



SOLAR/GRID HYBRID POWER OPTIMIZATION USING FUZZY LOGIC FOR LIGHT RAIL  
TRAINS IN ADDIS ABABA

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# SOLAR/GRID HYBRID POWER OPTIMISATION USING FUZZY LOGIC CONTROLLER FOR LRT of ADDIS ABEBA

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This is to certify that the thesis prepared by Birhan Gebrekirstos, entitled: Solar/grid hybrid optimization using fuzzy logic for Light Rail Trains of Addis Ababa and submitted in partial achievement of the requirements for the degree of Master of Sciences in Control System Engineering complies with the regulations of university and meets the accepted standards with respect to originality and quality.

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## **Declaration**

This thesis is a presentation of my original research work. Where ever contribution of others is involved, every effort is made to indicate this clearly, with proper citation of sources. I, the under signed, declare the thesis has not been presented for degree in any other university.

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Birhan.Gebrekrstos

### **Acknowledgment**

First, I would like to thank my GOD for everything. I would like to thank my advisor Dr. Dreje Shiferaw for his positive feedbacks, support and motivation. Next, I would like to thank my families, good friends and colleague for their undeniable comments and motivation. Finally, I would like to thank all those open source code providers and models for laying the foundation in implementing optimization algorithm.

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## List of Abbreviations

MPPT	maximum power point tracking
MPP	maximum power tracking
ICE	internal composition engine
SOC	state of charge
EMS	energy management system
LRT	light rail train
PV	photovoltaic
DC	direct current
AC	alternative current
ESS	energy storage system
DOD	depth of discharging
PWM	pulse width modulation
GHG	greenhouse gas
PHP	power hybridization potential
EMI	electromagnetic interference

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## **Abstract**

The idea of powering railway locomotives using green energy is one that could, theoretically, reduce or save power from grid supply in Ethiopian railway sector. Solar Energy is one method of conserving energy in rails and regenerative braking other method. We can also combine the two for maximum optimization. In this thesis is to assess the technical feasibility of employing solar power combined with grid supply in Addis Ababa light railway vehicle that could reduce consumption of power from grid supply. This is meant to serve as reference to future work regarding the cost-benefit analysis that employs this power source option.

This thesis presents a design of grid-solar hybrid system for powering auxiliary system of Addis Ababa Light Train. The power management system consists of a PV and auxiliary power box of the train of the LRT powered by grid (pantograph) to replace or use solar panels on the roof of the train to reduce power consumption, considering variation in the load and solar radiation. The proposed system aimed to minimize the power drawn from the grid and operate the PV within a specific power range and also maximum power point tracker will be used in order to get the best out of PV. It provides theoretical studies of photovoltaic systems and modeling techniques using equivalent electric circuits.

As the system employs the maximum power point tracker (MPPT), it is consisting of MPPT algorithms, control methods and MATLAB simulations verify the DC-DC converter design. The power management involves the control of power where a proportional and Fuzzy based integral (PI) controller is used. A fuzzy logic controller is also developed to generate appropriate control parameters. MATLAB modeling and simulation of the whole system will be done and result will be discussed.

## **CHAPTER ONE**

### **INTRODUCTION**

#### **1.1 Background**

A light weight metropolitan electric railway system is characterized by its ability to operate single cars or short trains along exclusive right-of-way at street level [12]. These vehicles are usually powered by overhead electrical wires, and offer a frequent, fast, reliable, comfortable and high quality service that is environmentally sustainable [1].

Solar energy is one of the most important renewable energy sources that have been gaining increased attention in recent years. Solar energy is plentiful; it has the greatest availability compared to other energy sources. The amount of energy supplied to the earth in one hour by the sun is sufficient to power the total energy needs of the earth for one year [2]. Solar energy is clean and free of emissions, since it does not produce pollutants or by-products harmful to nature.

Railway propulsion technology has developed tremendously since the introduction of the first steam engine [7]. The use of liquid fossil fuels in internal combustion engines enabled faster and more reliable operation. Very powerful trains that could haul hundreds of people and tones of goods were manufactured. Unaware of their impact on the environment, governments started competing in building an increasing number of complex and innovative railroad networks. That leads the development of diesel trains.

Due to their characteristics of noisy, pollutant emitting, and very hazardous, the diesel train did not survive for long. Its replacement, the diesel-electric train promised better traction, safer operation, higher efficiencies and reduced emissions. Unlike diesel trains that have a mechanical coupling between the diesel engine and the wheel sets, diesel-electric trains have an electromechanical coupling. While still having a diesel engine as the prime-mover, diesel-electric trains depended on electric motors for traction. Mechanical energy produced by the diesel engine is converted to electrical energy by an on-board generator (alternator), which is

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then converted to mechanical energy at the wheels by electric traction motors. This arrangement improved the overall reliability of trains, and drastically reduced the cost of maintenance.

The next big step in railway emission reduction was the full electrifications of railroads. Fully electrified railway systems were cleaner than diesel-electric trains. They were also quieter, faster, safer and much more reliable. Having a train directly connected to the electricity grid enabled it access to a practically unlimited power supply, and also improved its acceleration. However, the cost of complete electrification remained prohibitively high in a majority of cases. Recent developments in energy storage system (ESS) technology prompted research in hybrid electric power trains for railway vehicles. Electrical ESS such as batteries and super capacitors can be placed on-board locomotives or motive units, and are able to store braking energy that is otherwise lost as heat when using frictional brakes [11].

They are typically needed for two reasons:

- 1) To provide the needed power for high acceleration rates,
- 2) To more efficiently absorb regenerated energy during braking.

According to the literature reviewed, hybrid electrical ESS have so far been used to reduce the overall energy consumption of fully electrified railways. A hybrid powertrain is one where more than one type of power source is employed. The inherent properties of power sources and the type of load influence the need for hybridization, the type of hybrid system, and the degree of hybridization. In particular, load dynamics and power source energy density are the main factors when it comes to decisions regarding hybridization. Typically, hybrid systems are employed as an attempt to optimize certain parameters including, for example: power train efficiency, range of travel, acceleration, regenerative braking, and emissions. Like any optimization problem, the optimization of hybrid ESS is subject to several physical and operational constraints. Physical constraints, such as mass and volume limits, are the only constraints considered in this study. The work presented in this thesis explains alternative power sources and the importance of solar power as an alternative power source. In particular feasibility study on power management system on solar/grid hybrid power supply system for auxiliary units of ADDIS ABABA LIGHT RAIL TRAIN (LRT).

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This project does not aim to focus on any one particular figure of merit, but to introduce a feasible range of scenarios. We do pay special attention to minimum component sizes that are required for continuous operation.

Now Addis Ababa light railway is one of the newly constructing railway transport system. East-West and South-North lines are under construction in Addis Ababa (Phase I). Total length of main lines is around 33.6875km, where the East-West main line is around 16.998km long; the South-North main line is around 16.689km long. It has the sub grade section about 10.057km in length, the elevated section about 5.977km in length (including a common rail section 2.662km in length), and the underground section about 0.655km in length [1]. There are 39 LRT stations and five of them are shared with both South-North and East-West corridor. The minimum separation distance between stations is 435 meter; the maximum separation is 1972 meter and the average interval is 775 meter for both South-North and North and East-West corridor [1].

## **1.2 Problem Statement**

Now days the flexibility in the definition of light rail transit (LRT) alludes to its significant advantages. But LTR in usually encounters failure due to power disruption and decreased the efficiency of the LTR. And another Negative impact on the electrical grid (harmonics, voltage outages and fluctuations) this is due to the lack of storage back up power and the inability to have other power sources to operate the LRT and also frequent power interruption due to technical failures in the power supply. Hence, a hybrid energy management system includes solar energy, grid source and battery needs to charge the backup storage and intelligently control the power demand of the LTR and also to be designed to use the maximum efficiency of the system.

## **1.3 Objective of the Research**

### **1.3.1 General Objective**

The main goal of this research was to deploy solar panel on roof top of Addis Ababa light rail train LRT capable of producing power to supply auxiliary units and develop hybridization with grid supply by using energy optimization system or EMS (energy management system) options

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for railway applications, to find an optimal mix of these options, and to comment on the viability of the proposed solutions as a part of a gateway technology in Ethiopia to all-electric locomotives.

## **1.3.2 Specific Objective**

The objectives of the research presented in this thesis were to:

- Analyze the technical feasibility and operational convenience of using solar panels over the roof of trains.
- Develop Maximum power point tracking charge controller to get the best out of the PV system
- Develop a grid/solar parallel hybrid power model and use that mode to simulate and discuss the result leading to optimization recommendations.
- Analyze the overall performance of the controller and solar panel system.

## **1.4 Thesis Organization**

The thesis is organized as follows:

- Chapter 2 includes a review of the literature as well as other background material relevant to the scope of this study.
- Chapter 3 explains the application of solar power and the work done to develop full PV system with MATLAB modeling simulation process.
- Chapter 4 presents the work done to develop the hybrid system of the two power supplies. Those are trains auxiliary power box from pantograph/Grid and solar power from roof top installed solar panel.
- Chapter 5 is the final chapter and in its conclusions is made regarding the results of the simulated models and Recommendations on future work.

## CHAPTER TWO

### LITERATURE REVIEW

#### 2.1 Catenary-Electric Technology

The benefit of electrifying railway lines using catenary is that the prime mover no longer needs to be located on-board the locomotive. This allows any train operating on the line to access a practically unlimited power supply, and improves its acceleration [26]. Electrified trains are also safer, as there is less risk of explosion in case of derailment since the train does not carry any combustible fuel. This comes at a price, however; the price to install continuous-feed electrification infrastructure can usually only be justified on busy routes. Figure 2.1 illustrates the operation of catenary-electric technology which is employed by most EU railway systems.

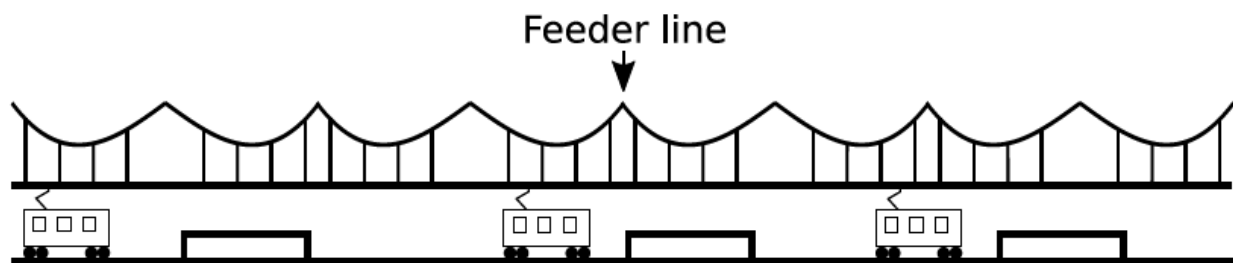


Figure 2. 1The operation of continuously electrified railroads [25]

Electrified overhead cables are usually single phase AC power drawn from the main three phase supplied by the local utility company. An electrified route will typically be divided into sections, each supplied from a different substation, and each fed from a different part of the utility network for increased security. Electricity is taken at very high voltage from the grid, transmitted in large cables to the substations, where the voltage is usually stepped down and then used to electrify a section of the track.

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Single phase transformers inside the feeder stations aim to create a balanced load with respect to the other phases. Utility companies require balanced loads so as to ensure balanced currents and therefore good power quality. Having a train with power levels in the megawatts suddenly show up on a single phase line will inevitably create unbalanced currents within the three phase utility supply.

Electrifying an entire route is a complex process, partly due to the reasons mentioned earlier and partly due to other considerations such as safety, security, grounding and electromagnetic interference (EMI). Maintenance personnel who operate close to such high voltages are at constant risk of electric shock or electrocution. The measures required to ensure the safety of personnel add to the cost of any electrification project. Having very high currents in overhead cables or in the rails will create large magnetic fields which could interfere with electronic devices like pacemakers or other similarly sensitive equipment in the vicinity. There was also documented evidence that EMI causes corrosion in underground pipelines [12, 13].

Electrified routes also enable the use of regenerative braking, a mechanism by which a train's kinetic energy was transformed into electrical energy and is fed back through the overhead cables. The energy returned to the overhead cable can be used for driving other trains [2], or stored on-board the locomotive. If no storage system exists on-board the locomotives or in the substations, the energy returned can only be consumed if another train is nearby. This creates a need for regeneration and consumption to occur at the same time, otherwise the regenerated energy is wasted [2].

Electrifying over large distances requires conductor loss calculations to be taken into consideration [14]. The further an electric train is from the substation; the less voltage is available to it as there is a greater voltage drop across the conductor's resistance. This requires all the power electronic and control systems to be designed to work for a range of voltages which further addition to the complexity of the system.

The current collection system, as the name suggests, is the system responsible for collecting the supply current and delivering it to the on-board electric traction motors. There are many accepted designs, but they all fall under two categories: overhead and track-level current collection

systems. Generally, all overhead running systems utilize a current collector, otherwise known as a **pantograph** that establishes contact with the overhead current carrying cables [15].

There are many different configurations and arrangements of the overhead running cables, also known as **catenary**. These usually depend on the electrification system used, whether AC or DC, and on the level of voltage across the cables.

Track level electrification is very popular in metro systems that run in tunnels. It is much easier on the eyes than overhead electrification, but carries a significant safety risk factor. The current collector in track level electrification is typically called a **conductor shoe**, and it has the job of establishing contact with the third current carrying rail to close the circuit and allow current to reach the electric traction motors.

The powertrain of a fully electric train is the same as a diesel-electric train minus the diesel generator set. Electric trains will typically employ more sophisticated power electronics modules and energy management systems. Recent developments in ESS technology has sparked a debate on the potential for reintroduction of electrified railways [20]. This would in turn reduce capital cost requirements, and encourage railway companies to reconsider all-electric locomotives and electrification.

## **2.2 Hybrid Energy Storage Technology**

In this section, we will explore the state of the art in hybrid propulsion systems applied to railway vehicles. We will start with an introduction to ICE hybrids, also known as “Green Goats”. This will be followed by a discussion on discontinuous electrification, and then a review of the application of clean power sources as prime movers in railway vehicles.

### **2.2.1 Diesel-Electric Hybrids**

Green Goats are trains that employ a secondary power source, normally an electrical one. Batteries and SCs have been popular choices in diesel-electric hybrid projects [9, 21,23]. The main goal of hybridization with diesel powered vehicles is the optimization of the diesel engine efficiency. Diesel engines operate at their maximum efficiency when producing rated power, and at their lowest when idling. By reducing the size of the engine to have a rated power equal to the

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average trip power, we can guarantee that the engine will operate at its most efficient power levels and hence reduce particulate and greenhouse gas (GHG) emissions and energy waste.

A secondary source is therefore needed to supply any excess power that cannot be delivered by the engine. The authors in [9] present a review of the different types of ESS that can be used in diesel hybrids, and the various diesel-hybrid powertrain architectures. This means that the system is highly inefficient for most of the operating time which is the motivation behind the development of green goat technology.

**Discontinuous Electrification** aims to reduce the cost of catenary technology, as well as extend the range of operation of any train, as a gateway or transition technology from diesel to full electrification or as a means to present a cheaper alternative to full electrification. On electrified sections, power provided by the overhead catenary is used to simultaneously propel the vehicle, and charge the on-board ESS. On non-electrified sections as presented in Figure 2.2, the ESS provides the power required for propulsion. The range of such trains could be further enhanced through the use of charging facilities that could be installed at stations along the non-electrified section. Employing ESS in railway systems increases the utilization of regenerated energy, reduces voltage drop across the conductors, reduces required electrification infrastructure and its maintenance, and reduces the visual impact of overhead cables and in-tunnel electrification. Depending on the capacity of the installed electric storage system, it may be possible to increase the regeneration braking force at the high-speed range as compared to full electrification.

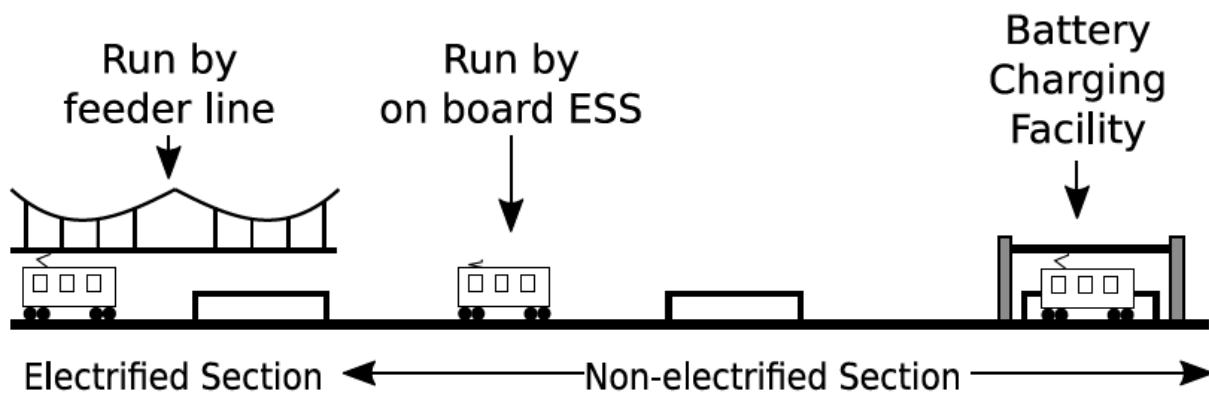


Figure 2. 2 The operation of discontinuously electrified railroads [9]

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A research project conducted at the Environmental Engineering Research Laboratory at East Japan Railway Company [3] studied a discontinuous electrification configuration. The project experimented with a typical 600 V line fed from a 1500 V DC electrified line through a DC/DC converter. The electricity fed the traction motors, ESS, and an auxiliary power supply unit to power a single railcar; no information was given about the route except that it was run in an urban area. The magnitude and direction of the current were controlled by a DC/DC converter by adjusting the output voltage.

Experimental vehicle operation modes:

- Non-electrified sections the battery system provides the entire power required, with the converter turned off. Dynamic braking generates electric power that supplies both the battery bank and the auxiliary power unit.
- Electrified sections the overhead catenary supplies electricity to the locomotive through the pantograph. This electricity is converted to the 600 V level by the DC/DC converter, which is then used to drive the traction motors.

Depending on the SOC of the battery bank, some of the electricity supplied by the overhead catenary could also be used to charge the battery bank. Electricity regenerated from braking is used to charge the battery bank, or is supplied back to the overhead catenary for use elsewhere in the electricity grid depending on the battery SOC. This configuration also allows for powering assistance mode, in which the storage battery supplies electric power additional to the power provided by the catenary in order to overcome steeper grades. Addis Ababa light rail train uses those Discontinuous Electrification systems.

Having a battery bank to supplement the power supplied by the catenary reduced fluctuations in the overhead voltage. Hybridizing with batteries reduced the stress on substations by reducing the peak power required. This eliminated the need for substation expansion to accommodate higher power requirements. Such setup has reportedly achieved over 30% energy saving in comparison to an inverter-fed regenerative train [2]. Traveling at 40 km/h, the length of the non-electrified sections reached 25.8 km in total. The result showed that a 1000A current could charge the on-board battery bank in about 60 seconds storing energy sufficient for 4 km or more

[1]. This energy management strategy works best with power dense devices such as SCs but will have an adverse impact on the life time of batteries due to the high charging/discharging frequency.

### **2.2.2 Solar – Grid Hybrid Power System**

Electrification System for trains are usually put in motion by hybridizing photovoltaic panels close to or on rail lines they can generate enough electricity to trigger a traction current that will be distributed to the grid or by hybridization solar power with the grid to get the efficient and continuous power and minimize the output grid power for the trains even though it is not enough for traction system of the train.

The performance of solar photovoltaic modules mounted on the rooftop of a rail coach of The Indian Railways tried in Indian trains. The focus of this experiment was to quantify the reduction in diesel consumption of the end-on generation system that powers the electrical load in the new generation coaches. Based on the experimental results, the benefits of operating solar rail coaches are projected. It is estimated that one solar rail coach can generate at least 18 kWh of electricity in a day [46].

## **2.3 The Science of Hybridization**

There are a number of factors to be considered when deciding on the need for hybridization of power sources for any application. The science of hybridization is essentially an assessment of supply and demand. The power demand profile must be analyzed to determine peak and mean values. The frequency of the power fluctuations and a statistical description of multiple power demand profiles would greatly aid in decisions regarding hybridization [39].

## **2.4 Energy Management Systems (Control Methods)**

Energy management is needed for systems that allow bidirectional power. Systems with bidirectional power capability and more than one source of power require even more complex EMSs, each designed with a goal in mind, an optimization objective. Variables to be optimized include parameters such as: efficiency, cost, energy source life time, emissions, and overall system volume.

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Optimal EMSs can be classified into two categories: offline or global optimization and online or real-time optimization. Online optimization methods rely on the prior knowledge of the driving cycle while online optimal EMS attempts to optimize parameters while the system is running and with no prior knowledge of the driving cycle. Dynamic programming [37{39], linear programming [30], genetic algorithm [32{33] and game theory [34] are examples of offline optimization methods.

Researchers typically employ a two phase EMS design process, first by using an offline optimization method to optimize certain variables given prior knowledge of the driving cycle and then using an online optimization method to improve the results further. In [40] the researchers combined a two stage offline-online strategy in which linear programming algorithms were chosen for offline optimization with PID control for the online optimization. The same work was repeated using a dynamic programming algorithm in [37] for the offline optimization phase. The authors in [35] combined a dynamic programming offline optimization method with an online optimal control based on neural networks and reported a 66% improvement in battery life when compared to rule-based control applied to a battery/super capacitor hybrid electric vehicle (HEV).

Optimal fuzzy logic is the term coined for control techniques that combine offline optimization methods with fuzzy logic online control. Fuzzy logic control is a heuristic control method that requires accurately defined membership functions. The offline optimization method is used to decide on the degree of hybridization and the fuzzy controller membership functions. The training sets provided by the offline optimization method replace the experimental calibration process that is often required for fuzzy logic control [10,18]

## **2.5 Summary**

Weather Catenary-Electric or Hybrid Energy Technology, a successful deployment of the Energy Control Management system is very important. Specially, considering the Solar – Grid Hybrid Power System, can become highly effective with a successful Energy Management System.

Nowadays, software backed Energy control system are being deployed and implemented. Such kind of systems is designed to suite with both the offline or global optimization and online or

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real-time optimization. By implementing optimization algorithms a significant improvement of energy production and battery life can be achieved.

## CHAPTER THREE

### Renewable Energy and Hybrid Technologies

#### 3.1 Introduction

Renewable energy source demand is increasing day by day as it is ecofriendly and pollution free. The increasing demand of total energy consumption has pushed more effort to produce more electricity to meet the demand. Out of all renewable energy sources solar energy has been emerged as one of the best source of energy supplier, as solar energy is clean, green, environmental friendly and inexhaustible. Grid connected and standalone systems are the two major utility in solar system [16].

The PV system has the ability to convert the incident sun light into direct current electricity. However, the voltage generated by one cell is low which cannot be used for any consumer load. So, for achieving high voltage many cells should be connected in series and for achieving reasonable current cells should be connected in parallel. The main objective of paper is to use the full available potential of the renewable energy source i.e. Solar Energy to generate electricity for giving power to the low power single phase industrial loads or domestic loads. Generally Solar panels are designed in such a manner to have output voltage of about 23-38 V at maximum power point (MPP) and rated power around 350 W at a radiation level of 1000 W/m<sup>2</sup>. In the next stage solar panels are connected to DC-DC converter. In this stage the maximum power can be tracked with the help of maximum power point algorithm and the output can be kept synchronized with loads. Generally, buck boost converters are used which increases the generated solar panels voltage [33,38].

The output voltage of Solar PV array is very much sensitive to solar irradiation and temperature hence to make a proper balance during sudden changes in the input of boost converter, a closed loop control of boost converter designed by “voltage mode control” method with PI controller is used. Maximum power point algorithm or Power-Voltage (P-V) or Voltage Current (V-I) or any characteristic of PV solar panel can be obtained using solar simulator. These characteristics will be required to decide what will be the numbers of cells required to be connected in series or

parallel as per the assigned load. In the next step inverter is used to convert the DC in to an AC. In this paper MAXIMUM POWER POINT TRACKING (MPPT) is used to control the fluctuating incoming of solar panel output due to the irradiance of solar energy and temperature which composed of a microcontroller, DC-DC convertor, a resistive load and lead acid battery. This helps to reduce total harmonic distortion (THD). Also this results in increase deficiency and reliability.

## **3.2 Solar Cells and their Characteristics**

Photovoltaic or solar cells, at the present time, furnish one of the most-important long duration power supplies. This cell is considered a major candidate for obtaining energy from the sun, since it can convert sunlight directly to electricity with high conversion efficiency. It can provide nearly permanent power at low operating cost, and is virtually free of pollution. Since a typical photovoltaic cell produces less than 3 watts at approximately 0.5-volt dc, cells must be connected in series-parallel configurations to produce enough power for high-power applications. Cells are configured into module and modules are connected as arrays. Modules may have peak output powers ranging from a few watts, depending upon the intended application, to more than 300 watts. Typical array output power is in the 100-watt-kilowatt range, although megawatt arrays do exist [5].

Photovoltaic cells, like batteries, generate direct current (DC), which is generally used for small loads (electronic equipment). When DC from photovoltaic cells is used for commercial applications or sold to electric utilities using the electric grid, it must be converted to alternating current (AC) using grid inverters, solid-state devices that convert DC power to AC [17].

### **3.2.1 Structure of Photovoltaic Cells**

Photovoltaic (PV) cell converts sunlight into electricity, which is the physical process known as photoelectric effect. Light which shines on a PV cell, may be reflected, absorbed, or passed through; however, only absorbed light generates electricity. The energy of absorbed light is transferred to electrons in the atoms of the PV cell. With their new found energy, these electrons

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escape from their normal positions in the atoms of semiconductor PV material and become part of the electrical flow, or current, in an electrical circuit. A special electrical property of the PV cell, called “built-in electric field,” provides the force or voltage required to drive the current through an external “load” such as a light bulb [20].

To induce the built-in electric field within a PV cell, two layers of different semiconductor materials are placed in contact with each other. One layer is an “n-type” semiconductor with an abundance of electrons, which have a negative electrical charge. The other layer is a “p-type” semiconductor with an abundance of holes, which have a positive electrical charge. Although both materials are electrically neutral, n-type silicon has excess electrons and p-type silicon has excess holes. Sandwiching these together creates a p-n junction at their interface, thereby creating an electric field. Figure: 3.2 Shows the p-n junction of a PV cell.

When n-type and p-type silicon come into contact, excess electrons move from the n-type side to the p-type side. The result is the buildup of positive charge along the n-type side of the interface and of negative charge along the p-type side, which establishes an electrical field at the interface. The electrical field forces the electrons to move from the semiconductor toward the negative surface to carry current. At the same time, the holes move in the opposite direction, toward the positive surface, where they wait for incoming electrons [42].

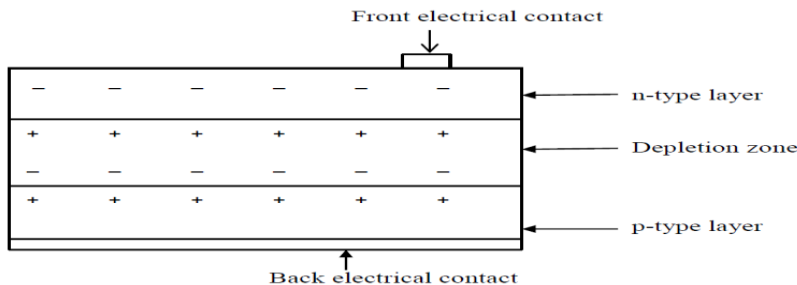


figure3. 1p-n junction of the PV cell [42]

Light travels in packets of energy called photons. As a PV cell is exposed to sunlight, many of the photons are reflected, pass right through, or absorbed by the solar cell. The generation of electric current happens inside the depletion zone of the p-n junction. The depletion region is the area around the p-n junction where the electrons from the “n-type” silicon, have diffused into the holes of the “p-type” material. When a photon of light is absorbed by one of these atoms in the

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“n-type” silicon it will dislodge an electron, creating a free electron and a hole. The free electron and hole has sufficient energy to jump out of the depletion zone. If a wire is connected from the cathode (n-type silicon) to the anode (p-type silicon) electrons will flow through the wire. The electron is attracted to the positive charge of the “p-type” material and travels through the external load creating a flow of electric current. The hole created by the dislodged electron is attracted to the negative charge of “n-type” material and migrates to the back electrical contact. As the electron enters the “p-type” silicon from the back electrical contact it combines with the hole restoring the electrical neutrality [42].

### 3.2.2 Photovoltaic Modules/Array

A PV or solar cell is the basic building block of a PV (or solar electric) system. An individual PV Cell is usually quite small, typically producing about 1 or 2W of power. To boost the power output of PV cells, they have to be connected together to form larger units called modules. The modules, in turn, can be connected to form larger units called arrays, which can be interconnected to produce more power. By connecting the cells or modules in series, the output voltage can be increased. On the other hand, the output current can reach higher values by connecting the cells or modules in parallel.

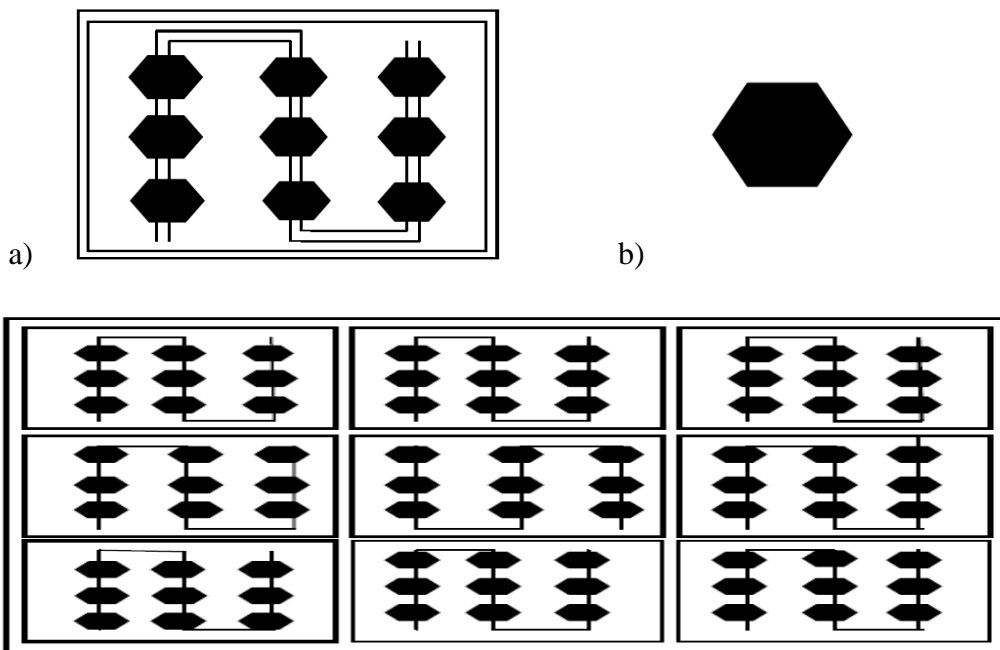


figure3. 2(a) PV cell, (b) PV module, (c) PV array [42]

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PV devices can be made from various types of semiconductor materials, deposited or arranged in various structures. The three main types of materials used for solar cells are silicon, polycrystalline thin films, and single crystalline thin film. Solar energy systems are typically classified into two systems: Passive and Active system. Passive systems do not involve panel system or other moving mechanisms to produce energy. Active systems typically involve electrical and mechanical components to capture sunlight and process it into usable forms such as heating, lighting and electricity [42].

### 3.2.3 Photovoltaic Cell Model

The use of equivalent electric circuits Figure: 3.4 makes it possible to model characteristics of a PV cell. The PV model consists of a current source, a diode and a series resistance. The effect of parallel resistance, represents the leakage resistance of the cell is very small in a single module; thus the model does not include it. The current source represents the current generated by photons, and its output is constant under constant temperature and constant incident radiation of light [43].



figure3. 3(a) Short circuit current and (b) Open circuit Voltage [43]

### Mathematical Equivalent Circuit for Photovoltaic Array

The equivalent circuit of a PV cell is shown in Fig. 3.5 the current source  $I_{PH}$  represents the cell photocurrent.  $R_{sh}$  and  $R_s$  are the intrinsic shunt and series resistances of the cell, respectively. Usually the value of  $R_{sh}$  is very large and that of  $R_s$  is very small, hence they may be neglected to simplify the analysis. Practically, PV cells are grouped in larger units called PV modules and

# SOLAR/GRID HYBRID POWER OPTIMISATION USING FUZZY LOGIC CONTROLLER FOR LRT of ADDIS ABEBA

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these modules are connected in series or parallel to create PV arrays which are used to generate electricity in PV generation systems [44]. The equivalent circuit for PV array is shown in Fig. 3.5. The voltage–current characteristic equation of a solar cell PV module is provided as shown below.

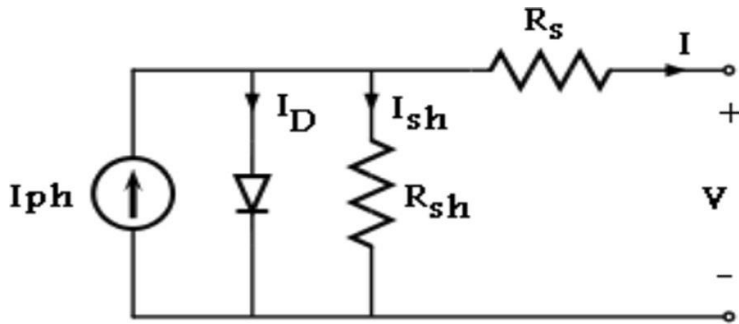


figure3. 4 PV cell equivalent circuit

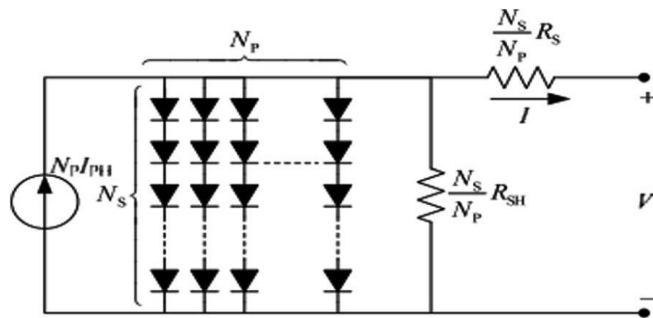


figure3. 5Equivalent circuit of PV module

### Module/cell photo-current $I_{ph}$ :

Radiant power from sun results in current flow through solar cell. Since thermal excitation of minority carriers contribute to current flow, reverse saturated current also affects Photo Current Equation. The temperature dependence of photocurrent is measured for reference cell and Operating cell temperature [44].

$$I_{ph} = [I_{sc} + K_i (T - 298)] \times G / 1000 \tag{3.1}$$

Where,

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$I_{ph}$ : photo-current (A);  $I_{sc}$  : short circuit current (A);

$K_i$ : short-circuit current of cell at 25 °C and 1000 W/m<sup>2</sup> ;

T: operating temperature (K);

G: solar irradiation (W/m<sup>2</sup>).

## Module Reverse Saturation Current $I_R$ :

The reverse saturation current also known as leakage current  $I_r$ , is the current that flows in the reverse direction when the diode is reverse biased. The reverse saturation current  $I_S$  is dependent on temperature, diffusion constants, Energy Band gap, ideality factor, Boltzmann constant as in equation.  $I_S$  represents a measure of the recombination in a device. It increases as T increases and decreases as material quality increases [45].

$$I_{RS} = I_{SC} / e^{(Q \times V_{OC} / N_s \times K_n \times T) - 1}. \quad (3.2)$$

Where,

Q: Electron charge, =  $1.6 \times 10^{-19}$  C;

$V_{OC}$ : Open circuit voltage (V);

$N_s$ : Number of cells connected in series;

N: The ideality factor of the diode;

K: Boltzmann's constant, =  $1.3805 \times 10^{-23}$  J/K.

The module saturation current  $I_0$ , which is given by:

$$I_0 = I_{RS} [T / T_n]^3 e^{[Q \times E_{go} / K_n (1/T - 1/T_n)]} \quad (3.3)$$

Here,

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$T_n$ : nominal temperature = 298.15 K

$E_{g0}$ : band gap energy of the semiconductor, = 1.1 e<sub>v</sub>

## Shunt Current

It can be shown that for a solar cell (low  $R_S$  and  $I_S$ , and high  $R_{Sh}$  and  $I_{Sh}$ ) alters expression of equations. Losses occurring in solar cell are due to manufacturing defects in values of series and shunt resistance. Solar cell behaves neither as current source nor as a voltage source. Since losses caused by series resistance are given by  $P_{LOSS} = IV = I^2 R_s$ , they increase quadratically with photocurrent. Similarly, current diverted through the shunt resistor increases causing the voltage-controlled portion of the IV curve to sag towards origin [45].

$$I_{Sh} = ((V \times N_p / N_s) + (I \times R_s)) / R_{Sh} \quad (3.4)$$

**Thermal voltage** the thermal voltage equation is used to describe average energy of electrons diffused in solar cell moving randomly at given temperature.  $V_T$  is about 25.85 mV at 300K at standard test condition (STC) [46].

$$V_T = (K \times T) / Q \quad (3.5)$$

The current out-put of PV module is:

$$I = N_p \times I_{ph} - N_p \times I_o \times [e^{((V/N_s + I \times R_s/N_p)/n \times V_t) - 1}] \quad (3.6)$$

Where:

$N_p$ : number of PV modules connected in parallel;

$R_s$  : series resistance ( $\Omega$ );

$R_{Sh}$ : shunt resistance ( $\Omega$ );

$V_t$ : diode thermal voltage (V).

### 3.3 Modeling of Photovoltaic Module with Tags

A mathematical model of PV array including fundamental components of diode, current source, series resistor and parallel resistor is modeled with Tags in Simulink environment. The simulation of solar module is based on equations given in the section above and done in the following steps.

Reference module rating for modeling in Simulink.

Table 3.1 PV specification

Maximum rated power ( $P_{MP}$ )	250W
Voltage at maximum power( $V_{MP}$ )	26.4V
Current at maximum power( $I_{mp}$ )	9.46A
Open circuit voltage ( $V_{OC}$ )	39.9V
Short circuit current( $I_{SC}$ )	8.6A
Total number of cells in parallel( $N_p$ )	1
Total number of cells in series( $N_s$ )	60

**Step 1** Provide input parameters for modeling:

$T_r$  is reference temperature = 298.15 K;

$N$  is ideality factor = 1.2;

$k$  is Boltzmann constant =  $1.3805 \times 10^{-23}$  J/K;

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$q$  is electron charge =  $1.6 \times 10^{-19}$ ;

$I_{sc}$  is PV module short circuit current at  $25^\circ\text{C}$  and  $1000\text{ W/m}^2 = 6.11\text{ A}$ ;

$V_{oc}$  is PV voltage module open circuit voltage at  $25^\circ\text{C}$  and  $1000\text{ W/m}^2 = 0.6\text{ V}$ ;

$E_{g0}$  is the band gap energy for silicon =  $1.1\text{ eV}$ .

$R_s$  is series resistor, normally the value of this one is very small, =  $0.0221\ \Omega$ ;

$R_{sh}$  is shunt resistor, the value of this is so large, =  $415.405\ \Omega$ .

Table 3.2 Constant and Variables for Modeling.

$I_{ph}$	Photo-current (A)	$I_{ph}$
$I_{sc}$	Short circuit current(A)	$I_{sc}$
$K_i$	Short circuit current at STC	0.0032
$T$	Operating temperature (K)	$T$
$T_n$	Nominal temperature(K)	298
$G$	Solar irradiance( $\text{W/m}^2$ )	$G$
$Q$	Electron charge (C)	$1.6 \times 10^{-19}$
$V_{oc}$	Open circuit voltage (V)	$V_{oc}$
$N$	Ideality factor of diode	1.3
$K$	Boltzmann constant(J/K)	$1.38 \times 10^{-23}$
$E_{g0}$	Band gap energy of semiconductor(eV)	1.1
$N_s$	Number of cells connected in series	$N_s$
$N_p$	Number of cells connected in parallel	$N_p$

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$R_s$	Series resistance( $\Omega$ )	0.221
$R_{sh}$	Shunt resistance( $\Omega$ )	415.405
$V_t$	Diode thermal voltage (V)	$V_t$

## Step 2

Module photon-current is given in Eq. (3.1) and modeled

As Fig.3.7 ( $G = 1000 \text{ W/m}^2$ ).

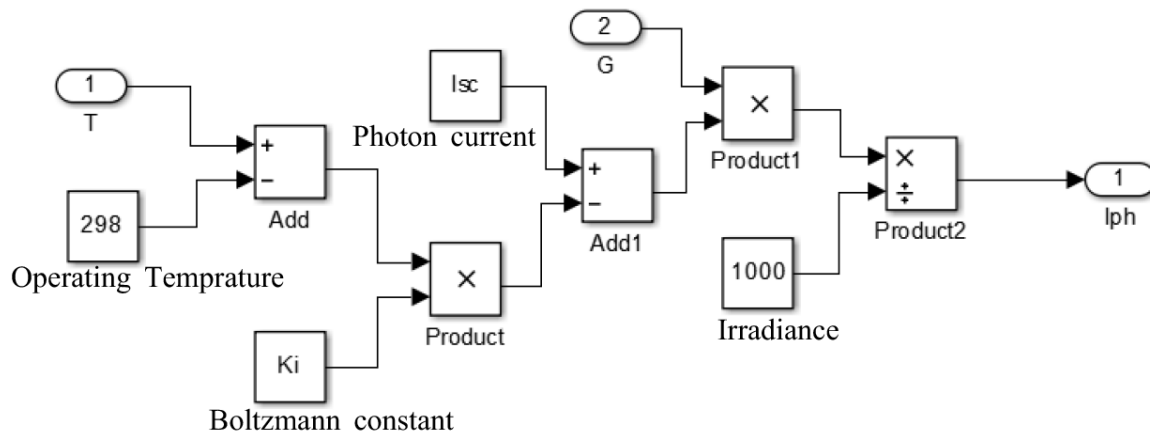


figure3. 6Model of photon current ( $I_{ph}$ )

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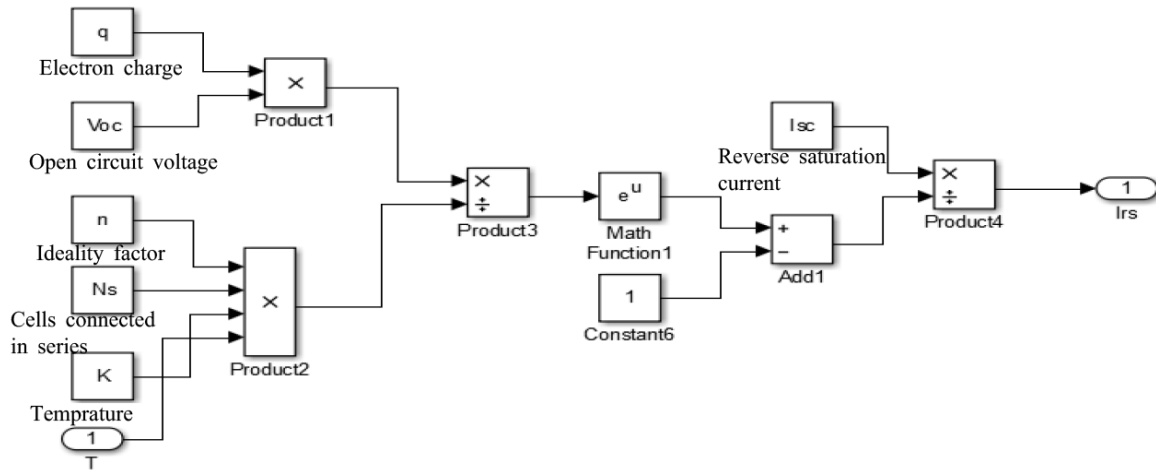


figure3. 7 Model for Reverse Saturation Current

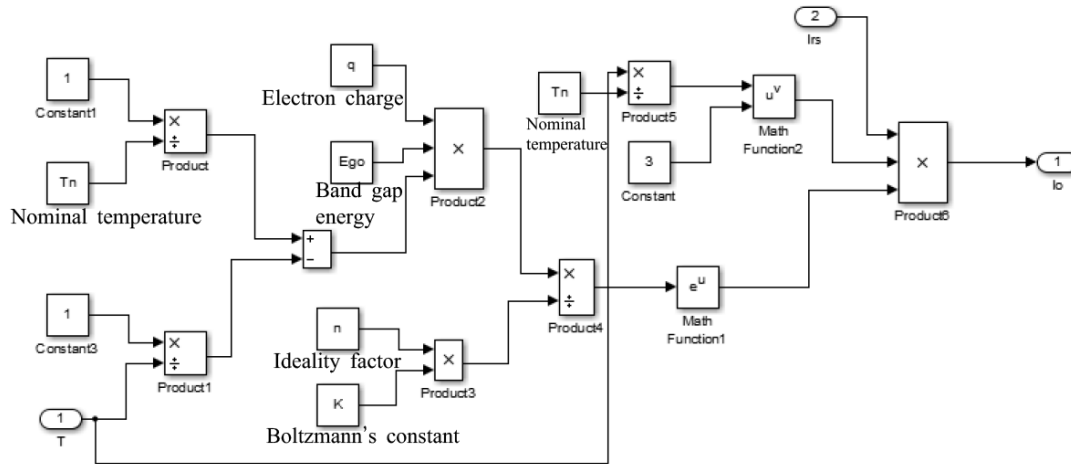


figure3. 8 Model for module saturation current

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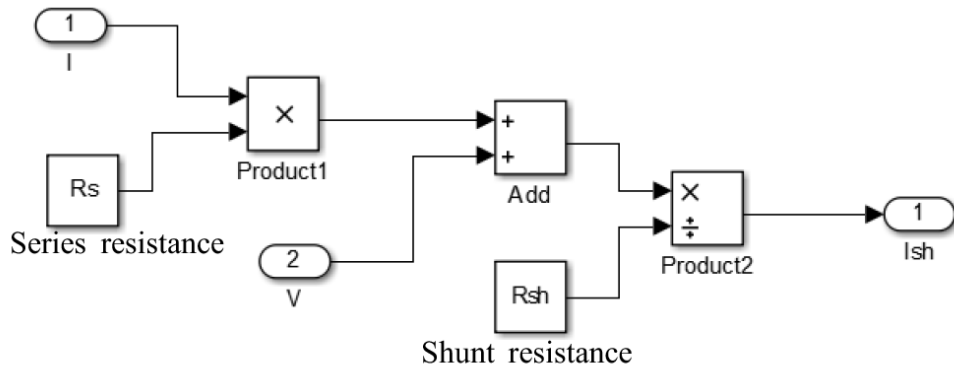


figure3. 9Model for thermal voltage

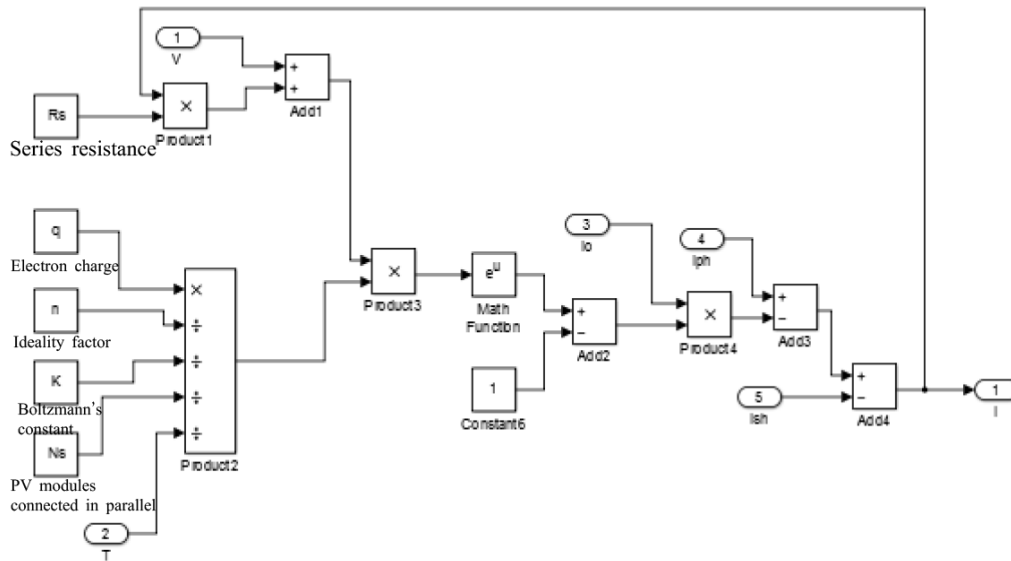


figure3. 10Model PV current output

To form a single PV module subsystem, the above all modeled circuits should combine in the form of subsystem. And modeled PV module is shown in the fig 3.11 bellow. Since PV solar energy is dependent on solar irradiation (G) and temperature (T).

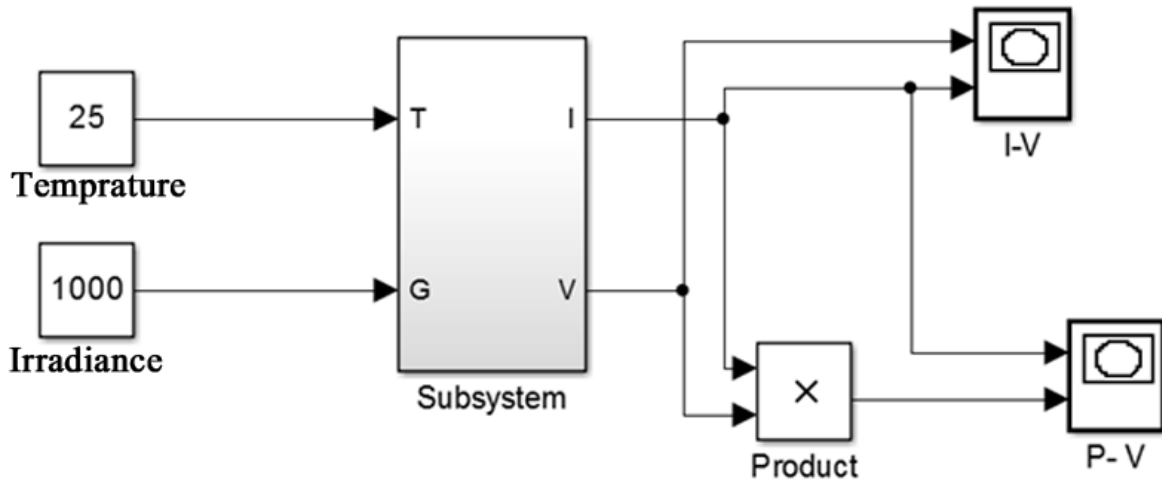


figure3. 11 PV module as Subsystem

### 3.4 Design of the Proposed PV System

A solar PV system design consist of the following fundamentals

- Power demand
- Number of PV panel
- Design of Charge controller
- Number of batteries

#### 3.4.1 Power Demand to Drive Auxiliary Units of the LRT

The Vehicles receive power supply from the pantograph, the rated power supply voltage is DC 750V, and the rails serve as a negative pole. The variation range of voltage supply is from DC500V to DC 900V.

The auxiliary power box includes input circuit, auxiliary inverter, charger and battery, which is applicable to the light rail vehicles in the Ethiopia Light Rail Project and light rail vehicles in similar projects. The auxiliary power box obtains DC 750V voltage from the contact network and then feed the power into the power modules of auxiliary inverter and the charger through EMI filter, fast fuse, contactor, input reactor and diode. The auxiliary inverter provides

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50HZ/AC and 380V/AC 220V power supply for equipment such as the air conditioning unit and the electrical heating and ventilators of equipment in passenger saloons. The charger mainly provides DC 24V power supply for traction system control, auxiliary power supply system control, door control, communication equipment, passenger saloon lightening, emergency lightening, and magnetic rail braking, etc.

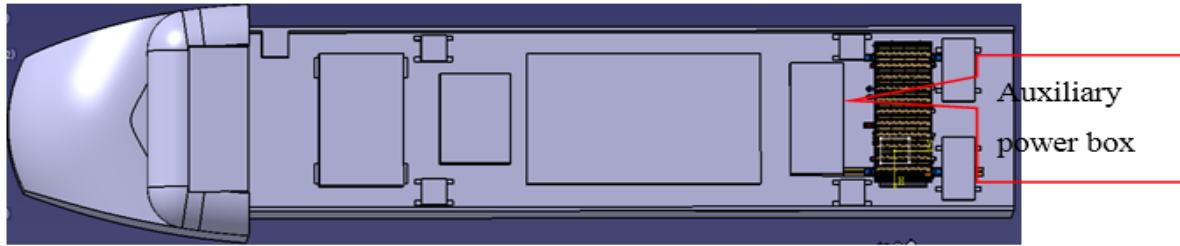


figure3. 12 Layout diagram of auxiliary power box train rooftop

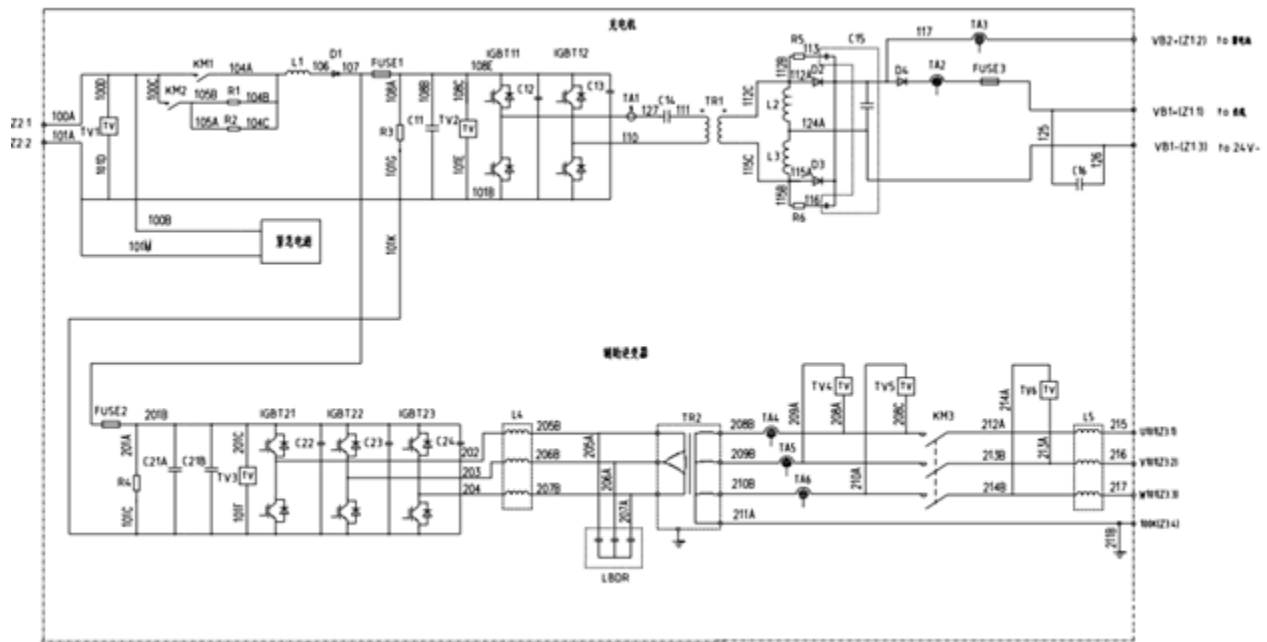


figure3. 13 Main circuit diagram of auxiliary power box [47]

The auxiliary inverter adopts the working mode of SVPWM (voltage space-vector pulse-width modulation) and its IGBT turn-on and turn-off frequency is 4KHz. The DC input voltage is inverted into a three-phase PWM wave through a three-phase Inverter Bridge. And then the PWM wave is filtered by the LC sinusoidal filter into a three-phase sinusoidal output voltage waveform with harmonic contents less than 5%. Since it is required out of safety consideration

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that the input and output be electrically isolated from each other, a 35KVA three-phase power-frequency transformer is added to the output side. The connection group of the power-frequency transformer is Dyn11. There is output at the output neutral point, which provides single-phase 220V power supply to a part of the single-phase load like some auxiliary components of the trains are working in single phase [47].

**Table 3.4 Total power demand of the LRT system**

No	Item description	Power demand	Energy in 12hrs	Remark
1	Traction system	350kw	4200kwh	This is total power consumption of traction system without auxiliary parts, and considering that Addis Ababa LRT works 12 hours per day
2	Auxiliary units	35kw	420kwh	Some of auxiliary parts are mentioned below but not all of them.
	2.1- air conditioning	25kw	300kwh	Some of the auxiliary power consumptions are approximate calculations and the energy is in 12 hours considering Addis Ababa trains working time.
	2.2- charger	8kw	96kwh	
	2.3- door	0.2kw	2.4kwh	

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	2.4-telvision	0.4kw	4.8kwh	
	2.5-Camera	0.18kw	2.16kwh	
	2.6-microfone	0.21kw	2.52kwh	

This power box supplies power for two main components of LRTs auxiliary units. The first one is air conditioning units which consumes three phase 380VDC and the second one is for single phase 220VAC. Technical parameters are shown below.

1) Technical parameters of saloon air conditioning unit

- Model: DLD25A
- Type: roof mounted unit
- Power supply: main circuit AC380V 3-phase 50Hz
- Control circuit DC24V
- Refrigerating capacity: 25kW

2) Technical parameters of charger

- Rated output power of the charger: 8kW.
- Range of output voltage: DC24V~29V.
- the output voltage can be adjusted based on the temperature of the battery.
- Output ripple voltage:  $\leq 1.5V$ .
- Maximum output current: DC330A.
- Mode of charging: limit current and constant voltage + battery float charging

Therefore, the power demand to drive single unit is:

- for the whole auxiliary power box is 35kw
- for air-conditioning units is 25kw
- for charger is 8kw

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## 3.4.1.1 Number of PV Panel

Since the proposed PV power is to be installed on the roof top of the LRT the area of the train must be known to calculate the number of module. The roof top area of the train is:

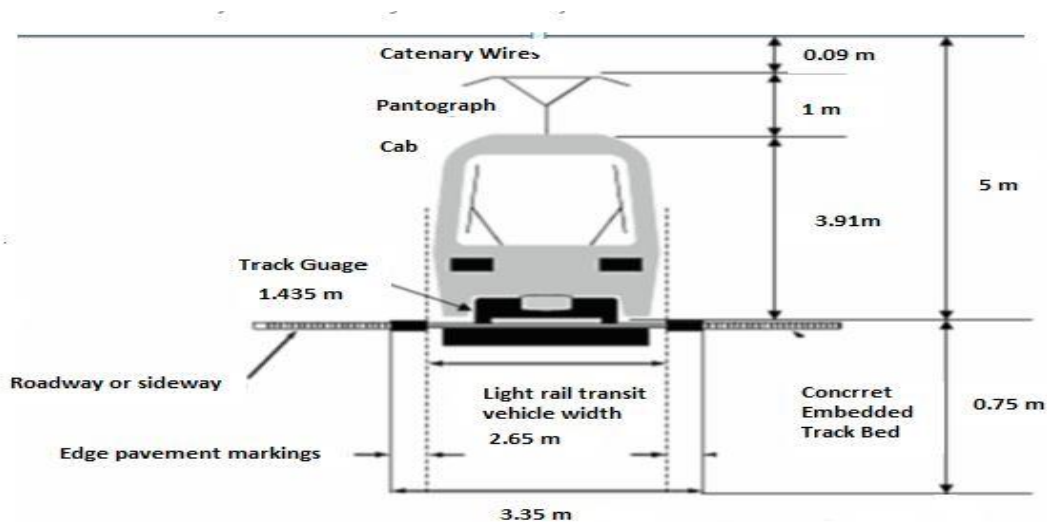


figure3. 14 System Specifications Diagram outlining average LRT vehicle measurements [from ERC LRT project].

Roof top area =Length \*Width

$$=29.7 *2.65$$

$$=78.7m^2$$

Area of selected PV modeled panel length is 1.65m and the height needed is 0.988m

$$\text{Area of the panel}=1.65*0.988=1.63m^2$$

Number of modeled module to be fit on the roof top is

$$\text{No of module} = 78.7/1.6 = 49$$

49 modeled modules are required to cover the roof top of the train

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These 49 modules produce maximum power  $P_{max}$ :

$$P_{max} = \text{No of module} * \text{peak power of module}$$

$$= 49 * 250W$$

$$= 12.25kW$$

Actual power output of modeled module

$$P_{act} = P_{max} / \text{Efficiency}$$

$$= 12250W * (1/0.85)$$

$$= 14.7KW$$

Actual number of module after getting actual power

$$\text{No of panels} = P_{act} / \text{peak power of module} = 58 \text{ panels}$$

The panels will arrange with some angle of inclination. Because width of the train and length of the panels will be greater than the height of the train.

The angle between the solar panels is  $36.6^\circ$  and (assuming spacing of the panels 10cm)

N;B  $P_{max}$  for maximum power and  $P_{act}$  is for actual power.

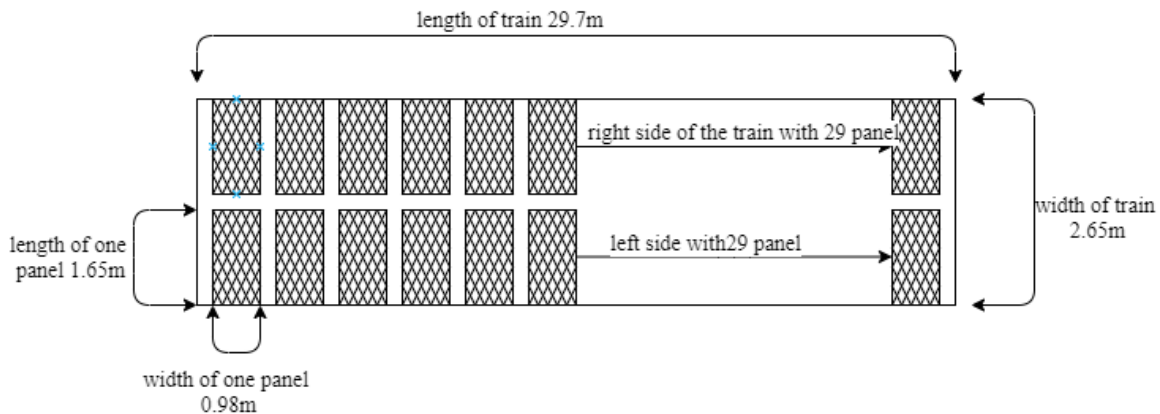


figure3. 15 Top view of the train with the solar panels on the roof

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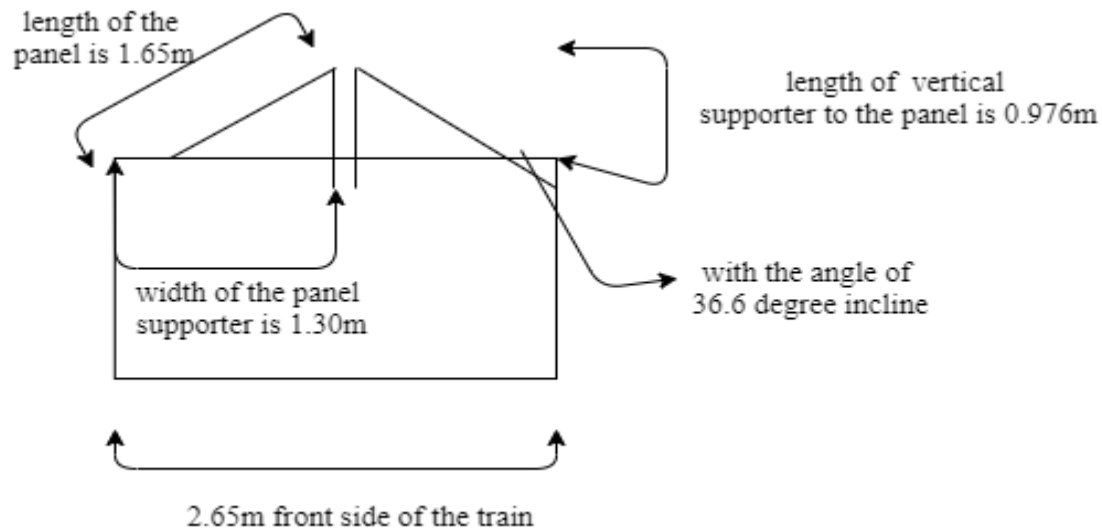


figure3. 16 Front view of the train with solar panel on the rooftop

### 3.4.1.2 Energy saving analysis

When the solar panel works, the system will be using less energy from the grid

Total energy conserved from solar panels of the train comparing with table 3.4 and effective production time of the solar panel is minimum of 5.6 hours per day.

$$E = 14.5 \text{KW} * 5.6 \text{hrs} = 81.2 \text{KWhrs}$$

$$\text{Monthly energy saving} = 81.2 \text{KWhrs} * 30 = 2436 \text{KWhrs}$$

$$\text{Yearly energy saving} = 29236 \text{KWhrs} = 29.2 \text{MWhrs}$$

Ethiopian railway may be able to save energy consumption of the total trains in auxiliary units in (42 trains) in year will be

$$\text{Yearly Energy} = 1227.7 \text{MWhrs}$$

The modeled solar panel is capable of powering the charger of auxiliary power box of LTR mainly provides DC 24V power supply for traction system control, auxiliary power supply system control, door control, communication equipment, passenger saloon lightening, emergency lightening, and magnetic rail braking, etc.

### **3.4.2 Charge Controller**

Charge controllers aim to provide the correct voltage and current ratings for a rechargeable battery by monitoring and regulating the solar panel output voltage to match the batteries [46,47]. This output voltage regulation is very important in battery charging because batteries require a specific charging method with various voltage and current levels for each specific stage, these charging methods are needed to prolong battery life and performance. Some common charge controller protection features to prevent battery damage are undercharge and overcharge protection. Undercharge protection entails disconnecting the battery when the charge is too low to continue powering connected loads, similarly, the charge controller stops providing energy to the battery when it is fully charged to prevent overcharge. This is where the charge controller does most of the work. Simple charge controllers disconnect the battery once the battery surpasses a threshold level and reconnect it once the battery level falls below a certain preset charge level. Other protection features include protection against over-voltage and completely draining ("deep discharging") a battery and regulating charging/discharging rates to protect battery life and improve its life span. From the above it is seen that the gist of a charge controller is a DC to DC converter that converts the solar panel voltage to a voltage suitable for charging the battery while protecting it. Implementing a DC to DC converter rather than a linear regulator (or just connecting the battery directly to the solar panel) ensures considerably higher power efficiency. Standard charge controllers will typically be used in a situation where the input voltage from the solar panel is higher than the voltage from the battery. In this case the voltage will be reduced by the controller while the current that the panel is outputting will stay the same. This will result in power loss from the total power generated from the panels. More sophisticated charge controllers include the PWM and MPPT types [47].

#### **Pulse-Width Modulating (PWM) Charge Controllers**

Pulse-Width Modulating (PWM) charge controllers use complex algorithms to determine the amount of charge going to a battery and tapering according to the battery's condition (State of charge) and recharging needs [23]. The controller periodically checks the battery's state of charge (SoC) to determine how fast to send pulses, and how long (wide) the pulses will be. In a discharged battery, the pulses would be very long and almost continuous, or the controller may

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go into "totally on" mode. When a battery voltage reaches the regulation set point, the PWM algorithm slowly reduces the charging current by slowly tapering off charging as the battery becomes full to avoid heating and gassing of the battery, however the charging still delivers the maximum amount of power to the battery in the shortest time. PWM is often used as one method of float charging where instead of a steady output from the controller, it sends out a pulse train of short charging pulses to the battery. In a fully charged battery with no load, it may just spike every few seconds and send a short pulse to the battery (trickle charge). PWM has the advantages of increasing battery life span, minimizing stress on battery, reducing battery overheating and ability to disulphate a battery but the drawback of PWM is it isn't as highly efficient as MPPT for higher panel ratings and colder operating conditions; the greater the voltage variation between battery voltage and the  $V_{mp}$  (Peak maximum solar panel voltage) of the array, the greater the energy dissipated by a PWM controller during in the battery's bulk charging state.

### **Maximum Power Point Tracking (MPPT) Charge Controller**

MPPT charge controller use fast processing controllers; e.g. Microcontrollers, to compute the highest instantaneous possible power output (Operation at the knee point of the P-V curve of Figure3.16) by suitably adjusting the load impedance seen by the panel under operation in addition to monitoring the different battery charging stages [47].

Therefore, in the same conditions as above for standard charge controllers, where the input voltage is higher than the output voltage, the MPPT charge controller will lower the voltage and simultaneously increase the current to the batteries. As  $P=VI$ , this results in higher power transfer efficiencies, which means less solar power is lost during the storage process. MPPT Charge controllers are designed to maximize the output efficiency of a solar panel, the main aim of such tracker is to vary the module operating current and voltage such that the maximum output power is achieved in a rapid but precise manner especially under variable atmospheric conditions it implements this through a DC-DC converter with variable duty cycle. MPPT will provide the maximum possible power to the battery while still using the full output of the solar panel by ensuring maximum current the PV can produce at the time is delivered [46,47].

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In this chapter we have presented the photovoltaic solar panel's operation. The foremost way to increase the efficiency of a solar panel is to use a Maximum Power Point Tracker (MPPT), a power electronic device that significantly increases the system efficiency. By using it the system operates at the Maximum Power Point (MPP) and produces its maximum power output. Thus, an MPPT maximizes the array efficiency, thereby reducing the overall system cost. In addition, we attempt to explain and design the MPPT by using the algorithm of a selected MPPT method which is "Perturb and Observe" and implement it by using a DC-DC Converter [16,17,23]. We have found various types of DC-DC converter. Among them we have selected the most suitable converter which is "buck boost" converter, for our design.

PV generation systems generally use a microcontroller based charge controller connected to a battery and the load. A charge controller is used to maintain the proper charging voltage on the batteries [18]. As the input voltage from the solar array, the charge controller regulates the charge to the batteries preventing any overcharging. So a good, solid and reliable PV charge controller is a key component of any PV battery charging system to achieve systems maximum efficiency. Whereas microcontroller based designs are able to provide more intelligent control and thus increases the efficiency of the system.

MPPT is one of many applications of power electronics. In order to understand and design MPPT, it is necessary to have a good understanding of the behaviors of PV. The thesis facilitates it using MATLAB models of PV cell and module in the previous chapter. The other things such as DC DC converter and MPPT are also explained elaborately.

## **Current - Voltage Characteristics of a PV**

For any given set of operational conditions, cells have a single operating point where the values of the current (I) and Voltage (V) of the cell result in a maximum power output. The power P is given by  $P=VI$ . A plot of panel output power vs. panel voltage is shown in figure: which have a peak point indicated by MPP which falls off on both sides. This is known as the maximum power point (MPP) and corresponds to the "knee" of the curve, at which the module operates with the maximum efficiency and produces the maximum output power.

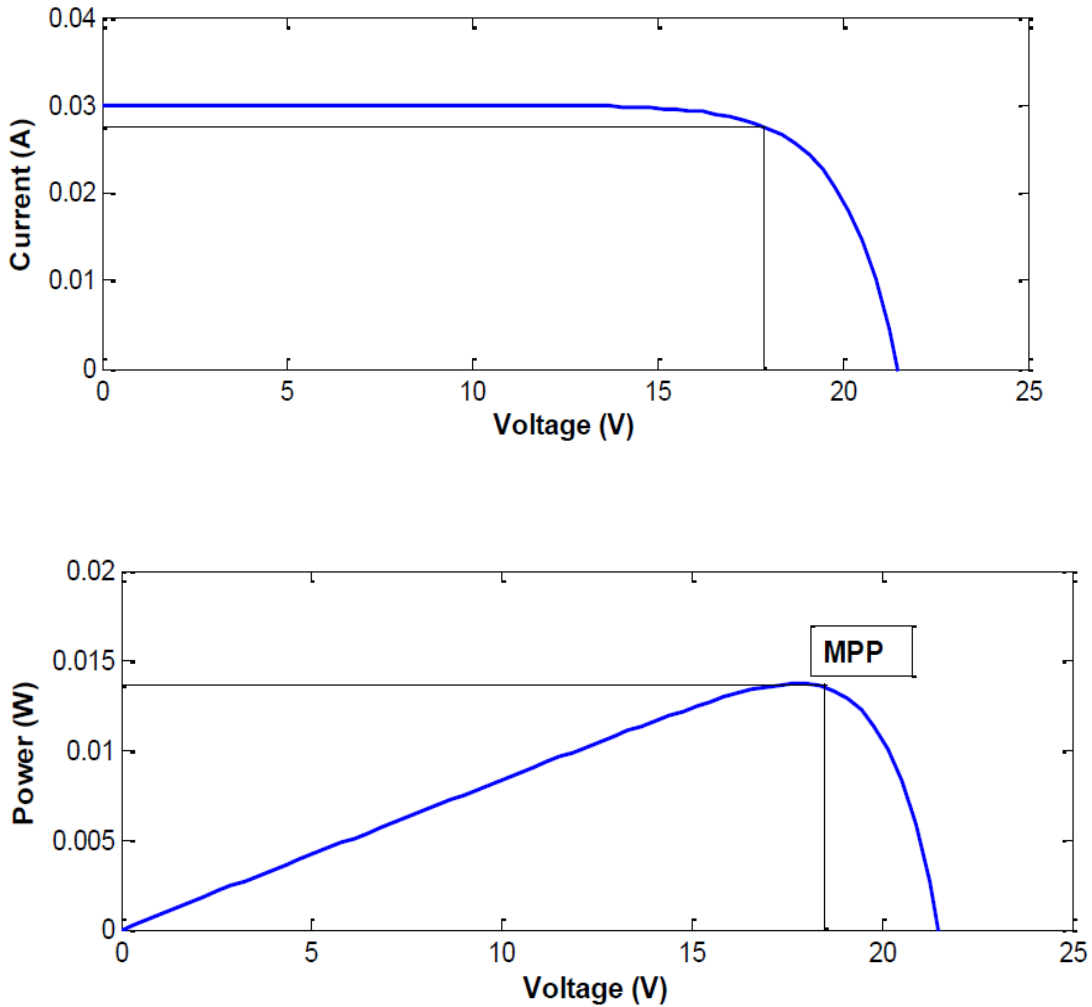


figure3. 17 I-V (top) and P-V (bottom) characteristic of a PV cell

### Effects of solar irradiance on MPP

There are two key parameters frequently used to characterize a PV cell. Shorting together the terminals of the cell, the photon generated current will follow out of the cell as a short-circuit current ( $I_{sc}$ ) [16]. When there is no connection to the PV cell (open-circuit), the photon generated current is shunted internally by the intrinsic p-n junction diode. This gives the open circuit voltage ( $V_{oc}$ ). The PV module or cell manufacturers usually provide the values of these parameters in their datasheet.

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In a PV cell current is generated by photons and output is constant under constant temperature and constant incident radiation of light. Varying the irradiation, we can get different output levels.

The current voltage relationship of a PV cell is given below.

The MATLAB simulation of I-V characteristics according to equation (3.6) for different Irradiance of a PV panel is shown in Figure: 2.9.

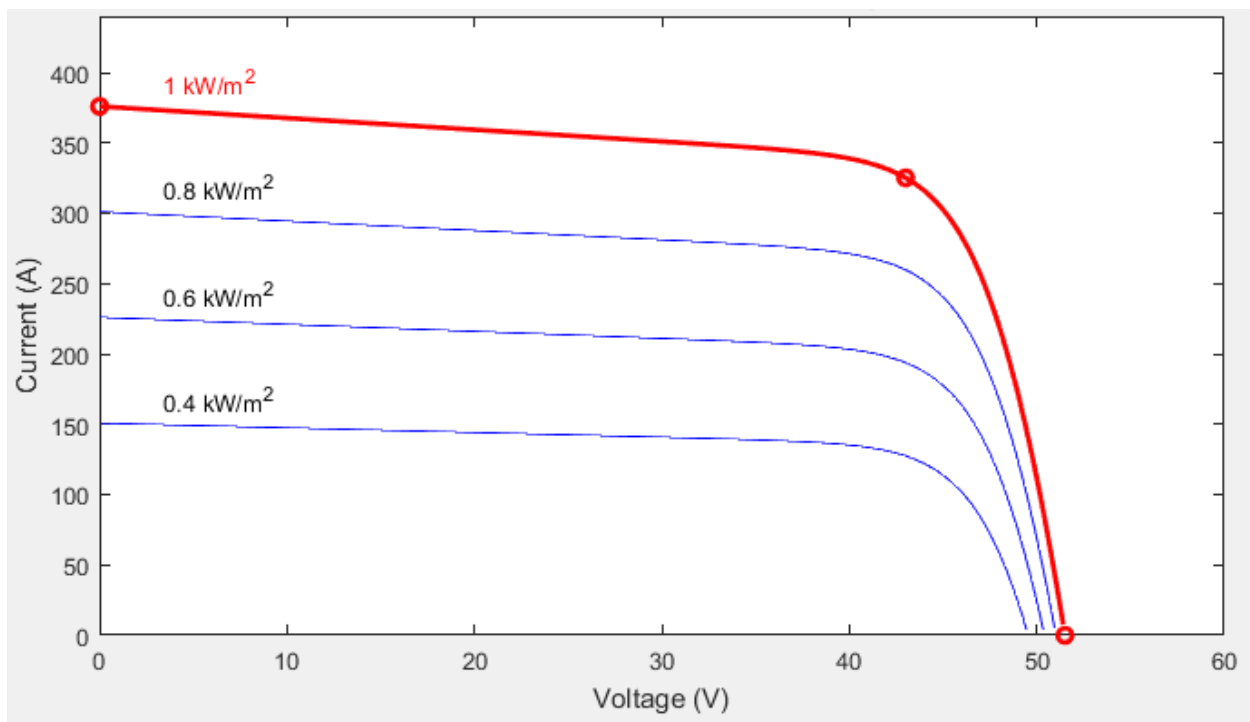


figure3. 18 I-V curve with different irradiance

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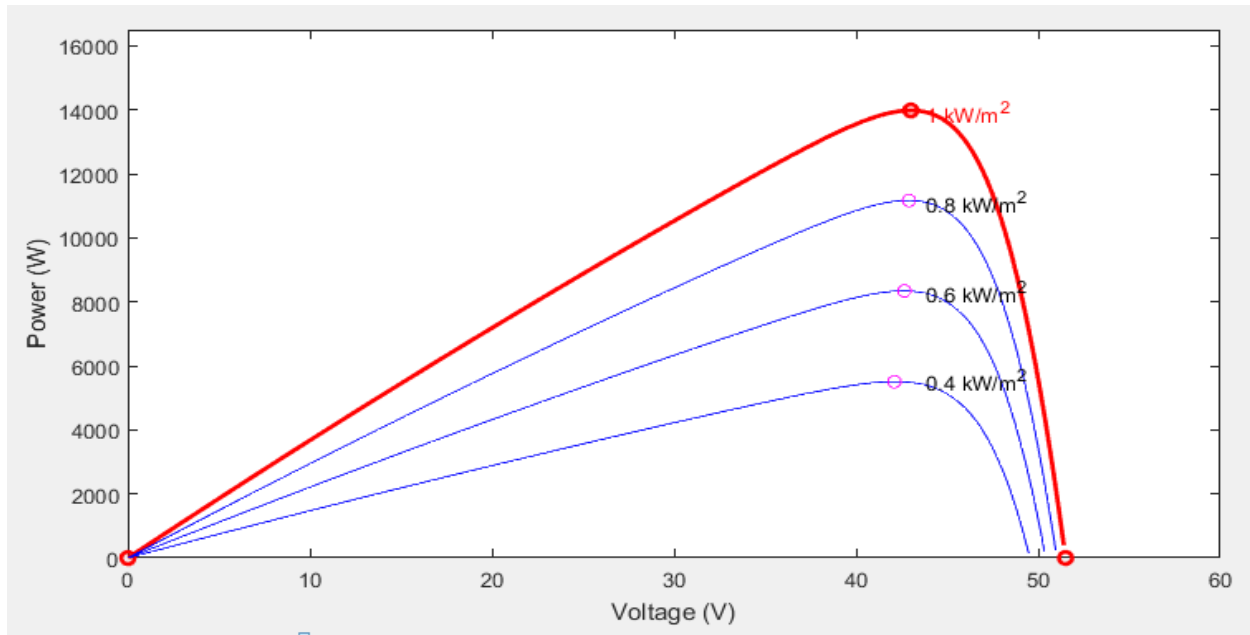


figure3. 19 P-V Curve with different irradiance

The PV cell output is both limited by the cell current and the cell voltage, and it can only produce a power with any combinations of current and voltage on the I-V curve. As shown in Figure: the P-V curve shifts with different irradiance so the MPP also shifts.

Now, as the I-V curve of a PV cell changes with different irradiance so it reveals that the amount of power produced by the PV module varies greatly depending on its irradiance. It is important to operate the system at the MPP of PV module in order to exploit the maximum power from the module.

### Effects of temperature on MPP

I-V characteristic of a PV module varies at various module temperatures.

I-V characteristic of the panel is plotted for three different temperatures,  $T=273\text{K}$ ,  $298\text{K}$  and  $323\text{K}$  and are shown in figure:

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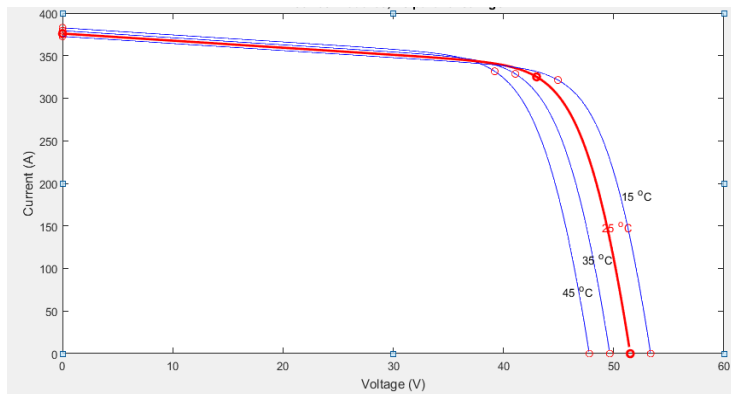


figure3. 20 I-V curve for varying temperature

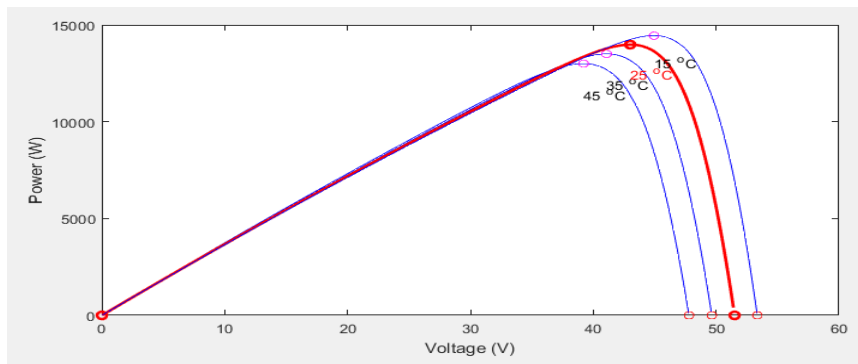


figure3. 21 P-V curve for varying temperature

With the increase of temperature, the I-V characteristics of a PV cell shifts toward lefts and so the MPP decreases with increase in temperature. Because of the photovoltaic nature of solar panels, their current-voltage, or IV, curves depend on temperature and irradiance levels. Therefore, the operating current and voltage which maximize power output will change with environmental conditions.

Therefore, the MPP needs to be located by a tracking algorithm, which is the heart of MPPT controller. MPPT algorithm tells controller how to move the operating voltage. Then, it is a MPPT controller's task to bring the voltage to a desired level and maintain it [11,17]. To obtain a stable voltage from an input supply (PV cells) that is higher and lower than the output, a high efficiency and minimum ripple DC-DC converter required in the system.

Buck-boost converters make it possible to efficiently convert a DC voltage to either a lower or higher voltage. Buck-boost converters are especially useful for PV maximum power tracking purposes, where the objective is to draw maximum possible power from solar panels at all times. As we have discussed the structure and the I-V characteristics of a photovoltaic cell and corresponds to the knee of the P-V curve we get the MPP. We have seen the MPP varies with the load resistance. Here, we can use a Buck-Boost converter to reach the MPP. But the MPP shifts with some other factors such as solar irradiance and temperature. Therefore, we need to track the MPP at any irradiance and temperature. So we have to use MPPT to get the maximum power output.

### **3.4.3 Maximum Power Point Tracker**

As the optimum point changes with the natural conditions so it is very important to track the maximum power point (MPP) for a successful PV system. So in PV systems a maximum power point tracker (MPPT) is very much needed. In most PV systems a control algorithm, namely maximum power point tracking algorithm is utilized to have the full advantage of the PV systems.

#### **Working of Maximum Power Point Tracking**

For any given set of operational conditions, cells have a single operating point where the values of the current (I) and voltage (V) of the cell result in a maximum power output. These values correspond to a particular load resistance,  $R = V/I$ , as specified by Ohm's Law. The power P is given by  $P = V \cdot I$ . From basic circuit theory, the power delivered from or to a device is optimized where the derivative of the I-V curve is equal and opposite the I/V ratio. This is known as the maximum power point (MPP) and corresponds to the "knee" of the curve[33].

The load with resistance  $R = V/I$ , which is equal to the reciprocal of this value and draws the maximum power from the device is sometimes called the characteristic resistance of the cell. This is a dynamic quantity which changes depending on the level of illumination, as well as other factors such as temperature and the age of the cell. If the resistance is lower or higher than this value, the power drawn will be less than the maximum available, and thus the cell will not be used as efficiently as it could be. Maximum power point trackers utilize different types of control

circuit or logic to search for this point and thus to allow the converter circuit to extract the maximum power available from a cell.

## **Methods of MPPT algorithms**

Maximum Power Point Tracking (MPPT) is used to obtain the maximum power from these systems [5,23]. In these applications, the load can demand more power than the PV system can deliver. There are many different approaches to maximizing the power from a PV system, this range from using simple voltage relationships to more complex multiple sample based analysis.

## **MPPT Methods**

There are some conventional methods for MPPT. Seven of them are listed here.

These methods include:

1. Constant Voltage method
2. Open Circuit Voltage method
3. Short Circuit Current method
4. Perturb and Observe method
5. Incremental Conductance method
6. Temperature method
7. Temperature Parametric method

In this paper we chose Perturb and Observe method is covered in this paper for their simplicity and reliability.

### **3.4.4 Perturb and Observe Method**

In this method the controller adjusts the voltage by a small amount from the array and measures power, if the power increases, further adjustments in the direction are tried until power no longer increases [19,23]. This is called P&O method. Due to ease of implementation it is the most commonly used MPPT method.

P&O is very popular and most commonly used in practice because of;

1. Its simplicity in algorithm.

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2. Ease of implementation.
3. Low cost
4. It is a comparatively an accurate method

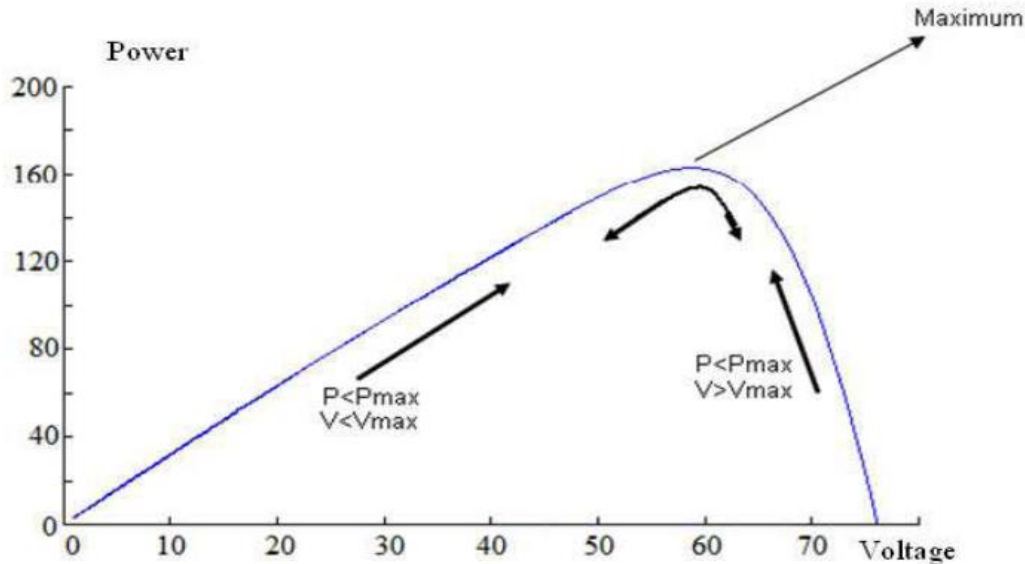


figure3. 22 Output power using P&O algorithm

The voltage to a cell is increased initially, if the output power increase, the voltage is continually increased until the output power starts decreasing. Once the output power starts decreasing, the voltage to the cell decreased until maximum power is reached. This process is continued until the MPPT is attained. This result is an oscillation of the output power around the MPP. PV module's output power curve as a function of voltage (P-V curve), at the constant irradiance and the constant module temperature, assuming the PV module is operating at a point which is away from the MPP.

In this algorithm the operating voltage of the PV module is perturbed by a small increment, and the resulting change of power,  $P$  is observed. If the  $P$  is positive, then it is supposed that it has moved the operating point closer to the MPP. Thus, further voltage perturbations in the same direction should move the operating point toward the MPP [19, 21,29]. If the  $P$  is negative, the operating point has moved away from the MPP, and the direction of perturbation should be reversed to move back toward the MPP.

The model and flowchart of this algorithm is given below:

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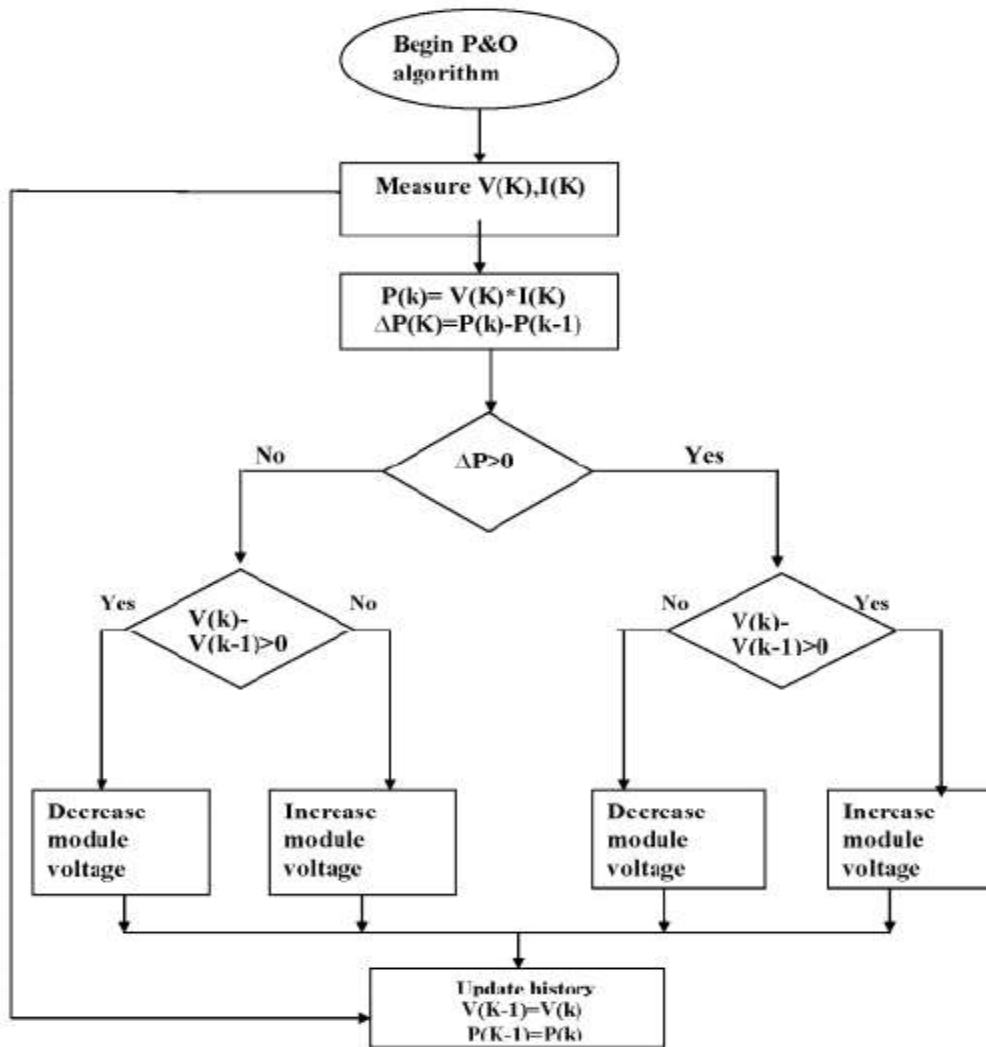


figure3. 23 Perturb and observe algorithm flow chart

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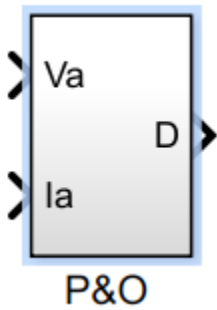
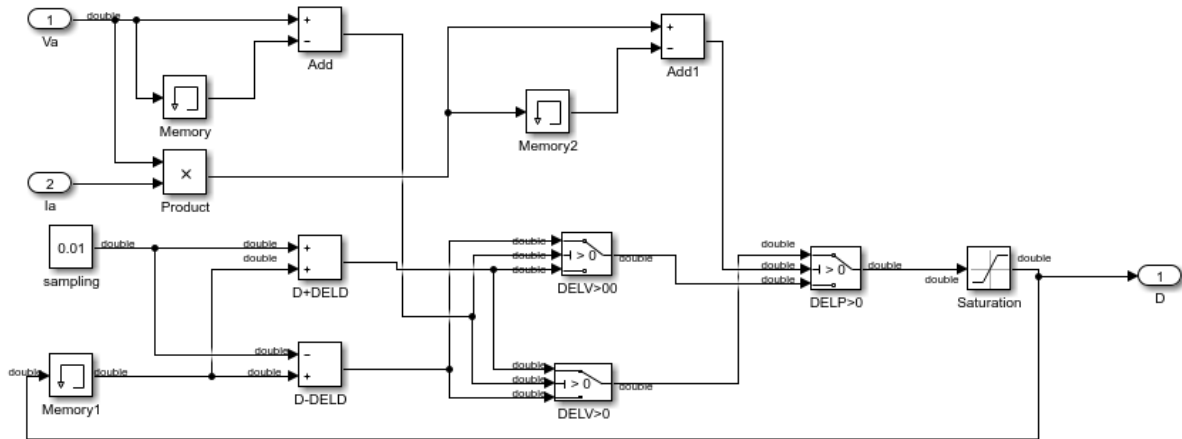


figure3. 24 P&O algorithm model(top) and subsystem(bottom)

To obtain a stable voltage from an input supply (PV cells) that is higher and lower than the output, a high efficiency and minimum ripple DC-DC converter required in the system for residential power production. Buck boost type converters are most efficient for this purpose. The MPPT algorithm drives the converter so that it can draw the maximum power always.

### 3.4.5 DC-DC Converter

DC-DC converter is an electronic circuit which converts a source of direct current (DC) from one voltage level to another. The DC-DC converters are widely used in regulated switch-mode dc power supplies and in dc motor drives applications [23]. Often the input of these converters is an unregulated dc voltage, which is obtained by rectifying the line voltage, and therefore it will fluctuate due to changes in the line voltage magnitude. Switch-mode DC-DC converters are used

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to convert the unregulated dc input into a controlled dc output at a desired voltage level. The heart of MPPT hardware is a switch-mode DC-DC converter. MPPT uses the converter for a different purpose: regulating the input voltage at the PV MPP and providing load matching for the maximum power transfer

.

## **Topologies**

There are many topologies are used as DC-DC converter. They are categorized into isolated or non-isolated topologies [23]. The isolated topologies use a small-sized high-frequency electrical isolation transformer which provides the benefits of DC isolation between input and output, and step up or down of output voltage by changing the transformer turns ratio. They are very often used in switch mode DC power supplies In PV applications, the grid-tied systems often use these types of topologies when electrical isolation is preferred for safety reasons.

There are topologies able to step up and down the voltage such as:

1. Buck-Boost
2. SEPIC (Single Ended Primary Inductor Converter)

For PV system with batteries, the MPP of commercial PV module is set above the charging voltage of batteries for most combinations of irradiance and temperature. A buck converter can operate at the MPP under most conditions, but it cannot do so when the MPP goes below the battery charging voltage under a low-irradiance and high-temperature condition. Thus, the additional boost capability can slightly increase the overall efficiency.

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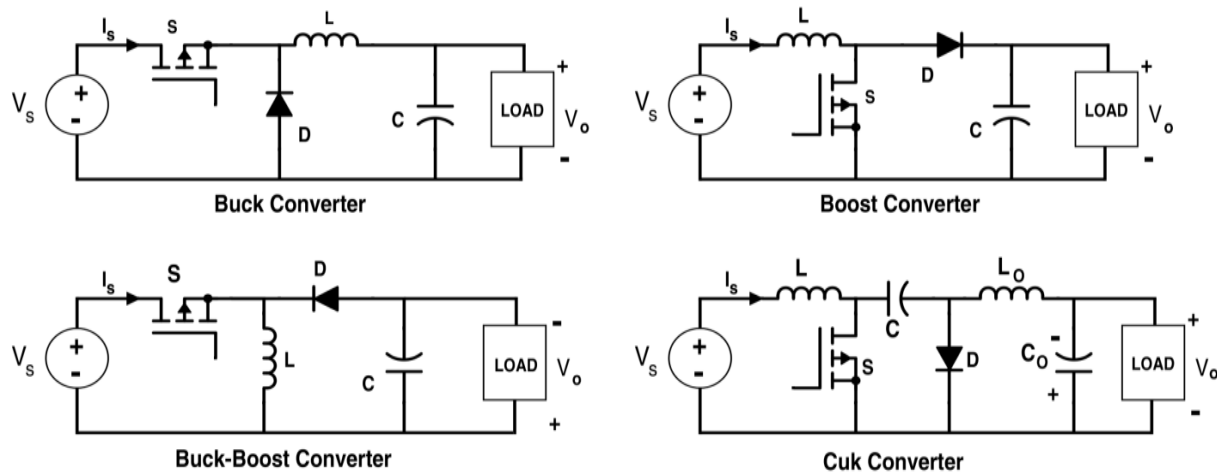


Figure 3. 25 DC-DC converter topology

### Buck-boost converter

To obtain a stable voltage from an input supply (PV cells) that is higher and lower than the output, a high efficiency and minimum ripple DC-DC converter required in the system for residential power production. Buck-boost converters make it possible to efficiently convert a DC voltage to either a lower or higher voltage. Buck-boost converters are especially useful for PV maximum power tracking purposes, where the objective is to draw maximum possible power from solar panels at all times, regardless of the load.

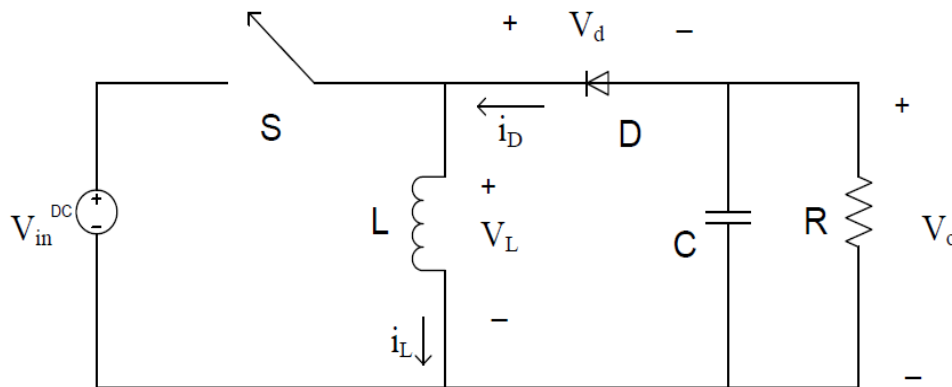


figure3. 25 Basic schematic of buck-boost converter

The buck boost converter can be obtained by the cascade connection of two basic converters: step up (Boost) and step down (Buck) converter.

In PV applications, the buck type converter is usually used for charging batteries. The boost

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topology is used for stepping up the voltage. The grid-tied systems use a boost type converter to step up the output voltage to the utility level before the inverter stage. The input output voltage conversion ratio is the product of the conversion ratios of the two converters in cascade (assuming that the switches in the both converters have the same duty ratio).

$$\frac{V_o}{V_{in}} = \frac{D}{1-D}$$

This the output voltage to be higher or lower than the input voltage based on the duty ratio. The cascade connection of the step up step down converters can be combined into single buck boost converters, when the switch is closed the input provides energy to the inductor and the diode is reversed biased. When the switch is open the energy stored in the inductor is transferred to the output. No energy is supplied to the output in this interval. The output capacitor is considered to be very large which results in a constant output voltage  $V_o$ .

The basic principle of the buck–boost converter is fairly simple.

- While in the On-state, the input voltage source is directly connected to the inductor (L). This results in accumulating energy in L. In this stage, the capacitor supplies energy to the output load.
- □ While in the Off-state, the inductor is connected to the output load and capacitor, so energy is transferred from L to C and R.

### **Modeling of DC-DC buck boost Converter**

PV generated voltage is fed to the converter and Cuk converter output connected to the load. By varying the duty cycle the voltage gain of Buck–Boost converters can be set higher or lesser than unity [8,10]. Although the CUK configuration is cheaper than the Buck–Boost but it has some limitations such as high peak and discontinuous input current, poor transient response and efficiency. The Buck–Boost converter has low switching losses and the highest efficiency among non-isolated DC-DC converters. It can also provide a better output-current characteristic due to the inductor on the output stage. The practical circuit of Buck–Boost converter using diode and MOSFET are shown in Fig.

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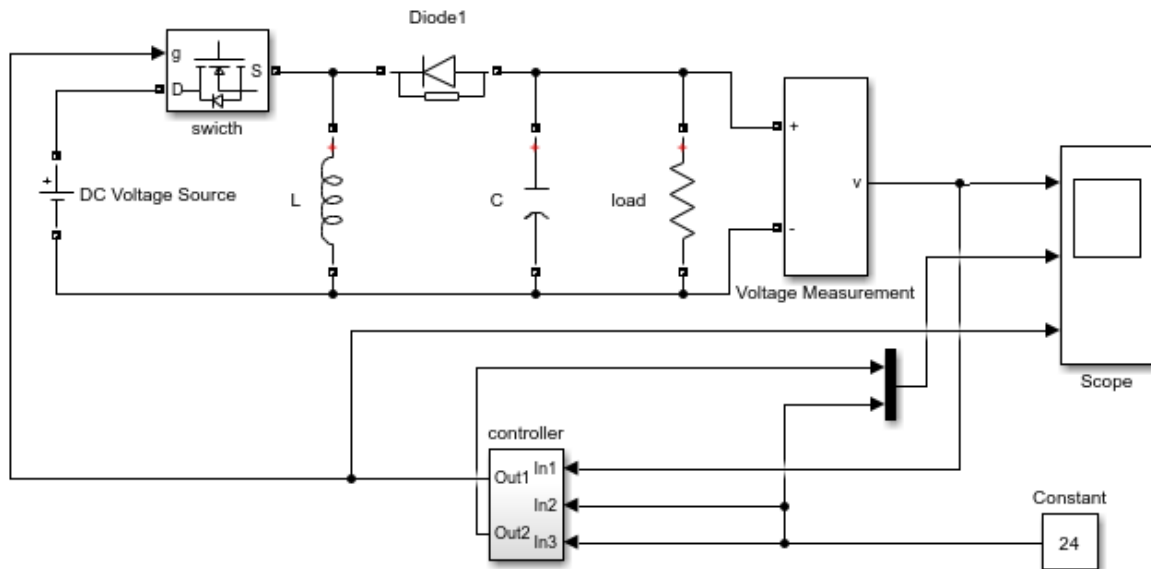


figure3. 26 Modeled buck-boost converter

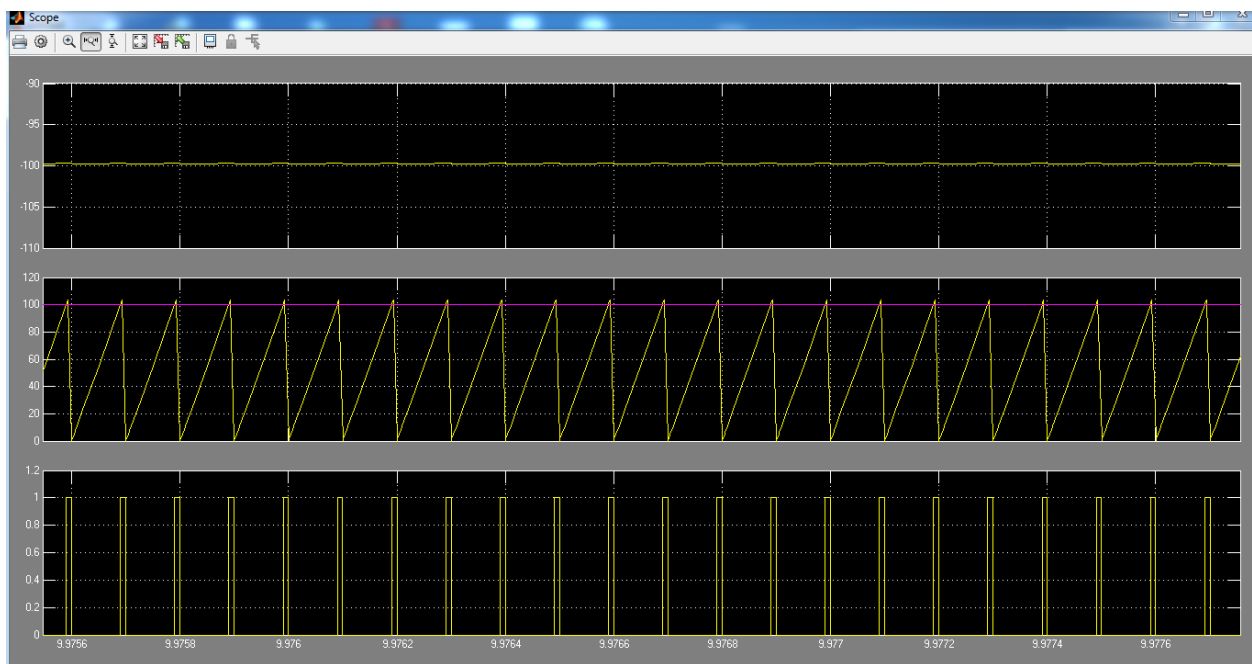


figure3. 27 Graph during boosting mode

The graph above shows 48DCV is boosted to 100DCV. The parameters of the DC-DC converter is shown below.

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Table 3. 3 DC-DC parameter

converter parameter	Values
resonant inductor	10e-6
resonant capacitor	40e-3
Resistor	100

Up until now we have discussed all components of the proposed PV system that is more that capable of powering the charger of auxiliary power box of ADDIS LRT without taking into account the power loss factor of any PV system. In the next chapter we will consider this power factor (0.75) that means around 10kw will be used for hybridization with 8kw power supply from auxiliary power box.

## **CHAPTER FOUR**

### **HYBRID SYSTEM AND FLC BASED EFFICIENT ENERGY MANAGEMENT CONTROLLER**

#### **4.1 Introduction**

The DC power either is used to serve the load directly or converted to good quality AC power supply to AC loads. Due to uncertainties of the renewable energy availability. In order to utilize power efficiently there has been growing interest to developing hybrid energy generation system, from different kind of renewable energy source. The hybrid energy generation system consist of some main issues are stability, reliability, and power quality. To use these problems storage element is used. The clean power generation world prefers PV panel and wind generation system. As we have discussed in the previous chapter the modeled standalone PV power which is DC power is going to be hybridized with train's grid DC power from Pantograph. In this Chapter multiport dc-dc converters have been proposed to do the efficient power management and load integration for the multiple sources. The isolated dc-dc converter has connected with two different sources:

- 1) Roof top solar panel,
- 2) Grid power form auxiliary power box

The multiport dc-dc converter with energy storage has become a promising option for many of power systems, which including fuel cell vehicle, hybrid vehicle, renewable energy application and so on [38]. It not only reduces the cost and improves the efficiency of the system performance. With its ability to reverse the direction of current flow and power. The multiport dc-dc converters are used to achieve the power transfer between sources and load. It is also regulated by the solar panel photovoltaic (PV) power production level, thus to maintain a stable load voltage and make fully usage of the solar panel, grid and the storage element battery.

This converter is applicable to provide constant high level DC voltage and obtain other important function. Isolated multi-port converter is mainly classified into two categories. One is separate

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winding method and other one is common winding method. In this common winding method consist of common ground for multi input source. This topology is proposed in power management system.

Power may be controlled simultaneously use of fuzzy control to extract the maximum power from sunlight, by using the proposed converter. This proposed converter has only one switch is connected for each input source. In the secondary side of the converter have no controlled switches. The efficiency of the converter is increased by switch ON or switch OFF time interval, depend upon decrease peak current.

## 4.2 Working Principle of Designs

There are two power sources to the system of onboard LRT Electrical devices, Catenary/Grid Line and Solar PV. The PV panel is considered as primary source of power. Hence, all onboard loads get power directly from the panel as long as enough sun light energy exists; i.e. during the day time. However, if the irradiance of the sun drops down in the evening or during rainy time, the system is made to automatically change to Catenary /Grid Line via the two switches GRID\_switch and PV\_switch. A fuzzy logic system employs the irradiance of the sun as an input to decide which of the switches should be ON or OFF. The input of the fuzzy logic is designed such that if irradiance is more than  $900 \text{ W/m}^2$ , the input is labeled as “High” and PV\_switch is activated according the fuzzy rule. If the irradiance gets below  $900 \text{ W/m}^2$ , the reverse happens, i.e. PV switch is automatically disconnected from the system but GRID\_switch comes into connection. In such a manner the DC/AC inverter Universal Bridge gets uninterrupted DC power, which is then converted to three phase AC with the help of DC/AC inverter and filter. The universal bridge employs an inverter control system and PWM generator function in order that generated signal has sinusoidal nature. After generation of three phase power, a delta star transformer is employed for the sake of circuit isolation and bringing neutral point for single-phase operated loads. There exist single phase and three phase driven electrical loads onboard the train. Hence, to kinds of loads (single phase and three phases) are modeled at the end of the circuit. The flow chart of the main design of the whole system is as following.

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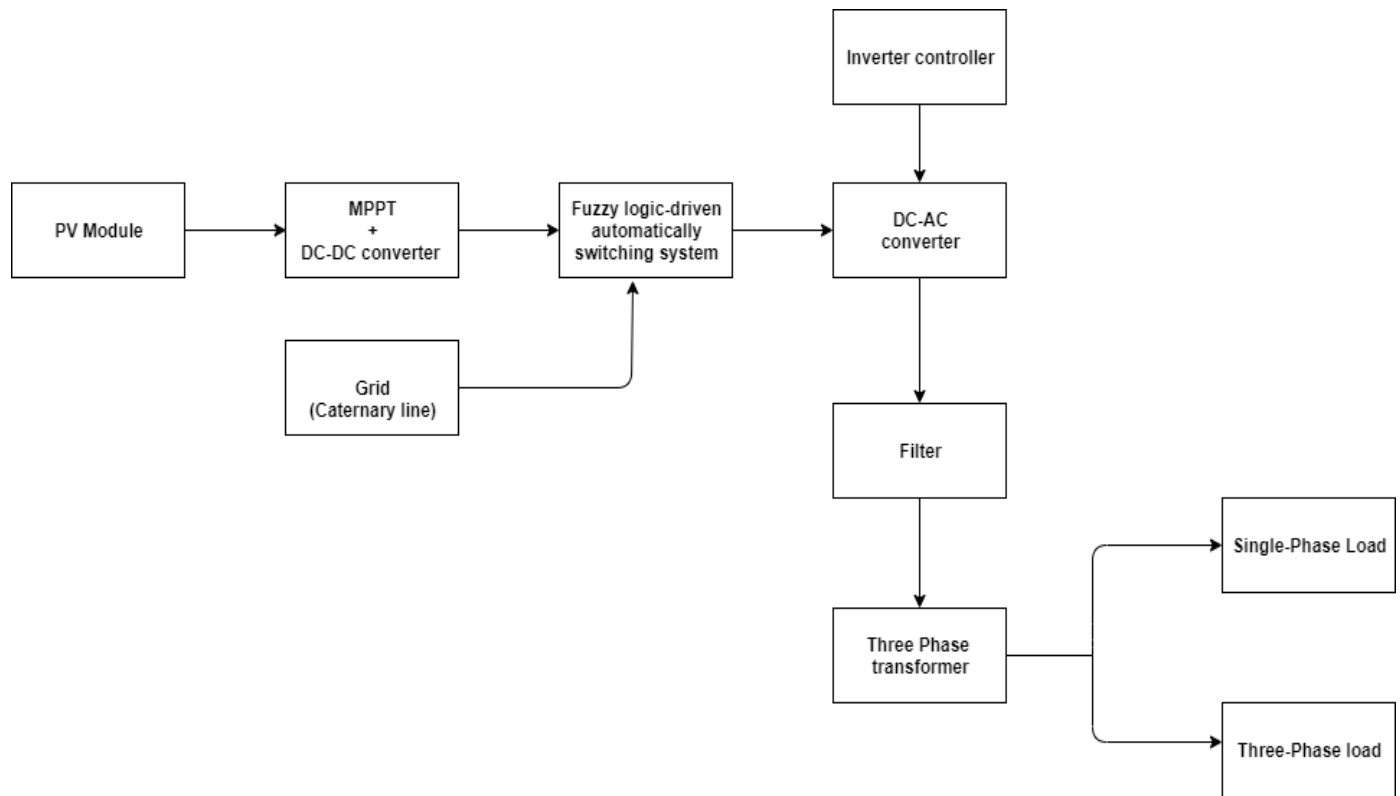


Figure 4. 1Flow chart of the whole system

## 4.3 Control Analysis

In this proposed system an intelligent power management system is deployed on multi-port converter which is controlled by the fuzzy logic controller. Switches and the modes of operation of the converter is controlled by the fuzzy control. It controls according to the output converter. For this, rules created depending up on the operation. Because fuzzy is a rule based system. By the membership function rules are created.

To verify the accuracy of the designed controller, a dynamic model of the proposed system is necessary. It is basically done by distributed energy and energy storage components were mainly built by MATLAB Simulink mathematical modules, based on equivalent circuits of the components. The model of each subsystem has been explained in detailed manner in the previous

chapter. The power management is modeled in MATLAB Simulink will be discussed later on in this chapter.

### **4.3.1 Design of fuzzy controller**

Fuzzy control theory is designed for the hybrid system to achieve the optimization of the system. The design criterion requires that the photovoltaic device is supplied by a maximum power point tracker to maintain the maximum operating point. The main objective of this paper is to minimize power consumption from grid. the difference between actual load and PV generated power is taken into account for battery in charge and discharge modes is the priority in this fuzzy control design. There are one input and four output functions.

FLC based Efficient Energy Management Controller (EEMC) monitors the status of load, power generated by sources (grid and PV system) and battery storage [18] [19]. It receives all sources existing power and load power. Depending on the load and available power generated by source, it selects individual source or combination of sources supply to the grid. It continuously monitors the power generated by PV and load power and activates the switches from controller whenever it is needed based on the rules created.

In this paper the proposed FLC based Energy Management Controller handles the non-conventional energy sources effectively and extends the life time of Battery bank. EEMC produces signal and actuate switches which power is in need also charging and discharging of the battery bank.

Fuzzy logic controller analyses the individual source power and load demand then controls the selector switch individually. In this paper Mamdani type of fuzzy is proposed with Min-Max method of fuzzification and centroid method of defuzzification [36]. It has one input named as change in power  $\Delta P$  the difference in power between the PV power ( $P_{PV}$ ) and load power ( $P_L$ ). It has 2 outputs such as SSW1, SSW2, SSW3 and SSW4. The input has 4 triangular membership functions such as Very Low, Low, Medium and High {VL, L, M and H} and it is shown below. Maximum possible combination of sources under various loads is formed as rules.

The definition of input and output variables are listed as follows:

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The input function is:

$$\diamond \Delta P = P_{pv} - P_L \text{ .....(4.19)}$$

The output functions are controlled signal of MOSFET switches;

- ❖ SW1
- ❖ SW2

The membership functions used for both input and output are triangular. The input membership functions of fuzzy control contain six grades: VH (very high), H (high), Z (zero), M (medium), L (low) and VL (very low). And the output membership function contains two grades ON and OFF as shown in Figs.

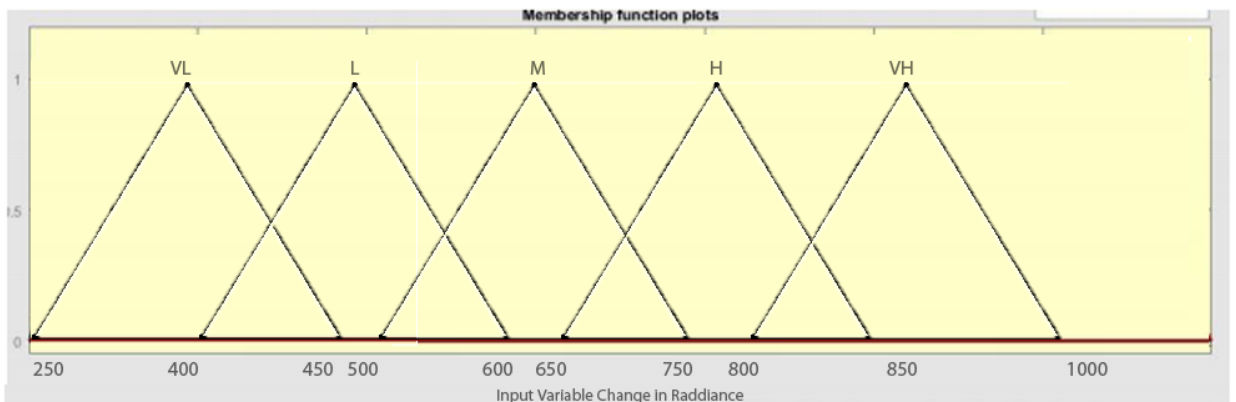
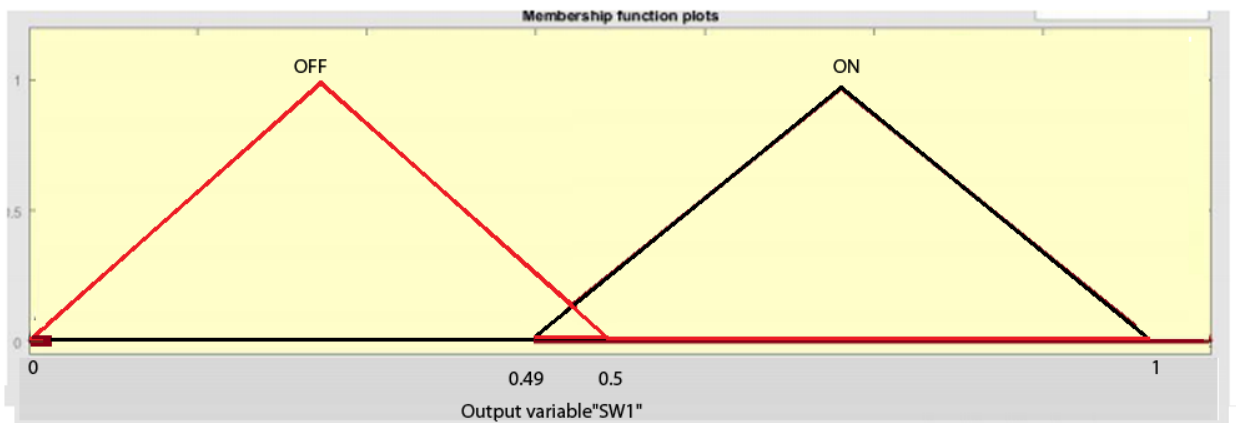


Figure 4. 2Membership Function for input



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Figure 4. 3 Membership Function for output

Full system of fuzzy logic switch control with one input that is the change in power ( $\Delta P$ ) between the PV generated power ( $P_{pv}$ ) and the load power ( $P_L$ ), and two outputs signals for each switches SW1, SW2 is shown in the figure below.

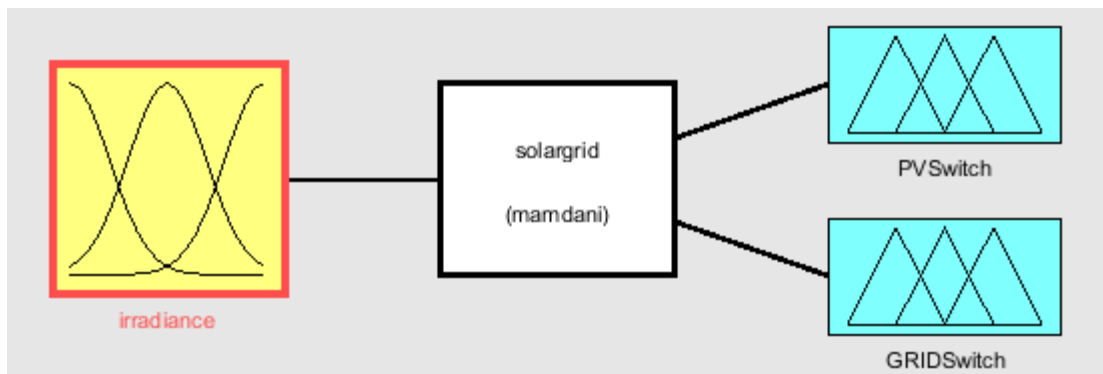


Figure 4. 4 Proposed fuzzy logic controller

## 4.3.2 Rule Viewer for Fuzzy Control

The below fig.4.6 shows the set of rules in fuzzy control. The linguistic values to numeric values changed by using center of the gravity defuzzification method.

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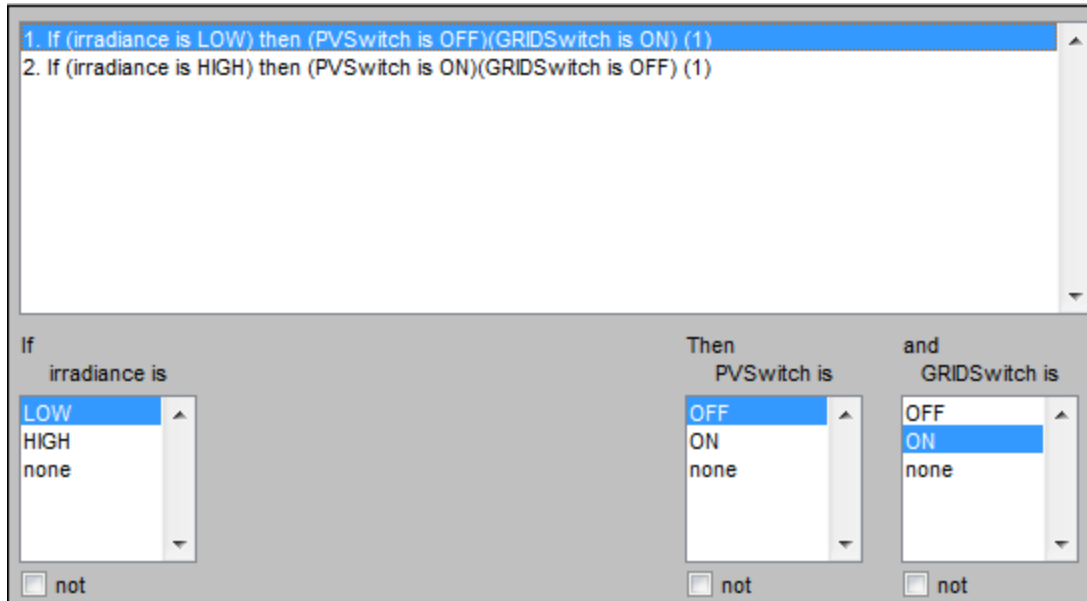


Figure 4. 5 Rules for controller

Working principle of fuzzy logic power management system is described as follows:

The Fuzzy Logic Controller is designed to control three switches, PV\_Switch1, PV\_Switch2 and GRID switch. PV\_Switch1 and PV\_Switch2 get ON or OFF at the same time to fully connect the solar panel to power supply system or disconnect it from the power supply and the converter. Hence the fuzzy controller has two modes of operation, though three switches. The model has irradiance level as input and two switches, PV switch and GRID switch as outputs.

The input irradiance has two states LOW or HIGH. If irradiance is LOW, PV switch is OFF and GRID switch is ON i.e. when the amount sun energy gets low, the PV panel gets disconnected and the power supply system switches automatically to the Grid power supply Catenary Line unless otherwise, the PV arrays keeps supplying power to the load.

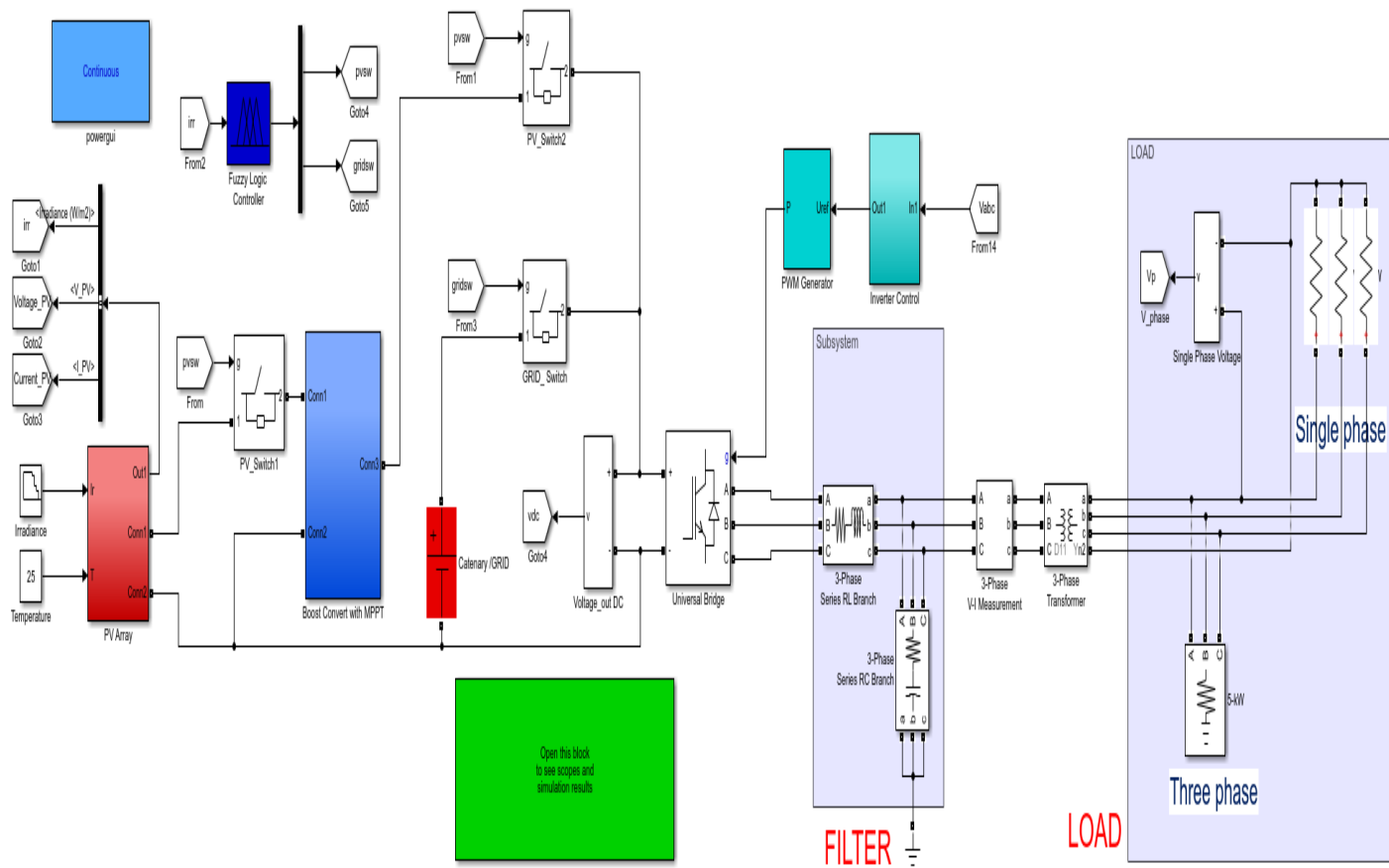
## 4.4 Simulation and Result

The designed controller, a dynamic model of the proposed system is shown in the figure below. It is basically done by distributed energy and energy storage components were mainly built by MATLAB Simulink mathematical modules, based on equivalent circuits of the components. The full model of the system is explained in detailed manner below.

#### **4.4.1 System Model**

It consists of four ports. There are two main source ports for grid supply and pv power supply, battery port and load port. It is operating in three modes. Under running condition any one port supplying, one port is charging and another one is load port. The simulation parameters are input voltage is 48V for PV, 24 for grid .The load output power is 8kw.

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Figure 4. 6 Hybrid intelligent power management with fuzzy controller

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## I. Simulated Input voltage of the inverter

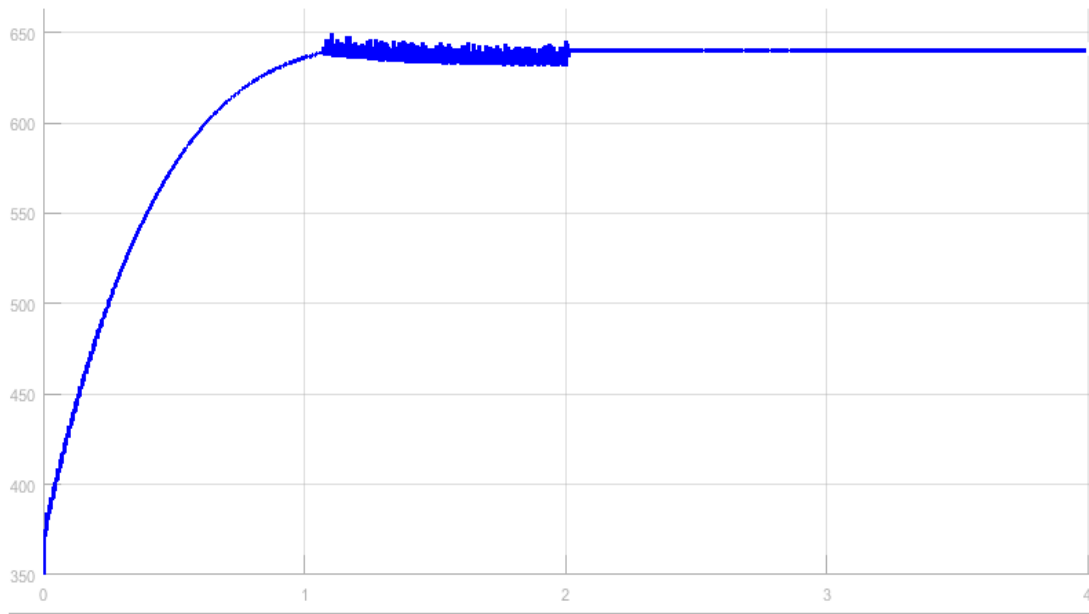


Figure 4. 7 Optimized DC voltage - input to the inverter

## II. Simulated input radiance

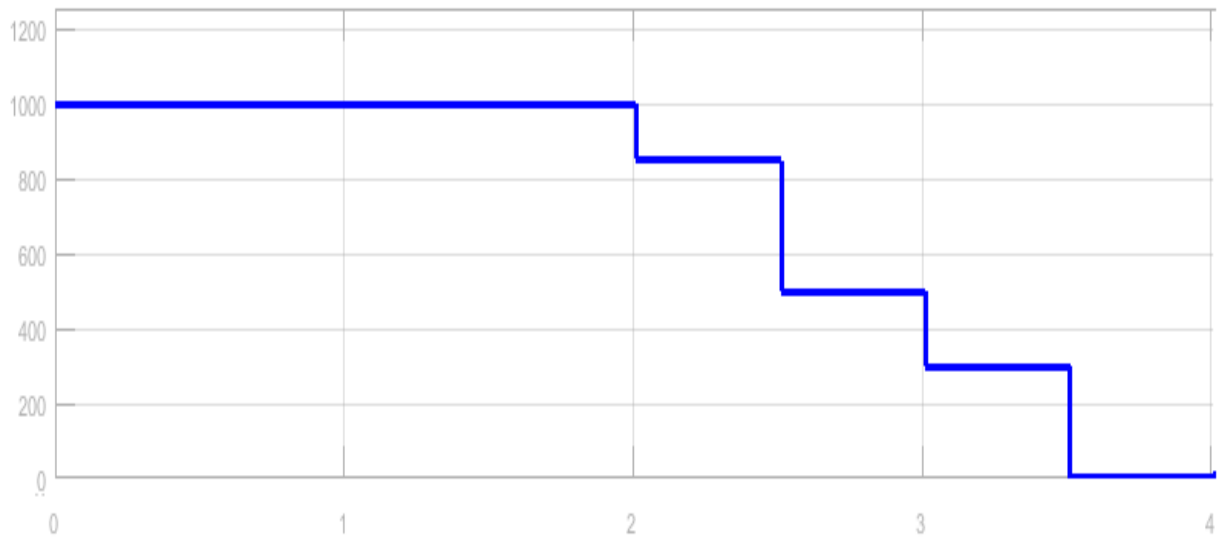


Figure 4. 8: Assumed irradiance variations

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## III. Output voltage and current

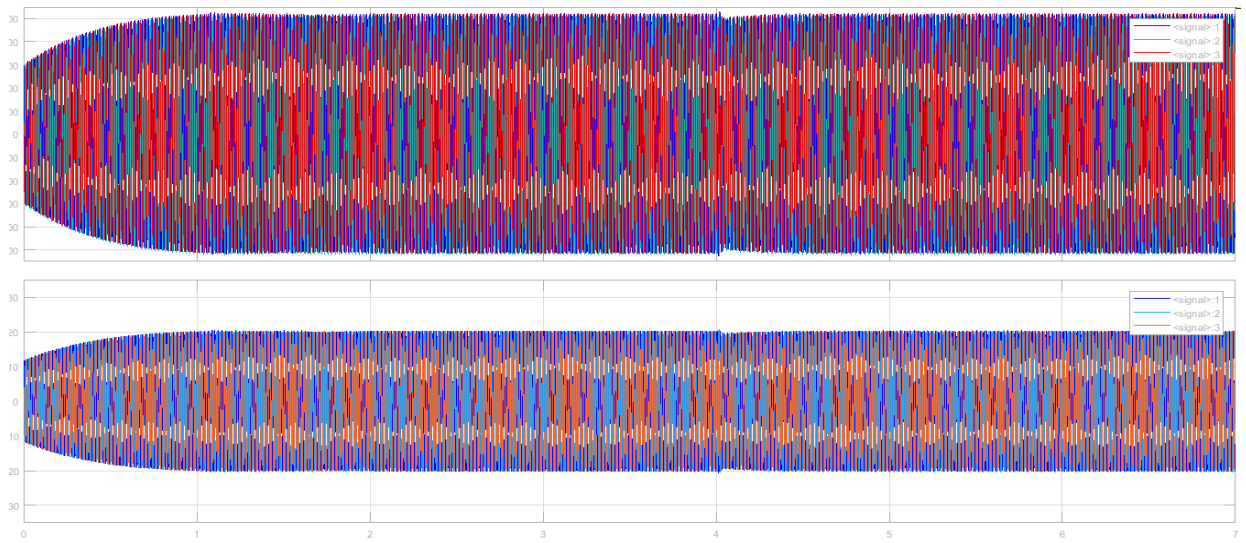


Figure 4. 9 Sinusoidal wave of output for three phase

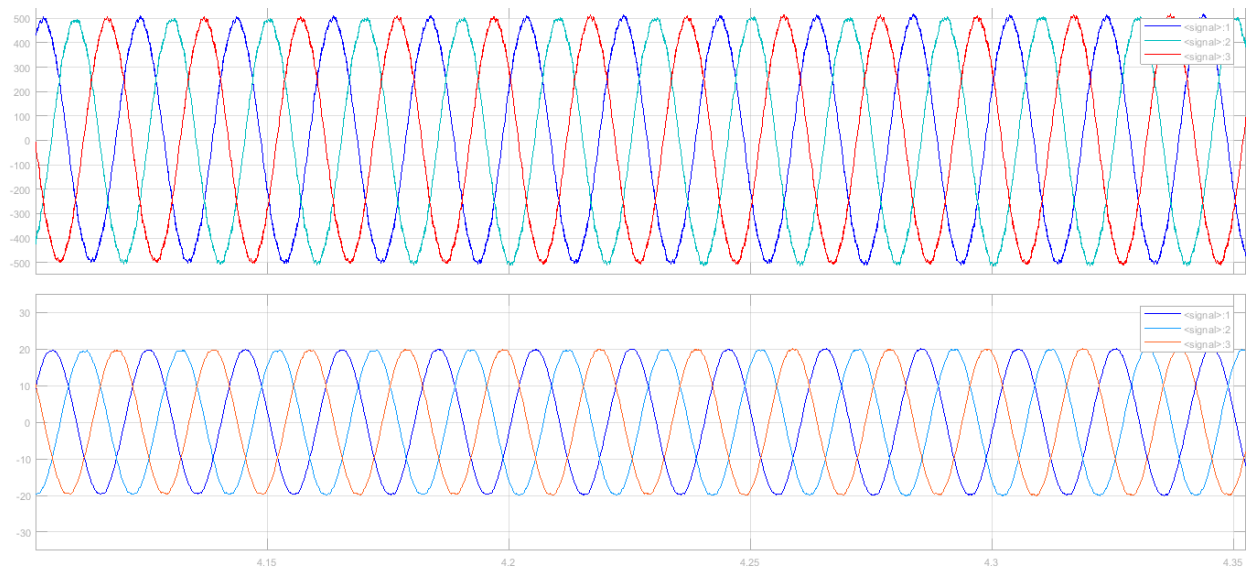


Figure 4. 10 3-phse out of the filter, 3-phase voltage (upper) and 3-phase current (lower)

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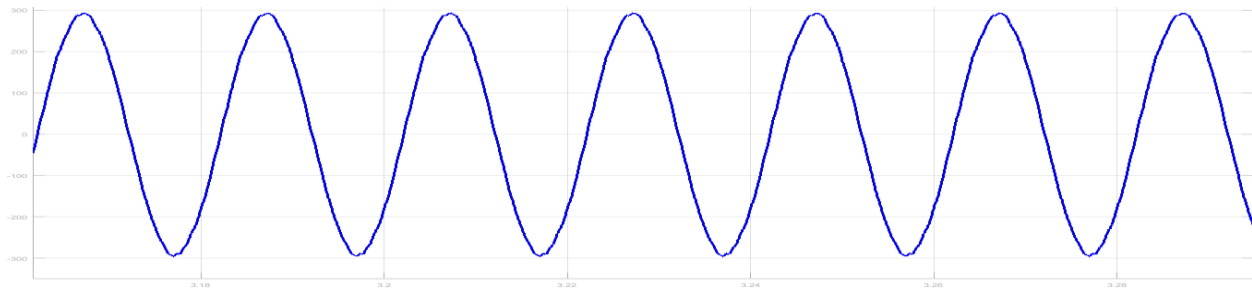


Figure 4. 11 Single phase voltage output- for single phase loads

## CHAPTER FIVE

### CONCLUSION AND RECOMMEDATION

#### 5.1 Conclusion

This paper presents the modeling, analysis, and design of fuzzy control to achieve optimization of a power management system for a grid/ Solar hybrid system for ADDIS ABABA LRT. According to the variation of the solar isolation and the load demand, the fuzzy logic controller used to work effectively by turning on and off the power source switches Simulation results were obtained by developing a detailed dynamic hybrid system model. From the simulation results, the system achieves power equilibrium and it is a multiple variable control problem with unexpected external disturbances. Many parameters such as the charging rate, the permitted maximum charging current, the internal resistor, the port voltage, the temperature and moisture, *etc.* keep changing during the charging and discharging process can't be directly obtained, so it is difficult to achieve the optimal operation performance by using traditional control methods. With MPPT charge controller and fuzzy control and power dispatching respectively used in a renewable energy generation system is developed. Simulation results based on fuzzy strategies show that the control unit has satisfied performance in Simulink and analytical analysis.

#### 5.2 Recommendation

The work done can further be researched upon hardware implementation and be studied on different pitch angle of solar panel so that, it will help to produce maximum energy and will able to use its optimum capacity all day long.

To achieve the optimum use of power, further study can be conducted on minimizing AC power so as to replace it with renewable energy or more efficient energy which require less power to operate.

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## Appendix

### A. MPPT Algorithm

```
function duty = mppt(vpv, ipv, delta)
    duty_init=0.1;
    duty_min=0;
    duty_max=0.85;
    persistent Vold Pold duty_old;
    if isempty(Vold)
        Vold=0;
        Pold=0;
        duty_old=duty_init;
    end
    P=vpv*ipv;
    dv=vpv-Vold;
    dp=P-Pold;
    if dp~=0 && vpv>0
        if dp<0
            if dv<0
                duty=duty_old-delta;
            else
                duty=duty_old+delta;
            end
        else
            if dv<0
                duty=duty_old+delta;
            end
        end
    end
end
```

### B. Fuzzy logic plots

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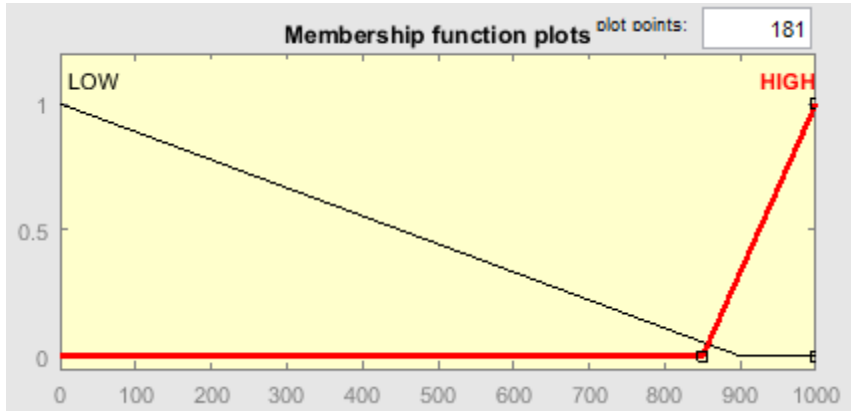


Fig B-1 Membership Function of Input Variable

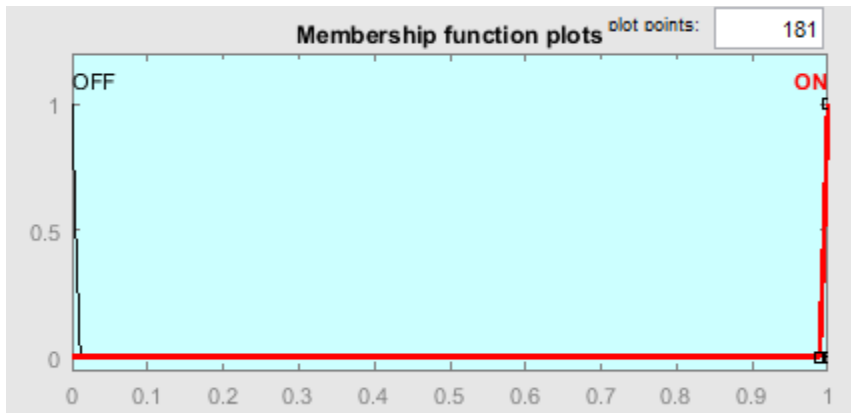


Fig B-2 Membership Function of one of Output Variable

## C.Subsystems of the entire model

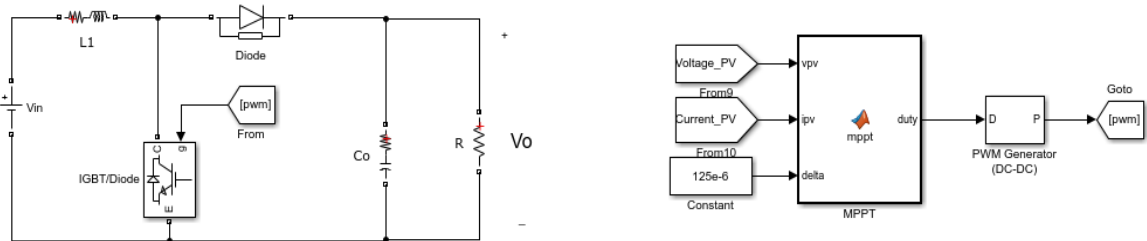


Fig C-1 Boost Converter with MPPT

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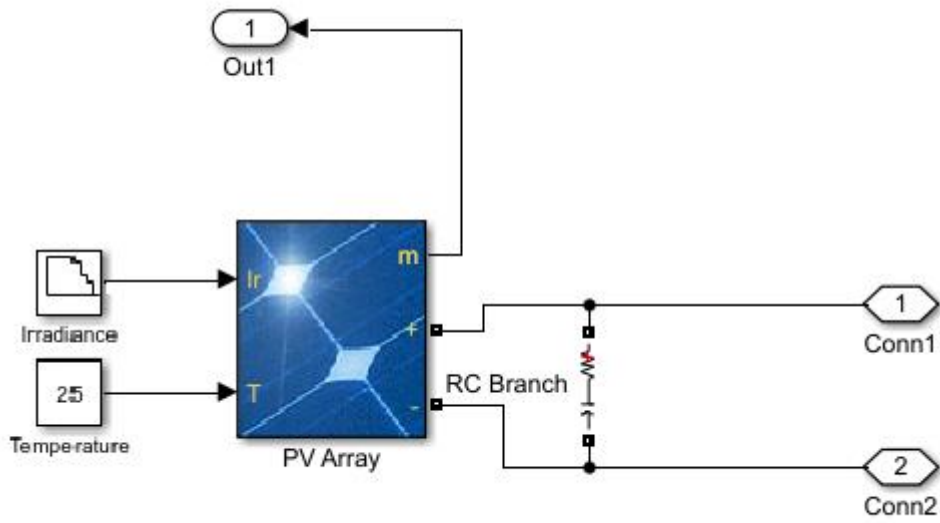


Fig C-2 PV array model