# DEVELOPMENT OF A FUZZY LOGIC BASED HYBRID BATTERY MANAGEMENT SYSTEM FOR A GRID INTEGRATED PHOTOVOLTAIC SYSTEM

A Thesis

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In Partial Fulfillment of the Requirements for the Degree of

**Master of Science in Electrical and Electronic Engineering**

by

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## Certification of Approval

The thesis titled **"Development of a Fuzzy Logic Based Hybrid Battery Management System for a Grid Integrated Photovoltaic System"** submitted by Md. Rahan Chowdhury, Student Number- 1015062270F, Session: October, 2015, has been accepted as satisfactory in partial fulfillment of the requirement for the degree of **Master of Science in Electrical and Electronic Engineering** on February 9, 2019.

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It is hereby declared that this thesis titled "**Development of a Fuzzy Logic Based Hybrid Battery Management System for a Grid Integrated Photovoltaic system",** or any part of it has not been submitted elsewhere for the award of any degree or diploma. This thesis is a presentation of original research work done by the undersigned. It does not breach copyright law and has not been taken from other sources except where such work has been cited and acknowledged within the text.

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Md. Rahan Chowdhury

# DEDICATION

*I would like to dedicate this thesis to my lovely parents who have supported me in every stage of my life.*

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All praise is to the Almighty Allah for giving me the opportunity to enlighten me with the power of knowledge and for every success or failure I have.

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I thank my parents, close relatives and friends for their continuous inspiration towards the completion of this works.

# Abstract

A new topology using fuzzy logic in grid connected Photovoltaic (PV) system with battery management system (BMS) is proposed and presented here. The photovoltaic cell operation has been analysed under various weather conditions. A 100 kW grid connected PV module with BMS is used for modelling and simulation in MATLAB/Simulink environment. A Maximum Power Point Tracking (MPPT) controller is developed by using intelligent fuzzy logic controller (FLC). Conventional MPPT techniques can be classified according to their complexity of implementation, convergence speed, and accuracy of the tracking method. But FLCs have the advantage of design simplicity as they do not require the knowledge of the exact model and work for nonlinear systems. The proposed FLC is evaluated and compared with Perturb & Observe and conventional Fuzzy logic techniques for grid-connected PV system in order to control the DC-DC converter. Under different solar irradiance and temperature, it gives relatively less oscillation, faster response, and better performance compare to other two techniques. The advantage of integrating BMS parallel with a PV system is that it will provide constant power supply to the load system under varying environmental conditions. Lithium-ion batteries are considered for the battery energy storage due to the advantages and recent improvements of battery technology. In the proposed BMS, fuzzy logic is used to control power management and fault detection of the system. Fuzzy based power management controller operates the bidirectional converter of battery energy storage system. It serves the purpose to support the active power production by charging and discharging the surplus and reduced power generation from PV. Power management controller also controls state of charge to avoid overcharge or deep discharge of the BMS which increase capacity and lifetime of battery. A comparative study on the proposed model of the effect on grid disturbances under different fault conditions is also discussed. For this system, Voltage Source Converter is used as an inverter in parallel with BMS to manage the power injection into the grid extracted from distributed generation. Here overall intermittent behaviour of the combined system is assessed. The proposed BMS performs better in all cases by minimizing voltage deviation and also provides robust response at any system failure or grid faults. This fuzzy logic based combined system can help to reduce the losses and improve power quality as well as stability in a grid connected PV system.

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# LIST OF SYMBOLS AND ABBREVIATIONS

| | |
|---|---|
| AC | Alternating Current |
| DC | Direct Current |
| PV | Photovoltaic |
| MPPT | Maximum Power Point Tracking |
| RES | Renewable Energy Sources |
| P&O | Perturb and Observe |
| ANFIS | Adaptive Neuro-Fuzzy Inference System |
| BESS | Battery Energy Storage System |
| FLC | Fuzzy Logic Controller |
| EMS | Energy Management System |
| BMS | Battery Management System |
| SSC | System Supervisory Control |
| PLL | Phase Locked Loop |
| PCC | Point of Common Coupling |
| THD | Total Harmonic Distortion |
| PWM | Pulse width modulation |
| SPWM | Single Pulse width modulation |
| SOC | State of Charge |
| DOD | Depth of Discharge |
| STC | Standard Test Condition |
| MOSFET | Metal Oxide Semiconductor Field Effect Transistor |
| IGBT | Insulated Gate Bipolar Transistor |
| VSC | Voltage Source Converter |
| VSI | Voltage Source Inverter |
| CSI | Current Source Inverter |
| PI | Proportional Integrator |

CHAPTER 1

# Introduction

## 1.1 Introduction

Electricity has become one basic commodity in today's world owing to key advancements in technology, population growth, raising standards of living in most parts of the world and widespread industrialization. Without electricity it is totally impossible to carry our daily life. It has become one of the parameters by which the economic growth of a country is measured. The following graph Fig.1.1 is showing the worldwide energy expenditure from 1990-2017 in TWh [1].

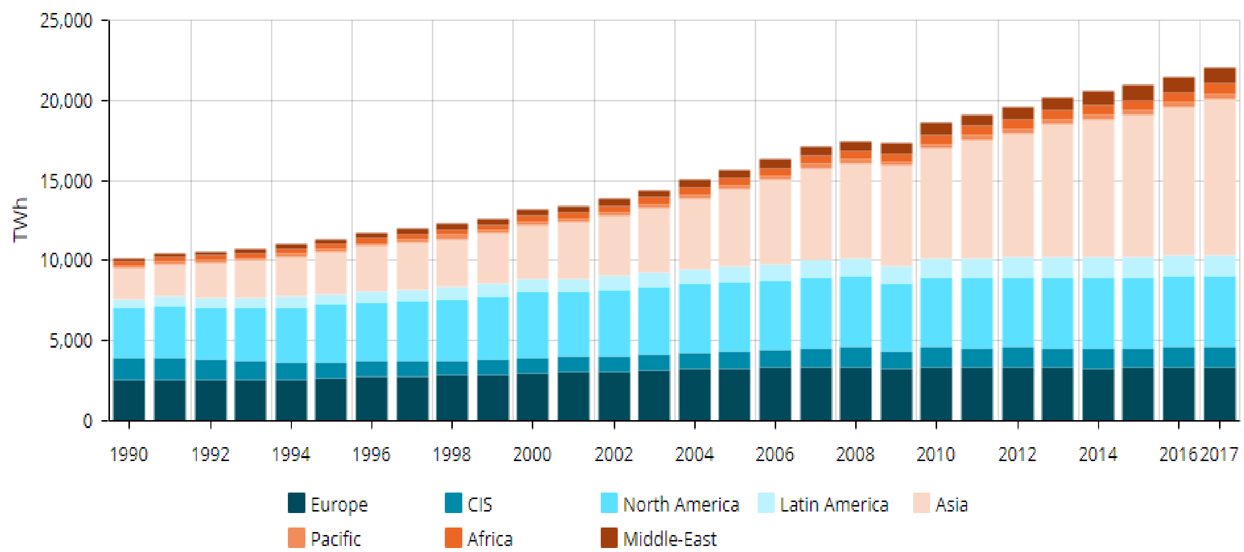



Fig. 1.1: Worldwide energy consumption from 1990-2017 in TWh [1].

Electrical energy is generated by using various sources. It is mainly categorized as non-renewable and renewable energy sources. Non-renewable sources use fossil fuels, coal, gas and nuclear resources, which are finite. It also increases the greenhouse effects and ocean waters pollution, posing a serious threat to the earth's environment. To reduce intimidation posed by continuing using non-renewable sources of electricity, the power industries are moving to renewable energy sources, which will be a sustainable and beneficial way for our environment [2].

Renewable energy is collected from renewable resources which are naturally replenished on a human timescale, such as sunlight, wind, rain, tides, waves, and geothermal heat [3]. According the REN21's report (2018), the electricity transition is well under way, due mostly to increases in installed capacity and in the cost-competitiveness of solar photovoltaic (PV) and wind power. Fig.1.2 shows renewable power generating annual capacity increases to 21% in 2017. Overall, renewables accounted for an estimated 70% of net additions to global power capacity in 2017, due in large part to continued improvements in the cost-competitiveness of solar PV and wind power.

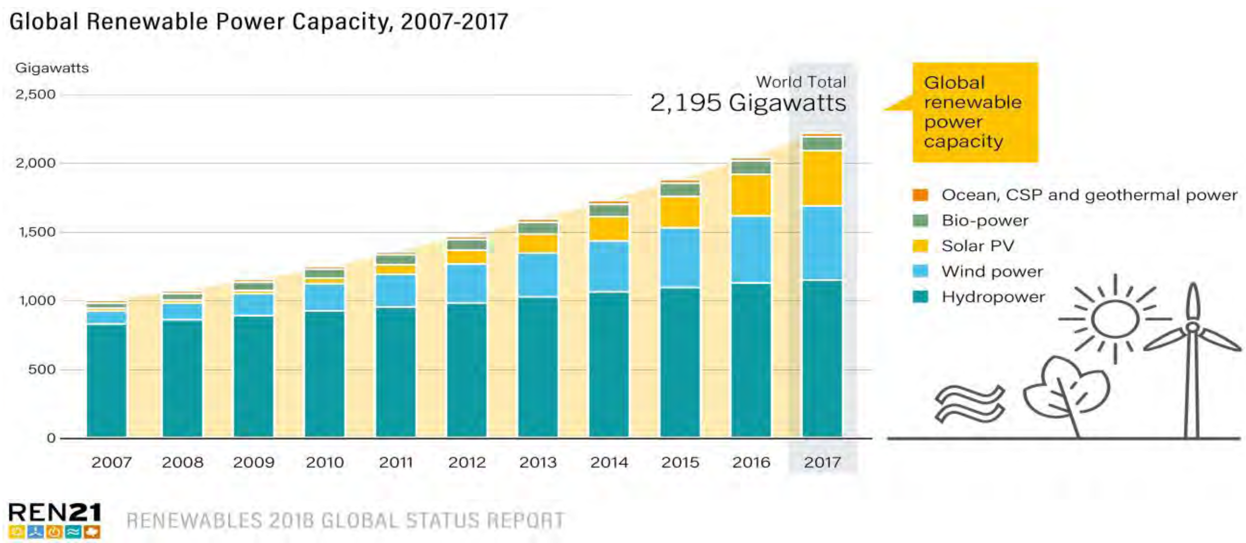



Fig. 1.2: Global Renewable Power Capacity, 2007-2017 [4].

In Fig.1.3, solar PV led the way, accounting for nearly 55% of newly installed renewable power capacity in 2017. More solar PV capacity was added than the net additions of fossil fuels and nuclear power combined. Wind (29%) and hydropower (11%) accounted for most of the remaining capacity additions. If we observe other countries we can see that several countries are successfully accomplishing higher percentage of variable renewable energy into electricity systems [4].

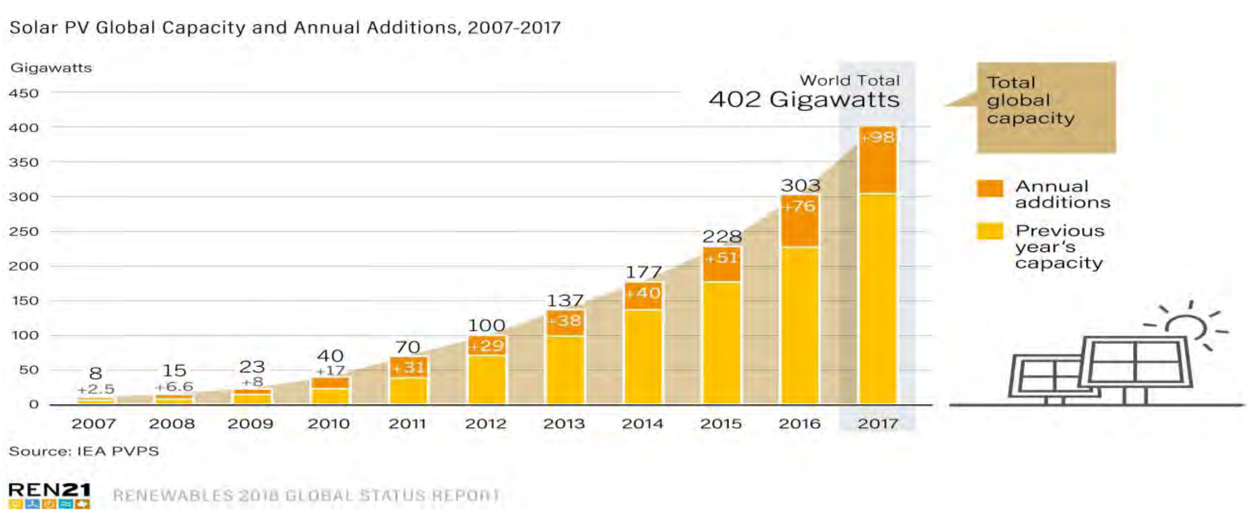



Fig. 1.3: Solar PV Global Capacity and Annual Additions, 2007-2017[4].

Among the renewable energy resources, the energy through the photovoltaic (PV) effect can be considered the most essential and prerequisite sustainable resource because of the ubiquity, abundance and sustainability of solar radiant energy. Solar energy is a renewable, inexhaustible, widely available and completely cost free ultimate energy source. Solar energy derived following advantages such as no emissions of greenhouse (mainly $CO_2$, $NO_x$) or toxic gasses ($SO_2$, particulates), reclamation of land erosion, reduction of transmission lines from electricity grids, increase of regional/national energy independence, diversification and security of energy supply, acceleration of rural electrification in developing countries [5]. Climatic and atmospheric factors, such as solar irradiance, temperature, and angle of incidence put direct effect on the PV power generation. Therefore, a PV system requires energy converters, energy storage system connected to the solar panel in order to provide appropriated voltage level, or alternating voltage in case of grid connection [6]. However, efficient utilization of solar energy is very challenging problem during grid connected mode, islanding mode and hybrid. PV systems associated with energy storage systems are widely used as energy supplies in remote areas or emerging micro grids. Energy storage devices offer energy buffer for intermittent PV generation to confirm a reliable and sustainable energy supply. Energy storage technologies also have important role to prevent factors affecting power quality [7].

## 1.2 Background and Present State of the Problem

The development of renewable energy technologies started in the earlier of 20$^{th}$ century even though the use of this energy started at the ancient time by using biomass to fuel fires, harnessing the wind in order to drive ships over water etc. The interest in renewable energy has been revived over last few decades, especially after global awareness regarding the hostile effects of fossil fuel burning. Due to the geographic location a developing country like Bangladesh, she is endowed with vast renewable energy resources such as solar, biomass, peat, and hydro-power; yet we suffer from frequent power failure during the day on a daily basis, which I think provoking our development in the industrial scale region. So, our government has recently emphasized on renewable energy and planning to set up some large-scale solar power projects, wind power projects, biomass projects.

The generation of electricity from solar system often suffers from the problems of variability and intermittency. Solar power is not always available where and when needed. Unlike conventional sources of electric power, solar resources are not dispatchable; the power output cannot be controlled. Daily and seasonal effects and limited predictability result in intermittent generation. This poses many challenges for the grid integration. Some of these challenges are given below as [8-10].

- Intermittent generation
- Cost, reliability & efficiency of grid interface
- Grid congestion, weak grids
- Bidirectional power flow in distribution network.

- Integrating energy storage
- Localized voltage stability problems
- Low power quality.

PV generation systems have two big problems [11], namely: 1) the efficiency of electric power generation is very low, especially under low radiation states, and 2) the amount of electric power generated by solar arrays is always changing with weather conditions, i.e., irradiation, temperature. To solve this problem, many researchers propose different maximum power extraction techniques [12] of a PV system. The Maximum Power Point Tracker (MPPT) techniques are accomplished through the DC/DC converter which interfacing the PV array to the inverter. There are several types of MPPT control techniques which are used to improve the solar energy efficiency such as; Perturb and Observe (P&O), incremental conductance, open circuit voltage, short circuit current, fuzzy or neural based etc.

Among the MPPT control techniques, Perturb and Observe (P & O) is one the simplest MPPT methods [13][14] with excellent performance and can be easily implemented in low cost systems. But if there is any shadow on any of panels (series or parallel) then the power- voltage curve of the PV is going to have several peaks and P & O method struggled to find the real peak accurately. On the other hand, Incremental Conductance (IC) algorithm has advantages over P&O in that it can determine when the MPPT has reached the MPP, where P&O oscillates around the MPP. IC also can track rapidly increasing and decreasing irradiance conditions with higher accuracy than P&O. However, it has dependency on specialized and accurate sensors (Voltage and/or Current sensors). The incremental conductance method can produce oscillations (unintentionally) and can perform erratically under rapidly changing atmospheric conditions. Fuzzy Logic method is very robust and easy meanwhile no mathematical model is required for designing of controller. Fuzzy control algorithm has the ability to improve the tracking performance for both linear and nonlinear loads as compared with the classical methods. Using adaptive neuro-fuzzy inference system (ANFIS) in MPPT has increased the efficiency of array power and MPPT response time [15]. This method is used to overcome slow tracking speed, more output oscillations, and power oscillations.

**Necessity of Energy Storage and Battery Management system in Grid connected PV Systems:**

The biggest challenge with incorporating renewable energy in to the current electrical power system is the fact that the energy produced by renewable energy sources is inconsistent and variable with meteorological conditions. A sunny day without any cloud, the more electric power can be produced with solar energy, but the amount of the produced electrical power is fluctuating continuously by depending on the climatic condition and solar irradiation of the day. When PV generation is low, some type of back-up generation will be needed to meet the demand. Due to the lack of energy storage devices within the grid system, energy must be immediately delivered to and used by the consumer [16]. Usage of energy storage technology has become an essential solution for providing more power quality to the loads by using smart micro grid structure. By utilizing energy storage, generation sources need not be ramped up or down, but can instead be run at optimal efficiency while energy storage accounts for variations in the demand. The applications that could benefit from energy storage within the electric grid have a wide range of requirements.

While many technologies have been developed for large-scale energy storage purposes such as pumped hydro and compressed air energy storage facilities as well as flywheels, capacitors, and superconducting magnetic storage, many are limited in their site dependence, capacity, or response capabilities. There is a long history of integrating batteries into grid applications, and while battery energy storage systems (BESSs) currently account for only small portion of energy storage within the grid, they have seen great growth recently due to their versatility, high energy density, and efficiency [17]. More grid applications have become suitable for BESSs as battery costs have decreased while performance and life have continued to increase [18]. BESSs require a battery management system (BMS) to monitor and maintain safe, optimal operation of each battery pack and a system supervisory control (SSC) to monitor the full system. Using hybrid energy storage system or BMS have following advantages in grid connected system:

i) Keeping the power equilibrium of all the system,
ii) Control of the produced PV power based on the maximum power point tracking (MPPT) algorithm,
iii) Increase the performance of the battery by preventing its action with high frequency ripple currents and high rate of depth of discharge to increase the battery lifetime,
iv) Renewable energy can be used in time shift/spinning reserve,
v) Increasing hosting capacity, voltage support/voltage stability and power quality etc.

Considering those problems and to improve the power quality and efficiency, various topologies are proposed, such as Maximum Power Point Tracker (MPPT) algorithms, use of different single-stage Modular Multilevel Converters at a point of common coupling (PCC). Sindhuja used adaptive neuro-fuzzy inference system (ANFIS) in MPPT to increase the efficiency of array power and MPPT response time [15]. The author used DC link capacitor voltage instead of battery management system (BMS) and transformer less topology which is applicable for low voltage AC source only. For extracting of maximum power from a solar PV system, Samal [19] proposed a fuzzy logic controller design and a comparison is made between fuzzy logic controller and P&O controller. The proposed method of MPPT is faster in comparison to conventional P&O method but it is time consuming while applying all fuzzy rules. Samal's work deals with only MPPT and energy management system is not considered.

Aktas proposed smart energy management algorithm for grid connected photovoltaic power system [20]. In his work, Perturb and Observe (P&O) method is used for MPPT control that wastes energy. The voltage regulation control is also absent in this model. Aktas energy management system has also lacking in the bi-directional DC/DC converter. It reduces the dynamic response of the ultra-capacitor group. In his work, there was no protection for system failure or grid fault. Using Fuzzy logic in energy management system (EMS) or battery management system minimizes voltage deviation thus reducing necessary reactive power injection/absorption. This also provides robust response at any system failure or grid faults [21]. But a model with fuzzy logic based algorithm both for MPPT control and battery management system for a grid connected inverter is yet to be proposed.

In this thesis work a new fast and effective fuzzy logic controller are proposed for MPPT and energy management system for grid connected PV system.

## 1.3 Research Objectives of the thesis work

The aim and objective of this thesis work are stated here as follows:

- To develop grid connected three phase PV system model.
- To develop Fuzzy based the maximum power point tracking scheme and to control on produced PV power.
- To develop fuzzy logic based hybrid smart energy management system.
- To develop Phase lock loop (PLL) based Voltage Source Controller (VSC) for grid integration.
- To study and investigate effects of proposed model performance on designed simulator and to compare the results with the other reported models.

**Possible outcomes:**

- Successful completion of this simulation work should help to optimize system size, improve the power quality at various weather conditions. It should also enhance performance of energy management system under different operating condition for grid integrated renewable energy sources.

## 1.4 Organization of This Thesis

The dissertation is structured as follows. Chapter 1 provides general introduction on electrical energy consumption, the importance of renewable energy and PV power followed by the background and the objectives of the work. Chapter 2 demonstrates the review of grid connected PV systems. Chapter 3 presents test modeling of systems and simulation tools. Results of analyses have been introduced and talked over in Chapter 4. Conclusion and future research suggestions are offered in Chapter 5.

CHAPTER 2

# Background of Photovoltaic System

## 2.1 Introduction

A photovoltaic (PV) system is a power system designed to supply usable solar power by means of photovoltaics. It consists of an arrangement of several components, including solar panels to absorb and convert sunlight into electricity, a solar inverter to change the electric current from DC to AC, as well as mounting, cabling, and other electrical accessories to set up a working system.

## 2.2 Principle of Photovoltaic Systems

A photovoltaic system is the combination of PV modules grouped in series and parallel combinations to meet a specified voltage, current and power rating [22]. A PV cell is made up of semiconductor materials, such as silicon or germanium. A typical PV cell is composed of n-type and p-type semiconductor materials exhibiting different electrical properties. When a PV cell absorbs a photon of sunlight, free electron and holes are created at the positive and negative junctions of the semiconductor assembly and generates DC power [23]. The general principle of a basic PV cell is shown in Fig.2.1. The power generated by the PV cells is collected through metallic contacts connected on both sides of the cell.

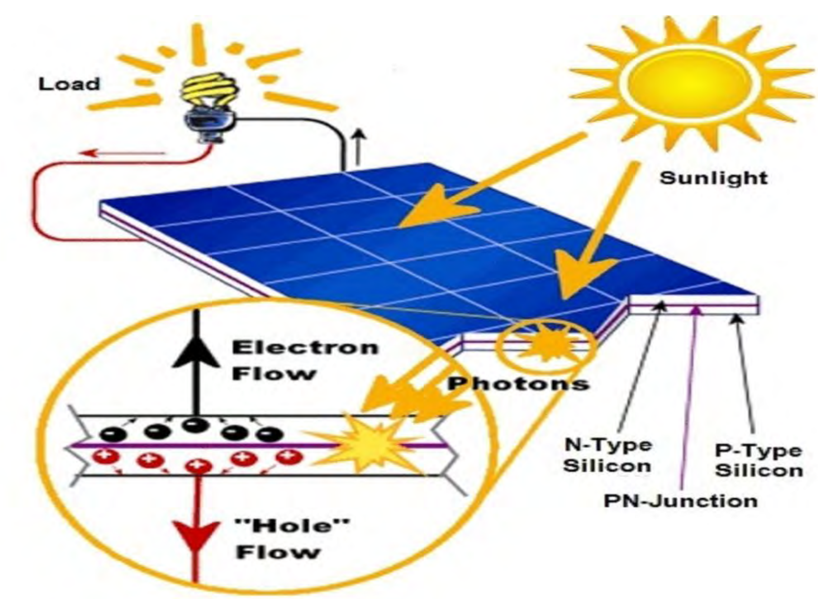



Fig. 2.1: Principle of Photovoltaic cells [23].

## 2.3 Type of PV cells

Over the recent decades, silicon has been used for manufacturing more than 80% of solar cells although other materials and techniques are developed. There are different types of solar cells which differ in their material, price, and efficiency, since the efficiency is the percentage of solar energy that is captured and converted into electricity. The efficiency values are an average percentage of efficiency, because it's difficult to give an exact number for the different types of solar panels output [24].

**2.3.1 Monocrystalline Solar cells:** They are made from a large crystal of silicon. These types of solar cells are the most efficient as in absorbing sunlight and converting it into electricity. However they are the most expensive. They do somewhat better in lower light conditions than the other types of solar cells. Also, their efficiency is around 15% - 20%.

**2.3.2 Polycrystalline Solar cells:** This type of solar cell consists of multiple amounts of smaller silicon crystals. This type is instead of one large crystal have efficiency approximately 13-16%.

They are the most common type of solar panels on the market today. They look a lot like shattered glass. They are slightly less efficient than the mono-crystalline solar cells and less expensive to produce.

**2.3.3 Amorphous Solar cells:** This type is consisting of a thin-like film made from molten silicon that is spread directly across large plates of stainless steel or similar material. One advantage of amorphous solar cells over the other two is that they are shadow protected.

That means when a part of the solar panel cells are in a shadow the solar panel continues to charge. These types of solar panels have lower efficiency than the other two types of solar panels, and economical to produce. These work great on boats and other types of transportation [24]. The efficiency of this type is around 8-10%.

## 2.4 Photovoltaic cell equivalent circuit and equations

There are different mathematical models that can be used to model a PV array. From the solid state physics point of view, the cell is basically a large area p-n diode with the junction positioned close to the top surface. The output of PV cell under various operating conditions generally represented by V-I curve and P-V curve is shown in Fig.2.2 where, $V_{oc}$ is open circuit voltage, $I_{sc}$ is short circuit current and $V_{mp}I_{mp}$ is maximum voltage and current at maximum power point.

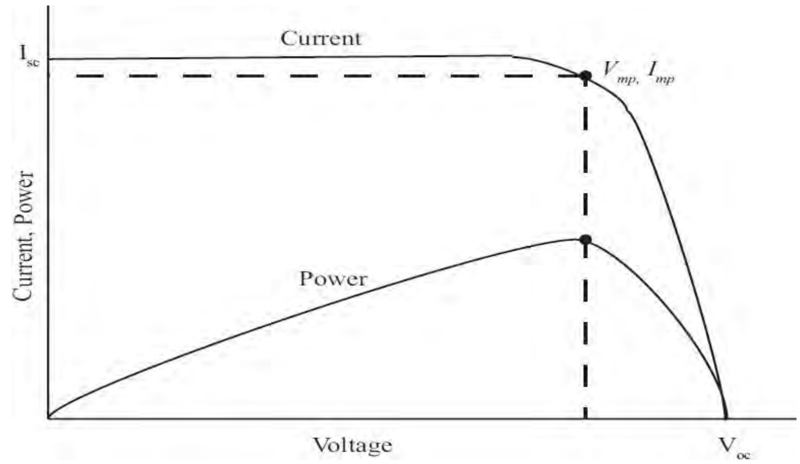



Fig. 2.2: The typical I-V and P-V curve of PV cell [25].

To model the PV cell, it is important to understand the properties of I-V characteristics. The DC current generated by PV cell generally given as [25]

$$I = I_L - I_o \left[\exp\left(\frac{qV}{nkT}\right) - 1\right] \tag{2.1}$$

where, $I_L$ is short circuit current, $I_o$ is saturation current, V is the voltage of PV cell.$k$ is the Boltzmann constant, $q$ is the electron charge, $T$ is the temperature. The electrical model of single diode PV cell is represented by Fig.2.3.

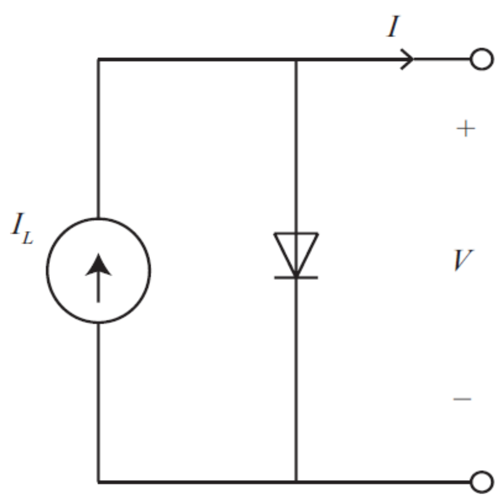



Fig. 2.3: Single diode of PV cell [25].

The short circuit current is the maximum current available when the voltage is zero and the open circuit voltage ($V_{oc}$) is the maximum voltage obtain at zero current and the open circuit voltage is given as

$$V_{oc} = \frac{nkT}{q} \ln(\frac{I_L}{I_o} + 1) \tag{2.2}$$

The fill factor is also one of the essential parameter which measure the performance of PV cell and quality of junction and it is given as,

$$F_F = \frac{V_{mp} I_{mp}}{V_{oc} I_{sc}} \tag{2.3}$$

The ideal fill factor value of the solar cell is 1, which defines the highest quality of PV cell. Due to existence of parasitic elements in the PV cell, the value of fill factor decreases. The circuit of PV cell with parasitic elements is shown in Fig.2.4.

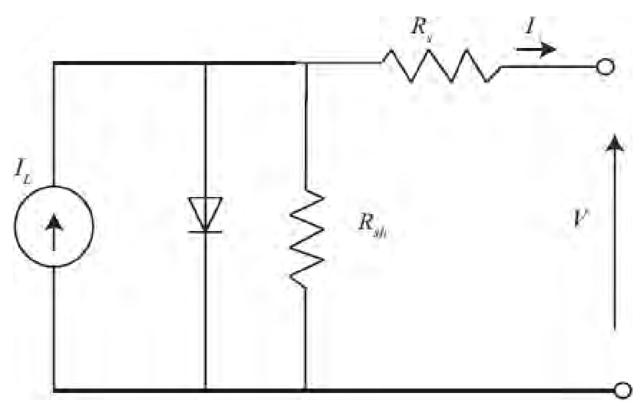



Fig. 2.4: The single diode of PV cell with parasitic elements [25].

The practical PV cells also contain parasitic elements, series resistance ($R_s$) and shunt resistance ($R_{sh}$). The presence of shunt resistance is due to impurities near the p-n junction and series resistance is due to high resistance of metal contacts, interconnections and, semiconductor material. The higher value of shunt resistance is desirable and thus it in- creases the performance of PV cell and the lower value of series resistance increase the output power of PV cell as shown in Fig.2.5.

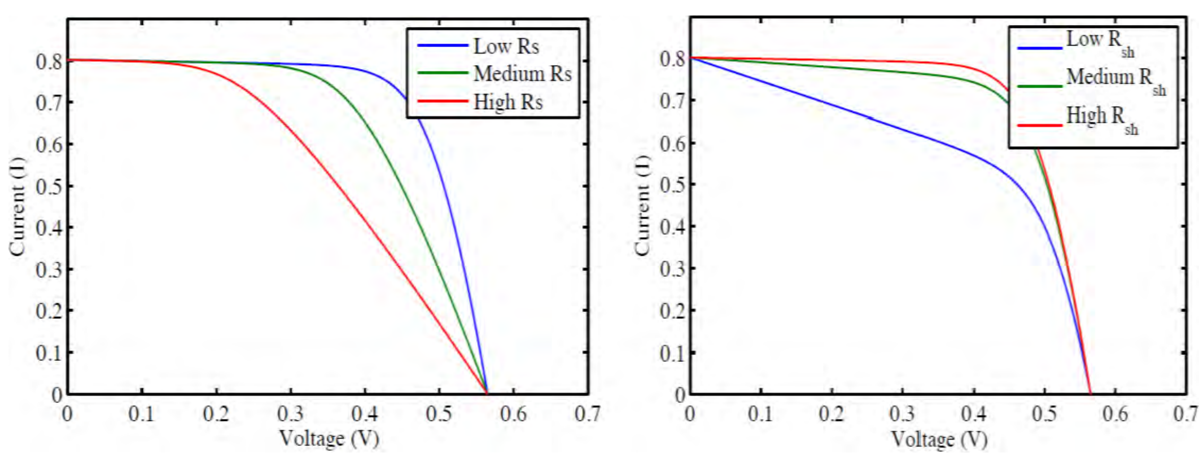



Fig. 2.5: The series and shunt resistance effect on V-I curve of a solar cell [26].

## 2.5 Maximum Power Point Tracking (MPPT)

A PV module has a nonlinear characteristics and its output power depends mainly on the irradiance (amount of solar radiation) and the temperature. Moreover for the same temperature and irradiance the output power of a PV panel is function of its terminal voltage. There is only one value for the terminal voltage that corresponding to maximum output power for each particular case. The procedure of searching for this voltage is called maximum power point tracking (MPPT). The MPPT, when applied to the switching control in the DC-DC converter, make the panel output voltage be such that, multiplied by the current, yields the highest possible power for each set of operation conditions [27].

Usually implemented in microprocessors or digital signal processing devices, the maximum power point tracking is an algorithm that automatically regulates the DC-DC converter switching. So that the current being drawn from the panel and the generated voltage are at the maximum power point for each specific set of operation conditions. In order to achieve that, the algorithm can use periodic measurements of the panel output voltage and current or external data like temperature and solar irradiance. The many MPPT techniques may differ from each other in the control strategy, complexity level, price, efficiency, application, converter used, among other factors [28].

**2.5.1 Perturb and Observe Technique:** Perturb and Observe is a widely used method. It is common because of the simple feedback structure and the fewer control perimeters. The basic idea is to give a trial increment or decrement in the voltage, and if this result in an increase in the power, the subsequent perturbation is made in the same direction or vice versa. This method is easy enough to handle and manipulate. However, this method of monitoring the perimeter causes a delay and therefore tracking a real time maximum power point is difficult [29].

Usually voltage or duty ratio will be the parameter used to perturb the system. This algorithm is not suitable when the variation in the solar irradiation is high. The voltage never actually reaches an exact value but perturbs around the maximum power point (MPP) as in this method, after obtaining the approximate maximum power point by scanning the entire P-V curve, the slope of the P-V curve dP/dV is determined by giving the step change in duty ratio of boost converter. If due to increase in duty cycle, the dP/dV decreases then next perturbation in duty cycle is kept unchanged otherwise the sign of the perturbation step is changed [30]. Fig.2.6 shows the flow chart for maximum power point tracking based Perturb and Observe algorithm.

This method does not stop the calculations even if the maximum power point is achieved. It is the drawback of the algorithm despite its simplicity and smooth implementation. This behavior sometimes causes hindrance to achieve and sustain maximum system efficiency.

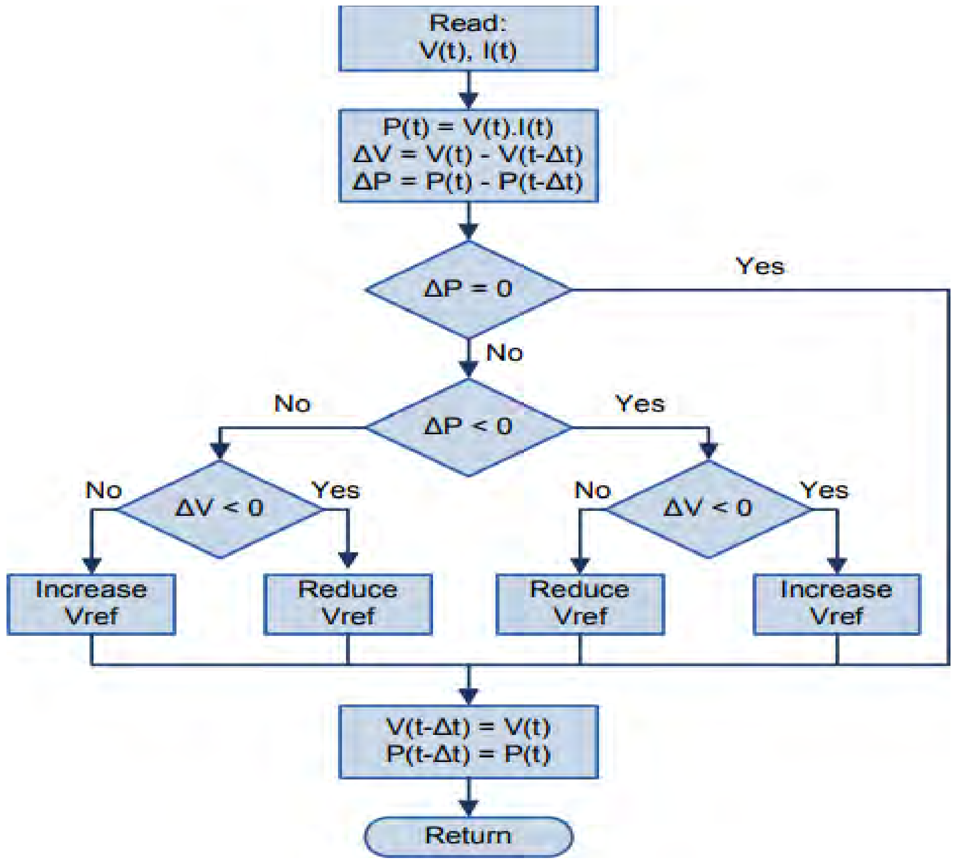



Fig. 2.6: The perturb and observe algorithm flow chart [31].

**2.5.2 Incremental Conductance Technique:** This method implements the comparison between incremental and instantaneous conductance values. It enables to determine the direction of the voltage change at the output. Once the maximum power point for PV system is achieved, this algorithm stops the further calculations. The algorithm will not carry out any further calculation until or unless there is some change in the conditions of the operating environment. The flowchart in Fig.2.7 briefly explains the algorithm for internal conductance [32].

The maximum operating point measured by calculating the change in voltage and change in current until the change becomes zero. The increase or decrease in the intensity of the radiation will impact the normal operation of the PV system at the maximum operating point. The control system behaves in accordance to increase or decrease the operating voltage to achieve the desired or maximum power point [32].

This method gives a very good and accurate performance under rapidly varying conditions. However, the drawback is that the actual algorithm is very complicated to handle. It requires sensors to carry out the computations and high power loss through the sensors.

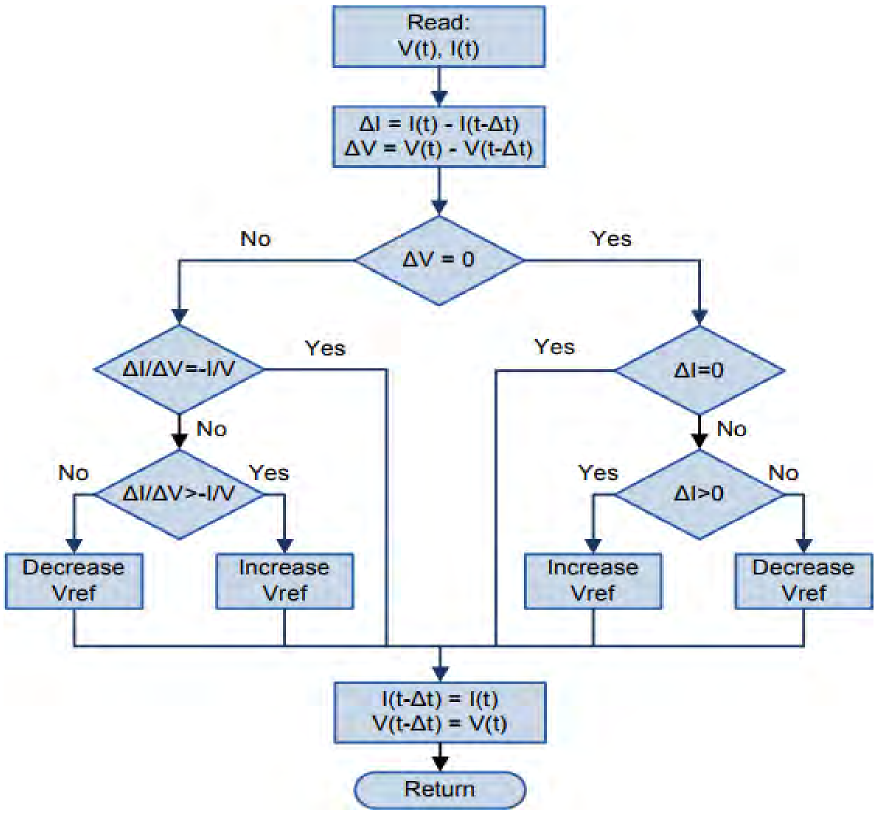



Fig. 2.7: Incremental conductance algorithm flow chart [31].

**2.5.3 Fuzzy Logic Technique:** In addition to the two previous techniques, a method based on Fuzzy logic was chosen to track the MPP. Fuzzy logic is based on the treatment of variables as non-binary values that can be categorized as any value between 0 and 1. Therefore it is possible to establish how much an input value belongs to a pre-defined category and, from that, calculate the output value. Fig.2.8 shows a flowchart of the main steps of control with Fuzzy logic applied to maximum power point tracking in a solar module.

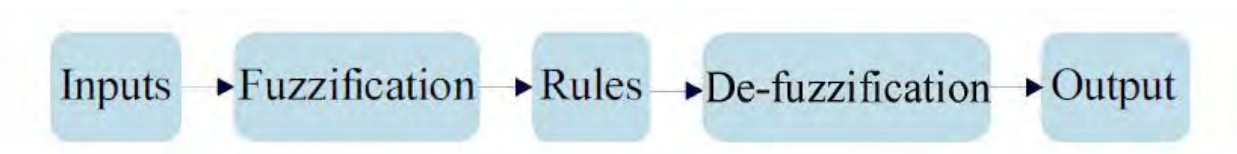



Fig. 2.8: Flowchart algorithm for MPPT method based on Fuzzy logic.

The inputs chosen are the rate of variation of power with respect to variation of voltage (Ψ) and the variation of Ψ (ΔΨ), given by

$$\Psi(n) = \frac{\Delta P}{\Delta V} = \frac{P(n)-P(n-1)}{V(n)-V(n-1)} \quad (2.4)$$

Where P(n) is the measured power and P(n-1) is the power previously measured. V (n) is the measured voltage an V (n-1) is the voltage previously measured, and

$$\Delta\Psi(n) = \Psi(n) - \Psi(n-1) \quad (2.5)$$

Where Ψ (n) and Ψ (n-1) are the rates of variation of power with respect to the variation of voltage in the current and previous instant, respectively [33]. Those inputs were chosen based on given equation which shows that the derivative of the power with respect to the voltage is zero at the maximum power point. The output chosen was the step size for incrementing or decrementing the emulator reference voltage.

The next step is called fuzzification, where the inputs and outputs are classified in membership functions - words that categorize the input or output value by its size. The words chosen were NB (negative big), NS (negative small), ZE (zero), PS (positive small) and PB (positive big) [33]. The most common way of representing a membership function is the triangular, as shown in Fig.2.9 [34]. The vertical axis indicates how much each value from the horizontal axis belongs to each word (triangle), in a scale from 0 to 100%. It is possible to observe that the same value can belong to two triangles at the same time, with a respective degree of membership for each one. During fuzzification, every input is tested for every word, incurring in a degree of membership for each word verified as active.

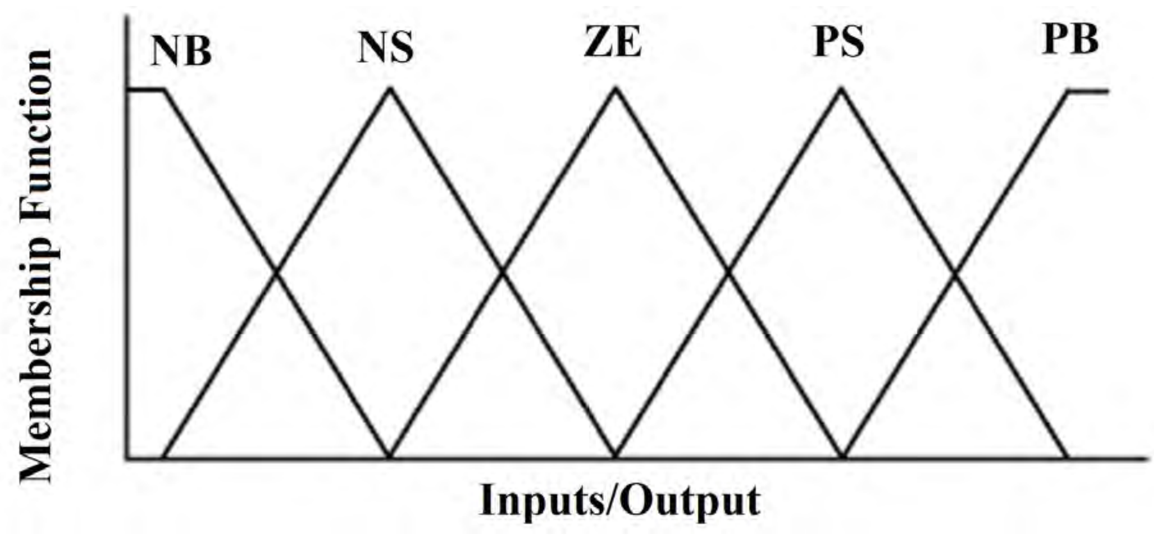



Fig. 2.9: Fuzzy membership functions for inputs and output [34].

The next step is the application of rules that relate the active input membership functions to the expected output membership functions. Table 2.1 shows the control rules that relate Ψ and ΔΨ to the output "step size". In the algorithm, each word from the first input must be related to each word from the second input, to result in a word for the output, for example: if Ψ is "positive big" and ΔΨ is "negative small", then the output must be "negative big". That process is made relating each active word of the first input to each active word of the second input, resulting in an output word for each case.

**Table 2.1:** Rules for MPPT with Fuzzy Logic

| Ψ \ ΔΨ (Step size) | NB | NS | ZE | PS | PB |
|---|---|---|---|---|---|
| NB | ZE | ZE | PB | PB | PB |
| NS | ZE | NS | PS | PS | PS |
| ZE | PS | ZE | ZE | ZE | NS |
| PS | NS | NS | NS | PS | ZE |
| PB | NB | NB | NB | ZE | ZE |

The last step is called de-fuzzification, where the output words activated by the input membership functions are converted into a real value. A common and useful defuzzification technique is center of gravity. First, the results of the rules must be added together in some way. The most typical fuzzy set membership function has the graph of a triangle. Now, if this triangle were to be cut in a straight horizontal line somewhere between the top and the bottom, and the top portion were to be removed, the remaining portion forms a trapezoid. The first step of defuzzification typically "chops off" parts of the graphs to form trapezoids (or other shapes if the initial shapes were not triangles). In the most common technique, all of these trapezoids are then superimposed one upon another, forming a single geometric shape. Then, the centroid of this shape, called the fuzzy centroid, is calculated. The x coordinate of the centroid is the defuzzified value [35].

## 2.6 Battery Energy Storage

Amongst the various energy storage methods commercially available to store electrical energy, batteries are perhaps the better developed. Due to continuous development of this technology, batteries are providing a vital role in storing electrical energy especially when energy is being generated from intermittent renewable energy resources. Batteries store and release energy using electrochemical reactions: when electrical energy is converted into chemical energy, the battery is in charging mode (it stores energy). The chemical compound within the batteries acts as a storage medium. While in discharging mode, the stored chemical energy is converted into electrical energy [36].

### 2.6.1 Components of batteries and cells

A cell, the elementary battery unit, consists of four major components:

1. The Positive electrode or cathode (during discharging reaction) is oxidizing by absorbing electron from the external circuit or oxidized (during charging reaction) by supplying electron to the external circuit
2. Negative electrode or anode (during discharging reaction) is oxidized by sup- plying electron through the external circuit or oxidizing (during charging re-action) by accepting electrons from the external circuit. The electrode because of its shape can also be referred as positive of negative plates.
3. The Electrolyte is a material which conducts electric current as separation into positively (anions) and negatively (cations) charged particles called ions. The electrolyte can be either acidic solution or alkaline solution to conduct current.
4. A Separator is commonly used to isolate the electric path between positive and negative plates.

Typical design of cell is shown in Fig.2.10.

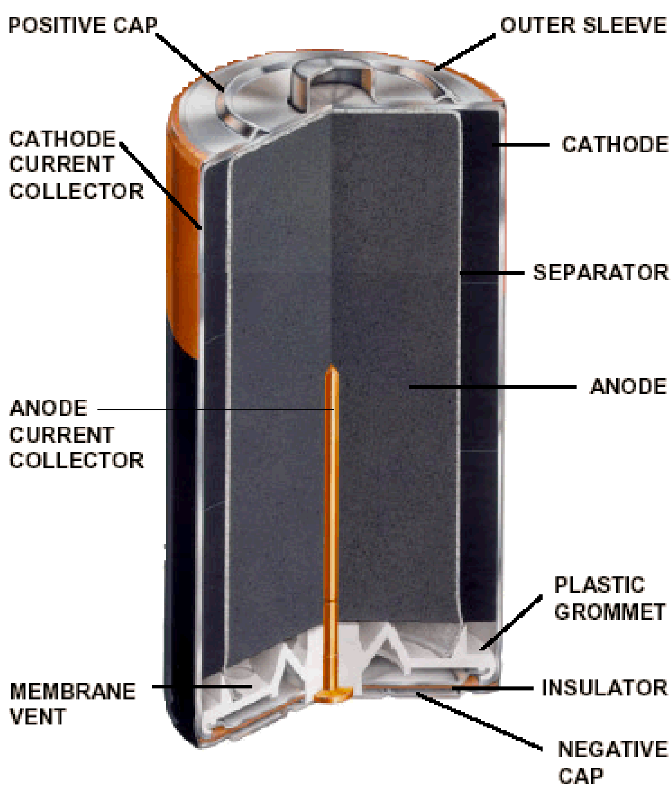



Fig. 2.10: Typical configuration of cell design.

### 2.6.2 Classification of batteries

According to the classification, two distinct system of battery are described in [37].

1. **Primary Batteries:**

Primary Batteries are irreversible batteries because of its chemical reaction and hence can only use once. These batteries are common for small usage because they are easy to use and cheap.

2. **Secondary Batteries:**

Secondary batteries are reversible batteries and they can be used over many cycles because of its charging/discharging capability. They possess true nature of electrochemical batteries. These batteries are highly used in industries and automotive application because of its rechargeable characteristics and have the capability to deliver high currents. Most common secondary batteries are Lead-Acid, Nickle/cadmium and lithium ion.

### 2.6.3 Important features and parameters of batteries

**State of charge (SOC):** The SOC is referred as the relative capacity of the battery as the percentage of maximum capacity of the battery. The 100% represents battery is fully charges. The capacity of the battery deteriorates over the period of time (battery aging). Many techniques are described to determine the status of SOC in [38][39] but the commonly used method is the current drawn/supplied to demonstrate the variation in the battery over a certain period of time.

**Depth of discharge (DOD):** Depth of discharge usually describes the how deeply the battery is discharged. It is opposite of the state of charge (SOC). If the battery is considered as fully charge i.e. 100% SOC then of DOD of the battery is 0%.

**Ageing:** Ageing of the batteries often quantified by the number of charging and discharging cycles. Ageing reduces the performance of battery by reducing capability to store energy and it depends on the many external factors such as depth of discharge, discharge rate, temperature conditions.

**Self-discharge:** Self-discharge is gradual discharge in the available capacity over time even when no load is connected or during open circuit condition. The rate of discharge varies according to the condition of the battery. It depends on various factors such as temperature, aging, electrode material and manufactures [37].

**Voltage:** When the batteries charges/discharges to provide the electric energy, voltage is one of the most parameters is to be considered. The open circuit voltage (OCV) is determined by chemical reaction of the internal parameters of the cell. In actual use, this value is different from theoretical value and it depends on many kinetic factors [40]. The power delivered to load depends on the voltage of the battery as seen in the equation.

$$P = \frac{V^2}{R} \tag{2.6}$$

The high voltage energy is more supervisor then low voltage energy due to the square relation of power and voltage. The voltage is also determined by current density, when more current drawn from the battery, it reduces the voltage and the charge capacity of the battery as shown Fig.2.11 [40].

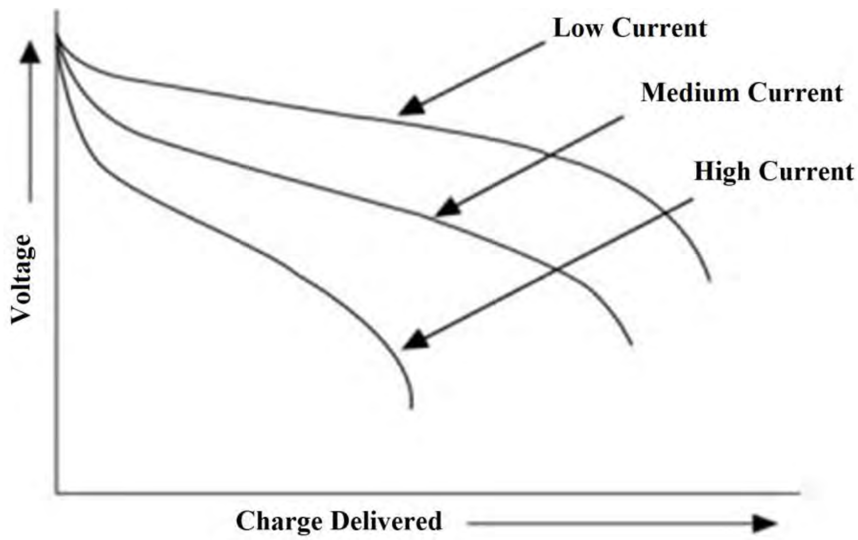



Fig. 2.11: The effect of the current density over the discharge curve.

## 2.7 DC-DC converters

DC-DC converters have wide applications in PV systems. Whether it is boost converter [41], [42], buck-boost converters or buck converters [43].

DC-DC converters are considered the main element in the maximum power point tracking process and without it the maximum power could not be achieved. In this thesis, the boost converter is used to change the terminal voltage of the PV array and from which maximum power point tracking can be obtained.

**2.7.1 Buck Converter:** The Buck converter or step-down converter reduces the input voltage to get desired output voltage. The circuit diagram and the output waveform of the buck converter are shown in Fig.2.12 (a). When the inverter current is above zero all the time then it is operating in continuous conduction mode (CCM). Buck Converter operates in two states when the switch is on state, the diode is reverse biased and input energy is supplied to charge inductor. When the switch is in off state, the diode is forward biased and inductor current discharge through the diode as shown in Fig.2.12 (b).

The transfer function of the buck converter is the ratio of output voltage to the input voltage, it can be given as:

$$D = \frac{V_o}{V_s} \tag{2.7}$$

Where $V_o$ is output voltage, $V_s$ is input voltage and D is duty cycle.

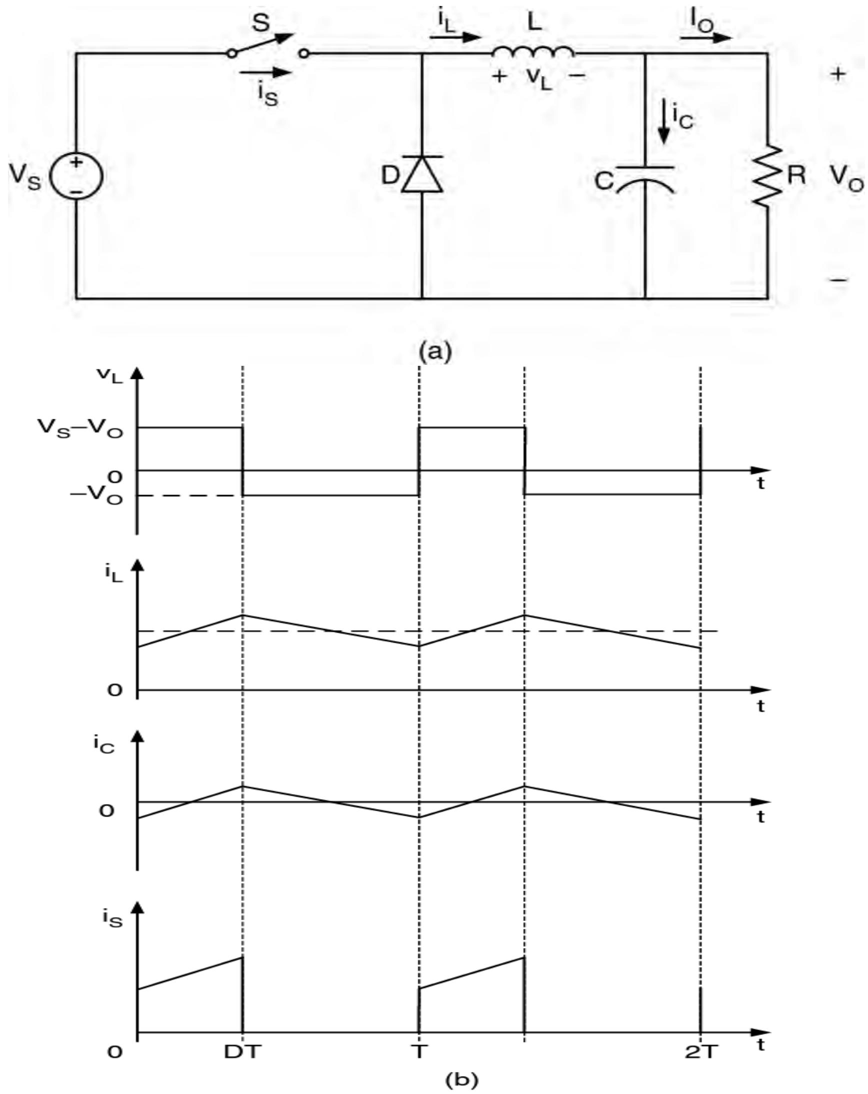
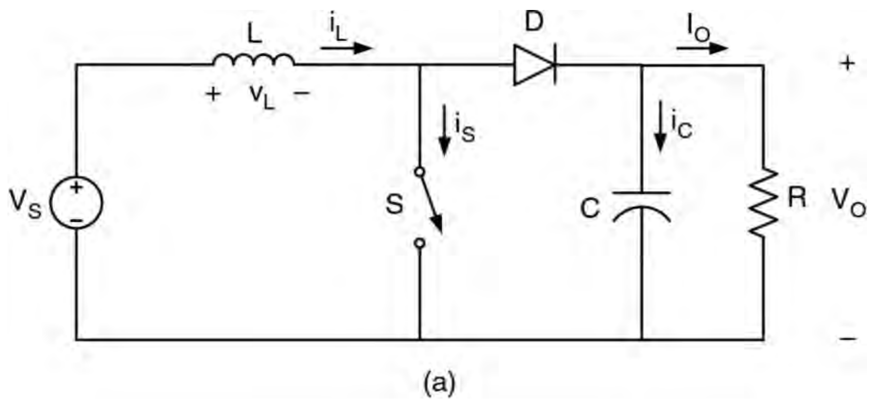



Fig. 2.12: Buck Converter (a) circuit diagram (b) waveform [44].

**2.7.2 Boost Converter:** The boost converter or step-up converter increases the input voltage to get desired output voltage. The circuit diagram and current and voltage waveform is shown in Fig.2.13 (a) Boost Converter also operate in two states When the switch is on state, the diode is off that time and current is inductor increases linearly. When the switch is in off state, the stored energy in the inductor, as well as the power from input supplies the energy to load, the waveform of current and voltage, are shown in Fig.2.13 (b).

$$\frac{1}{1-D} = \frac{V_o}{V_s} \qquad (2.8)$$

Where $V_o$ is output voltage, $V_s$ is input voltage and D is duty cycle.



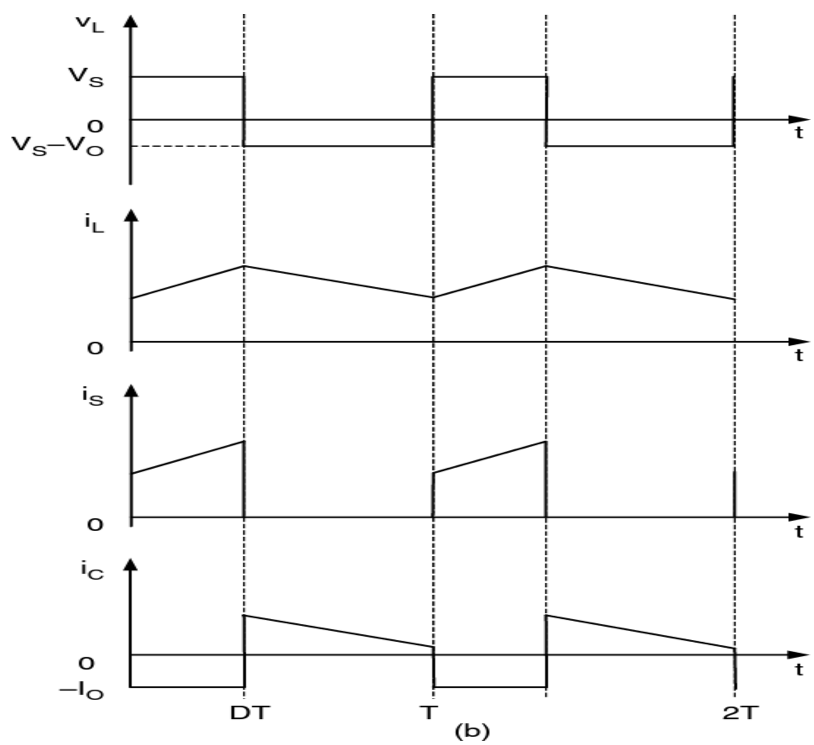




Fig. 2.13: Boost Converter (a) circuit diagram (b) waveform [44].

**2.7.3 Buck-Boost Converter:** The buck-boost converter is the combination of DC-DC buck and boost converters. They are seemed cascaded with each other in this arrangement. It enables the buck-boost converter the greater flexibility. It can be both step-up and step-down the output. It also incorporates the functionality to invert the voltage at the output. Thus, the voltage obtained at the output will be of the opposite polarity to that of the input voltage. The circuit diagram and output waveform is shown in Fig.2.14.

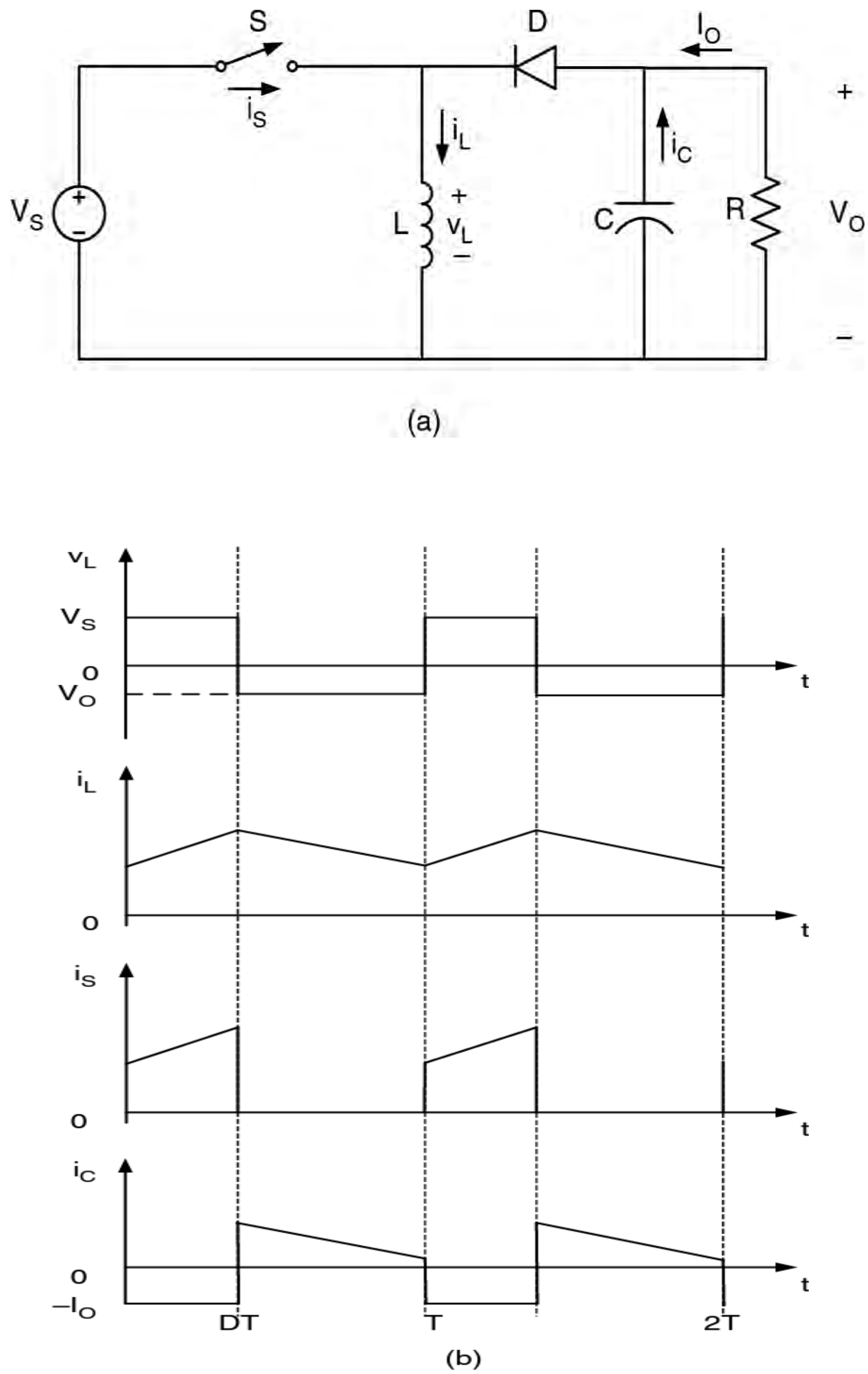


Fig. 2.14: Buck-Boost Converter (a) circuit diagram (b) waveform [44].

When the switch is closed, the diode acts as reverse biased and inductor stores the energy from the input power. The load at the output is powered by the already charged capacitor. On the other hand, when the switch is open the inductor acts as the source of the energy. It supplies the power for the capacitor and load at the output. The diode operates in forward biased mode in this state.

**2.7.4 Cuk Converter: T**he Cuk converter is the modified and advanced version of the buck-boost converter. It comes with the capability to the high or low voltage at the output as compared to the input voltage. The polarity of the voltage is also reversed at the output. The diagram of Cuk converter and output waveform as illustrated in Fig.2.15**.**

The transfer function of the buck-boost converter is:

$$-\frac{D}{1-D} = \frac{V_O}{V_S} \tag{2.9}$$

The Cuk converter offers many advantages over the buck-boost converter. The $C_1$ capacitor stores the energy from the input and has the capability to transfer at the output. The output current offered by the Cuk converter is continuous or smooth at the output which is not the case for the buck-boost converter. The complexity of the Cuk converter is much more than that of the buck-boost converter. The one drawback of the Cuk converter is that, it uses the large value of C to maintain the $V_C$ voltage at the output.

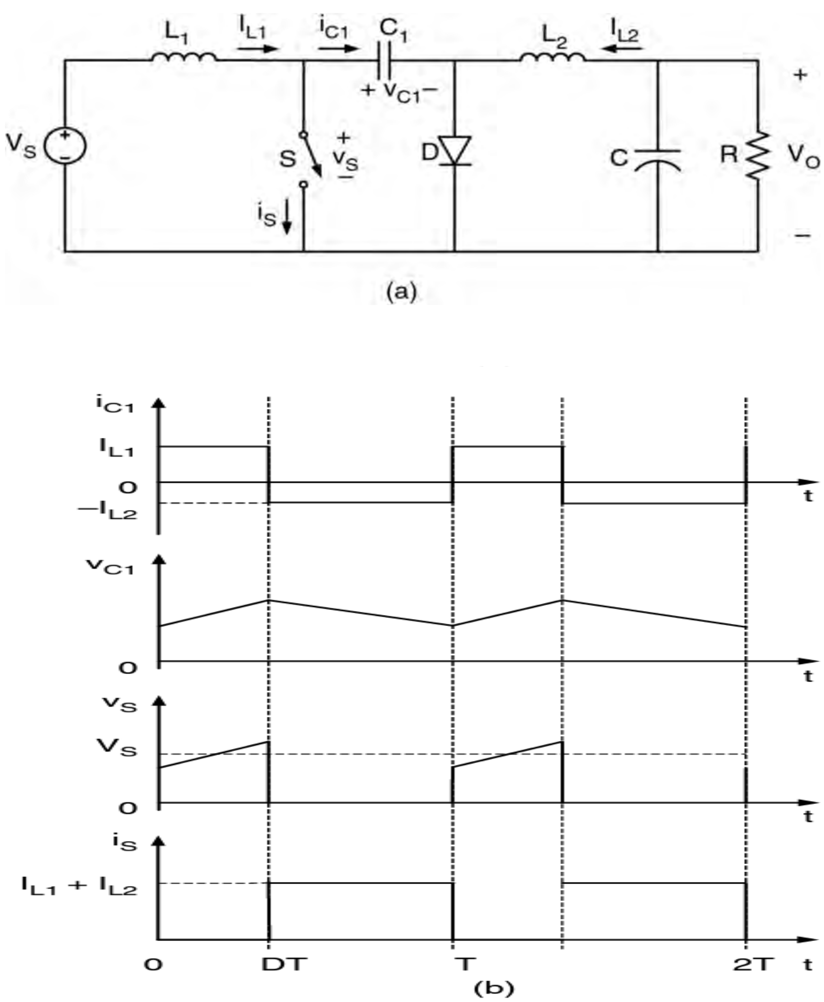



Fig. 2.15: Cuk Converter (a) circuit diagram (b) waveform [44].

## 2.8 DC-AC Inverters

Most of the renewable energy produces DC power output. The inverter is required to convert DC power to AC that can be directly interconnected with utility grid and it can use for consumption application. The control of inverter is a significant part to enhance the quality of power and meet the requirement of grid integration. The inverters are of two types mainly which includes the voltage source inverter (VSI) and current source inverter (CSI). The VSI comes with the zero or minimal impedance at the input whereas CSI comes with the very high impedance. These inverters can work in single phase or three phase system which entirely depends on the circuit arrangement of these inverters. The basic full bridge single-phase inverter is shown in Fig.2.16.

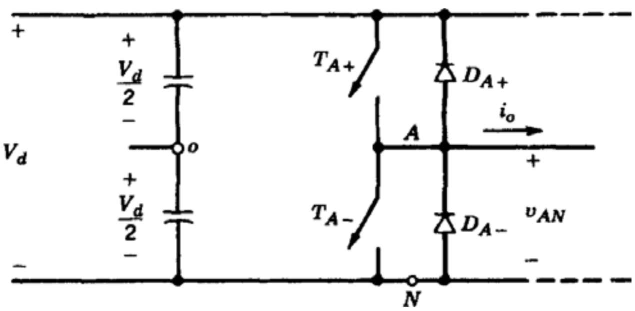



Fig. 2.16: Basic full bridge single leg inverter [45].

The switches in the inverter need to be turn *off* and *on* by triggering pulses at the gate to get AC signal from DC signal. Several technical have been used to general the pulses. The pulse width modulation (PWM) helps to produce sinusoidal output with controlled magnitude and frequency. Space vector based pulse width modulation and sinusoidal pulse width modulation are the most common in Voltage source inverters.

## 2.9 Pulse Width Modulation (PWM)

The DC-AC inverters usually operate on Pulse Width Modulation (PWM) technique. The PWM is a very useful technique in which width of the gate pulses are controlled by various mechanisms. PWM inverter is used to keep the output voltage of the inverter at the rated voltage irrespective of the output load. The pulse width modulation inverter has been the main choice in power electronic for decades, because of its circuit simplicity and strong control scheme [46]. Depending on the switching performance and good characteristic features, Sinusoidal Pulse Width Modulation (SPWM) will be used and the modulating signal as illustrated in Fig.2.17. As mentioned in [47], the advantages of using SPWM include low power consumption, high energy efficient up to 90%, high power handling capability, no temperature variation-and aging-caused drifting or degradation in linearity and SPWM is easy to implement and control. SPWM techniques are characterized by constant amplitude pulses with different duty cycle for each period [48].

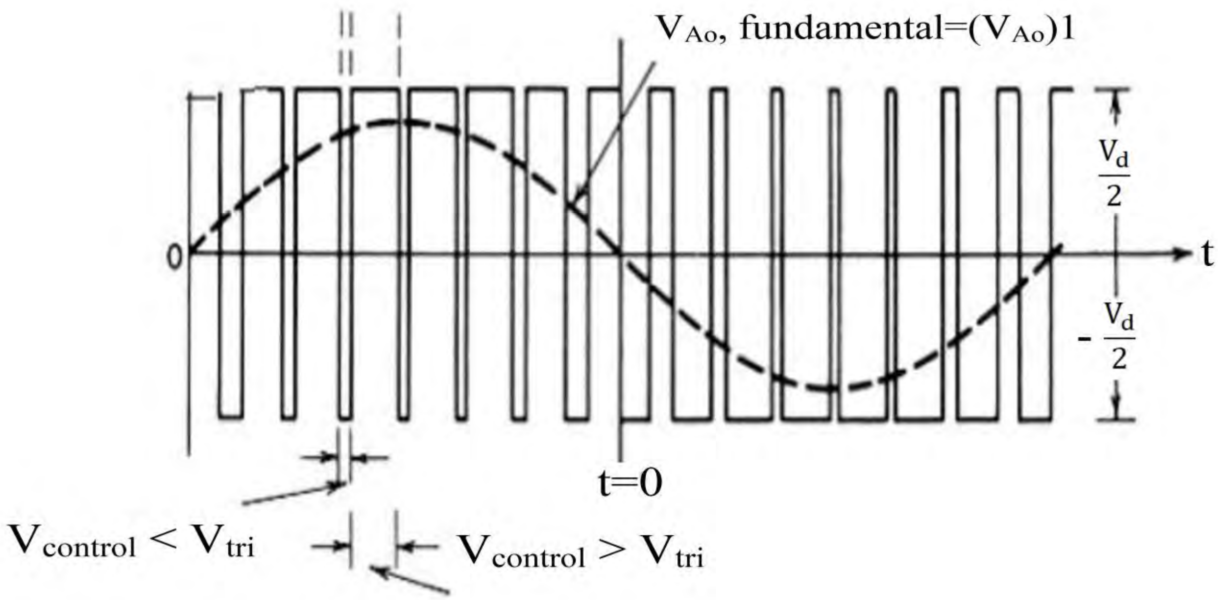



Fig. 2.17: Pulse width modulation waveforms

## 2.10 Grid Connected Voltage Source Converter (VSC)

The major purpose of the grid-connected inverter or Voltage Source Converter (VSC) is to manage the power injection into the grid extracted from distributed generation. The structure of a controller is shown in Fig.2.18. The control structure is mostly based on two cascaded loops for this purpose. A cascade loop can be used in many ways, but most popular strategy mentioned in [49] which uses an outer voltage loop and inner current loop.

The inner current loop regulates the power quality and decrease in harmonics in the current, which can be injected to the grid and the outer voltage loop which regulate balance the power flow of the system. It regulates the dc link voltages up to required level [49].

It is difficult to control the three-phase system, managing the control and sampling of the three-phase sinusoidal signal is the complex purpose and it required suitable transformation for sinusoidal signals. The control system can be designed into three reference frames namely, the natural frame, the stationary frame, and synchronous reference frame. The transformation diagram from synchronous reference dq0 frame is shown in Fig.2.19. Further information on reference frame grid-connected inverter can be seen in references [49, 50].

In synchronous reference frame, the sinusoidal variable (abc) are converted into frame (dq0) which rotates at synchronous speed with sinusoidal variables. This transformation also known as Park's transformation which makes these values appears as DC values in a steady state condition. The PI controller can be used to get satisfactory results [49].

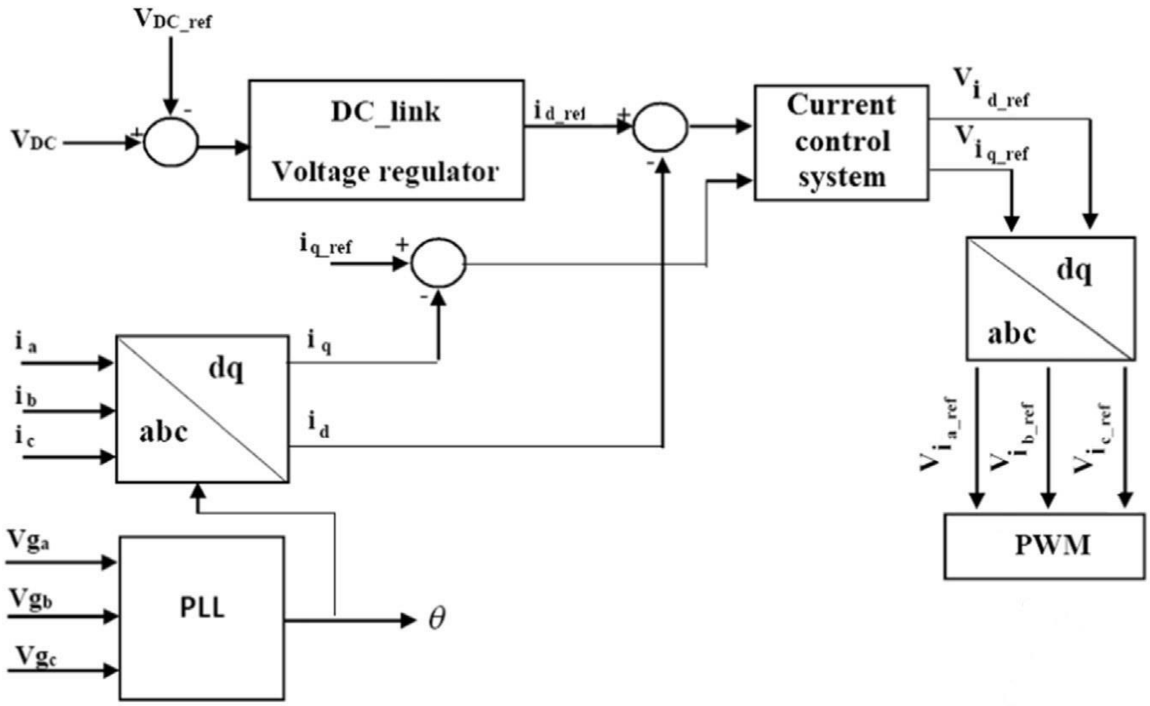



Fig. 2.18: The control system for grid-connected inverter [51].

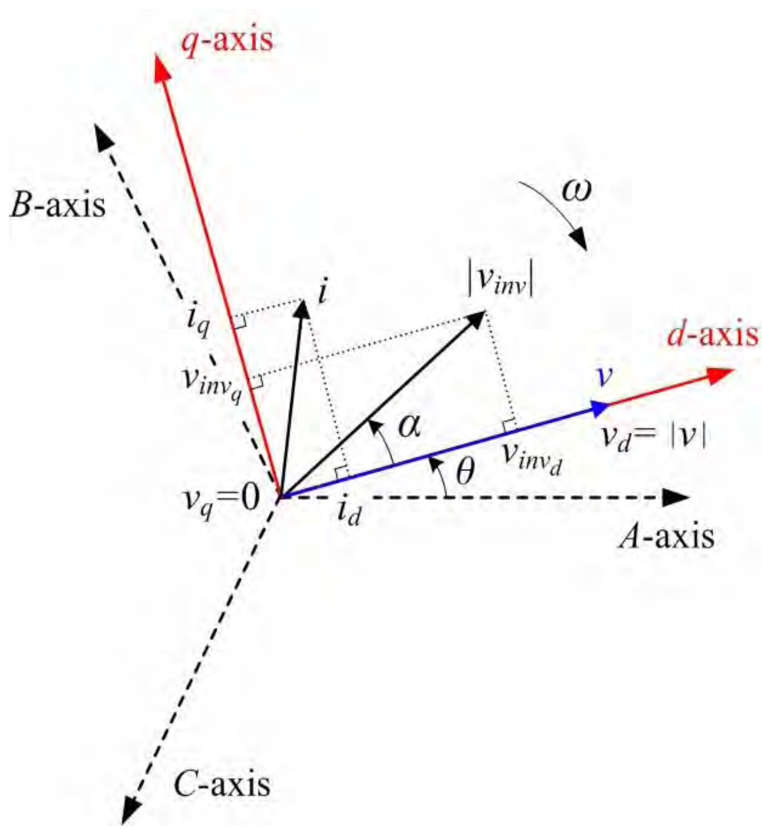



Fig. 2.19: Transformation diagram from reference frame [52].

## 2.11 Phase Locked Loop (PLL)

The phase-locked loop technique [53] has been used as a common way to synthesize the phase and frequency information of the electrical system, especially when it's interfaced with power electronic devices. The Phase Locked Loop block [54] measures the system frequency and provides the phase synchronous angle θ (more precisely [sin (θ), cos (θ)]) for the d-q Transformations block. In steady state, sin (θ) is in phase with the fundamental (positive sequence) of the α component and phase A of the PCC voltage $V_{abc}$. In the three-phase system, the d-q transform of the three-phase variables has the same characteristics and the PLL system can be implemented using the d-q transform. The block diagram of PLL system can be described in Fig.2.20.

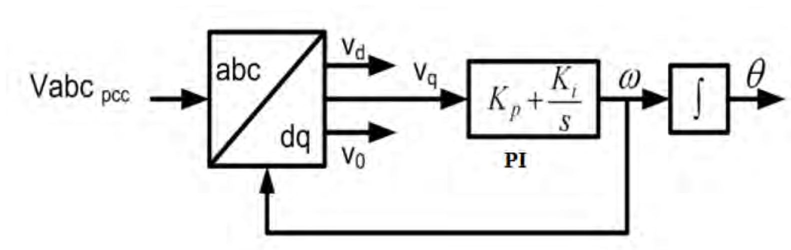



Fig. 2.20: Schematic diagram of the phase locked loop (PLL).

## 2.12 Filters

There are different types of filters available that are used in combination with the inverters to improve the overall output efficiency of the system. These filters are placed in different configuration schemes. It helps to remove the odd harmonics at the output. It also enables to compensate the voltage distortion from unbalanced or non-linear loads. The design of filter for such applications depends on various factors. It is ensured that filters have lowest possible power loss at the output to meet efficiency of the system at different levels of load voltages. The availability of components, size, and cost of the filter also has an impact on the overall low pass filter design. However, the voltage at the output and total harmonic distortion are the driving factors for optimal design and application of the filters [55]. There are commonly three kinds of passive filters used i.e. L, LC, and LCL as rep- resented in Fig.2.21.

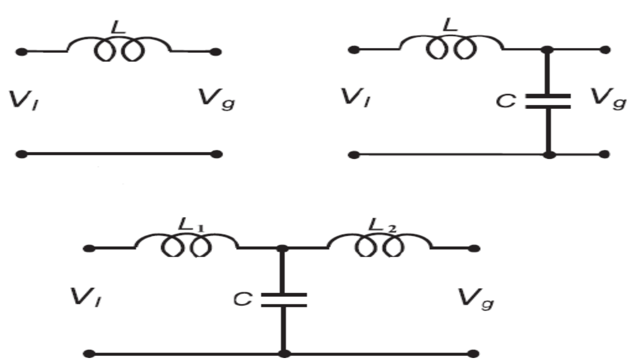



Fig. 2.21: L, LC and LCL filters [55].

CHAPTER 3

# Grid Connected PV System Modeling

## 3.1 Introduction

This chapter presents the implementation of a generalized grid connected photovoltaic model along with the Battery Management systems using Matlab/Simulink software package. Three main subsystems have been considered in detail for MATLAB Simulink modeling: a) PV system consists fuzzy logic based MPPT control and DC-DC boost converter, b) Fuzzy controller based Battery Management systems (BMS) consisting of a bi-directional converter, and c) Phase lock loop based DC-AC inverter while integrating to the grid. This makes the generalized model easily simulated and analyzed in different weather and conditions.

## 3.2 PV System Model

The following mathematical models of electrical characteristics are considered to design 100 kW photovoltaic module and simulated using MATLAB environment.

### 3.2.1 Open circuit voltage:

The open-circuit voltage, $V_{OC}$, is the extreme voltage offered from a PV cell (Fig.3.1), and this happens at zero current. The open-circuit voltage links to the amount of forward bias on the PV cell due to the bias of the PV cell junction with the light-generated current [56][57].

$$V = \frac{NKT}{Q}\ ln\frac{I_L - I_o}{I_o} + 1 \text{ Volt} \tag{3.1}$$

Where: V is the open circuit voltage

N is diode ideality constant

K is the Boltzmann constant (1.381*10^-23 J/K)

T is temperature in Kelvin

Q is electron charge (1.602*10^-19 c)

$I_L$ is the light generated current same as $I_{ph}$ (A)

$I_o$ is the saturation diode current (A)

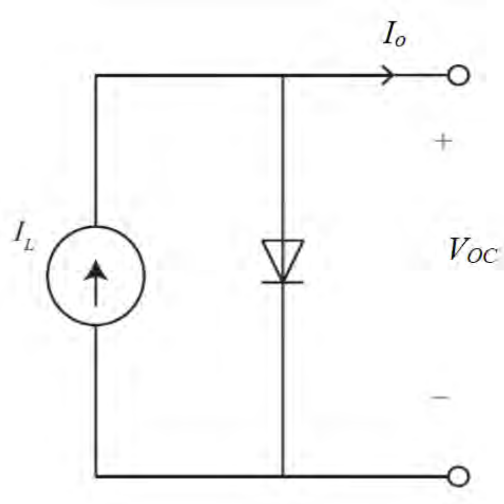



Fig. 3.1: Single diode of PV Cell.

**3.2.2 Light generated current (Radiation):**

$$I_L = \frac{G}{G_{ref}} * (I_{Lref} + \alpha_{Isc}(T_c - T_{c\,ref})) \tag{3.2}$$

Where: G is the radiation (W/m$^2$)

$G_{ref}$ is the radiation under standard condition 1000 W/m$^2$

$I_{Lref}$ is the Photoelectric current under standard condition 0.15 A

$T_{Cref}$ is module temperature under standard condition 298 K

$\alpha_{Isc}$ is the temperature co-efficient of the short circuit current (A/K)=0.0065/K

$I_L$ is the Light generated current (Radiation)

**3.2.3 Reverse saturation current:**

$$I_o = I_{or} * (T/T_{ref})^3 \exp^{\left(\left(\frac{QE_g}{KN}\right)*\left(\frac{1}{T_r}-\frac{1}{T}\right)\right)} \tag{3.3}$$

$$I_{orn} = \frac{Isc}{\exp^{(V_{ocn}/NV_{tn})}} \tag{3.4}$$

Where: $I_o$ is the Reverse saturated current

$I_{or}$ is the saturation current

N is the ideality factor 1.5;

$E_g$ is the band gap for silicon 1.10ev

### 3.2.4 Short circuit current:

***Ish* = $I_L$.** It is the extreme value of the current produced by a PV cell. It is formed by the short circuit situations: *V* = 0.

$$I_{sh} = I_L - I_o\left(\exp^{\left(Q\frac{V-IR_S}{NKT}\right)} - 1\right) \qquad (3.5)$$

**3.2.5 Irradiation**: G=radiation W/m$^{2.}$

In Fig.3.2 and Fig.3.3, I-V and P-V characteristics of the PV module are shown at different irradiances and constant temperature (25°C).

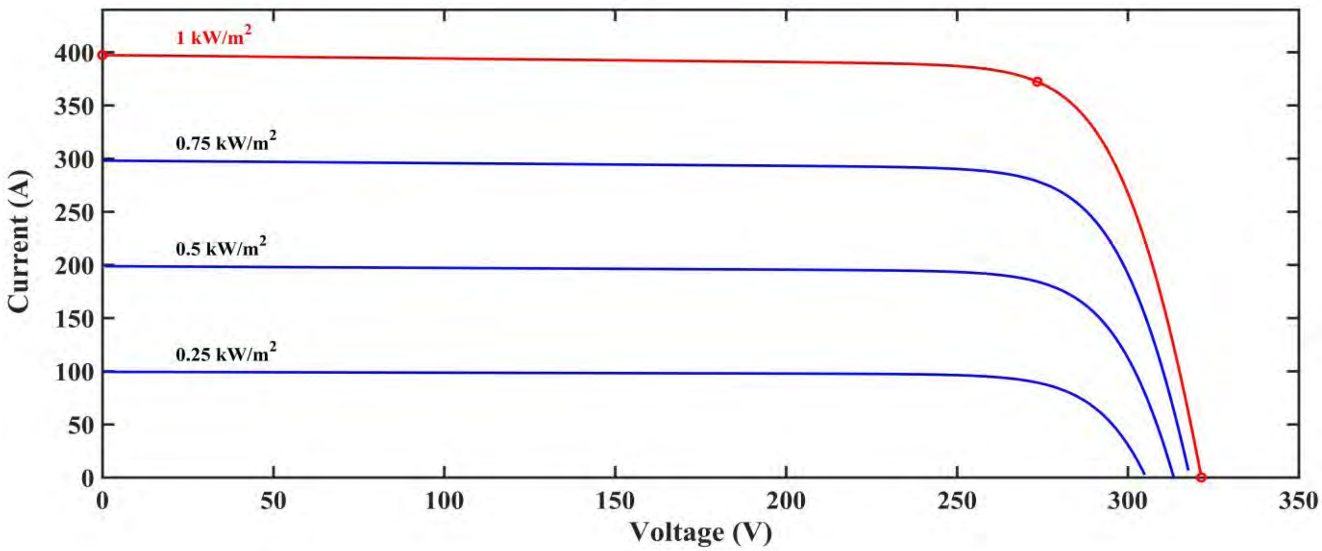



Fig. 3.2: PV - Voltage vs Current Characteristics.

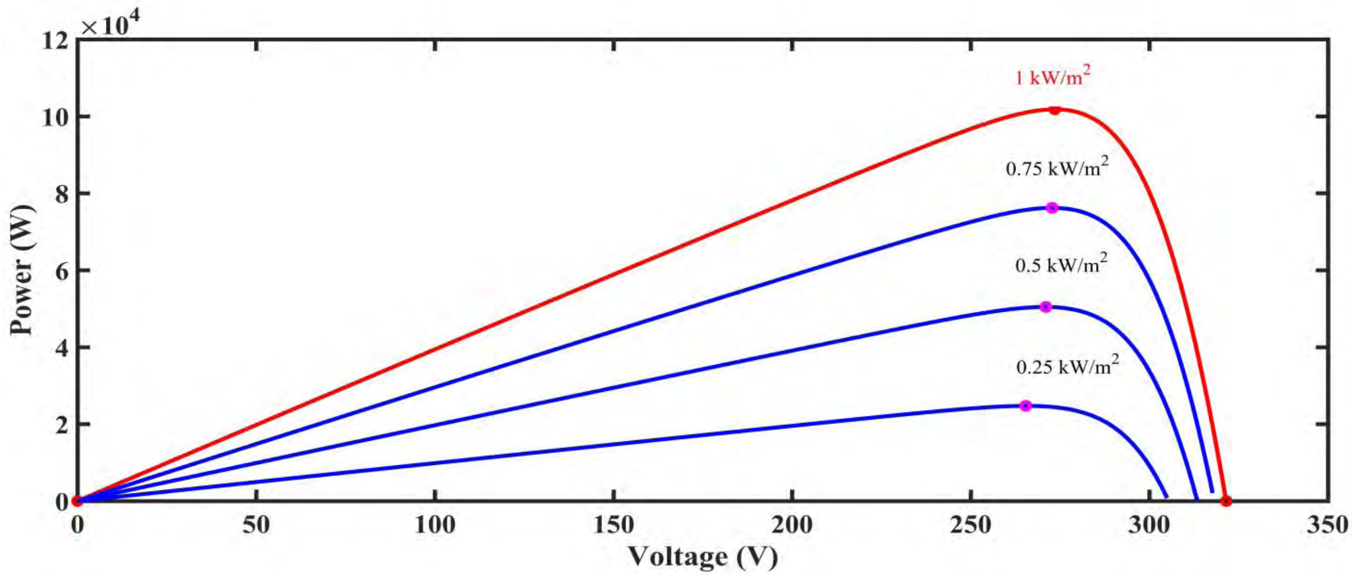



Fig. 3.3: PV - Power vs Voltage Characteristics.

### 3.2.6 Modelling of PV array:

PV array modelling can be done from Simulink using simpower components though MATLAB has built-in PV array block which can be used. The PV array comprises a total of 330 solar modules that provide 101.805 kW under standard test conditions (STC). The layout of the PV array consists of 66 parallel strings where each string has 5 series- connected SunPower SPR-308E-WHT-D modules. The array layout is shown in Fig.3.4. Note that each string has 5 modules. The PV array has an optimum capacity of 66×5×308.508 W = 101.805 kW at 25 ºC or STC.

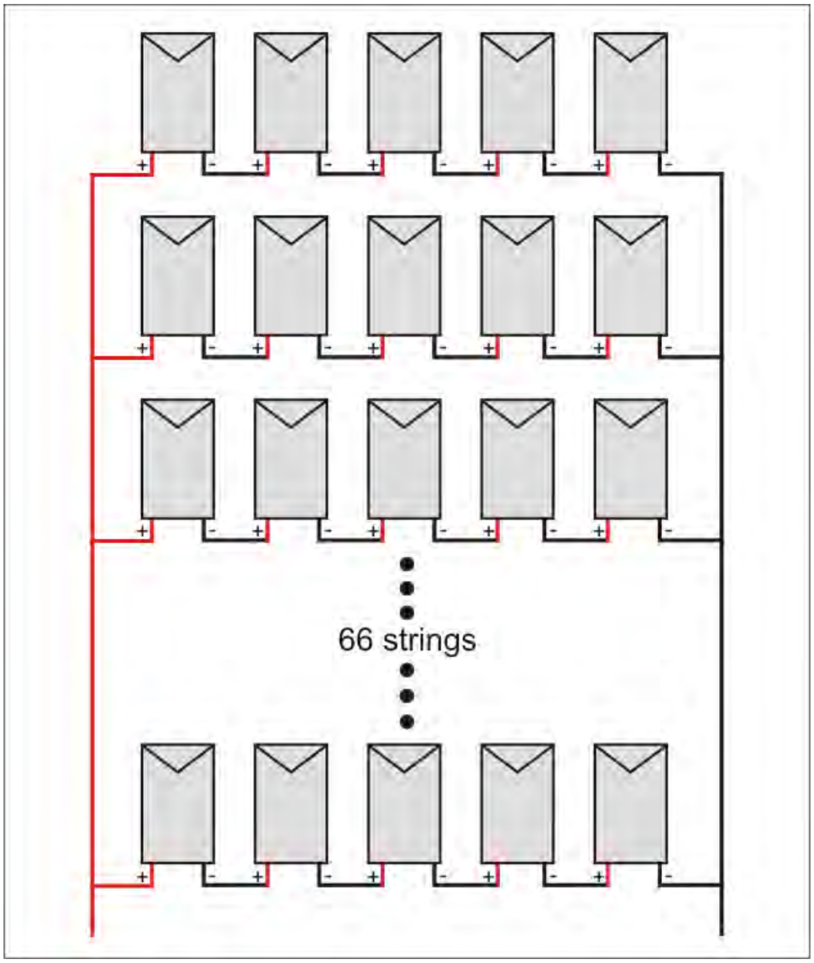



Fig. 3.4: Series and parallel connection of PV array for 100 kW.

## 3.3 Maximum Power Point Tracking (MPPT) For PV System

The renewable energy sources play an important role to meet consumer power demand due to their abundant availability and a lesser amount impact of environment [58]. The main hurdle in PV energy expansion is the investment cost of the PV power system implementation. PV energy generation is not constant throughout the day due to the change of weather. The efficiency of power generation is very low (the range of efficiency is only 14-17% in low irradiation regions).

Therefore, MPPT technologies have an important role in PV power generation for optimal power generation at various weather conditions.

In this thesis work, a fuzzy logic based MPPT controller for 100 kW PV system has been discussed and analysed. The proposed fuzzy based MPPT block diagram is shown in Fig.3.5.

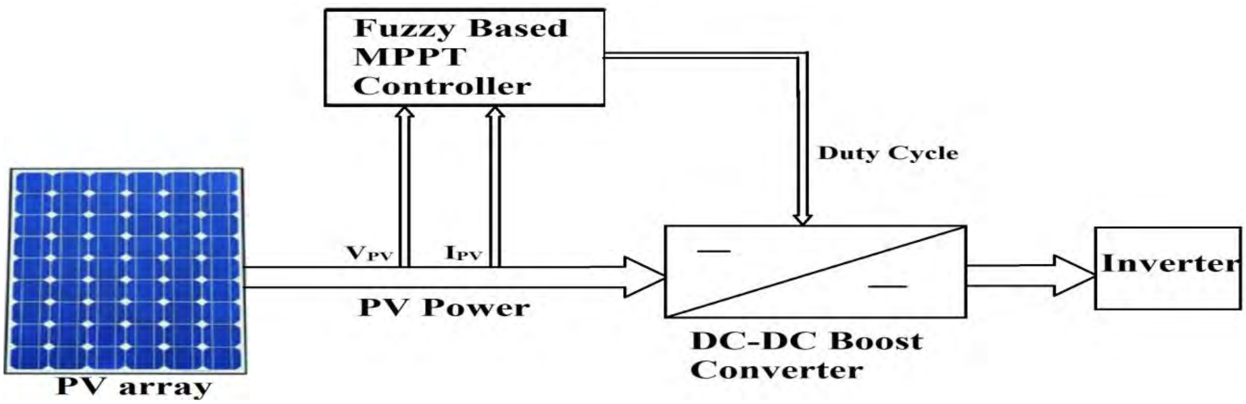



Fig. 3.5: PV - MPPT Block diagram.

The basic structure of fuzzy logic MPPT controller is shown in Fig.3.6 which has two inputs and one output. The proposed model takes as inputs of PV array voltage and current shown in Fig.3.7 and Fig.3.8 respectively. The MPPT fuzzy controller generates duty cycle based on input of fuzzy controller and fed into boost converter shown in Fig.3.9. In the fuzzification stage, numerical input variables are converted into linguistic variables such as Low, Medium and High. The fuzzy membership function has been designed by trapezoidal method for both input and output membership values. The fuzzy inference engine processes the inputs according to the rules and produces the linguistic output. In defuzzification, proposed fuzzy controller has been used to centre of gravity. The fuzzy interference rules are designed based on changes of PV voltage and current under various weather condition shown in Fig.3.10. Fuzzy surface rules and nine fuzzy ruler view are presented in Fig.3.11 and Fig.3.12.

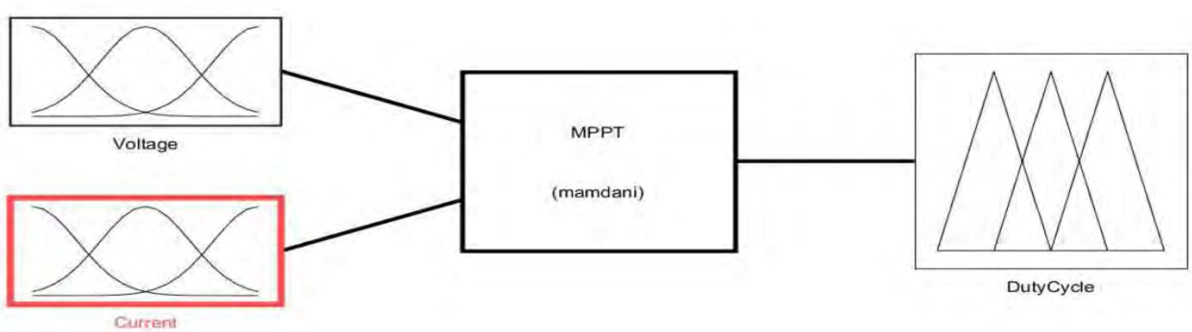



Fig. 3.6: Fuzzy Controller Structure for MPPT of PV system.

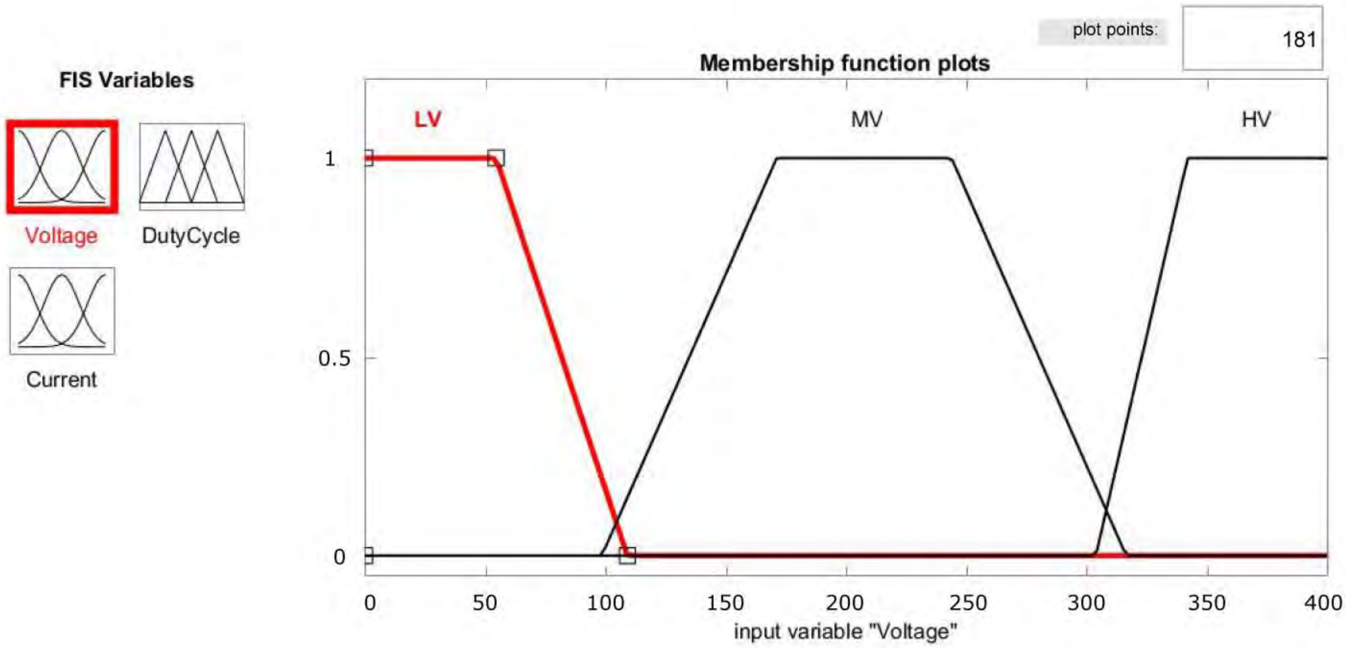



Fig. 3.7: Fuzzy input membership function (Voltage) for MPPT of PV system.

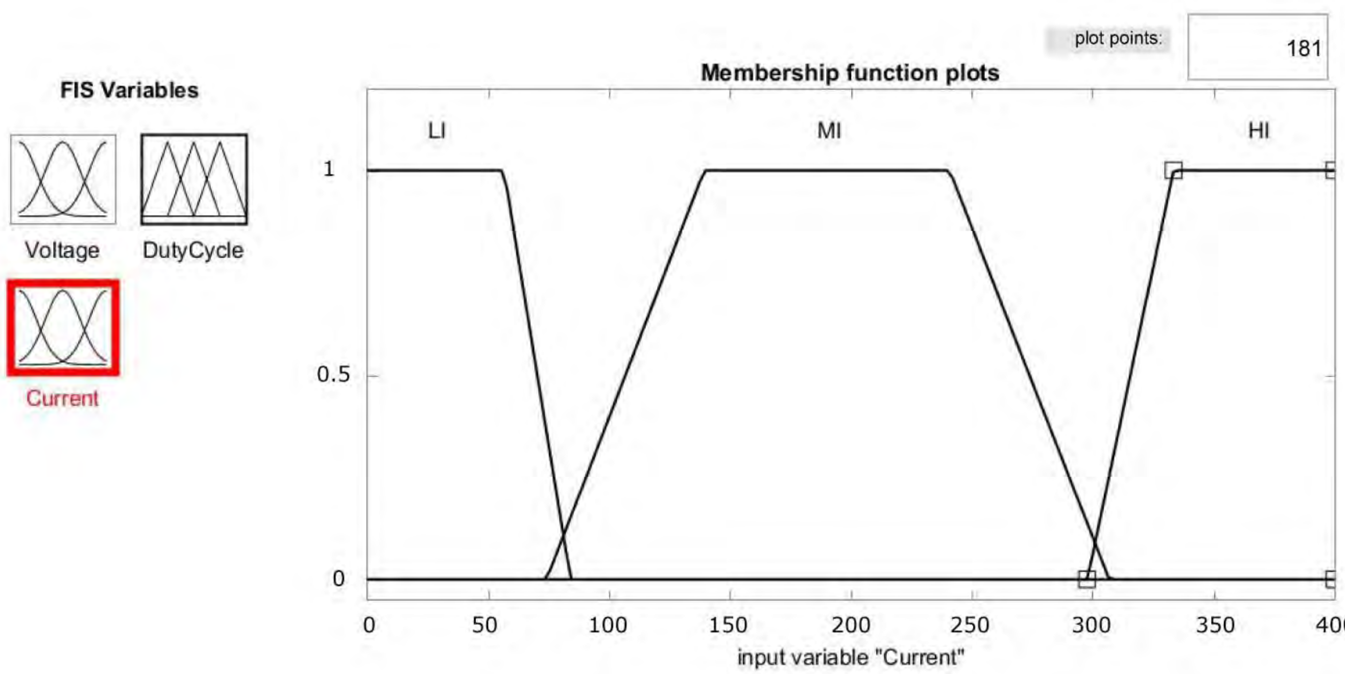



Fig. 3.8: Fuzzy input membership function (Current) for MPPT of PV system.

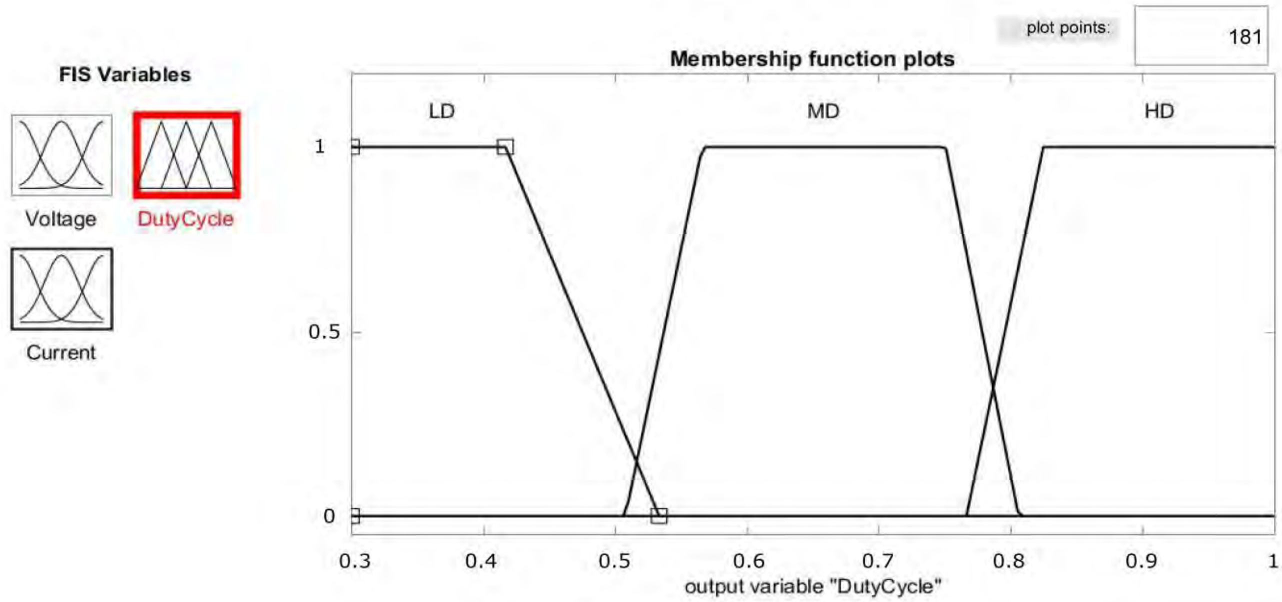



Fig. 3.9: Fuzzy Output membership function (Duty Cycle) for MPPT of PV system.

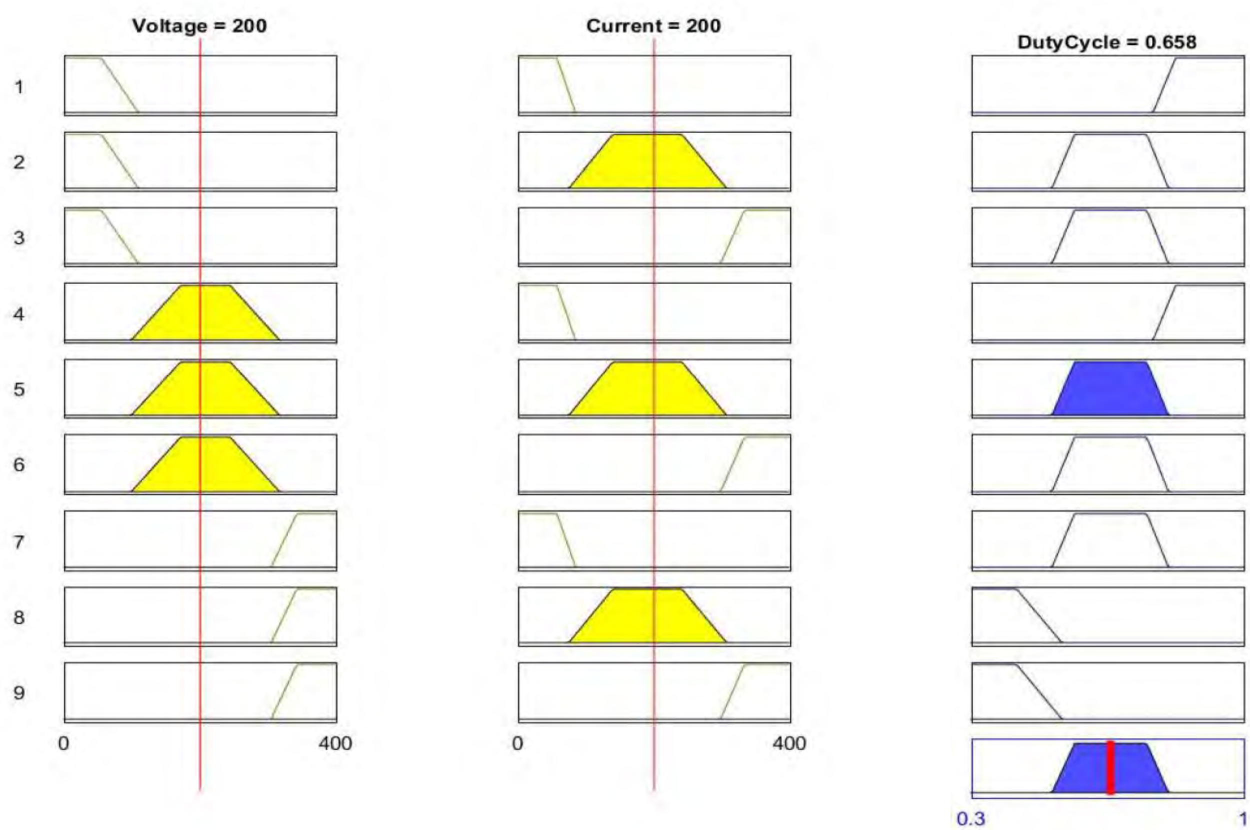



Fig. 3.10: Fuzzy Rules for MPPT of PV system.

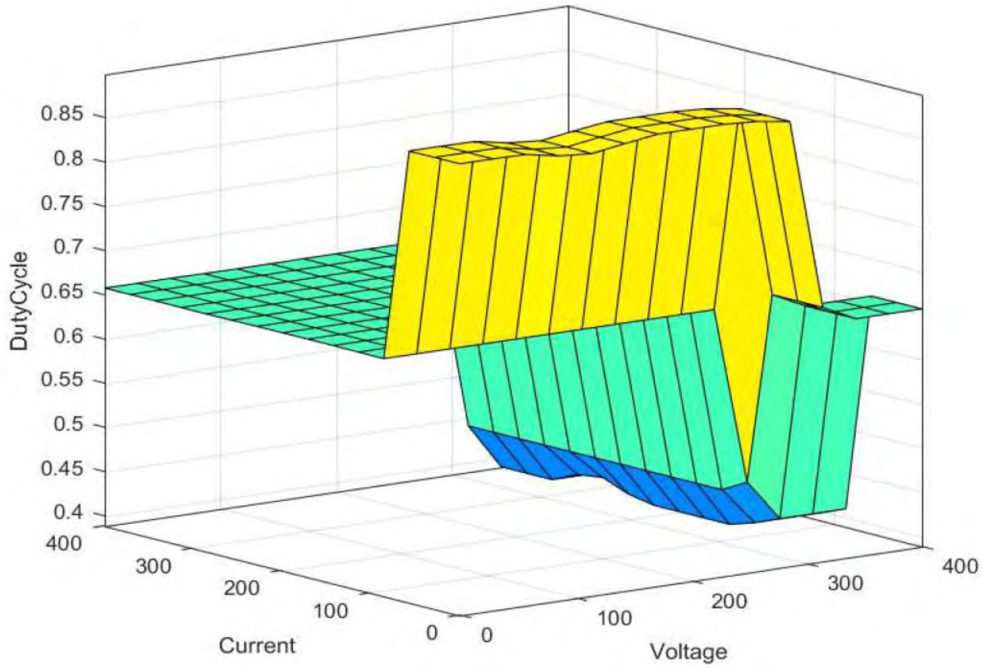



Fig. 3.11: Fuzzy surface for MPPT of PV system structure.

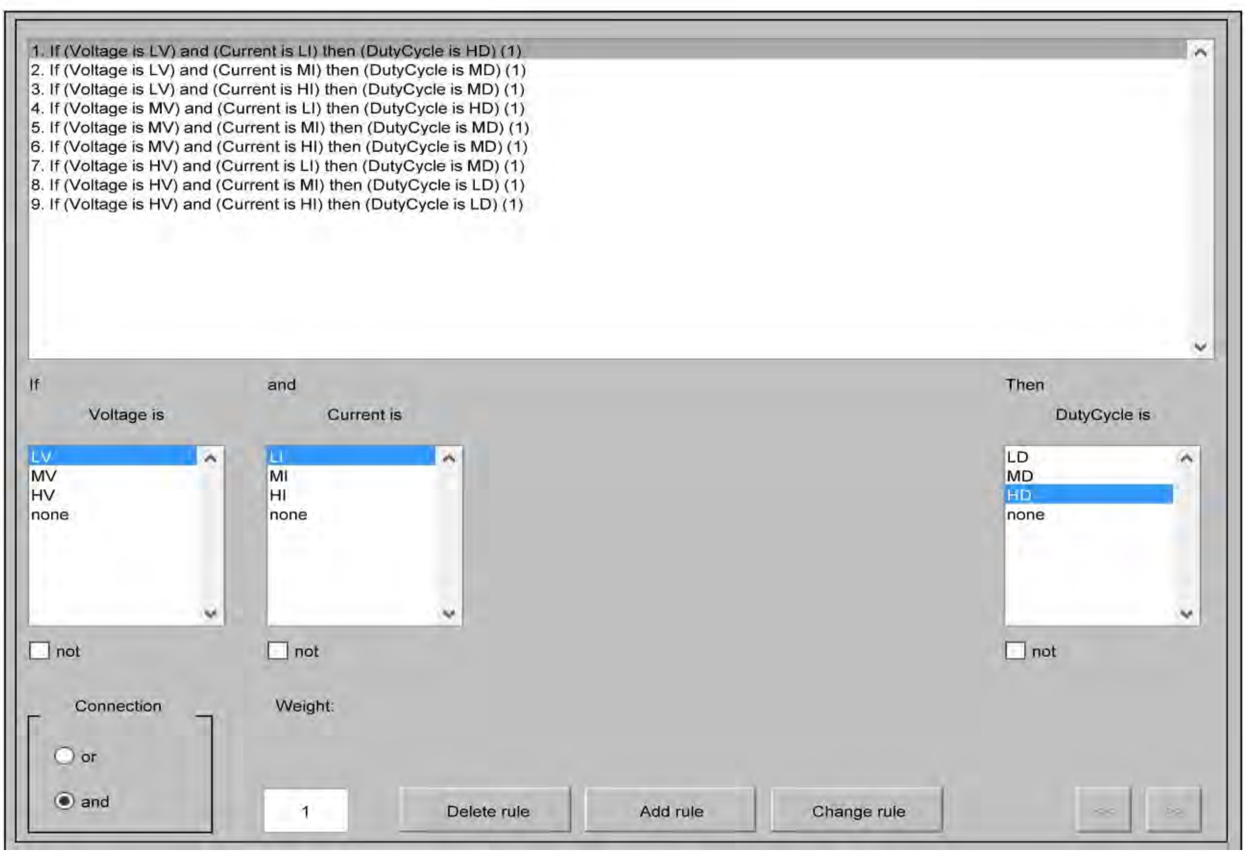



Fig. 3.12: Fuzzy ruler view for MPPT of PV system structure.

The above designed fuzzy controller has been implemented in MATLAB simulation of 100 kW PV system and its boost converter is shown in Fig.3.13.

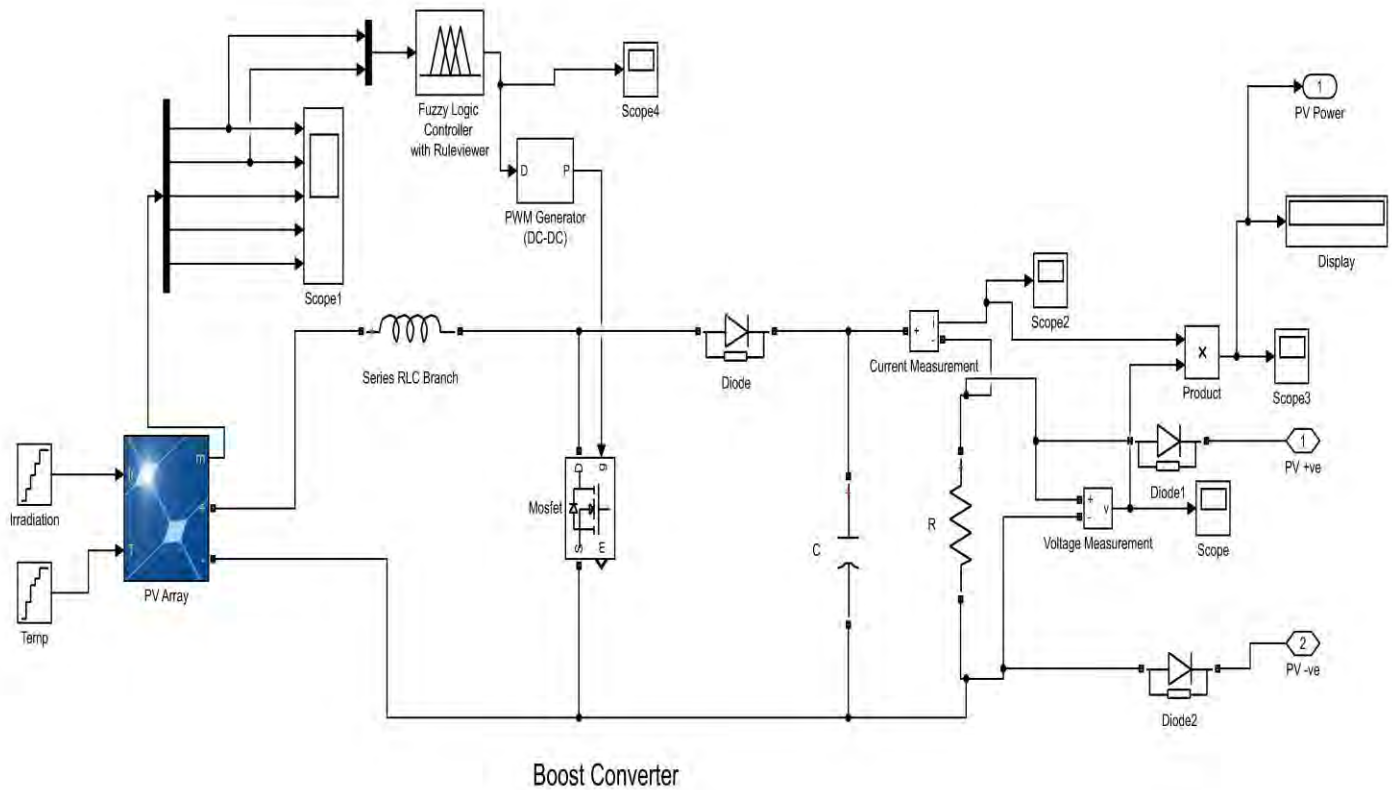



Fig. 3.13: Fuzzy Simulation model for MPPT of PV system.

## 3.4 Battery Management System

A smart energy management system for grid integration of PV power system has been designed and modelled. The energy management system play vital role for battery operation such as charging, discharging and SOC control [57][59]. The main objective of BMS is to deliver the power to the load when PV system is unable to deliver the total power required by the load. BMS complements the total power generated from the PV system. The main purpose of the battery is to supply the additional energy to the load. This increases the efficiency of the overall plant. Battery's power management flow chart is given in Fig.3.14. This BSM can also detect external fault in the grid and isolate PV system from the grid. The basic structure of fuzzy controller based energy management system presented in Fig.3.15. The proposed controller has one input and two outputs. In the fuzzification stage, numerical input variables are converted into linguistic variables such as Negative error (NE), Zero Error (ZE) and Positive Error (PE). The fuzzy membership function has been designed by trapezoidal method for power management and fault detection which are shown in Fig.3.16 and Fig.3.17. The fuzzy inference engine processes the inputs according to the rules and produces the linguistic output. The output membership function is modelled by trapezoidal method (On and OFF) shown in Fig.3.18 and Fig.3.19. Fuzzy ruler view for BMS is given in Fig.3.20.

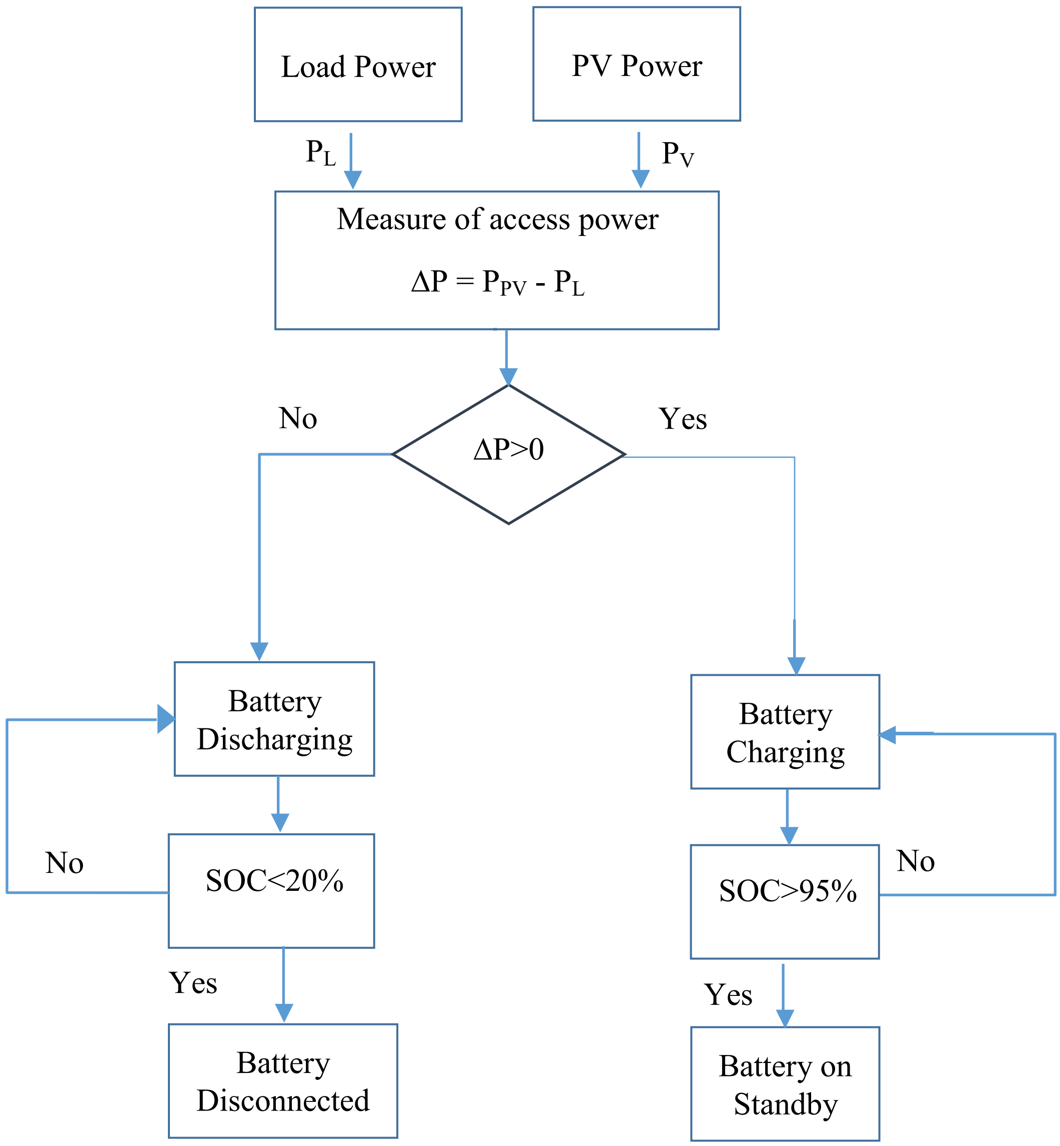



Fig. 3.14: Power management flow chart.

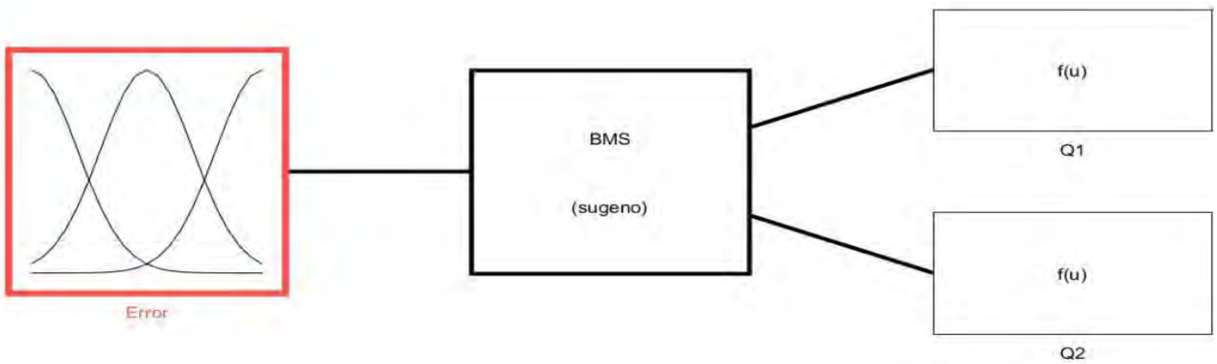



Fig. 3.15: Fuzzy Controller structure for battery management system.

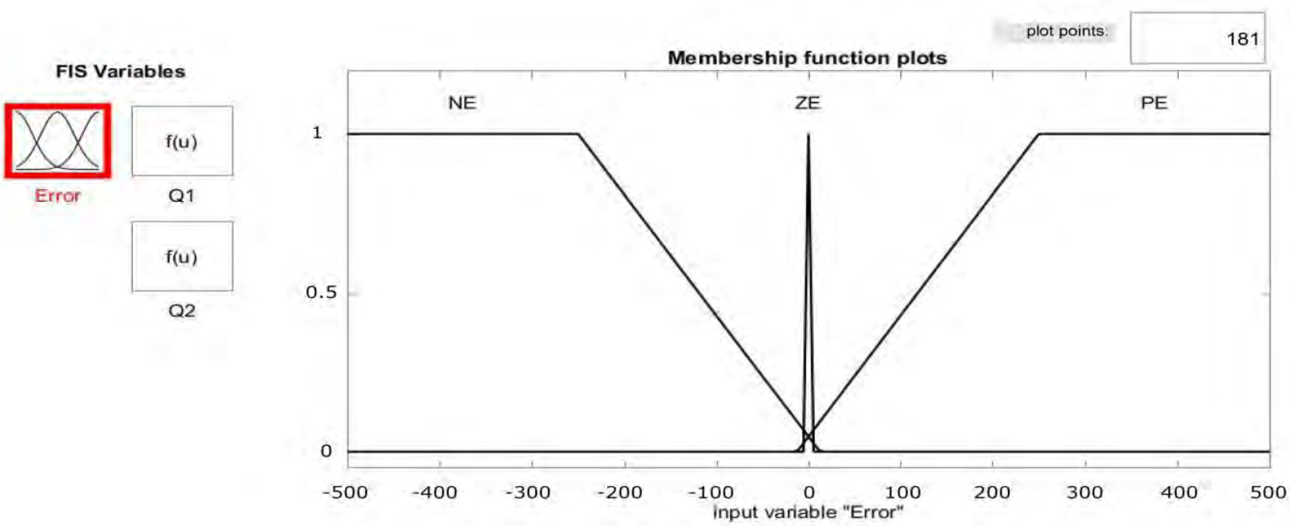



Fig. 3.16: Fuzzy input membership function for power management.

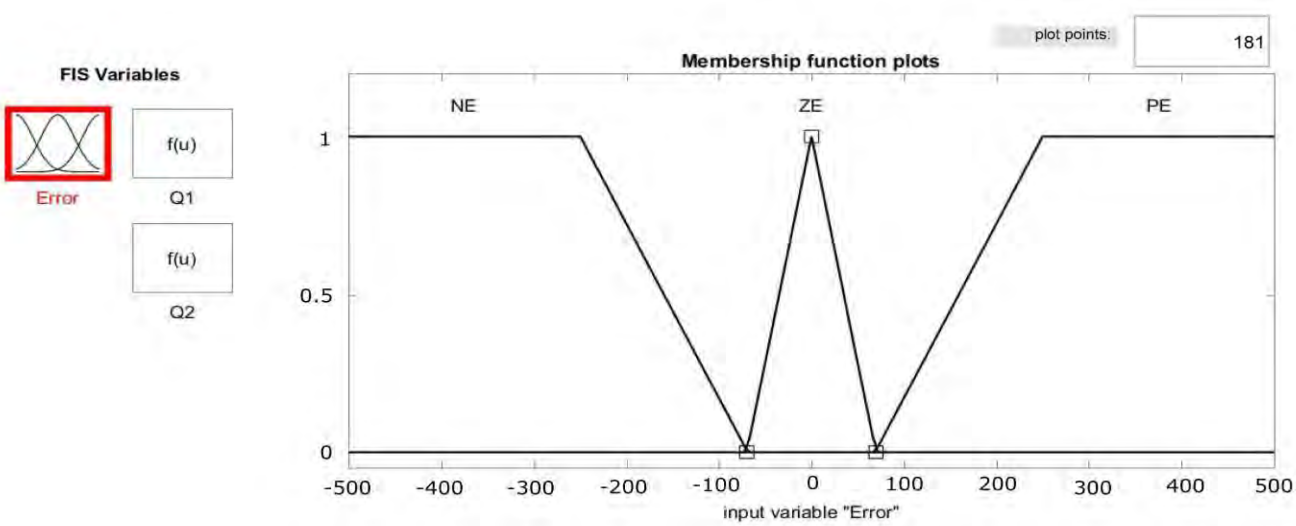



Fig. 3.17: Fuzzy input membership function for fault management.

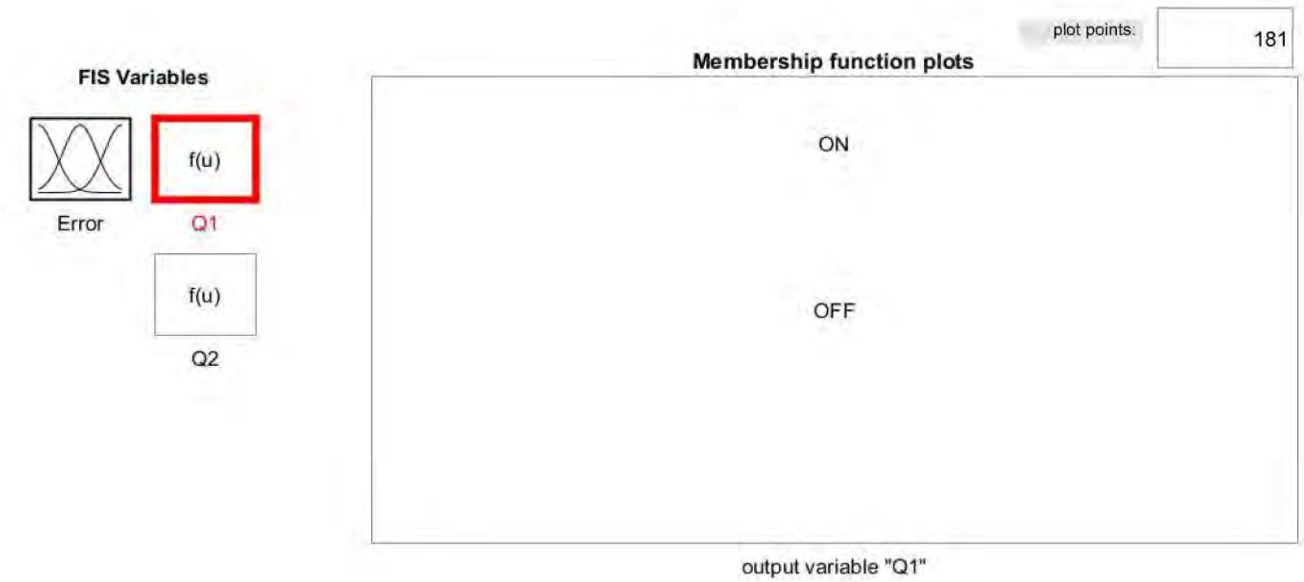


Fig. 3.18: Fuzzy output membership function (Q1) for battery management system.

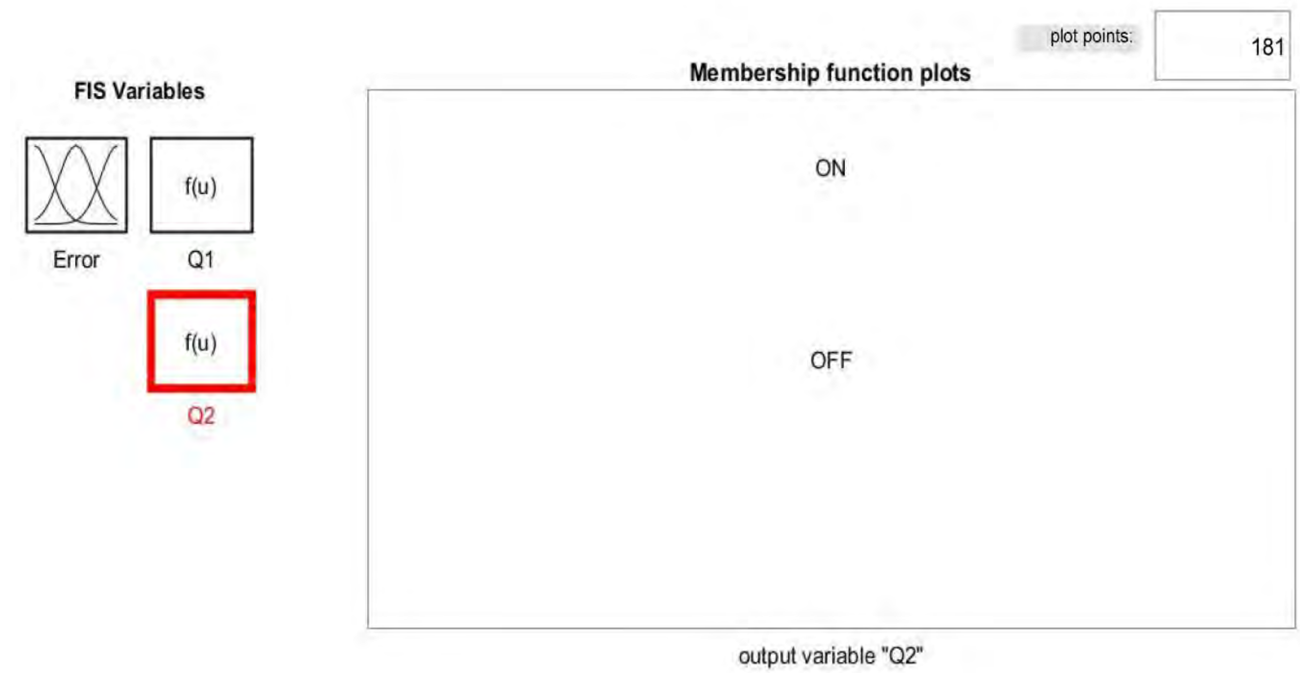


Fig. 3.19: Fuzzy output membership function (Q2) for battery management system.

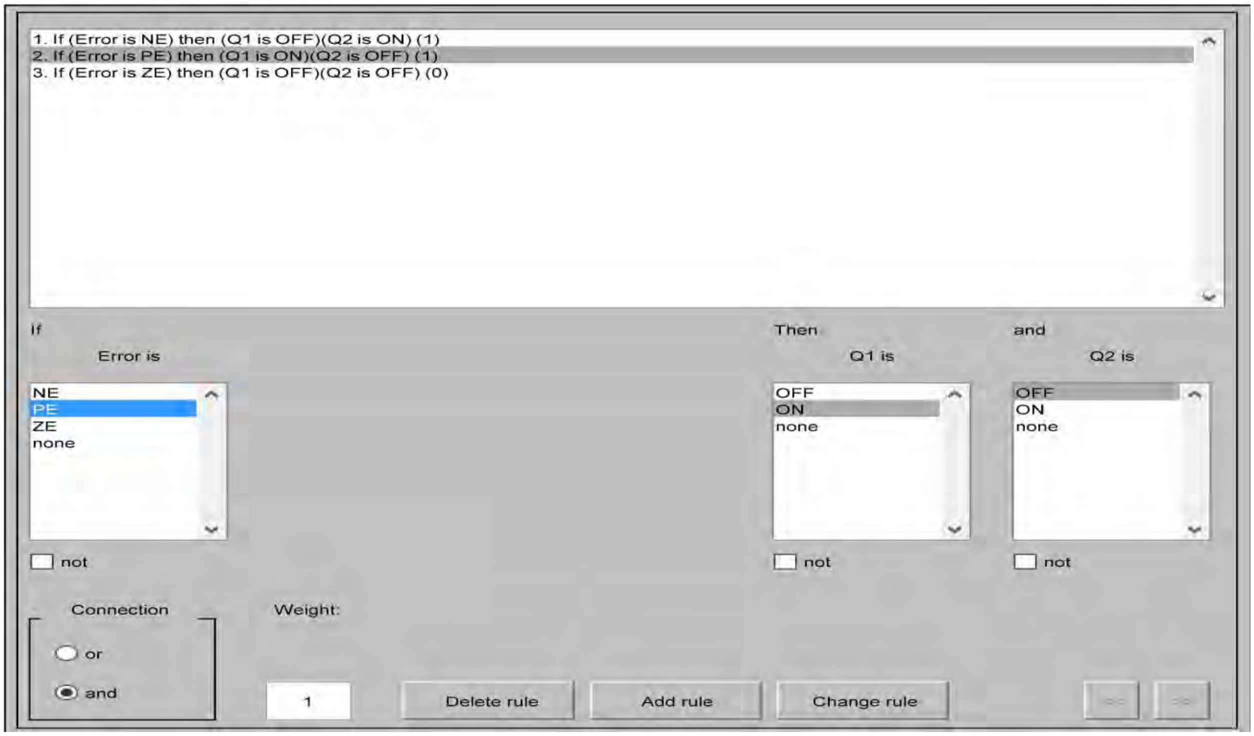



Fig. 3.20: Fuzzy ruler view for battery management system.

There are two cases such as battery charging and discharging. These two cases will discuss in the chapter 4. The fuzzy controller is implemented for bidirectional converter (buck-boost) shown in Fig.3.21.

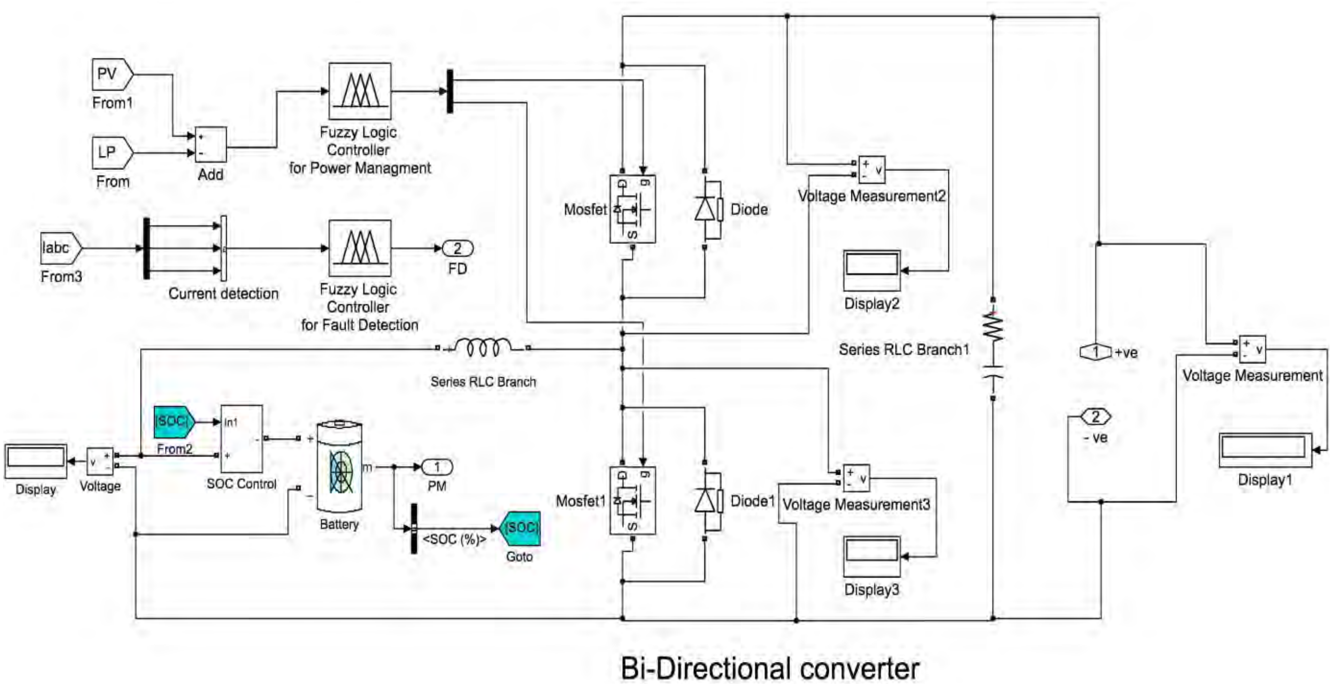



Fig. 3.21: Fuzzy based bi-directional converter for battery management system.

## 3.5 Battery Pack

MATLAB Simulink provides the simulation capability of the sophisticated battery dynamics that is very useful for this work. However, it does not incorporate battery aging and temperature dependency. The battery model & characteristics is shown in Fig.3.22 and Fig.3.23 respectively; battery parameters are presented in Table 3-1.

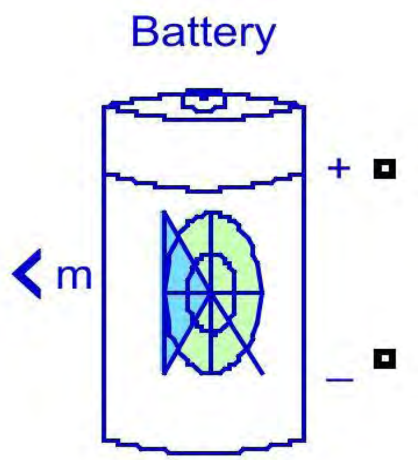



Fig. 3.22: General Battery Model in Simulink.

**Table 3-1:** The parameters of battery

| Type | Lithium-ion |
|---|---|
| Nominal voltage (V) | 500 |
| Rated Capacity (Ah) | 200 |
| Initial state of charge (SOC) | 50 |
| Maximum capacity (Ah) | 200 |
| Cut-off Voltage (V) | 375 |
| Fully charged voltage (V) | 581.9936 |
| Nominal discharge current (A) | 86.9565 |
| Internal resistance (Ohms) | 0.025 |
| Capacity (Ah) at nominal voltage | 180.8696 |

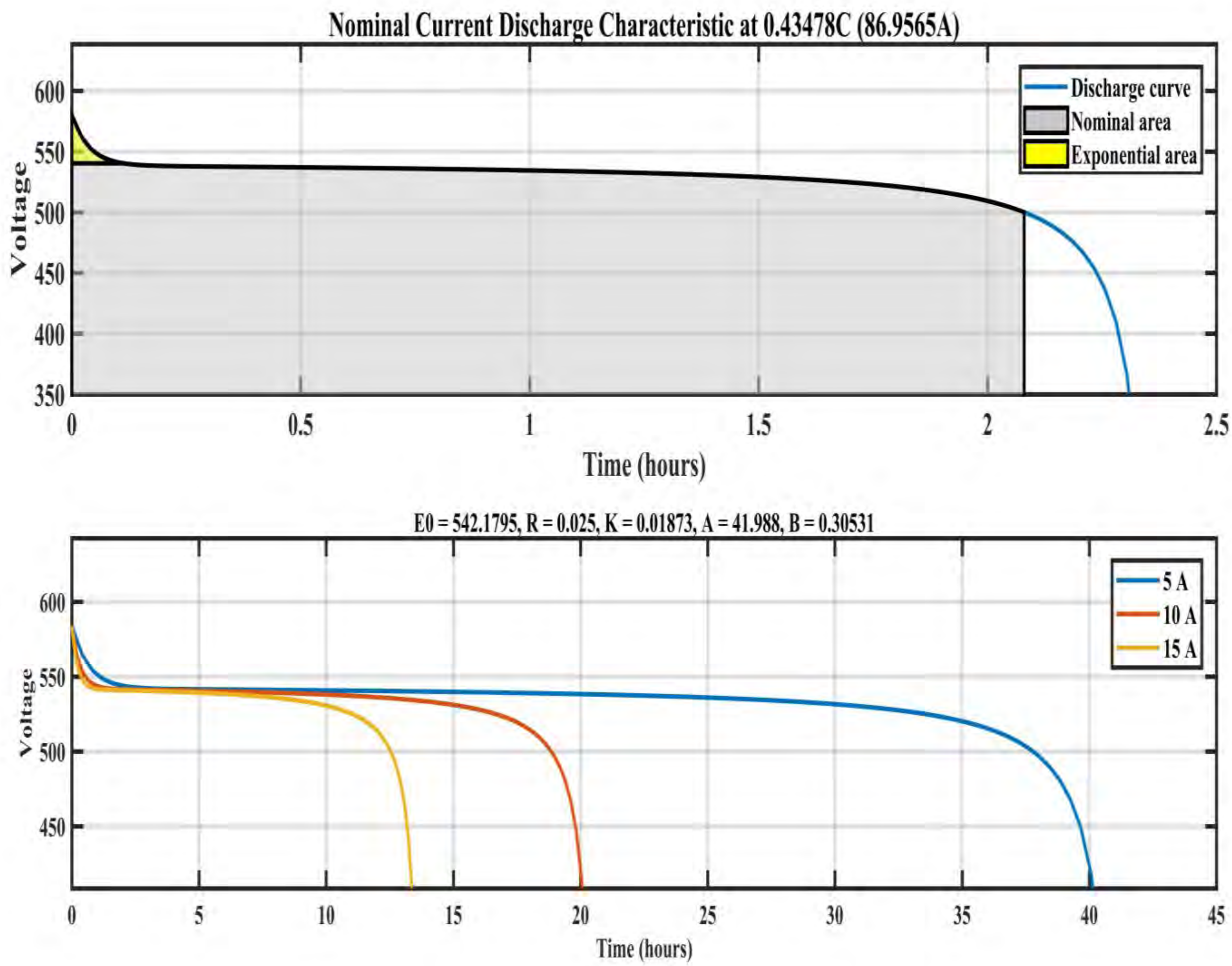



Fig. 3.23: Battery Characteristics.

## 3.6 DC-AC Inverter

This simulation used an MOFET/Diodes based inverter that converts the dc supply into an AC supply. The efficiency of the inverter (e.g., less harmonic distortion) determines its ability to convert the dc into ac with the accurate waveform. These inverters use high-efficient multi-level PWM (pulse width modulation) technique for DC to AC conversion.

In this thesis, the universal bridge of MATLAB Simulink has been used as MOFET/Diodes, as shown in Fig.3.24. The Simulink model of voltage source converter or inverter is presented in Fig.3.25.

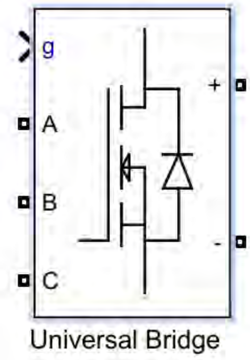



Fig. 3.24: Universal Bridge (MOSFET/Diodes) Block.

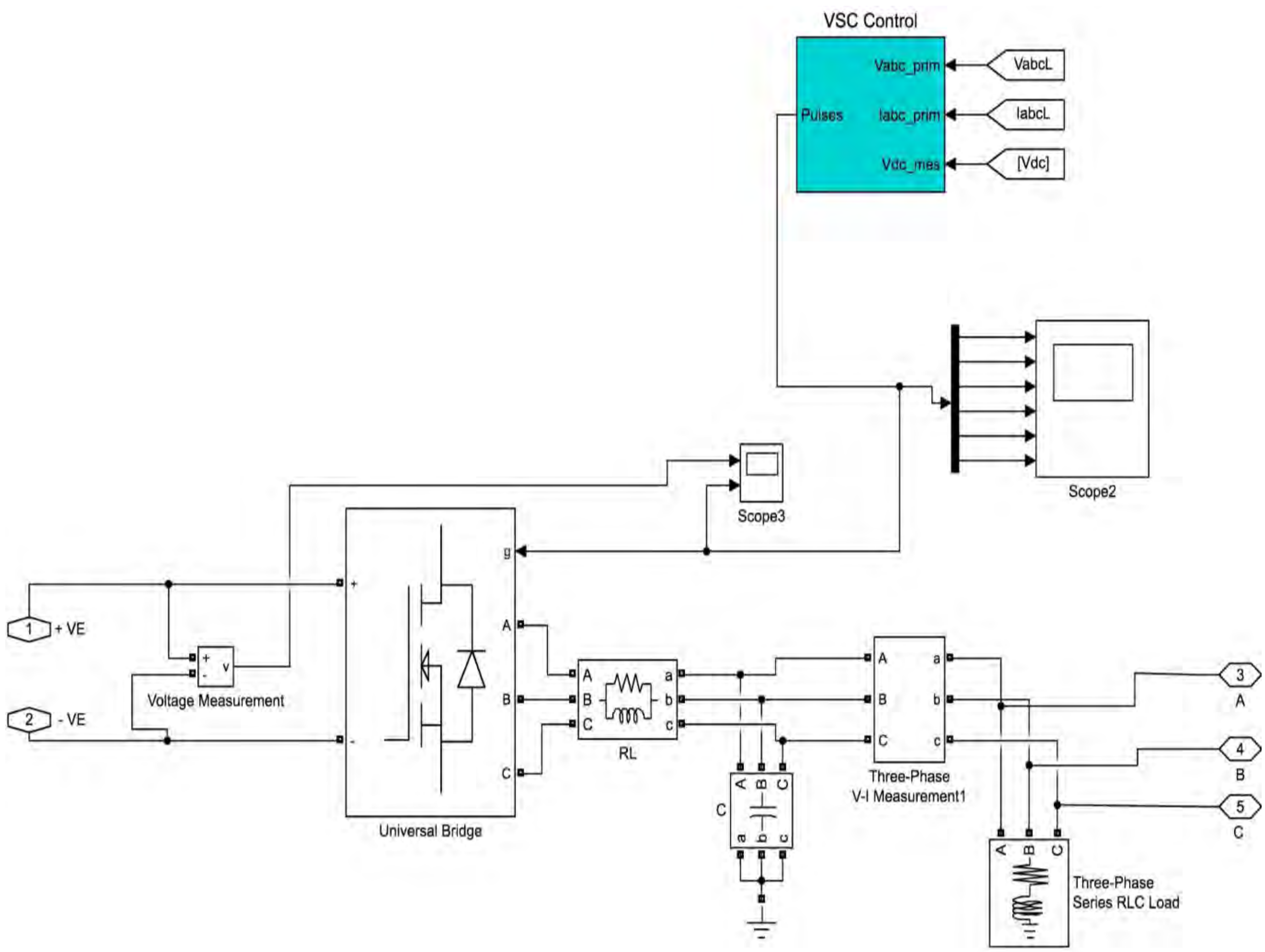



Fig. 3.25: Simulink model of VSC or inverter.

## 3.7 Grid Integration of PV Power System

The proposed 100 kW PV power system and fuzzy based energy management battery storage system has been penetrated to distributed power grid. The propose model simulated in MATLAB environment and presented in Fig.3.26. The voltage source converters (VSC) play important role for grid integration of PV system. Because PV generates only DC power, so we need to convert DC to AC power by using inverter [60][61]. The grid integrated inverter is controlled by Phase lock loop, voltage regulator, current regulator and finally based on the regulator output the PWM generator provide operating signals to inverter for synchronising process as shown in Fig.3.27. The proposed model will be tested and simulated with various power demand conditions and observed the power waveform from PV, Grid, Load Demand and Battery.

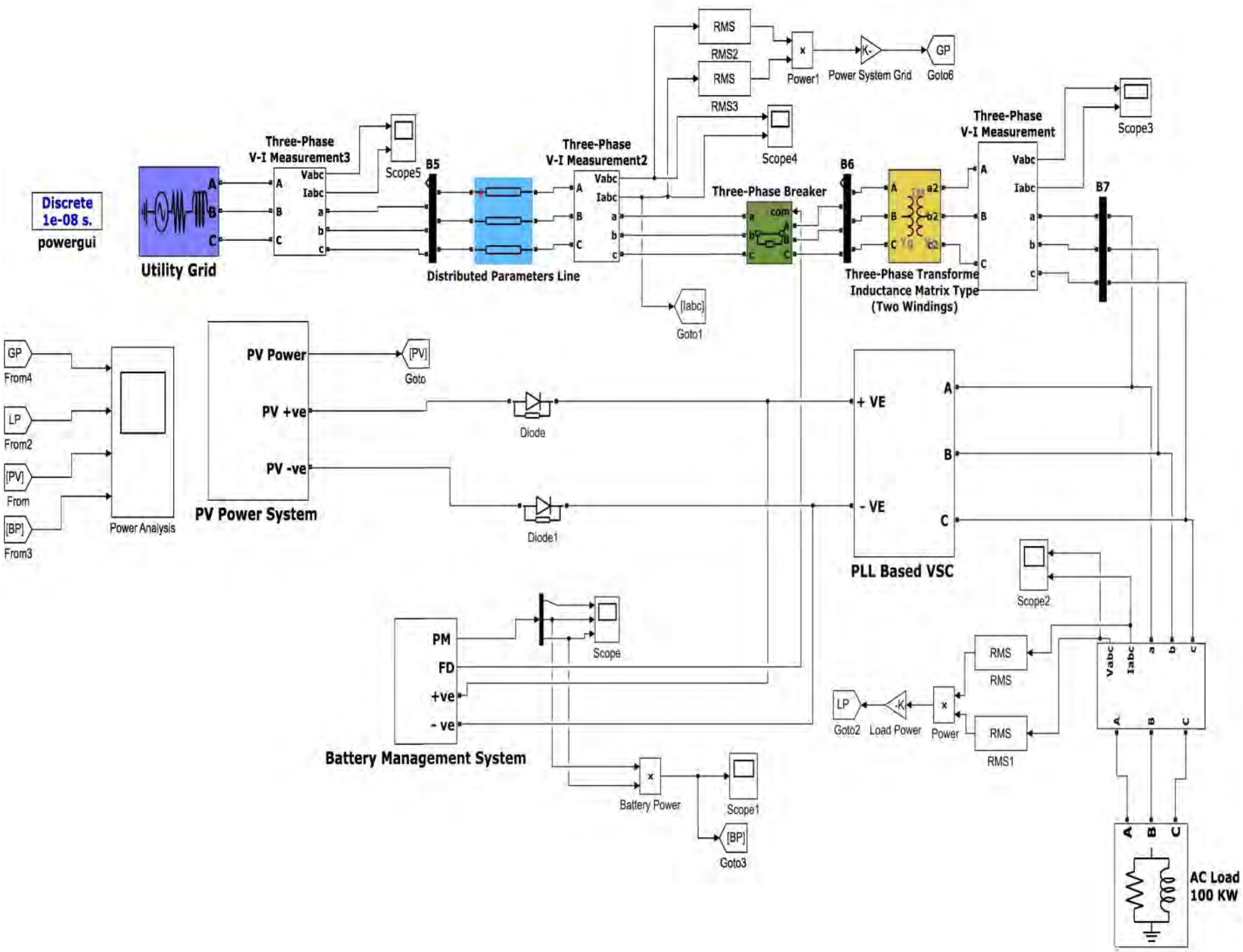



Fig. 3.26: Proposed Simulation Model.

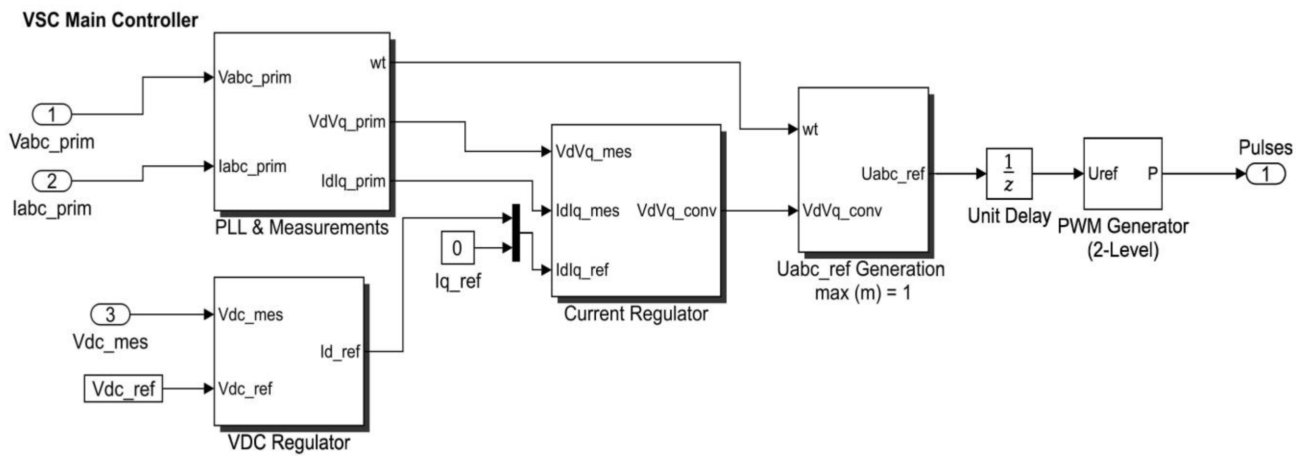



Fig. 3.27: Voltage Source Converter controller design for grid integration of PV system.

For the modeling and control of the individual subsystems, MATLAB Simulink has been extensively used. For this thesis, several tool boxes from MATLAB Simulink have been used to model different components that allow testing of the grid connected PV power system under different test conditions. The Simulink implementation of this system facilitated the simulation, test results are provided in Chapter 4.

CHAPTER 4

# Results and Discussion

## 4.1 Introduction

This chapter reports on the simulation results which is furnished by the Simulink model of the proposed 100 kW PV power system and fuzzy based energy management system, discussed in Chapter 3. The MATLAB Simulink environment facilitates the modelling and simulation of rather complex engineering systems, such as the PV power system with based energy management system, which is the object of this research project. A sample of key results have been recorded and presented in this chapter using plots and tables. The salient points of these results are also described.

## 4.2 Performance of PV module and array

At first, each PV module and entire PV array's Matlab simulation test results have been shown respectively. The PV array comprises a total of 330 solar modules that provide 101.805 kW under standard test conditions (STC). The layout of the PV array consists of 66 parallel strings where each string has 5 series connected with SunPower SPR-308E-WHT-D modules (specification in provided in Table 4.1). The PV array has an optimum capacity of 66×5×308.508 W = 101.805 kW at 25 ºC or STC, as per Table 4.2.

**Table 4.1:** Technical data of a PV module (SunPower SPR-308E-WHT-D) at STC

| | |
|---|---|
| Short Circuit Current, $I_{sc}$ | 6.02 A |
| Current at maximum power point, $I_{mpp}$ | 5.64 A |
| Voltage at maximum power point, $V_{mpp}$ | 54.7 V |
| Open circuit voltage, $V_{oc}$ | 64.3 V |
| Number of cells in Series | 96 |

**Table 4.2:** Technical data of the PV array (capacity 100 kW at STC).

| | |
|---|---|
| Number of modules in string series | 5 |
| Number of modules in string parallel | 66 |
| Output Voltage rating | 273.5 V |
| Output Current rating | 372.24 A |
| Maximum Power Output | 101.805 KW |

The voltage and current characteristics of a single PV module under varying irradiance had been shown in Fig.4.1. The output current of each PV module is linearly connected with related with the amount of irradiance. The irradiance also affects the voltage of the PV module, but it is not so significant. Due to change in irradiance, the overall power of the PV module also varies as shown in Fig.4.2. Decreasing the irradiance will reduce the overall performance of the PV module. Similarly, the impacts of temperature have been analyzed on entire PV array shown in Fig.4.3 and Fig.4.4. The temperature impacts the voltage of the PV array. Increasing the temperature reduces the performance of the PV panel.

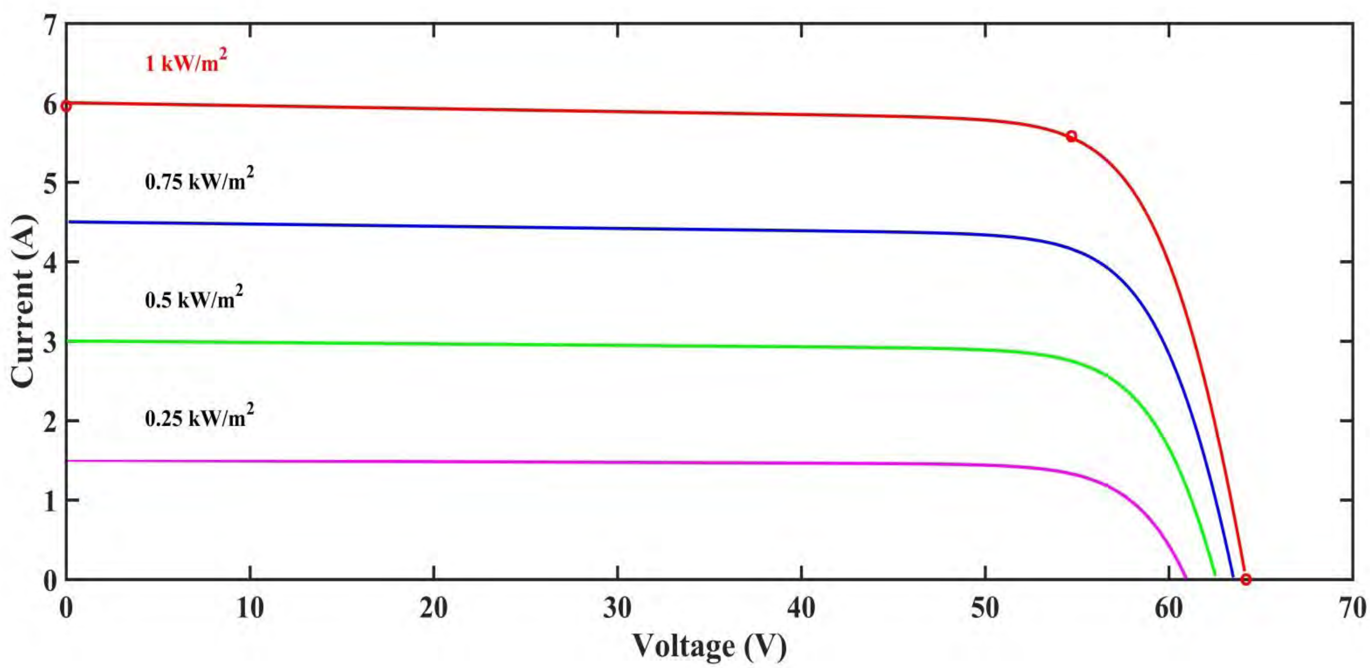



Fig. 4.1: I-V Characteristics of the PV module under varying irradiance.

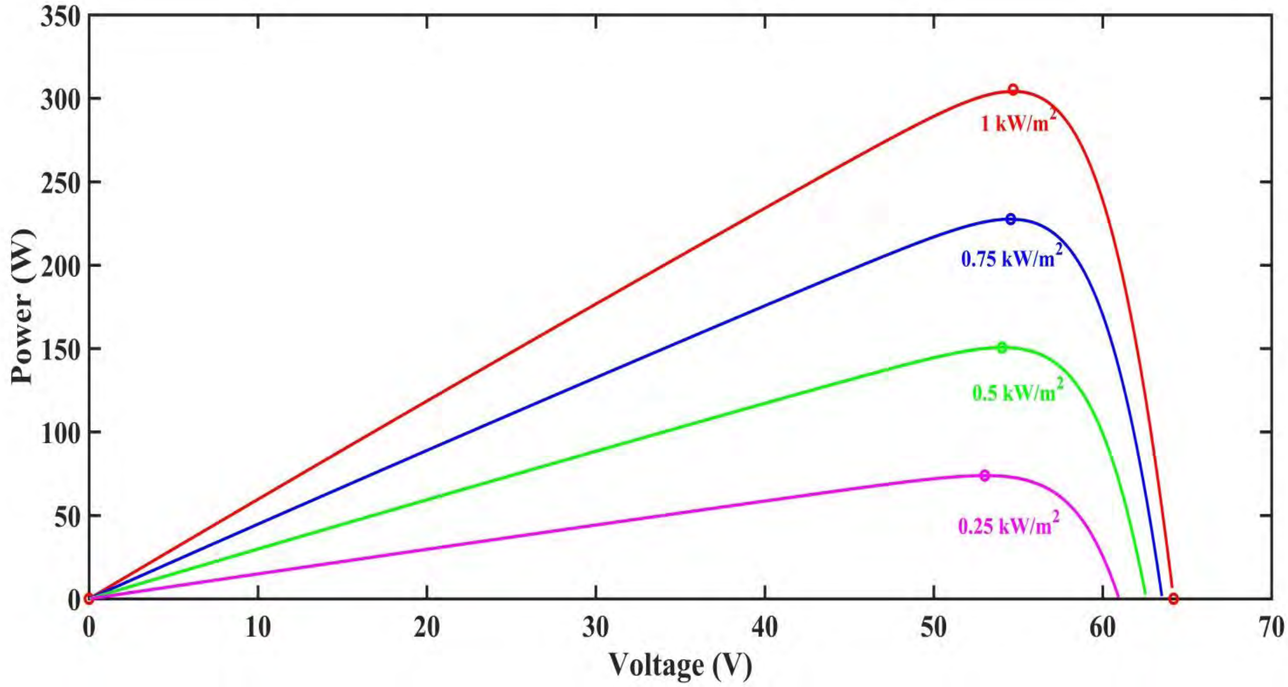



Fig. 4.2: P-V Characteristics of the PV module under varying irradiance.

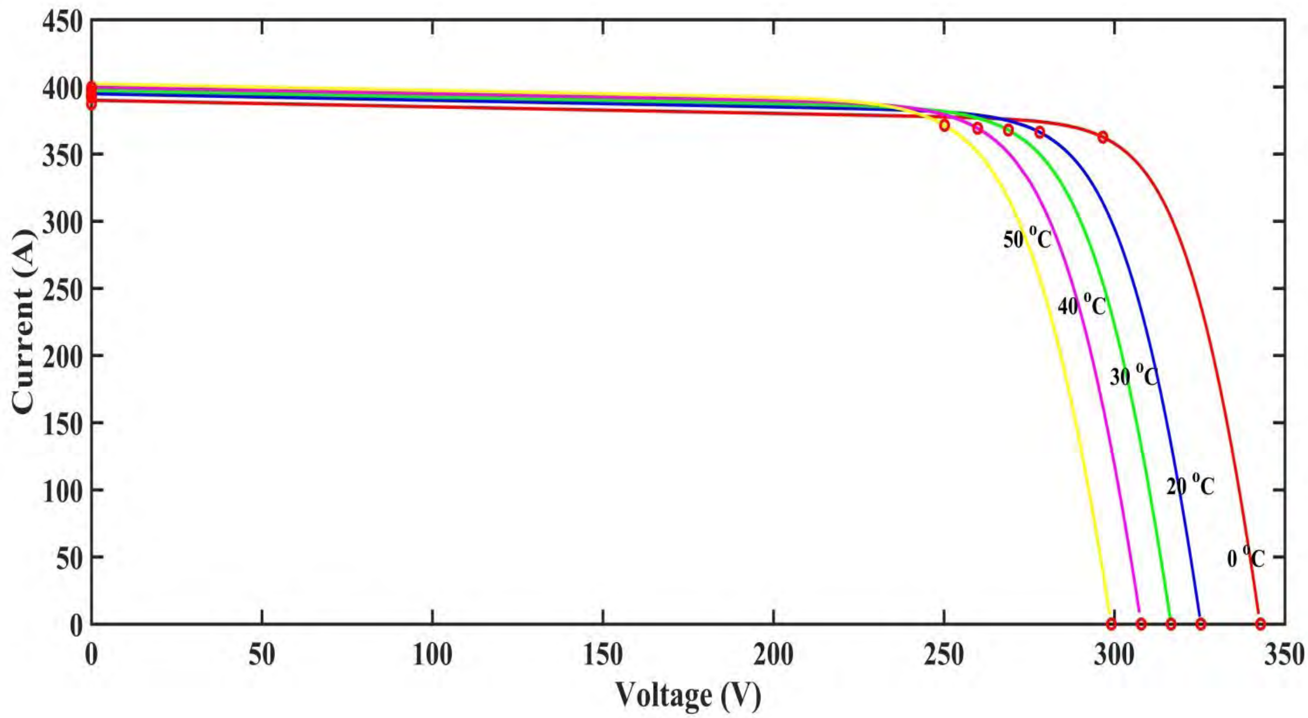



Fig. 4.3: I-V Characteristics of the PV array under varying temperature.

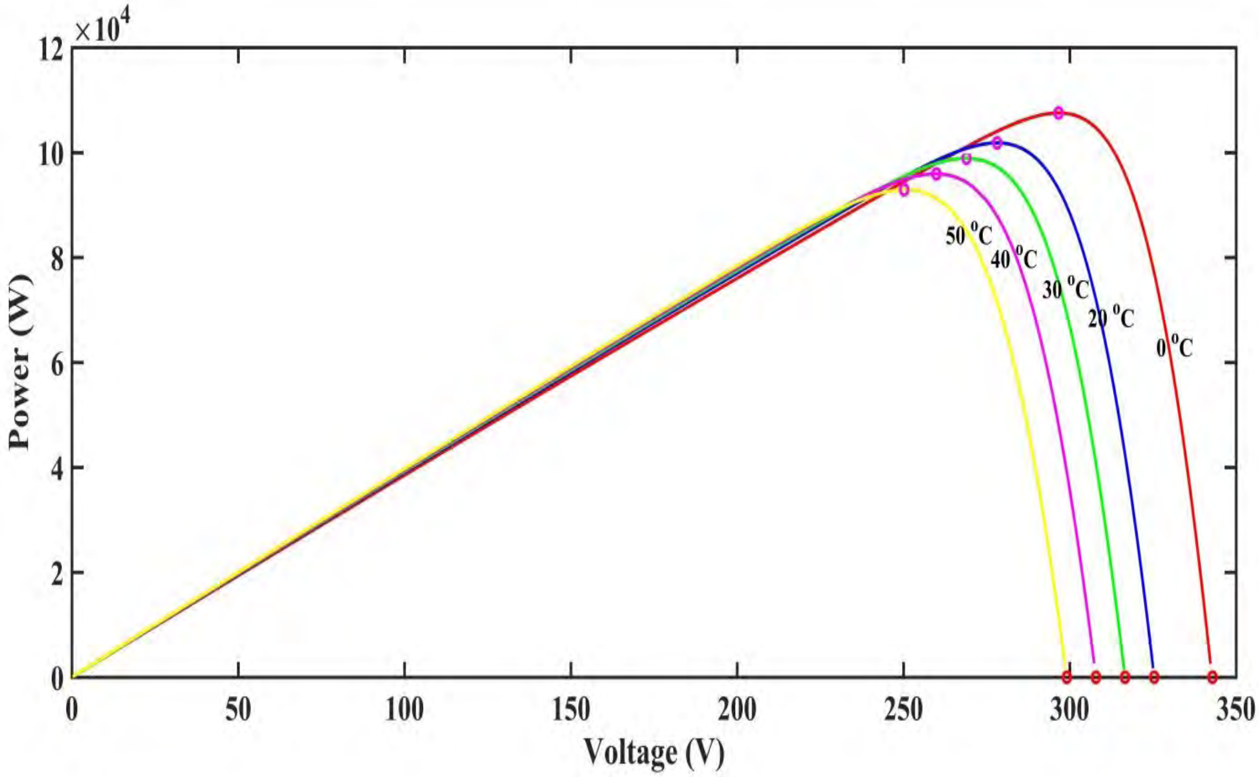



Fig. 4.4: P-V Characteristics of the PV array under varying temperature.

## 4.3 Fuzzy MPPT logic based PV system Performance

The developed model shown at chapter 3 in Fig.3.12 where fuzzy logic controller (FLC) based PV system has been tested and simulated in MATLAB environment. The PV system performance is simulated in two parts.

In part (a), the fuzzy controller performance is analyzed under various weather conditions such as variable irradiance (1000 W/m$^2$, 750 W/m$^2$, 500 W/m$^2$ and 250 W/m$^2$) and temperature (20 °C, 25 °C, 30 °C, 32 °C and 35 °C). The simulated results are analyzed the above conditions. The Fig.4.5(a) represented PV boost converter output voltage at various irradiance. The Fig.4.5(b) represented PV boost converter output current at various irradiance. The Fig.4.5(c) represented PV boost converter output power of solar irradiance changes from 250 W/m$^2$ to 1000 W/m$^2$. The output from the PV array varies to 25 kW to 101 kW respectively. The fuzzy controller output signal of boost converter duty cycle is analyzed at various weather condition shown in Fig.4.5(d) and variation of irradiance shown in Fig.4.5(e).

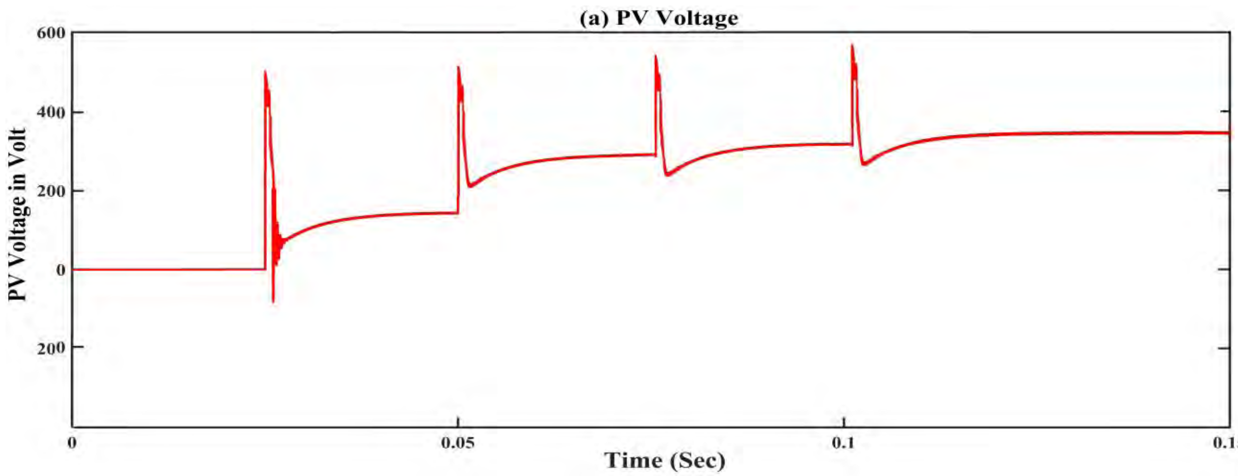



Fig. 4.5 (a): Fuzzy based 100 kW PV system output voltage at various irradiance.

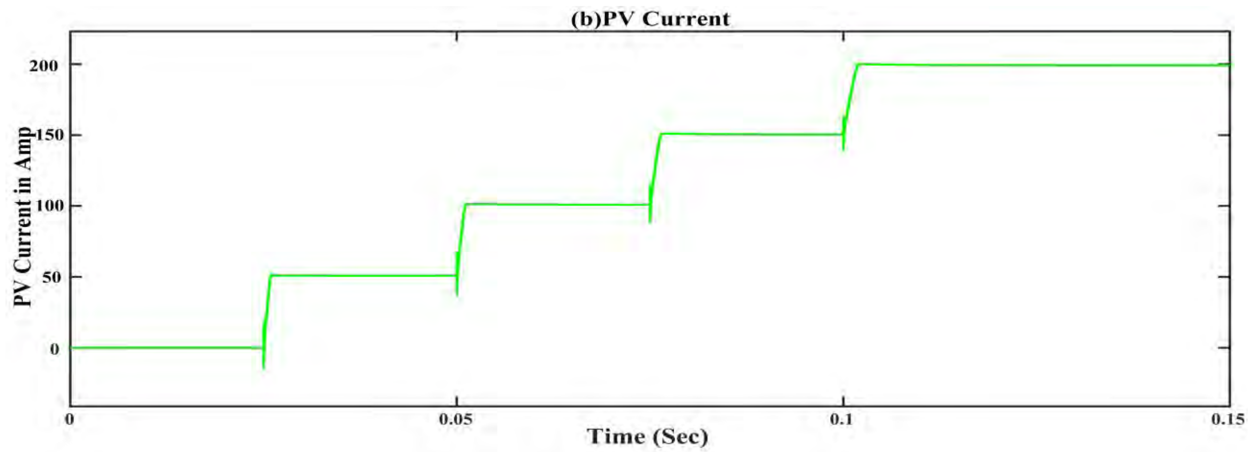



Fig. 4.5 (b): Fuzzy based 100 kW PV system output Current at various irradiance.

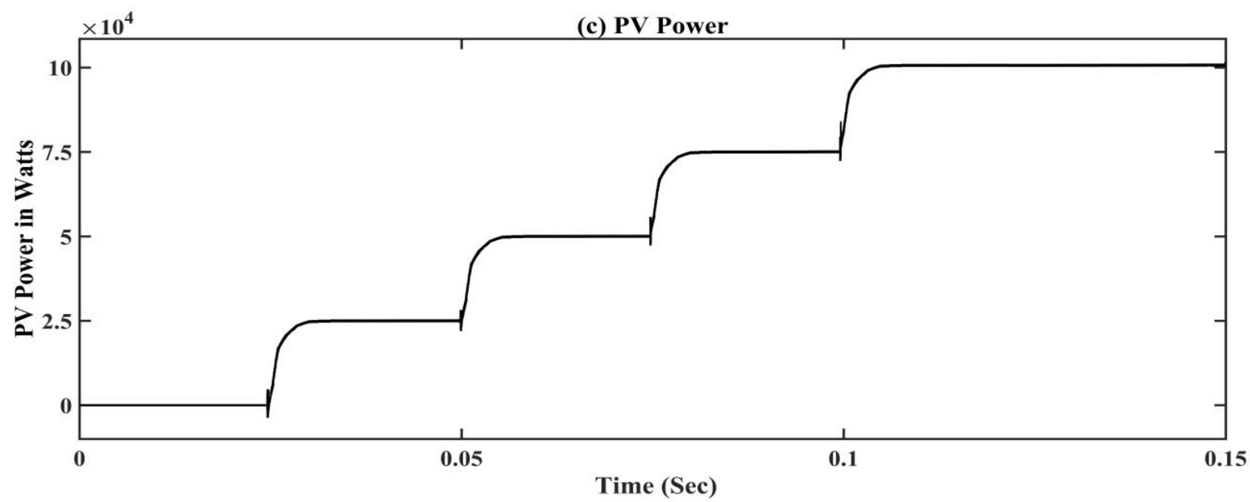



Fig. 4.5 (c): Fuzzy based 100 kW PV system Output Power at various irradiance.

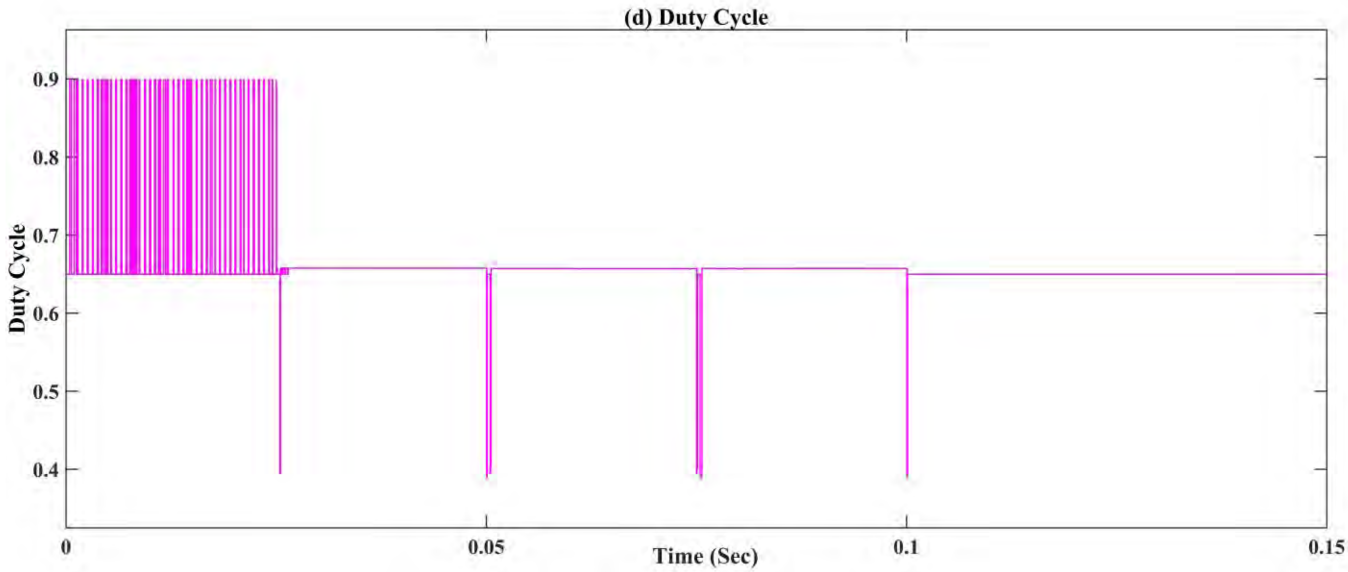



Fig. 4.5(d): Duty cycle generation at various weather condition.

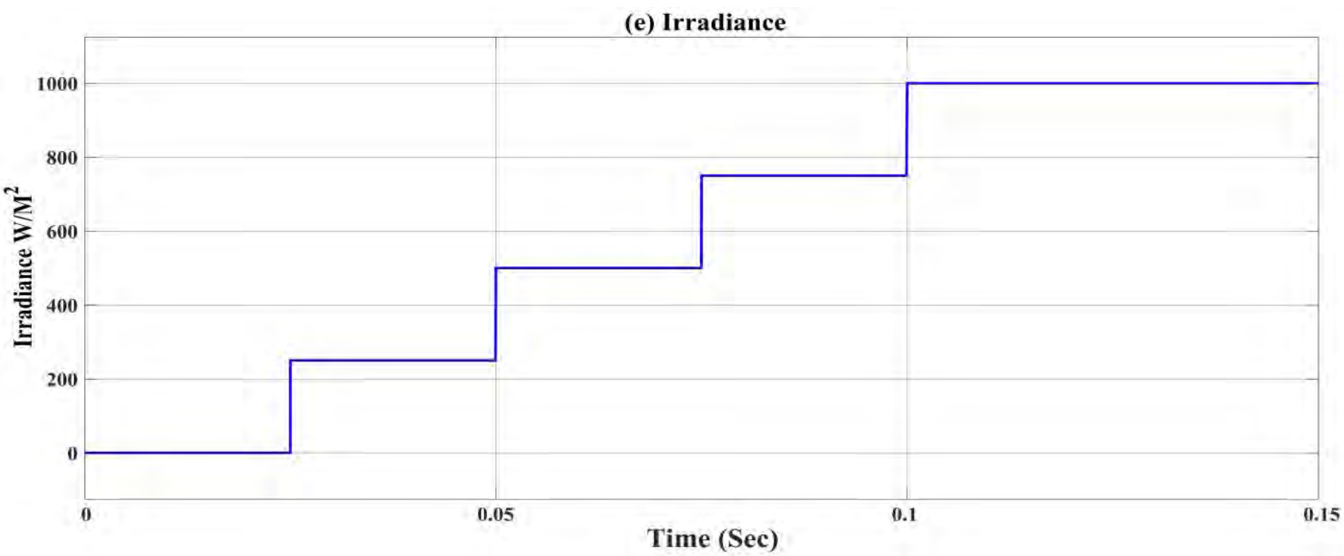



Fig. 4.5(e): Varying irradiance for PV system.

In Part (b), the proposed fuzzy logic based MPPT system has been analyzed and compared with MPPT Controller using Perturb & Observe (P&O) technique (Appendix A) and conventional Fuzzy technique [62] in two different cases.

(i) Case-1: constant irradiance (1000 W/$m^2$) and variable temperature (20 °C to 35 °C)
(ii) Case-2: constant temperature (25 °C) and variable irradiance (250 to 1000 W/$m^2$)

**Case-1:**

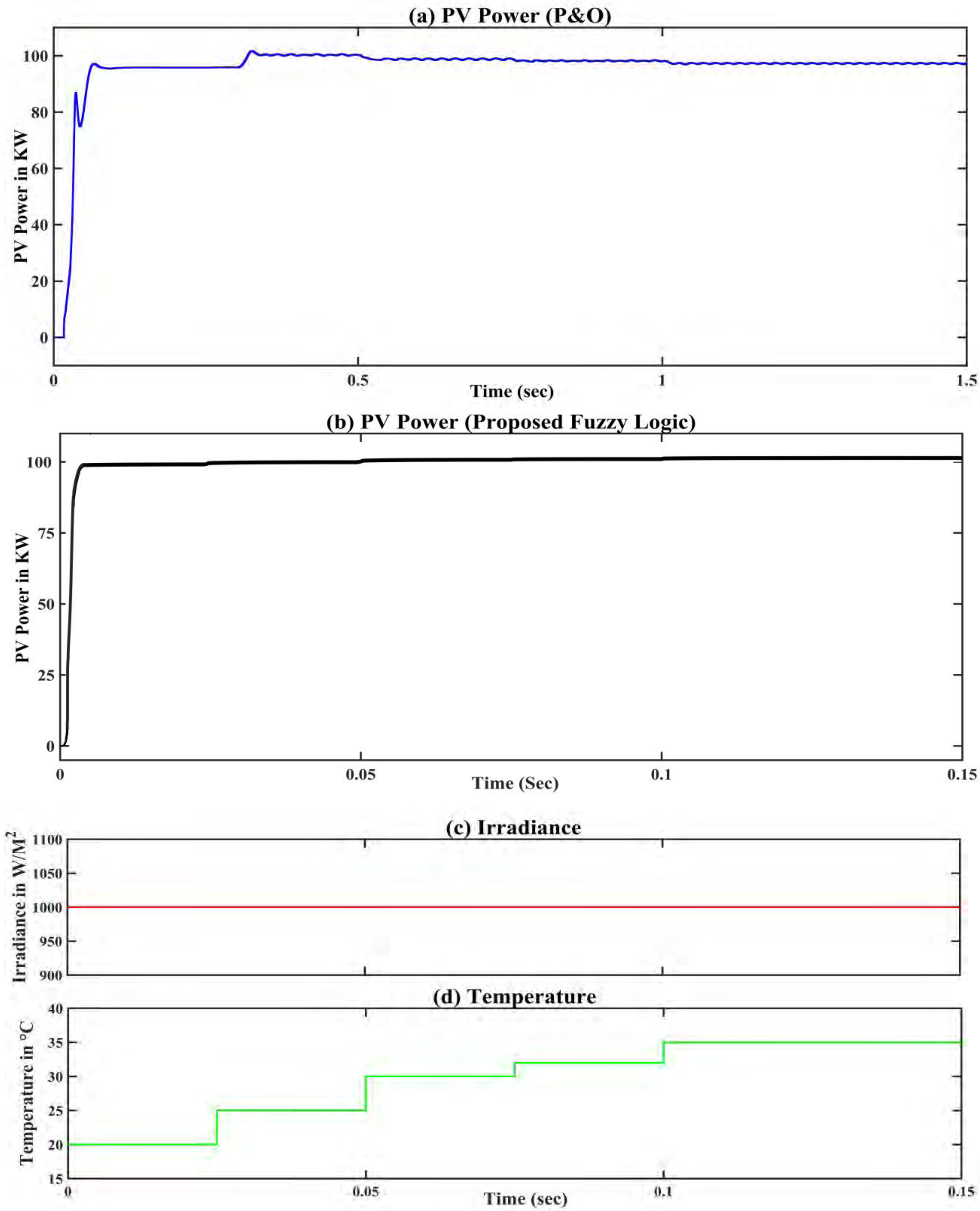



Fig. 4.6: Analysis of PV System performance at (a) P&O based PV Power, (b) Proposed Fuzzy logic based PV Power, (c) Constant Irradiation (1000 W/m$^2$) and (d) Variable Temperature.

**Case-2:**

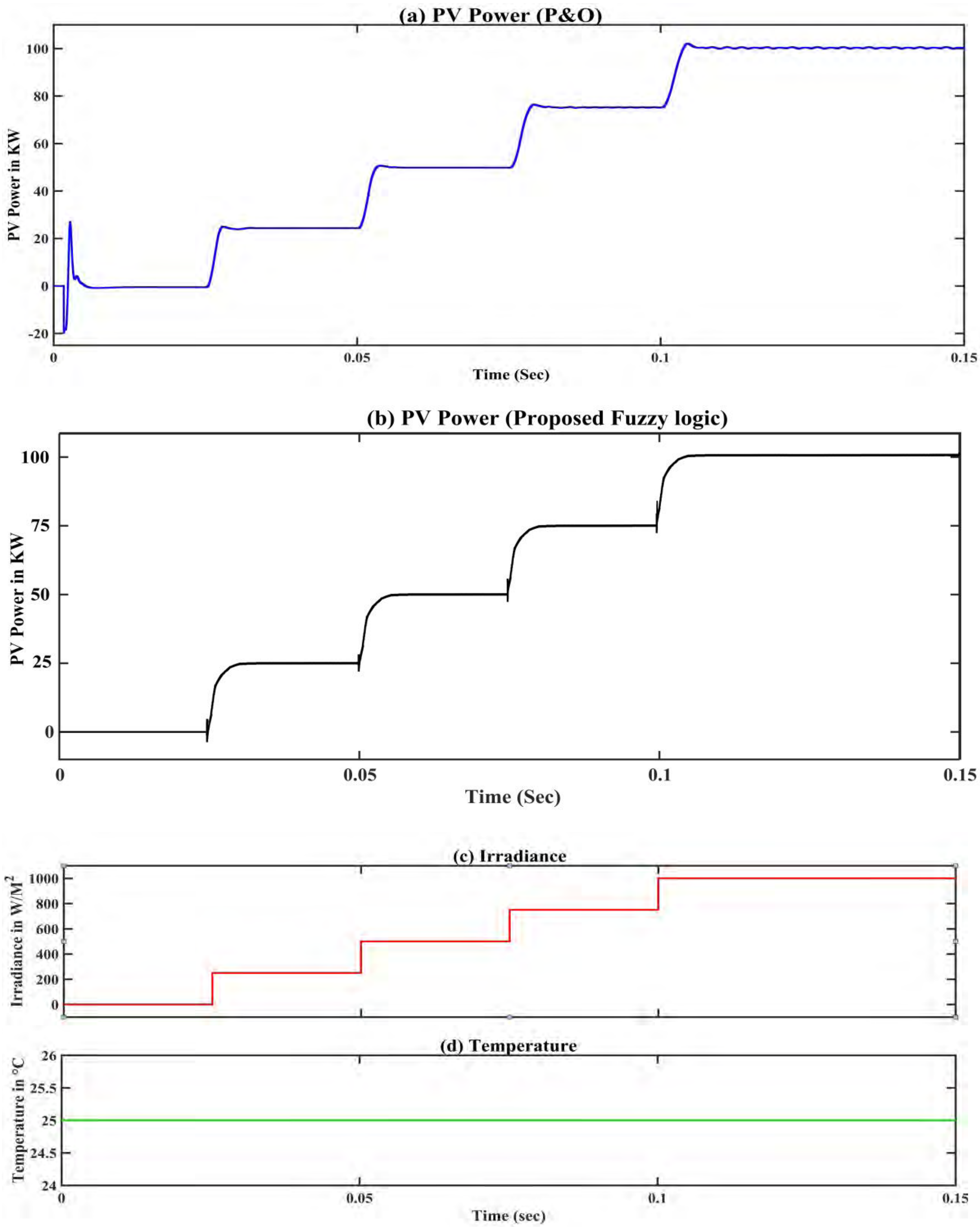



Fig. 4.7: Analysis of PV System performance at (a) P&O based PV Power, (b) Proposed Fuzzy logic based PV Power, (c) Variable Irradiation and (d) Constant Temperature (25°C).

The system is simulated at different atmospheric condition in two different cases (Case: 1 and Case: 2). The value of solar irradiation is considered as 250 W/m$^2$, 500 W/m$^2$, 750 W/m$^2$ and 1000 W/m$^2$ and the temperature is 20 °C, 25 °C, 30 °C, 32 °C and 35 °C. During the system simulation, there was some fluctuation due to the nonlinearity. It can be seen that the proposed fuzzy based algorithm shows faster response in both cases while tracking the maximum power point under variable and constant irradiance and temperature. Proposed Fuzzy based algorithm gives minimum oscillations around the final operating point compared to P&O based algorithm. It can be also seen from Fig.4.6 (a-d) and Fig.4.7 (a-d) that the P&O algorithm gives slower response as compared to the fuzzy based algorithm. Therefore the propose FLC gives relatively less oscillation and the highest response as compared to the P&O and conventional Fuzzy technique [62][63].

The performance, efficiency and tracking time of PV system in both cases of two different algorithms are summarized in Table 4.3 and Table 4.4, which show that the Fuzzy-controller is a best control system.

**Table 4.3:** Efficiency analysis comparison of Conventional P&O and Conventional Fuzzy logic Technique [62] with Proposed Fuzzy Logic Technique for PV System performance

| **Reference** | | **Theoretical Maximum Power (kW)** | **Maximum Power Reached (kW)** | | | **MPPT Efficiency (%)** | | |
|---|---|---|---|---|---|---|---|---|
| **Irradiance** | **Temp** | | **Conventional P&O Config.** | **Conventional Fuzzy Config.** | **Proposed Fuzzy Config.** | **Conventional P&O Config.** | **Conventional Fuzzy Config.** | **Proposed Fuzzy Config.** |
| 0 to 1000 | 25 | 101.805 | 100.6 | 100.724 | 101.321 | 98.82 | 98.94 | 99.52 |
| 1000 | 20 to 35 | 101.805 | 100.65 | N/A | 101.53 | 98.87 | N/A | 99.73 |

**Table 4.4:** Performance comparison of rise time and settling time of Conventional P&O and Conventional Fuzzy logic Technique [63] with Proposed Fuzzy Logic Technique for PV System performance

| **Type of Algorithm** | **Rise Time (ms)** | **Settling Time (ms)** |
|---|---|---|
| Conventional P&O controller | 6.8 | 12.6 |
| Conventional fuzzy controller | 4.9 | 8 |
| Proposed fuzzy controller | 3.52 | 6.8 |

## 4.4 Energy Management System performances for Grid connected PV System

Fuzzy based energy management system has been designed and modelled in chapter 3 for grid integrated PV power system. Aktas proposed model has lacking in voltage regulation control and bi-directional DC/DC converter [20]. In his work, there was no protection for system failure or grid fault. Proposed Fuzzy logic based battery management system minimizes voltage deviation and also provides robust response at any system failure or grid faults.

The BMS performance is simulated in two parts such as power management and fault detection. In the power management analysis, two following conditions have been taken in account for battery operation based on power management flow chart presented in Fig.3.14.

(i) Case-1: Battery will charge when PV power is greater than power demand.
(ii) Case-2: Battery will discharge when PV power is lesser than power demand.

The fuzzy controller outputs will operate the bidirectional converter switches such as Q1 and Q2. The fuzzy interference rules are formed by with respect of input values. There are two cases such as battery charging and discharging.

**(i) Case-1:** In this case PV system and BMS system are connected in parallel with utility grid and load. The PV array generates electricity at its optimum capacity of 101 kW. Here, battery will charge during PV power greater than power demand and fuzzy rules are presented in Fig.4.8.

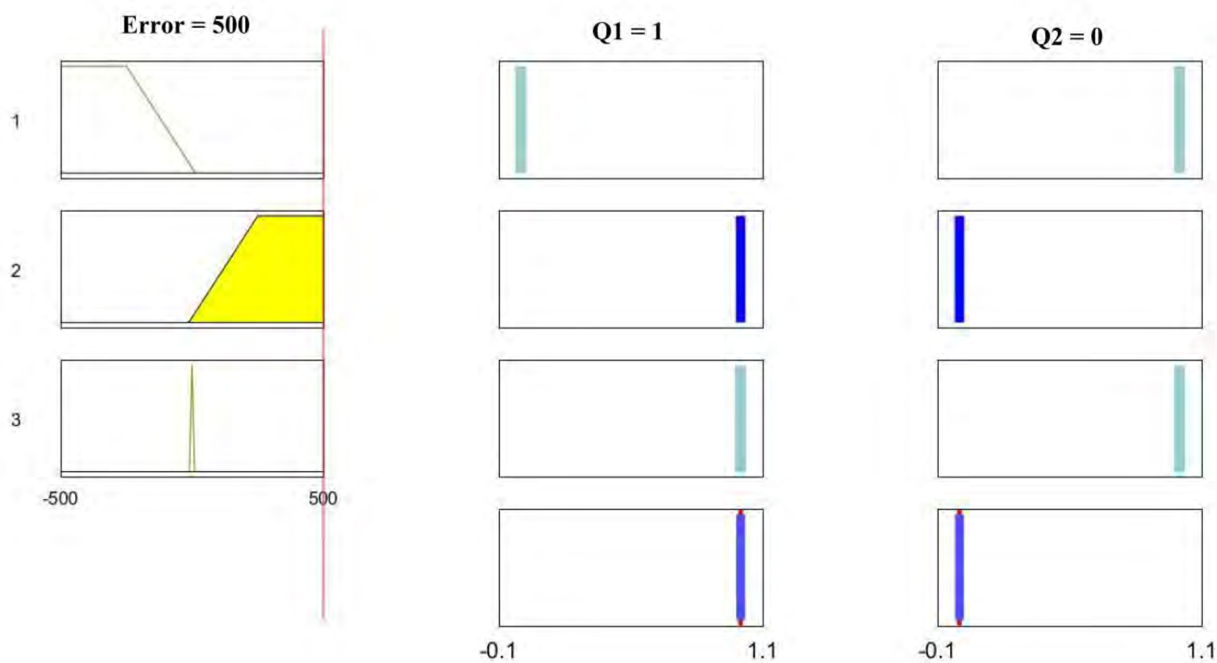
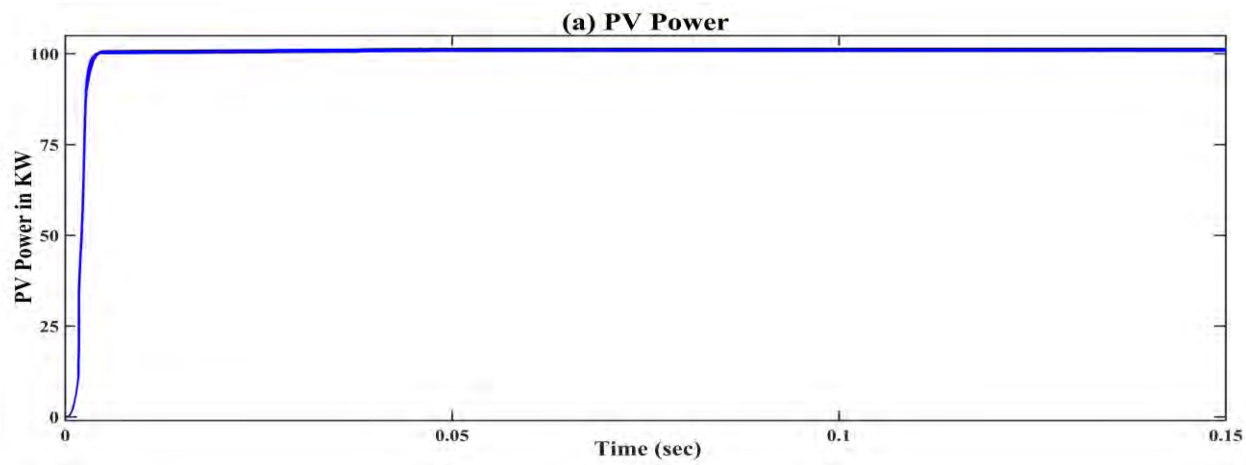
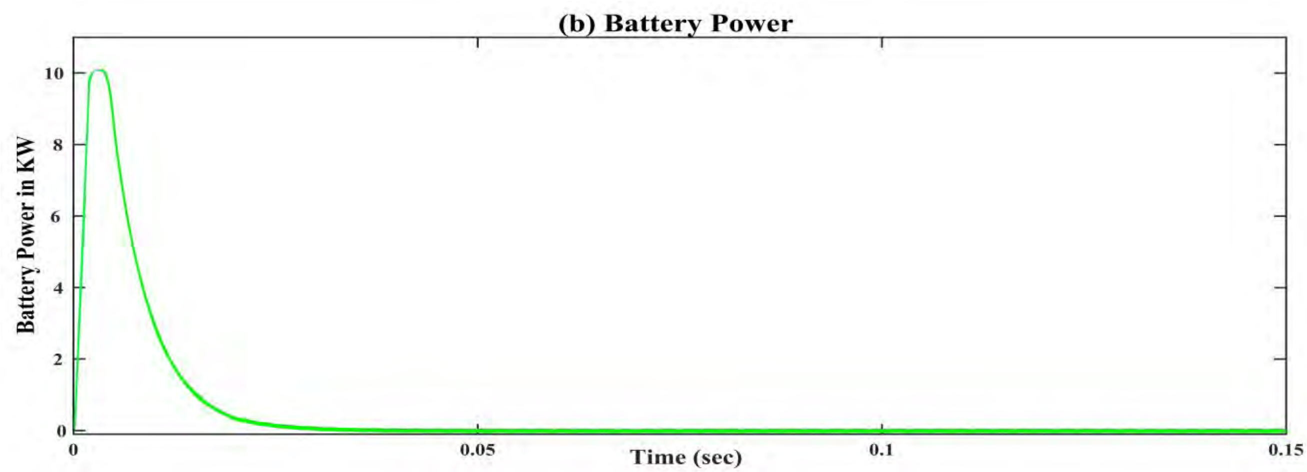
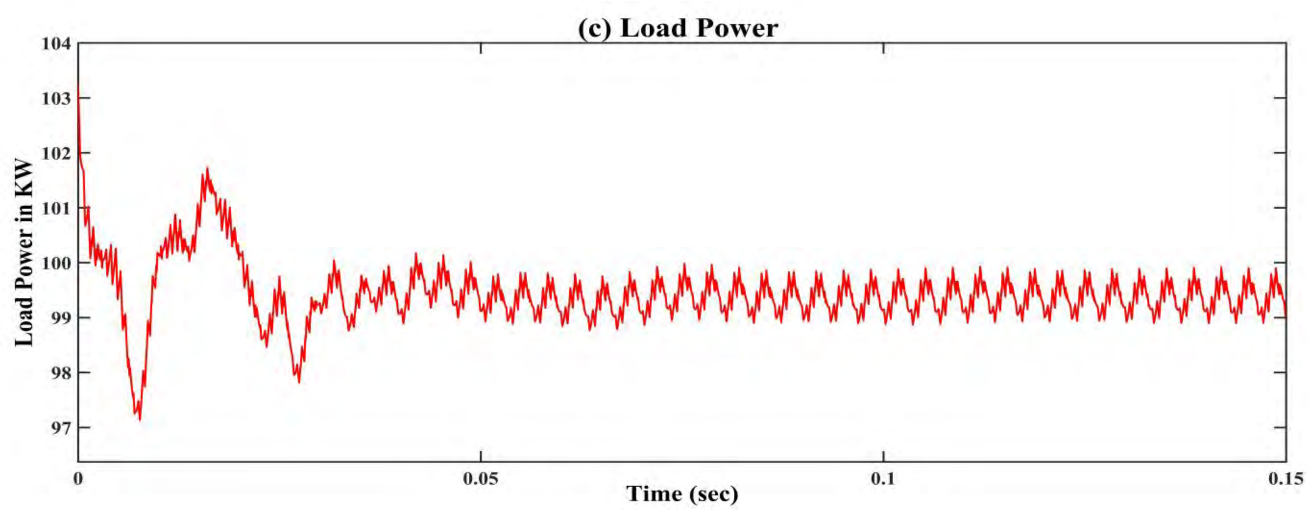



Fig. 4.8: Case-1 Fuzzy Rules for battery management system.

The power output from PV, Battery, Load (or power delivered to load) and grid shown in Fig.4.9 (a-d).



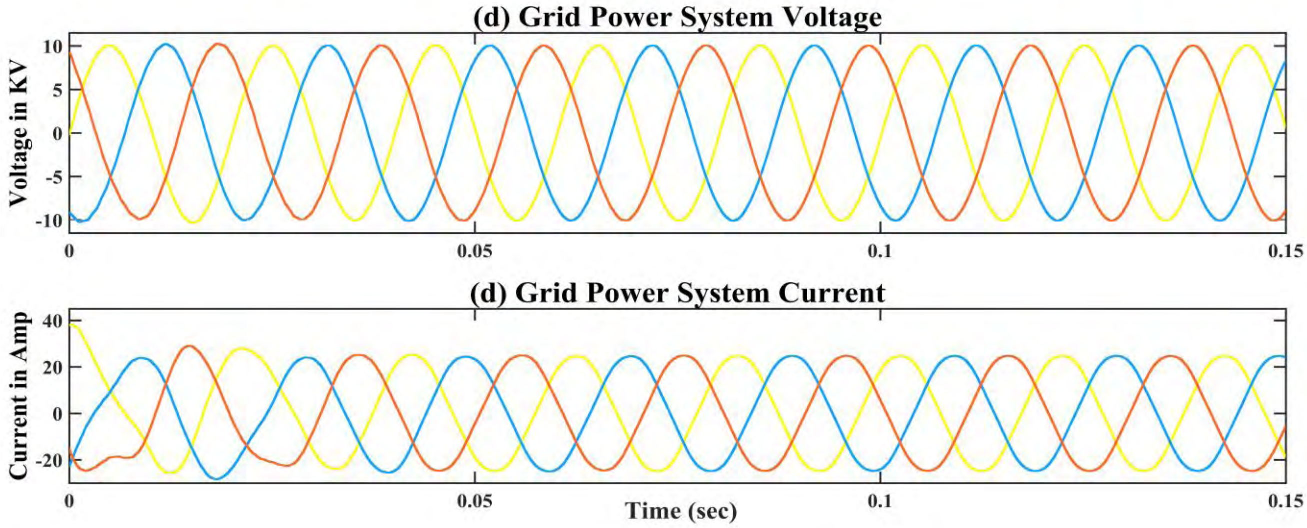



Fig. 4.9: Power Generation Waveform at constant irradiance (a) PV Power, (b) Battery Power, (c) Load Power and (d) Voltage and current waveform of Grid.

**(ii) Case-2:** In this case, simulation assumed that the PV output power fluctuates due to change in irradiance during certain intervals from 1000 W/m$^2$ to 250 W/m$^2$. To supply the required amount of power to the load, BMS delivers power to the load by discharging the battery; assume the battery was previously charged. This ensures continuous power to the load. For case-2, fuzzy rules are presented in Fig.4.10.

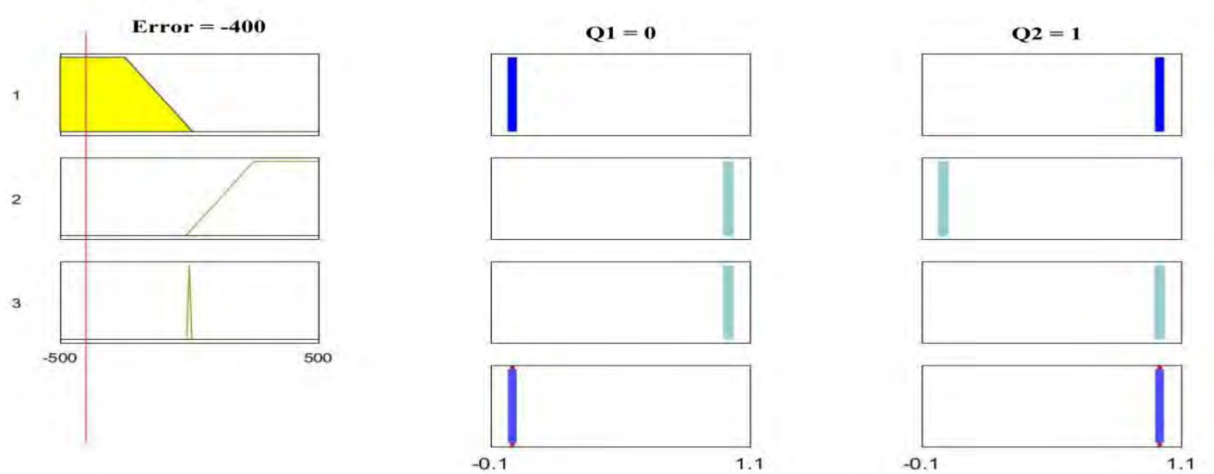
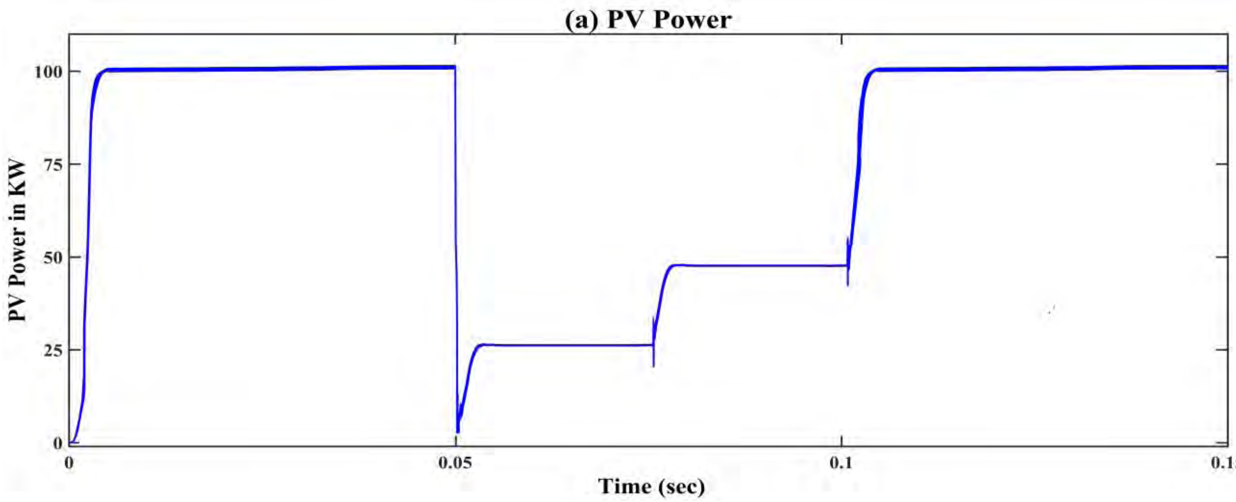
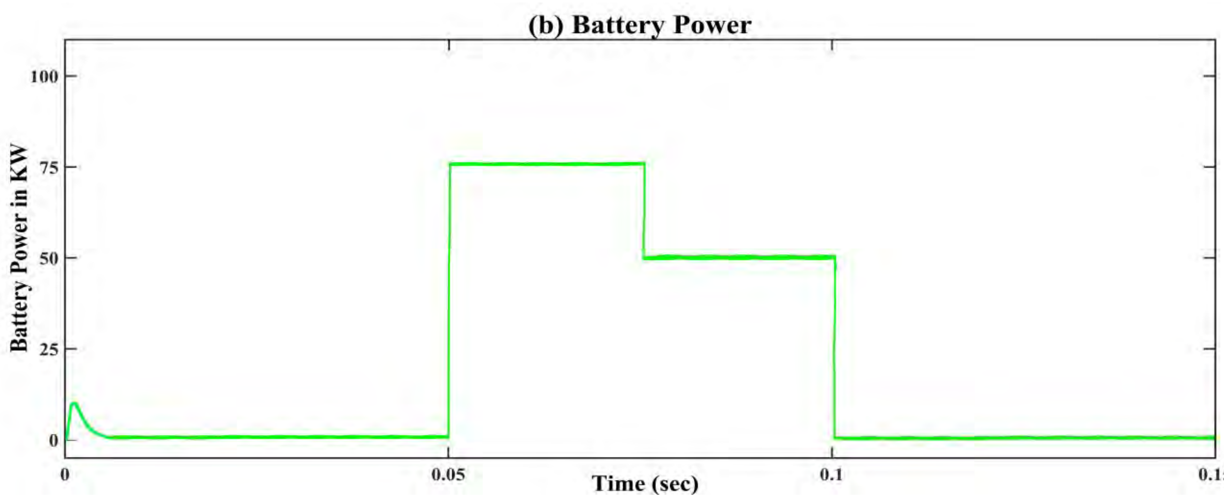
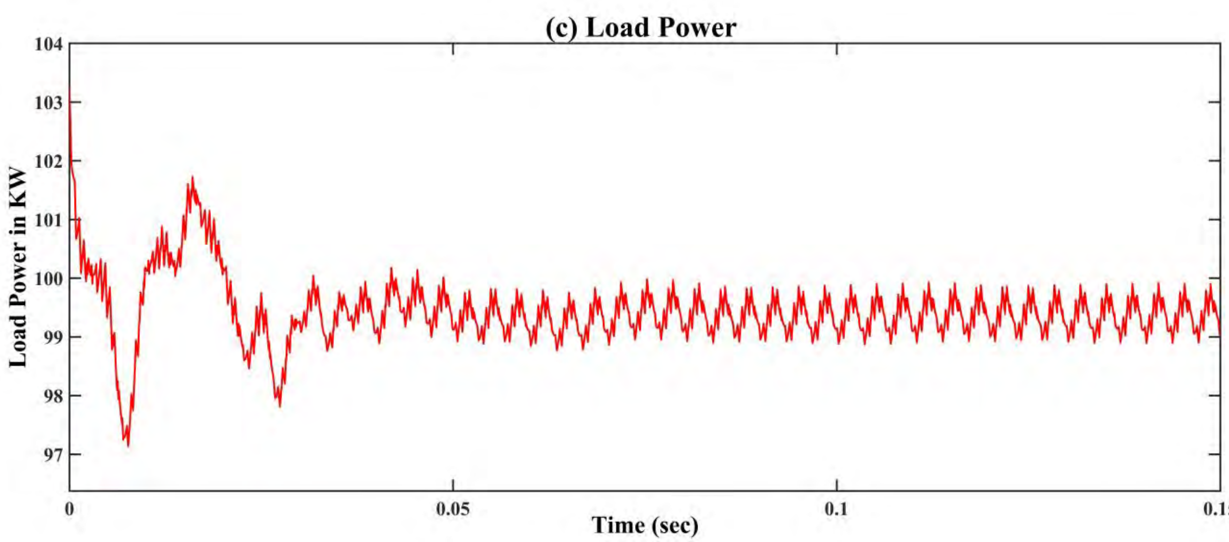



Fig. 4.10: Case-2 Fuzzy Rules for battery management system.

For Case 2, battery discharge compensates the shortfall of electricity generation by the PV array. Total load requirements are met both by the battery discharge and by the PV. Fig.4.11 (a) shows that the power generated from PV under varying irradiance pattern from t = 0 sec to t = 0.15 sec, total power delivered varies from 101 kW to 25 kW. Fig.4.11 (b) shows power drawn from the battery to supply constant power to the load. Fig.4.11 (c) shows the total power delivered to the load and Fig.4.11 (d) shows the voltage and current supplied to the grid.



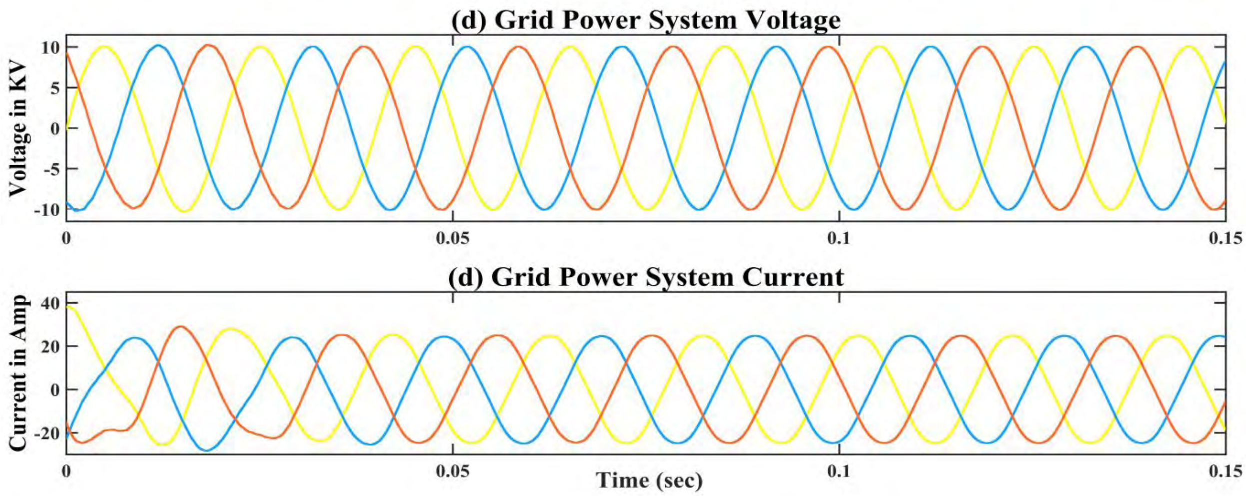



Fig. 4.11: Power Generation Waveform at variable irradiance (a) PV Power, (b) Battery Power, (c) Load Power and (d) Voltage and current waveform of Grid.

## 4.5 Fault Analysis

In this section, the fuzzy based battery management system performance has been simulated on the basis of fault detection flow chart shown in Fig.4.12 under different fault conditions such as

a) Line to ground fault (L-G)
b) Line to line fault (L-L)
c) Double line to ground fault (L-L-G)

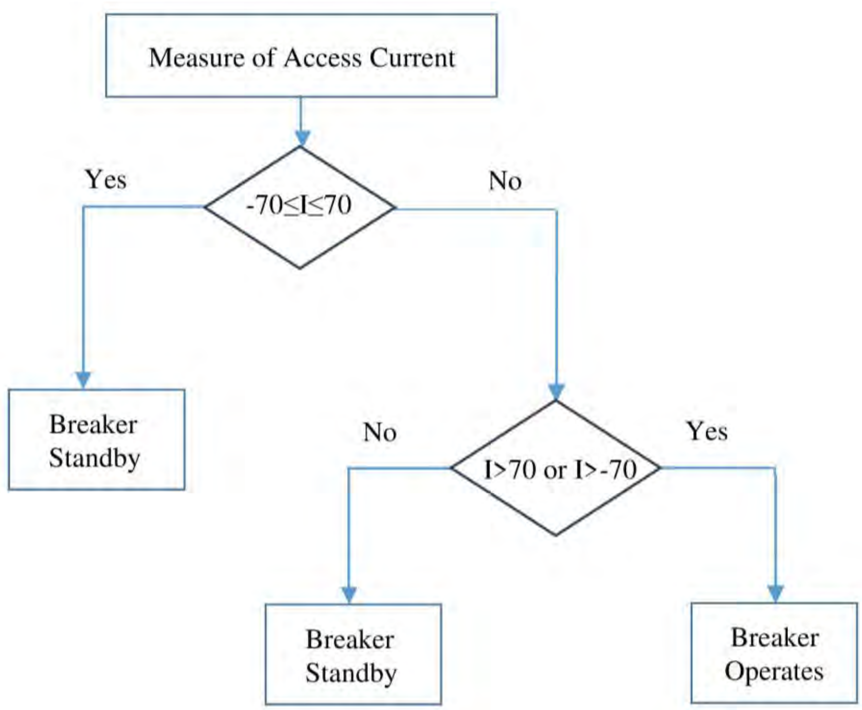



Fig. 4.12: Fault detection flow chart.

The simulation is accomplished under nominal condition irradiance (250 W/m$^2$, 500 W/m$^2$, 250 W/m$^2$ and 1000 W/m$^2$) and temperature (20 °C, 25 °C, 30 °C, 32 °C and 35 °C). As shown in Fig.4.13 the fault is applied on the grid side. The fault duration is 0.01 seconds from 0.06 to 0.07 seconds. All types of faults will be discussed under the same condition while applying Fuzzy based technique.

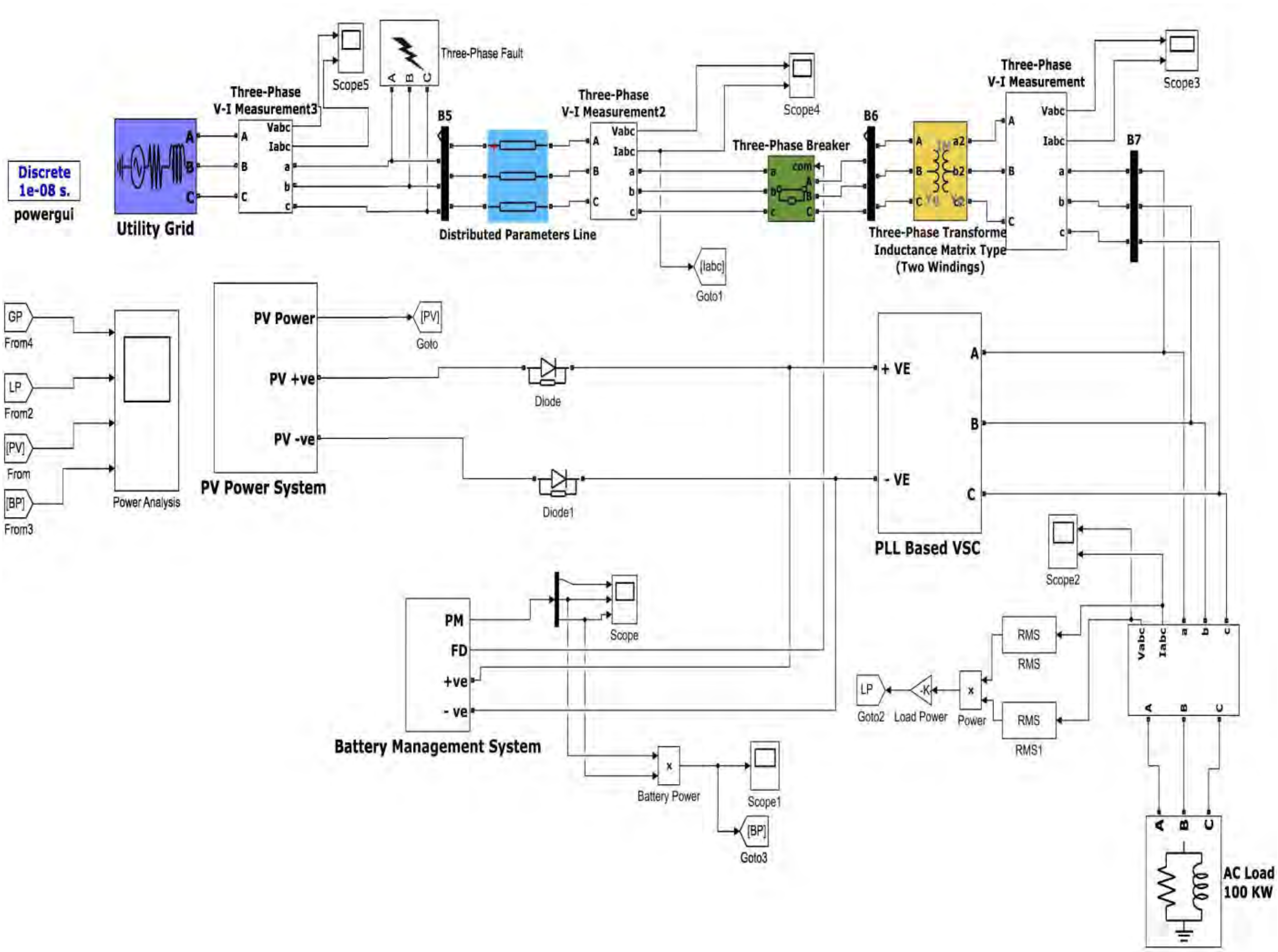



Fig. 4.13: Fault Analysis of Grid connected proposed model.

### 4.5.1 Line-to-Ground Fault

The model shown in Fig.4.13 is simulated while applying single line to ground fault (L-G) on phase A. The output voltage and current at the point of common coupling PCC is shown in Fig.4.14.

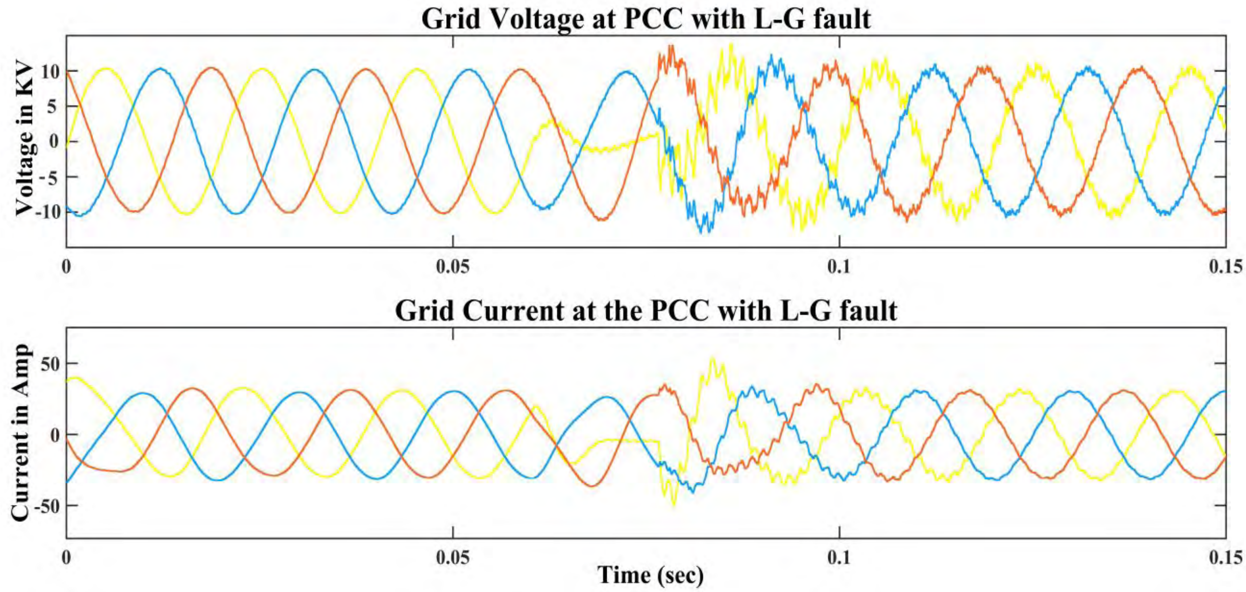



Fig. 4.14: Output Voltage and current at the PCC with L-G fault (with EMS).

In the same model without considering BMS simulation is done while applying single line to ground fault (L-G) on phase A. The output voltage and current at the point of common coupling PCC is shown in Fig.4.15.

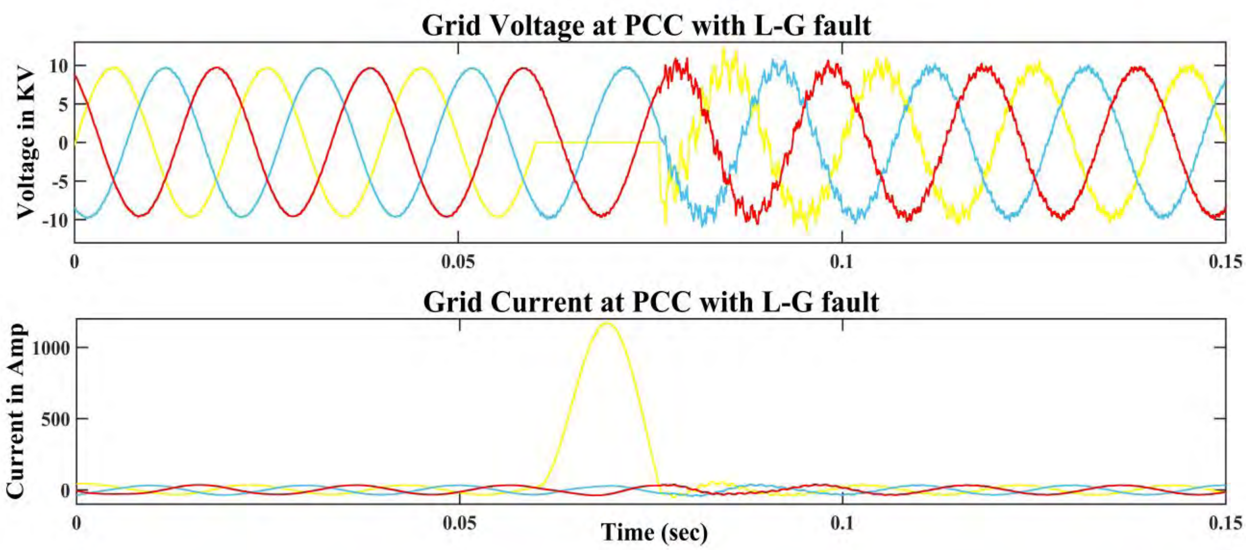



Fig. 4.15: Output Voltage and current at the PCC with L-G fault (without EMS).

### 4.5.2 Line-to-Line Fault

The model shown in Fig.4.13 is simulated while applying single line to line fault (L-L) on between phases A and B. The output voltage and current at the point of common coupling PCC is shown in Fig.4.16.

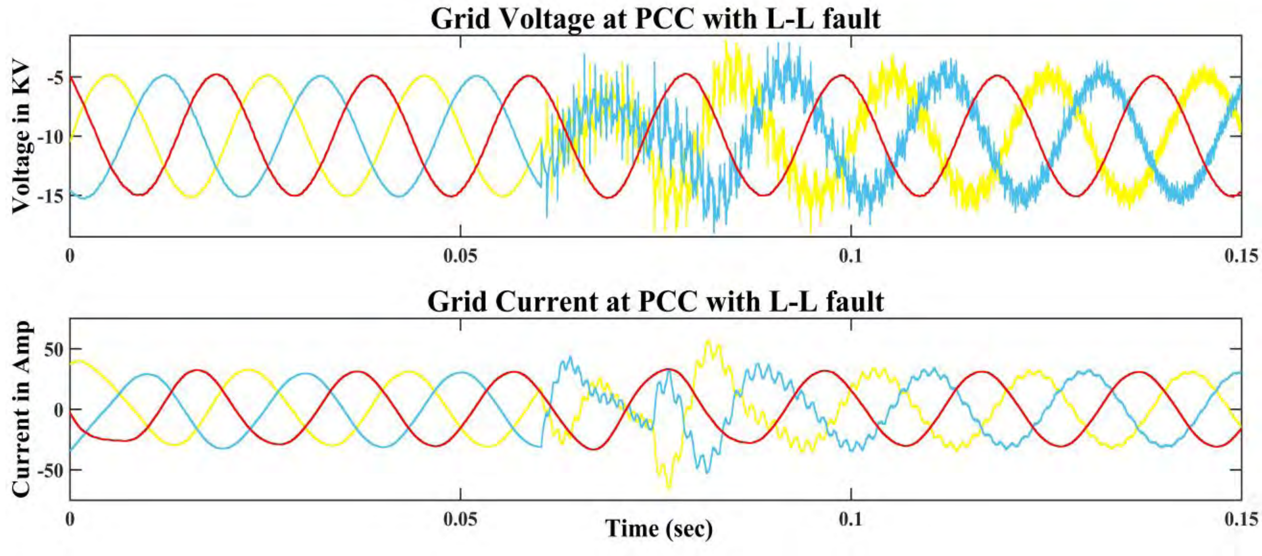



Fig. 4.16: Output Voltage and current at the PCC with L-L fault (with EMS).

Similar simulation is done without considering BMS while applying single line to line fault (L-L) on between phases A and B. The output voltage and current at the point of common coupling PCC is shown in Fig.4.17.

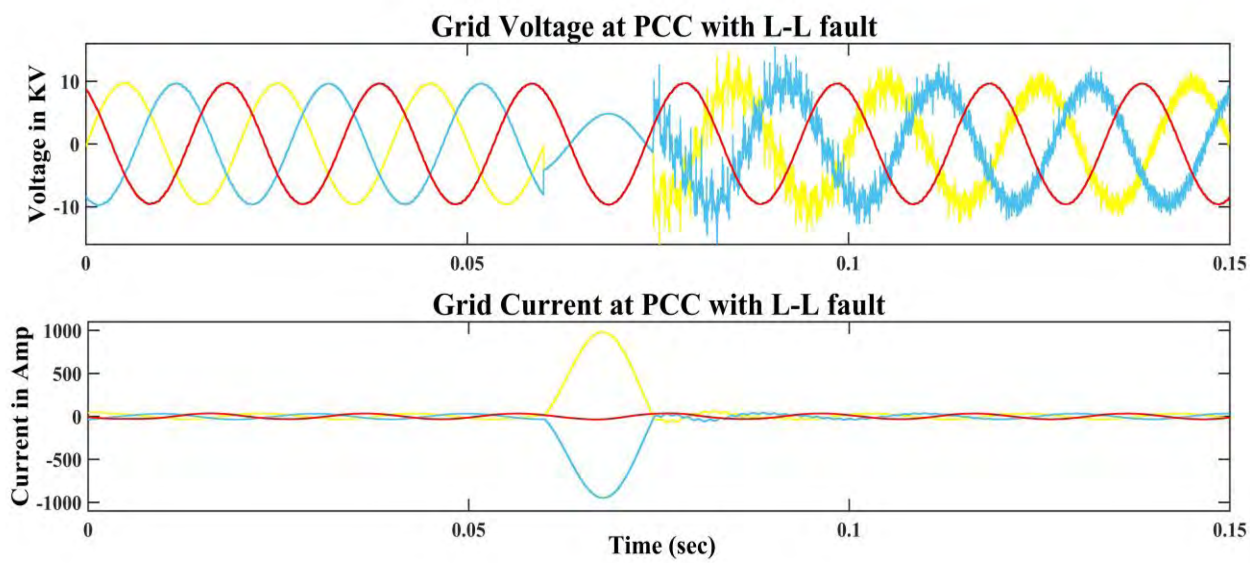



Fig. 4.17: Output Voltage and current at the PCC with L-L fault (without EMS).

### 4.5.3 Double Line-to-Ground Fault

The model shown in Fig.4.13 is simulated while applying double line to ground fault (L-L-G). The output voltage and current at the point of common coupling PCC is shown in Fig.4.18.

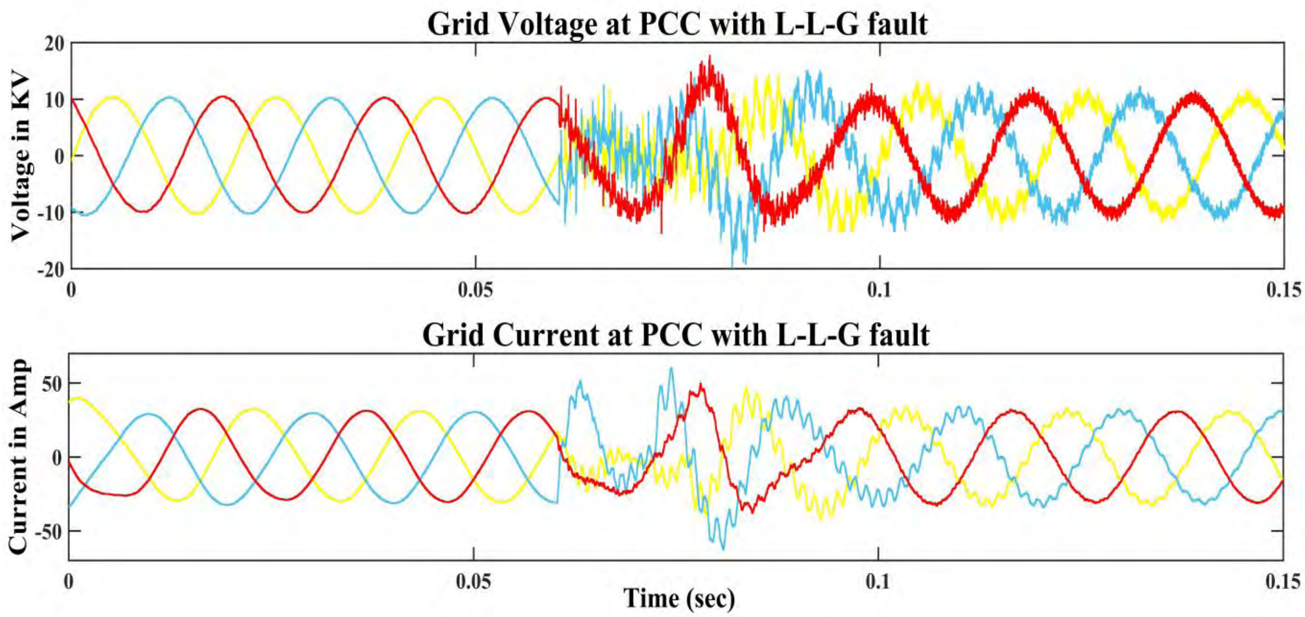



Fig. 4.18: Output Voltage and current at the PCC with L-L-G fault (with EMS).

Similar simulation is done without considering BMS while applying double line to ground fault (L-L-G). The output voltage and current at the point of common coupling PCC is shown in Fig.4.19.

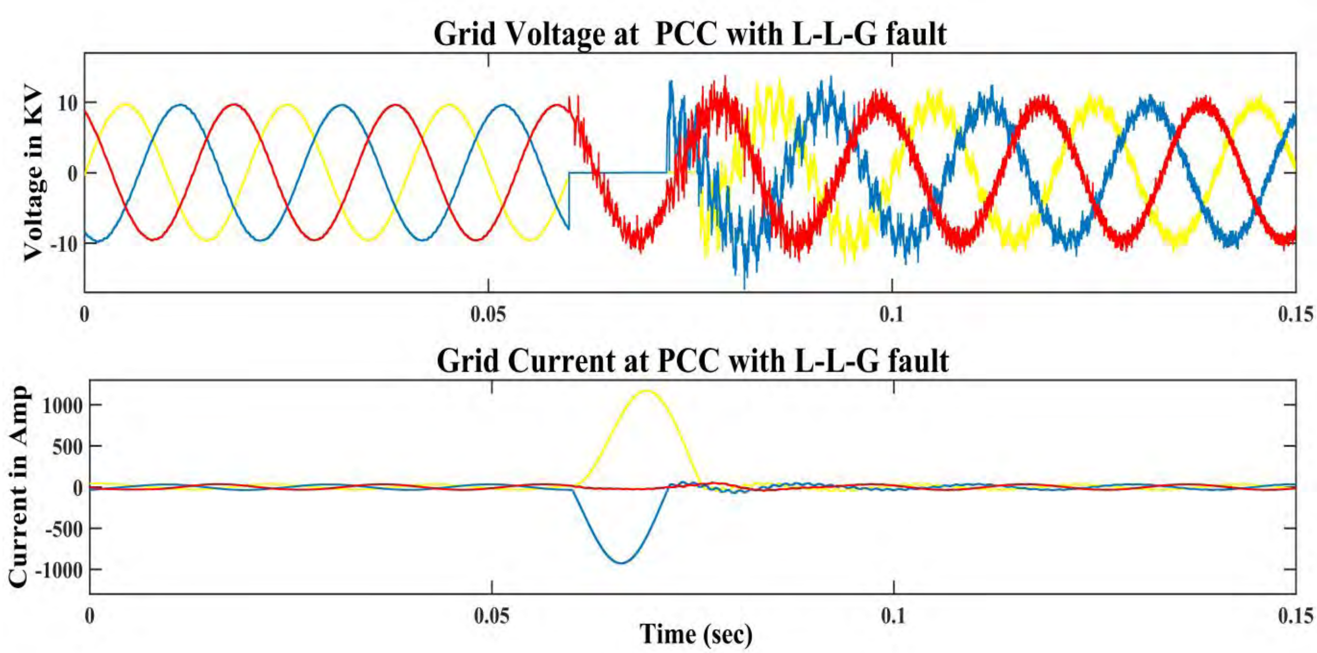



Fig. 4.19: Output Voltage and current at the PCC with L-L-G fault (without EMS).

## 4.6 Discussion

From the simulation results, it is clear that the proposed fuzzy logic for tracking maximum power shown better performance than conventional P&O and conventional fuzzy method. The study showed that PV with BMS is a feasible approach to provide electric power to a load consistently in different irradiance conditions. Simulation results exhibited a performance improvement over that of a PV system only that does not have any batteries. Further improvement in the controller of the BMS has been a suggestion to improve the overall power quality of proposed model. The propose model showed better performance in different fault conditions compare to without BMS. The simulation results provided in the thesis are taken for a short period of time because MATLAB takes a long time to run the simulation. But it provides the analogy with original changes in the atmosphere.

CHAPTER 5

# Conclusion and Future Works

## 5.1 Conclusion

This chapter summarizes the central features of this research and its outcomes. This is followed by the plan for future research work. The MATLAB/Simulink environment has been used in this thesis to carry out a wide range of simulations of the grid integration of PV power system with intelligent controller based energy management and improve the power quality.

The proposed algorithm of fuzzy logic controller (FLC) is designed to maximize the energy received from solar cells by tracking the maximum power point with a boost-type DC-DC converter to keep the PV output power at the maximum point all the time. This controller was tested using P&O and fuzzy logic through Matlab/Simulink software. It was also evidenced that in the presence of variations in solar irradiance the two controllers presented a good performance and extracted the maximum power according to the electrical characteristics of the PV module. The comparison shows that the fuzzy logic based controller was faster response in tracking the maximum power point under variable and constant irradiance and temperature gives minimum oscillations around the final operating point compared to the P&O algorithm.

The fuzzy based energy management system is developed and tested under various power demand then analysis operation of battery charging and discharging. The designed EMS model comprises the battery pack, a buck-boost bi-directional DC/DC converter, three-phase VSC-type DC/AC inverter and its coupling transformer to connect to a load point and a point of common coupling of an equivalent power grid. The results show that when the output power of the PV system fluctuates or when it provides less power than that required by the load, the BMS system compensates the defaulted power by discharging the right amount of power to provide a constant power supply to the load. On the other hand, when the PV system generates more power than that required by the load, the BMS system absorbs the power surplus to replenish its storage capacity and thus to be able to compensate for future power defaults by the PV system. Finally, the simulation results under different fault conditions show that, the output power injected to grid from PV array is approximately constant while utilizing the proposed FLC and the PV system can still connect to grid and deliver power to grid without any damage.

## 5.2 Future Work

The contributions of this thesis indicate the opportunities of extending this work in future to meet other goals. The scopes for future works are:

(i) In this thesis work only simulation is done via Matlab/Simulink. Implementation of a physical model for the fuzzy logic controller technique based MPP using microprocessor or microcontroller and testing it on a real PV panel. The most popular method of implementing fuzzy controller is using a general-purpose microprocessor or microcontroller. The changes in the environmental conditions assumed in this work are very fixed; future work should consider more realistic environmental scenarios of solar radiation and temperature on the PV panel and a measured daily demand curve at point of common coupling, where the load point is.

(ii) The performance of the EMS should be assessed during change of load conditions on the DC circuits and in the AC circuit. More stability study and analysis can be done on the fault conditions.

(iii) In VSC, current regulator's Proportional Integral (PI) controller can be improved by using fuzzy logic. This integration in PLL based VSC will reduce the deviation and power quality can be improved applying fuzzy logic in inverter control.

(iv) There is scope of study to ingrate PV power generator along with wind, fuel cells and small hydro system by establishing proper interfacing and controllers.

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# Appendix A

## Matlab Code :

### Code of Perturb and Observe Algorithm

```
function D  = PandO(Param, Enabled, V, I)

% MPPT controller based on the Perturb & Observe algorithm.

% D output = Duty cycle of the boost converter (value between 0
and 1)
%
% Enabled input = 1 to enable the MPPT controller
% V input = PV array terminal voltage (V)
% I input = PV array current (A)
%
% Param input:
Dinit = Param(1);  %Initial value for D output
Dmax = Param(2);   %Maximum value for D
Dmin = Param(3);   %Minimum value for D
deltaD = Param(4); %Increment value used to increase/decrease
the duty cycle D
% ( increasing D = decreasing Vref )
%
persistent Vold Pold Dold;

dataType = 'double';

if isempty(Vold)
    Vold=0;
    Pold=0;
    Dold=Dinit;
end
P= V*I;
dV= V - Vold;
dP= P - Pold;

if dP ~= 0 & Enabled ~=0
    if dP < 0
        if dV < 0
            D = Dold - deltaD;
        else
            D = Dold + deltaD;
        end
    else
```

```
        if dV < 0
            D = Dold + deltaD;
        else
            D = Dold - deltaD;
        end
    end
else D=Dold;
end

if D >= Dmax | D<= Dmin
    D=Dold;
end

Dold=D;
Vold=V;
Pold=P;
```