Selection of Appropriate DC Voltage Level Solar Powered for DC Residential Rural Area (Case Study Tullu Gudo)

By

Berhanu Kuma Hawas

A Thesis Submitted to the Department of Electrical Power and Control Engineering School of Electrical Engineering and Computing

Presented in Partial Fulfillment of the Requirements for the Degree of Masters of Science in Electrical Power Engineering

Office of Graduate Studies

Adama Science and Technology University

July 2020 G.C

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Approval by Board of Examiners

We, the undersigned, members of the Board of Examiners of the final open defense by Berhanu Kuma have read and evaluated his thesis entitled "***Selection of Appropriate DC Voltage Level Solar Powered for DC Home System***" (Case Study of Tullu Gudo) and examine the candidate. This is, therefore, to certify that the thesis has been accepted in partial fulfillment of the requirement of the Degree of Masters of Science in Electrical Power Engineering.

Name	Signature	Date
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Declaration

I, Berhanu Kuma, declare that this thesis is my own original work and it has not been presented and will not be presented by me to any other university for similar or any other degree award.

Signature___________________________ date______________________

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Abstract

This thesis presents a selection of appropriate DC voltage levels used for DC in residential remote area. The DC bus is the common link between distributed sources and loads. The most common voltage values nowadays are 24V, 48V and 120V DC. Several criteria have be considered, such as efficiency and reliability, voltage drop and power losses through the cables connecting loads to DC bus. The final choice of the DC voltage was a single bus of 120V DC. This paper also presents a detailed model of DC home system solar powered in Tullu Gudo. The system is composed of a Photovoltaic array, Maximum Power Point Tracker (MPPT) Controller, DC-DC converters, charge controller and battery. The modeling carried out by estimating the required load, selecting and determining the proper specifications of the components involved in the system. The daily average load demand is 8.835 kWh/day. This load demand can be met by the solar array of 18 panels with a backup of 30 units of the battery having a capacity of 276 Ah. The system implemented in MATLAB/simulink platform with the solar radiation and temperature. The voltage regulation of 120V DC is 3.09 and its efficiency is 99.4%. Simulated results indicate that the proposed DC home system model meet the load demand and show good performance.

Keywords: *Photovoltaic system, DC/DC converters, MPPT, DC voltage levels, PI controller, DC home appliances and MATLAB simulation.*

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Abbreviations

AC ……………………………………………Alternating Current

AM………………………………….………..Air Mass

CCS…………………………………………Current Controlled Sources

CSA …………………………………………Central Statistics Agency

DC …...………………………………………Direct Current

EEPCO ……………………………………....Ethiopian Electric Power Corporation

FAO ………………………………….………... Food and Agriculture Organization

GPS …………………………………………..…Geographic Positioning System

LED ……………………………….…………..…..Light Emitting Diode

MPPT …………………………………….….Maximum Power Point Tracking

NASA ………………………………… ……National Aeronautics and Space Administration

NEC ………...…………………………...…. National Electrical Code

NGO ……..…………. ………………………. Non-Governmental Organization

NMA ……………………..……………………National Meteorological Agency

PSH …………………………………………Peak Sun Hours

PV ….…………………………………………Photovoltaic

PWM …………………………...…….…….Pulse Width Modulation

RET ………………………………….……..Renewable Energy Technologies

SHS ………………………………….……….Solar Home System

SMPS…………………………………………Supply Mode Power System

Chapter One

1. Introduction

1.1 Background

Direct current is gaining more and more popularity due to the increasing use of renewable distributed sources such as wind turbines and photovoltaic systems. Many researchers have compared AC to DC micro-grids [1] and concluded that DC are more efficient and cost effective because of the elimination of the wasteful conversion stages from AC to DC and DC to AC. This recently emerging concept is either integrated in commercial and residential buildings for many reasons. In fact, the first argument is the predominance of household devices consuming DC power such as electric vehicles, consumer electronics, computers, lighting, chargers, etc. Add to that, the widespread of in small-scale renewable energy resources generating DC current and the easy energy DC storage.

In a DC micro-grid and depending on its topology, a single DC bus generally connects all loads to the distributed sources with fixed voltage level, which needs to be maintained by the appropriate control. Unfortunately, this area suffers of lack of standardization [2] and DC bus voltage level is generally chosen in reference to past engineering experiences in a way to fulfill safety, efficiency and cost effective criteria. Hence, numerous DC bus voltage levels, varying from 12V to 380V in DC home application, are encountered in literatures. These DC bus voltages are inspired from existing standards and codes in other domains. Several DC homes with a bus voltage of 380V-400V, copied on data center applications can be found in. Other applications, inspired from telecommunication, adopting 48V as DC bus level voltage, are found in [1]. The use of 12V-24V, inspired on camping car or yacht applications, is also popular in DC home.

Solar power system is very reliable and clean source of electricity that can suit a wide range of application such as residence, industry, agriculture, livestock etc. the system is almost maintenance free which makes it ideal for remote areas. Direct current from the PV system is converted to alternating current by the inverter. That power is then distributed to the AC loads in the conventional, supplying 240Vac to certain high power loads, such as electric HVAC or electric ovens and stoves, and 120Vac to low power loads. In direct-DC home, power from DC power systems or storage devices would be sent directly to DC appliances, rather than first converting it to AC. That is, power distribution within the house is in DC form. This approach eliminates the usual DC-AC-DC conversion losses incurred in powering DC-internal products. However, it incurs other losses because AC grid backup power converted to DC when PV power is not sufficient to power products and any excess DC power inverted to AC for net metering. The PV array still needs a maximum power point tracker, which provides the necessary constant voltage to the load and adjusts the apparent load characteristics seen by the PV array to force it to operate at maximum power output. DC-DC converter would be needed to convert the high voltage DC coming from the array and going to high power loads to lower power loads that operate at lower voltage.

Most remote rural areas of Ethiopia are not yet electrified. Electrifying these remote areas by extending grid system to these rural communities is difficult and costly. As the current international trend in rural electrification is to utilize renewable energy resources, like; solar, wind, biomass, and micro hydropower systems can be seen as alternatives. Among these, solar energy system thought to be ideal solution for rural electrification due to enough solar radiation availability nearby the rural community.

Renewable energy systems have beneficial impact on the environmental, economic, and political issues of the world. According to [3], by the middle of the 21st century, renewable energy sources could account for three fifths of the world's electricity market and two fifths of the market for fuels used directly. Moreover, making a transition to a renewable energy intensive economy would provide environmental and other benefits not measured in standard economic terms.

- Advantages of DC system:
  - DC needs only two wires of transmission, while a 3 phase AC may need up to four wires.
  - Almost all household electronic devices use DC power (Phones, TV's, Laptops, etc.).
  - LED lights use DC power.
  - The Corona loss associated with DC is negligible, while for AC, it increases with its frequency.
  - The skin effect is observed in AC, leading to problems in transmission conductor designs.

- No inductive and capacitive losses.
- No proximity effect.

The aim of this paper is to select appropriate voltage level of solar PV energy system for electrification of rural area of Oromia region around Batu town specific name called Tullu Gudo that not electrified via national grid system. The people in this village use kerosene for lamp, diesel for water pumping and grain-milling machines, fire wood for cooking and dry cells for radio and tape recorders.

Most appliances work internally on DC power. They take AC as input and after conversion process bring the required DC voltage level. These DC internal appliances take AC as input followed by AC/DC converter. This conversion process creates heat losses in working mode and standby mode. If these appliances were fed with solar PV power, transformer and rectifier would terminated from the circuit that saves a considerable amount of energy.

The absence of skin effect in DC system reduces the material cost of the wiring as the whole cross section carries the current. The overall cost of the system is greatly reduced as the equipment for the power factor improvement, AC/DC and DC/AC conversion and reactive power compensation is not required in DC distribution system. With the advancement in semiconductor materials, DC can generated by using solar PV cell. Solar PV cell generates clean and green renewable energy. Historically, this energy is either stored in batteries or delivered to the AC grid through inverters that brings major conversion losses.

New developments in the area of power electronics have made a huge impact in DC power transmission. The main advantages of DC power transmission are reduction of energy losses, simple integration of renewable energy resources such as PV, simple coupling with storage systems, and higher power densities. Many authors have investigated the feasibility of the adoption of direct current in low and medium voltage systems. It shown, that if the losses in DC-DC converters are considerably reduced the total system losses also decreased significantly when DC is used.

1.2. Statement of the Problem and Motivation

DC can be very interesting for remote community. Renewable energy such as solar PV power can be used to provide the energy source. Some researchers have proposed the DC voltage as low as 12V, 24V, and 48V, 120V while others have proposed 380V or higher. There are no standards. An adequate and reliable power supply system is essential for any developing country like Ethiopia. During the past two decades, standalone solar photovoltaic power system has been introduced to remote communities in developing countries. These are of great importance for Ethiopia especially in the rural communities where there is little or no access to electricity. Indeed, standalone solar photovoltaic system can be considered as one of the most promising renewable energy systems. It was adopted globally in meeting basic electricity needs of rural areas that are not connected to the grid. Obviously, standalone photovoltaic power systems installed in some regions of Ethiopia. Unfortunately, the expectations and degrees of satisfactions of the rural communications, PV system performance and reliability, and maintenance issues relating to the photovoltaic systems are not well assessed and investigated carefully and effectively.

1.3. Objectives

The thesis work comprises of the following general and specific objectives:

1.3.1. General Objective

The main objective of the thesis is to study the selection of appropriate DC voltage level and modeling the off-grid photovoltaic power system for DC home at a selected site.

1.3.2. The Specific Objectives

The specific objectives of this thesis are:

- Estimation of average daily load profile at the select site.
- Proposing a basic solar home system layout and stand-alone (off-grid) system configuration.
- Modeling of DC home.
- Performance assessment of DC home system for the different voltage levels (12V, 24V, 48V, 120V and 380V).

- Draw relevant conclusion and recommendations from the result of the investigation.

1.4. Significance of the Study

Electrical power access plays the vital role in accelerating economic development by improving health and life standards. Significant investments made in energy sector to improve electricity access in households and more efforts made by Ethiopian for the above targets accomplished. Combination of various solutions that focus on the geographical location, income and consumption level is needed instead of using the traditional connection to the grid that may not be suitable for all rural households. Off grid PV, systems proposed as a sustainable solution to be implemented with a wide range of technologies from a basic solar home system that can produce electricity for the single house with a radio, mobile phone and for LED lamps to stand-alone systems that can generate high levels of electrical power that can be used by households.

This approach can serve as an economical and reliable solution for increasing the rate of electricity access by the entire rural community as well as for the country in general. Therefore, since the selected place is dry with high intensity of sun radiations, this makes the site more attractive for the use of PV systems for electricity generation and storage.

1.5 Description of the Study Area

Tullu Gudo Island is surrounded by Lake Ziway. It is one of the islands on Lake Ziway located nearly at the center of the Lake and it is located about 60 miles South East of Addis Ababa. The woredas holding the lake’s shoreline are Adami Tulu and Jido kombolcha, Dugda Bora, and Ziway dugda.

Figure: 1.1 Map of the study area

1.6. Scope of the Study

This thesis covers, studying the selection of the appropriate DC voltage level, which is vital for performance of the entire system.

1.7. Methodology

Relevant power components related to the off-grid PV/storage residential system such as, PV, energy storage (battery banks), maximum power point tracking (MPPT), DC-DC converter and battery charge controller have been modeled by using MATLAB® /Simulink. The fundamental structure of PV system given below.

The following methods used to do this thesis work:

- Literature survey: - ideas from different books and journals gathered that helped me to do this work.
- Data collection: - data that are necessary for analysis work collected from Metrology Agency of Ethiopia and manufacturing data sheet.

- The performance assessment of DC home system for the different voltage levels have been conducted on the basis of selected home appliances
- Computer simulation and data analysis: by the use of ideas and data collected, simulate an hourly variation on electrical performance of a PV panel at constant electric load using MATLAB R2019a/simulink.

Chapter Two

2. Theoretical Background and Literature Review

2.1 Introduction

The sun is the largest energy source of life at the same time it is the ultimate source of all energy (except tidal and geothermal power), even the energy in the fossil fuels ultimately comes from the sun. The sun radiates 174 trillion kWh of energy to the earth per hour. In other words, the earth receives 1.74 x 10 17 watts of power from the sun [4].

The sun is a typical star with mass 2×1030 kg, beam length 700,000 km and it has roughly 5 billion more years of life. Its surface temperature is about 5800 Kelvin while the internal temperature is approximately 15 million Kelvin. This temperature derives from reactions, which based on the transformation of hydrogen to helium, the process called nuclear fusion, which produces high temperature of the sun and the continuous emission of large amounts of energy. It is calculated that for each gram of hydrogen that converted to helium sun radiates energy equal to 1.67×105 kWh. The solar energy is emitted to the universe mainly by electromagnetic radiation. Approximately one-third of energy radiated from sun is reflected back. The rest is absorbed and retransmitted to the space while the earth reradiates just as energy as it receives and creates a stable energy balance at a temperature suitable for life.

Ethiopia is one of the horns of African countries, having a population size of over 100 Million. Its total area is 1,104, 300 km^2 with climatic condition of tropical monsoon with wide topographic-induced variation. It has topography of high plateau with central mountain range divided by Great Rift Valley. Energy from the sun offers probably the best potential for a decentralized insertion in Ethiopia. An assessment study indicated in 2002, that the average daily solar radiation reaching the ground for Ethiopia as a whole is 5.26 kWh/m^2. This varies significantly during the year, ranging from a minimum of 4.55kWh/m^2 in July to a maximum of 6.55 a kWh/m^2 in February and March [5].

Renewable energy, which includes solar energy, insures a clean energy supply and it has considered playing an important role of global warming prevention by fighting against climate change. Solar Energy generated depending on the intensity of the sunrays reaching the solar panel and their wavelengths.

Performance assessment of DC home system for residential loads is the focus of this chapter. This review emphasizes on direct current home system concepts in particular about solar energy, voltage level selection, safety issues, and environmental concerns and for DC home system.

There are normally two ways to generate electricity from sunlight: through photovoltaic (PV) and solar thermal systems. In this thesis, photovoltaic power system will be discussed.

2.2 Photovoltaic Power System

A Photovoltaic (PV) power system is a large to medium-scale system designed to supply power; it can be implemented to work on-grid, off-grid and/or accordant with generators. Solar cells convert sunlight directly into electricity. Solar cells are used to power calculators and watches. They are made of semiconducting materials similar to those used in computer chips. When these materials absorb sunlight, the solar energy knocks electrons loose from their atoms, allowing the electrons to flow through the material to produce electricity. This process of converting light (photons) to electricity (voltage) is called the photovoltaic (PV) effect.

Solar cells are combined into modules that hold up to 72 cells; a number of these modules mounted in PV arrays that can be measure up to several meters on a side. These flat-plate PV arrays mounted at a fixed angle facing south, or they mounted on a tracking device that follows the sun, allowing them to capture the most sunlight over the course of a day. Several connected PV arrays can provide enough power for a household; for large electric utility or industrial applications, hundreds of arrays can be interconnected to form a single, large PV system.

Thin film solar cells use layers of semiconductor materials only a few micrometers thick. Thin film technology has made it possible for solar cells to now double as rooftop shingles, roof tiles, building facades, or the glazing for skylights or atria. The solar cell version of items such as shingles offer the same protection and durability as ordinary asphalt shingles.

The performance of a solar cell is measured in terms of its efficiency at turning sunlight into electricity. Only sunlight of certain energies will work efficiently to create electricity, and much of it is reflected or absorbed by the materials that make up the cell. Because of this, a typical commercial solar cell in 2019 has an efficiency of about 19-22 percent; meaning about one-fifth of the sunlight striking the cell generates electricity. Low efficiencies mean that larger arrays are needed, and that means higher cost. Improving solar cell efficiencies while holding down the cost per cell is an important goal of the PV industry, NREL researchers, and other U.S. Department of Energy (DOE) laboratories, and they have made significant progress. The first solar cells, built in the 1950s, had efficiencies of less than 4%.

2.2.1 Photovoltaic Technology

Photovoltaic (PV) materials and devices convert sunlight into electrical energy. A single PV device is known as a cell. An individual PV cell is usually small, typically producing about 1 or 2 watts of power. To boost the power output of PV cells, they are connected together in chains to form larger units known as modules or panels. Modules can be used individually, or several can be connected to form arrays. One or more arrays are then connected to the electrical grid as part of a complete PV system. Because of this modular structure, PV systems can be built to meet almost any electric power need, small or large. Metallic contacts are provided on both sides of the junction to collect electrical current induced by the impinging photons. A thin conducting mesh of silver fibers on the top surface collects the current and lets the light through. The spacing of the conducting fibers in the mesh is a matter of compromise between maximizing the electrical conductance and minimizing the blockage of the light. Conducting-foil (solder) contact is provided over the bottom surface and on one edge of the top surface. In addition to the basic elements, several enhancement features are also included in the construction. For example, the front face of the cell has an antireflective coating to absorb as much light as possible by minimizing the reflection. The mechanical protection is provided by a cover glass applied with a transparent adhesive.

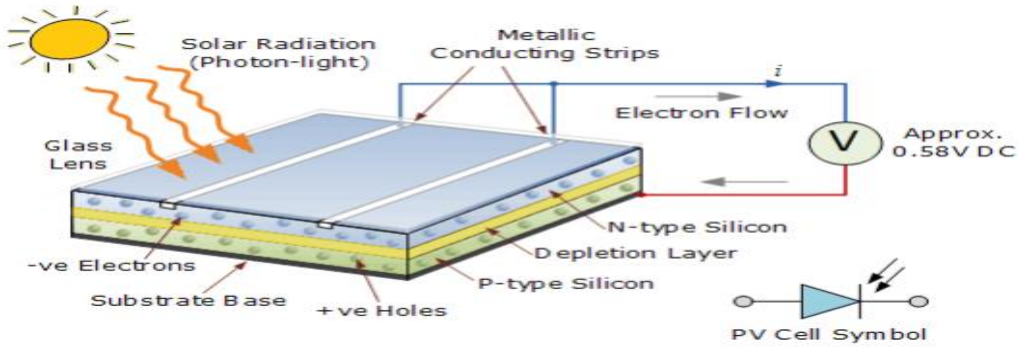


Figure 2.1: Basic structure of a generic silicon PV cell [6]

PV cells are made up of semiconductor material, such as silicon, which is currently the most commonly used element in semiconductor industry. When light strikes the cell, a certain portion of it is absorbed within the semiconductor material. When energy knocks semiconductor electrons loose, allowing them to flow freely. PV cells have one or more electric fields that act to force electrons that are freed by light absorption to flow in a certain direction.

This flowing of electrons is a current and by placing metal contacts on the top and bottom of the PV cell, we can draw that current off to be used externally. This current, together with the cell's voltage, which is a result of its built-in electric field or fields, defines the power in watts that the solar cell can produce.

The material that is used widely in the industry for the production of photovoltaic cells is silicon. Based on the structure of the basic material from which they are made and the particular way of their preparation, the photovoltaic cells of silicon are categorized into four.

The types are the following ones:

- Single-Crystalline Silicon: The basic material is mono-crystalline silicon. In order to make them, silicon is purified, melted, and crystallized into ingots. The ingots are sliced into thin wafers to make individual cells. It is the oldest and more expensive production technique, but it is also the most efficient and widely used sunlight conversion technology available. Cells efficiency oscillates between 14% and 18%.
- Polycrystalline or Multi-Crystalline Silicon: The particular cell is relatively large and it can be easily formed into square shape, which virtually eliminates any inactive area between

cells. It has a slightly lower conversion efficiency compared to single crystalline and manufacturing costs are lower. Cells efficiency oscillates between 10% and 13% [7].

- String Ribbon: This is a refinement of polycrystalline silicon production. There is less work in its production so costs are even lower. Cells efficiency averages 8% to 10%.
- Technology, which uses thin film solar cells while the total thickness of a semiconductor is about 1μm. Amorphous or thin film silicon cells are solids in which the silicon atoms are much less ordered than in a crystalline form. By using multiple junctions this kind of photovoltaic cells achieve maximum efficiency, which estimated at about 13% while the installation cost reduced. The efficiency of this cell oscillates between 6% and 10% [Patel, 2006]. Furthermore, the output of an amorphous silicon cell not decreased as temperature increases and much cheaper to produce than crystalline silicon.

Cells efficiency decreases with increases in temperature. Crystalline cells are more sensitive to heat than thin films cells. The output of a crystalline cell decreases approximately 0.5% with every increase of one degree Celsius in cell temperature. For this reason, modules should be kept as cool as possible, and in very hot condition, amorphous silicon cells may be preferred because their output decreases by approximately 0.2% per degree Celsius increase.

Many crystalline or thin film PV modules power a solar PV system. Individual PV cells interconnected to form a PV module. This takes the form of a panel for easy installation. PV cells are made of light-sensitive semiconductor materials that use photons to dislodge electrons to drive an electric current. There are major groups of technologies used for PV modules: Mono and Poly Crystalline Cell and newer one thin film.

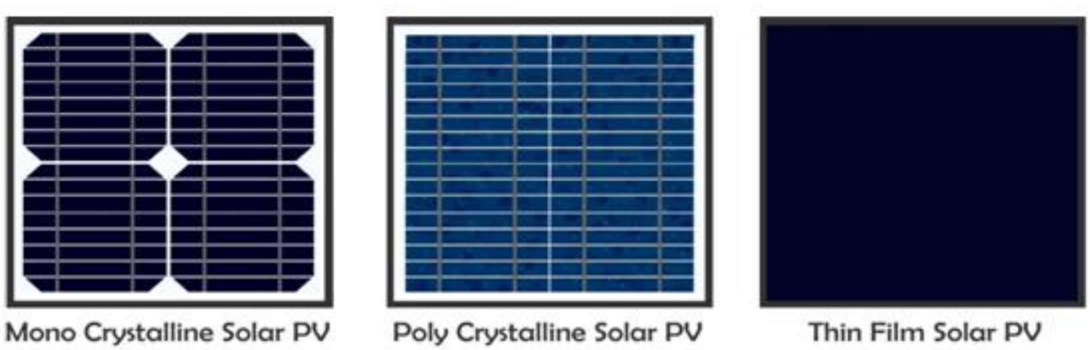


Figure 2.2 types of PV cells modules

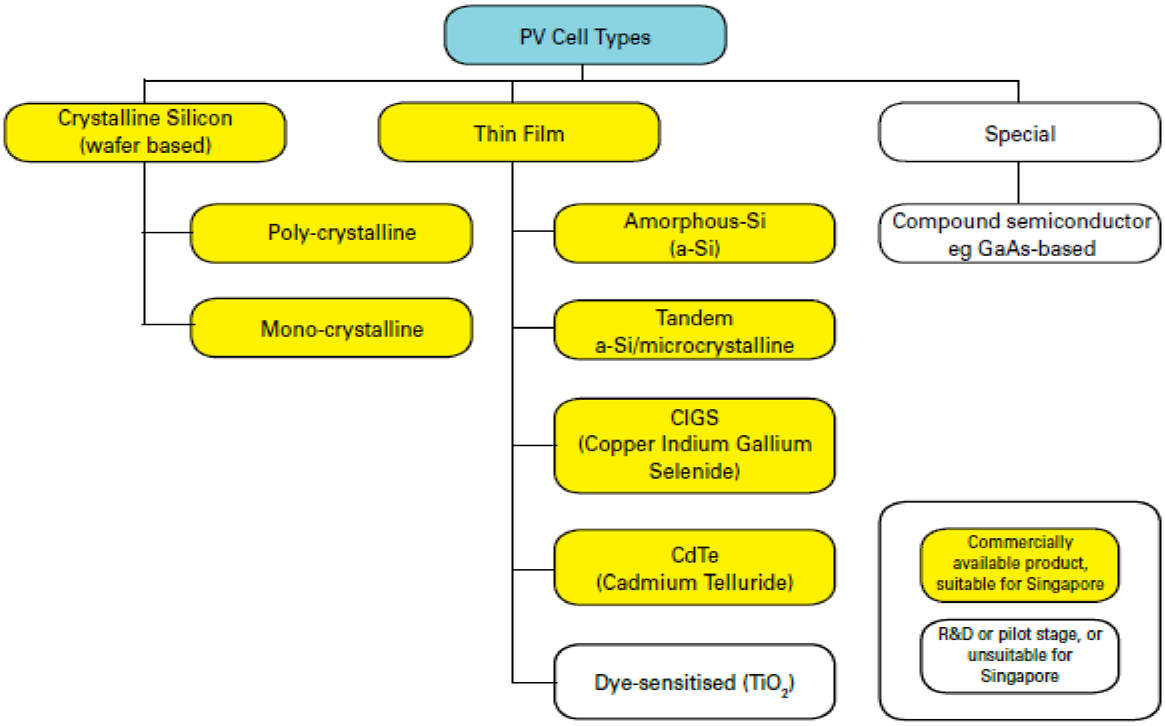


Figure 2.3 PV technology family trees [8]

2.3. PV Module and Array

The solar cell is the basic building block of the PV power system. However, it is rarely used individually because it is not able to supply device with enough voltage and power. For this reason, many photovoltaic cells are connected in parallel or in series in order to achieve as higher voltage and power output as possible. Cells connected in series increases the voltage output while cells connected in parallel increases the current. The solar array or panel is a group of several modules electrically connected in series-parallel combination to generate the required current and voltage and hence the power.

2.4. Equivalent Electrical Circuit of PV Cell

The equivalent electrical circuit shown in Figure 3.4 below can represent the complex physics of the PV cell. The following parameters call for consideration. The current I at the output terminals is equal to the light-generated current I_{pv}, less the diode current I_d and the shunt-leakage current I_{sh}. The series resistance R_s represents the internal resistance to the current flow, and depends on the p-n junction depth, impurities, and contact resistance.

The PV conversion efficiency is sensitive to small variations in R_s, but insensitive to variations in R_{sh}. A small increase in R_S can decrease the PV output significantly.

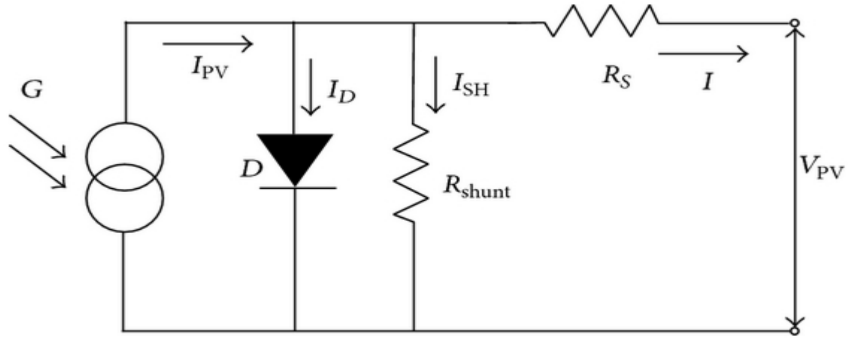


Figure 2.4: A PV cell equivalent electrical circuit [9]

The open-circuit voltage V_{OC} of the cell obtained when the load current is zero and given by the following:

$$V_{0C} = I_O(I_{PV} - I_D)R_{Sh} \quad (2\text{-}1)$$

The diode current is given by the classical diode current expression:

$$I_D = I_O[\exp\left(\frac{qV_{oc}}{AKT}\right) - 1] \quad (2.2)$$

Where I_o is the saturation current of the diode (A), q is electron charge (1.6×10–19 C), A is curve-fitting constant, K is Boltzmann constant (1.38×10–23 J/°K), T is temperature on absolute scale °K.

Thus, the load current is given by the expression:

$$I = I_L - I_O\left[\exp\left(\frac{qV_{oc}}{AKT}\right) - 1\right] - \frac{V_{oc}}{R_{Sh}} \quad (2.3)$$

The last term is the leakage current to the ground. In practical cells, it is negligible compared to

I_L & I_O. Moreover, it ignored.

The two most important figure of merits widely used for describing PV cell electrical performance are the open-circuit voltage V_{oc} and the short-circuit current I_{sc} under full illumination. The short-circuit current is measured by shorting the output terminals and measuring the terminal current. Ignoring the small diode and ground leakage currents under zero voltage, the short-circuit current under this condition is the photocurrent I_L.

The maximum photo voltage is produced under the open-circuit voltage. Again, by ignoring the ground leakage current, equation 2.3 with I give the open-circuit voltage as follows:

$$V_{oc} = \frac{AKT}{q}\left(\frac{I_{PV}}{I_O}\right) + 1 \qquad (2\text{-}4)$$

2.5 I-V and P-V Curves

The current verses voltage (IV) curve generally represents the electrical characteristic of the PV cell. The figure below (Figure 2.5) depicts the I-V curve of typical PV cell. This curve shows the variation of current and voltage when cell resistance varies from zero to infinity. In this curve the point at which the voltage is zero is called the short-circuit current. This is the current we would measure with output terminal shorted. On the other hand, the point at which current is zero is known as open-circuit voltage. This voltage would measure with output terminal open. Somewhere in the middle of the two regions, the curve has a knee point.

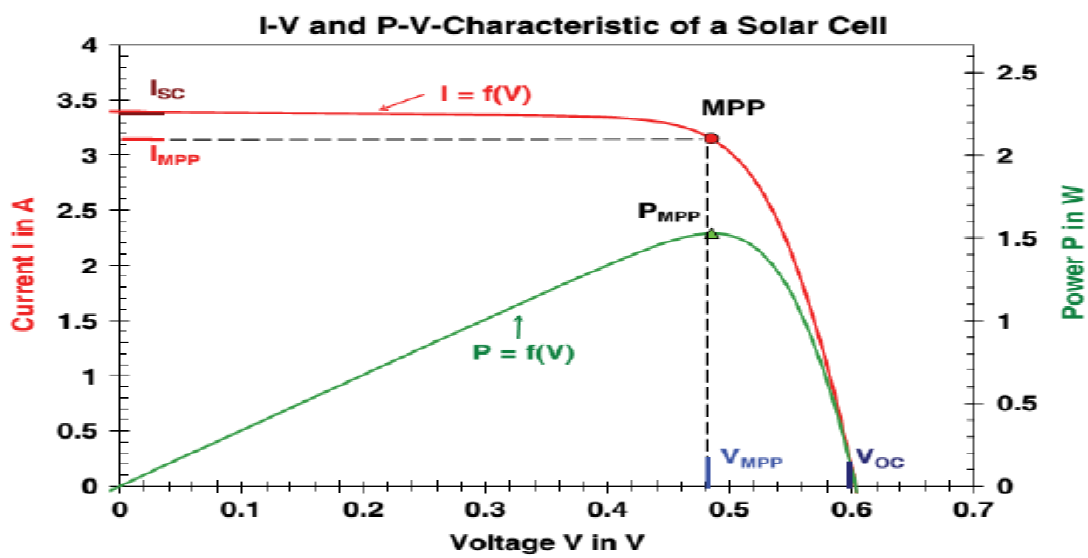


Figure 2.5: Characteristic curves I-V and P-V solar cell

The power output of the panel is the product of the voltage and current outputs. The power plotted against the voltage, which is P-V curve of the PV cell. Note that the cell produces no power at zero voltage or zero current, and produces the maximum power at the voltage corresponding to the knee point of the I-V curve. This is why the PV power circuit is always designed to operate close to the knee point with a slight slant on the left-hand side. The PV circuit is modeled approximately as a constant current source in the electrical analysis of the system.

Finally, in order to measure the photovoltaic cells, output power the following standard test conditions established internationally. The irradiance level is 1000 W/m², with the reference air mass 1.5 solar spectral irradiance distributions and cell or module junction temperature of 25°C.

2.6 DC Home System Layout and Components

Since the development of electricity, AC has been a better choice for power transmission and distribution. However, Thomas Edison one of the founders of electricity, supported the use of DC. No method at that time existed for boosting and controlling DC voltage at the load, so that transmission of DC power from generation to load resulted in a large amount of losses and voltage variations at different load locations. Westinghouse proposing AC distribution resolved the problem. Later on Nikola Tesla developed the transformer, which had the capability of boosting voltage in AC. This makes the transmission losses to be reduced and efficient transmission of power to takes place from one location to another resulting in a complete transformation of the power systems to AC [10].

Although many things have changed since the invention of electricity, AC is still the fundamental power type of our power infrastructure. However, due to the development of power converters and DC energy sources, interest in dc has returned. A detailed block diagram of the system is shown in Figure: 2.6, which consists major components.

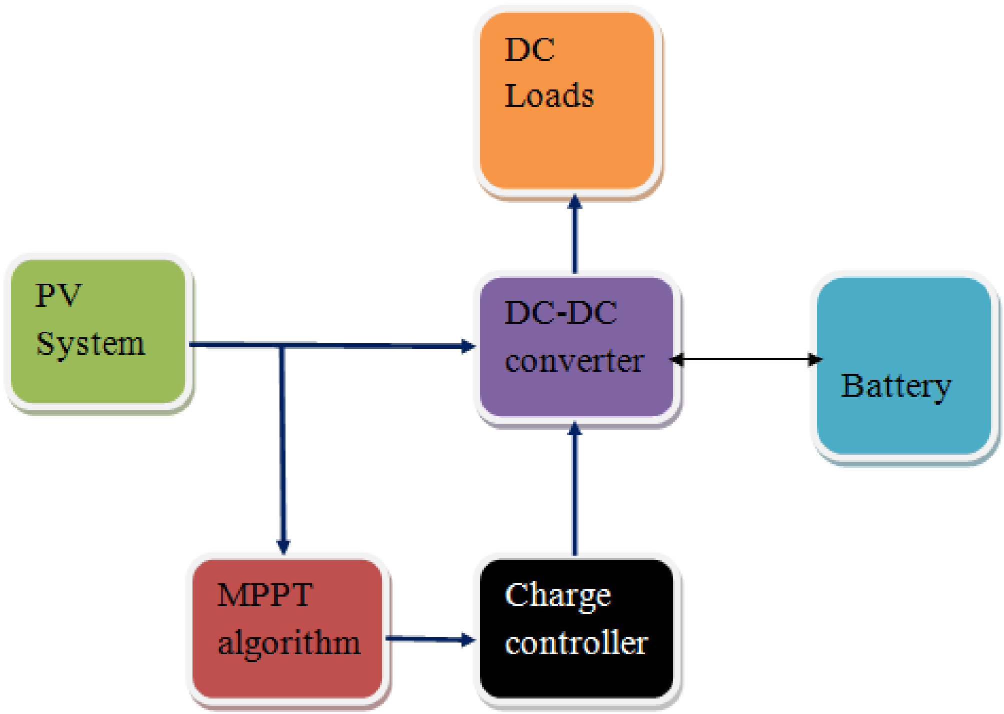


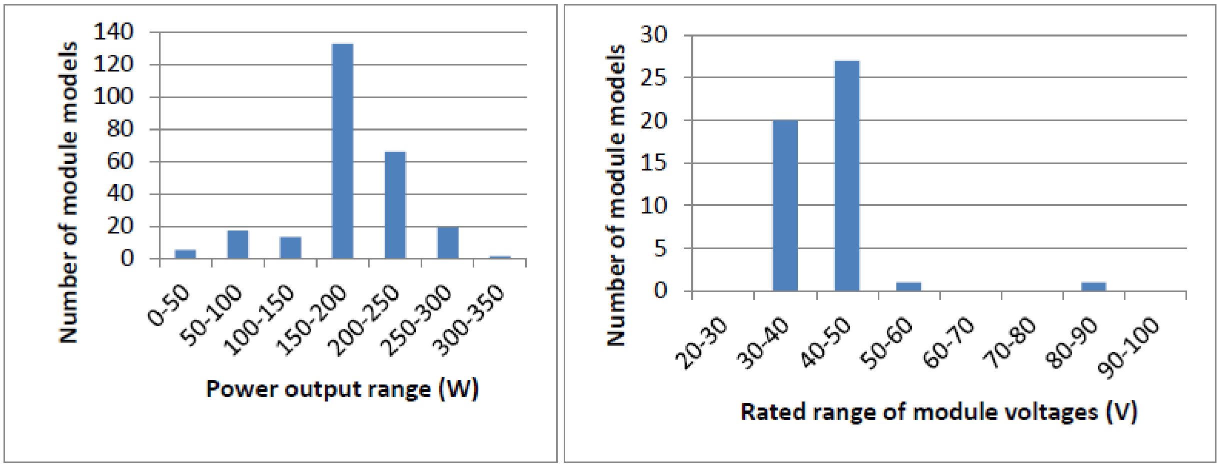
Figure: 2.6 Layout of DC home system

Solar Power DC home system consists the following:

- Solar panel
- Battery
- Charge Controller
- Maximum Power Point Tracker
- DC-DC converter
- DC appliances/DC loads

2.6.1 PV Modules

Module power outputs, range from 20W to 380W, but generally cluster in the range of 150W to 250W.



(a) (b)

Figure: 2.7 (a) Rated power output versus number of module models and (b) Rated range of module voltages versus number of module models of PV modules satisfying the Guidelines for Solar Electric.

Table: 2.1 Market shares of PV modules in PV system.

Numbers	PV module manufacture	Market shares
1	Sun-Power	22%
2	Sharp	19%
3	BP Solar	8%
4	Kyocera solar	8%
5	Evergreen solar	7%
6	Sanyo electric	6%
7	Sun-tech power	5%
8	Solar world	3%
9	Andalay solar	3%
10	Mitsubishi electric	3%
11	REC solar	3%
12	Canadian solar	3%
Total		90%

Module efficiencies plotted in Figure: 2.8, which shows both a histogram of module efficiencies and the breakdown of module efficiency by cell technology type amorphous silicon, cadmium telluride, mono-crystalline, polycrystalline, and ribbon. Efficiencies have increased only very slowly over the years, with most of the models and technologies in the (11 – 15) percentage range and still being produced with polycrystalline and mono-crystalline silicon cells.

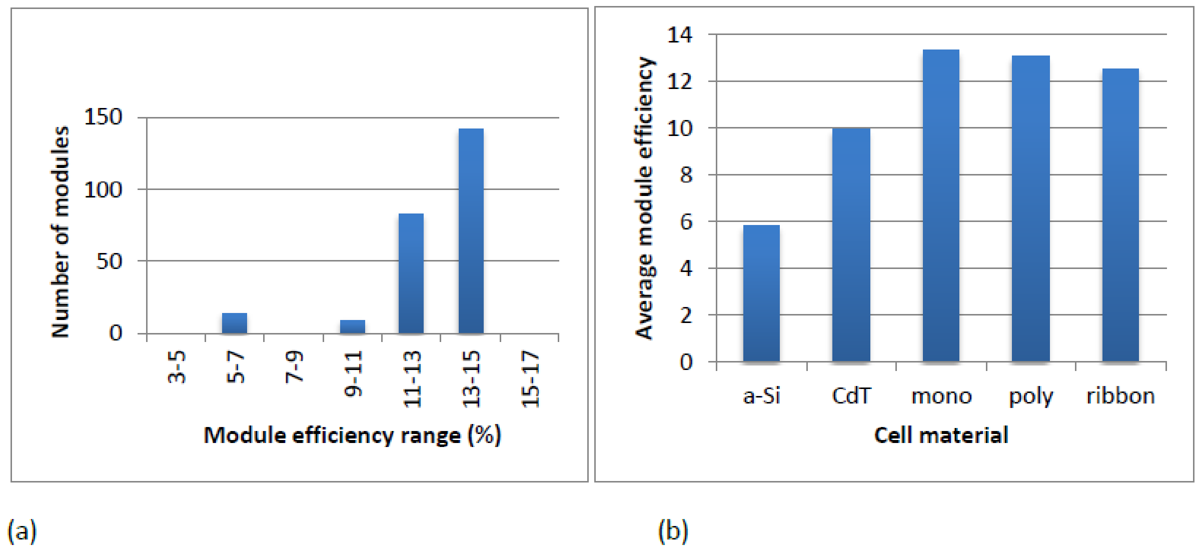


Figure: 2.8 (a) Efficiencies of PV modules, (b) Efficiency by cell type [12].

2.6.2 Battery

During nights when irradiance is low, battery supplies the power to loads. Battery is acting as load and source, a clear analysis is made on this. During day time, it is acting like load and during night, it is acting as source of power. Bi-directional converter and controller help in acting as load and source. Lead-acid battery technology has been available for more than 150 years, and lead-acid batteries have been used in PV systems for some decades. Figure below shows a comparison of the technical maturity of different storage technologies.

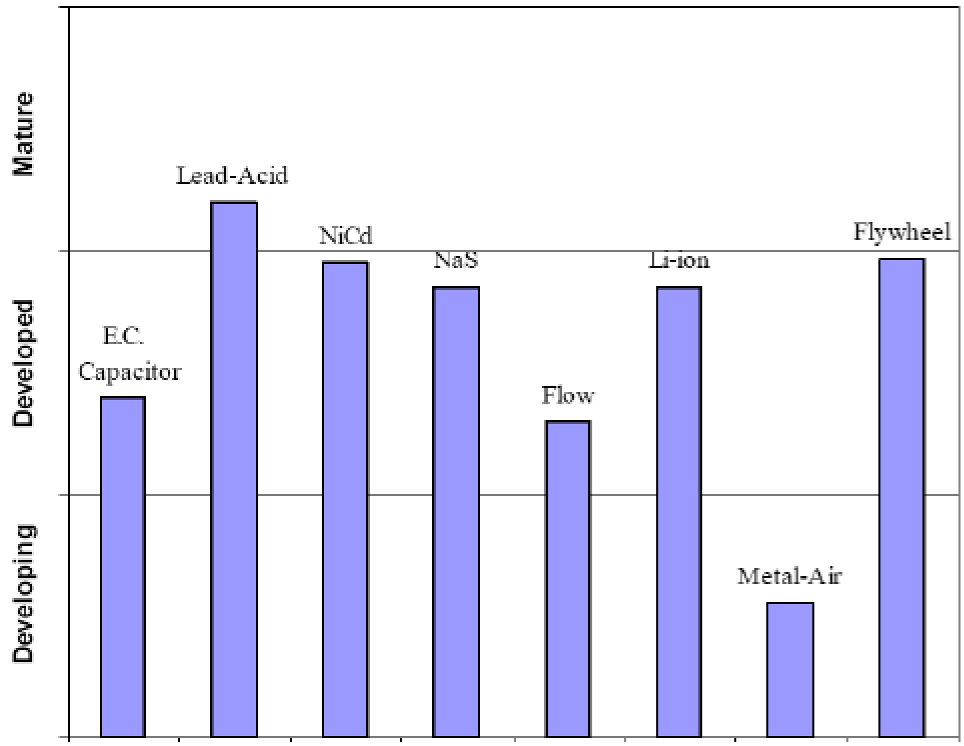


Figure: 2.9 Technical maturities of storage technologies

Lead-acid batteries are considered the most mature technology currently available [13]. Battery efficiency, measured as round-trip efficiency, is not constant but is a function of the battery's state of charge. Lead-acid battery round-trip efficiency ranges from 70-80%. Necessary parameter for the battery is the State of Charge (SOC) and the Depth of Discharge (DOD). The SOC describes the state of the battery capacity in percentage meaning that for example, 100% SOC is a fully charged battery and DOD is the complement of SOC, which would be 0% DOD in this case. The units are used to describe the current state or the lifetime of the battery. To calculate the SOC the current can be integrated over time. This method is called coulomb counting. The downside to this calculation is that it is impossible to know the SOC at start up, the battery voltage must first reach the maximum voltage to set the SOC to 100% after which it can start calculating the SOC.

Batteries modeled as a voltage source have a voltage tied to them. The voltage of a battery depends on how many voltaic cells connected in series and their individual voltage, which varies depending on which type of cells is used. The voltage varies depending on the SOC, where the voltage goes down with decreasing SOC. Battery is used for physical form of storage of energy; it is one form of electro chemical cells. It supports the bi-directional flow of energy from one form to another, i.e. chemical to electrical and vice-versa. There are two types of batteries, re-chargeable and non-rechargeable batteries.

The main purpose of batteries in this thesis is to store the excess power. As it mentioned in the earlier chapters, the leftover power (after supplying to loads) is stored during the daytime when irradiance is more. During nights when irradiance is low, battery supplies the power to loads. Battery is acting as load and source, a clear analyzation is made on this. During daytime, it is acting like load and during night, it is acting as source of power. Bi-directional converter and controller help in acting as load and source.

For DC home photovoltaic system, the electrical energy produced by the PV array cannot always be used when it produced because the demand for energy does not always coincide with its production. Electrical storage batteries are commonly used in PV system. The primary functions of a storage battery in a PV system are:

- Energy Storage Capacity and Autonomy: to store electrical energy when it is produced by the PV array and to supply energy to electrical loads as needed or on demand.
- Voltage and Current Stabilization: to supply power to electrical loads at stable voltages and currents, by suppressing or smoothing out transients that may occur in PV system.
- Supply Surge Currents: to supply surge or high peak operating currents to electrical loads or appliances.

2.6.3 Charge Controller

Solar Charge controller is a device, which controls the battery charging from solar cell and controls the battery drain by load. The simple Solar Charge controller checks the battery whether it requires charging and if yes it checks the availability of solar power and starts charging the battery. Whenever controller found that the battery has reached the full charging voltage levels, it then stops the charging from solar cell. On the other hand, when it found no solar power available then it assumes that it is night time and switch on the load. It keeps on the load until the battery reached to its minimum voltage levels to prevent the battery dip-discharge. Simultaneously Charge controller also gives the indications like battery dip-discharge, load on, charging on etc.

A charge controller, charge regulator or battery regulator limits the rate at which electric current added to or drawn from electric batteries. It prevents overcharging and may prevent against overvoltage, which can reduce battery performance or lifespan, and may pose a safety risk. To protect battery life, charge controller may prevent battery from deep discharging or it will perform controlled discharges, depending on the battery technology. Either the terms “charge controller” or “charge regulator” is stand-alone device, or to control circuitry integrated within a battery pack, battery-powered device, or battery recharger.

Solar Charge Controllers are the controllers, which regulate the power output or the DC output voltage of the solar PV panels to the batteries. Charge controllers take the DC output voltage as the input voltage converts it into same DC voltage required for battery charging. These used in off grid scenario and uses Maximum Power Point Tracking scheme, which maximizes the output efficiency of the Solar PV Panel. In battery charging system, the output voltage regulation is an important factor, as batteries require specific charging method with various voltage and current levels for specific stage. These charging processes enhance battery performance and battery life.

In this thesis, we are using microcontroller based charge controller. Microcontroller is a kind of miniature computer containing a processor core, memory, and programmable input/output peripherals. The Functions of a microcontroller in charge controller are measures solar cell voltage, measures battery voltage, decides when to start battery charging, decides when to stop battery charging, decides when to switch on the load and decides when to switch odd the load.

Most importantly in this thesis, microcontroller also tracks the MPP of the output power.

2.6.4 Maximum Power Point Tracker (MPPT)

MPPT is one of many applications of power electronics, and it is a relatively new area. 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. The maximum power point tracker (MPPT) is now prevalent in grid-tied PV power system and is becoming more popular in stand-alone systems. MPPT is a power electronic device interconnecting a PV power source and a load, maximizes the power output from a PV module or array with varying operating conditions, and therefore maximizes the system efficiency. MPPT is made up with a switch-mode DC-DC converter and a controller. For grid-tied systems, a switch-mode inverter sometimes fills the role of MPPT. Otherwise, it is combined with a DC-DC converter that performs the MPPT function.

This thesis, therefore, chooses a method Perturb and Observe algorithm for digital control for MPPT. The design and simulations of MPPT will be done on the premise that is going too built with a microcontroller.

2.6.5 DC/DC Converter

DC-DC converters are power electronic circuits that convert a dc voltage to a different dc voltage level, often providing a regulated output. In many industrial applications, it is required to convert a fixed-voltage DC source into a variable voltage DC source. A DC-DC converter converts directly from DC to DC and is simply known as a DC converter. A DC converter can be considered as DC equivalent to an AC transformer with continuously variable turn ratio. Like transformer, it can be used to step down or step up a DC voltage source.

Pulse-width modulation (PWM) is used to control the output voltage of DC/DC converters by controlling the on and off state of the switch/switches. As the name implies the width of a pulse is controlled by varying the time the pulse is “on” in relation to the switching period. This ratio between the time the switch is in the “on” position t_{on} and the switching period T_S, is called the duty cycle.

PWM can be implemented to control a switch with a certain duty cycle that determines the average (output voltage) v_o even though the input voltage and output load may fluctuate.

The key ingredient of MPPT hardware is a switch-mode DC-DC converter. It is widely used in DC power supplies and DC motor drives for converting unregulated DC input into a controlled DC output at a desired voltage level. MPPT uses the same converter for a different purpose, regulating the input voltage at the PV MPP and providing load matching for the maximum power transfer.

2.6.6 DC Appliances and End Uses

The following sections examine existing, emerging, and potential future DC products. In this catalog, *‘DC products’* refers to products marketed in a form that take DC input. This excludes products that are sold with external power supplies intended to convert AC to DC, which really designed for AC markets. Clearly, such products could be easily used in a direct-DC context if their DC power input requirements were standardized.

Most of the home appliances internally operate on DC that is obtained after a transformer and a rectifier constituting a major part of the power losses. According to [14] state a 22% reduction in resources if we use DC than conventional AC for residential loads and it is safe for human even in direct touch. This portion discusses the modified 48V DC appliances in which transformer and rectifier are replaced by a DC-DC power electronics converter. These modified appliances are more efficient than traditional AC fed appliances.

2.6.6.1 Appliances with Motors

Most of the appliances having rotor part use universal dc motors or single-phase induction motors, which have low efficiency because of carbon brush and mechanical commutation bearing a major maintenance cost and mechanical losses. All such motors can replaced with BLDC, which has a high efficiency, low noise [15], low power consumption and a wide range of speed. In BLDC, motor permanent magnet acts as a rotor while three-phase DC supply given to the static stator coil. There is low stator and rotor air gap, which increases the efficiency by increasing the magnetic torque on the rotor by the stator. Therefore, no need of carbon brushes to supply the current, which makes it maintenance free. However, because of the presence of magnet, electronics and sensor, BLDC motor is costly than induction and universal motor. With the adoption of DC grid and BLDC motor in industrial and residential appliances, the cost will definitely be reduce in future [16].

The main manufacturers of DC refrigeration products and their targeted markets are including marine and off-grid homes. Refrigerator efficiency is dominated by two factors: compressor efficiency and insulation. As with air conditioners, costly off-grid power provides an incentive for energy efficiency, especially with large power users like air conditioning and refrigeration. Again, variable-speed compressors offer large energy savings, with brushless DC motors being the logical choice of driver. In general, currently marketed DC refrigerators are smaller than standard AC residential refrigerators; the efficiency of DC models only with AC models in the same capacity range, using the typical refrigerator efficiency metric of kilowatt-hours per year of operation. Only combination refrigerator/freezers, powered by either AC or DC, were selected for comparison. The DC products use considerably less energy, on average less than half of the energy of their AC counterparts.

While DC refrigerators are more efficient, they are also far costlier than AC Energy Star products with similar capacities. This is probably only in part due to the advanced technologies used to reduce their energy use. It is well known that appliances prices tend to fall with cumulative production.

2.6.6.2 Electronics Appliances

Laptop computer, TVs, security cameras and data centers are the major electronics load which can be made efficient or even energy star just by replacing input AC/DC converter with the buck-boost converter.

In current laptop adapter, 220V AC is taken from the distribution line. After stepping it down and rectification process, it decided by the switching technique whether to charge the battery or run the laptop or both. Using buck converter, the output 19V DC is reduced to 5, 3.3, 2 and 1.5V for various components to operate.

In proposed scheme, input directly taken from DC distribution line followed by a buck converter with the 19V output. Hence this proposed DC adapter is much efficient than current AC adapter as major power conversion losses are eliminated in proposed architecture.

The DC lighting market includes more companies and a larger diversity of products than the DC air-conditioning market, but, like DC air-conditioning, DC lighting represents an insignificant share of the mainstream market, except in such niche markets as outside emergency lighting. This section documents DC lighting products marketed on the Internet. The six known, companies that produce DC light sources, for the DC niche markets: Ablamp, Nextek Power Systems, Phocos, Steca, Thin-Light, and SunWize. These products include DC lamps (fluorescent, compact fluorescent (CFL), and light-emitting diode (LED) for various fixture types and applications), DC ballasts, fixtures designed for DC lamps (or all kinds), and ballasts for 12V, 24V, and 48V operation. For CFLs and LEDs, as with air conditioners, the DC technologies have higher efficiencies on average than their AC counterparts. In the case of CFLs, the DC product efficacy is almost 10% higher than AC with the same power consumption [17]. For LEDs, the improvement in DC product efficacy is even larger and depends on lamp power. For other fluorescent lighting (non-compacts) it is difficult to make a reliable comparison because there is very little overlap in the DC and AC technologies in terms of power consumption.

Until now, incandescent lights are widely used in residential areas. These are highly inefficient because of their resistive nature. Compact Fluorescent CFL replaced the incandescent light because of high efficiency. The reason of inefficiency is again the power conversion stage from AC-DC and old technology. LED (Light-Emitting Diode) lights are the most efficient one with low energy consumption and long operating life. They best work on the DC distribution system resulting highly efficient. LED converts 80% of the input energy into light as compared to 10% of the incandescent bulbs [18].

In AC fed LED TVs, input AC is passed through EMI filter, transformer followed by a rectification stage and a PFC (Power Factor Correction) stage to take the input line PF close to unity. A DC-DC fly-back converter is used to operate CCFL and standby power stage.

These conversion losses can be eliminated if LED TVs operated directly on DC distribution line.

2.6.6.3 Resistive Loads

Resistive loads are typically used to convert current into forms of energy such as heat. Unlike inductive loads, resistive loads generate no magnetic fields. Common examples include most electrical heaters, and traditional incandescent lighting loads. It is a type of load that draws current in the same proportion with the apply voltage. They are typically used to convert current into form of energy such as heat.

That is the voltage and current are of the same phase. This kind of electrical load converts electrical energy to heat. Best examples of resistive loads are injera mitad and stoves.

2.7 Appropriate DC Voltage Level Selection for DC home Appliances

DC home is composed by a set of distributed energy sources, energy storage system and loads. The sources are connected to a DC bus voltage by the means of line regulating converters. Loads are directly connected to the bus in the case where their operating voltage is the same as the bus voltage one or by the means of point of load converter in other cases.

Selection of the voltage level is one of the most important tasks in defining a DC home system setup. The lack of standardization is evident when observing the voltage levels used for DC home systems. When analyzing DC home systems, for residential applications; there are some voltage levels that come as natural choices, depending on the regulation imposed by the standards, the availability of commercial solutions, or to ensure compatibility with the AC grid.

Currently there are broadly available DC compatible devices that can be used with either AC or DC system that makes it suitable to bring LVDC distribution systems to homes and buildings. Different voltage levels are sensitive to use for different groups, while optimizing efficiency for each scenario, safety, and compatibility with other systems. The appropriate DC voltage level selection is the key step in the dc distribution system design, which has great impact on the performance and characteristic of the entire power system.

The distribution voltages adopted for different solutions depend on what features are the main design criteria. For instance, 12V distribution systems are used, in the automotive industry. Nevertheless, since modern cars advanced in electronic technology, this leads to higher electricity consumption. Due to this reason, the voltage level boosted to 24-48 to improve the efficiency and reduce the size of the conductors. This voltage level safely supply power to a number of low power electronic equipment in homes. Medium power consuming appliances can be supplied with 230-400 V. Beyond 400V there is no significant efficiency improvement and the protection system becomes a concern [19].

Power distributions in data centers can be accomplished with voltage levels of 380-400 V DC. This voltage level is convenient because, it has been tested in different applications with unipolar model. Power consumption of a regular home is much lower than the consumption of the data center; therefore, lower DC voltages could be use, without significantly increasing the distribution losses, while increasing safety in the system. For instance, power distribution up to several hundred watts, can be efficiently performed using 48 V DC, which would cover low power consuming equipment. The increase of the voltage level is unavoidable, if the distribution losses need to be minimized, and therefore a more effective protections system need to be developed.

The efficiency improvement using 380 V DC as voltage levels for supplying energy to the high power loads, stoves and Injera Mitad, only brings an efficiency improvement of 0.3 %, when compared with 120 V DC. 120V DC is considered as extra-low voltage; hence, the damage caused by electrical shock is reduced [20].

A number of organizations as EMerge Alliance, the European Telecommunications Standard Institute (ETSI), International Electro Technical Commission (IEC), IEEE and others, are working on developing the required regulation for the implementation of the dc system for building/residential applications.

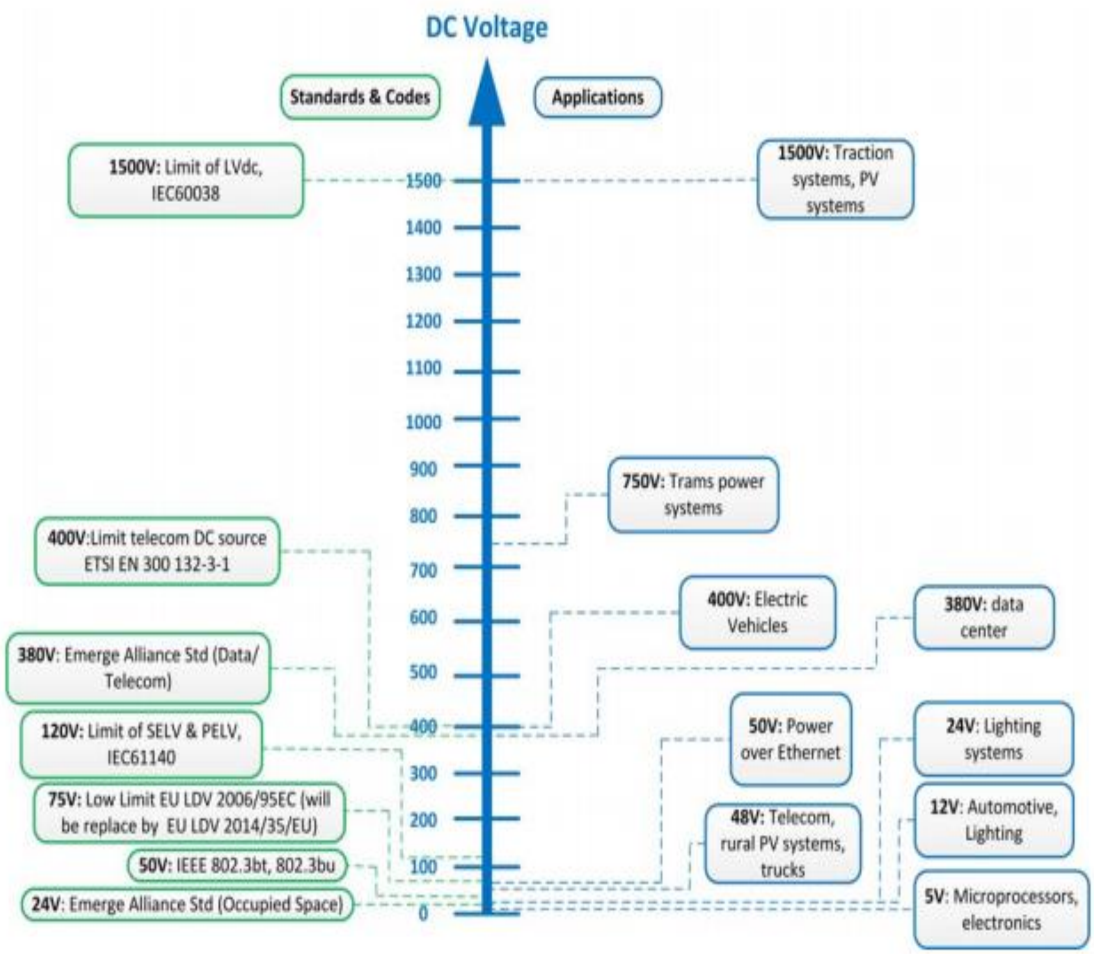


Figure: 2.10. DC voltages applications Standards, codes [21].

2.8 Applications of DC home System for Residential Building

A wide expansion of distributed generation sources especially solar photovoltaic (PV) panels, battery energy storage systems, and advanced electronic loads, provides DC technologies a competitive advantage over its rival AC system for residential applications. Most renewable energy generators, such as PV panels and fuel cells (FCs), are DC generators, even wind turbines. Battery energy storage systems produce DC as well. These renewable energy sources like solar and wind have been widely utilized in household, industry and commercial areas.

Most of modern home electronic appliances (TVs, LED lights, satellite receivers, DVD, computers, etc.) are all internally DC loads, and the energy consumed by these devices is increasing every day. Moreover, appliances like fridge and washing machine, although intrinsically AC loads, can be interfaced better with a DC supply and avoid the AC-DC conversion. In doing so significant loose reduction and simplicity can be achieved which shows DC home system a more natural interface between mostly DC devices, which allows a considerable power conversion stages reduction, hence achieving a significant loss reduction, as well as simplicity and potential cost reduction in the power converter units.

Since the frequency of DC, system is zero, the voltage drops and reactive power, which comes due to inductive component of the distribution line, is negligible. DC system becomes apparently simpler and more efficient than ac system as it does not need any synchronization.

A DC powered residence then proposed to eliminate the transformer/rectifier stages, eliminating standby losses.

Furthermore, the absence of reactive power lowers the current needed to transfer the same amount of power [22]. However, some appliances might need a DC/DC converter properly adjust the DC voltage needed for the appliance. Harmonics and power factor issues eliminated. Furthermore, with advances in power electronics technology, motor driver devices and brush less DC motors considered to replace actual motors in home appliances.

2.9 Factors Influencing DC Home System

DC distribution system for residential/building application has brought high expectations regarding simplicity, cost reduction, reliability improvement, and energy savings. The major factors, which influence the choice of DC grid voltage, are safety, connection type, and compatibility, with or without storage system, system efficiency and cost savings. Standards, codes and regulations are not well developed for DC system as it done for AC. For a consumer, the lack of commercially available products that operate on DC is also a major challenge for this system [23]. When designing the DC home electrical power system, it would not be easy to find products (power converters, protection devices, connectors, chargers, plugs, switches, circuit breakers etc.) that are compatible with the system's requirements, especially regarding the voltage level.

2.10. Protection for Safety

The user must be protected against dangerous touch voltages. The touch voltage is the voltage experienced in the case of an insulation defect between two simultaneously touchable parts. Two cases can considered direct touch (touch of active parts); indirect touch (touch of metal frames, which become live due to a fault).

Figure 2.11 shows the maximum switch off time in relation to the touch voltage. It illustrates how long a voltage can be touched without any serious physical damage; to guarantee safety, faults that cause dangerous touch voltages should be cleared within the maximum switch off time. Figure 2.11 shows that voltages below 120 V DC and 50 V AC do not form a direct danger to people. Contact with DC voltage gives a smaller body current than touch of AC voltage. Therefore, DC is safer in relation to body currents, which may cause physical damage, for example, a heart attack.

It becomes clear that protection against electric shock is possible by using a very low system voltage (NEN 1010; 411.1). If the nominal voltage is below 60 V, no special measures are necessary to protect against direct touch. Otherwise, live parts need to be insulate. As long as the system voltage does not exceed 120 V DC, protection against indirect touch is not needed.

For the layouts presented of DC systems in the previous chapter protection against electric shock is achieved by using a system voltage below 120 V. No special measures such as earth protection or protective conductors are required. The systems may be earthed or not, the only requirement is that the system must be separated safely from higher voltage (>120 V) systems.

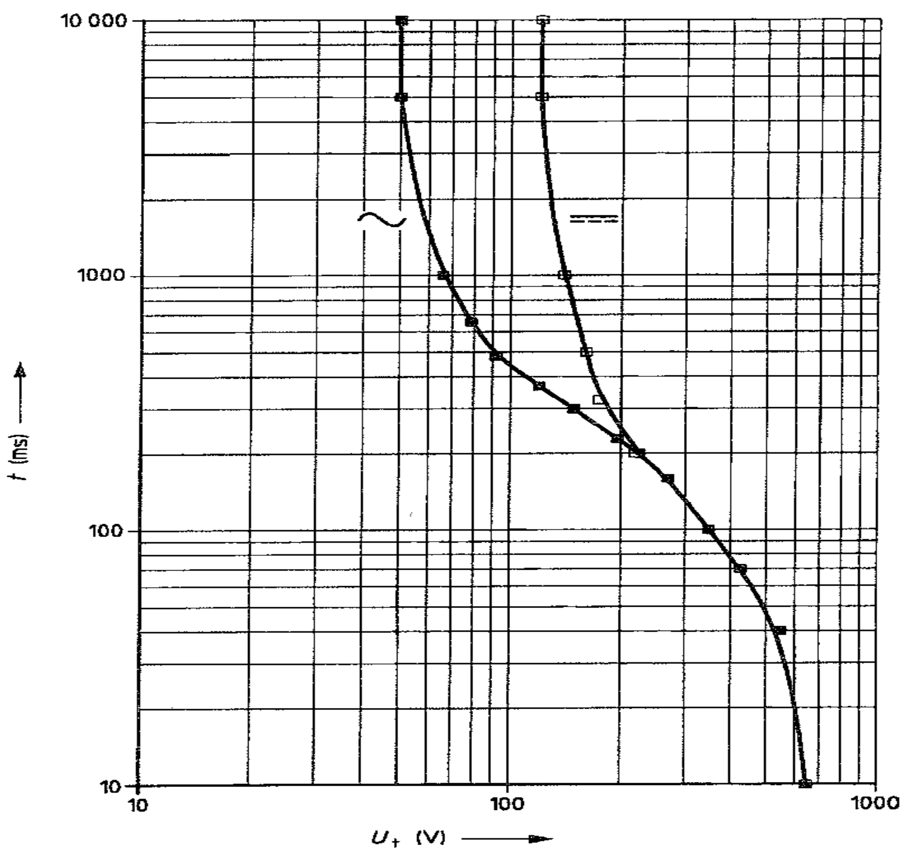


Figure: 2.11. Maximum switch off time and touch voltage of DC vs AC [24].

Chapter Three

3. Data Analysis and DC voltage Evaluation and Selection

3.1 Introduction

This chapter deals with the presentation and analysis of the data gathered from selected sites in Tullu Gudo Island near to Ziway town of Oromia regions of Ethiopia. The data collected were analyzed using descriptive survey; theoretical, mathematical formulation and modeling by matlab/simulink software.

Ethiopia is one of known countries to have high directional normal sun radiation over the whole year. A solar PV module can be described as an arrangement of solar cells in series and parallel enclosed in protective casing. The solar cells are stacked in series and parallel to generate a notable amount of power. A solar cell is a device, which converts sunlight into electrical energy.
It can be described as a silicon (or other material) PN junction diode. A single solar cell generates a voltage of 0.6V depending on the technology with which it made of. Matlab/Simulink is a platform where any component can be modeled using its respective -mathematical expressions.

3.2 Load Estimation

In electrical engineering, a load profile is a graph of the variation in the electrical load versus time. A load profile will vary according to used hours (typical examples include morning, day and night), temperature and holiday seasons.

Table: 3.1 Average daily load profile

Hours	Power consumption (W)	Hours	Power consumption (W)	Hours	Power consumption (W)	Hours	Power consumption (W)
00	110	06	1500	12	1050	18	1200
01	110	07	170	13	250	19	700
02	110	08	170	14	250	20	110
03	110	09	170	15	200	21	110
04	110	10	240	16	200	22	110
05	2210	11	4500	17	180	23	110

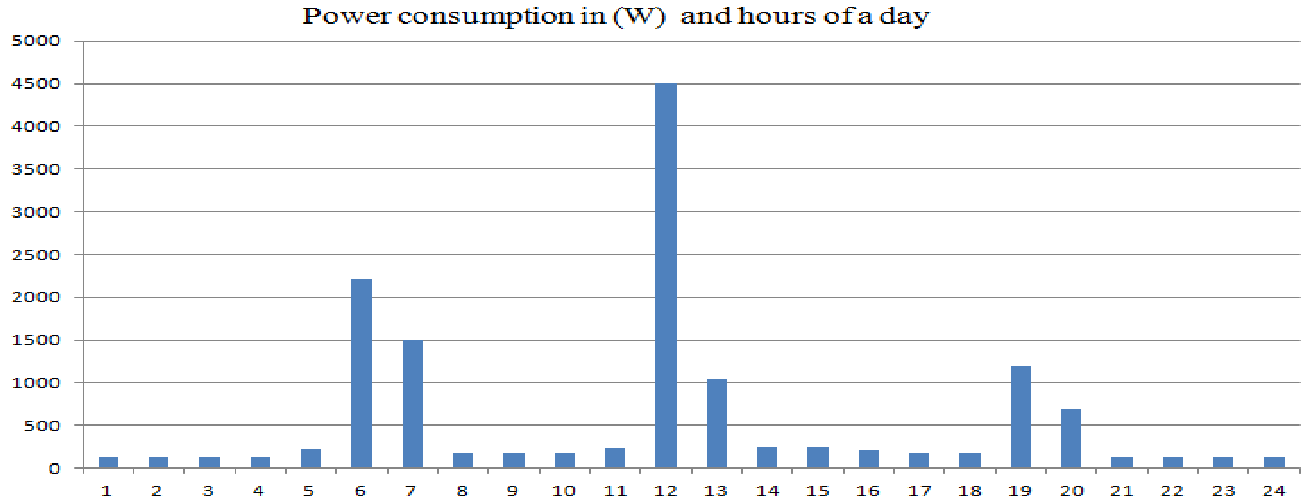


Figure: 3.1 Average daily load profile for a typical single house

Power producers use this information to plan how much electricity they will need to make available at any given time.

3.3 Meteorological Data

Meteorological data is required as a basis for system design. In particular, this data is necessary for deciding PV system capacity, the specification of components, and the design strength for the PV array structure. This data is also useful for site selection and planning the installation schedule.

3.3.1 Solar Energy Analysis

Irradiation data generally stated as a daily average per month. The unit used for irradiation is mega joules per square meter per day (MJ/m^2/day) or kilowatt-hours per square meter per day (kWh/m^2/day) and is measured using a pyrometer. There are many areas where irradiation data is not available; this can estimated based on the sunshine hours recorded at an established site near to the location of the project area.

For sizing a photovoltaic system or any other system that uses solar energy to convert it into electricity, it is very important to have data relating to solar radiation. Tullu Gudo is located in Oromia region, East Shoa zone near to Ziway/Batu town. Moreover, it is located on latitude of 7°56' N and longitude of 38°43'E.

The sunshine duration data from the nearby station is used to analytically calculate (estimate) the monthly average solar radiation using the modified version of angstrom equation [3.1,3.2,3.3].

$$H = H_O(a + b\frac{n}{N}) \tag{3-1}$$

Where:

H = Monthly average daily radiation on horizontal surface (MJ/m^2).

H_O = Monthly average daily extraterrestrial radiation on a horizontal surface (MJ/m^2).

n = Monthly average daily number of hours of bright sunshine.

a and b are regression coefficients and has been calculated from the relationship given by:

$$a = -0.11 + 0.235\cos\phi + 0.323(\frac{n}{N}) \tag{3-2}$$

$$b = 1.449 - 0.553\cos\phi - 0.694(\frac{n}{N}) \tag{3-3}$$

Finally, their average value has been taken as a =0.33 and b=0.43 and used in equation 3.1.

N →the maximum possible daily hours of bright sunshine given by equation below:

$$N = \frac{2}{15}\omega_S \tag{3-4}$$

More over the values of monthly average daily extraterrestrial radiation (H_O) calculated for days giving average of each month as:

$$H_O = \frac{24*3600*G_{SC}}{\pi}[1 + 0.033 * \cos\left(\frac{360n_d}{365}\right)] * (\cos\phi\cos\delta\sin\omega_s + \frac{\pi\omega_s}{180}\sin\phi\sin\delta) \tag{3-5}$$

Where:

G_{SC} = 1367W/m^2, the solar constant,

n_d = day number of the year starting at January 1st as 1

ϕ = latitude of the site under consideration (^{0})

δ = solar declination angle (^{0}) and given by

$$\delta = 23.45\sin(360(240 + \frac{n_d}{365})) \tag{3-6}$$

$$\omega_S = \cos^{-1}(-\tan^{-1}\phi\tan\delta \qquad (3\text{-}7)$$

The Ethiopian Meteorological Service collects only the average sunshine hours for some cities of the country and the solar radiation are calculated from the average sunshine hours. The solar radiation estimated as shown in table Appendices A by using the equations given above.

For solar system to supply power throughout the year the minimum daily horizontal solar radiation value is taken on the month of July which is 5.15(kWh/m$^{2)}$/day.

Table: 3.2 Daily solar irradiance variations [25]

Time (hr.)	00	01	02	03	04	05	06	07	08	09	10	11
Irradiance(w/m^2)	0	0	0	0	0	50	250	320	540	630	700	850
Time (hr.)	12	13	14	15	16	17	18	19	20	21	22	23
Irradiance(w/m^2)	980	960	830	750	600	480	260	0	0	0	0	0

3.3.2 Temperature

The average daily high and the low temperatures are necessary for PV system design. Monthly average data of humidity also taken into account to decide the component specifications and installation points.

Table: 3.3 Daily temperature variations

Time (hr.)	00	01	02	03	04	05	06	07	08	09	10	11
Temperature(°C)	16	15	15	14	13	13	12	13	17	21	23	26
Time (hr.)	12	13	14	15	16	17	18	19	20	21	22	23
Temperature(°C)	27	27	27	26	25	24	21	20	19	18	17	15

Photovoltaic (PV) power system converts sunlight directly into electricity. The total load profile shows a peak load of 4.5 kW during peak hours. The PV system designed to fulfill this load demand, **Sun-power SPR-X20-255** solar panel selected with the specification.

Most country uses alternating voltage of magnitude 220Vrms as a single phase and 380Vrms as a three phase system with power frequency of 50 Hz to supply power to its' residential, commercial and industrial customers.

As it is common worldwide, almost all household appliances are currently supplied with alternating current, although small part of customers has developed the tradition of using direct current from locally available resources, especially from solar photovoltaic (PV).

For studying the performance assessment of DC home system in the residence, household appliances are identified that used by a home located in Tullu Gudo. Based on the data obtained from these appliances, power consumption, feeder loss and efficiency analysis is will be done for 24V, 48V and 120V.

The uses of DC appliances for solar home systems in developing countries on the rise. However, the range of appliances manufactured are limited to equipment such as lighting, multimedia, cooling application, well pumps, running on 12V or 24V DC. The power demand of these appliances varies from few Watts to few hundred Watts [26].

3.4 Wire size selection

The selection of wire cable type is based on NEC (National Electric Code) requirements. Wire sizes including cost per foot are taken from [27]. Cable impedance of distribution line designed to be low. While currents flow through the cable, there is a voltage drop between the origin point and the end. Hence, the line voltage drop must take into account in order to ensure the proper operation of appliances. In order to minimize power loss and voltage drop, the proper wiring size has to choose based on the design of the household.

The electrical design must meet standard regulations. The conditions, which determine the wire diameter, are:

- Highest tolerable temperature of conductors;
- Allowable voltage drop;
- Maximum impedance at which short circuit protection [28].

Voltage losses should not cause malfunction of household appliances. A footnote (NEC 210-19 No. 4) states that a voltage drop of 5% at the further receptacle in a branch wiring circuit is acceptable for normal efficiency. Special attention must be paid to the insulation of the conductors to prevent arcs and corrosion. The number of conductors in a low-voltage system will increase as the main bus voltage decreases due to the increase in current.

The resistance of the wiring determined by its resistivity, length, and cross-sectional area, which shown in Equation 3-8.

$$R = \frac{\rho\, L}{A} \quad (3\text{-}8)$$

Where, $\rho = (1.7 * 10^{-8}\Omega/m)$ is the resistivity for copper, L is the length of the feeder and A is the area of the feeder.

Typically, copper conductors used for household wiring due to copper's low resistivity and high-power appliances are placed closer to the power supply to reduce the resistance of the wiring. This becomes more apparent when in larger households; wiring from the feeder can reach up to 80 m in length. Thus, minimizing the resistance of the wire directly affects the power loss and express in the following equation:

$$P = I^2R \quad (3\text{-}9)$$

Where:

P: Power

I: Current

R: Resistance

Conductor area of the feeder selected according to the table: 3.3.

Table: 3.4 DC resistances and current rating of wires [29]

Cross-sectional area (mm^2)	Copper resistance, R (Ω/m)	Current rating, I (A)
1.0	0.0170	14
1.5	0.0113	18
2.5	0.0068	24
4	0.0043	32
6	0.0028	40
10	0.0017	53

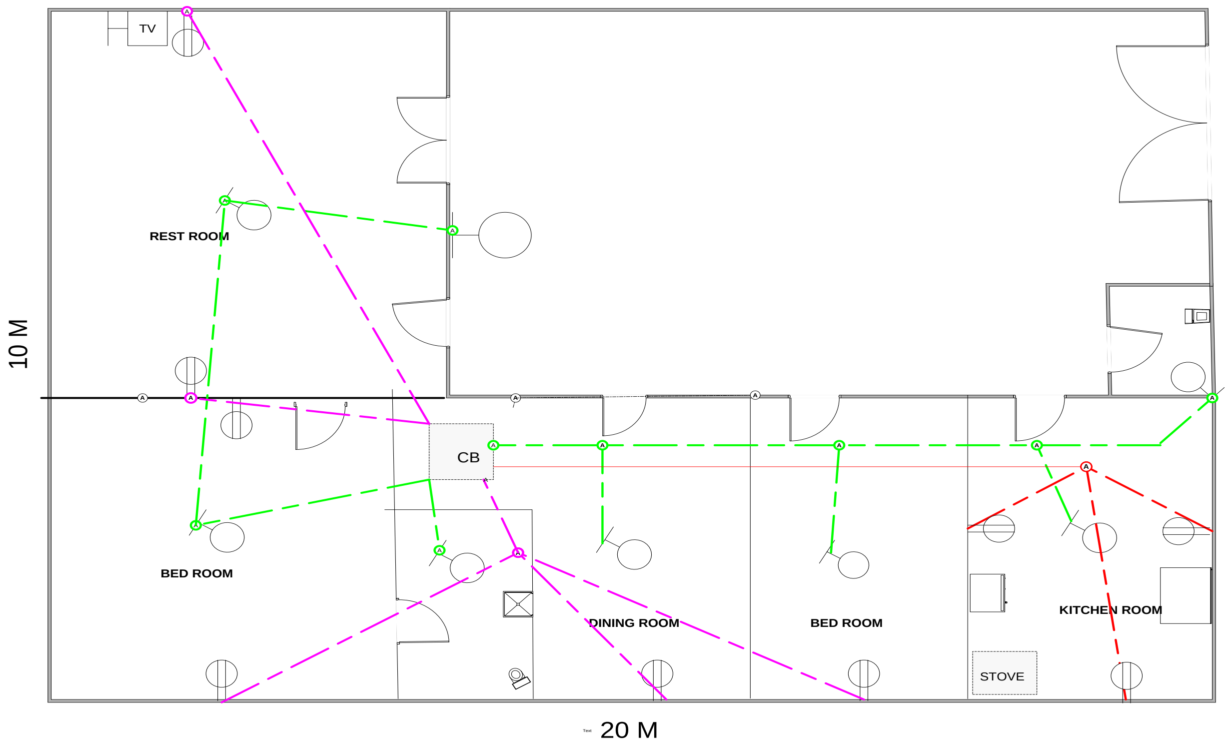


Figure 3.2 Wiring diagram of a typical single house

The length of feeder cables in a house depends on the size of the room and power rating of the appliances. The feeder length for the different loads varies. In this investigation, feeder length selected as an average length. For the appliances, whose power rating less than 200W, feeder lengths considered 50m (phase and neutral) and feeder length is 20m for the appliances with power rating greater than 200W. The feeder length of the refrigerator is 10m as it is located in the kitchen.

3.5 Investigated loads

Household appliances that are used for a family in Ethiopia can found in Table: 3.5 with their ratings.

Table 3.5 the investigated appliances and the power rating, feeder length and estimated on time per day.

Appliances	Appliances numbers	Power in (w)	Operating time in a Day (hrs.)	Wire length (m)	Cross sectional area of wire mm^2
LED lamp	8	80	7	50	2.5
Laptop	1	45	6	50	2.5
32 LED TV	1	55	7	50	2.5
Satellite receiver	1	20	7	50	2.5
Mobile phone	3	18	3	50	2.5
DVD player	1	12	3	50	2.5
Refrigerator	1	125	12	50	2.5
Stove	1	1000	3	20	4
Coffee machine	1	990	0.5	20	4
Injera mitad	1	3700	3 hrs. in a week	10	6

The devices, which are selected to be studied, are mainly household devices that are needed to daily life. Number of appliances in a house is different. In this study, the kitchen appliances, and electronics appliances are investigated. Appliances with different power ratings are available in the market. The investigated devices are Refrigerator, Stove, Coffee maker, Laptop, 32-inch LED television, Mobile phone, LED lamp, Satellite receiver, DVD player and Mitad the power rating of the investigated loads are in the range of 6 W to 3700 W.

3.6 Direct current (DC) circuit Analysis

Typically, a residential DC home system is composed of the PV system, energy storage system and various loads. The sources are connected to a DC bus voltage by the means of line regulating converters. Loads are directly connected to the bus in case where their operating voltage is the same as the bus voltage one or by the means of DC/DC converter in other cases.

There are two types of DC home systems topologies [30]: bipolar type distribution system and unipolar type distribution system. The bipolar type home system is composed of 3-wire line with positive, negative and neutral line while the unipolar type composed by 2-wire line. The bipolar distribution system presents the advantage of reducing the voltage level with respect to the ground. This makes the distribution safer for users; to allow the load side converter to choose from three different voltage levels $+V_{dc}$, $-V_{dc}$ and $2V_{dc}$ and to increase the reliability in case of fault occurrence in one of the lines. The unipolar distribution system presents the advantage to be simple with a low cost. In this study, the unipolar distribution system adopted since it is the most common and cost effective distribution topology.

The energy consumption, losses and the voltage drop across the feeder cable for different home appliances are calculated for the proposed DC distribution system with different voltage levels, namely 12V, 24V, 48 V, 120V and 380V.

The losses in the home appliances and in the distribution system is an important issue in the context of energy saving. Electronic appliances such as TV, DVD, Personal Computer, Laptop, etc. operate internally on DC. The electronics appliances that operate on a low DC voltage need a DC/DC converter, which is, takes the voltage from a DC source and converts the voltage of supply into another DC voltage level.

Since the frequency of the supply system is zero in dc system, the reactance of the feeder becomes zero i.e. $X_L = 0$

Let V_{dc} = the voltage of the source

R = the resistance of the feeder

V_L = the load voltage

I_{dc} = current via the feeder and the load

P = power consumed by the loads `

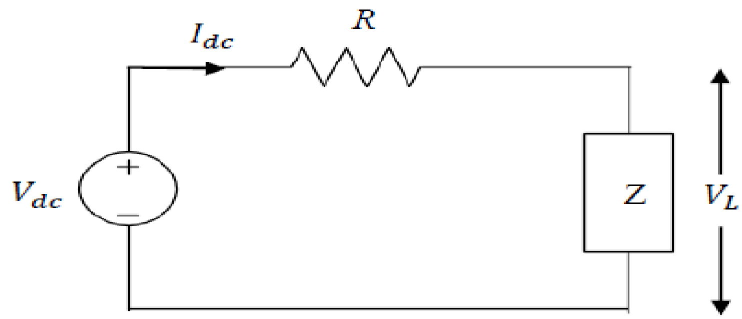


Figure: 3.3 Simple DC circuit

The load voltage can calculated:

$$V_{DC} = V_L + I_{dc}R \tag{3-10}$$

$$V_L = V_{dc} - I_{dc}R$$

$$V_L^2 = V_{dc}\,V_L - V_L I_{dc}R$$

$$V_L^2 - V_{dc}\,V_L + PR = 0$$

Then the load voltage becomes

$$V_L = \frac{V_{dc} \pm \sqrt{V_{dc}{}^2 - 4PR}}{2} \tag{3-11}$$

The percentage of voltage drop across the feeder:

$$\%\,V_{drop} = \left(\frac{V_{dc} - V_L}{V_{dc}}\right) * 100 \tag{3-12}$$

Current through the load is determined as:

$$I_{dc} = \frac{P}{V_L} \tag{3-13}$$

The real power loss across the feeder can calculated as

$$P_{loss} = I_{dc}^2 R \tag{3-14}$$

Table 3.6 Total energy consumption of home appliances (kWh)

Appliances	Appliances numbers	On duration in a Day (hrs.)	Wire length (m)	Cross sectional area of wire mm^2	Power (W) of all Items	On energy consumption (kWh/day)
LED lamp	8	7	50	2.5	80	0.560
Laptop	1	6	50	2.5	45	0.270
32 LED TV	1	7	50	2.5	55	0.385
Satellite receiver	1	7	50	2.5	20	0.140
Mobile phone	3	3	50	2.5	18	0.540
DVD player	1	3	50	2.5	12	0.360
Refrigerator	1	12	50	2.5	125	1.500
Stove	1	3	20	4	1000	3.000
Coffee machine	1	0.5	20	4	990	0.495
Injera mitad	1	3 hrs. in a week	10	6	3700	1.585
Total energy consumption of home load(kWh)						8.835

In DC system, the voltage and currents are in phase, which implies that the power factor becomes one. Therefore, there will be only real power loss in the feeder. The proposed DC powered eliminates the transformer/rectifier stages and also standby losses.

In this thesis, 24V, 48V and 120V DC systems are compared for DC home system. The energy consumption, feeder power loss and percentage of voltage drops are being calculated for the respective voltage levels. Energy consumption and loss Calculation for different DC voltage Systems are as follows:

Sample Calculation for LED light at 24V DC system:

LED light has 80 watts power rating. Its operating time is 7 hours (table 3.2).

- Load voltage (V_L):

$$V_{DC} = V_L + I_{dc}R$$

$$V_L = V_{dc} - I_{dc}R$$

$$V_L^2 = V_{dc} V_L - V_L I_{dc}R$$

$$V_L^2 - V_{dc}\,V_L + PR = 0$$

$$V_L = \frac{V_{dc} \pm \sqrt{{V_{dc}}^2 - 4PR}}{2}$$

$$V_L = \frac{24 \pm \sqrt{(24)^2 - 4 * 80 * 0.34}}{2} = 22.81V$$

- The percentage of voltage drop across the feeder

$$\%\,V_{drop} = \left(\frac{V_{dc} - V_L}{V_{dc}}\right) * 100$$

$$\%\,V_{drop} = \left(\frac{24 - 22.81}{24}\right) * 100$$

$$\%\,V_{drop} = 4.875$$

- Current through the load is determined as:

$$I_{dc} = \frac{P}{V_L}$$

$$I_{dc} = \frac{80}{22.81} = 3.3A$$

- The real power loss across the feeder can be calculated as:

$$P_{loss} = I_{dc}^2 R$$

$$P_{loss} = (3.5)^2 * 0.34 = 4.165W$$

- Feeder energy losses (kWh/year) = $P_{loss} * \frac{operating\ time*365}{1000}$

$$= 4.165 * \left(\frac{7 * 365}{1000}\right) = 10.64$$

- Total energy consumption (kWh/year) = $P * \frac{operating\ time*365}{1000}$

$$= 80 * \frac{7 * 365}{1000} = 204.4$$

Sample Calculation for LED light at 120V DC system*:*

- Load voltage($\mathrm{V_L}$)

$$\mathrm{V_L} = \frac{120 \pm \sqrt{(120)^2 - 4 * 80 * 0.34}}{2}$$

$$\mathrm{V_L} = 119.77\mathrm{V}$$

- The percentage of voltage drop across the feeder

$$\%\ \mathrm{V_{drop}} = \left(\frac{\mathrm{V_{dc}} - \mathrm{V_L}}{\mathrm{V_{dc}}}\right) * 100$$

$$\%\ \mathrm{V_{drop}} = \left(\frac{120 - 119.77}{120}\right) * 100$$

$$\%\ \mathrm{V_{drop}} = 0.19$$

- Current through the load is determined as:

$$\mathrm{I_{dc}} = \frac{\mathrm{P}}{\mathrm{V_L}}$$

$$\mathrm{I_{dc}} = \frac{80}{119.77} = 0.668\mathrm{A}$$

- The real power loss across the feeder can be calculated as

$$\mathrm{P_{loss}} = \mathrm{I_{dc}^2 R}$$

$$P_{loss} = (0.668)^2 * 0.34 = 0.152W$$

- Feeder energy losses (kWh/year) = $P_{loss} * \frac{operating\ time*365}{1000}$

$$= 0.152 * \left(\frac{7 * 365}{1000}\right) = 0.388$$

- Total energy consumption (kWh/year) = $P * \frac{operating\ time*365}{1000}$

$$= 80 * \frac{7 * 365}{1000} = 204.4$$

It is concluded from the above sample calculation for LED light is that power losses and voltage regulation of 120V DC system is less than that of in 24V DC system.

The other values are calculated by the same procedures and the results are given in Table (3.8, 3.9 and 3.10).

3.6.1 Energy Consumption and Loss Calculation for 24 V DC Systems

Table 3.7 Energy consumption and feeder power loss for 24V DC system

List of appliances	Power in (W)	Time of use in a Day (hrs.)	Current (A)	Wire area (mm^2)	Wire resist ances (Ω/)	Feeder power losses (W)	voltage drop(V) %	Feeder energy losses kWh/yr	Total energy consum ption kWh/yr.
LED light	80	7	3.5	2.5	0.34	4.165	4.875	10.64	204.4
Laptop	45	6	1.93	2.5	0.34	1.267	2.73	2.77	98.55
32 LED TV	55	7	2.37	2.5	0.34	5.62	3.36	14.36	140.525
Dish receiver	20	7	0.84	2.5	0.34	0.242	1.21	0.618	51.1
Mobile phone	18	6	0.76	2.5	0.34	0.196	1.08	0.43	19.71
DVD player	12	3	0.5	2.5	0.34	0.085	0.708	0.093	13.14
Refrigerat or	125	12	5.664	2.5	0.34	10.9	8.04	47.74	547.5
Stove	1000	12	50.98	4	0.086	223.51	18.27	978.97	730
Coffee machine	990	0.5	50.32	4	0.086	217.78	18.03	39.74	180.675
Injera mitad	3700	3hrs a week	201.51	6	0.028	1137	38.92	23.5	578.786
Total								1118.2	2564.38

For the 24 V DC systems, the current is high and hence the voltage drop across the feeder cable is high. This drop depends on the length and cross section of the cable as well as the power rating of the house appliances. The energy losses in the feeder and the on energy consumption are calculated for the investigated appliances for the 24 V DC system. The total energy losses in year 1118.2

kWh. Injera mitad have high voltage regulation and power losses over others appliances. The voltage regulation of Mitad is 38.92 in a year.

3.6.2 Energy Consumption and Loss Calculation for 48 V DC Systems

Table: 3.8 Energy consumption and feeder power loss for 48V DC system

List of appliances	Power in (W)	Time of use in a Day (hrs.)	Current (A)	Wire area (mm^2)	Wire resistances (Ω)	Feeder power losses (W)	voltage drop(V) %	Feeder energy losses kWh/yr	Total energy consumption kWh/yr.
LED light	80	7	1.69	2.5	0.34	0.971	1.19	2.48	204.4
Laptop	45	6	0.944	2.5	0.34	0.3	0.67	0.657	98.55
32 LED TV	55	7	1.155	2.5	0.34	0.454	0.67	1.16	140.525
Dish receiver	20	7	0.418	2.5	0.34	0.06	0.3	0.027	51.1
Mobile phone	18	6	0.376	2.5	0.34	0.048	0.267	0.105	19.71
DVD player	12	3	0.376	2.5	0.34	0.048	0.177	0.053	13.14
Refrigerator	125	12	2.66	2.5	0.34	2.406	2.063	10.54	547.5
Stove	1000	3	21.67	4	0.086	40.38	3.84	44.23	730
Coffee machine	990	0.5	2145	4	0.086	39.57	3.844	7.22	180.675
Injera mitad	3700	3hrs in a week	80.86	6	0.028	183.07	4.73	28.64	578.786
Total								95.112	2564.38

Compared to the 24 V DC, for the 48 V DC case, the current has decreased for same power rating appliances. The energy losses in the feeder and the on energy consumption are calculated similarly. The total energy losses of 48V DC in year is 95.112 kWh, which is 1023.1 kWh less compared with the 24 VDC system. The voltage regulation of mitad in 48V DC system is smaller than that of 24V DC system. The voltage regulation of mitad in 48V DC system is 4.73, which is 34.19 less, compared with that of 24V DC system.

3.6.3 Energy Consumption and Loss Calculation for 120 V DC Systems

Table: 3.9 Energy consumption and feeder power loss for 120V DC system

List of appliances	Power in (W)	Time of use in a day (hrs.)	Current (A)	Wire area (mm^2)	Wire resistances (Ω)	Feeder power losses (W)	voltage drop(V) %	Feeder energy losses kWh/yr	Total energy consumption kWh/yr.
LED light	80	7	0.668	2.5	0.34	0.152	0.19	0.388	204.4
Laptop	45	6	0.38	2.5	0.34	0.048	0.108	0.105	98.55
32 LED TV	55	7	0.459	2.5	0.34	0.071	0.13	0.18	140.525
Dish receiver	20	7	0.17	2.5	0.34	0.01	0.010	0.0242	51.1
Mobile phone	18	6	0.15	2.5	0.34	0.00	0.042	0.0167	19.71
DVD player	12	3	0.1	2.5	0.34	0.00	0.028	0.0037	13.14
Refrigerator	125	12	1.045	2.5	0.34	0.37	0.3	1.63	547.5
Stove	1000	3	8.38	4	0.086	6.045	0.6	0.04	730
Coffee machine	990	0.5	8.3	4	0.086	5.92	0.6	1.08	180.675
Injera mitad	3700	3hrs in a week	31.06	6	0.028	27.01	0.725	4.225	578.786
Total								6.614	2564.38

For 120V DC system the feeder, energy loss and voltage regulation is much smaller than others system. The energy losses in the feeder and the on energy consumption are calculated for the investigated appliances for the 120V DC system. The total energy losses in year are 6.614 kWh, which is 1111.59 kWh and 88.5 kWh less compared with the 24V DC and 48V DC system respectively. Injera mitad has highest voltage regulation appliances. For 120V DC system the voltage regulation of Injera mitad is much smaller than 24V and 48V DC system. In 12OV DC the voltage regulation of Injera mitad is 0.725, which is 38.92 and 4.73 for the 24V and 48V DC system respectively.

3.7 Comparison of the Systems

Figure 3.3 presents the losses for the different voltage levels systems. The power loss of the 24V DC system is higher than for the other systems. In the case with the 120V, DC system losses could be reduced compared with 24V and 48V DC systems.

Table: 3.10 Different voltage levels efficiency comparison

Different DC voltage systems	Feeder energy losses (kWh/yr.)	Efficiency in %
24V DC	1,118.2	56.4
48V DC	95.112	96.3
120V DC	6.614	99.7

Feeder energy loss of the 24V DC system is higher than for the other systems.

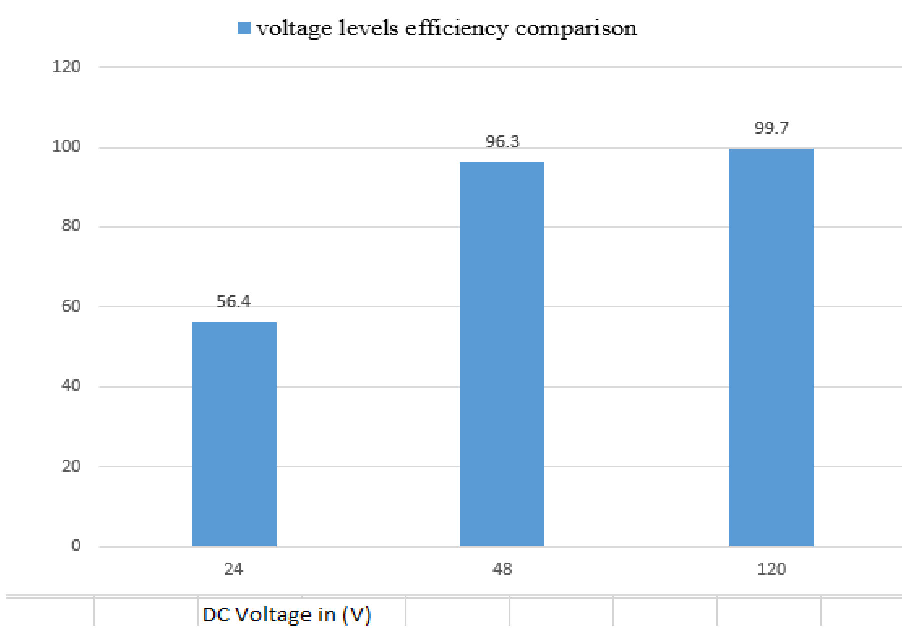


Figure: 3.4 DC voltage levels comparison by their efficiencies

Comparison for the voltage regulations by taking the Mitad as a sample:

Table: 3.11 Different voltage levels of Mitad voltage regulation comparison

Different voltage level	Voltage regulation (%)
24V DC	38.92
48V DC	4.73
120V DC	0.725

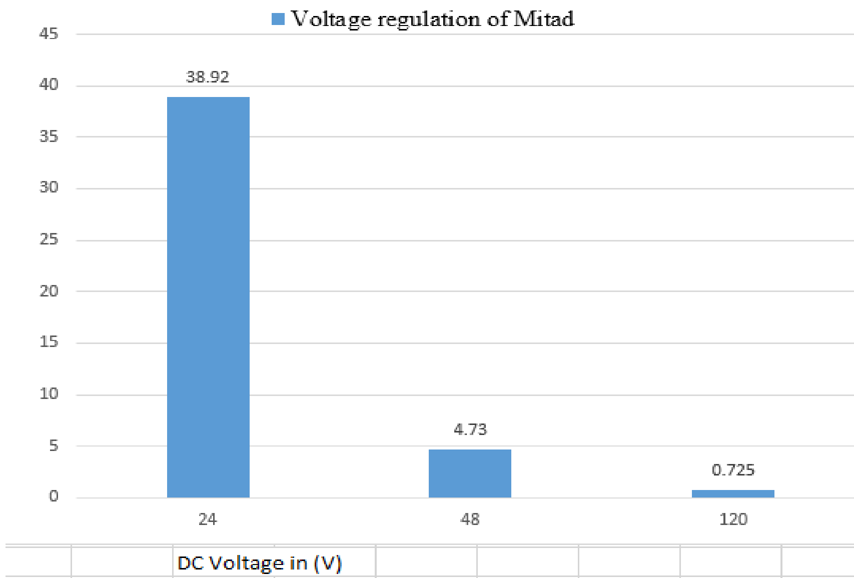


Figure: 3.5 Different DC voltage levels of Mitad comparison by voltage regulation

In general, 120V DC is selected as a best voltage level for DC home system to supply power for the selected home, as this voltage, level is more energy efficient and has smallest voltage regulation as compared to other DC systems.

Chapter Four

4. Design of PV DC System

Renewable Energy Sources (RESs) like wind, fuel cells and solar power plants play an important role to produce electricity without the harmful emission of greenhouse gasses. Since these resources produce DC as their output, DC system can be directly integrated with these resources effectively [31]. Solar Energy is an environmental friendly renewable energy resource that does not emit carbon to the atmosphere that causes global warming.

4.1 PV Module

The array characterized by its average efficiency. The solar cell is an electric component with the ability to produce energy from sunlight. The solar cell is more commonly called a photovoltaic cell (PV cell), where the term photovoltaic originates from the conversion of light into electricity. Table 4.1 shows electrical and mechanical characteristics of **Sun-Power SPR-X20-255** solar modules at standard test condition (STC).

Table: 4.1 Electrical and mechanical characteristics of solar panel.

Module: **sun-power XPR-X20-255**	
Maximum power(w)	254.66
Open circuit voltage V_{OC}(V)	51
Voltage at maximum power point Vmax(V)	42.8
Temperature coefficient of V_{OC}(% °C)	-0.24
Short circuit current I_{sc}(I)	6.3
Current at maximum power point Imax(A)	5.95
Temperature coefficient of I_{sc}(%°C)	0.04
Cells per modules	72
Mechanical characteristics of panels	
Type	Polycrystalline Silicon
Size (Length*width*depth)	(1425*990*36) mm
NOCT	46°C

The solar panel design is based on mathematical equations, some theoretical calculations should be done and test the circuit under standard test conditions (STC). By using the theoretical values, the required values can extracted for designing the practical circuit in MATLAB/SIMULINK. Initially solar panel designed and tested the circuit for different irradiances, temperature and number of cells.

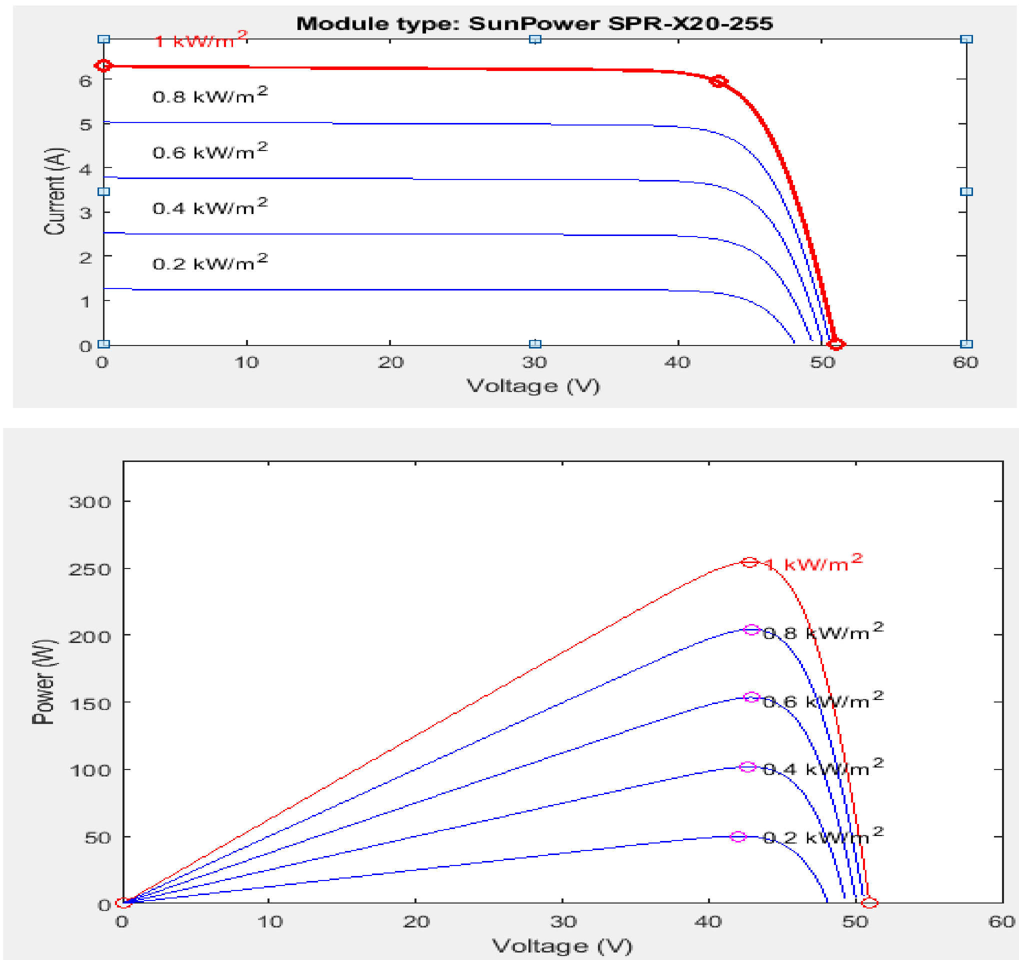


Figure: 4.1 I-V and P-V curve under different irradiance

From the figure it is apparent that the power will increase with the irradiance rises. When comparing the power under different temperature, the default irradiance is 1000W/m^2.

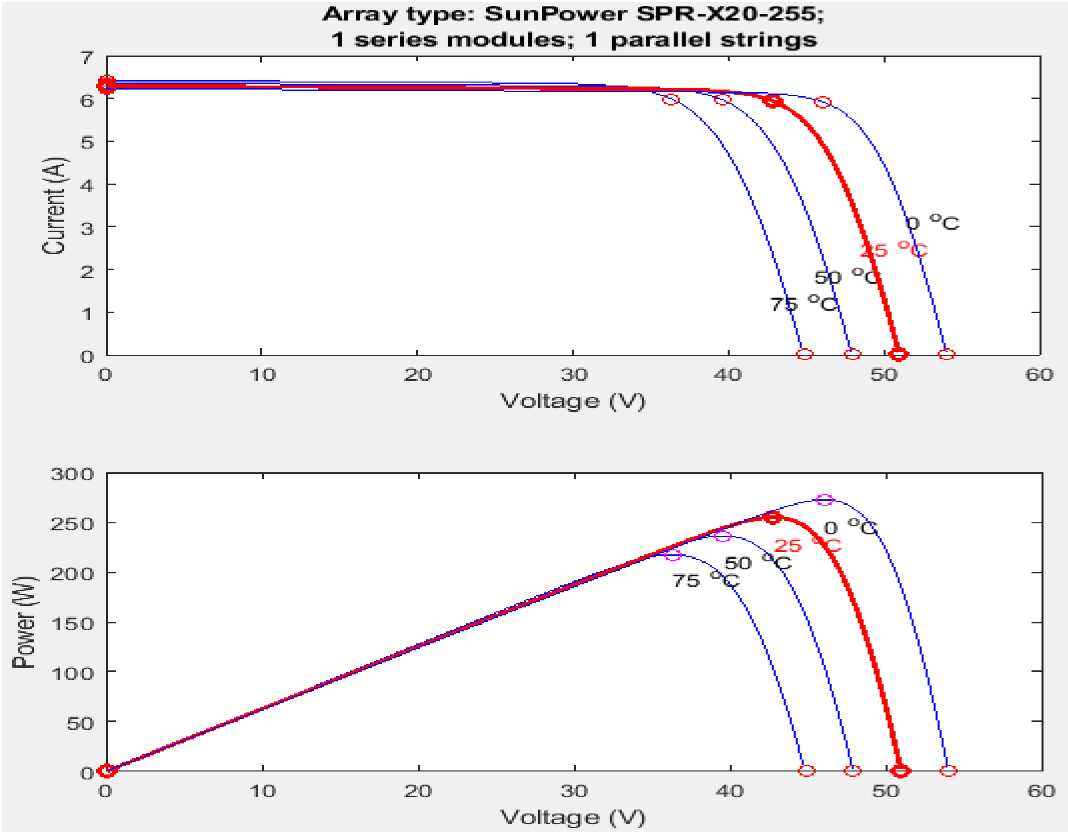


Figure:4.2 I-V and P-V of PV module behaviors with different temperature

When the current remains the same for low voltage conditions whatever how much the insolation is. In addition, it begins to drop down when getting close to the maximum power point. High temperature will reduce the power output; it verified by the curves. When temperature reaches 75°C, the maximum power voltage is as low as less than 45V. For the reference temperature of 25°C, the voltage can reach to about 50V and makes the maximum power higher.

4.2 Design of SHS Solar PV System

In this part, the design of the PV system is accomplished for the selected voltage based on the power required by the typical home.

Table 4.2 DC appliances daily use time and their wattages

Appliances	Appliances numbers	Daily use (hr.)	Total wattage in (W)	Daily energy consumption (kWh)
LED lamp	8	7	80	0.560
Laptop	1	6	45	0.270
32 LED TV	1	7	55	0.385
Satellite receiver	1	7	20	0.140
Mobile phone	3	3	18	0.540
DVD player	1	3	12	0.360
Refrigerator	1	12	125	1.500
Stove	1	3	1000	3.000
Coffee machine	1	0.5	990	0.495
Injera mitad	1	3/7	3700	1.585
Total daily energy (kWh) = 8.835				

Energy demand calculated from the total appliance:

Module required per string;

$$\mathrm{N_s} = \frac{\text{required voltage}}{\text{module } \mathrm{V_{max}}} \tag{4-1}$$

$$N_S = \frac{130}{42.8} = 3$$

$$\mathrm{I_{max}} = \frac{\text{peak power}}{\text{required module voltage}} \tag{4-2}$$

$$I_{max} = \frac{4500}{130} = 34.6$$

Number of string in parallel

$$\mathrm{N_P} = \frac{\text{load current}}{\text{module } \mathrm{I_{max}}} \tag{4-3}$$

$$N_p = \frac{34.6}{5.95} = 6$$

The total number of modules required $= N_S * N_p = 3 * 6 = 18$

4.3 PV System with MPPT and Buck Boost converter

4.3.1 Maximum Power Point Tracking

The photovoltaic system has a non-linear current-voltage and power-voltage characteristics that continuously varies with irradiation and temperature. In order to track the continuously varying maximum power point of the solar array, the MPPT (maximum power point tracking) control technique plays an important role in the PV systems. The task of a maximum power point tracking (MPPT) network in a photovoltaic (PV) system is to continuously tune the system so that it draws maximum power from the solar array regardless of weather or load conditions [32]. The Maximum Power Point (MPP) of the PV array changes continuously; consequently the PV system's operating point must change to maximize the energy produced. Therefore, a Maximum Power Point Tracking (MPPT) is an essential part of the PV system to ensure that the system operates at the maximum power of the PV array. To achieve this, MPPT control algorithms is required. The output voltage (V_{pv}) and the output current (I_{pv}) of the PV array are used to determine the duty ratio of the voltage, which is then modulated to get the gating pulses for the buck boost convertor. The PWM uses control parameter, duty ratio D, which is used for the tuning of the network for maximum extraction of power.

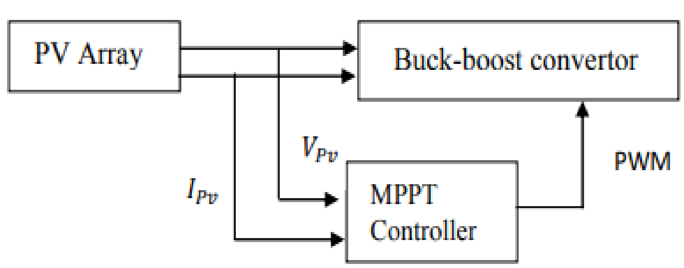


Figure: 4.3 PV array with MPPT

MPPT algorithms are used to control the duty cycle or the operating voltage of a photovoltaic system to ensure maximum power at all times.

Perturb and Observe (P&O): is the most commonly used algorithm for maximum power point tracking. In this algorithm, the controller adjusts the voltage by using the array voltages. These array voltages are initially set with some values. It starts with some threshold value at first iteration and goes on increasing until the power starts decreasing. If the power increases, then the approach is in a right direction i.e. towards maximum power point.

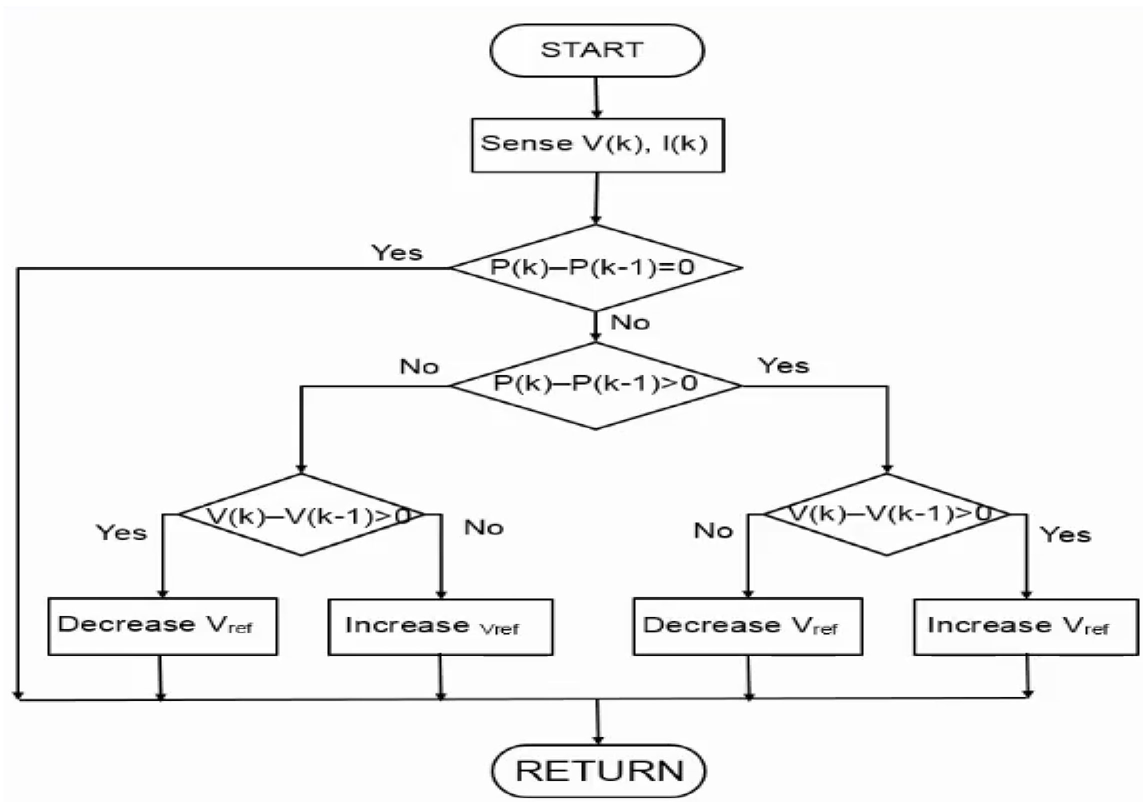


Figure: 4.4 MPPT algorithm based on P&O technique [33]

According to the P&O algorithm shown above, the following circuit shown in figure 4.10 is designed. The outputs from solar panel are given to MPPT circuit. Those array signals may have some higher frequencies, which are unwanted frequencies. In order to attenuate those, a low pass filter is used with specifications of 0.8V, 60 degree of phase. After that signal, sampling is done and held for a period of 0.1ms. A unit delay block is used for both voltage and current, further power is calculated. $\Delta P = P_a - P_b$ & $\Delta V = V_a - V_b$ are calculated, where ‘a’ is the original signal and ‘b’ is the delay signal.

$\Delta P * \Delta D$, is control the action of switch. When $\Delta P * \Delta V > 0$, then the value is decremented and if $\Delta P * V\Delta < 0$, then the value is incremented. Fixed step size, ΔD is multiplied in the process for setting the linear response. The output signal after multiplying the step size is passed through the delay block, the original multiplied signal and the delayed signal are added together to form the initial MPPT signal. This signal is further passed through saturation and sample hold blocks. The saturation block is set with a lower limit of 0 and upper limit of 0.8, whereas sample and hold is set for 0.1ms. The saturated signal is compared with the repeating sequence to generate the gating signal. This signal is the final output from the MPPT circuit; it is used to drive the boost converter.

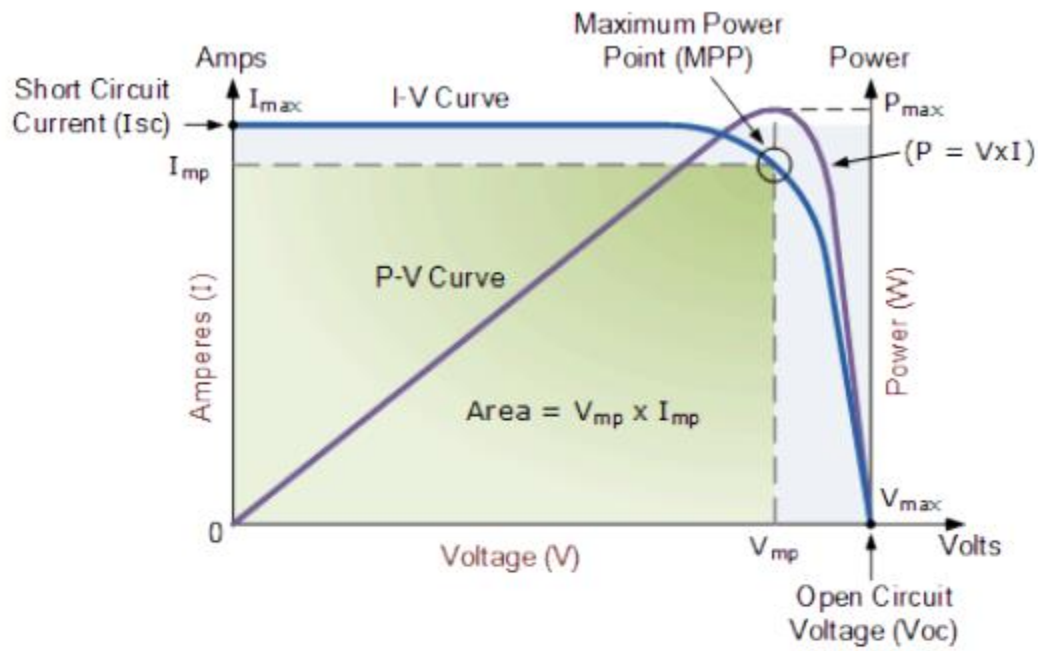


Figure: 4.5 Ideal graphs for P&O algorithm

4.3.2 Buck-Boost Converter

A Buck Boost converter is a switch mode DC-to-DC converter in which the output voltage can be transformed to a level less than or greater than the input voltage. The magnitude of output voltage depends on the duty cycle of the switch. It is also called as step up/step down converter.

Buck boost convertor coupled with maximum power point tracking is implemented to make constant output voltage from the PV panel. The equivalent circuit of buck boost convertor is shown in (Figure 4.4)

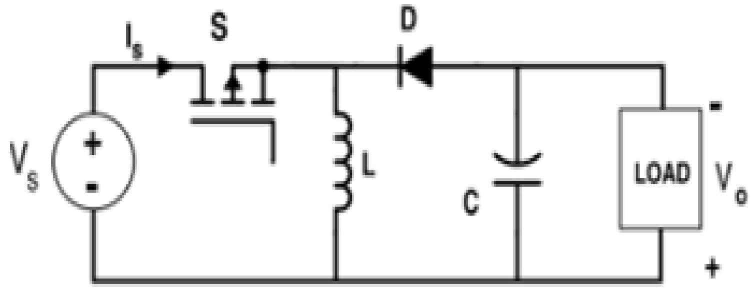


Figure: 4.6 Buck Boost converter circuit

$$Load(R) = \frac{V_{out}^2}{P} \qquad (4\text{-}5)$$

Where: $V_{Out} = Output\ voltage, which\ selected\ 120V$

$P = is\ load\ power\ (in\ watt)$

From the load profile, the peak and the minimum load is 6320W and 110W respectively and the corresponding load resistances for the buck boost convertor becomes

$$R_{min} = \frac{130^2}{4500} = 3.75\ \Omega$$

$$R_{max} = \frac{130^2}{110} = 151.6\ \Omega$$

$$V_{Out} = \frac{D}{1-D} V_{in} \qquad (4\text{-}6)$$

Where D is the duty ratio of the convertor and $V_S$is the source voltage.

$$120 = \frac{D}{1-D} 130$$

$D = 0.49$ (Duty ratio of the converter)

Assuming the source voltage V_{in} 5% deviation from the nominal output voltage V_{out}, of the convertor, then the duty ratio of the convertor will be 0.52.

Capacitor (C) and inductor (L) of the circuit for continuous output voltage is as the follows:

$$C \geq \frac{D}{2Rf_2} \tag{4-7}$$

Where the f_s switching frequency is selected to be 10 KHz.

$$C \geq \frac{0.52}{2 * 3.75 * 10{,}000} \geq 6.93\mu\text{F}$$

$$L \geq \frac{R(1-D)}{2f_2} \tag{4-8}$$

$$L \geq \frac{151.6(1-0.49)}{2(10000)} \geq 3.86mH$$

4.4 Battery with bidirectional buck boost DC/DC converter

4.4.1 Battery sizing

- State of Charge (SOC): An expression of the present battery capacity as a percentage of maximum capacity. SOC is generally calculated using current integration to determine the change in battery capacity over time.
- Depth of Discharge (DOD): The percentage of battery capacity that has discharged expressed as a percentage of maximum capacity. A discharge to at least 80 % DOD referred to as a deep discharge.
- Terminal Voltage: The voltage between the battery terminals with load applied. Terminal voltage varies with SOC and discharge/charge current.
- Open-circuit voltage: The voltage between the battery terminals with no load applied. The open-circuit voltage depends on the battery state of charge, increasing with state of charge.
- Internal Resistance: The resistance within the battery, generally different for charging and discharging dependent on the battery state of charge. As internal resistance increases, the battery efficiency decreases and thermal stability reduced as more of the charging energy converted into heat.

Total energy consumed by the system:

$= (80\text{W} * 7\text{hr}) + (45\text{W} * 6\text{hr}) + (55\text{W} * 7\text{hr}) + (20\text{W} * 7\text{hr}) + (18\text{W} * 3\text{hr}) + (12\text{W} * 3\text{hr}) +$

$(125\text{W} * 12\text{hr}) + (1000\text{W} * 3\text{hr}) + (990\text{W} * 0.5\text{hr}) + \left(3700\text{W} * \frac{3}{7\text{hr}}\right) = 8835\ \text{kWh/day}$

Total energy consume by the system is 8.835 kWh/day.

- (Ah) demand per day $= \frac{\text{daily energy consumption}}{\text{battery voltage}} (Ah)$ (4-4)

$$= \frac{8835}{120} = 73.6\ (Ah)$$

- Depth of Discharge (DOD) of battery be 80%

$$required\ battery\ capacity = \frac{73.6}{0.8} = 92Ah$$

Nominal battery voltage is 12V, 100Ah; sealed lead acid battery selected:

- Day of autonomy =3days.

$$92 * 3 = 276Ah$$

  - ✓ Number of batteries in series $= \frac{120}{12} = 10$
  - ✓ Number of batteries in parallel $= \frac{276}{100} = 2.76 \approx\ 3$
  - ✓ The total number of batteries $= 10 * 3 = 30$

4.4.2 Bidirectional Buck Boost DC/DC converter

Bidirectional converter is present in most of the stand-alone systems. It acts as a barrier between source and load. The excess power leftover after load requirements is stored in a battery. During night times when there is no sun light, home appliances supplied by battery system. In other times when there is sufficient output from the PV panels supplying the loads, the energy storage system is being charged by solar system. Buck boost bidirectional convertor used to charge and discharge the battery during these occasions. A bi-directional converter and controller used to control the flow between source and load. This converter operates in buck mode for charging the battery, because it supplies the power to load and meanwhile it sends small amount of charge to battery. While the battery is discharging, it acts in boost mode, because it has to give all its power to the load immediately. A capacitor placed before the battery for blocking the ripples in the current, so it increases the lifetime of the battery.

In a renewable energy generation system, a bidirectional DC-DC converter typically used to interface the energy storage device with the renewable energy sources. When the power demand is lower than that provided, the excessive energy will be stored in the batteries, which is called charging mode. Conversely, when the power demand is higher than that provided by the PV system, the energy flows from batteries to the load, which is called discharging mode. For charging modes, if the voltage of battery is higher than that of the dc link, the system will boost the voltage to charge; otherwise, the voltage will lowered to charge. For discharging modes, if the voltage of battery is higher than that of the dc link, the voltage of batteries will lowered to discharge; otherwise, the voltage of batteries will boosted to discharge

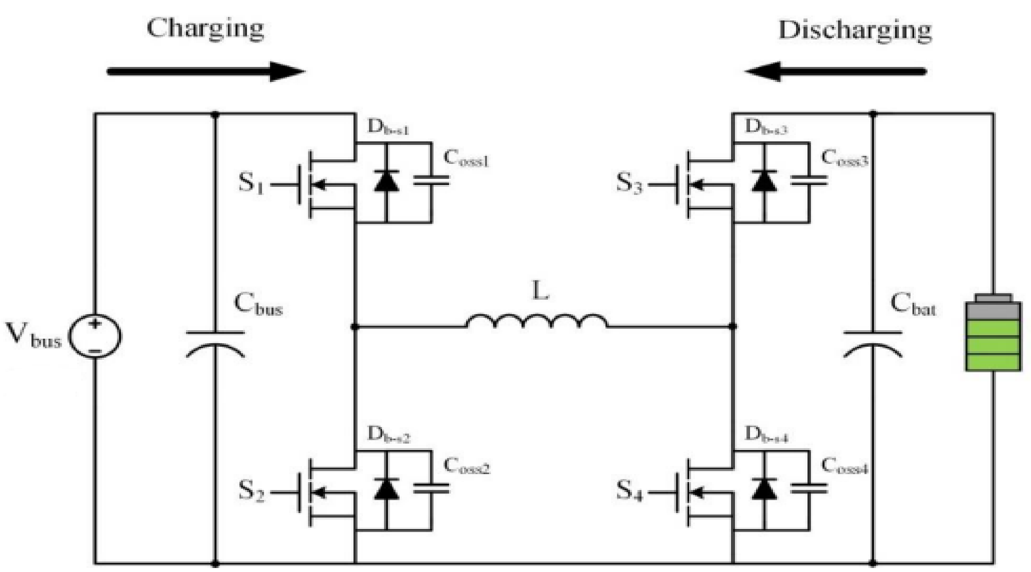


Figure: 4.7 Circuit diagram of universal bi-directional buck-boost converter [34]

The charging/discharging mode defined as that the energy transferred from the DC bus/battery to the battery/dc-bus. Since the battery voltage may be higher or lower than the DC-bus voltage during the entire operation, there exist four operation modes as follows: boost charging, buck charging, boost discharging and buck discharging.

Modes	**Buck**	**Boost**
Charging	$S1$= controlling signal (duty ratio =d), $S2$=off, $S3$=on/off and $S4$ =off	$S1$= on, $S2$=off, $S3$=on/off and $S4$ = controlling signal (duty ratio =d)

Discharging	$S1$= on/off, $S2$=off, $S3$= controlling signal (duty ratio =d) and $S4$ =off	$S1$= on/off, $S2$= controlling signal (duty ratio =d), $S3$=on and $S4$ =off

Buck (discharge), $\mathrm{D} = \frac{\mathrm{V_{bus}}}{\mathrm{V_{batt}}} = \frac{130}{154} = 0.84$

Boost (discharge), $\mathrm{D} = \frac{\mathrm{V_{bus}} - \mathrm{V_{batt}}}{\mathrm{V_{bus}}} = \frac{130-116}{130} = 0.1$

$$Load(R) = \frac{{V_{out}}^2}{P}$$

Where: $\mathrm{V_{Out}} = \mathrm{Output\ voltage, which\ selected\ 120V}$

$\mathrm{P} = \mathrm{is\ load\ power\ (in\ watt)}$

From the load profile, the peak and the minimum load is 4500W and 110W respectively and the corresponding load resistances for the buck boost convertor becomes

$$\mathrm{R_{min}} = \frac{(120)^2}{4500} = 3.2\ \Omega$$

$$\mathrm{R_{max}} = \frac{(120)^2}{110} = 131\ \Omega$$

The maximum resistance during minimum loading is 131Ω. The inductances and capacitances under the two operating mode then becomes:

Buck discharge:

$$\mathrm{L} \geq \frac{\mathrm{R}(1-\mathrm{D})}{2*\mathrm{f}} \tag{4-5}$$

$$L \geq \frac{131(1-0.84)}{2*10000} = 1.05\mathrm{mH}$$

$$c \geq \frac{(1-D)}{16Lf^2} \tag{4-6}$$

$$c \geq \frac{(1-0.84)}{16 * 0.0012 * 1000^2} = 0.083\mu F$$

Boost discharge:

$$L \geq \frac{RD(1-D)^2}{2f} \tag{4-7}$$

$$L \geq \frac{3.2 * 0.1(1-0.1)^2}{2 * 10000} = 0.013mH$$

$$C \geq \frac{D}{16Rf_S} \tag{4-8}$$

$$c \geq \frac{0.1}{16 * 3.2 * 10000} = 0.195\mu F$$

4.5 Buck Converter and PI controller

4.5.1 Buck Converter

Power converters are an integral part of many electrical systems that require energy transfer between one-voltage levels to another, as the voltage required may be different to the voltage supplied. To achieve energy-efficient conversions, switch-mode conversion is used [35].

A buck converter (step-down converter) is a DC/DC power converter, which steps down voltage (while stepping up current) from its input (supply) to its output (load). The buck convertor in this thesis used to produce constant output voltage irrespective of load variation using PI controllers. It accepts the output of the buck boost convertor and energy storage system and converts it to lower value 120V, and supply it to the load. The load voltage is maintained constant by using buck convertor with PI controller.

The equivalent circuit of buck converter shown in the Figure below:

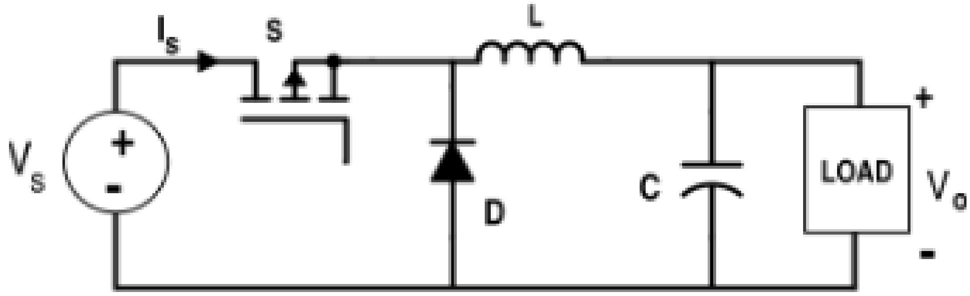


Figure: 4.8 Buck DC-DC converters

The frequency of the switch equals to $\frac{1}{T_S}$, and is usually in the range of 1 kHz to1MHz, where the switching component often is a semiconductor device.

In addition to the switching network, there is also a low-pass filter (LP-filter) connected in the circuit. This is because the desired voltage component, in addition has undesired harmonics due to the switching frequency. These harmonics are removed using the LP-filter. The filter has a corner frequency given by: $f_s = \frac{1}{2\pi\sqrt{LC}}$

Assuming the switching frequency 10 kHz.

Duty ratio of the buck convertor is:

$$D = \frac{V_O}{V_S} = \frac{120}{130} = 0.92$$

$$R_{min} = \frac{120^2}{4500} = 3.2\Omega$$

$$R_{max} = \frac{120^2}{110} = 130.9\Omega$$

$$L \geq \frac{R(1-D)}{2f_S}$$

$$L \geq \frac{151.6(1-0.92)}{2(10{,}000)} = 0.61mH$$

$$C \geq \frac{1-D}{16L{f_S}^2}$$

$$C \geq \frac{1-0.92}{16*0.61*10^{-3}(10000)^2} = 0.0082\mu\text{F}$$

From the load profile, the peak and the minimum load is 4500W and 110W respectively and the corresponding load resistances for the buck convertor becomes, since the maximum and minimum resistance is 131 Ω and 3.2 Ω respectively.

4.5.2 PI Controller of Load Voltage Control

The voltage loop takes the output voltage as a feedback signal and compares it to a reference voltage, and produces an error. The error is sent to a PI controller to produce a stable output voltage under steady-state operation [36]. The error is then multiplied to the absolute value of the source voltage to create a reference current for the inner loop. The inner loop operates just like the outer loop, and compares the inductor current to reference current created from the outer loop to produce an error, which then is sent to the PI controller and produces a waveform that is compared to a reference waveform to generate a firing pulse sequence, which is applied to the switches.

The PI controller consists of two components; namely proportional and integral components. The proportional component takes the inputted signal and increases it by the proportional gain, K_P, specified. The integral component integrates the inputted signal with respect to time and multiplies it by integral gain, Ki. The two are then added together to create the output signal.

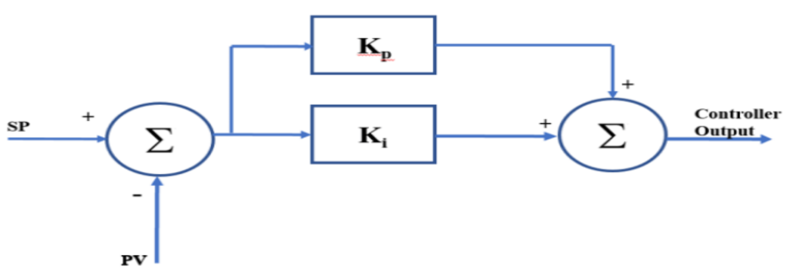


Figure: 4.9 PI controller block diagram

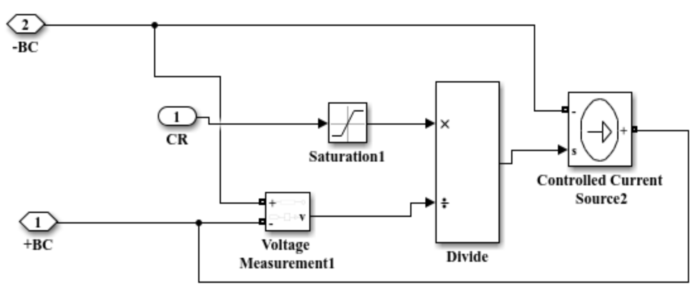
When the error is reduced, voltage in the loop can be controlled. In this thesis, a controlled current source (CCS) is used in the feedback loop. It takes the Simulink input signal and converts into the same amount of current. Current source can be usually of two type's independent and dependent current source. Independent current source gives the constant current with respect to particular voltage. Current dependent source may absorb or deliver the current, which will depend on the other linked circuits. CCS is a dependent current source.

In the whole process of voltage control in a loop, set point or reference voltage is very crucial. Value of set point should decide depending on the application. It depends on the designer for choosing the reference value.

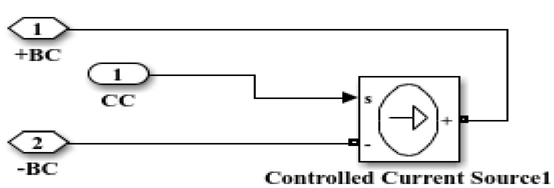
4.6 Load modeling

Loads are only modeled as constant resistance (CR), constant current (CC) or constant power (CP), and no further description is given. An interesting question that arises with a wider use of dc is if existing loads can used without any changes and, if so, how they will operate in steady state and in response to voltage variations. Finally, it is also of interest to find out what is the most suitable voltage level for the loads. Model blocks accept constant resistance (CR) for heating loads, constant power (CP) for Electronic loads and constant current (CC) for electronic lighting loads.

The household loads varies continuously throughout the day. These loads cannot represented directly in MATLAB Simulink software, as a simscape power system lacks a formal block for varying resistive loads for evaluating the load profiles. The variable load block can be designed as a controlled current source, with the output current being determined by the varying resistance value and voltage measurements.



Resistive load



Electronic lighting

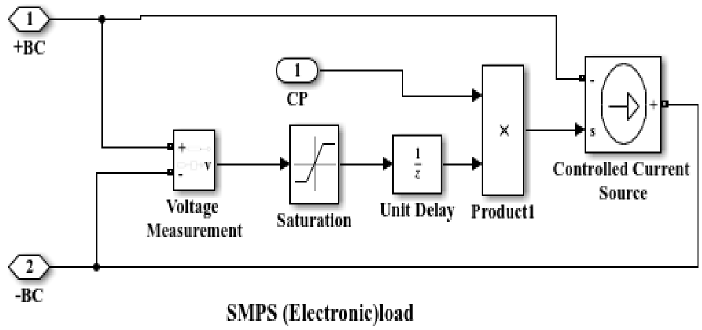


Figure: 4.10 Models of different variable loads.

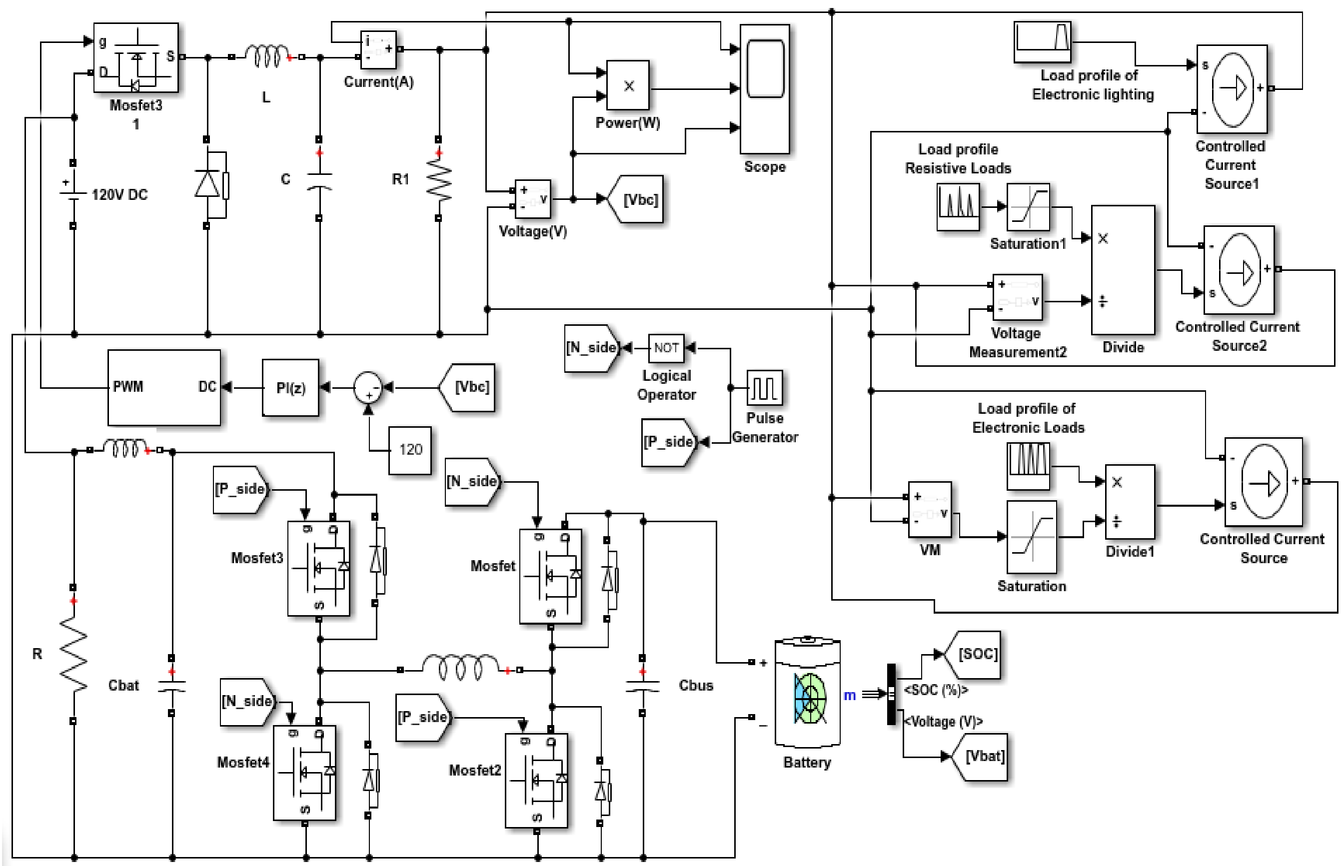


Figure: 4.11 Buck converter and Bidirectional buck boost converter with battery circuit and load

Chapter Five

5. Modeling and Simulation

5.1 Modeling of DC Home System

The DC system can be divided into many parts: the source (PV array with MPPT), the DC/DC converter with controller, battery (energy storage) and the load. Modeling of these parts will be needed to perform system efficiency and reliability. Performing voltage level is an essential part of predicting efficiency and reliability of the system based on different voltages levels (24, 48 and 120V DC). Since this thesis focus on DC home system, the performance assessment of DC home system will be analyzed. Voltage levels of 24V, 48V and 120V identified for analysis, as there is no standard DC voltage currently.

As it known, during night times there is no solar radiation. Therefore, the PV system cannot supply power to the loads. Battery (energy storage) system plays a vital role when the power output of the solar panels is less than the load power requirement. During night and cloudy day, the loads get their supply from the battery, as there is no solar radiation during this time. Which means the battery is in discharging mode. During daytime PV, panels produce enough power to supply the load and charge the battery. In this case, the battery (energy storage) system enters into the charging mode.

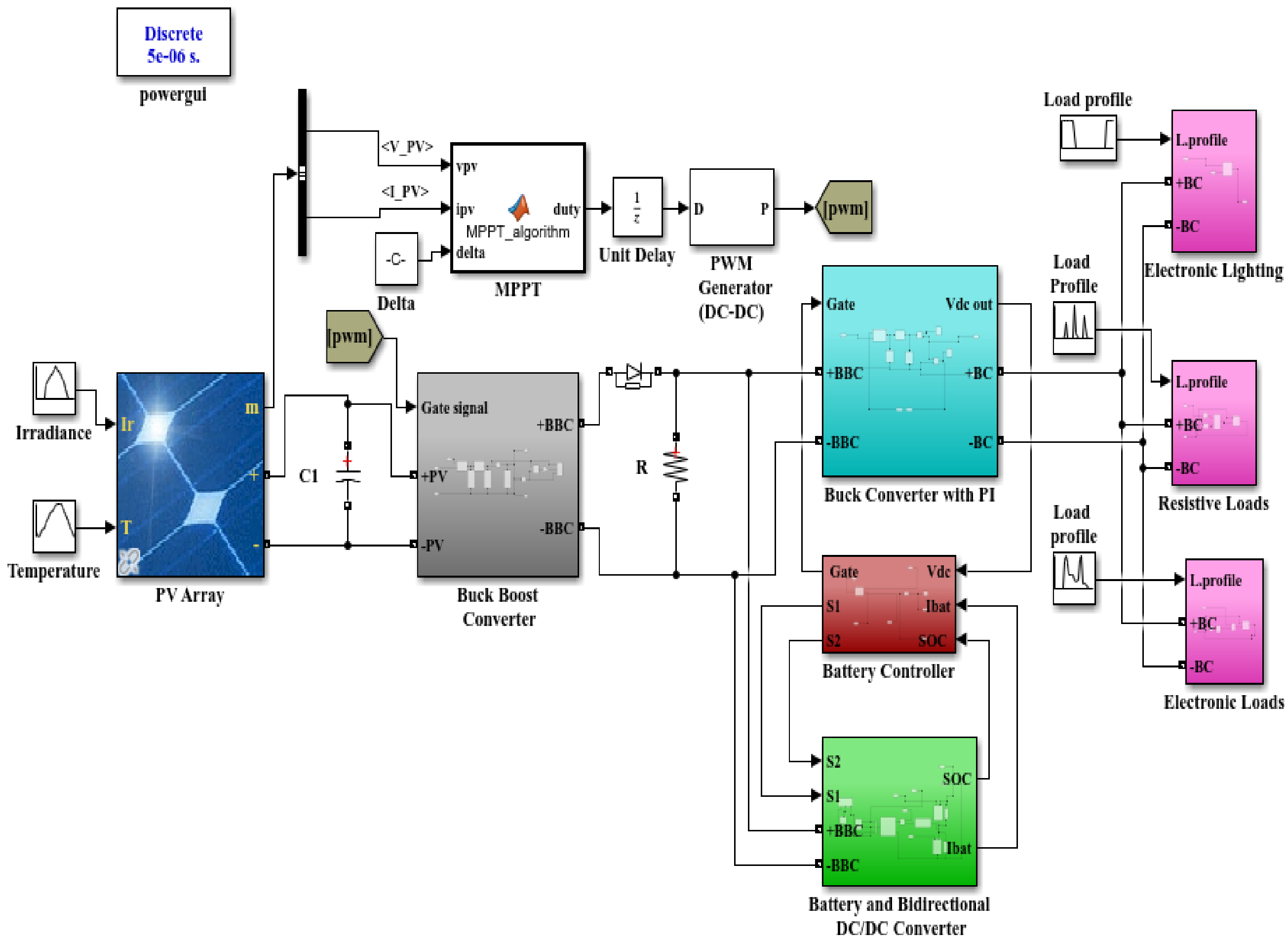


Figure: 5.1 MATLAB/simulink model of overall solar power DC systems

5.2 Simulation Studies

Voltage levels of 24V, 48V and 120V DC are identified for analysis. DC home system implemented with buck convertor with PI controller to maintain constant voltage with variation of load especially during peak hours. Energy storage system with bidirectional convertor to manage the direction of power flow during charging and discharging of the battery.

In 24V, DC, at peak hours when large power consuming devices are connected to the system, large current is flowing. That means, as current increases in a conductor there is increased voltage drop in electrical conductors so there is less voltage at the load. This causes unreliability on the system. Moreover, efficiency and reliability of the system become worse as a result.

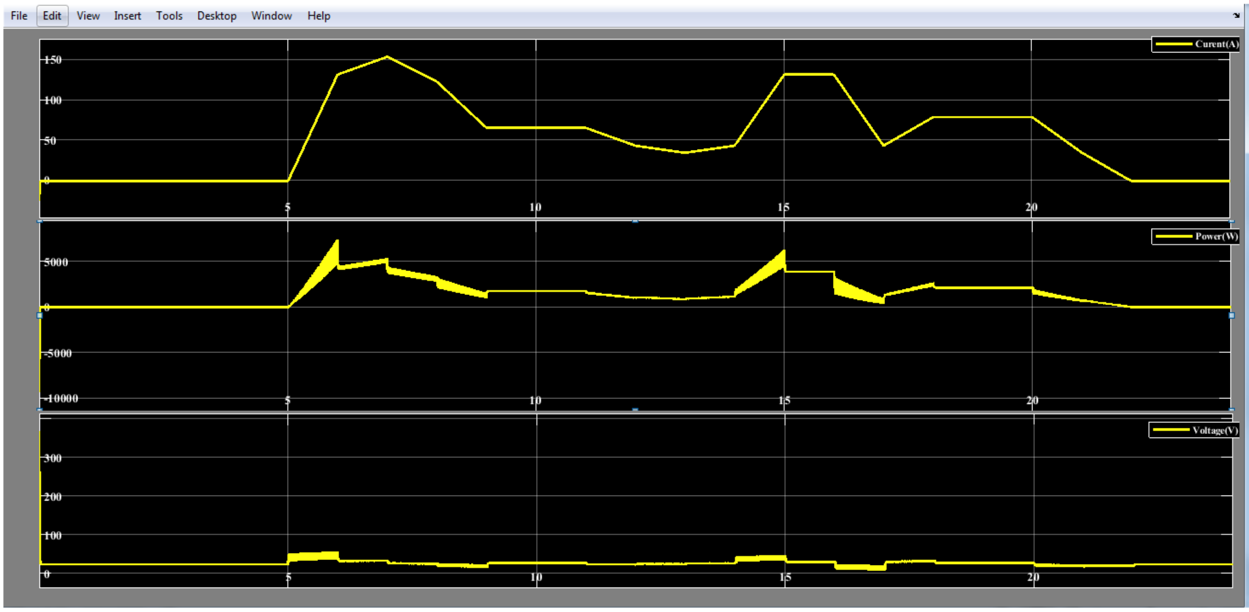


Figure: 5.2 Simulation results of voltage, current and power output for 24V in DC home system

For the 48V, DC system the current is decreased somewhat compared to the 24V DC system. As a result, the voltage drops and power losses.

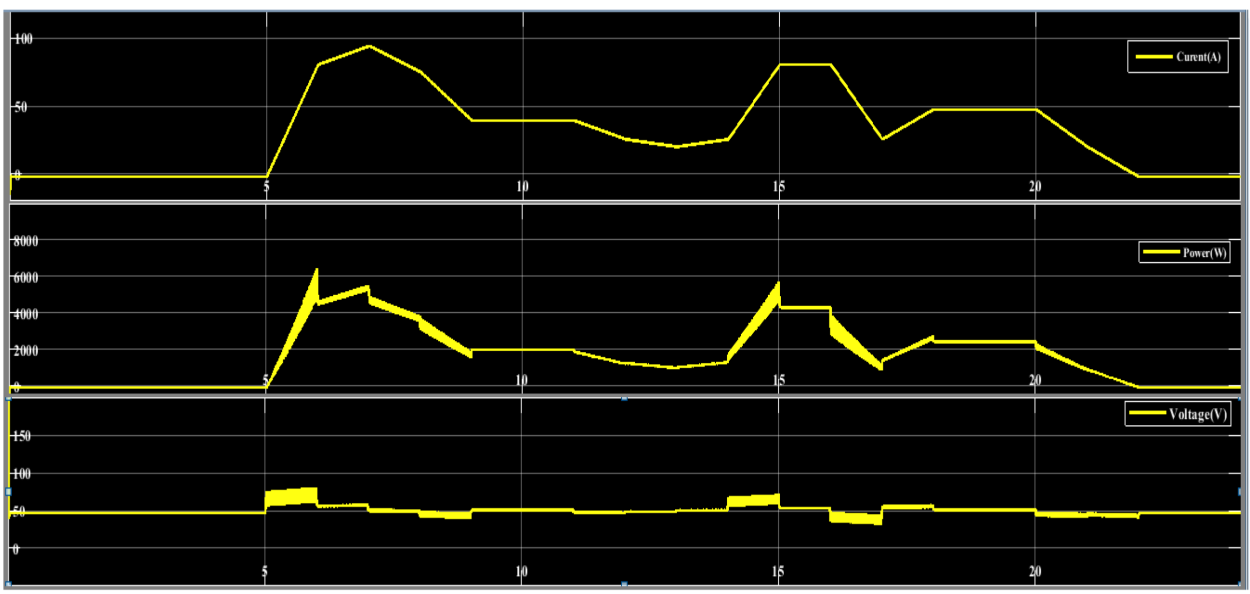


Figure: 5.3 Simulation results of voltage, current and power output for 48V in DC home system

In 120V, DC, at peak hours (6-7, & 12-13) when large power consuming devices connected to the system, current is lower compared to the other voltage levels and the voltage remains also almost constant.

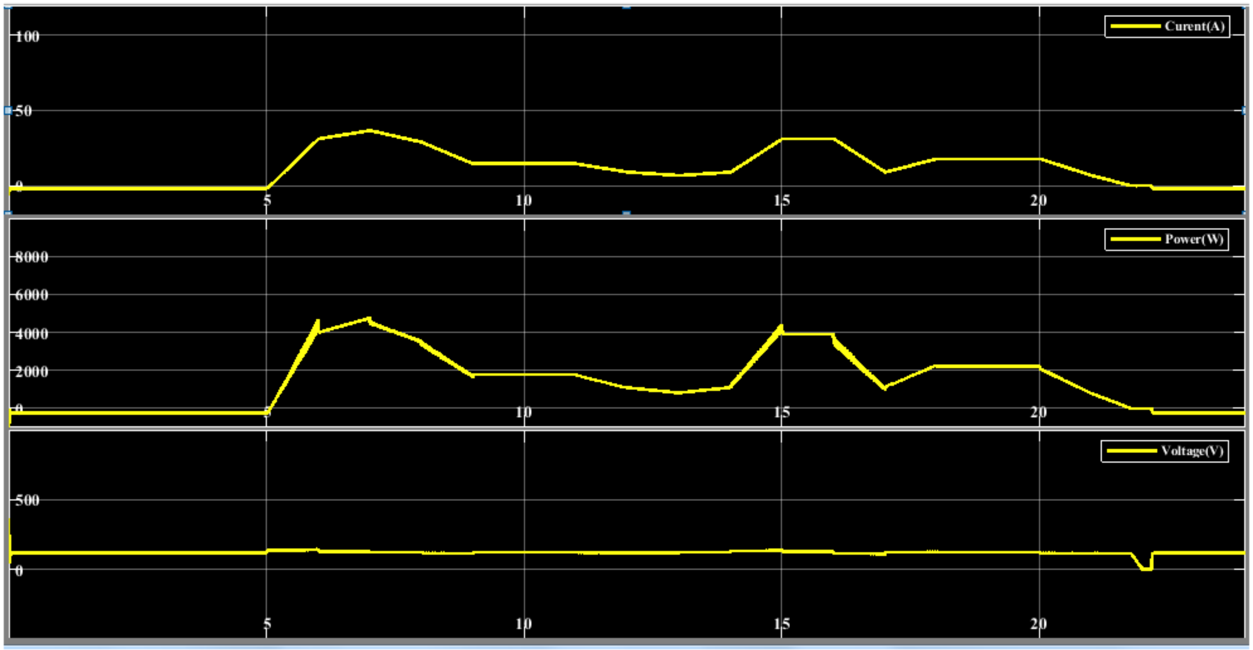


Figure: 5.4 Simulation results of voltage, current and power output for 120V in DC home system

The result verifies that 120V DC is highly efficient compared to the other DC voltage levels. The analysis shows that 120V DC home system is more efficient and reliable than the other voltage levels. 120V DC voltage level is electrically safe for indirect contact and does not require special protection mechanism. All appliances except refrigerator get the power from buck converter.

Chapter Six

6. Conclusion, Recommendations and Future Works

6.1 Conclusion

This study investigated the performance of different DC voltage level and modeling overall DC home system of solar powered. Based on this thesis work, the following conclusions are drawn.

- The use of photovoltaic technologies for electricity production and supply has been a sustainable solution for the population in rural villages that are far from national electric grid.
- The design presented in this paper based on the power demand estimation, photovoltaic panel selection, battery sizing and wire selection for a typical home and can be extended to various homes.
- Photovoltaic systems are not capable of ensuring a continuous electric power supply without storage system and batteries have been associated with solar home system.
- The designed systems have been modelled and simulated in MATLAB software, to determine the best voltage level system that can be more efficient and reliable for supplying power to rural areas.
- The average daily load demand of a residential unit considered here is 8.835 kWh/day.
- A battery storage system having a capacity of 276 Ah with a proper charging and discharging system is employed to meet the load while the PV array fails to provide the required power. The stored energy can be effectively used during periods of low solar irradiation (at night, or when it is cloudy).
- Simulation results found in MATLAB/ SIMULINK platform of manual computation.
- In generally, 120V DC is highly efficient and reliable as compared to the two DC voltage levels (24 and 48 V). Therefore, it is recommended to be selected for DC home system.

6.2 Recommendations

Ethiopian government should create awareness to the people to use direct current system, especially in rural areas and island of the country, which are far from the national grid. As far as the environmental aspects are concerned, DC systems have wide spread in order to cover the energy demands of rural communities and in that way to help reduce the greenhouse gases and the pollution of the environment.

6.3 Future Works

This thesis work mainly focus on selection of appropriate DC voltage level in DC home system for a residence of rural area. To further develop and research the DC home system, there are several steps that can be taken and other considerations that have not been made in this thesis. These steps are in terms of realizing the DC home system as a contender for a spot in the standardized home system. Some of these steps are as following:

- The DC home system design works well for the intended application. However, limited to residential applications. Further research need to be done to expand this work in commercial and industrial areas to make our people beneficial with solar energy resource.
- Fault detection, analysis, and protection of DC voltage for DC home system.
- The implementation for this DC home system as a pilot system in country can be done if a subsidy is available for this thesis, this will make it possible for more research, study and analysis.

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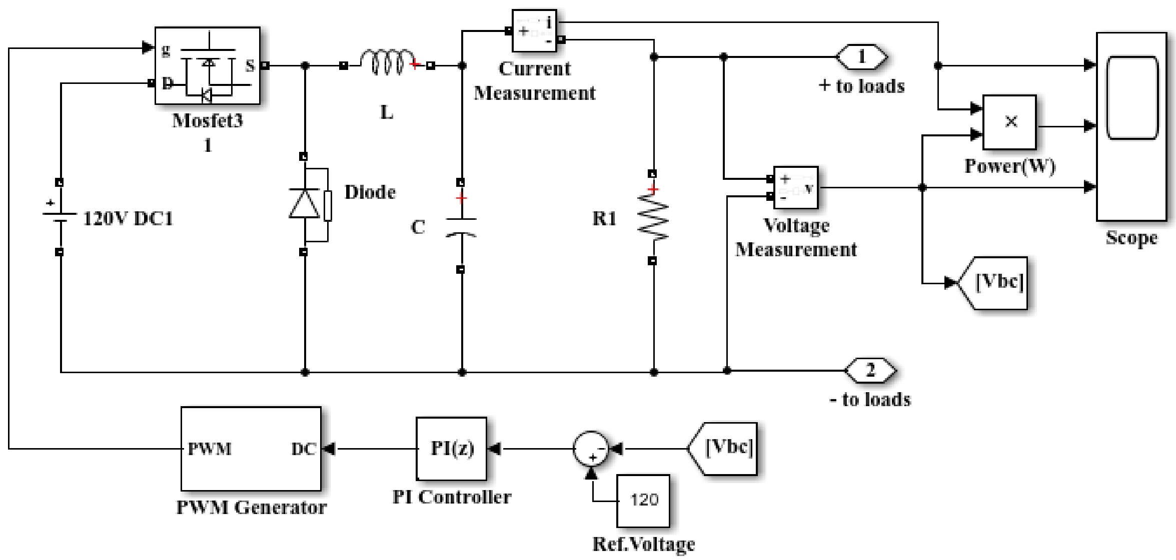
Appendices

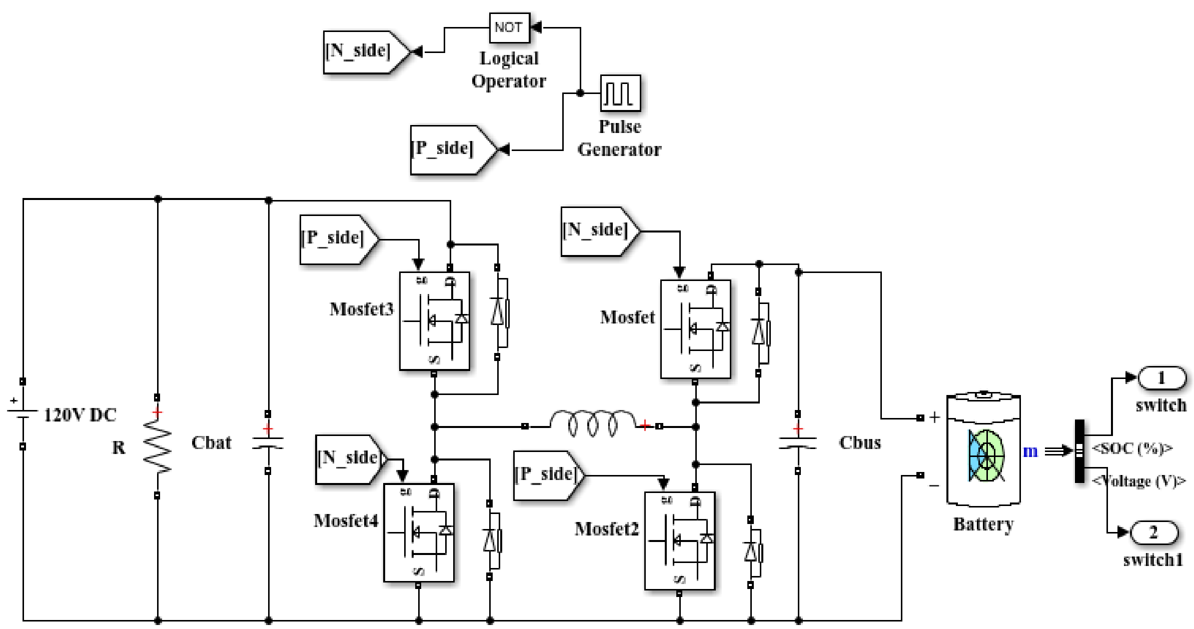
Appendix A: Solar energy radiation of daily average per month.

Middle of the Month	n_d (hr)	δ (^{0})	ω_s(^{0})	N (hrs.)	n (hrs.)	H_o(kWh/ m^2/d)	H (kWh/ m^2/d)	NASA
January 15	15	-21.2694	87.46	12.29	7.1	9.30	5.50	5.55
February 15	45	-13.6197	88.41	12.61	6.4	9.88	5.57	5.92
March 15	74	-2.81887	89.68	12.29	6.1	10.38	5.70	5.73
April 15	105	9.41488	91.08	11.37	5.6	10.47	5.53	5.51
May 15	135	18.79192	92.22	6.94	5.5	10.20	5.33	5.37
June 15	166	23.31441	87.19	14.20	4.8	9.91	5.03	5.03
July 15	196	21.51733	92.53	12.53	3.7	10.02	4.60	4.86
August 15	227	13.78344	91.60	14.00	3.3	10.28	4.59	5.14
September 15	258	2.216904	90.25	6.89	4.4	10.35	5.04	5.48
October 15	288	-9.5994	88.90	10.46	5	10.01	5.12	5.31
November 15	319	-19.1478	87.73	10.82	5.3	9.42	4.94	5.19
December 15	349	-23.3352	87.18	6.22	6.1	9.09	5.05	5.34
Average							5.15	5.37

Appendix B: Buck converter coupled with PI controller and Bidirectional buck boost converter with battery circuit



Buck converter coupled with PI converter circuit



Circuit of bidirectional buck boost converter with battery