ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING

STUDY ON LOW VOLTAGE DIRECT CURRENT DISTRIBUTION SYSTEM SUPPLIED BY SOLAR ENERGY

BY

AWRARIS GETACHEW

THESIS SUBMITTED TO ADDIS ABABA INSTITUTE OF TECHNOLOGY IN
PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

ADVISOR: DR. ING. GETACHEW BIRU

JUNE 26, 2018

ADDIS ABABA, ETHIOPIA

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Declaration

I, the undersigned, declare that this M.Sc. thesis is my original work, has not been presented for fulfillment of a degree in this or any other university, and all sources and materials used for the thesis have been acknowledged.

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This thesis work has been submitted for examination with my approval as a university advisor.

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Acknowledgment

First and foremost, I would like to thank God Almighty for giving me the strength, knowledge, ability and opportunity to undertake this research study and to persevere and complete it satisfactorily. Without his blessings, this achievement would not have been possible.

Secondly, I would like to express my sincere gratitude to Dr. -Ing. Getachew Biru for his excellent supervision, bright ideas, and continuous encouragement throughout the course of this research. It has been a great privilege for me to pursue my higher education under his supervision.

I have great pleasure in acknowledging my gratitude to my colleagues at School of Electrical and Computer Engineering, and friends for their support, encouragement and credible ideas as they are great contributors in the completion of the thesis.

Last but not least, I would like to thank my family members who always stand at my side with an attentive ear to my requests and wishes and are always ready to help to fulfill my dreams.

Table of Contents

Contents

Abstract

Low voltage direct current distribution system has been widely used in data centers, aerospace, automotive and marine. Nowadays dc distribution system gaining advantage over ac system in residential applications due to increasing number of dc based loads, advancement of power electronic convertors and widespread use of renewable energy resources like solar and wind. However lack of standard voltage level and protection mechanisms are major challenges for dc distribution system for residential application.

This thesis work focuses on studying the technical and economic feasibility of low voltage direct current distribution system supplied by solar energy as a renewable source. Household appliances are selected and assessment is made on their energy consumption. Finally low voltage direct current distribution system model is designed and simulated using Matlab/Simulink R2016a software.

120V dc voltage level is set as the optimal for low voltage dc distribution system for residential applications on the basis of efficiency, compatibility and cost. Using this voltage level 0.88% energy efficiency improvement is achieved over its rival 220V ac system for 7.4kW household load. Constant load voltage is maintained using PI controller coupled with buck convertor irrespective of variation of load and irradiance.

120V dc system is classified under extra low voltage level having low risk and safe for human beings for indirect contact. Consumers can get electricity accesses from the proposed dc system at a unit energy cost of $0.21/kWh. Resistive home appliances can be directly connected to the proposed system, whereas electronic loads with switch mode power supplies and rotating loads can be connected to dc distribution system with little modification done on the internal circuitry.

The existing installation wires can be used for low voltage dc distribution system without any rapture in insulation as dc systems have less potential stress over ac system for the same voltage level.

Key words: DC distribution, Compatibility of home appliances, safety issues, load modeling, low voltage dc distribution system design

List of Figures

List of Tables

List of Abbreviations

AC	Alternating Current
Ah	Ampere hour
ALCC	Annual Life Cycle Cost
CB	Circuit Breaker
CCFL	Cold Cathode Fluorescent Lamp
CRT	Cathode Ray Tube
DC	Direct Current
DCM	Discontinuous Conduction Mode
DVD	Digital Video Disc
EEU	Ethiopian electric utility
ETSI	European Telecommunications Standard Institute
HF	High Frequency
IEC	International Electro-technical Commission
IEEE	Institute of Electrical and Electronics Engineers
IET	Institution of Engineering and Technology
kWh	kilo Watt hour
LCC	Life Cycle Cost
LCD	Liquid Crystal Display
LED	Light-Emitting Diode
LVAC	Low Voltage Alternating Current
LVDC	Low Voltage Direct Current
MPPT	Maximum Power Point Track
NOTC	Normal Operating Cell Temperature
PV	Photovoltaic
PVC	Polyvinyl chloride
PMSM	Permanent Magnet Synchronous Motor
RES	Renewable Energy Sources
rms	root mean square
SMPS	Switch Mode Power Supplies

STC	Standard Test Conditions
TV	Television
WHO	World Health Organization
yr	year
ZCS	Zero Current Switching
C_R	Replacement cost
C_{bat}	Battery Capacitance
C_{bus}	Bus Capacitance
$C_{o\&M}$	Operation and maintenance cost
C_o	Purchasing cost
I_{mp}	Maximum operating current
I_{sc}	Short circuit current
V_{bat}	Battery voltage
V_{bus}	Bus voltage
V_{mp}	Maximum operating voltage
V_{oc}	Open circuit voltage

Chapter One

Introduction

1.1 Background

Starting in the late 1880s, Thomas Edison and Nikola Tesla were involved in a battle known as the War of the Currents. Edison developed direct current (dc) that runs continually in a single direction. Direct current is not easily convertible to higher or lower voltages. High voltage dc transmission allows more power to be transmitted over a long distance with a less loss compared to an ac transmission. On the other hand, Tesla showed that alternating current (ac) can be stepped up easily using a transformer which reduces the transmission loss. Tesla's empirical results were the deciding factor, at least for the time being that an ac system was to prefer [1].

Today ac systems have been widely used for supplying power for residential, commercial and industrial appliances. But ac systems suffer a number of problems. The voltage conversion uses transformers which causes power losses even at no load conditions. The harmonic current, power factor and many other power quality problems exist in ac system.

In the past, ac system gains advantage over dc, but in recent year's dc has seen a bit renaissance with the development in the power electronics and availability of renewable energy resources that produce dc. Nowadays, many electronic appliances such as computers, televisions and digital set top boxes operate internally at dc voltages and thus have built-in voltage conversion circuits. DC systems are free from inductance, skin effect, dielectric losses, and interference with communication system [2]. The absence of inductance in dc system makes voltage drop very low. Due to the absence of skin effect, small cross section conductor is required in dc system compared with ac. The current electronic devices requires the conversion of ac to dc. Losses can be reduced if the number of successive voltage conversions is decreased by using dc voltage within electronic appliances.

1.2 Problem Statement and Motivation

The number of devices that operate on dc continues in both homes and offices. Most of the devices that are currently used in homes and offices are using dc internally and this requires ac to dc conversion between ac supply and the dc side of the devices.

In Ethiopia more than 80% of the population lives in rural areas [3] where are far from the national grid. The majority of rural population lives in dispersed homesteads. The transmission and distribution cost of electricity using national grid for such a dispersed population is high.

The country has a huge potential of renewable energy resources like solar energy. In recent years the cost of solar energy per kWh has been reducing since the price of solar panels keep falling. Moreover frequent power interruptions happen in developing countries like Ethiopia, due to the problems which arise from transmission and distribution networks and poor infrastructure of the currently existing system.

In remote areas where the national grid don't reach the rural residents, like most parts of Ethiopia, locally available renewable energy resources can be used for small scale electricity generation. Energy obtained from sustainable sources like solar, fuel cell and wind (coupled with dc generators) produce dc as an output. This energy has been converted back to ac using dc-ac converter to supply power for the currently existing ac loads and again ac is converted back to dc internally inside the devices. This causes multiple power conversions to take place and power loss in the devices to increase. The harmonic currents, power factor and many power quality problems exist in ac systems. Power failure and interruption is also a big issue in these systems. The size of equipment's is also higher due to the inclusion of transformers.

Low Voltage DC (LVDC) distribution system is a promising candidate that can create an innovative solution for distribution networks that can serve electric power with high quality and efficiency and can be accessible for rural residents using locally available renewable sources.

1.3 Objectives

General objective

The general objective of this research is to study the feasibility of low voltage dc distribution system for residential loads.

Specific objectives

The specific objectives are:

- To make comparative evaluation of LVAC and LVDC system in terms of power and efficiency
- To study different power architectures and topologies of dc distribution system
- To make loss calculation and energy consumption in dc and ac system
- To determine standard voltage level for LVDC system
- To design and simulate LVDC distribution system
- To study the economic feasibility of dc distribution system

1.4 Scope of the Thesis

The scope of this thesis work is limited to studying the feasibility of low voltage direct current distribution system for a residence. The house is being supplied with standalone solar PV system. Analysis has been made on low voltage direct current distribution system for its compatibility with current home appliance. Efficiency, voltage drop and unit energy cost of the LVDC system is analyzed and comparison has been made with its rival 220V ac system. LVDC system design and simulation has been made for a peak load of 7.4kW for a single residence using Matlab/Simulink R2016a software.

1.5 Methodology

This thesis work is started by reviewing literatures related to the currently existing ac distribution system and the newly proposed low voltage dc distribution system. An average residential home located in ‘Sululta’ , one of the ‘woredas’ in the Oromia region of Ethiopia, is selected and the energy consumption of appliances, the specific time with in a day at which the equipment is in normal operational mode and standby conditions is studied in detail. The loss of power on wires and converters is also investigated. Appropriate voltage level is selected considering safety, technical compatibility to the appliances, efficiency and overall cost of the system.

Since dc distribution system can be done with locally available renewable energy resources, comparative study and selection has been made on these resources in terms of cost, compatibility and technological advancement. Load profiles are generated using ‘LoadProGen’ software by classifying loads in to appropriate groups. Solar energy has been selected for this research work as a renewable energy resource. PV system sizing and battery energy storage system design is done based on the loads connected to the system.

Home appliances are modeled classifying them into resistive, switch mode powers supplies (SMPS) and electronic lighting loads. Solar system integrated with MPPT is used as a renewable energy resource. During times when there is no solar radiation, the loads can be supplied effectively with battery energy storage system and when there is surplus of power production from the PV system, the battery will be charged through bi-directional buck boost convertor. This is done by using energy management system. PI control system with buck convertor is designed to maintain constant voltage irrespective of load variation throughout the day.

Additionally the efficiency of the two rival systems (LVAC and LVDC) is analyzed. Low voltage DC distribution model is designed for the selected loads and the behavior of the system is simulated considering the daily load profiles. The investment cost of the new wiring system and installation of PV system is estimated. The modification that is needed for replacing the currently existing ac system with dc distribution system is studied in detail. Overall model system is designed and simulated with Matlab/Simulink R2016a software using power convertors, battery energy storage system and load models.

Conclusion and recommendation has been made based on the overall analysis of the system. The final document has been prepared after complete design and simulation has been done. Future works in the area and limitations of this thesis work is also indicated in the document.

1.6 Organization of the Thesis

The thesis is organized as follows:

Chapter 1 describes theoretical background, objectives and methodology of this work.

Chapter 2 reviews literatures related to low voltage distribution systems

Chapter 3 discusses the technical feasibility of low voltage dc distribution system

Chapter 4 gives detail design of low voltage dc distribution system

Chapter 5 discuss the simulation results of the designed system

Chapter 6 gives conclusion, recommendations, future works and limitations of the this thesis work

Chapter Two

Literature Review

2.1 Introduction

This literature review focuses on the feasibility of low voltage dc distribution system for residential application on the basis of theoretical and practical perspectives. This review emphasizes on direct current distribution system concepts in particular about solar energy, distributed generation, low voltage distribution system topologies, voltage level selection, safety issues, environmental concerns and applications of low voltage dc distribution system for residential customers.

2.2 DC Distribution System

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. The problem was resolved by Westinghouse proposing ac distribution. 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 [4].

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.

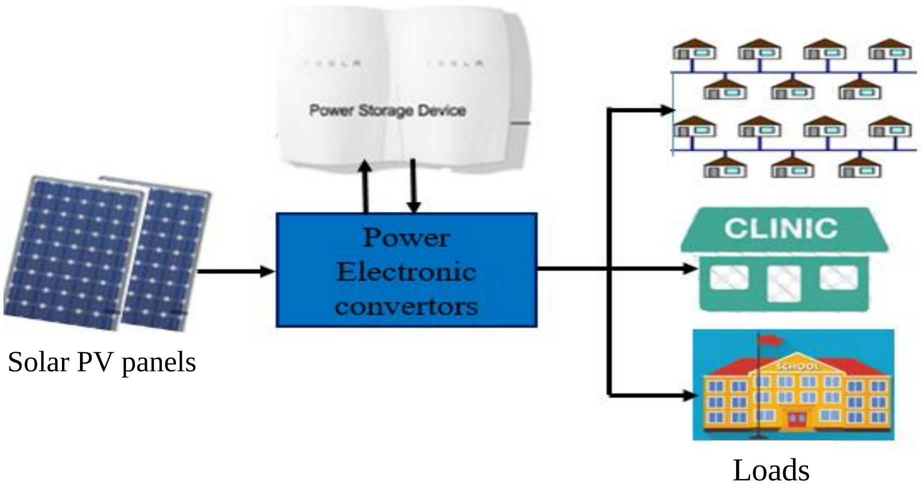

Figure 2.1 DC distribution system layout

The existing distribution system is based on alternating current (ac), but a number of the renewable energy sources, in particular solar cells, produce direct current (dc). This requires the application of power electronic devices to convert the dc energy from renewable sources to ac for transmission and distribution. Yet, this can induce considerable losses into the distribution system, reducing the acceptance and impact of renewable energy. Furthermore, a significant portion of loads now within buildings are dc, demanding more power electronic devices to reconvert the ac to dc.

Since dc power is purely real, the inductive and capacitive elements of the distribution line can be ignored, condensing the complexity of calculations for system analysis. Moreover, these reactive components have been linked to an increase in the magnitude of current ensuring the depreciation of real power transmission and magnifying losses. DC distribution improves energy conservation by avoiding standby losses that are caused due to transformers [5]. The power electronics devices implemented in power converters have the capability to deactivate when not needed whereas the transformer conducive to ac systems must remain energized. DC distribution system is also favorable over ac system as it does not require synchronization as it is mandatory for ac system.

The reason why dc systems are a viable option nowadays is the development of power electronics industry, which allows conversion of dc voltage to the required level for transmission, distribution and consumption.

Most appliances are able to work internally with dc power; they contain an input transformer and a rectifier to obtain the proper dc operating voltage. Standby losses still happens even in open circuit due to the inclusion of transformers in ac systems.

Recently, a lot of research is going on in dc distribution system due to advantages like higher efficiency and reliability, fewer conversion stages, and uninterrupted power delivery compared to conventional ac systems [6]. Furthermore, renewable resource systems, such as photovoltaic power generation, wind power generation, and electric vehicles are considered to be good alternatives in electric power systems. Due to these advantages, the applications of dc systems in residential areas becoming increasing.

Internally electronic devices (such as computers, florescent lights, variable speed drives, and many other household and business appliances and equipment) operate on direct current (dc). However, all of these dc devices require conversion of the building’s ac power into dc for use, and that conversion typically uses inefficient rectifiers. Moreover, most distributed renewable sources produces dc power but must be converted to ac to be consumed by household appliances. These ac-dc conversions result in substantial energy losses.

2.3 Solar Energy

Electricity is one of the elements required for agricultural, commercial, industrial, or residential development. The use of photovoltaic (PV) to produce electricity from sunlight would strongly benefit and improve the quality of life for those less developed countries such as Ethiopia. The decentralized approach based on power produced with locally available renewable energy resources is, for various reasons, gradually being recognized as a viable alternative in remote places.

Solar energy is an important source of renewable energy. The radiant light and heat from the Sun can be harnessed using a range of ever-evolving technologies such as solar heating, photovoltaic and solar thermal energy. There are about as many people living without electricity today as there were when Thomas Edison lit his first light bulb. Solar electricity on the other hand, has become inexpensive in part because the price of solar panels has fallen at the same time that the efficiency of light bulbs and appliances has dramatically increased.

DC energy produced by photovoltaic panels have to be converted into ac energy due to the fact that the consumers are all ac. Such a dc/ac conversion causes harmonics and loss of energy in the convertors during conversation stages.

In Ethiopia more than eighty percent of the population resides in rural areas. Rapid economic growth has increased the pace of energy demand growth in Ethiopia: 6% for biomass fuels, 11% for electricity [7].

The main application area of PV system is now off-grid telecom systems, particularly for mobile and landline network stations, which account for 87% of the total installations [8]. PV systems are also used in social institutions including health stations, schools and for water pumping.

2.4 Distributed Generation

Distributed generation is the arrangement of multiple generation sources within the distribution system instead of at a centralized location. The established distribution system is founded on a centralized theme: a utility transmits power from generation facilities to substations and substations reduce the voltage for transmission to its customers. This transmitted power causes sizable losses and extensive costs from transmission lines and transformers. A distributed generation network can reduce energy transmission by applying energy sources in the more immediate neighborhood of the loads. Decreasing the transmission power not only conserves energy but enables a reduction in distribution line and power device rating. Additionally, distributed generation liberates the transmission lines to deliver more power to necessary loads without incorporating extra lines.

Environmental concerns and new energy policies are making the energy systems to shift towards decentralization and sustainability .By decentralizing the electricity generation, the production is moved closer to the consumer, therefore avoiding transmission and distribution losses, and increasing the efficiency of the electricity grid, as well as, higher power reliability.

2.5 Low Voltage Distribution System Topologies

There is a lack of regulation and standardization on dc technology. Therefore, there are several different configurations and voltage levels that can be employed. Since dc distribution systems have been widely implemented in the telecommunication industry, the voltage levels used for residential application seems to converge to the standards used in data centers (380-400 V dc)[9]. However it is still far from being standardized, and several topologies of LVDC distribution system are being studied.

DC distribution system can be made with different connection types. The most common types are unipolar, and bipolar connections and are the most commonly known in dc system. The difference between these two connections is the number of voltage levels [10].

A. Uni-polar Low Voltage DC Distribution Systems

The distribution in this system is made by a 2-wire line, with positive and neutral line. The uni-polar system is inexpensive but decreases the transmission capacity of the system.

B. Bipolar Type Distribution Systems

The distribution in the system is made by a 3-wire line, with positive, negative and neutral line. It can be easily appreciated that this concept reduces the voltage level with respect to ground, which makes the distribution system safer for the users. Also, this concept allows the converter on the load side to choose from three different voltage levels; $+V_{dc}$, $-V_{dc}$ and $2V_{dc}$. Furthermore, the system increases the reliability of the power supply, because, in case of a fault in one of the lines, the energy can still be supplied using the other two lines.

In bipolar system, the loads can be connected either (i) between the current conductor and zero conductor, or (ii) directly between the ± conductors.

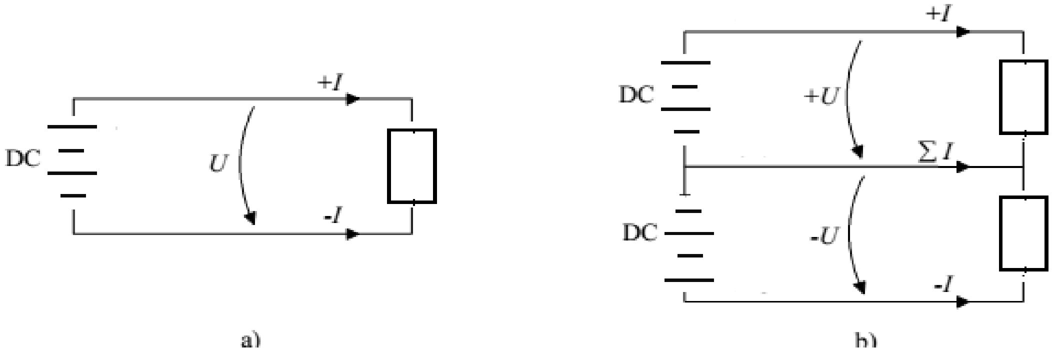

Figure 2.2 DC distribution connection types a) uni-polar connection system and b) bipolar connection system

2.6 Voltage Level Selection for Residential Application

Selection of the voltage level is one of the most important tasks in defining an LVDC system setup. The lack of standardization is evident when observing the voltage levels used for LVDC distribution systems. When analyzing LVDC distribution systems for residential applications, there are some voltage levels that come as a 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 be used for different groups, while optimizing efficiency for each scenario, safety, and compatibility with other systems. The appropriate dc bus 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 basically depend on what features are the main design criteria. For instance, 12 V distribution systems are used, in the automotive industry. Nevertheless, since modern cars becomes advanced in electronic technology, this leads to a higher electricity consumption. Due to this reason the voltage level is boosted to 24-48 V 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 [11].

Power distributions in data centers can be accomplished with voltage levels of 380-400 V dc [12]. 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 used, 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 still considered as extra-low voltage, hence, the damage caused by electrical shock is reduced [9].

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.

Table 2.1 LVDC levels, standards, codes and application areas [11]

DC voltage level(V)	Standards and codes	Applications
1500	IEC60038	Traction systems
400	ETSI EN 300 132-3-1	Electric vehicles
380	Emerge alliance standard	Data centers
120	IEC61140 Limit of SELV	--------
75	EU LDV 2014/35/EU	--------
50	IEEE 802.3bt,802.3bu	Power over Ethernet
48	Not known	Telecom rural PV systems, trucks
24	Emerge alliance standard	Lighting systems
12	Not known	Automotive, lighting
5	Not known	Microprocessors, electronics

2.7 Applications of LVDC Distribution 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, although intrinsically ac generators, a dc integration can be more convenient.

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 loos reduction and simplicity can be achieved which shows dc distribution 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 drop 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 is then proposed to eliminate the transformer/rectifier stages, completely eliminating standby losses.

Furthermore, the absence of reactive power lowers the current needed to transfer the same amount of power [13]. Though some appliances might need a dc/dc converter to properly adjust the dc voltage needed for the appliance, harmonics and power factor issues are eliminated. Furthermore, with advances in power electronics technology, motor driver devices and brush less dc motors are being considered to replace actual motors in home appliances.

2.8 Factors Influencing LVDC Electrical Distribution System

LVDC 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, compatibility, with or without storage system, system efficiency and cost savings. Standards, codes and regulations are not well developed for dc system as it was done for ac. For a consumer, the lack of commercially available products that operate on dc is also a major challenge for this system [11].

When designing the LVDC 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.

2.9 Electrical Safety, Protection and Control of LVDC Systems

Electrical safety of LVDC systems

Electric shock is defined as a case of current passing directly through a living organism. Changes in the human body caused by the action of touch current depend on the current intensity and duration of the shock. Besides the level of the currents flowing through the body, the duration the body is exposed to the current has an influence on the effects to the human being [14].

Power system is usually associated with shock and fire hazards. In ac system due to natural zero crossing, shock and fire hazards are less severe. But safety and protection systems are not well developed for dc systems.

For rural applications, where users frequently connect/ disconnect their devices to/from the power sources and level of awareness is low, safety has to be given higher priority. So, battery based systems being under extra safe limit voltage (ESLV) are recommended.

The degree of danger for the victim is a function of the magnitude of the current, the parts of the body through which the current passes, and the duration of current flow [15].

The international electro-technical commission (IEC) has developed time-current characteristics delineating areas of different reactions of the human body to direct current.

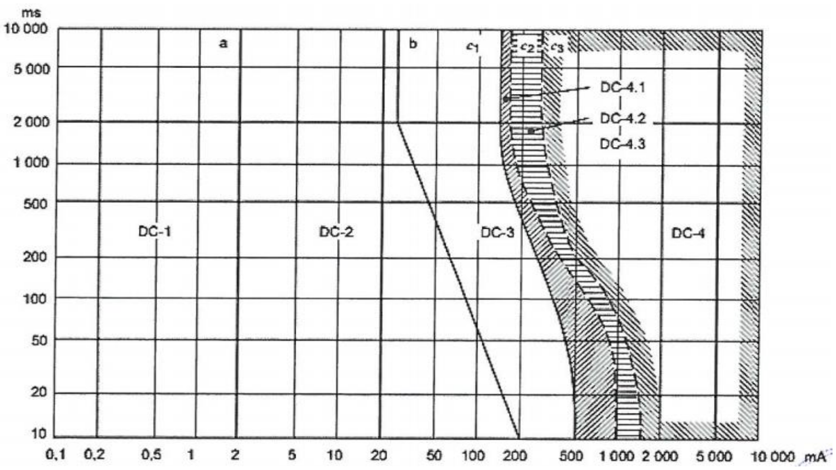

Figure 2.3 Time/current relation with respect to human body according to IEC 60479-1 DC current

Description of time current areas for direct current

DC-1- no noticeable effects

DC-2-noticible but harmless pathophysiological effects occur

DC-3- no treat of ventricular fibrillation, only muscle contraction

DC-4-threat of ventricular fibrillation,

DC-4.1-probabilty of threat of ventricular fibrillation less than 5%

DC-4.2-probability of threat of ventricular fibrillation up to 50%

DC-4.3-probability of threat of ventricular fibrillation above 50%

International Electro-technical Commission (IEC) sets standard for various voltage levels based on the level of risk for humans and is given in Table 2.2

Table 2.2 Safety voltage range for AC and DC system [16, 17]

IEC voltage range	**AC rms voltage (V)**	**DC voltage (V)**	**Defining risk**
High Voltage	> 1000	> 1500	Electrical arcing
Low Voltage	50 to 1000	120 to 1500	Electrical shock
Extra-Low Voltage	< 50	< 120	Low risk

Protection and control of LVDC systems

To ensure reliable operation of a low-voltage dc micro grid, well-designed control and protection systems are needed. An adaptive controller is required to coordinate the different resources based on the load-generation balance on the LVDC system [18].

Regarding protection devices, fuses and circuit breakers (CBs) can sometimes directly be used in dc systems, however, these devices are mostly designed for ac system, the current interruption mechanisms rely on the natural of zero-crossing of the ac current, however dc current does not naturally go to zero, as a consequence, a re-design of these elements is required for a reliable protection system.

It is difficult to extinguish arc that is caused due to short-circuit faults via conventional circuit breakers due to the lack of natural zero crossing of dc current. Also the dc breakers are usually more bulky and costly.

The switch or breaker should be revisited as the dc breaking condition is different from ac condition. All switching units are examined and new dc switching units need to be introduced. New Thermistor dc circuit breakers with Novel ZCS technique is recommended for breaking the dc current [19].

2.10 Environmental Concerns

Pollution and carbon dioxide emissions which comes from burning of fossil fuels have been attributed to many harmful effects including global warming, the acidification of rain (which contributes to substantial damage to buildings, harvests, and local ecosystems), and health related diseases. Renewable energy sources are expected to curtail these problems through energy sources that mitigate pollution and furnish energy security [20-21].

Only 8 percent of the total energy consumption in Ethiopia comes from modern fuels [22]. The heavy reliance on biomass fuels has been one of the prime causes of forest degradation and deforestation in Africa in general and in particular in Ethiopia.

At present more than 90% of the domestic supplies of industrial and fuel wood comes from natural forests .Fuel wood accounts for the bulk of the wood used, and is the predominantly preferred domestic fuel in both rural and urban areas [23]. Forest clearing leads to release of carbon dioxide, methane, carbon monoxide, nitrous oxide and oxides of nitrogen.

Amongst others, reduction of fuel wood consumption will help significantly to reduce mortality in rural areas due to indoor air pollution. WHO estimates that, the improvement of fuel wood consumption in Ethiopia could reduce the number of annual deaths by 1,000 to 2000 [24]. Hence, to reduce consumption of wood and ensure the sustainability and benefits of forests it is imperative to use LVDC system for rural residents.

2.11 Compatibility of Home Appliances for LVDC System

Commercially, most appliances are readily available with an input voltage of 12 and 24V. Some appliances are available with an input voltage of 48V [25]. Low voltage dc appliances demand higher currents, making feeder losses considerable, and the overall appliance efficiency is practically low. In a near future, the market for dc appliances will be so high that appliances will be manufactured at higher voltage levels.

Resistive Loads: Current ac home appliances that are considered as resistive loads (heaters) include Stoves, Electric-Mitad, Ovens, dryers, toasters, kettle, coffee machine, incandescent lamp and tungsten halogen lamp. Since these loads can be effectively modeled as a resistance [26], they can be directly supplied with dc distribution system without any modification.

Appliances equipped with Motors: As of today, many different types of motors are used in most home appliances. Mixers, vacuum cleaners, automatic gates, freezers, garage doors, dishwashers, ventilation fans, cloth washers and cloth dryers, among other appliances, are examples of loads that incorporate the use of a single phase ac motors. Motors produced for home applications vary up to 1hp, and their efficiency is often very low, often less than 50% [27].

The most commonly used single-phase motor for those appliances is the universal motor, because of the high speeds and capability of operating with ac and dc voltages. Cloth washers, cloth dryers, and old refrigerators usually incorporate a single phase induction motor, between capacitor start and capacitor run motors [28].

With advances in power electronics technology, the use of three-phase induction and synchronous motors with drivers in dc applications is becoming attractive, due to the fact that these motors exhibit greater efficiencies and higher power densities than the actual motors used for appliances .However, the usage of induction motors with drives provide many disadvantages, as compared to the Brushless DC motor (BLDC): Induction motors may never achieve synchronism, and at the same time, rotor losses will always be higher due to the fact that they depend of the slip. Another disadvantage of induction motors is that they are manufactured to be operated at a rated frequency; operating these motors at different frequencies means increased iron losses and the possibility of thermal breakdown of the motor [29]. Furthermore, the control of induction motors is more complicated than the control of a BLDC motor.

For the reasons above, BLDC motors are recommended for appliances considered; again, this motor is a three-phase Permanent Magnet Synchronous Motor (PMSM) fed with a dc input, and it exhibits a high power density, high torque, low noise, low power consumption, extended operating life due to the absence of brushes, reduced electromagnetic emissions (EMI), simpler control and a wide range of speed. With small modification, BLDC motors can be used for air conditioners, refrigerators, cloth washers and microwave ovens [15].

Efficiencies of different ac and BLDC motors for various home appliances are collected and it is estimated that an overall 24% efficiency of the system is improved by replacing AC motors with BLDC motors [30].

Freezers & Fridges - Freezers and fridges are one of the most popular appliances that are available commercially with dc input power. They are manufactured separately, as well as together with voltage inputs of 12V and 24V [31].

Electronic Loads: Laptop computer, TVs, satellite receivers, phone chargers and security cameras are the major electronic loads which can be made efficient or even energy star just by replacing input ac/dc converter with the buck-boost converter. Old electronic loads use a low-frequency transformer to step down the voltage, which is then rectified using a diode bridge. This type works only with a certain voltage amplitude and frequency. But due to the introduction of switch mode power supply (SMPS), the load can be connected to a wide range of inputs. However, SMPS can be operated with dc without any design modifications as long as the dc voltage is in the same range as the appliances voltage requirement [15].

Laptop computers and TV’s: These are commonly used electronic loads in homes. For these appliances, a considerable power reduction is achieved by modifying only the input power conversion stages.

Liquid Crystal Display (LCD) and Plasma TV’s are rapidly replacing televisions which employ Cathode Ray Tubes (CRTs). Plasma TV’s demand more power than LCD’s, are heavy, and they have a limited operating life of 5 years; on the contrary, LCD’s consume less power, and they exhibit a long operating life [32].

Current LCD power supplies are composed of the regular transformer/rectifier stage followed by a Power Factor Correction (PFC) stage, which typically a boost DC/DC converter is working in discontinuous conduction mode (DCM). The dc bus voltage after both stages above mentioned is around 380-400V; this voltage needs to be lowered further in order to operate the inverter needed for the CCFL, which is from 8-20V. Since the CCFL needs a sinusoidal voltage, a transformer must be used to provide the high voltage level. Also, a standby voltage of 5V must be derived from the bus. A fly-back dc/dc converter is used to lower the voltages to the desired levels [32].

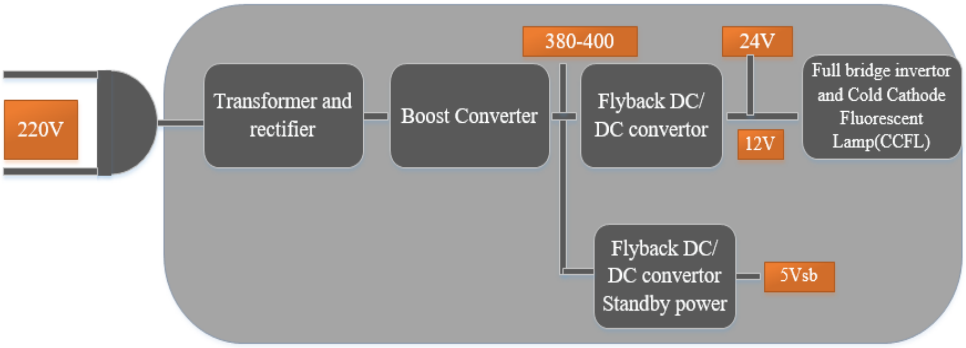

Figure 2.4 Current LCD TV appliance schematic diagram [32]

LCD’s are considered due to their reduced power consumption. In order to operate an LCD with dc power, the transformer/rectifier stage can be eliminated. The Boost PFC can be replaced by a synchronous buck converter to lower 120V input voltage to 8- 24V desired level. This allows the removal of the fly-back dc/dc converter.

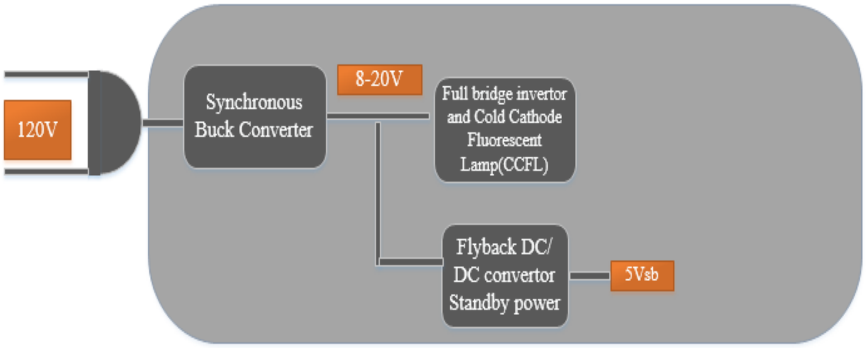

Figure 2.5 Proposed LCD TV schematic diagram

Laptop Computers – Laptop computers are expected to oversell desktop computers in the near future [33], due to their low power consumption and portability. An internal switch inside the laptop computer controls the flow of power to the internal circuitry. The switch allows the mains to supply the power (when available), or the batteries to supply power (when the mains is unavailable). Normally, the bus voltage of the distribution system varies between 19.5V when the wall adaptor is connected and 14.8V when the laptop is running with battery power. The bus voltage range will be from 10.8V to 19.5V, depending on the configuration and number of cells in the battery [34].

Voltage regulators (dc/dc converters) are connected to the distribution bus to supply different voltages for different loads inside the computer, including the microprocessor.

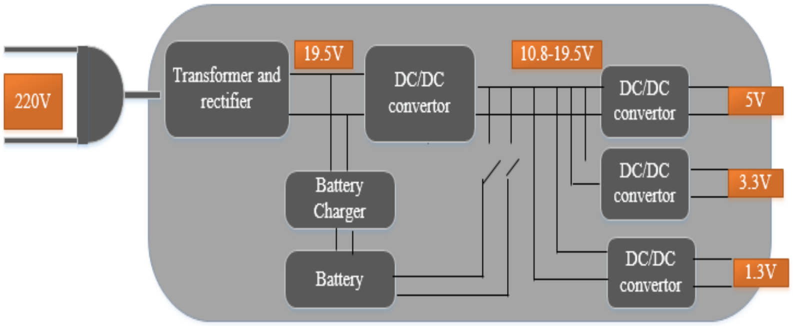

Figure 2.6 Current laptop schematic diagram [32]

The Current ac configuration of laptops demands a battery charger, which first rectifies the mains voltage, and then maintains the state of charge of the battery. Considering that the laptop computer is capable of running with dc power when removing the transformer/rectifier stages, a Synchronous buck converter will be utilized to model the step down dc/dc converters needed. Figure 2.7 shows the proposed schematic for the laptop computer.

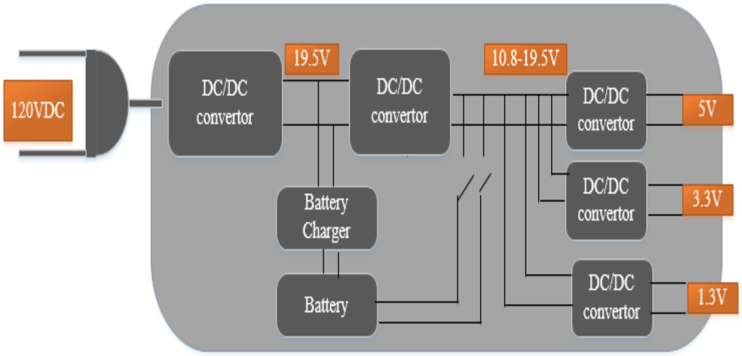

Figure 2.7 Proposed laptop computer schematic diagram

2.12 Conclusion

The electrical appliances today are designed to operate with ac, but many of them can run on dc without modification. All resistive loads like heaters, incandescent lamps, 'Electric-Mitad' and stoves, operate with both ac and dc as long as the required power is delivered. All electronic loads like computers, fluorescent lamps with electronic ballast, flat screen TV, battery charger, which all internally use dc, have a bridge rectifier to convert ac to dc. This rectification will introduce current harmonics, which have a negative effect on the power system. All these electronic loads can directly be supplied with dc as long as they are supplied with appropriate voltage. This is accomplished due to the inclusion of SMPS to electronic loads [35]. Rotating loads driven by a universal machine, or frequency controlled machines can also be supplied with dc. Instead of using universal and induction motors in rotary appliances, BLDC motors are proposed that are highly efficient with minimum electro-mechanical and no commutation losses.

In electricity supply, using extra low voltage is one of several means to protect against electric shock. 120V dc is defined by IEC as the upper boundary of extra low voltage, which is low risk under dry conditions for human beings. So 120V dc will be a promising standard voltage level for low voltage dc distribution system.

By increasing the voltage level in dc system, efficiency improvement can be gained. The study shows that, using 380 V dc as voltage levels for supplying energy to the high power loads (kitchen appliances and air conditioner) only brings an efficiency improvement of 0.3 %, when compared with 120 V dc [9].As the voltage level keeps increasing, it leads to bigger safety hazards.

Chapter Three

Technical Feasibility Analysis of LVDC Distribution System for Residential Loads

3.1 Introduction

Ethiopia 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 have developed the tradition of using direct current from locally available resources, especially from solar photovoltaic (PV).

For studying the feasibility of dc distributions in the residence, household appliances are identified that are commonly used by an average home located in 'Sululta', one of the woredas in the 'Oromia' region of Ethiopia. Based on the data obtained from these appliances; power consumption, feeder loss and efficiency analysis is done for 24V, 48V, 120V and 120V dc coupled with 48V dc system in comparison with 220V ac.

3.2 220V Alternating Current (AC) System Analysis

Single phase ac power distribution is done using two wires, one for phase and the other for neutral. Each conductor has its own resistance and inductance. The real and reactive power consumed by the load and the voltage drop across the feeders can be determined using the simple ac circuit model of Figure 3.1.

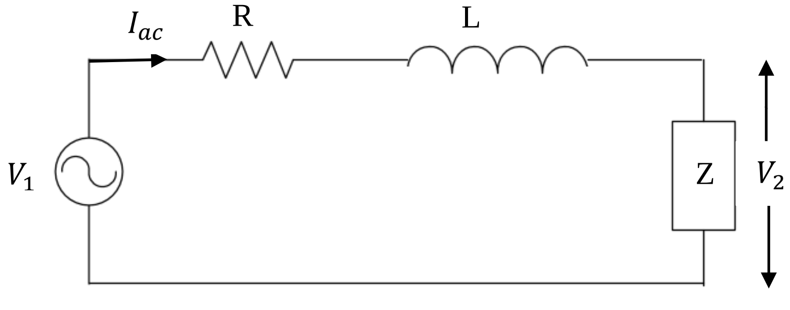

Figure 3.1 Single phase alternating current circuit model

$$V_1 = V_2 + I_{ac}\,(R + jX_L) = V_2 + I_{ac}Z \tag{3.1}$$

Where V_1 = rms value of supply voltage

V_2 = rms value of the load voltage

I_{ac} = load current (current through the feeder)

R = resistance of the feeder

L= inductance of the feeder

X = reactance of the feeder

Z = impedance of the feeder

Taking the load voltage as V_2 a reference, the load current becomes

$$I_{ac} = |I_{ac}|\cos\theta - j|I_{ac}|\sin\theta \tag{3.2}$$

Where θ is the angle between V_2 and I_{ac}

The supply voltage becomes

$$V_1 = V_2 + (R + jX)\big(|I_{ac}|\cos\theta - j|I_{ac}|\sin\theta\big) \tag{3.3}$$

The active power consumed by the load is $P_L = |V_2||I_{ac}|\cos\theta$ (3.4)

and the reactive power of the load becomes $Q_L = |V_2||I_{ac}|\sin\theta$ (3.5)

Then,

$$V_1 = V_2 + \frac{RP_L + XQ_L}{|V_2|} + j\,\frac{XP_L - RQ_L}{|V_2|} \tag{3.6}$$

It is known that most of the power in residential homes is consumed by kitchen equipment’s, like Electric-Mitad, stoves and water heaters. These high power consuming equipment are purely resistive loads. Taking this into account and avoid complexity in the circuit analysis, the power factor of local homes can be reasonably taken to be 1, i.e. the reactive power of the load becomes zero $(Q_L = 0)$.

Then equation (3.6) can be simplified as $V_1 = V_2 + \frac{RP_L}{|V_2|} + j\frac{XP_L}{|V_2|}$

$$V_1 = V_2 + \frac{ZP_L}{|V_2|}$$

$$|V_2|^2 - |V_1||V_2| + ZP_L = 0$$

The load voltage then given by equation (3.7)

$$|V_2| = \frac{|V_1| \pm \sqrt{|V_1|^2 - 4|Z|P_L}}{2} \tag{3.7}$$

The percentage of voltage drop across the feeder is given by

$$\%\ \text{Voltage drop} = \frac{V_1 - V_2}{V_1} * 100 \tag{3.8}$$

The real power loss across the feeder (in watt) is given by

$$P_{ac} = |I_{ac}|^2 * R \tag{3.9}$$

3.2.1 Resistance and Inductance of Feeder

Electrical conductors or wires in households run mostly using PVC pipe with an inner diameter of 13 mm. The inductance of the conductors varies since the distance between the conductors changes.

The inductance of the feeder (in Henry) is given by

$$L = 0.05 + 0.2ln\ (d/r) \tag{3.10}$$

Where d is the distance between the phase and the neutral conductors (in meter), r is the radius of the wire (in meter). The ac resistance of the conductor varies with little amount from the dc resistance due to a phenomena known as skin effect. A skin effect correction factor k, for a 50Hz frequency is estimated to be 1.02 [36]. The ac resistance of solid copper conductor is determined by multiplying the dc resistance given in Table 3.5 by skin effect factor 1.02.

The resistance and inductance of the feeders for various cross-sectional areas is given in Table 3.1

Table 3.1 Inductance and resistance variation with respect to cable size of conductors

Nominal conductor area (mm^2)	Approximate Overall diameter (mm)	Radius (mm)	Minimum distance (mm)	Maximum Distance (mm)	Inductance (μH/m)	Resistance/m	Reactance/m
1	2.8	0.56	1.67	10.74	0.64	0.0180	200.77
1.5	3.2	0.69	1.82	10.24	0.59	0.0123	185.09
2.5	3.7	0.89	1.92	9.43	0.52	0.0075	163.81
4	4.6	1.13	2.34	8.48	0.45	0.0047	142.44
6	5.2	1.38	2.44	7.48	0.39	0.0031	121.84
10	6.2	1.78	2.63	5.86	0.29	0.0019	90.43

3.2.2 Energy Consumption and Feeder Power Loss for 220V AC System

Most commonly used household equipment including high power consuming ones are selected for analysis. Their normal and standby power consumption data is obtained from the name plate and manufacturers datasheet. Standby power, also called vampire power refers to the way electric power is consumed by electronic and electrical appliances while they are switched off (but are designed to draw some power) or in a standby mode. This only occurs because some devices claimed to be "switched off" on the electronic interface, but are in a different state from switching off at the plug, or disconnecting from the power point. The input voltage of the ac system at the source is taken to be of fixed value 220V rms. The length of the distribution feeders for the selected home is estimated assuming that the house has one living room, two bedroom and one kitchen,

The identified appliances power rating, feeder length and operation-hours per day is given in Table 3.2.

Table 3.2 Power consumption, feeder length and on time duration of selected appliances

Appliance Name	On Power (W)	Standby power (W)	Current at 220V (standby) (A)	Current at 220V AC (A)	Cable Size (mm^2)	Wire length (m)	Power on time in day	Power on time in day (Standby by)
Light bulb(CFL)	77	−	0	0.35	1.5	65	7hrs	−
Fluorescent	80	−	0	0.36	1.5	25	7hrs	−
Refrigerator	125	10	0.045	0.568	2.5	15	12hrs	−
Iron	1200	−	0	5.45	2.5	20	2hrs in a week	−
Laptop	45	4.5	0.0205	0.204	2.5	20	7hrs	5hrs
32 LCD TV	285	1	0.0045	1.295	2.5	25	7hrs	7 hrs
Stove	1000	−	0	4.54	4	25	3hrs	−
Injera Mitad	3700	−	0	16.82	4	25	4hrs in a week	−
DVD player	12	1.55	0.007	0.054	2.5	15	5hrs	7hrs
Satellite receiver	20	1.5	0.007	0.09	2.5	15	7hrs	7 hrs
Mobile phones	6	0.5	0.0023	0.027	2.5	20	5hr	2hrs
Coffee maker	990	−	0	4.5	2.5	20	0.5hr	−

The total resistance, inductance, reactance and impedance of the distribution wires is calculated and given in Table 3.3 .The power loss across the feeder during normal and standby operation is determined using equation (3.9)

Table 3.3 Power loss across the feeder during normal and standby conditions

Appliance Name	Wire Resistance (Ω)	Inductance (μH)	Reactance (Ω)	Impedance (Ω)	Power loss across the feeder (W)	Power loss across the feeder (Standby) (W)
Light bulb(CFL)	0.73	38.32	0.0120	0.73	0.090	0
Fluorescent	0.17	14.74	0.0046	0.17	0.022	0
Refrigerator	0.10	7.83	0.0025	0.10	0.033	$2.06*10^{-4}$
Iron	0.14	10.43	0.0033	0.14	4.040	0
Laptop	0.14	10.43	0.0033	0.14	0.006	$5.69*10^{-4}$
32 LCD TV	0.02	13.04	0.0041	0.02	0.029	$3*10^{-7}$
Stove	0.10	11.34	0.0036	0.11	2.190	0
Injera Mitad	0.10	11.34	0.0036	0.11	30.059	0
DVD player	0.10	7.83	0.0025	0.10	0.000	$5.1*10^{-6}$
Satellite receiver	0.10	7.83	0.0025	0.10	0.001	$4.7*10^{-6}$
Mobile Phones	0.14	10.43	0.0033	0.14	0.000	$7*10^{-7}$
Coffee Maker	0.14	10.43	0.0033	0.14	2.754	0

Yearly energy consumption of the house is determined for both normal and standby case by summing the energy consumption of all the appliances selected for this study.

i.e. Energy consumption = On energy consumption + Standby energy consumption

$$\text{Where On energy consumption (kWh/yr)} = \frac{\text{on power}*\text{Turn on time perday}*365}{1000} \tag{3.10}$$

and

$$\text{Standby energy consumption (kWh/yr)} = \frac{\text{standby power}*\text{Turn on time perday}*365}{1000} \tag{3.11}$$

Power is distributed to consumers through ac distribution lines. Almost all electronic equipment like computers, TV, mobile phones and other home electronic appliances are powered by dc power sources, either by batteries or dc power supplies obtained from an ac source. AC has to be converted to direct current to supply these loads internally. During this ac to dc conversion within electronic equipment, there will be some power loss due to the voltage drop on the diodes and is called rectifier loss.

The power loss in the diodes is given by: $\mathrm{P_{diode}} = \mathrm{V_F} * \mathrm{I_{rms}}$ (3.12)

Where V_F the forward voltage drop of diodes and $\mathrm{I_{rms}}$ is the rms value of the current flows through the diode. Approximately the forward voltage drop of diodes can be taken as 0.7V [37].

Table 3.4 220V AC distribution system yearly energy consumption and feeder loss

Appliance Name	Voltage drop (%)	Rectifier loss(W)	Energy loss in the feeder (kWh/yr)	Rectifier loss (kWh/yr)	Standby Energy (kWh/yr)	On Energy consumption (kWh/yr)	Total Energy Consumption (kwh/yr)
Light bulb(CFL)	0.1167	––––	0.23	––––	0	196.73	196.74
Fluorescent	0.0278	––––	0.06	––––	0	204.4	204.40
Refrigerator	0.0263	0.7952	3.14	3.48	43.8	547.5	591.30
Iron	0.3359	––––	7.42	0	0	124.83	124.83
Laptop	0.0126	0.2863	0.01	0.73	8.2	114.97	123.19
32 LCD TV	0.0103	1.813	0.07	4.63	2.5	728.17	730.73
Stove	0.2189	––––	9.4	0	0	1095	1095.00
Injera Mitad	0.8062	––––	15.25	0	0	769.78	769.79
DVD player	0.0025	0.07623	0.001	0.14	3.97	21.9	25.86
Satellite receiver	0.0042	0.126	0.002	0.32	3.83	51.1	54.93
Mobile Phones	0.0017	0.0378	0.00	0.069	0.36	10.95	11.32
Coffee Maker	0.2775	––––	4.5	0	0	180.67	180.68
Total			40.1	9.37	62.72	4046.02	4108.75

From Table 3.4, it can be seen that the total energy requirement of the selected home is 4148.84 kWh/yr and 40.1 kWh/yr is lost in the feeders.

3.3 Low Voltage Direct Current (LVDC) System Analysis

Almost all of home appliances are currently supplied by alternating current. Locally available renewable energy sources like wind (coupled with dc generator) and solar produce direct current as their output. Since household electronic equipment’s operates internally on dc, it can be supplied directly with these renewable energy sources.

AC systems are well developed and widely used in various applications. This is not the case for dc distribution systems. There is no standard voltage level for dc distribution system. The protection and safety system are not well developed for low voltage dc distribution systems. A number of companies establish voltage level for their products and services. In this study 24V, 48V and 120V low voltage dc distribution system is analyzed for its technical and economic feasibility.

Direct current (DC) circuit Analysis

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 = Resistance of the feeder

V_L = load voltage

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

P = power consumed by the load

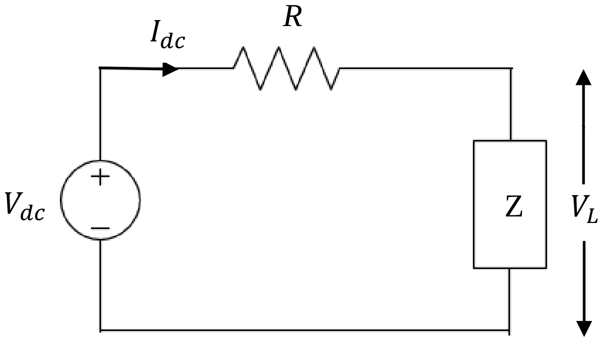

Figure 3.2 Direct current circuit model

Then the voltage at the load side can be calculated as

$$V_{dc} = V_L + I_{dc} R \tag{3.13}$$

$$V_L = V_{dc} - \mathrm{I}_{\mathrm{dc}} R$$

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

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

Then the load voltage becomes

$$V_L = \frac{V_{dc} \pm \sqrt{V_{dc}^{\,2} - 4PR}}{2} \tag{3.14}$$

The percentage of voltage drop across the feeder is given by

$$\%\ \text{Voltage drop} = \frac{V_{dc} - V_L}{V_{dc}} * 100 \tag{3.15}$$

Current through the load is determined as

$$I_{dc} = \frac{P}{V_L} \tag{3.16}$$

The real power loss across the feeder can be calculated as

$$P_{loss} = {I_{dc}}^2 R \tag{3.17}$$

The minimum dc resistance of the conductors in mΩ/m according to IEC 60228 is given in Table 3.5.

Table 3.5 DC resistance of wires [38]

Cross-sectional area(mm^2)	Copper resistance(mΩ/m)
0.5	36
0.75	24.5
1	18.1
1.5	12.1
2.5	7.41
4	4.61
6	3.08
10	1.83
16	1.15

In dc system the voltage and currents are in phase which implies that the power factor becomes 1. Therefore there will be only real power loss in the feeder. Electronic devices has to convert ac to dc internally using rectifiers. This incurs loss due to the voltage drop across the diode. In this proposed design home appliances are supplied with dc directly. This avoids some of the conversion steps, meanwhile avoids rectifier losses. A proposed dc powered residence also eliminate the transformer/rectifier stages, which completely eliminates standby losses.

For this thesis work 24V, 48V and 120V dc systems are analyzed for dc distribution system. The energy consumption, feeder power loss and percentage of voltage drop is calculated for the dc distribution using the selected voltage levels.

Table 3.6 Energy consumption and feeder power loss for 24V DC system

Appliance Name	Power (W)	Wire area (mm^2)	Wire resistance (Ω)	Voltage drop %	Feeder current (A)	Feeder power loss(w)	Feeder energy loss (kWh/yr)	On Energy consumption (kWh/yr)
Light bulb(CFL)	77	1.5	0.79	11.94	3.64	10.44	26.67	196.735
Fluorescent	80	1.5	0.30	4.39	3.49	3.68	9.40	204.4
Refrigerator	125	2.5	0.11	2.47	5.34	3.17	13.86	547.5
Iron	1200	10	0.04	8.32	54.54	118.85	12.4	124.83
Laptop	45	2.5	0.15	1.17	1.90	0.53	1.36	114.975
32 LCD TV	285	2.5	0.19	10.21	13.23	32.40	82.78	728.175
Stove	1000	6	0.08	15.89	49.54	188.98	206.93	1095
Injera Mitad	3700	50	0.01	6.66	165.16	263.92	54.91	769.785
DVD player	12	2.5	0.11	0.23	0.50	0.03	0.05	21.9
Satellite Receiver	20	2.5	0.11	0.39	0.84	0.08	0.20	51.1
Mobile Phones	6	2.5	0.15	0.15	0.25	0.01	0.02	10.95
Coffee Maker	990	4	0.09	19.75	51.40	243.58	44.45	180.675
Total							453.1	4046.03

Table 3.7 Energy consumption and feeder power loss for 48V DC system

Appliance Name	Power (W)	Wire area (mm^2)	Wire resistance (Ω)	Voltage drop %	Feeder current (A)	Feeder power loss (W)	Feeder energy loss (kWh/yr)	On Energy consumption (kWh/yr)
Light bulb(CFL)	77	1.5	0.786	2.70	1.65	2.14	5.46	196.74
Fluorescent	80	1.5	0.302	1.06	1.68	0.86	2.19	204.40
Refrigerator	125	2.5	0.111	0.61	2.62	0.76	3.34	547.50
Iron	1200	2.5	0.148	8.43	27.30	110.46	11.49	124.83
Laptop	45	2.5	0.148	0.29	0.94	0.13	0.33	114.98
32″ LCD TV	285	2.5	0.185	2.35	6.08	6.85	17.50	728.18
Stove	1000	4	0.115	5.28	21.99	55.76	61.05	1095.00
Injera Mitad	3700	4	0.115	4.85	81.01	188.70	39.26	769.79
DVD player	12	2.5	0.111	0.06	0.25	0.01	0.01	21.90
Satellite Receiver	20	2.5	0.111	0.10	0.42	0.02	0.05	51.10
Mobile Phones	6	2.5	0.1482	0.04	0.13	0.00	0.00	10.95
Coffee Maker	990	2.5	0.1482	6.84	22.14	72.63	13.26	180.68
Total							153.94	4046.03

Table 3.8 Energy consumption and feeder power loss for 120V DC system

Appliance Name	Power (W)	Wire area (mm^2)	Wire resistance (Ω)	Voltage drop %	Feeder current (A)	Feeder power loss(W)	Feeder energy loss (kWh/yr)	On Energy Consumption (kWh/yr)
Light bulb(CFL)	77	1.5	0.7865	0.42	0.64	0.33	0.83	196.74
Fluorescent	80	1.5	0.3025	0.17	0.67	0.13	0.34	204.40
Refrigerator	125	2.5	0.111	0.10	1.04	0.12	0.53	547.50
Iron	1200	2.5	0.1482	1.25	10.13	15.20	1.58	124.83
Laptop	45	2.5	0.1482	0.05	0.38	0.02	0.05	114.98
32″ LCD TV	285	2.5	0.18525	0.37	2.38	1.05	2.69	728.18
Stove	1000	4	0.11525	0.81	8.40	8.13	6.91	1095.00
Injera Mitad	3700	4	0.11525	3.05	31.80	116.58	14.25	769.79
DVD player	12	2.5	0.111	0.01	0.10	0.00	0.00	21.90
Satellite Receiver	20	2.5	0.111	0.02	0.17	0.00	0.01	51.10
Mobile Phones	6	2.5	0.1482	0.01	0.05	0.00	0.00	10.95
Coffee Maker	990	2.5	0.1482	1.03	8.34	10.30	1.88	180.68
Total						151.87	29.08	4046.03

Table 3.9 Energy consumption and feeder power loss for 120V DC coupled with 48V DC system

Appliance Name	Power (W)	Wire area (mm^2)	Wire resistance (Ω)	Voltage drop %	Feeder Current (A)	Feeder power loss(W)	Feeder Energy loss (kWh/yr)	On Energy Consumption (kWh/yr)
Light bulb(CFL)	77	1.5	0.79	2.7	1.65	2.14	5.46	196.74
Fluorescent	80	1.5	0.30	1.06	1.68	0.86	2.19	204.40
Refrigerator	125	2.5	0.11	0.61	2.62	0.76	3.34	547.50
Iron	1200	2.5	0.15	1.25	10.13	15.20	1.58	124.83
Laptop	45	2.5	0.15	0.29	0.94	0.13	0.03	114.98
32 LCD TV	285	2.5	0.19	2.35	6.08	6.85	17.50	728.18
Stove	1000	4	0.12	0.81	8.40	8.13	6.91	1095.00
Injera Mitad	3700	4	0.12	3.05	31.80	116.58	14.25	769.79
DVD player	12	2.5	0.11	0.06	0.25	0.01	0.01	21.90
Satellite Receiver	20	2.5	0.11	0.10	0.42	0.02	0.05	51.10
Mobile Phones	6	2.5	0.15	0.04	0.13	0.00	0.00	10.95
Coffee Maker	990	2.5	0.15	1.03	22.14	72.63	1.88	180.68
Total							53.2	4046.03

From Tables 3.6, 3.7, 3.8 and 3.9, it can be seen that the feeder energy losses has been decreased by 27.48% for 120V dc and increased by 283.89% for 48V dc and 32.6% for 120V dc coupled with 48V dc system as compared to 220V ac system.

The energy efficiency for the selected system is presented in Table 3.10

Table 3.10 Energy efficiency of the system for different voltage levels

Supply type	Energy Efficiency
220V AC	98.4%
24V DC	89.93%
48V DC	96.33%
120V DC	99.28%
120V+48V DC	98.69%

If 5% voltage drop is allowed along the distribution lines, the maximum load that can be connected and the maximum length that the conductor should stretch with variation of the cross-sectional area is given in Table 3.11.

Table 3.11 Maximum load that can be connected and maximum length the conductors stretch for 5% voltage drop

Cross-section (mm^2)	Maximum current(A)	Resistance (mΩ/m)	Maximum power (W)			Maximum length(m)		
			24V	48V	120V	24V	48V	120V
1.5	14	12.1	319.2	638.4	1596	7.08	14.17	35.42
2.5	19.2	7.41	437.76	875.52	2188.8	8.43	16.87	42.17
4	25.6	4.61	583.68	1167.36	2918.4	10.17	20.34	50.84
6	32.8	3.08	747.84	1495.68	3739.2	11.88	23.76	59.39
10	45.6	1.83	1039.68	2079.36	5198.4	14.38	28.76	71.90
16	61.75	1.15	1407.9	2815.8	7039.5	16.90	33.80	84.49
25	80.8	0.772	1842.24	3684.48	9211.2	19.24	38.48	96.19
35	104.5	0.524	2382.6	4765.2	11913	21.91	43.83	109.57

For this thesis work 120V dc is selected as an optimal voltage level for low voltage dc distribution system to supply power for the selected home, as this voltage level is more energy efficient as compared to the rival 220V ac system and other low voltage dc systems and is safe electrically for humans for indirect contact and may not require special protection mechanisms. This voltage level is also compatible with most home appliances with little or no modification made on the internal circuitry of the appliances. Using locally available energy resource, solar power, sparsely dispersed populations of the rural areas of Ethiopia, which are very far from the national grid, can be electrified using this voltage level with an affordable cost.

Chapter Four

LVDC Distribution System Design and Simulation Studies

4.1 Introduction

In this chapter, the overall low voltage dc distribution system design is done. The selected home appliances are modeled classifying them into resistive, rotating and electronic loads. MPPT algorithm is used to produce maximum power with variation of irradiance. Power electronic convertors like buck boost, buck and bidirectional buck boost dc-dc convertor design is made to convert variable voltages level and produce constant output at the load. PI controller coupled with buck convertor is used to control the load voltage and produce constant output irrespective of the load variation. The unit energy cost of 120V dc system is also compared with the current tariff set for 220V ac system.

Depending on the construction and operation, household loads can be classified into three groups [39]:

- Resistive loads (further divided into heating and lighting loads),
- Rotating loads (split into induction machine-based and universal machine based), and
- Electronic loads (comprising power supplies and lighting appliances)

Resistive Loads: Resistive loads can be divided into two subcategories depending on the function of the load. Heating loads are used for heating, such as stoves, Injera Mitad, kettles, and coffee makers. Measurement results show that these loads have a constant resistive characteristic. However, lighting loads (incandescent lamps) do not have a constant resistance. In these cases measurements show that the resistance is temperature dependent [39].

Rotating Loads: Universal machines are usually used in small household appliances, such as mixers, food processors and vacuum cleaners. A universal machine has the same construction as a series-magnetized dc machine, and therefore operates equally well with ac as dc [40] .However, larger household appliances such as washing machines, refrigerators and tumble dryers are instead using induction machines. These machines are often supplied by power-electronic converters.

Electronic Loads: The number and size of home electronic products has increased fast the last few years. Common household electronic loads are supplied through power electronic converters. Furthermore, lighting appliances such as compact fluorescent lamps and fluorescent tubes with HF ballasts also utilize power-electronic converters. In most cases the grid voltage is first rectified by a diode rectifier and then adjusted by a power-electronic converter, which together are called a switch mode power supply (SMPS) [39].

4.2 Load Modeling

A load model in this thesis is, a mathematical representation of the relationship between voltage and current or power and voltage. The detailed power consumption of the home appliances was analyzed and the load profiles were generated by taking different utilization modes of the devices into account. In general, load model for the above classified loads can be summarized as shown in Table 4.1 [41].

Table 4.1 Summary of load models

Types of Loads		Model	Parameters
Resistive loads	Heating	$R = R_0$	R_0-from measurement
	Lighting	$R = R_1 I + R_0$	R_1-from measurement R_0 –from rated power
Rotating loads	Induction machine	$R = R_0$-for VSD $R = \frac{U^2}{P_0}$ for SMPS	P_0 –from measurement
	Universal machine	$I = Y_0 U + I_0$	Y_0 & I_0-from measurment
Electronic loads	Switch mode power supplies(SMPS)	$R = \frac{U^2}{P_0}$	P_0-from measurement
	Lighting	$R = \frac{U}{I_0}$	I_0-from measurement

Load profile is generated for the selected resistive, rotating, and electronic loads using LoadProGen software. This Matlab integrated software displays a graph of the variation of electrical load in watt versus time. The software is feed with power consumption of appliances and their daily switching times. The software assumes that if the appliance contributes to the peak power it samples with normal distribution and if the appliance doesn't contribute to the peak power the sampling is done with uniform distribution. The sampling is done at 1 minute interval for 24hours (1440 minutes) [42].

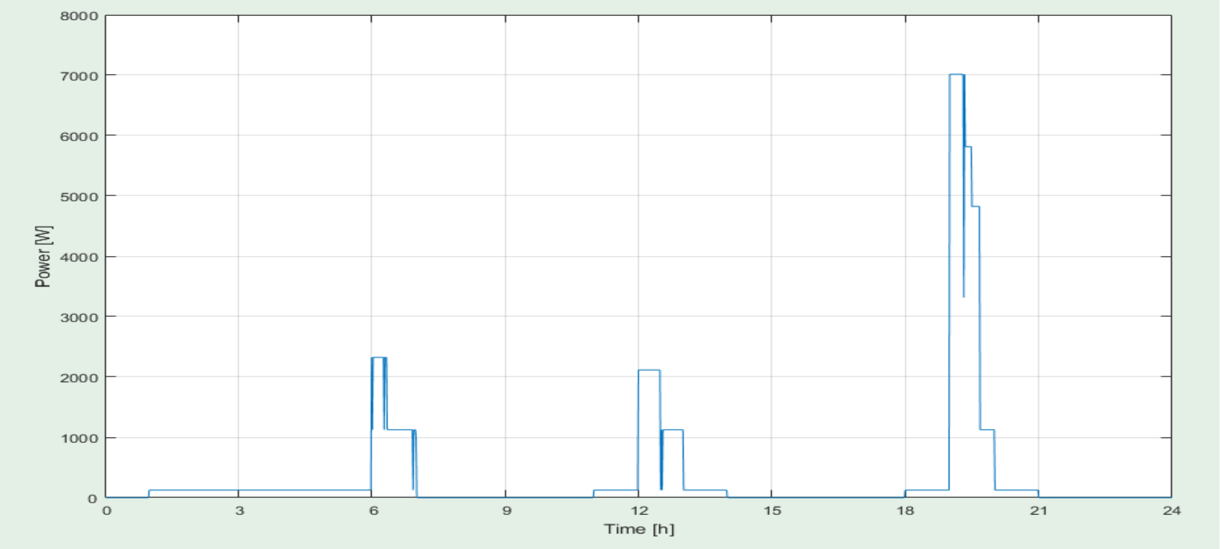

Figure 4.1 Resistive load profile

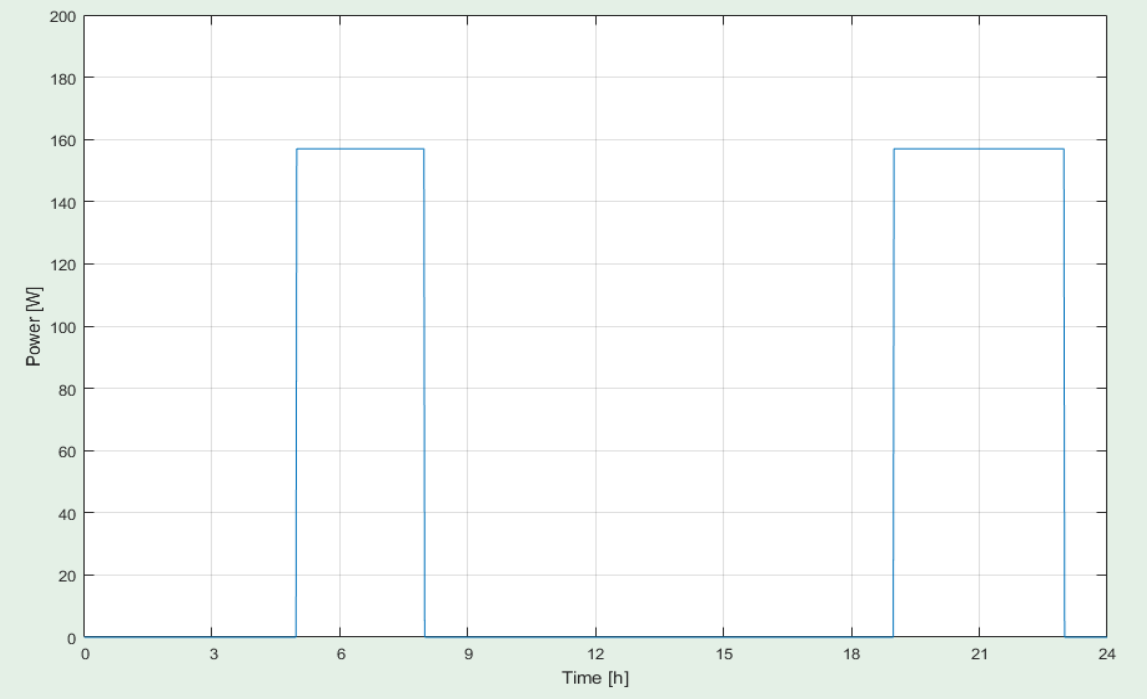

Figure 4.2 Electronic lighting load profile

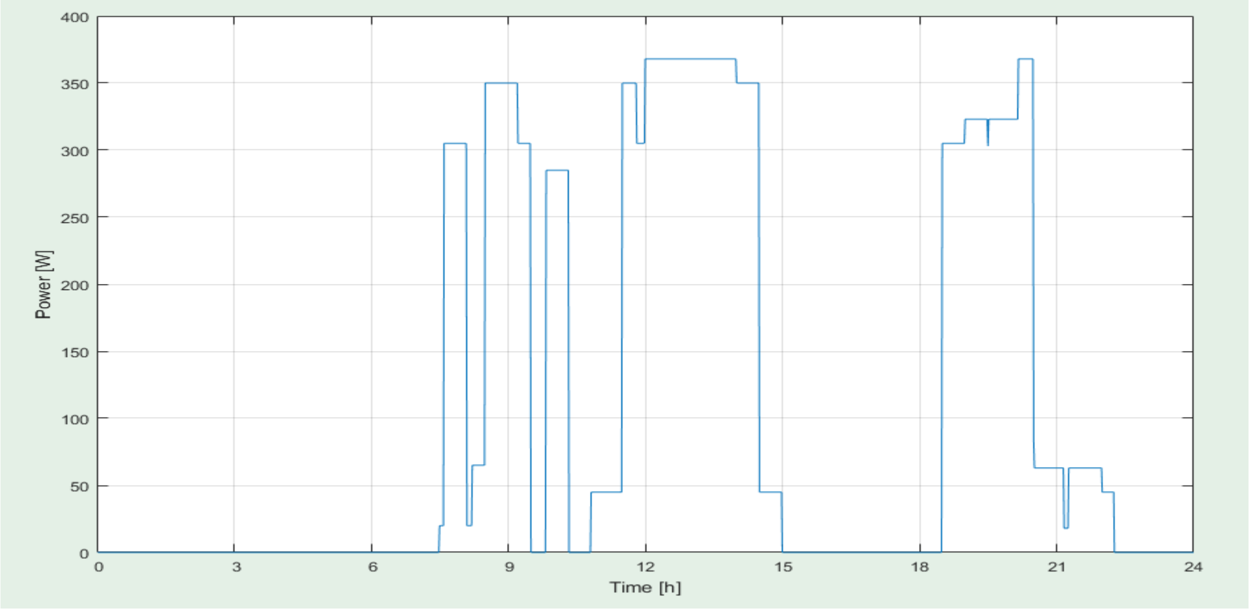

Figure 4.3 SMPS load profile

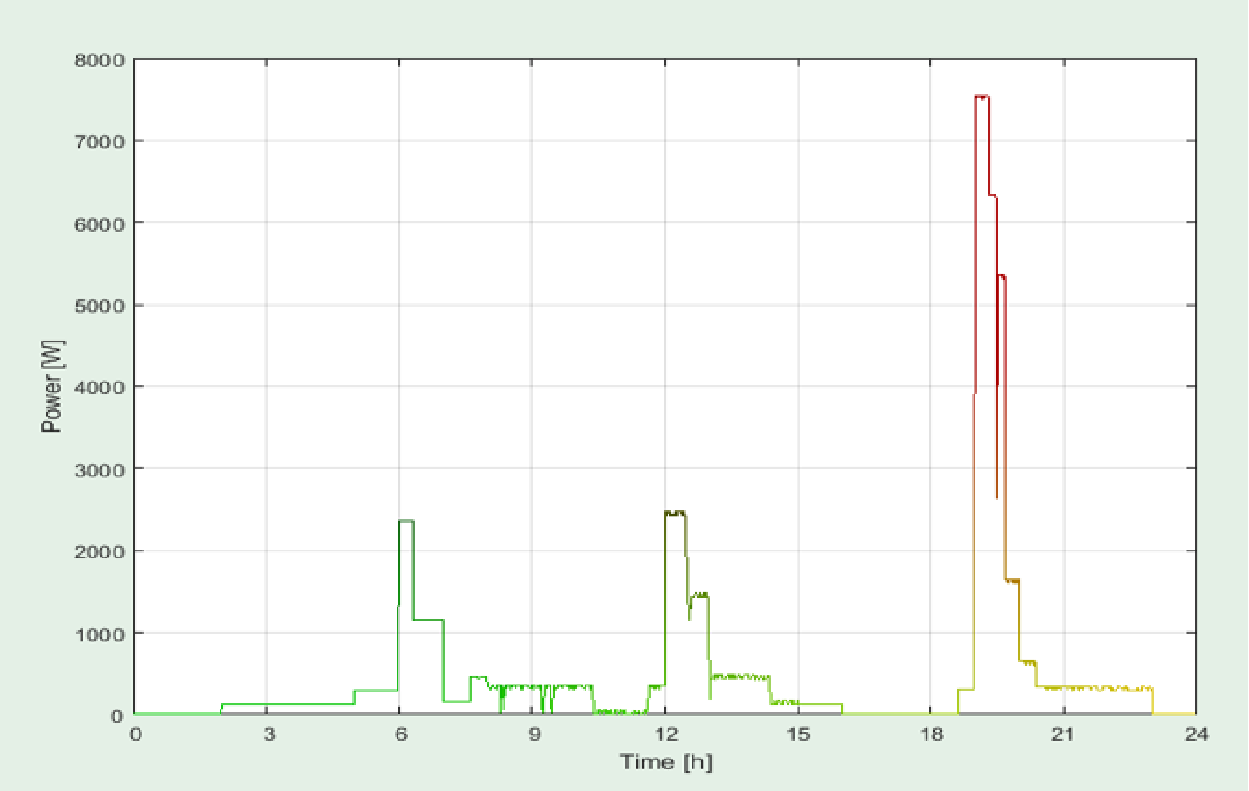

Figure 4.4 Total household load profile

From the load profiles generated using the LoadProGen software the following points can be concluded:

- Resistive loads modeled as $R = R_0$ shows a peak load of 7kW between 19 and 20hrs
- Electronic lighting loads modeled as $R = \frac{U}{I_0}$ shows a constant load of 157W between 5-8hrs and 19-23hrs.
- SMPS loads modeled as $R = \frac{U^2}{P_0}$ shows a peak power of 360W between 12-14 hrs and between 20-20.5hr.
- The total household profile shows a maximum peak load of 7.4 kW during night times between 19-21hrs.

The household loads varies continuously throughout the day. These loads can't be represented directly in Matlab Simulink software, as a simpscape power system lacks a formal block for a 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.

The variable load models shown in Figures 4.5, 4.6 and 4.7 will accept inputs from the load profiles generated using LoadProGen software. These model blocks accept R_0 for heating loads , P_0 for SMPS and I_0 for electronic lighting loads from the load profile generated using the software [41].

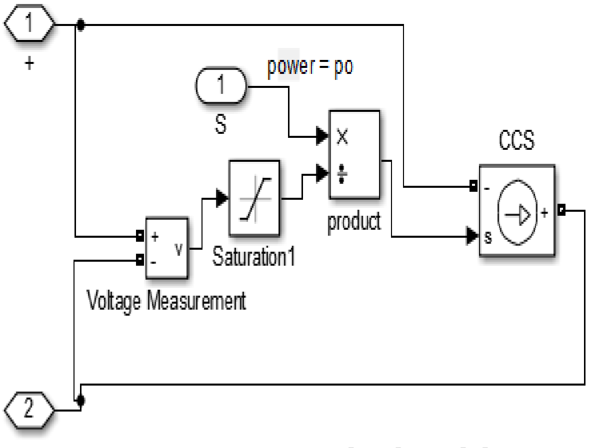

Figure 4.5 SMPS load model

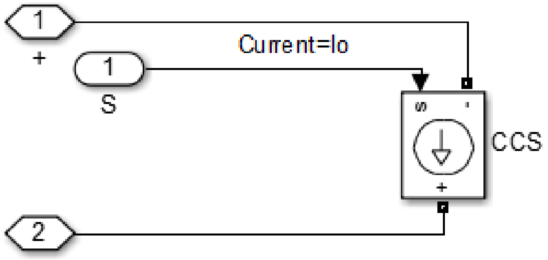

Figure 4.6 Electronic lighting load model

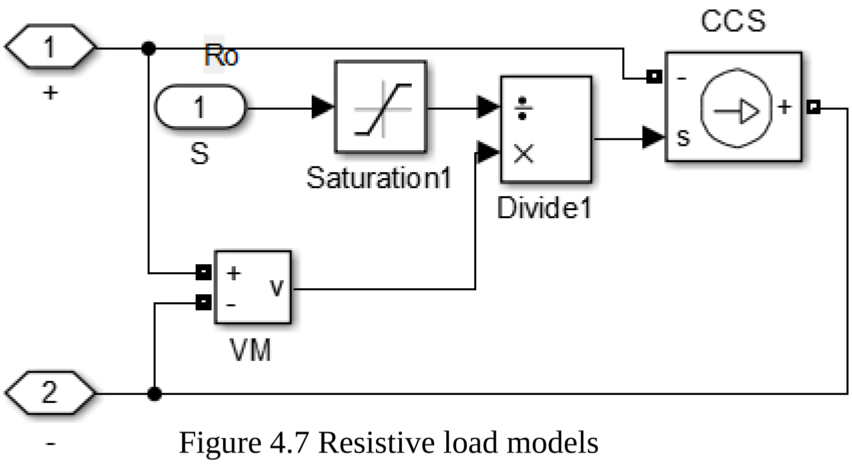

Figure 4.7 Resistive load models

4.3 PV System Design

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 distribution system can be directly integrated with these resources effectively [43].

Solar Energy is an environmental friendly renewable energy resource that does not emit carbon to the atmosphere that causes global warming. Research conducted by US Energy firm Green Technology Africa Incorporated, shows that solar is a viable renewable energy for Ethiopia [44]. Based on resource capacity, solar energy is highly preferable for the country. On this thesis, PV system design has been done for 120V dc system.

‘Sululta’, one of the woredas in the Oromia region of Ethiopia, is located at a latitude of 9.1853° N and 38.7604° E.

The monthly average daily horizontal solar radiation [45] and temperature variation [46] of ‘Sululta’ is given Table 4.2 and Table 4.3

Table 4.2 Monthly average daily horizontal solar radiations (kWh/m^2/d)

Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Daily solar radiation horizontal (kWh/m^2/d)	6.18	6.59	6.52	6.48	6.42	5.86	5.15	5.18	5.84	6.4	6.31	6.11

Table 4.3 Daily temperature variation of ‘Sululta’

Time(hr)	00	01	02	03	04	05	06	07	08	09	10	11	12
Temperature(C^0)	16	15	15	14	13	13	12	13	17	21	23	25	26

Time(hr)	13	14	15	16	17	18	19	20	21	22	23
Temperature(C^0)	27	27	27	26	25	24	21	20	19	18	17

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/d. Using this value and the data given in [45] the hourly irradiance variation in w/m^2 can be estimated and listed in Table 4.4

Table 4.4 Hourly irradiance variation of ‘Sululta’ in w/m^2

Time(hr)	00	01	02	03	04	05	06	07	08	09	10	11	12
Irradiance(W/m^2)	0	0	0	0	0	0	250	320	540	630	700	850	980

Time(hr)	13	14	15	16	17	18	19	20	21	22	23
Irradiance (W/m^2)	960	830	750	600	480	260	0	0	0	0	0

Photovoltaic (PV) power system convert sunlight directly into electricity. The total load profile shows a peak load of 7.4 kW during peak hours. The PV system is designed to fulfill this load demand and expected to produce a constant voltage of 130V dc. To realize this, Yingli Solar YL255P-32b Solar Panel is selected with the specification given in Table 4.5 and Table 4.6.

Table 4.5 Electrical characteristics of Yingli Solar YL255P-32b Solar Panel

STC Power Rating	255W
I_{mp}	7.85A
V_{mp}	32.5V
V_{oc}	41V
I_{sc}	8.4A
NOCT	46C^0

Table 4.6 Mechanical characteristics of Yingli Solar YL255P-32b Solar Panel

Type	Polycrystalline Silicon
Size(L*W*H)(mm)	1650*990*40
Weight	19.1Kg

Number of modules required per string

$$Ns = \frac{required\ voltage}{Module\ V_{mp}} \tag{4.1}$$

$$Ns = \frac{130}{32.5} = 4$$

The maximum (peak current)

$$I_{\ max} = \frac{Peak\ power}{required\ moduel\ voltage} = \frac{7400}{130} = 56.92A \tag{4.2}$$

Number of strings in parallel

$$Np = \frac{load\ current}{Module\ I_{mp}} \tag{4.3}$$

$$Np = \frac{56.92}{7.85} = 7.25 \approx 8$$

The total number of modules required becomes 4*8 = 32

4.4 Battery Energy Storage System (BESS)

The energy produced from PV panels cannot fully supply the load as there is no irradiance during night times and the amount may significantly reduce during rainy seasons. To overcome this shortage of power, battery energy system is designed for the selected house.

The total daily energy consumption of the house is 11.1 kWh/day.

$$\text{Total amp} - \text{hour demand per day} = \frac{\text{Daily Enery consumption}}{\text{Battery voltage}}\ (\text{Ah}) \tag{4.4}$$

$$\text{Total amp} - \text{hour demand per day} = \frac{11134}{130} = 85.67\text{Ah}$$

It is normal practice to assume depth of discharge (DOD) of battery be 0.8 [47]. So considering this DOD, the battery capacity becomes;

$$Required\ battery\ capacity = \frac{85.27}{0.8}$$

$$= 106.6\mathrm{Ah}$$

Ritar 12V, 60AH, Sealed Lead Acid Battery is selected for this design and detail specification is given in Appendix A.

$$\text{Number of batteries in parallel} = \frac{106.6}{60} = 1.77 \approx 2$$

$$\text{Number of batteries in series } = \frac{130}{12} = 10.8 \approx 11$$

Total Number of batteries = 2* 11= 22.

4.5 Modeling of Convertors and BESS in LVDC Distribution System

For supplying power for the selected house using low voltage dc distribution system, 120V dc voltage level is selected. The PV panel output varies continuously with variation of irradiance. The load voltage is also varied upon variation of the load, especially during peak hours. Buck boost convertor coupled with maximum power point tracking is implemented to make constant output voltage from the PV panel. The load voltage is maintained constant by using buck convertor with PI controller. During night times when there is no sun light, home appliances are supplied by battery energy storage system. In other times when there is sufficient output from the PV panels and surplus power while supplying the loads, the battery energy storage system is being charged by solar system. Buck boost bidirectional convertor is used to charge and discharge the battery during these occasions.

4.5.1 Buck boost convertor design

The buck–boost converter is a type of dc-to-dc converter that has an output voltage magnitude that is either greater than or less than the input voltage magnitude. The equivalent circuit of buck boost convertor is shown in the Figure 4.8.

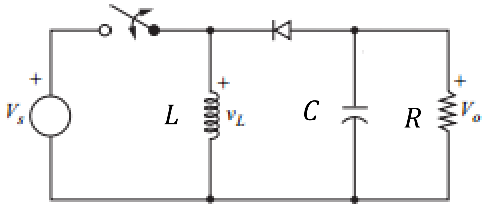

Figure 4.8 Buck-boost convertor circuit [48]

$$R = \frac{{V_0}^2}{P} \qquad (4.5)$$

Where $V_0(output\ voltage)$=130V and P is load power (in watt)

As it is seen from the load profile, the peak and the minimum load is 7.4kW and 125W respectively and the corresponding load resistances for the buck boost convertor becomes

$$R_{min} = \frac{(130)^2}{7400} = 2.3\Omega$$

$$R_{max} = \frac{(130)^2}{125} = 135.2\Omega$$

$$V_0 = \frac{D}{(1-D)} V_s[48] \qquad (4.6)$$

Where D is the duty ratio of the convertor and V_s is the source voltage

Assuming the source voltage (V_s) 5% deviation from the nominal output voltage V_0 , of the convertor, then the duty ratio of the convertor varies between 0.488 and 0.513.

For continuous output voltage the capacitance C and inductance L is given by [48],

$$C \geq \frac{D}{2f_s R} \qquad (4.7)$$

$$L \geq \frac{R(1-D)}{2f_s} \qquad (4.8)$$

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

$$C \geq \frac{0.513}{2 * 10 * 10^3 * 2.3} = 11.15\mu F$$

$$L \geq \frac{135.2(1-0.488)}{2*10*10^3} = 3.46\text{mH}$$

From the datasheet, a capacitor having magnitude of 300V, $150\mu F$ and an inductor with magnitude of 35mH, 70A that can withstand the maximum rated current is selected for the buck boost convertor.

4.5.2 Buck convertor design

A buck converter (step-down converter) is a dc-to-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 is used to produce constant output voltage irrespective of load variation using PI controllers. It accepts the output of the buck boost convertor and battery energy storage system and converts it to lower value 120V, and supply it to the load.

The equivalent circuit of buck convertor is shown in the Figure 4.9.

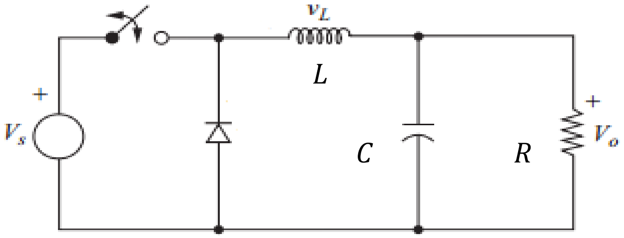

Figure 4.9 Buck DC-DC convertor [48]

It can be seen that from the load profile, the peak and the minimum load is 7.4kW and 125W respectively and the corresponding load resistances for the buck convertor becomes

$$R_{min} = \frac{(120)^2}{7400} = 1.946\Omega$$

$$R_{max} = \frac{(120)^2}{125} = 115.2\Omega$$

$$V_0 = DV_s \text{ [44]} \tag{4.9}$$

The duty ratio of the buck convertor becomes $D = \frac{V_0}{V_s} = \frac{120}{130} = 0.923$

For continuous output of voltage and current, the capacitance C and inductance L is given by [48]

$$C \geq \frac{1-D}{16Lf_s{}^2} \tag{4.10}$$

$$L \geq \frac{R(1-D)}{2f_s} \tag{4.11}$$

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

$$C \geq \frac{1-0.923}{16 * 40 * 10^{-3} * (10 * 10^3)^2} = 0.0012\mu F$$

$$L \geq \frac{115.2 * (1-0.923)}{2 * 10 * 10^3} = 0.443\text{mH}$$

From the datasheet, a capacitor having magnitude of 300V, $5\mu F$ and an inductor with magnitude of 25mH, 70A is selected for the buck dc-dc convertor.

4.5.3 Bidirectional buck boost convertor design

In a renewable energy generation system, a bidirectional dc-dc converter is 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 be lowered to charge. For discharging modes, if the voltage of battery is higher than that of the dc link, the voltage of batteries will be lowered to discharge; otherwise, the voltage of batteries will be boosted to discharge [49].

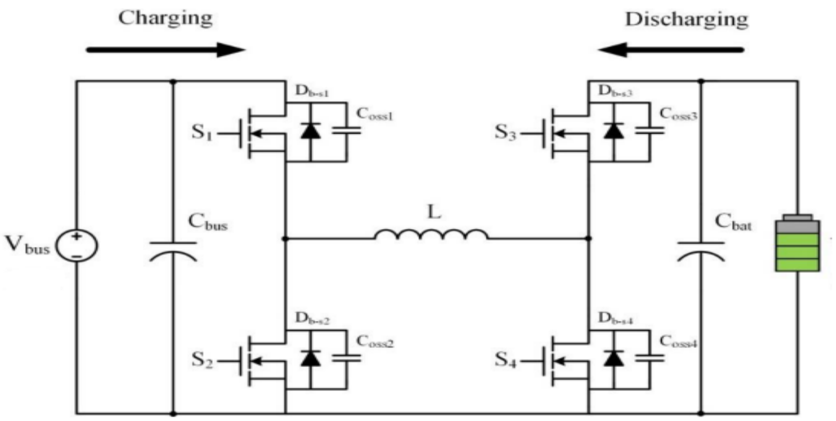

Figure 4.10 Circuit diagram of universal bi-directional buck-boost convertor [49]

The charging/discharging mode here is defined as that the energy is 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.

Table 4.7 Gating signals for four operating modes of the bidirectional buck boost convertor [49]

Modes	**Buck**	**Boost**
Charging	S_1 = controlling signal (duty ratio =d),S_2=off, S_3=on/off, S_4 =off	S_1 = on, ,S_2=off, S_3=on/off, S_4 = controlling signal (duty ratio =d)
Discharging	S_1 = on/off,S_2=off, S_3= controlling signal (duty ratio =d),S_4 =off	S_1 = on/off ,S_2= controlling signal (duty ratio =d), S_3=on,S_4 =off

For continuous output of voltage and current, equation (4.9), (4.10), (4.11) can be used during buck conversion and for boost conversion mode of the bidirectional convertor equations (4.12), (4.13), and (4.14) can be used.

$$V_0 = \frac{1}{1-D} V_s \tag{4.12}$$

$$L \geq \frac{RD(1-D)^2}{2f_s} \tag{4.13}$$

$$C \geq \frac{D}{2Rf_s} \tag{4.14}$$

Battery charging undergoes three steps. These charging stage voltages are given in Appendix A

- Bulk charge phase (up-to 80% state of charge) =14.7*11=161.7V
- Absorption charge(between 80 to 95% state of charge)= 14*11=154V
- Float charging phase(between 95 to 100% state of charge) = 13.6*11=149.6V

Duty ratios of the bidirectional buck boost convertors is varied during charging and discharging modes of the battery.

Charging mode: Boost charging

From equation (4.12) the duty ratio becomes

$$D = \frac{V_0 - V_s}{V_0} = \frac{V_{bat} - V_{bus}}{V_{bat}} = \frac{161.7 - 130}{161.7} = 0.196 \text{ (bulk charge phase)}$$

$$D = \frac{154 - 130}{154} = 0.156 \text{(Absorption charge phase)}$$

$$D = \frac{149.6 - 130}{149.6} = 0.131 \text{(Float charging phase)}$$

The internal resistance of the selected battery is 8mΩ.Since there are 22 batteries connected in series and parallel, the total internal resistance of the battery bank is 44 mΩ.

During boost charging mode, the inductance and capacitance can be calculated using equation (4.13) and (4.14)

$$L \geq \frac{44 * 10^{-3} * 0.196 * (1 - 0.196)^2}{2 * 10 * 10^3} = 27\mu F$$

$$C_{bat} \geq \frac{0.196}{2 * 44 * 10^{-3} * 10 * 10^3} = 222\mu F$$

Discharging mode:

The battery can operate with a minimum discharge voltage 10.5V.Taking this into account the total battery voltage during discharging mode varies from 115.5V to 154V.Therefore the duty ratio for discharging mode during boost and buck conditions becomes:

Boost discharge :

$$D = \frac{V_{bus} - V_{bat}}{V_{bus}} = \frac{130 - 115.5}{130} = 0.1115$$

Buck discharge

$$D = \frac{V_{bus}}{V_{bat}} = \frac{130}{154} = 0.84$$

The maximum resistance during minimum loading is 135.2Ω.The inductances and capacitances under the two operating mode then becomes:

Boost discharge

$$L \geq \frac{135.2 * 0.1115 * (1 - 0.115)^2}{2 * 10 * 10^3} = 0.6mH$$

$$C_{bus} \geq \frac{0.115}{2 * 2.3 * 10 * 10^3} = 2.4\mu F$$

Buck discharge

$$L \geq \frac{135.2 * (1 - 0.84)}{2 * 10 * 10^3} = 1.1mH$$

$$C_{bus} \geq \frac{1 - 0.84}{16 * 1.1 * 10^{-3} * (10 * 10^3)} = 0.09\mu F$$

From the datasheet C_{bat}=250μF, 300V; C_{bus}=50 μF, 300V and L=80mH, 100A is selected for the bidirectional buck boost convertor.

Battery energy storage system operates by comparing the load power consumption with the output power of the PV panel and the current status of the state of charge of the battery. When there is no sunlight, and the state of charge of the battery is greater than 0.3, the load will be supplied by the battery and the battery becomes in discharging mode. When there is enough supply of solar radiation (when the power produced by PV modules is greater than the load), and the state of charge of the battery falls below 0.95,the PV panel will supply power to the load and battery, now the battery enters in charging mode. Otherwise if the system is out of the above two conditions, the loads will be disconnected from the system. The algorithm of battery energy storage system is shown in Appendix D.

4.6 PV System with Maximum Power Point Tracking (MPPT)

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 [50].

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 is 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.

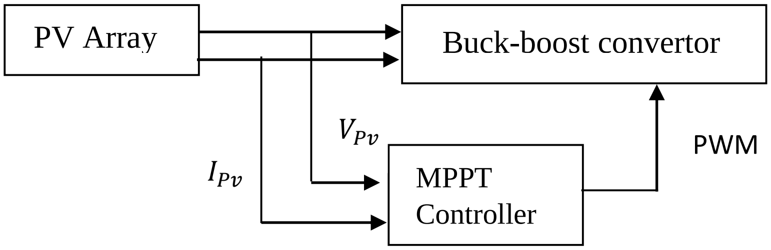

Figure 4.11 PV system with MPPT

Many MPPT methods have been suggested in the literature; examples are the Perturb and Observe (P&O) methods, Incremental Conductance (IC) methods and constant voltage methods. etc. [51-52].

The most commonly used MPPT algorithm is P&O method. This algorithm uses simple feedback arrangement and little measured parameters. In this approach, the module voltage is periodically given a perturbation and the corresponding output power is compared with that at the previous perturbing cycle [53]. In this algorithm a slight perturbation is introduced to the system. This perturbation causes the power of the solar module to vary. If the power increases due to the perturbation then the perturbation is continued in the same direction. After the peak power is reached, the power at the MPP is zero and next instant decreases and hence after that the perturbation reverses.

Among all, perturb and observe (P and O) algorithm is selected for this MPPT tracking, because P & O algorithm has a simple control structure and few measured parameters are required for the power tracking. It also has low cost and high tracking capability [54]. A common problem in P & O algorithms is that the array terminal voltage is perturbed every MPPT cycle. Therefore when the MPP is reached, the output power oscillates around the maximum, resulting in power loss in the PV system. This is especially true in under rapidly changing atmospheric conditions [55].

In this method, the sign of the last perturbation and the sign of the last increment in the power are used to decide what the next perturbation should be on the left of the MPP incrementing the voltage increases the power whereas on the right decrementing the voltage increases the power.

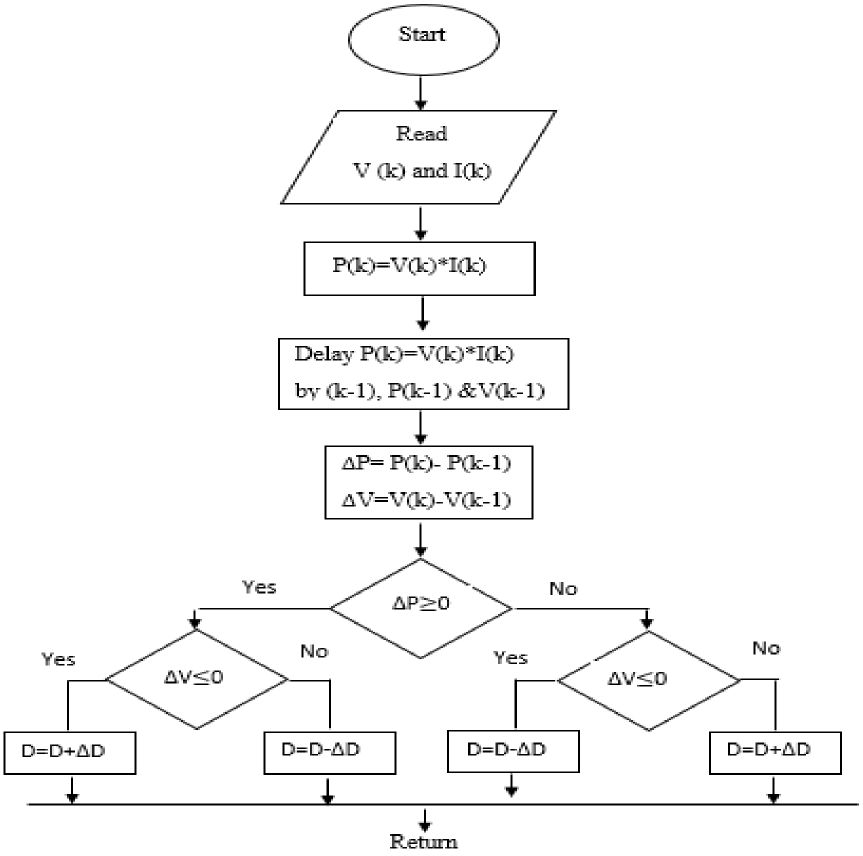

Figure 4.12 Flow chart for P & O algorithm [55]

Where D is the duty cycle of the buck boost convertor which varies between 0.488 and 0.513 which is calculated in section 4.5.1.The details of P & O algorithm is shown in Appendix C.

4.7 Load Voltage Control

Buck convertor is connected to the load and is used to provide constant output voltage of 120V DC. But since there is a continuous variation of load throughout the day, the load voltage may not be constant. This is the case especially when high power consuming appliances like stoves and Injera Mitad are connected and disconnected from the system. To maintain constant load voltage, buck convertor coupled with PI controller is used.

A PI Controller (proportional-integral controller) is a special case of the PID controller in which the derivative D of the error is not used [56]. At present, the PI controller is most widely adopted in industrial application due to its simple structure, easy to design and low cost. Despite these advantages, the PI controller fails when the controlled object is highly nonlinear and uncertain [57].

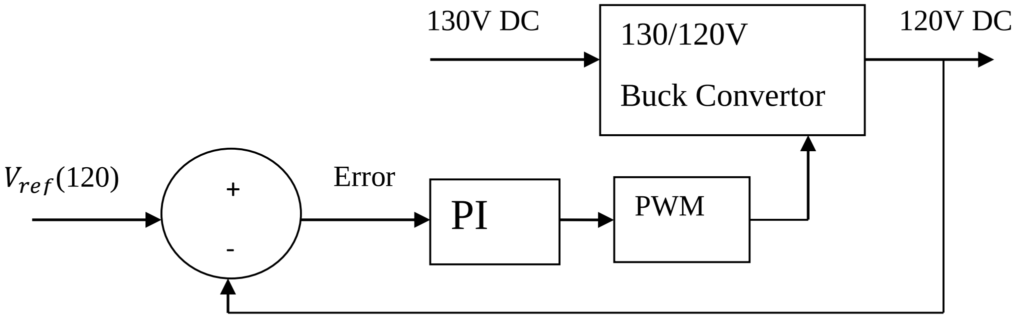

Figure 4.13 Load voltage control using PI and Buck convertor [41]

The above control uses the output voltage of the convertor as a feedback and compares this output with the fixed reference value. Then the error is given to the PI controller which will then produce the corrected modulated voltage signal so that the buck convertor will produce a constant output voltage.

In order to design the controller parameters, buck convertor is represented using small signal single input-single output transfer function between the output voltages $\widehat{V_o}$ and the duty cycle $\hat{d}$.The transfer function of the buck convertor is then give by equation (4.15) [58].

$$\frac{\widehat{V_o}}{\hat{d}} = \frac{\frac{U}{LC}}{S^2 + \frac{S}{RC} + \frac{1}{LC}} \tag{4.15}$$

Where U is the input voltage for the buck converter. R, L and C are the resistance, inductance and capacitances for the buck convertor respectively. Substituting the values of inductance, capacitance and resistance that has been calculated in section 4.5.2 the transfer function becomes.

$$\frac{\widehat{V_o}}{\hat{d}} = \frac{130}{4 * 10\verb|^|(-8)S^2 + 0.347 * 10^{-3} + 1}$$

Using Matlab Simulink software, the PI controller parameters are determined and given in Table 4.8.

Table 4.8 PI control parameters of buck convertor

Controller parameters	**Tuned**
Kp	0.025
Ki	3.544
Performance and Robustness	**Tuned**
Rise time(second)	0.000213
Setting time(second)	0.0223

The overall equivalent circuit of the proposed low voltage DC distribution system is given in Figure 4.14.

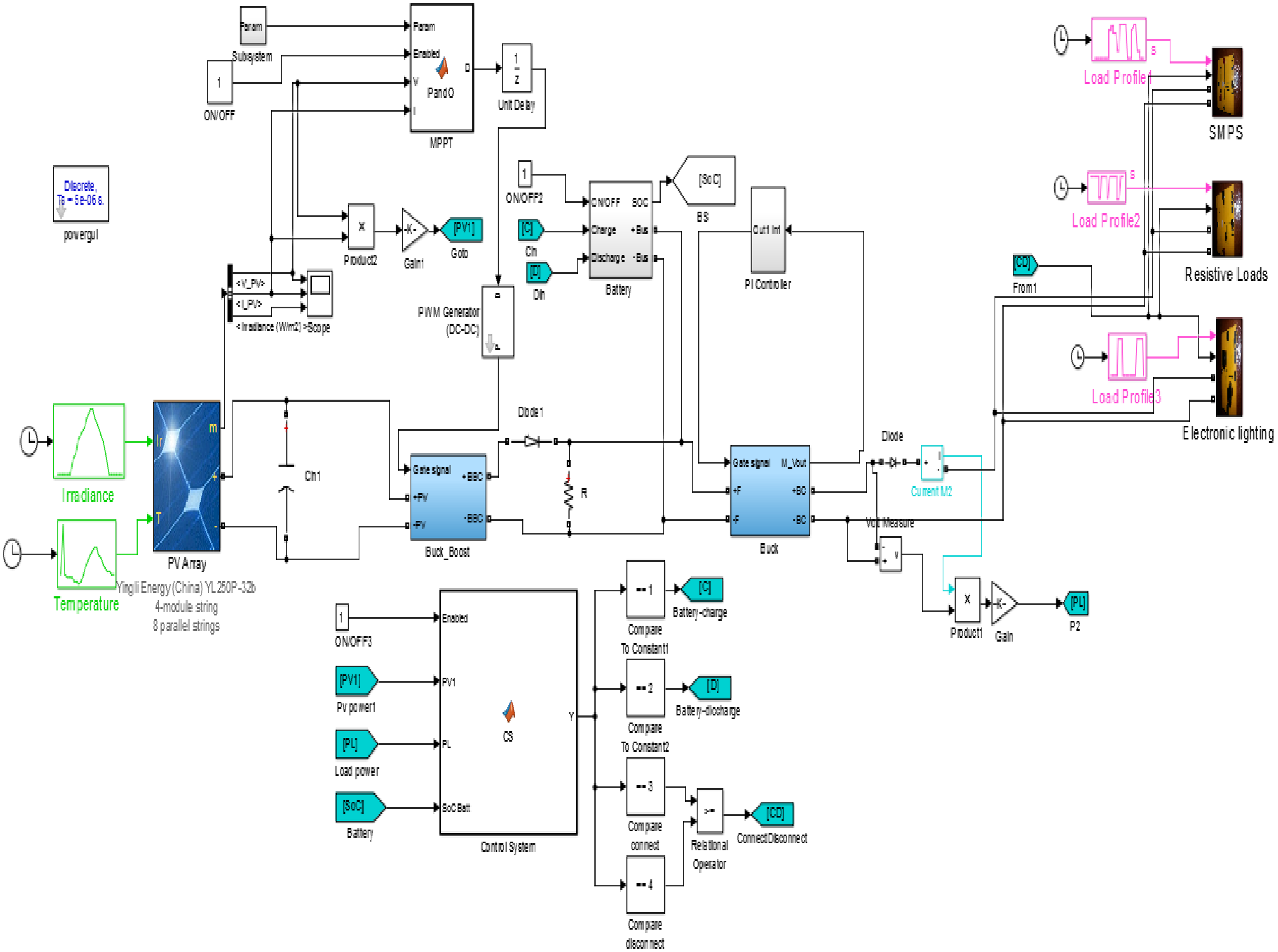

Figure 4.14 Proposed Low voltage DC distribution system

4.8 Simulation Studies and Analysis

In this thesis, the technical and economic feasibility of low voltage direct current distribution system is analyzed. Voltage levels of 24V, 48V and 120V dc are identified for analysis, as there is no standard dc voltage currently. It has been found that 120V dc is highly efficient as compared to the two lower dc voltage levels and even this voltage shows some energy efficiency improvement from its rival 220V ac distribution system.

The selected voltage level, 120V dc, is electrically safe for indirect contact and doesn't require special protection mechanism. Since dc electrical systems has less potential stress over ac system for the same voltage level, the existing installation wires can be used to build new low voltage dc distribution system for a residence. Unipolar distribution system with two wires is selected for the system due to its simplicity in its structure and low cost.

Almost all of home appliances get their supply from ac system (although internally operate with direct current) and convert this ac to dc using power electronic convertors. This conversion causes some power loss during normal and standby conditions. High power consuming devices like Injera Mitad and stoves can operate directly with direct current without any modification. Similarly with some changes made in the internal circuitry of electronic and rotating appliances, they can be supplied directly with 120V dc system.

Solar power is used as a renewable energy resource to supply power to the selected house as Ethiopia has huge potential of this resource. Since the main component of solar system, PV modules, shows a sharp decline in terms cost, rural towns of the county which is known with its highly dispersed nature of the rural community can get electricity access with this well-known system. The unit electricity cost of the proposed system is higher than the current electricity tariffs set by EEU.

The overall low voltage dc distribution system is implemented with buck boost convertor coupled with maximum power point tracking at the source which is used to produce constant voltage with variation of solar radiation, buck convertor with PI controller to maintain constant voltage with variation of load especially during peak hours, battery energy storage system with bidirectional buck boost convertor to manage the direction of power flow during charging and discharging of the battery.

Load variation of the system is represented in Matlab Simulink software using current source convertors and three different load models were developed for resistive, electronic lighting and switch mode power supplies. The overall implementation of the low voltage direct current distribution system is implemented using Matlab Simulink software for 24hrs.The simulation is intended to show that the proposed system will deliver constant voltage irrespective of the load variations and the energy management control systems switches the source of the power supply between solar PV and battery energy storage system for variation of irradiance, temperature and load conditions.

Figure 4.15 shows the output of solar PV modules with maximum power point tracking. Since there is no solar radiation before 5hr and after 18hr there is no voltage and current output from the panel. Between 5hr and 18hr, constant voltage of magnitude of 150V dc is produced from the system. The irradiance curve in the third picture of Figure 4.15 shows that solar radiation reaches its peak value of 980 w/m^2 at 12hr.

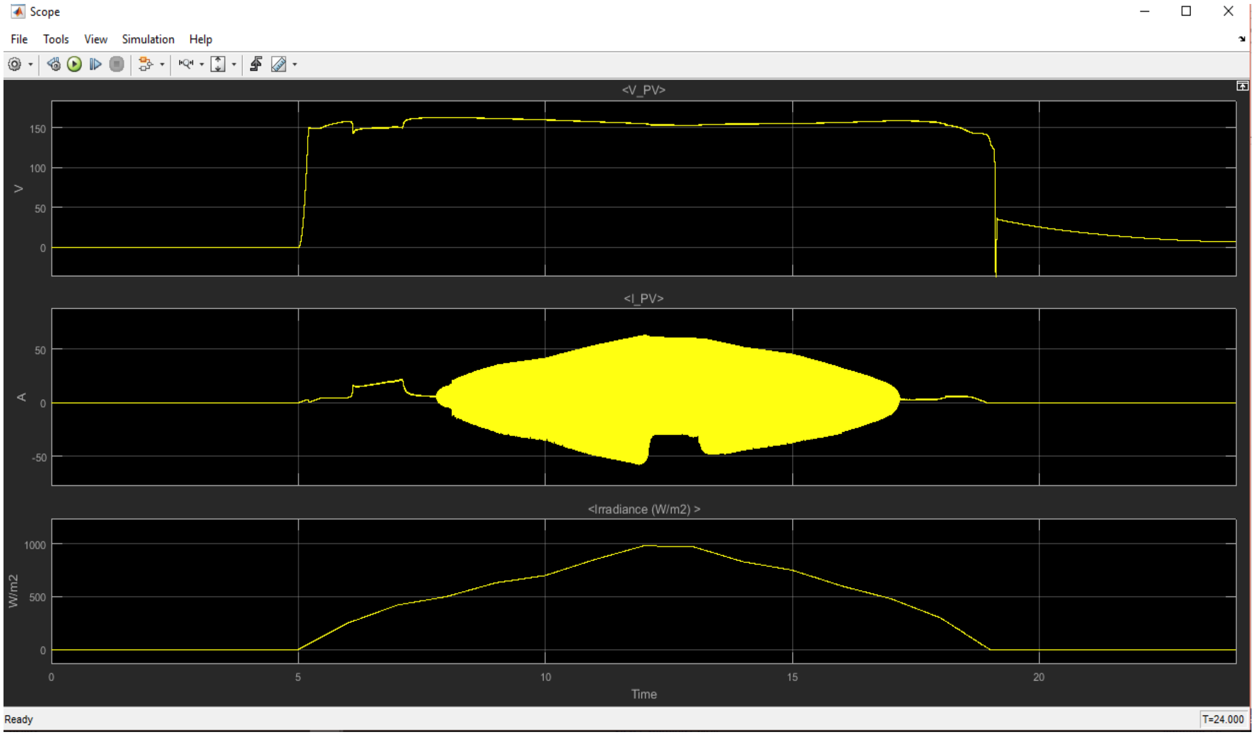

Figure 4.15 Voltage, current and solar radiation output of PV modules

As it is explained in section 4.5, the source convertor (buck boost convertor), is expected to produce constant voltage with variation of irradiance throughout the day. Figure 4.16 shows the output of the source buck boost convertor. The convertor produces constant voltage of d130V dc during when there is sunlight radiation between 5 and 18hrs. As it is seen from Figure 4.16, although the current is designed to operate in continuous conduction mode, the buck boost convertor current enters in discontinuous conduction modes. Due to this effect, the output power of the buck boost convertor undergoes discontinuous conduction mode. The power output of the convertor becomes zero before 5hrs and after 18hrs as there is no solar radiation during these times.

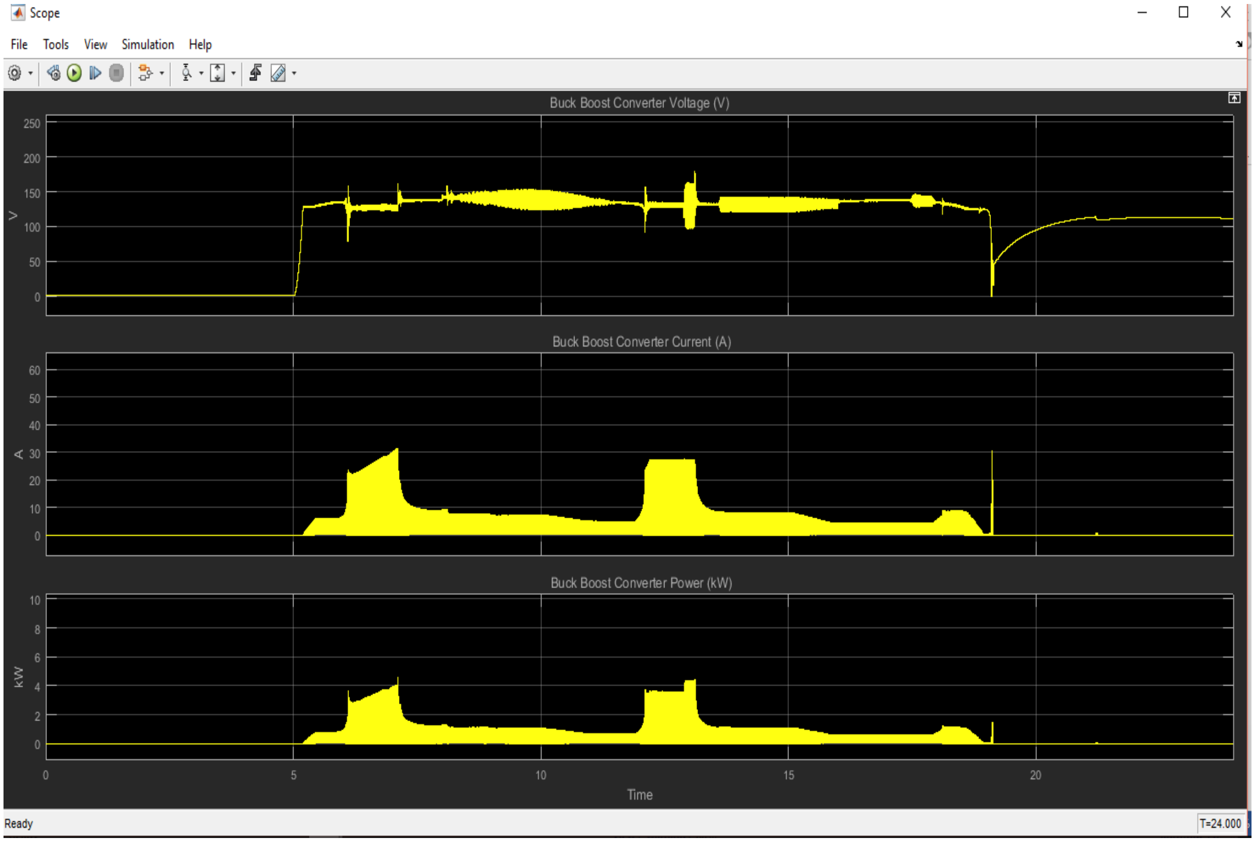

Figure 4.16 Voltage, current and power output of buck boost convertor (source convertor)

The voltage, current and power output of the buck convertor is shown in Figure 5.3. It is seen that irrespective of the solar radiation and load variation, the buck convertor produces constant voltage of magnitude of 120V dc throughout the day. Voltage spikes with small magnitude happened at 6hr, 8hr and 21hr. A large voltage spike is also observed at 19hr and 21hrs as this is the peak hour of the day. Voltage spikes are caused due to sudden connection and disconnection of the load. Between 6 & 7hrs and between 12 & 13hrs, the load current reaches 22 ampere. While during peak hours when large power consuming devices are connected to the system, 62A is observed as shown in the second picture of Figure 4.17. Power output of 2.6kW is recorded between 6 & 7hrs and between 12 & 13hrs. At peak hours, between 19 & 21hrs the load reaches a maximum power of 7.4kW.

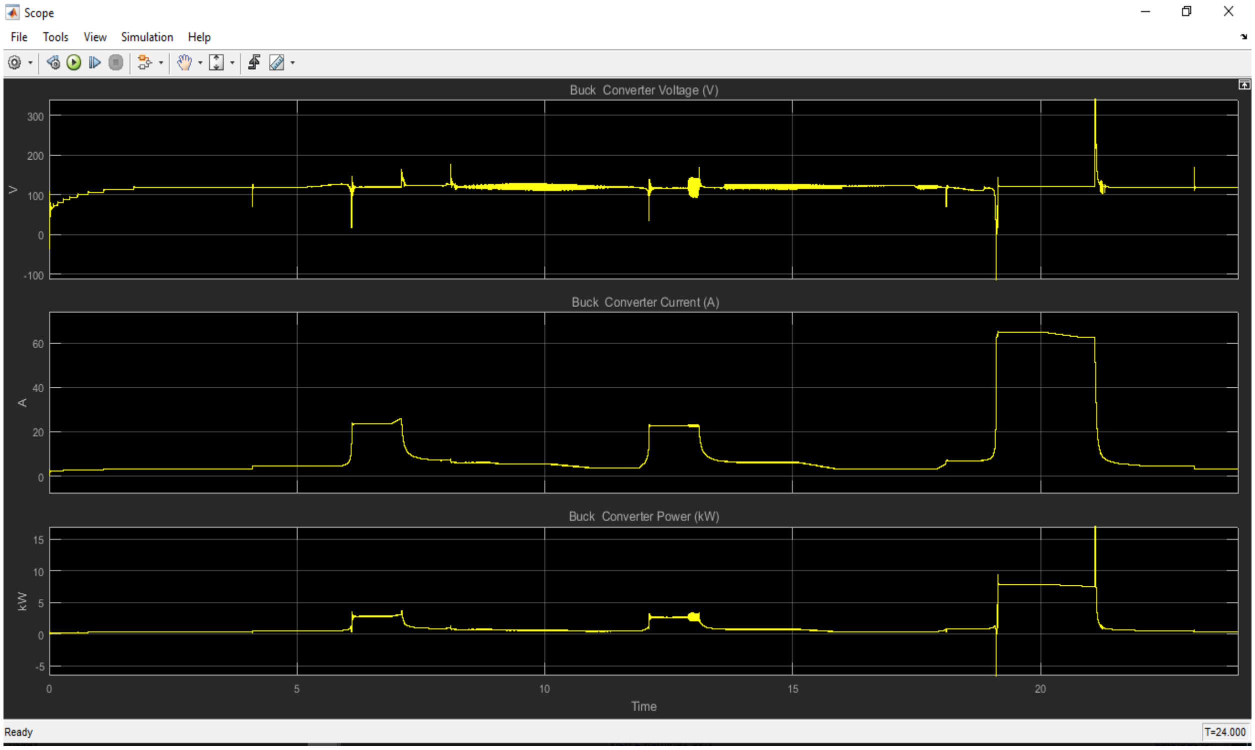

Figure 4.17 Voltage, current and power output of buck convertor

During night times before 5hr and after 18hr 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. Figure 4.18 shows energy management system. Before 5hr 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. Between 5 and 18hrs, 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. Again after 18hrs, since there is no output from the PV system, the battery discharges and supplies power to the load.

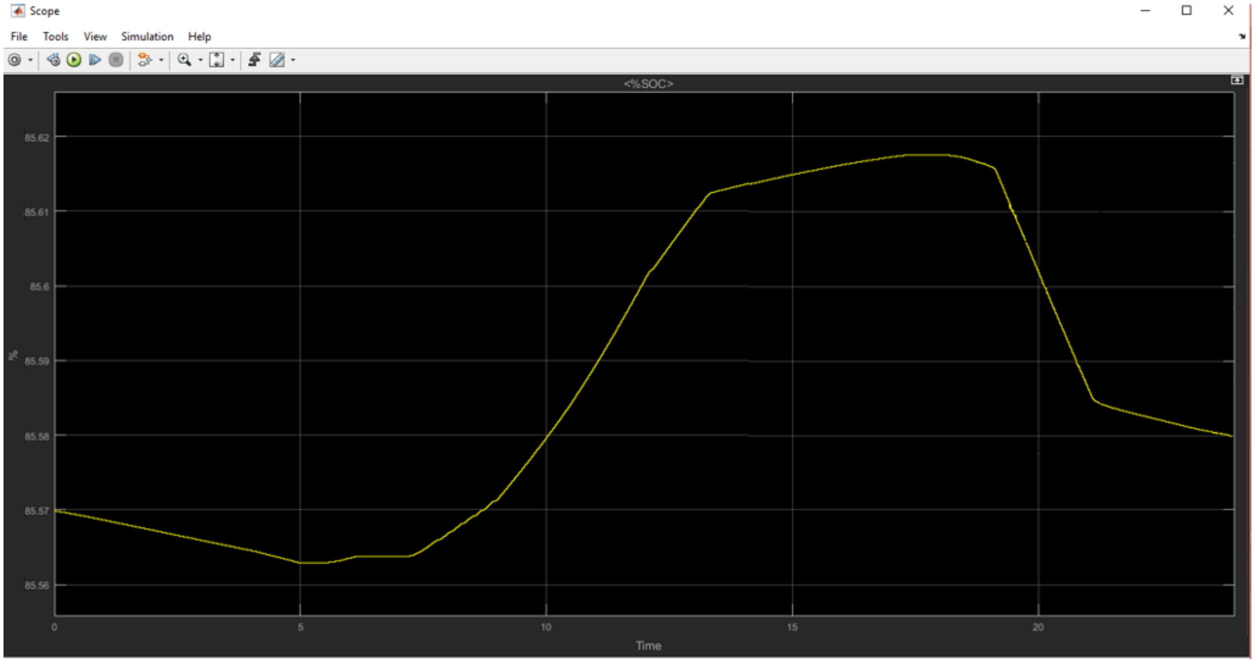

Figure 4.18 Battery energy storage system charging and discharging upon variation of irradiance and load

4.9 Economic Analysis of LVDC System

Costs in photovoltaic supplied system include purchase, operating, maintenance and replacement costs. The overall components and cost required for normal operation of the PV supplied low voltage dc distribution system is shown in Table 4.9.

Table 4.9 Overall cost of LVDC distribution system

Type of Device	**Quantity**	**Model**	**Unit cost ($)**	**Total cost ($)**
PV module	32	YL-255P-32b	114	3648
Battery	22	Ritar -12V-60AH	50	1100
Design, labor, metering			200	200
Total				4948
Others (5%)				247.4
Over all Total				**5195.4**

4.9.1 Energy cost calculation

The unit energy cost (C_E) can be calculated by dividing the annual life cycle cost (ALCC) by annual energy consumption of load [59].

$$C_E = \frac{ALCC}{E} (\$/kWh) \tag{4.16}$$

Where E is the yearly energy consumption of the household (in kWh)

The ALCC can be calculated by using equation (4.18)

$$ALCC = LCC \left[\frac{(1+d)^n . d)}{(1+d)^n - 1}\right] (\$/year) \tag{4.18}$$

Interest (discount) rate (d) is associated with the amount of profit that can be obtained from saving capital. Inflation rate (i) is a measure of the decline in the value of money.

LCC, Life cycle cost is defined as the sum of present values of all components in the system. Basically, the calculated LCC should include purchasing, replacement, maintenance, fuel and operating costs of each component [59].

$$LCC = C_0 + C_{O\&M} + C_R \tag{4.19}$$

Where $C_o$the purchasing is cost, $C_{o\&M}$ is the present value of operation and maintenance cost and C_R is the present value of replacement cost.

From the datasheet then, it can be seen that the PV panels can serve for more than 25 years. The operation and maintenance of the PV system for less than 10kW can be estimated to be \$23/kW [60]. It is therefore for 7.4kW, \$170 is required. The battery energy storage system is assumed to be replaced every eight years. Interest and inflation rate is taken as 10% and 7% respectively. The present value of the item (P_{worth}) is calculated by using equation (4.20) [59].

$$P_{worth} = C_o * \left(\frac{1+i}{1+d}\right)^n \tag{4.20}$$

Where n is the number of years

The life cycle cost (LCC) of the overall system becomes \$8053.8.The annual life cycle cost of the system can be determined by using equation (4.19)

$$ALCC = 8053.8\left[\frac{(1+0.1)^{25}.\,0.1)}{(1+0.1)^{25}-1}\right](\$/year) \qquad (4.21)$$

$$ALCC = 887.183\$/year$$

The total yearly energy consumption of the selected residence is 4075.11kWh/yr. The Unit electricity cost of designed PV system can be determined using equation (4.16)

$$C_E = \frac{887.183}{4075.11}(\$/kWh)$$

$$= 0.21\ \$/kWh$$

Ethiopian Electric Utility (EEU), sole provider of electricity to the country, sales electricity to its residential customers with $0.06/kWh [61]. Here the cost of the proposed low voltage dc distribution system is higher than the tariff set by the utility company. However, this can be an acceptable alternative for people who have no access to electricity and may want to get their supply from diesel generator which has unit electricity cost of 0.3 $/ kWh.

Chapter Five

Conclusion, Recommendation and Future Work

5.1 Conclusion

The aim of this thesis is to study the technical and economic feasibility of low voltage direct current distribution system supplied with solar power. Based on this thesis work, the following conclusions are drawn.

- There is no standard voltage level for dc distribution system for residential applications. From the results obtained from this thesis work, it can be concluded that 120V dc distribution system can be used as a standard LVDC voltage level which shows an efficiency improvement of 0.88% over its rival 220V ac system.
- The proposed LVDC distribution system produces constant voltage of 120V irrespective of variation of load and radiation using solar PV and battery energy storage as an input.
- 120V dc can effectively be used to supply power for home appliances with little or no modification made in the current internal circuitry of the appliances.
- Safety and protection is a main issue in dc distribution system. 120V dc system is electrically safe and may not require special protection mechanism.
- The size of appliances can be reduced since transformers and some of the conversion steps are omitted from the low voltage dc distribution system.
- Since dc system has less potential stress over ac system for the same voltage level, the current existing installation wires can be used without any rapture in insulation.
- The unit electricity cost of the proposed LVDC system is 0.21 $/kWh, which is somehow higher than the electricity tariff set by the Ethiopian Electric utility (EEU). But, the price of PV panels has fallen rapidly in the past few years. This in turn reduces the unit price cost of the PV system. The Ethiopian Electric Utility is also planning to increase the current subsidized tariff. Therefore, the proposed LVDC system can be best alternative especially for rural community where they are far from the national grid and have no accesses to electricity.
- Burning of wood for fuel is the main cause of pollution in developing countries. Deforestation rates have shown a tremendous growth in recent years as forests are used for

fuel wood and the land is used for farming. Nowadays carbon dioxide emission becomes a global concern. Solar powered LVDC system becomes a viable solution to alleviate the above mentioned problems, additional income can be generated nationally also from carbon trade by preserving forests and switching energy consumption habits to solar powered dc system.

- Power interruption is the main problem of ac transmission and distribution system. This problem can be greatly reduced and the power quality can be improved, using power produced from locally available renewable sources, solar power and LVDC distribution system.
- DC distribution system can be scaled up to supply a large number of loads including schools and clinics, but safety, control and protection issues will be a major challenge.
- Finally from the study, it can be conclude that 120V low voltage direct current distribution system is technically and economically feasible, energy efficient and compatible to household appliances.

5.2 Recommendation

Based on this thesis work it is recommended that the Ethiopian government should create awareness to the people to use low voltage direct current distribution system, especially in rural areas of the country which are far from the national gird. Subsidizing power system components that are used for PV system installation and giving support to the people who want to use the technology, the goal of electrifying all areas of the country with decentralized dc distribution system can be achieved. The government can greatly reduce the alarming deforestation rate of forests in the country by switching the fuel wood consumption habit of the people to solar powered dc distribution system. Additionally by implementing the proposed solution at large scale, low voltage dc distribution system can be integrated to the national gird and improve the power shortage and reduce fluctuation of power.

5.3 Suggestion for Future Work

Low voltage dc distribution system is not widely used as there is no standard voltage level. This research work mainly focus on the feasibility of low voltage dc distribution system for a residence. A lot of research is already being done in this field. Further research should be done in low voltage dc distribution system that would lead realization of the low voltage dc distribution system be standardized distribution system. The following research areas may put the foundation for such that realization;

- Research on low voltage dc circuit breakers and electrical safety
- Setting electrical building codes for dc distribution system
- Research on improving efficiency by developing high efficient convertors
- Fault detection and analysis and protection of low voltage dc distribution system to improve the power quality and reliability
- Developing home appliances that are compatible with dc distribution system
- Developing dc plugs, switches ,sockets and circuit breakers
- In depth research on low voltage dc distribution system to reduce the cost so that it can be affordable to a large number of people
- Optimization of energy management system

5.4 Limitations

The low voltage dc distribution system design works well for the intended application. The scope of this projected is limited to residential applications. Further research need to be done to expand the dc distribution system in commercial and industrial areas. The simulation results shows that there is voltage spikes when high power consuming devices connect and disconnect from the power system, although the voltage need to be constant with such a load variation. It takes 0.8 second for the load voltage to reach its nominal value during start up. More work also required to improve the overall performance the low voltage dc distribution system.

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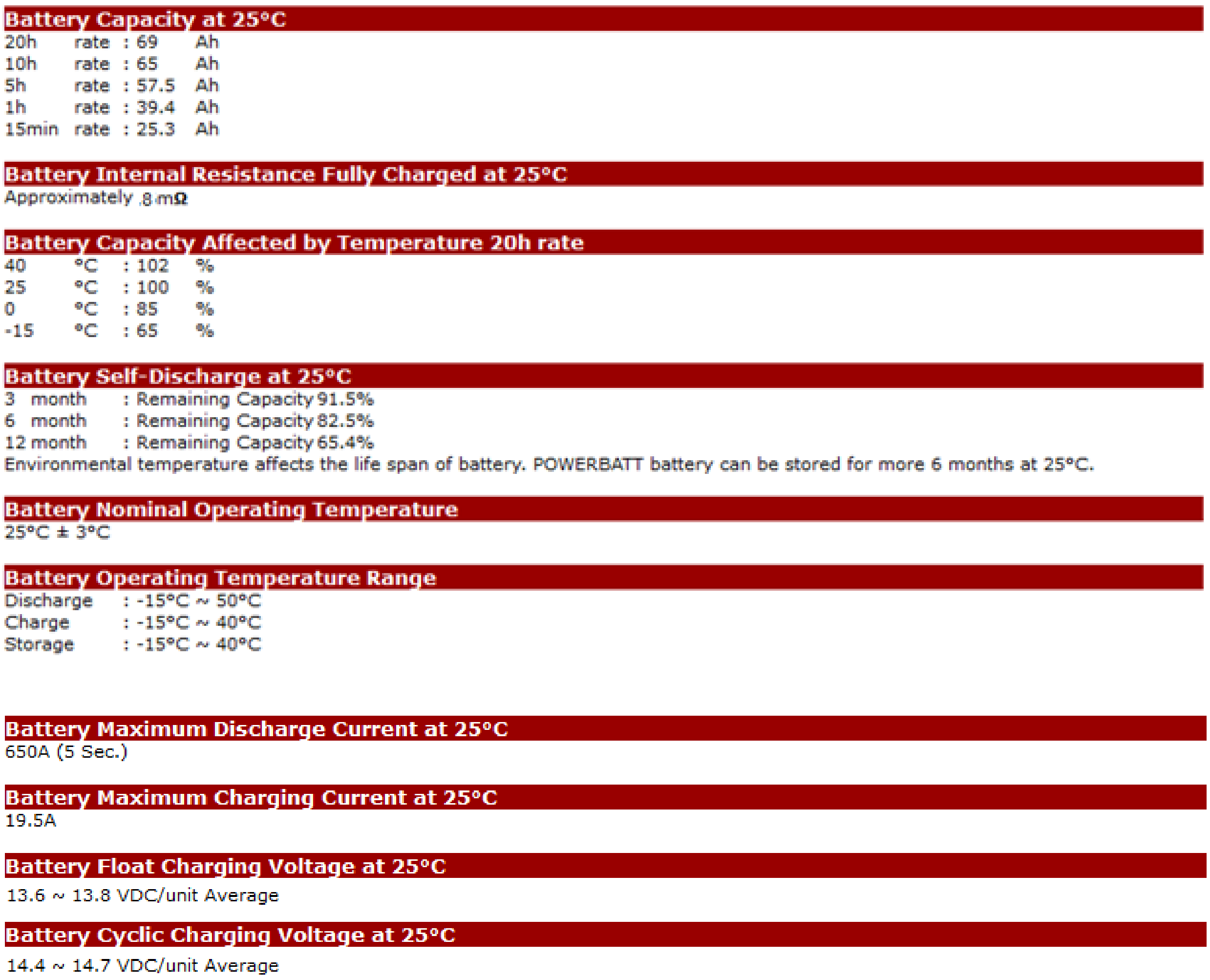
Appendices

Appendix A: Ritar 12V, 60AH, Sealed Lead Acid Battery specifications



Battery Capacity at 25°C

20h rate : 69 Ah
10h rate : 65 Ah
5h rate : 57.5 Ah
1h rate : 39.4 Ah
15min rate : 25.3 Ah

Battery Internal Resistance Fully Charged at 25°C

Approximately 8 mΩ

Battery Capacity Affected by Temperature 20h rate

40 °C : 102 %
25 °C : 100 %
0 °C : 85 %
-15 °C : 65 %

Battery Self-Discharge at 25°C

3 month : Remaining Capacity 91.5%
6 month : Remaining Capacity 82.5%
12 month : Remaining Capacity 65.4%
Environmental temperature affects the life span of battery. POWERBATT battery can be stored for more 6 months at 25°C.

Battery Nominal Operating Temperature

25°C ± 3°C

Battery Operating Temperature Range

Discharge : -15°C ~ 50°C
Charge : -15°C ~ 40°C
Storage : -15°C ~ 40°C

Battery Maximum Discharge Current at 25°C

650A (5 Sec.)

Battery Maximum Charging Current at 25°C

19.5A

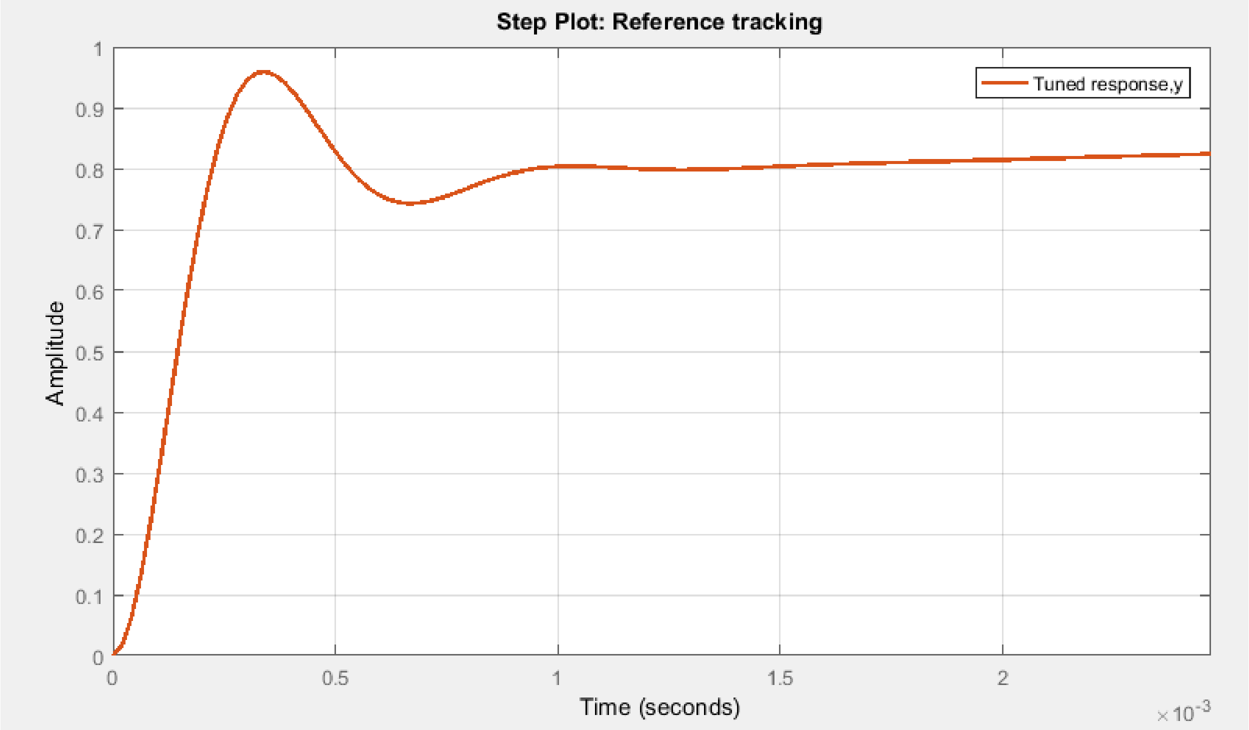
Battery Float Charging Voltage at 25°C

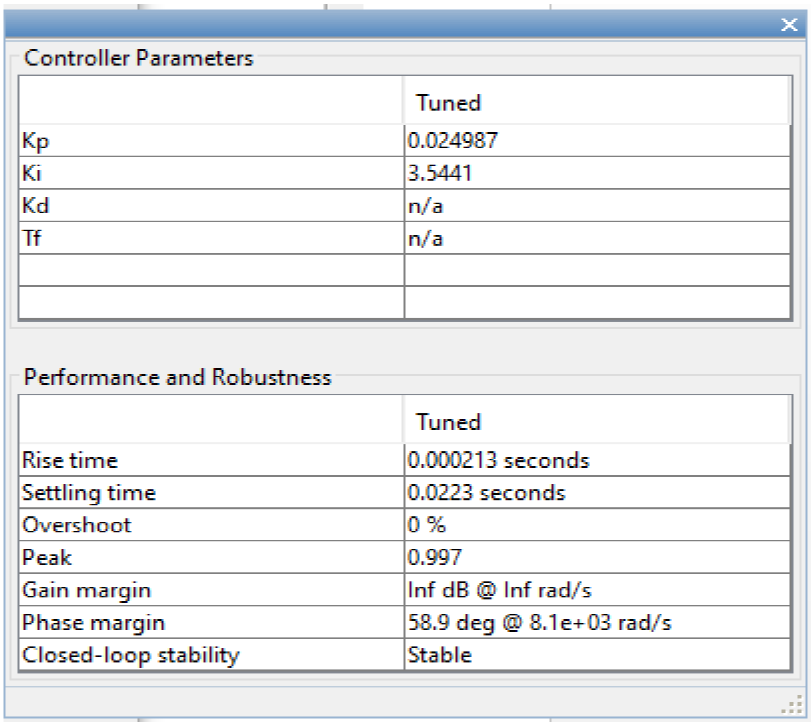
13.6 ~ 13.8 VDC/unit Average

Battery Cyclic Charging Voltage at 25°C

14.4 ~ 14.7 VDC/unit Average

Appendix B: Tuned response and parameters of the PI controller





Controller Parameters

	Tuned
Kp	0.024987
Ki	3.5441
Kd	n/a
Tf	n/a

Performance and Robustness

	Tuned
Rise time	0.000213 seconds
Settling time	0.0223 seconds
Overshoot	0 %
Peak	0.997
Gain margin	Inf dB @ Inf rad/s
Phase margin	58.9 deg @ 8.1e+03 rad/s
Closed-loop stability	Stable

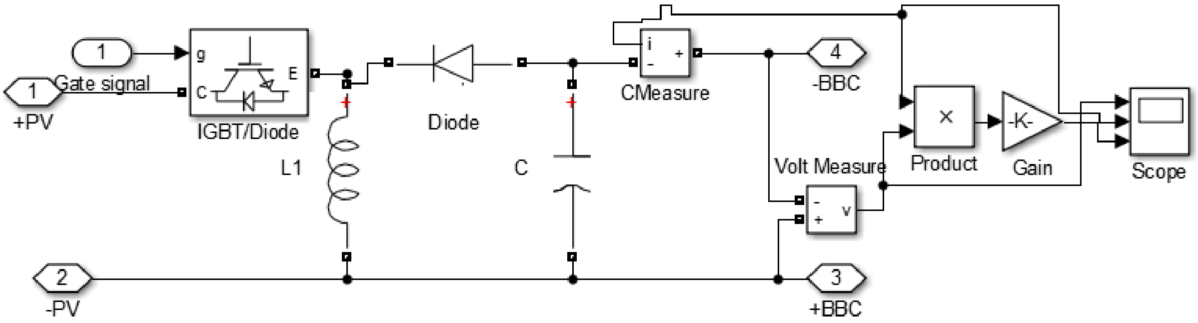
Appendix C: Maximum power point tracking algorithm (MPPT)

```
function D  = PandO(Param, Enabled, V, I)
% MPPT controller based on the Perturb & Observe algorithm.
% D output = Duty cycle of the boost converter (value between 0 and 1)
% Enabled input = 1 to enable the MPPT controller
% V input = PV array terminal voltage (V)
% I input = PV array current (A)
% Param input:
Dinit = Param(1);
Dmax = Param(2);
Dmin = Param(3);
deltaD = Param(4);
persistent Vold Pold Dold;
dataType = 'double';
if isempty(Vold)
    Vold=0;
    Pold=0;
    Dold=Dinit;
end
P= V*I;
dV= V - Vold;
dP= P - Pold;

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

if D >= Dmax || D<= Dmin
    D=Dold;
end
Dold=D;
Vold=V;
Pold=P;
return
```

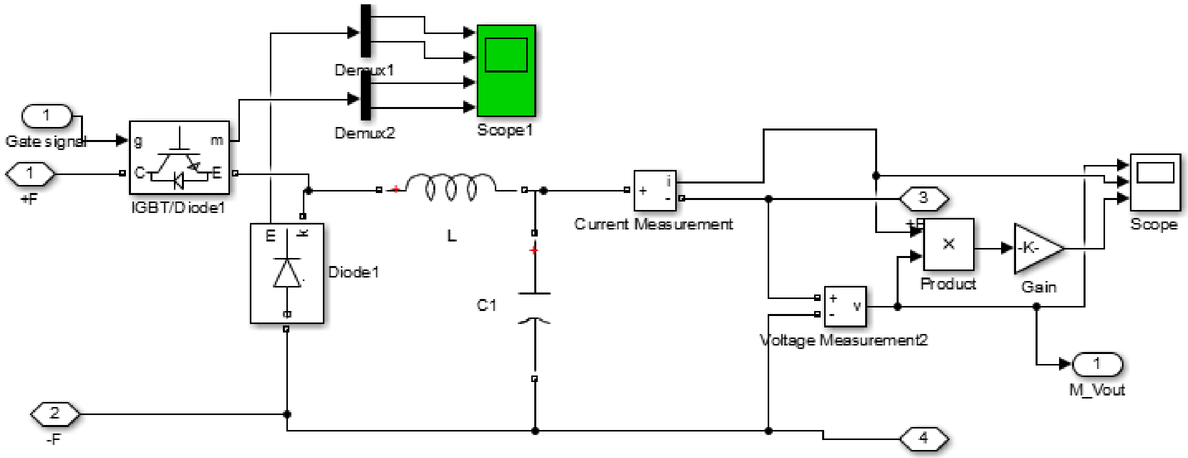
Appendix D: Control system algorithm for battery energy storage system

```
function Y = CS(Enabled,PV1,PL, SoCBatt)
Y = 0;
if PV1 ~= 0 && Enabled ~=0
if PV1 > PL
if SoCBatt < 0.95
Y = 1;%charging battery
else
Y = 3; %connect load
end
end
else
if SoCBatt > 0.3
Y = 2;% discharging battery
else
Y = 4;%disconnect load
end
end
if PV1 == PL || Enabled==0
Y = 0;
end
return
```

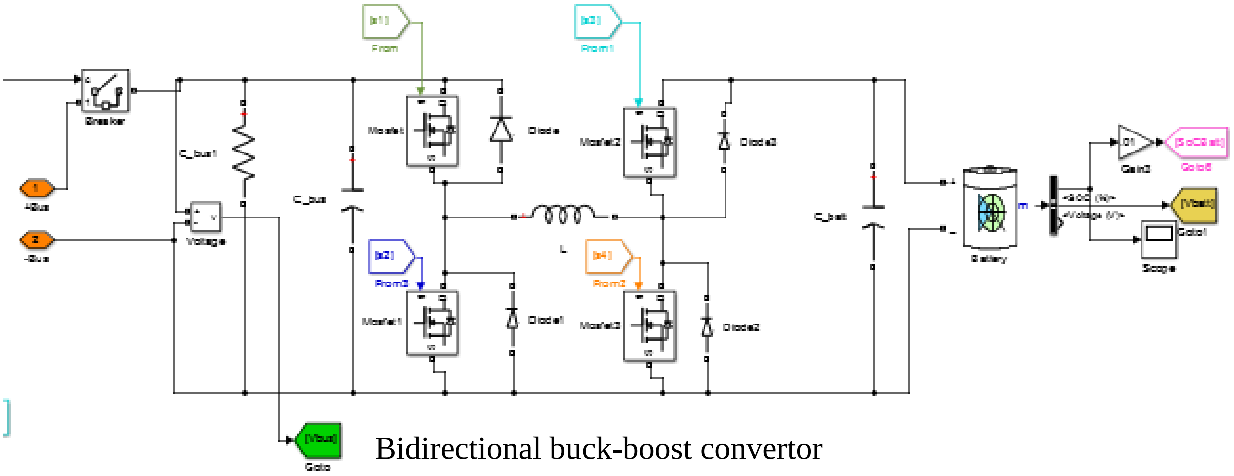
Appendix E: Detail circuits of subsystem of buck-boost convertor, buck convertor, bidirectional buck boost convertor



Buck boost convertor



Buck Convertor



Bidirectional buck-boost convertor