)

Where: A and B are the fuzzy sets in the previous

$z = f(x, y)$ is a crisp function in the consequent. usually, $f(x, y)$ is a polynomial for the input variables x and y. When $f(x,y)$ is a constant, a zero-order Sugeno fuzzy model is formed which may be considered to be a special case of mundane fuzzy inference system [22] where each rule base consequent is specified by a fuzzy singleton. if $f(x, y)$ is taken to be a first-order polynomial a first-order Sugeno fuzzy model is formed for a first-order two rule Sugeno fuzzy inference system, the two rules can be stated as:

1) rule : if x is a1 and y is b1 then we can put f1 to be as $f1 = p1x + q1y + r1$

2) rule : if x is a2 and y is b2 then we can put f2 to be as $f2 = p2x + q2y + r2$

here type-3 fuzzy inference system proposed by Takagi and Sugeno [22] is used. It is clear that in the output of each rule above is a linear combination of the inputs added by a constant term. The final output is the weighted average of each output rule. In fig.4.4 the equivalent ANFIS architecture is shown in fig. 4.6.
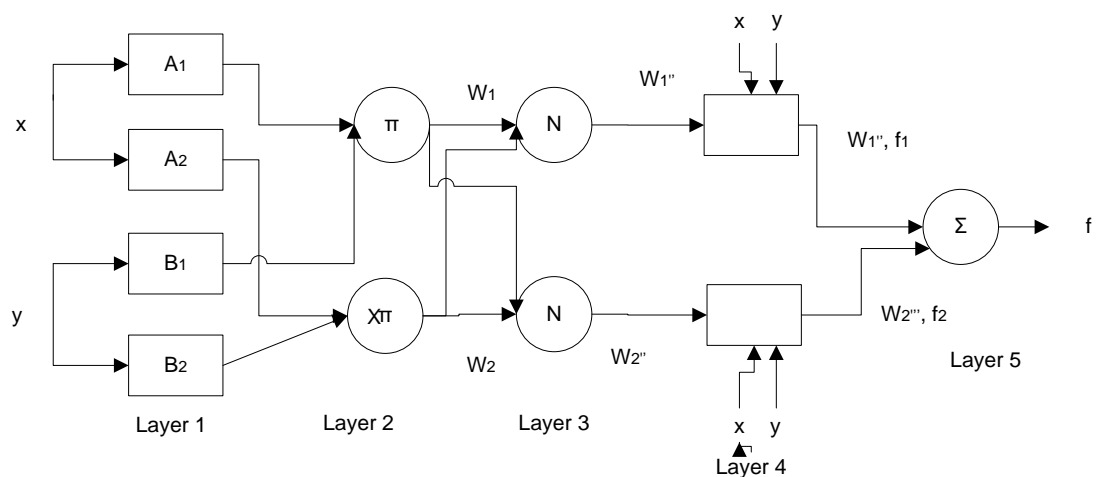

Fig. 4.6: ANFIS architecture

Description of the above ANFIS structure it is important to understand the entire process working principle. The first layer takes the input values and decides the membership functions belonging to them and the membership of each function are computed by using the premise parameter set.

$$O_i^1 = \mu A_i(x) \qquad (4.1)$$

Where:

x: input to node i

A_i: linguistic variable associated with the node

μA_i: membership function of A_i

$$\mu A_i(x) = exp\left\{-\left(\left(\frac{x-c_i}{a_i}\right)^2\right)\right\} \qquad (4.2)$$

Where:

x: is the input

a_i, b_i, c_i: are the premises parameter set

The 2nd layer is responsible of generating the firing strengths for the rules. Due to that is denoted as rule layer.

$$O_i^2 = \omega_i = \mu A_i(x) \times \mu B_i(y), \; i = 1,2 \qquad (4.3)$$

The role of the 3rd layer is to normalize the computed firing strengths, by dividing each value for the total firing strength.

$$O_i^3 = \bar{\omega}_i = \frac{\omega_i}{\omega_1 + \omega_2}, \; i = 1,2 \qquad (4.4)$$

The 4th layer takes as input the normalized values and the consequence parameter set. All values returned by this 4th layer are the defuzzification ones and are passed to the last layer to return the final output

$$O_i^4 = \bar{\omega}_i f i = \bar{\omega}_i(p_i x + q_i y + r_i), \; i = 1,2 \qquad (4.5)$$

Where:

$\bar{\omega}_i$: is the output of Layer 3 and $\{p_i, , q_i, r_i\}$ is the consequent parameter set

Layer 5: This layer comprises of only one fixed node that calculates the overall output as the summation of all incoming signals.

$$O_i^5 = all\ output = \sum_i \bar{\omega}_i f_i = \frac{\sum_i \omega_i f_i}{\sum_i \omega_i} \qquad (4.6)$$

4.2.3.2 Learning Algorithm

In the ANFIS structure, it is observed that given the values of premise parameters, the final output can be expressed as a linear combination of the consequent parameters. The output f in Fig. 4.1 can be written as

$$f = \frac{\omega_i}{\omega_1 + \omega_2} f1 + \frac{\omega_i}{\omega_1 + \omega_2} f2$$

$$= \bar{\omega}_1 f1 + \bar{\omega}_2 f2$$

$$= (\bar{\omega}_1 x)p_1 + (\bar{\omega}_1 y)q_1 + (\bar{\omega}_1)r_1 + (\bar{\omega}_2 x)p_2 + (\bar{\omega}_2 y)q_2 + (\bar{\omega}_2)r_2 \quad (4.7)$$

Where f is linear in the consequent parameters $(p_1, q_1, r_1, p_2, q_2, r_2)$.

In the forward pass of the learning algorithm, consequent parameters are identified by the least squares estimate. In the backward pass, the error signals, which are the derivatives of the squared error with respect to each node output, propagate backward from the output layer to the input layer. In this backward pass, the premise parameters are updated by the gradient descent algorithm [23].

Below is shown the building block diagram of ANFIS based MPPT
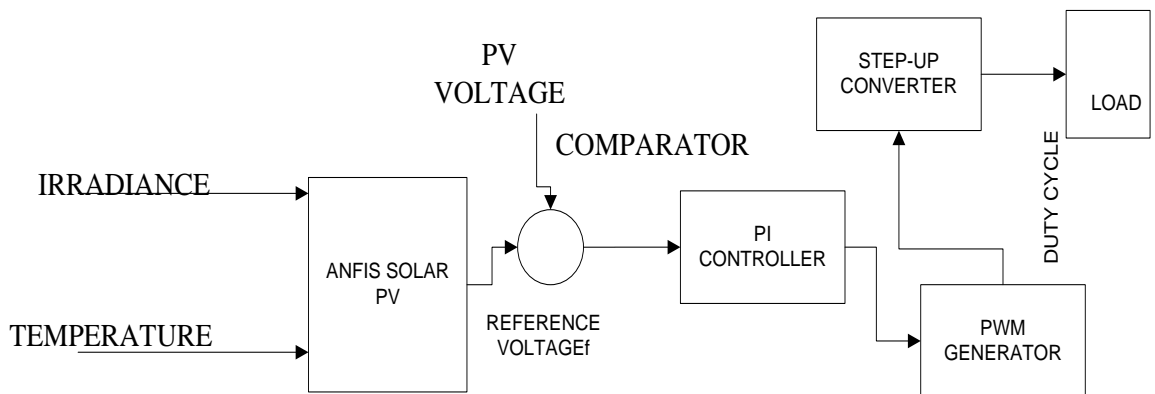
Fig.4.7: Block diagram of ANFIS controller based MPPT

In order to build ANFIS based MPPT controller, the two input parameters which are the temperature and irradiance must be given to initialize the training process. Random values for temperature and irradiance are obtained based on the characteristics and parameters of the solar module. It can be noted from the fig.4.8 a clear picture of the training process.

ANFIS training data in Matlab after running a code.

Number of nodes: 35

Number of linear parameters: 9

Number of nonlinear parameters: 18

Total number of parameters: 27

Number of training data pairs: 1000

Number of checking data pairs: 0

Number of fuzzy rules: 9

Start training ANFIS ...

1   3.84745e-07

2   8.72226e-05
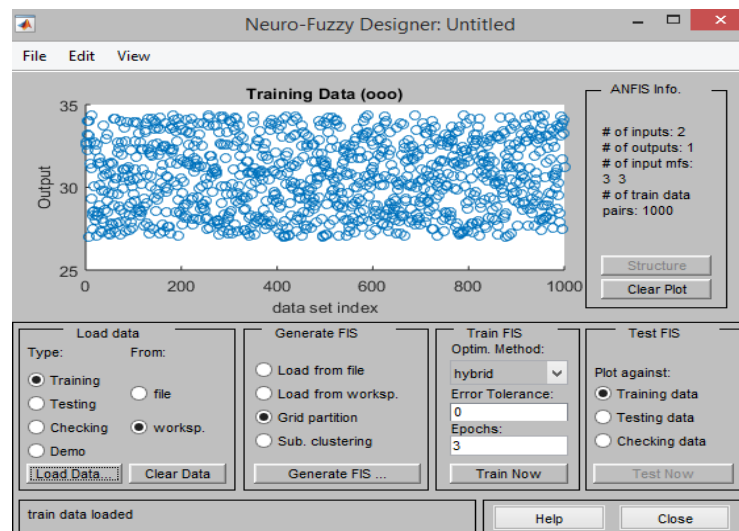
Fig.4.8: Screen showing after data is loaded for training of ANFIS controller

After the data is loaded, follows the generation of fuzzy inference system by selecting the Grid partition and clicking on Generate FIS. Once clicked defining a number of membership functions is a must. According to fig. 4.9, three membership functions are selected followed by the type of membership function which is triangular function.
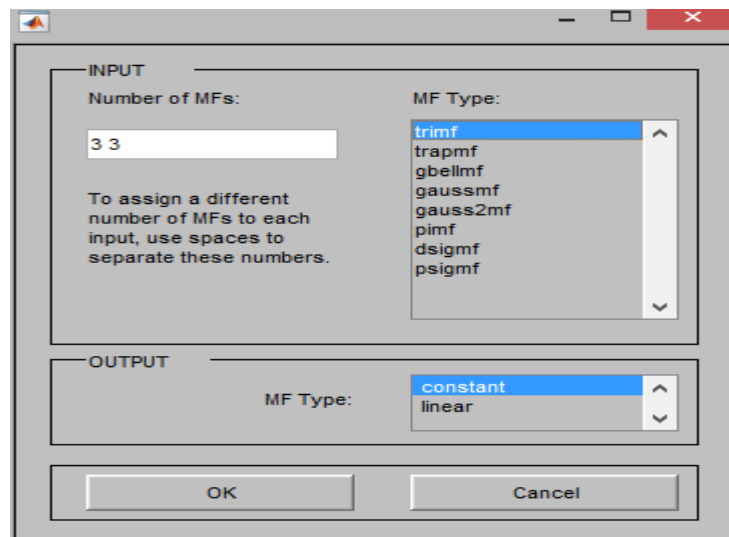
Fig.4.9: Selection of number of membership function for the ANFIS controller

The optimization method selected is hybrid and the number of epochs is 50. As it can be seen in fig. 4.8 the error obtained is low approximately 3.56e-07.
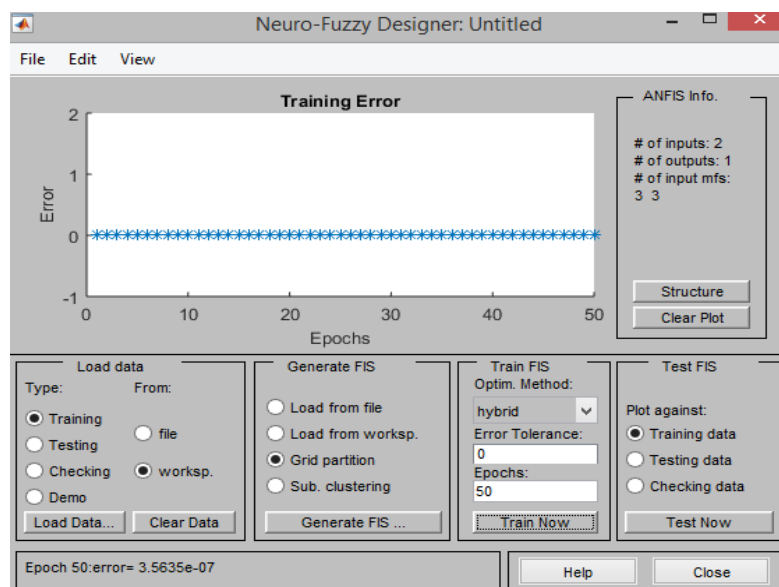
Fig.4.10: Training error for 50 epochs

After training the data, the same is tested. See fig.: 4.11
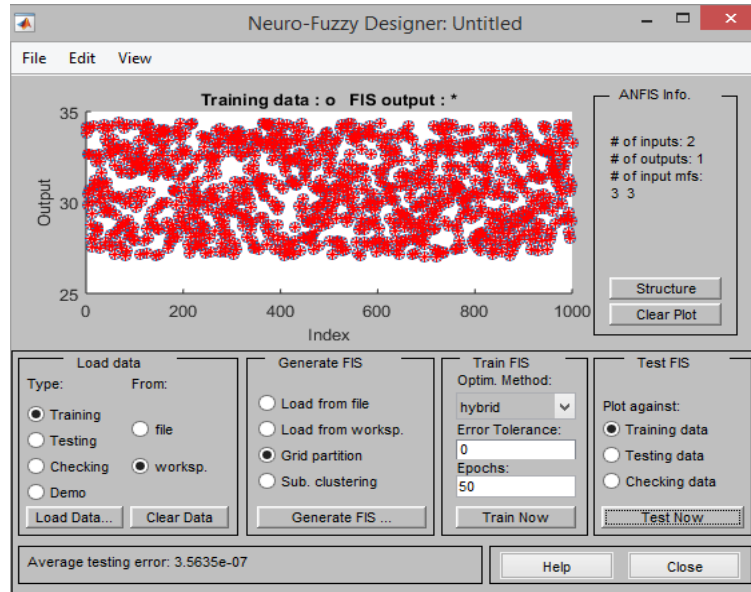
Fig.4.11: Testing the trained data

After testing the trained sets, it is possible to check for the structure of the ANFIS model
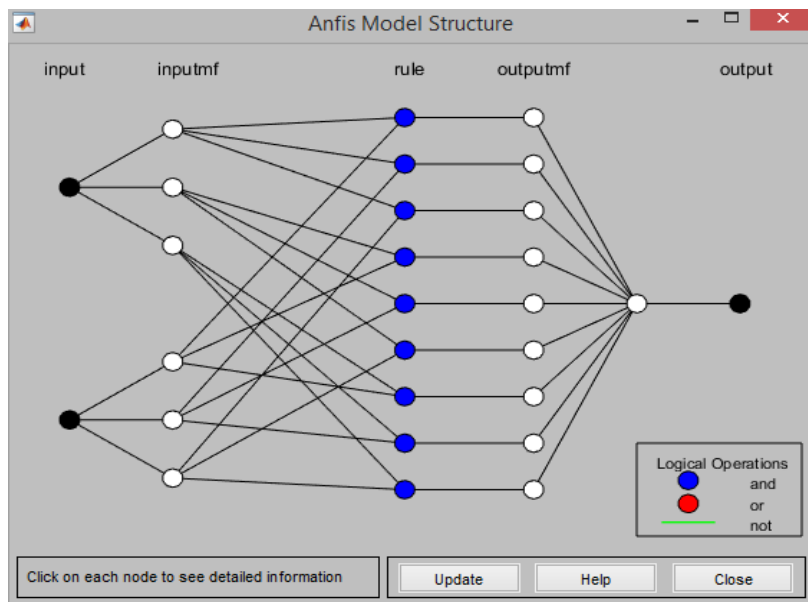
Fig.4.12: ANFIS model structure

4.2.4 PROPORTIONAL INTEGRAL CONTROLLER

A PID Controller is a feedback control loop mechanism widely used in many industries for the purpose of control of their processes. The Proportional integral derivative controller calculates the error by means of the difference between the measured variables and the desired set point.

As noted above, the word PID consists of three elements denoted by P, I, and D. In the present system plant only the combination of proportional and integral are used

Design of PID controller

The mathematical formula for PID is as follows:

$$u(t){=}K_p + K_i \int_0^t e(t)dt + K_d \frac{d}{dt}e(t) \tag{4.8}$$

Where:

K_p : proportional gain

K_i : integral gain

K_d : derivative gain

4.3 CONCLUSION

In this chapter is introduced and discussed about different control algorithms used to track the maximum power point of the PV module. However its seen that in spite of some disadvantage of Perturbation and observation method, it is one of most popular technique applied. Incremental Conductance algorithm improves some drawbacks of P&O method. FLC has capability to deal with non-linear and complex problems. Therefore, since this paper focusses on ANFIS based MPPT controller, a combination of ANN and FLC it is introduced and proposed resulting in better performance overcoming shortcomings of other well-known techniques.

CHAPTER 5 CONTROLLER DESIGN OF THE SYSTEM PLANT

5.1 DESIGN OF STEP-UP CONVERTER

Before designing the controller, all parameters must be known in order to have a clear picture of the plant to be controlled. With that being said, inductor, capacitor and resistance values for the step-up converters are calculated and then fed to the system.

Taking into account our input voltage source from the PV module that is 36V and its desired to boost the output voltage to 120 voltage

Parameters of the step-up converter design

Input voltage from the source	36 volts

Power of the source	230 watts
Switching frequency	25KHZ
Efficiency	100%

Table 5.1 : Parameters for Step-up design

By the down equation the duty cycle can be determined

$$D = 1 - \frac{V_S}{V_0} * \eta \qquad (5.2)$$

Where:

D: duty cycle

V_S: input voltage from the source

V_0: desired output voltage

η : efficiency

So solving, we get

$$D = 1 - \frac{36}{120} * 100 = 0.7$$

Once the duty cycle is determined, follows the calculation for the inductor which plays an important role in the system. With that being said, first the output current (I_0) is determined by using the following formula:

$$P = V_0 * I_0 = V_S * I_S \qquad (5.3)$$

Where P is the power from the source.

Calculation, we get the values as follows:

Output current

$$I_0 = \frac{240}{120} = 2 \ A$$

Inductance current:

$$I_L = \frac{240}{36} = 6.67 \ A$$

Now taking ΔL_i 30% of the inductance current following calculation can be performed

$$\Delta I_L = 30\% * I_L \tag{5.4}$$

$$\Delta V_0 = 30\% * I_L \tag{5.5}$$

So, calculations can be done

$$\Delta I_L = 0.3 * 6.67 = 2.001$$

$$\Delta V_0 = 0.01 * 120 = 1.2$$

Now finding the value of the inductor by using the following formula

$$L = \frac{V_s(min)*D}{f_s*\Delta I_L} \tag{5.6}$$

Where:

L: inductance

f_s: switching frequency

$$L = \frac{V_s(min) * D}{f_s * \Delta I_L} = \frac{36 * 0.7}{25 * 10^3 * 0.3 * 6.67} = 503 * 10^{-6}$$

Capacitor calculation

Taking into account that $V_C = V_0$, ΔV_C can be obtained by taking 1 to 5% of the desired output voltage

$$\Delta V_0 = 1\% * V_0 \tag{5.7}$$

So we get

$$\Delta V_0 = 1\% * V_0 = 1.2$$

Now determining the value of the capacitor by using the following equation

$$C = \frac{I_0(max)*D}{f_s*\Delta V_C} \tag{5.8}$$

Calculating we get

$$C = \frac{I_0(max) * D}{f_s * \Delta V_C} = \frac{2 * 0.7}{25 * 10^3 * 1.2} = 46.6 * 10^{-6}H$$

Load at rated power can be calculated as follows:

$$P = V_0^2 * R \tag{5.9}$$

$$R = \frac{V_0^2}{P} = \frac{120^2}{240} = 60 \ ohm$$

5.2 State space equations

Based on boost converter electric circuit, equation can be derived by applying KVL and KLC principles we get the following equations
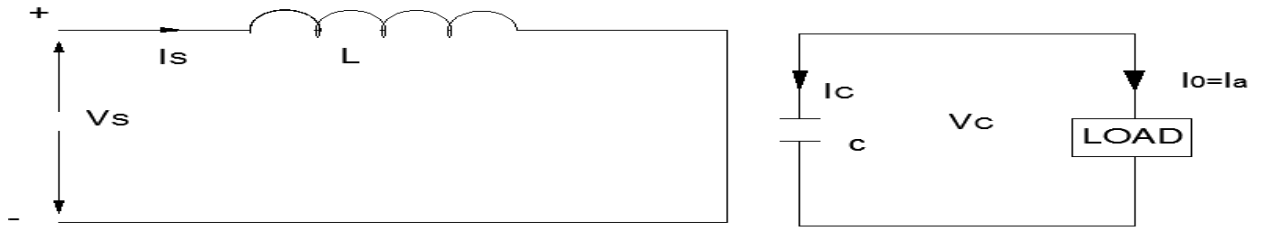
Fig.5.1: Switch on equivalent circuit

$$L\frac{di}{dt} = V_{in} - R * i_L - R_L * i_L \tag{5.10}$$

$$V_{out} = i_0 * R \tag{5.11}$$

$$C\frac{dV_c}{dt} + \frac{V_{out}}{R} = 0 \tag{5.12}$$

And

$$V_{out} = V_c + i_c * R_c$$

$$V_{out} = V_c \left[\frac{R}{R_C}\right] \tag{5.13}$$

From above equations

$$C\frac{dV_c}{dt} = \frac{-V_c}{R + R_C}$$

$$i_{in} = i_L$$

Based on that we get the following state equation representation

$$\begin{bmatrix} \frac{di_L}{dt} \\ \frac{dV_C}{dt} \end{bmatrix} = \begin{bmatrix} \frac{-(R_{on}+R_L)}{L} & 0 \\ 0 & \frac{-1}{C(R+R_C)} \end{bmatrix} \begin{bmatrix} i_L \\ V_C \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{in} \tag{5.14}$$

Where:

$$V_{out} = \begin{bmatrix} 0 & \dfrac{R}{R + R_C} \end{bmatrix} \begin{bmatrix} i_L \\ V_C \end{bmatrix}$$

$$A = \begin{bmatrix} \dfrac{-(R_{on} + R_L)}{L} & 0 \\ 0 & \dfrac{-1}{C(R + R_C)} \end{bmatrix}$$

$$B = \begin{bmatrix} \dfrac{1}{L} \\ 0 \end{bmatrix}$$

$$C = \begin{bmatrix} 0 & \dfrac{R}{R + R_C} \end{bmatrix}$$

$$D = [0]$$

5.3 PV module design in Simulink

According to derived equations obtained in PV modelling, the following subsystem block is obtained.
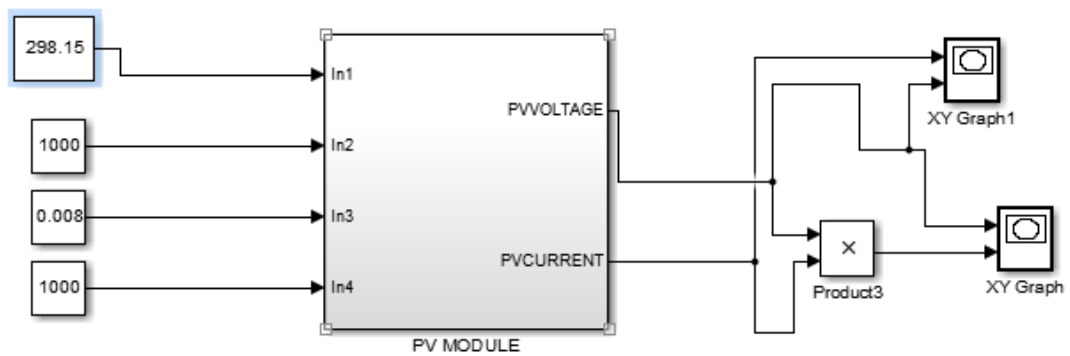
Fig.: 5.2 PV PV modelling in Simulink

Based on model of PV obtained, I-V and P-V characteristics are plotted as shown in fig.5.3
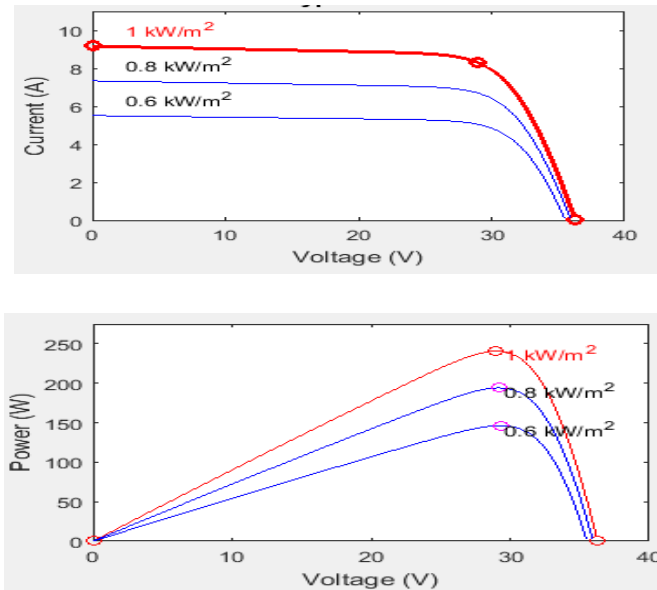
Fig.5.3 I-V AND P-V characteristics of PV module at different irradiance and fixed temperature of 25 degree

5.4 Step-up converter design connected with PV Module in Simulink/Matlab

Fig.3 represents a PV module connected with step-up converter in Simulink. The pulse generator is configured to duty ratio equal to 0.7.
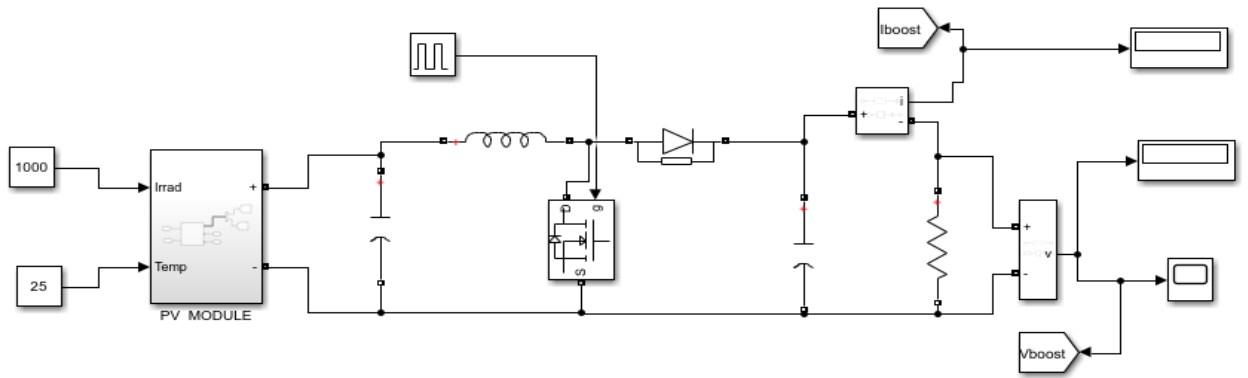
Fig.5.4: PV connected with step-up converter in Simulink
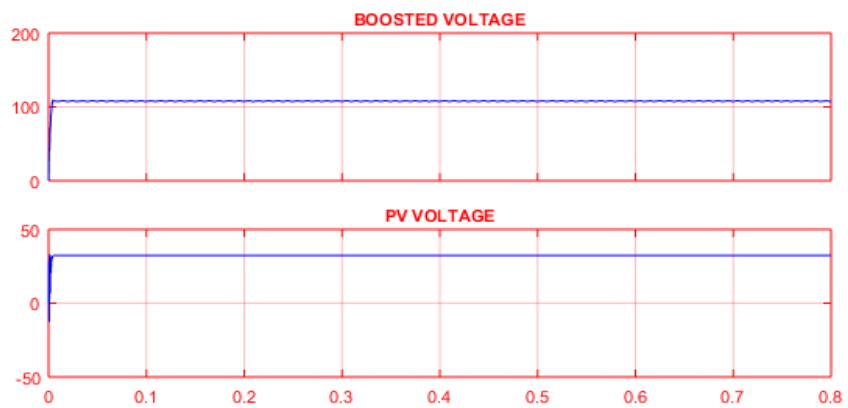
Fig.5.5: Voltage output at duty ratio 0.7 and irradiance 1000 and temperature at 25 degree
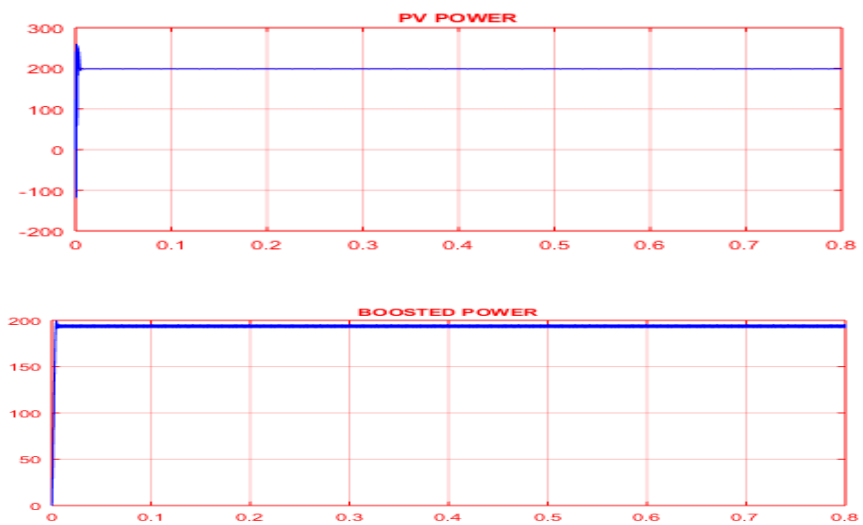
Fig.5.6: Power output at duty ratio 0.7 and irradiance 1000 and temperature at 25 degree

From the above simulations plot we can see that the maximum power point is tracked successfully by setting the duty ratio at 0.7

5.5 Fuzzy logic controller

Fig 5.7 shows the design of fuzzy controller based MPPT in Simulink/Matlab.
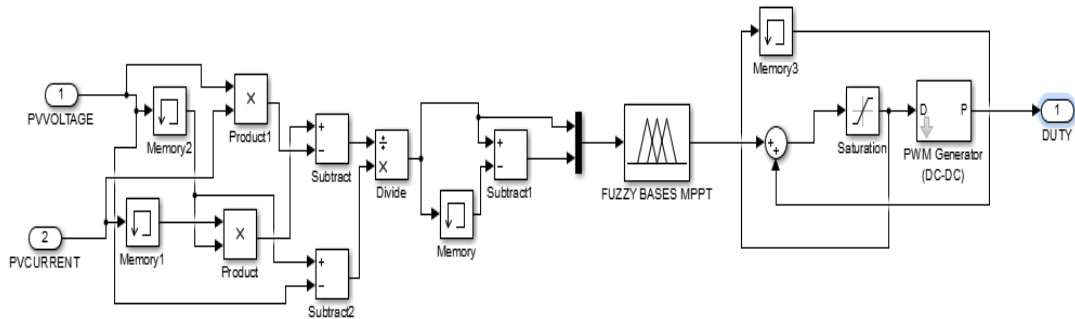
Fig.5.7: Fuzzy logic controller design in Simulink

Fig 5.8 shows the complete system of Fuzzy based MPPT controller.
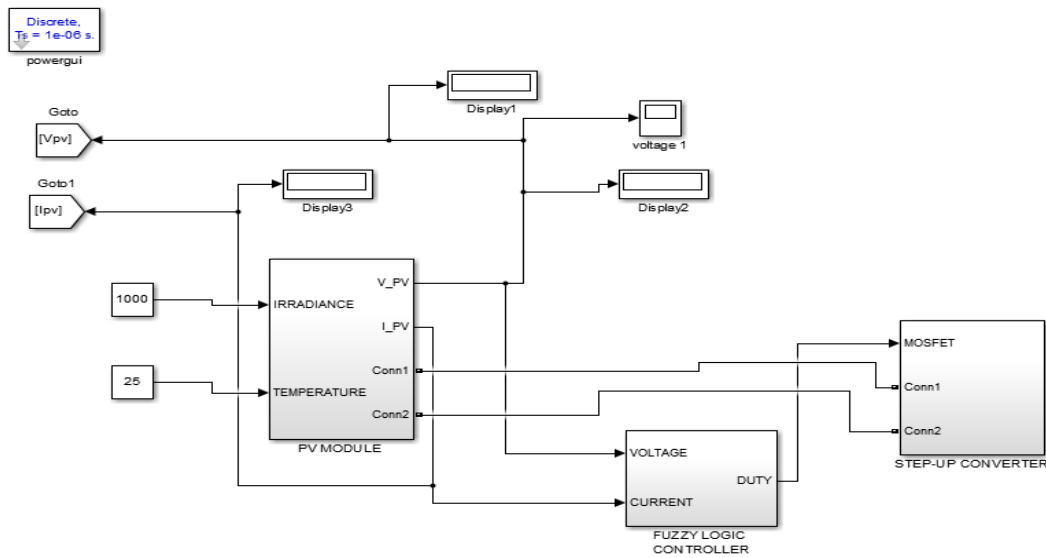
Fig.5.8: Fuzzy based MPPT design in Simulink

The Simulations results are shown below at fixed temperature and at varying irradiance.
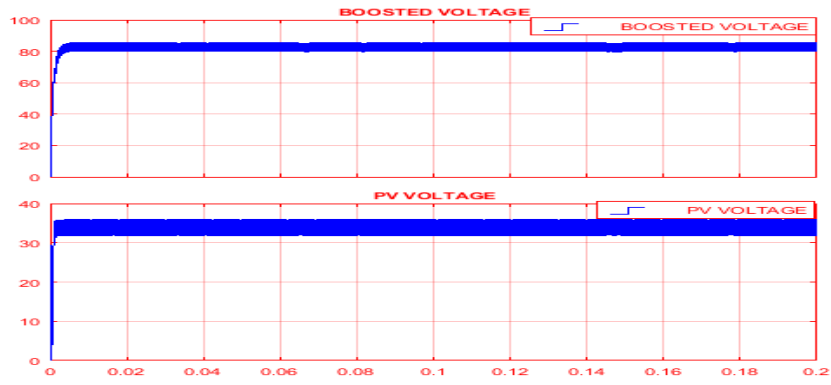
Fig.5.9 Fuzzy logic output voltage result
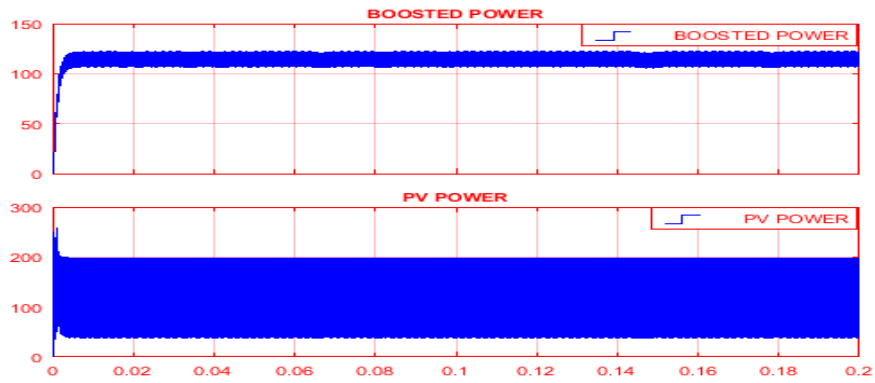
Fig.5.10: Fuzzy logic output power at 1000 and 800 irradiance and fixed temperature of 25.
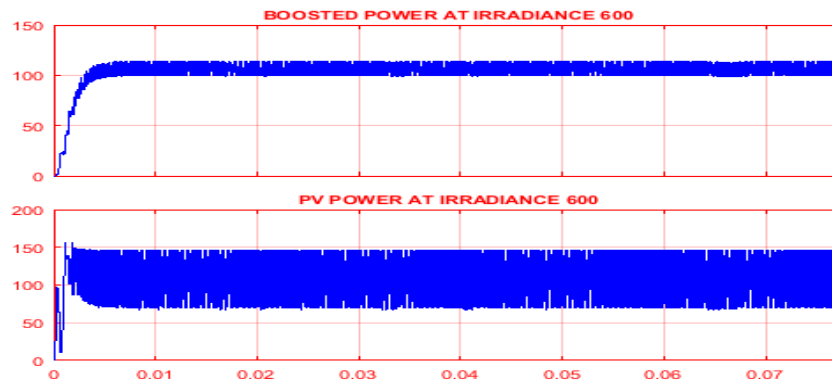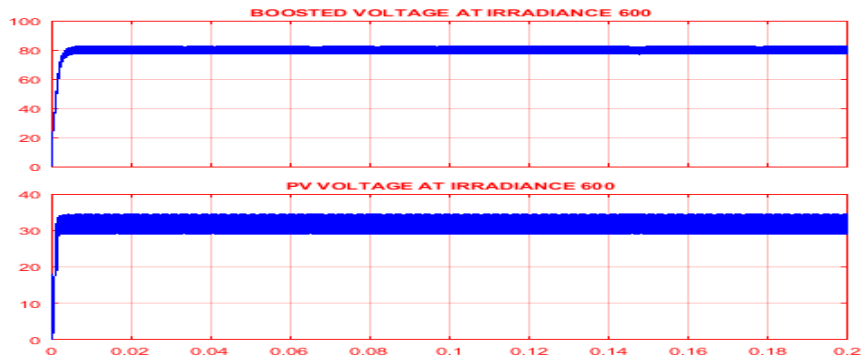

Fig. 5.11 Output power using fuzzy logic

Fig. 5.12 Output voltage using fuzzy logic

5.6 ANFIS controller design in Simulink

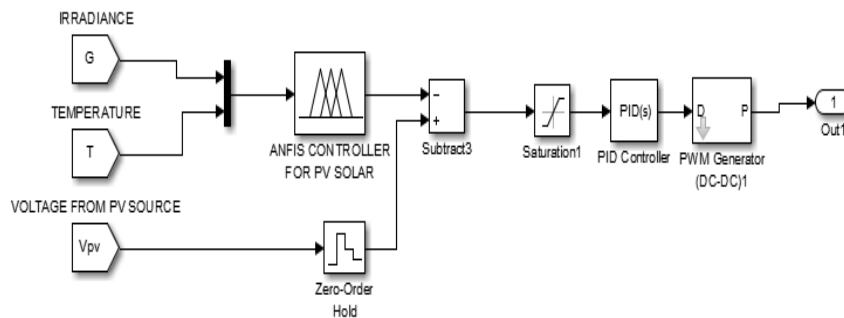Fig 5.13 shows the controller design of ANFIS based MPPT controller

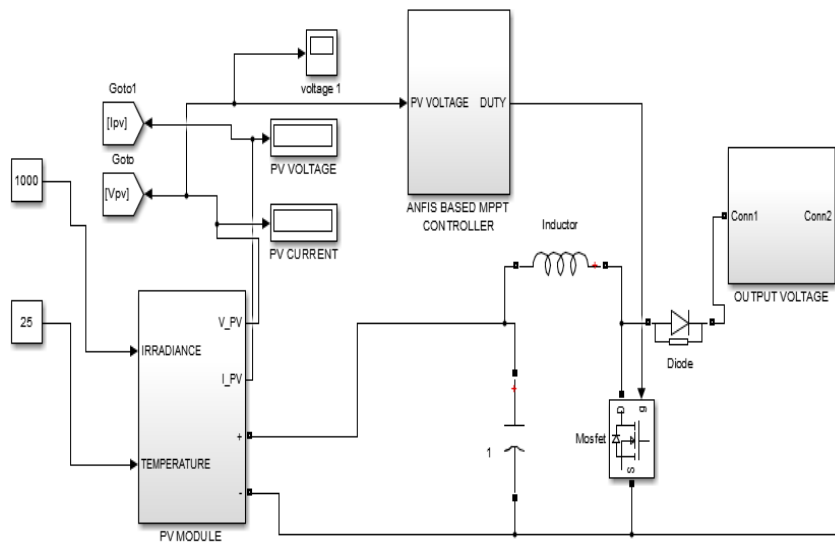Fig.5.13 :ANFIS controller design in Simulink

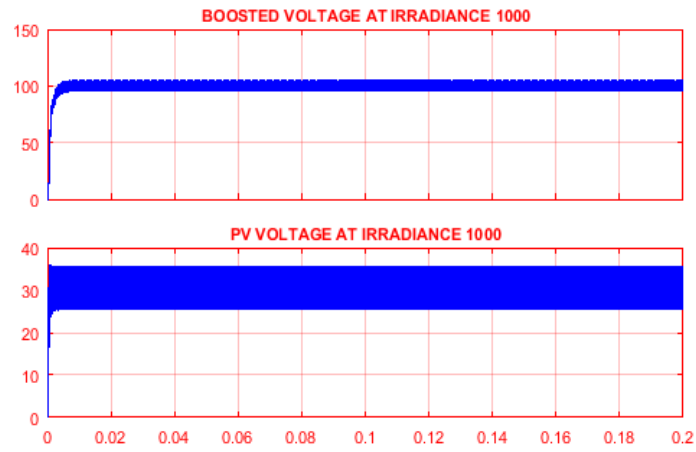Fig. 5.14: ANFIS based MPPT Controller design

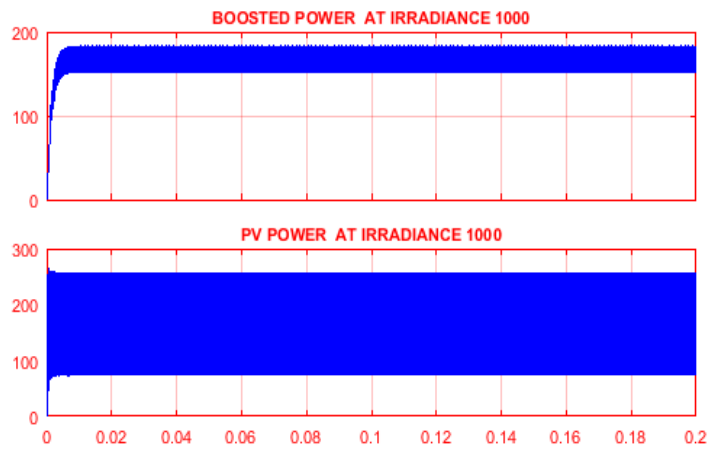Fig.5.15 ANFIS voltage result at 1000 irradiance

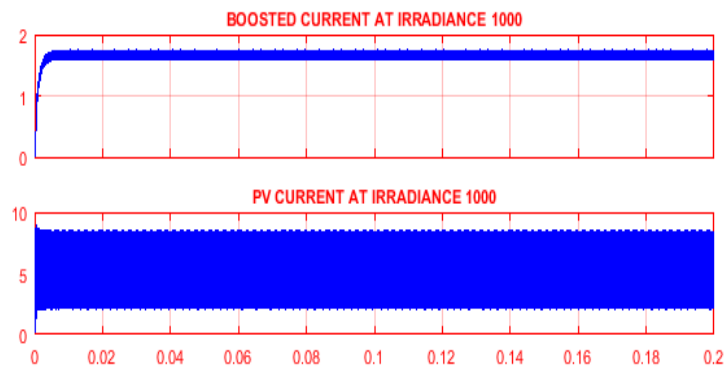Fig.5.16 ANFIS power output result at 1000 irradiance

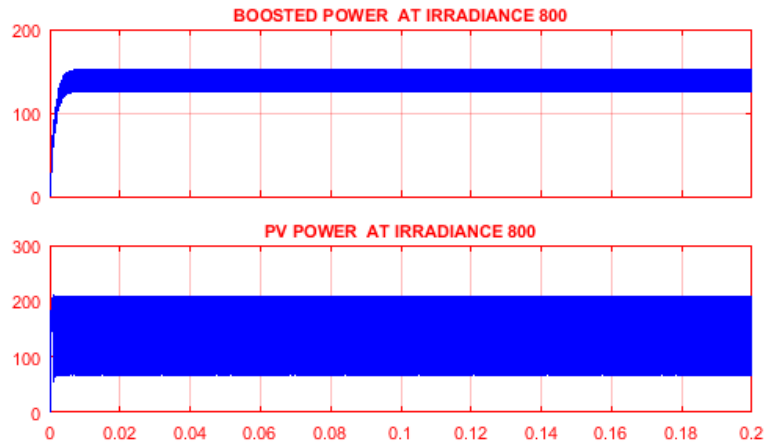Fig.5.17 ANFIS current output result at 1000 irradiance

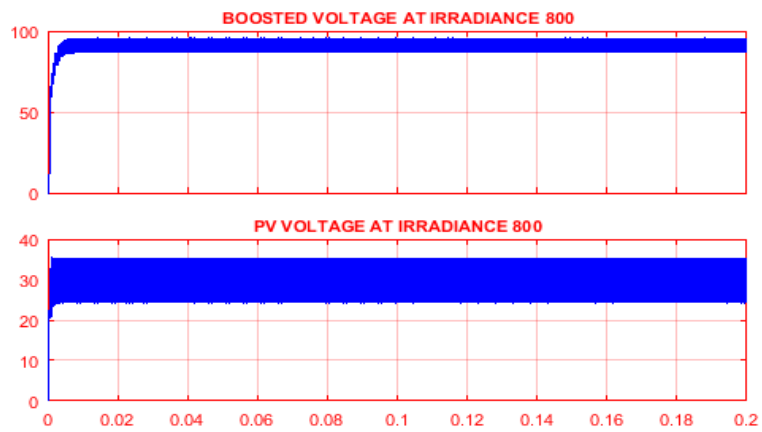Fig.5.18 ANFIS power result at 800 irradiance

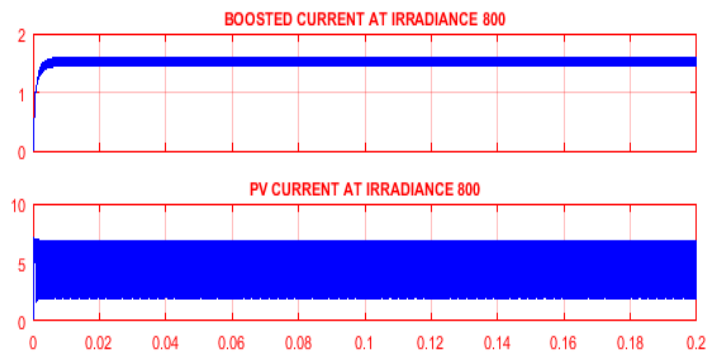

Fig.5.19 ANFIS voltage result at 800 irradiance

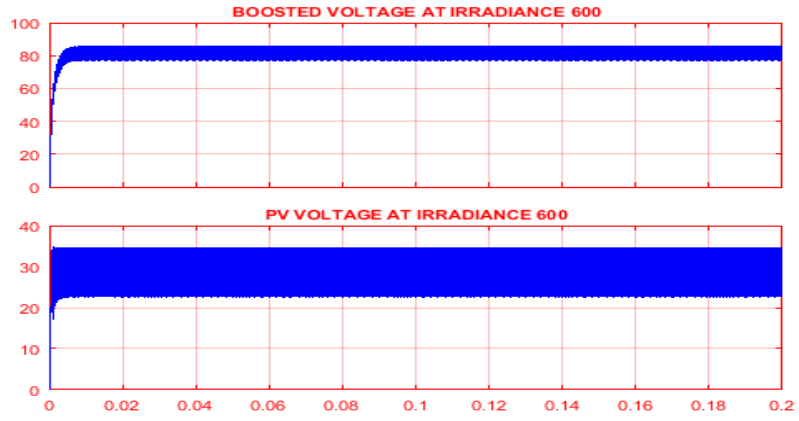Fig.5.20 ANFIS current result at 800 irradiance

Fig.5.21 ANFIS voltage result at 600 irradiance
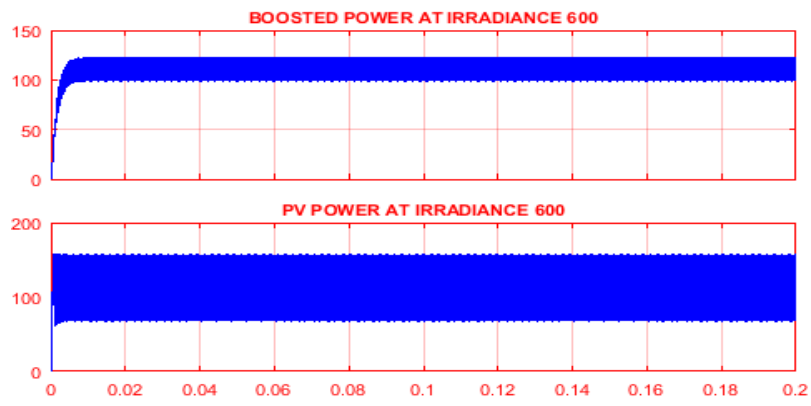
Fig.5.22 ANFIS power result at 600 irradiance and 25 degree
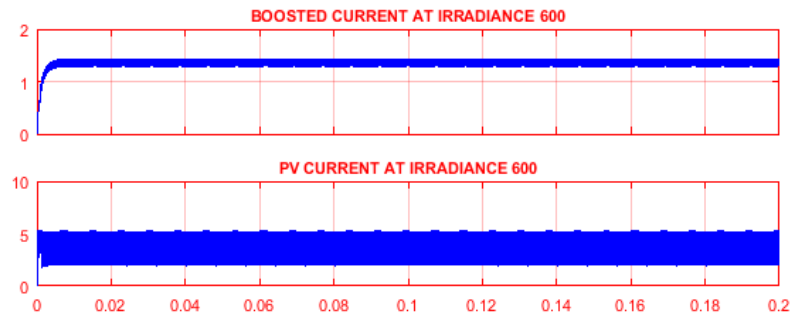
Fig.5.23 ANFIS current result at 600 irradiance and 25 degree

Irradia tion	T	I_{out}	V_{out}	P_{out}
1000	25	1.4	84.06	117.7
800	25	1.37	82.66	113.9
600	25	1.353	81.18	146

Table 5.2 Fuzzy based MPPT controller simulation results

Irrad	T	I_{out}	V_{out}	P_{out}
1000	25	1.616	96.95	156.6
800	25	1.448	86.87	125.8
600	25	1.376	82.55	147.6

Table 5.3 ANFIS based MPPT controller simulation results

5.7 Conclusion

Two different controller were designed to control the duty ratio and track the maximum power point of our entire nonlinear plant. As noted from the simulation results both designed controller perform in a very good way and the power is tracked successfully. However the ANFIS based MPPT controller showed better result when compared to fuzzy based MPPT controller

CHAPTER 6 CONCLUSION AND FUTURE WORK

6.1 Conclusion

This paper discusses about ANFIS based MPPT controller connected with step-up converter implementation in order to boost the voltage and track the maximum power generated by the system plant overall. ANFIS controller performs better according to the simulation result obtained when compared to fuzzy logic.

6.2 Future works

ANFIS MPPT controller showed great performance in tracking the maximum power point of our solar system. Many other controllers can be developed in order to overcome some inefficiency of ANFIS like a combination of PSO with ANFIS which could provide better performance and it is for sure a purpose of future works in developing a robust controller for MPPT power tracking.

REFERENCE

1. Dinniyah, Farah S.. Simulasi perangkat buck-boost converter untuk panel surya dengan pengendali PID, thesis(in Indonesian), Universitas Indonesia, Dept.E.E., July 2016.

2. Azadeh Safari and Saad Mekhilef, Simulation and Hardware Implementation of Incremental Conductance MPPT With Direct Control Method Using BoostConverter, IEEE Transactions on industrialL electronics, vol. 58, no. 4, april 2011.

3. Arjyadhara Pradhan, Dr. S.M.Ali, Analysis of solar PV performance with change in temperature International Journal of Applied Engineering Research Volume 11, Issue 7, 1 May 2016.

4. Yazdani, A., Di Fazio, A.R., Ghoddami, H., Russo, M.; Kazerani, M.; Jatskevich, J.; Strunz, K.; Leva, S.; Martinez, J.A., "Modeling Guidelines and a Benchmark for Power System Simulation Studies of Three-Phase Single-Stage Photovoltaic Systems," IEEE Transactions on Power Delivery, vol.26, no.2, pp.1247-1264, April 2011.

5. B.Bendib, F.Krim, H.Belmili, M.F.Almi, S. Bolouma, "An Intelligent MPPT Approach based on Neural- Network Voltage Estimator and Fuzzy Controller, Applied to a Stand-alone PV System", IEEE Conference 2014.

6.M.A. Alsumiri, L. Jiang, W.H. Tang, "Maximum Power Point Tracking Controller for Photovoltaic System Using Sliding Mode Control" IET Journal-2014.

7.https://www.greenmatch.co.uk/blog/2015/06/advantages-and-disadvantages-of-solar-cells

8. R. Kumar and R. Muralidharan, "Mathematical modeling, simulation and validation of photovoltaic cells," International Journal of Research in Engineering and Technology, vol. 3, no. 10, pp. 170–174, 2014.

9.B. Habbati, Y. Ramdani, and F. Moulay, "A detailed modeling of photovoltaic module using MATLAB," NRIAG Journal of Astronomy and Geophysics, vol. 3, pp. 53–61, 2014.

10. S. Sumathi, A. L. Kumar, and P. Surekha, Solar PV and Wind Energy Conversion Systems. An Introduction to Theory, Modeling with MATLAB/Simulink, and the Role of Soft Computing Techniques, Green Energy and Technology, Springer, New York, NY, USA, 2015.

11.D. Sera, R. Teodorescu, and P. Rodriguez, "PV panel model based on datasheet values," in Proceedings of the IEEE International Symposium on Industrial Electronics (ISIE '07), pp. 2392–2396, Vigo, Spain, June 2007.

12.M. G. Villalva, J. R. Gazoli, and E. R. Filho, "Modeling and circuit-based simulation of photovoltaic arrays," Brazilian Journal of Power Electronics, vol. 14, no. 1, pp. 35–45, 2009.

13.Carl Nelson & Jim Williams, "Linear Technology, LT1070 Design Manual", 1986.

14**.**D Maksimovic, AM Stankovic, VJ Thottuvelil and GC. Verghese, "Modeling and simulation of power electronic converters", Proceedings of the IEEE Volume 89, no. 6, pp. 898-912, June 2001.

15.Femia, N., Lisi, G., Petrone, G., Spagnuolo, G. and Vitelli, M. (2008) Distributed Maximum Power Point Tracking of Photovoltaic Arrays: Novel Approach and System Analysis. IEEE Transactions on Industrial Electronics, 55, 2610- 2621. http://dx.doi.org/10.1109/TIE.2008.924035

16.Ali, A.N.A., Saied, M.H., Mostafa, M.Z. and Abdel-Moneim, T.M. (2012) A Survey of Maximum PPT Techniques of PV Systems. 2012 IEEE Energytech, Cleveland, 29-31 May 2012, 1-17.

17.Barakati, M., Kazerani, M. and Aplevich, D. (2009) Maximum Power Tracking Control for a Wind Turbine System Including a Matrix Converter. IEEE Power & Energy Society General Meeting, 24, 705-713. [Citation Time(s):1]

18.Chen, L.R., Tsai, C.H., Lin, Y.L. and Lai, Y.S. (2010) A Biological Swarm Chasing Algorithm for Tracking the PV Maximum Power Point. IEEE Transactions on Energy Conversion, 25, 484-493. http://dx.doi.org/10.1109/TEC.2009.2038067[Citation Time(s):1]

19.Salas, V., Olias, E., Barrado, A. and Lazaro, A. (2006) Review of the Maximum Power Point Tracking Algorithms for Stand-Alone Photovoltaic Systems. Solar Energy Materials and Solar Cells, 90, 1555-1578. http://dx.doi.org/10.1016/j.solmat.2005.10.023[Citation Time(s):3]

20. Liu, C., Wu, B. and Cheung, R. (2004) Advanced Algorithm for MPPT Control of Photovoltaic Systems. Canadian Solar Buildings Conference, Montreal, 20-24 August 2004. [Citation Time(s):3]

21. T. Takagi and M. Sugeno, "Derivation of fuzzy control rules from human operator's control action," in Proc. IFAC Symp. Fuzzy Inform., Knowledge Representation and Decision Analysis, July 1983, pp. 55–60

22. Karaboga, Dervis; Kaya, Ebubekir (2018). "Adaptive network based fuzzy inference system (ANFIS) training approaches: a comprehensive survey". Artificial Intelligence Review. 52 (4): 2263–2293. doi:10.1007/s10462-017-9610-2. ISSN 0269-2821. S2CID 40548050.

23. S. Haykin, Neural Networks - A Comprehensive Foundation, 4th ed. Pearson Education (Singapore) Pvt. Ltd., Indian Branch, 2003.

APPENDIX

MATLAB PROGRAM DATA GENERATION CODE FOR ANFIS
MODELLING

```
clear all
ISCS = 9.2;      % short circuit current
IMPS = 8.28;       %maxim current of v
VMPS = 30.7;
VOCS = 36;        % open circuit voltage
VMP =   40.7;          % maximum voltage f pv
alpha = 0.102;  % current temperature
beta = - 0.36901;  % voltage temp from manufacture
Gs = 1000;               %standard irradiatin
Ts = 25;                 % standard temperature
for i = 1:1000
    Tmin = 15;
    Tmax=35;
    T = (Tmax - Tmin)*rand + Tmin;
    Gmin = 0;
    Gmax = 1000;
    G= (Gmax - Gmin)*rand + Tmin;
    IMP(i) =IMPS * (G/Gs)*(1 + (alpha*(T-Ts)));
    VMP(i) = VMPS +(beta *(T-Ts));
    PMP(i) = VMP(i)* IMP(i)
    imput(i, :) = [G T];
    output(i, 1) = VMP(i);
    output1(i, 1) = IMP(i);
    output2(i, 1) = PMP(i);
   data(i, :) = [G T output(i, 1)];
end
```