Design and Evaluation of Solar Based DC Distribution over AC System for Data Center Efficiency and Reliability Improvement

Case Study: Debre Berhan University Data Center

By

Tesfaye Birara Sisay

A Thesis Submitted to School Electrical Engineering and Computing Electrical Power and Control Engineering Program in Partial Fulfillment of the Requirement of the degree of Master of Science in Electrical Power and Control Engineering

(Specialization in Electrical Power Engineering)

Office of Graduate Studies

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Adama, Ethiopia

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Approval Page

We, the undersigned, members of the Board of Examiners of the final open defense by Tesfaye Birara Sisay have read and evaluated his thesis entitled **"Design and Evaluation of Solar Based DC Distribution over AC System for Data Center Efficiency and Reliability Improvement"** and examined the candidate. This is, therefore, to certify that the thesis has been accepted in partial fulfillment of the requirement of the Degree of Master of Science in Electrical Power and Control (Electrical Power) Engineering.

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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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To: Electrical Power and Control Engineering department

Subject: Thesis Submission

This is to certify that the thesis entitled **“Design and Evaluation of Solar Based DC Distribution over AC System for Data Center Efficiency and Reliability Improvement”** has submitted in partial fulfillment of the requirements for the degree of Masters of Science in Electrical Power and Control (Electrical Power) Engineering, has been carried out by Tesfaye Birara Sisay with Id. No PGR/18244/11, under my supervision. Therefore, I recommend that the student has fulfilled the requirements and hence hereby he can submit the thesis to the department.

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Advisor Name Signature Date

Dedication

This thesis is dedicated for those addicted and lost their expensive life abroad this planet because of the pandemic disease called COVID-19 which changes the common activity of the world.

Acknowledgement

First and foremost, I would like to express my sincere gratitude to my advisor, Dr. Tefera T. Yetayew, who has supported me throughout my thesis with his patience, motivation and immense knowledge. His guidance helped me in all the time of research and writing of this thesis. Dr. Tefera gave many constructive suggestions and his instructions paved the way to this thesis.

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Abstract

Recently, DC distribution system have many advantages over an AC distribution system. It offers higher efficiency and reliability at an improved power quality. Since the power is distributed in DC, there is no reactive power or skin effect in the system and it does not require any synchronization. Telecommunication systems and data centers are among the few surviving examples of DC distribution systems. Data centers are very fast growing structures with significant contribution to the world's energy consumption. A data center is a multipurpose internet based center which needs to perform different tasks without any perturbation of electric power. A data center's critical and sensitive load consists of IT equipment's such as servers, switches storage devices and UPS systems that are typically DC-based loads. Thus, this study leads to push on the design of DC distribution system for data center power distribution architecture to improve the efficiency and reliability of the system. To do this, Debre Berhan University data center is selected for reliability and efficiency evaluation of both AC and DC distribution system architecture. The study is based on two power distribution cases for selected data center electrical power architecture. One is the existing AC power distribution layout of the selected case area which gets supply from Ethiopian electric utility (EEU) with a nearby diesel generator as a backup power supply system in a case of power outage from the utility system. Another case is the proposed data center power distribution model with an off grid solar powered 380 V DC distribution system. Results show that an AC distribution system have an average efficiency of 72.96% while a proposed DC distribution system have an average efficiency of 82.63%. From this it shows that, a DC power distribution system is 9.67% efficient than AC power distribution architecture of a selected data center. The reliability comparison of both AC and DC powering option for power distribution in data centers IT load is also considered and results show that 380V DC distribution system is more reliable than existing AC distribution system with a relative lower failure rate. The simulation analysis was done in both Powertechnic's Analyst tool and MATLAB.

Key Words: - *Data center, IT load, AC distribution, DC distribution, Efficiency, Reliability.*

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Acronyms

Abbreviations	Description
AC	Alternating Current
ALCC	Annual Life Cycle Cost
ATS	Automatic Transfer Switch
CRAC	Computer Room Air Conditioner
CSI	Current Source Invertor
DC	Direct Current
DCCE	Data Center Computer Effectiveness
DCIE	Data Center Infrastructure Efficiency
EEU	Ethiopian Electric Utility
ERE	Energy Reuse Effectiveness
ETSI	European Telecommunications Standards Institute
FBI	Federal Bureau of Investigation
FEMA	Federal Emergency Management Agency
HV	High Voltage
IGBT	Insulated Gate Bipolar Transistor
IT	Information Technology
KW	Kilo Watt
LV	Low Voltage
LCC	Life Cycle Cost
MATLAB	Matrix Laboratory
MOSFET	Metallic Oxide Semiconductor Field Effect Transistor
MPPT	Maximum Power Point Tracker
MPW	Maintenance Present Worth
MTBF	Mean Time Between Failure
MTTR	Mean Time to Repair
MV	Medium Voltage
NASA	National Aeronautics and Space Administration
PSU	Power Supply Unit

PV	Photo Voltaic
PW	Present Worth
PWM	Pulse Width Modulation
PDU	Power Distribution Unit
PSU	Power Supply Unit
PUE	Power Usage Effectiveness
RBD	Reliability Block Diagram
TTF	Time to Failure
TTR	Time to Repair
USEPA	United States Energy and Power Authority
VSI	Voltage Source Invertor
WUE	Water Usage Effectiveness

CHAPTER - ONE

1. INTRODUCTION

1.1 Background

Recently, DC distribution system has many advantages over an AC distribution system. It offers higher efficiency and reliability at an improved power quality. It has a reduced installation costs as it requires fewer power conversion stages, less copper, and smaller floor space. DC distribution enables simpler integration of renewable energy sources and energy storage systems. Since the power is distributed in DC, there is no reactive power or skin effect in the system and it does not require any synchronization. Telecommunication systems and data centers are among the few surviving examples of DC distribution systems [1]. Data centers are very fast growing structures with significant contribution to the world's energy consumption. The main source of electricity for a data center is usually the grid connection which is provided by utility companies, although there are some exceptions like Apple's data centers which claim to use 100% renewable energy [2].

Now a day, the renewable energy sources such as solar PV, wind, geothermal, biomass energy and other sources of energy leads to replace the dependency of electricity from utility system. Power converters like DC-DC, DC-AC, AC-AC and AC-DC are also more applicable to change the voltage type and level from one state to another. These converters are now more applicable for DC distribution systems [2]

A data center is a multipurpose internet based center which needs to perform different tasks without any perturbation of electric power. A data center's critical and sensitive load comprises of IT equipment's such as servers, switches storage devices and UPS systems that are typically DC-based loads. Thus, this study leads to push on the design of DC distribution for data center power distribution architecture to improve the efficiency and reliability of the system. To do this, Debre Berhan University data center is selected for reliability and efficiency evaluation of AC and DC distribution system by properly designing an off grid solar power with a backup diesel generator to supply the data center loads to replace utility power supply.

Debre Berhan University is one of thirteen new universities which were established in 1999 E.C by the Ethiopian government. It is located in Amhara region north showa zone in the town of Debre Berhan. The university gets electric power supply from Ethiopian electric power industry at a nearby substation through 15 kV distribution line. Debre Berhan university data center is one of the large loads of the university which is very sensitive to the power interruption in the utility side. In most cases the power is interrupted due to different faults at the feeder lines of the substation as shown in the appendix which feeds the university loads leads to fail the data center power supply. System failure is the problem of data center power reliability. High reliability requirement of a data center can be achieved by appropriate design of the data center electric power distribution architecture. Use of more than one main supplies, alternative energy sources such as solar and wind and stand-by diesel generators increases the power availability [3].

The reasons for low data center efficiency is due to many cascaded power conversion stages and low efficiency of each converter. Furthermore, all power dissipation is basically heat which requires additional power to run cooling system for removal of excess heat. This further lowers the overall efficiency. In order to attain high overall efficiency, all the power conversion stages in the power distribution system should have the highest possible efficiency. Hence, implementation of a DC distribution system instead of AC distribution system results in elimination of a number of conversion stages, thereby reducing the distribution losses resulting in efficient distribution system [3].

1.2 Statement of the Problem

Debre Berhan University data center is one which consumes electric power to perform different tasks like access control, security camera, video conferences, Wi-Fi, Ethernet and others. To perform the above tasks, efficient and reliable power without interruption is a critical issue. The main source of electric supply for this data center is from Ethiopian Electric Utility (EEU). Power in the utility side is mostly interrupted by the cause of earth fault, short circuit fault and over voltage leads to interrupt datacenter power supply. The data center power distribution system is also AC type and has a number of conversion stages inside the system which leads to in efficient system operation. It is because every conversion wastes energy and produces heat. Considering the above, in this thesis work, the comparison of efficiency and reliability analysis in both AC and

DC distribution system has carried out. This was done by using the existing data center power distribution system (AC) and by designing an off grid solar powered DC distribution system.

1.3 Objectives

1.3.1 General Objectives

The main objective of this study is to improve efficiency and reliability of Debre Berhan University data center power distribution by designing solar powered DC distribution system and comparing it with existing system.

1.3.2 Specific Objectives

The following are the specific objectives to complete the study.

- To design an off grid solar power to supply the loads in the data center
- To design DC distribution system in the data center power load architecture
- To develop a mathematical model for data center power distribution components in AC and DC distribution systems to determine efficiency for the selected case area
- To compare efficiency of data center power distribution for AC and DC distribution case
- To compare reliability of data center power distribution for AC and DC distribution case

1.4 Significance of the Study

The DC distribution system is providing technical and economic benefits when directly connected to DC loads. This study will helps to increase the efficiency and reliability of any data center. Generally this study will contribute the following advantages.

- Improves the efficiency of the data center.
- Improves the reliability of data center.
- Minimizes system complexity of a data center distribution system by reducing the number of convertors.

1.5 Scope of the Study

The scope of this thesis work is design of solar power to supply data center loads by appropriate model of DC distribution system to improve data center system reliability and efficiency. Analysis have been made on the comparison of system reliability and efficiency of the designed DC distribution with the existing distribution system architecture. All stated objectives above is designed and simulated using MATLAB simulation software and a reliability analysis software called Powertechnic's Analyst tool.

1.6 Thesis Outline

This paper is organized as follows:

Chapter one is an introduction, this chapter contains background, problem statement and objectives of the study. It also contains the scope and limitations of this study.

Chapter two provides the literature review. Under this chapter related papers are reviewed and theoretical knowledge of topics used in this thesis are clearly explained.

Chapter three is methodology, in this chapter a necessary data required for this study will be described. All mathematical equations and procedures required throughout this study is also considered by this chapter.

Chapter Four presents system design. It is based on applying renewable energy to data center power supply systems. In this study case a standalone solar power system is considered and all requirements of solar system design will be calculated.

Chapter five presents the result and discussions. This chapter will present the efficiency and reliability analyses of AC and 380V DC power distribution system of the selected data center. The efficiency analysis will be done using MATLAB simulation software and the results for reliability analyses of both AC and DC distribution system model also will be performed using a software package called Powertechnic Analyst software. Lastly,

Chapter six discusses the conclusion, recommendation and future works related to this study.

CHAPTER - TWO

2. THEORETICAL BACKGROUND AND LITERATURE REVIEW

2.1 Literature Review

In this section, previous work done on data center power distribution, efficiency and reliability is reviewed.

2.1.1 Previous Work on Data Center Efficiency and Reliability

S. B. Levente J. Klein, Hans-Dieter Wehle, Stephan Barabasi, Hendrik F. Hamann, [4] studies on Sustainable Data Centers Powered by Renewable Energy. They presented different methods to increase the operational performance of a data center. One of the methods are integration of renewable energy sources in to a system. Two possible connections of the renewable energy in the power distribution of data center are presented (1) into the PDU or UPS systems and (2) directly to the ATS. The study conclude that the first case is more desirable as it will maximize the contribution of the renewable energy integration by eliminating the losses associated with AC/DC conversion. But this study is considering only integrating renewable energy in to the system and lacks to describe the reduction of losses in the system. The types of loads and its power distribution architecture of a data center is also not clarified. In this study, by considering the data center load types, a better distribution path for data center power distribution architecture would be proposed.

In 2013, Kristopher Jones [5] studied AC versus DC Power Distribution in the Data Center. The benefits of using DC power distribution in data centers has been more discussed. This paper discusses on how DC system can be an efficient, reliable, and cost effective due to low maintenance costs as compared with AC. In theoretical point of view, typically the study is focused on 5 different power distribution concepts that are either in use or being proposed today such as 480/120VAC distribution, 415/240VAC distribution, 380V DC distribution, 240VDC distribution, 48V DC distribution. Safety of DC supply system in terms of electric shock, electric arc flash and equipment concerns has been compared with conventional AC system. AC and DC architectures also has been compared on their ability to incorporate renewable energy sources such as solar and wind. As seen from the above, among the three standard voltage of DC distribution benefits, it did not explain which voltage standard is more preferred. Thus, this study will be based on 380V dc distribution due to many advantages for data center efficiency and reliability improvement.

Robert Arno et. Al, Addam Friedl PE, Peter Gross PE and Robert Schuerger PE [6] in 2010 compared the reliability of an example data center complying with different tier classification as defined by the Uptime Institute. Reliability block diagram (RBD) method was used to calculate the reliability of the system. The study quantify Tier IV data center has better reliability and compare with lower tiers. Also, the availability and the reliability metrics such as Mean time to failure (MTBF), Mean time to repair (MTTR) have improved values as the redundancy is increased in Tier IV data centers. This paper shows that tier IV with 2(N+1) configuration is better than tier IV with 2N configuration. This study will use better comparison method called Monte Carlo simulation to overcome the problem with RBD for showing DC data centers can achieve higher reliability than the existing AC data centers. The paper lacks to consider the reliability of lower tier configurations such as Tier I, II, and III. But this study will also analyses the reliability of Tier II configuration.

2.2 Theoretical Background

In this section all theories used by this thesis has been explained. First it starts about data center and its topology, tier classification, power distribution system for data center and components of a data center. Following it, renewable energy source mainly solar power generation mechanism is explained. Finally the basics of power electronics converters are described at the end.

2.2.1 Data Center Definition

The term “data center” means differently to different people. Some of the names used include data center, data hall, data farm, data warehouse, computer room, server room, and so on. The U.S. Environment Protection Agency defines a data center as “Primarily electronic equipment used for data processing (servers), data storage (storage equipment), and communications (network equipment). Collectively, this equipment processes, stores, and transmits digital information.” Data centers are involved in every aspect of life running Google, Amazon, eBay, Facebook, FEMA, FBI, NASA, Twitter, Gmail, Yahoo, Zillow, etc. This A–Z list reflects the “basic needs” of food, clothing, shelter, transportation, health care, and social activities that cover the relationships among individuals within a society. A data center could consume electrical power from KW to over 500 MW depending on size and purpose. All data centers serve one purpose, and that is to process information [7].

Generally for this study, in addition to above data center is considered a centralized building that holds servers, cooling devices and power equipment's. Data centers are considered as one of the major electric power consumers today. A large number of servers requires more amount of electric power. An additional power is also required for cooling as the power consumed by the servers are mostly converted to heat.

2.2.2 Data Center Topologies

One of the major concerns of data centers is to ensure continuous energy supply to its load and to improve the energy efficiency [8]. As servers in data center runs applications for flow of information and data to and from different parts of the world, continuous supply of power to the server load and supporting infrastructure (cooling and lighting loads) is needed at all times. Nowadays, there are different topologies used in data center's power distribution system. Based on the reliability and availability of the power distribution topologies and type and size of a data center, an appropriate powering option is chosen.

2.2.2.1 Tier Classifications

Uptime Institute standardized the Tier classification system for data centers as a means to evaluate data center infrastructure in terms of their availability. The Uptime Institute has defined four Tier system topologies for describing the availability as shown in figure 2.1 [8]. These are Tier I, Tier II Tier III and Tier IV. Each tier has a specific function and its appropriate criteria for power, cooling, maintenance, and capability to withstand a fault. Tiers are progressive, meaning each Tier incorporates the requirements of all the lower Tiers.

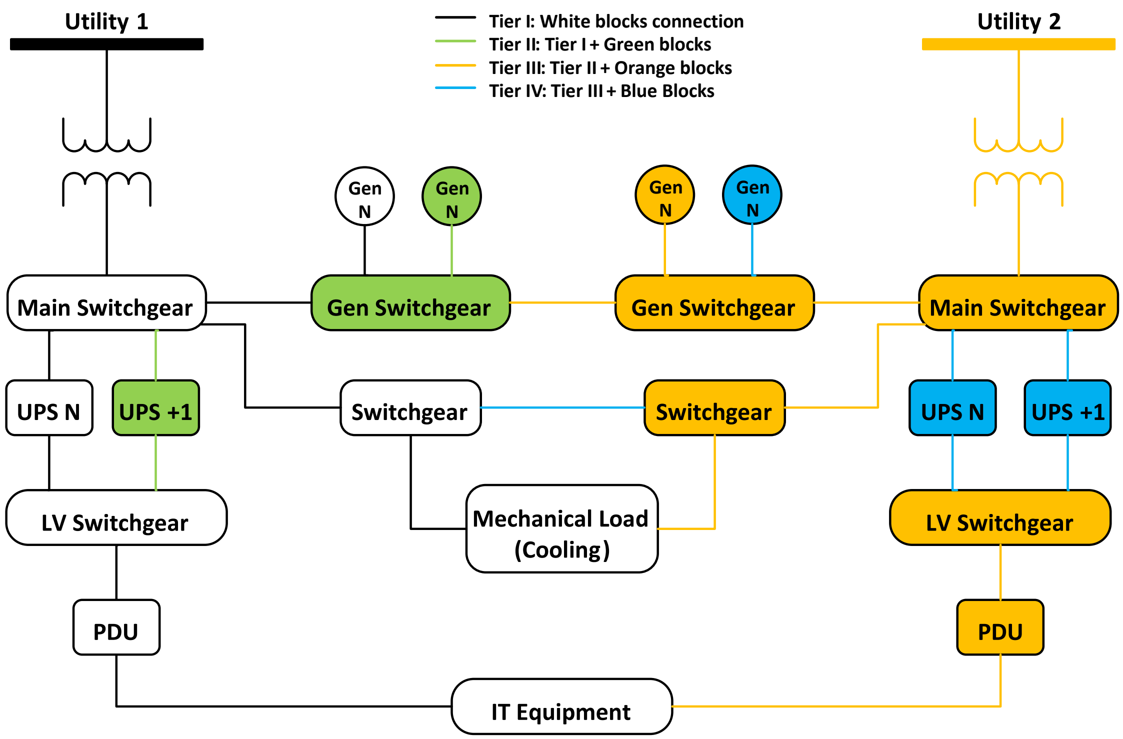


Figure 2.1. Topologies for different tier systems [9]

It can be seen in figure 2.1 that the difference between Tier I and Tier II is the number of generator and UPS. In Tier II, additional generator and UPS systems provide redundancy in the power supply system for most critical components. However, the most significant difference between Tier II and Tier III configurations is the number of power delivery path. An additional (passive) power delivery path from a different substation provides parallel power support for critical data center loads in case of power failure in the primary power delivery path. As there is no requirement to install UPS in the passive path in Tier III solutions, the system is vulnerable to the utility conditions. Tier IV provides a complete redundant system by using two active power delivery paths. Both power delivery paths simultaneously supply power to the load. Both power paths consists of N+1 UPS and generator sets. The comparison of different Tier systems is shown in Table 2.1.

Table 2.1. Comparison of Tier systems [9]

	Tier I	Tier II	Tier III	Tier IV
Distribution paths	Only one	Only one	1 active and 1 Alternative	2 simultaneously active
Concurrently maintainable	No	No	Yes	Yes
Fault tolerance	No	No	No	Yes
Annual IT downtime	28.8 hr	22 hr	1.6 hr	0.4 hr
Site Availability	99.67%	99.75%	99.98%	99.99 %

The data center in case of this study is a Tier II standard which has one active supply system with two sources, one from utility and the other is a diesel generator as a backup source. So throughout this study this Tier standard will be used.

2.2.3 Power Distribution in Data Center

Power distribution in data centers is responsible to transfer electrical power needed from source to the load. In real data centers, electrical energy is consumed by devices (loads) in a data center room. Such loads are called IT loads and supporting infrastructures. Supporting loads are data center loads other than IT loads because they help keeping the IT equipment properly housed, powered, cooled, and protected. Such equipment's are transformers, uninterruptible power supplies (UPS), fans, air conditioners, lighting and others and more explained in the next section. The breakdown of electrical energy in a data center room is indicated in figure 2.2.

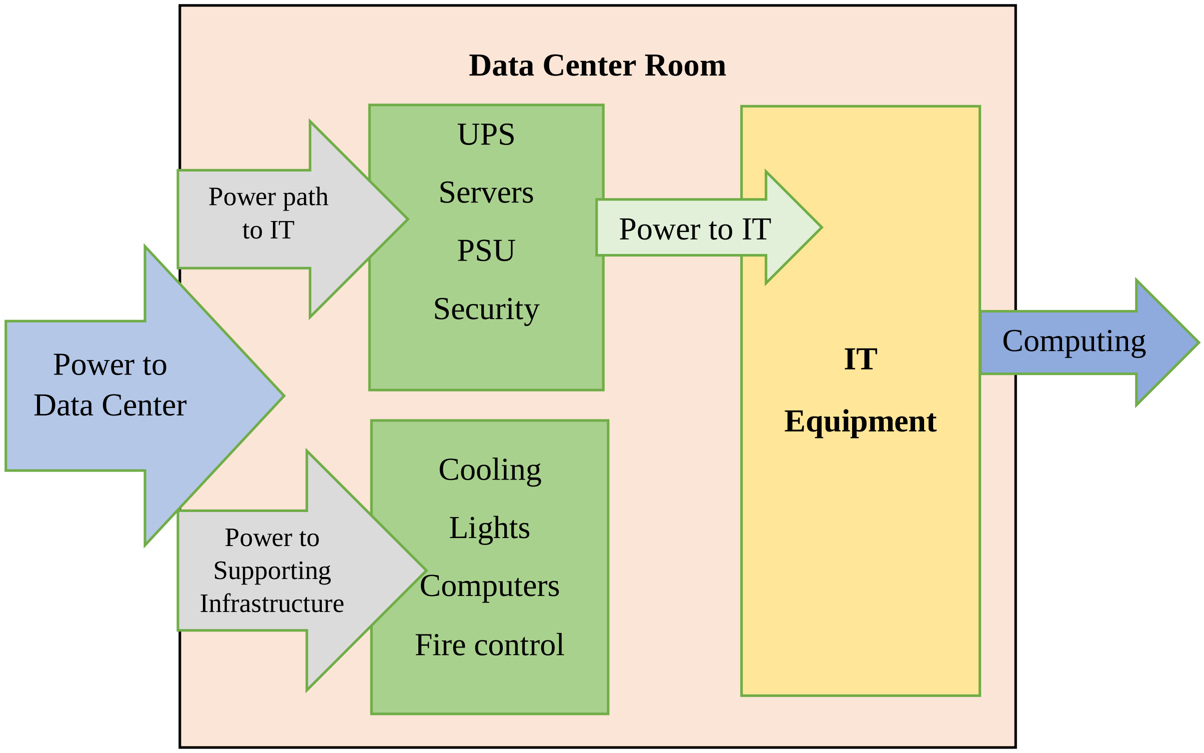


Figure 2.2. Data center power path breakdown.

2.2.4 AC and DC Power Distribution in Data Centers

The discussion of AC versus DC in the data center starts with efficiency. Since a data center draws a notable amount of power, a comparatively small increase in efficiency can lead to a reduction in operating costs. The advantages of DC data center over AC are energy efficiency, reliability, lower installation and maintenance costs, scalability, easier integration of renewable energy, utility rebates and credits, and safety" [10]. Data center components in an AC distribution system uses number of conversion stages that causes significant power loss in the distribution path, impacting the overall system efficiency. Reduction in the number of converters is possible by moving to a DC distribution system. Because there are fewer power conversions in a DC system, making it more efficient and reliable than an AC system. With fewer power conversions, there is also less heat to affect the electronic equipment. It is because every conversion wastes energy and produces heat.

2.2.5 Components of a Typical Data Center

The components of any data center can be broadly categorized into energy source, power distribution path and data center load. These components are described in the next section.

2.2.5.1 Energy Source

This provides electrical energy to data center for its operation. The primary energy source used is the grid supply. In addition to grid supply, data center uses backup energy sources during emergency situations like diesel generators. Renewable energy sources such as solar and wind are also used by data center from nearby plants. Mostly the primary source of energy for data centers is the utility (grid). However, powering data centers only by a single source will not allow them to have high reliability and availability. Hence, data centers have a backup energy sources to ensure uninterrupted supply of electrical power to its load. Diesel or natural gas generators are the most widely used for providing back up supply during utility outage. Diesel or natural gas generators cannot start instantly after there is a utility power outage. It takes some time to start before it can supply the load. This means there will be an interruption in power during the generator start-up time. Batteries or ultra-capacitors take up the load instantly when grid supply is absent, until generators turns on. This is known as uninterruptable power supply (UPS) will be explained in the next section.

To reduce the dependability of data centers in utility powered plants in coming years, the data center industry will face increasing pressure to find ways to integrate renewable energy sources. Interest in renewables is driven by two key requirements: environmental sustainability and energy savings [11]. A general distribution scheme of the power supply in a standard data center is indicated in figure 2.3 as follows. In this work, a standalone solar power is proposed and has been done to overcome the dependency of electricity from utility (EEU) system. The design, model and operational characteristics of solar PV system is explained more in the new chapter.

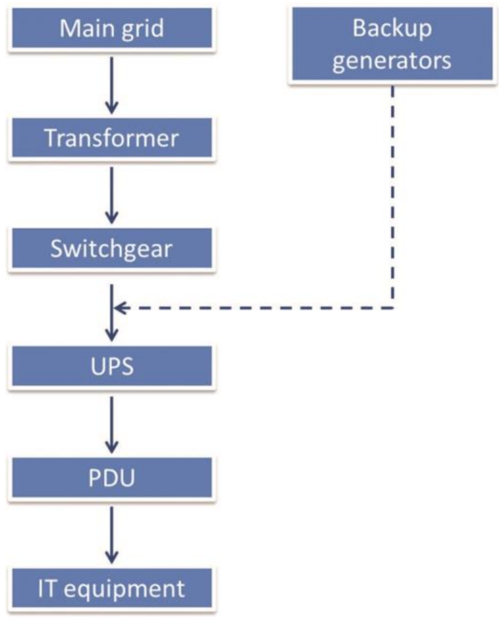


Figure 2.3. Scheme of the power supply in a standard data center [11].

2.2.5.2 Power Distribution Path

Electrical power distribution in data centers is responsible to transfer electrical power needed from source to the load. The power distribution path is further divided into distribution transformer, UPS and PSU, which are described below.

Distribution Transformer

Typically the utility supplies a medium voltage (MV) service to a dedicated data center. Then the MV is stepped down to low voltage (LV) by a MV/LV transformer located in the data center. LV power is distributed to the different electrical loads such as IT devices inside the racks, cooling system, lighting, etc by the electrical distribution equipment. Some small data centers are supplied from utility pad-mounted transformers at low voltage, while large multi-megawatt data centers can specify the operational voltage level to be high voltage (HV) or MV. The type and location of the HV/MV substation can be contracted by the data center owner and the utility [12].

In this study case of existing system, the distribution transformer steps down the three phase distribution voltage level (15 kV) from the grid (utility) to three phase 400V at the data center entrance.

Uninterruptible Power Supply (UPS)

An uninterruptible power supply (UPS) systems are typically installed in the electrical space or IT space of the data center to provide uninterrupted power to the critical equipment to a load when the input power source fails. Unlike standby generators, UPS will provide protection from input power interruptions, by supplying energy stored in batteries, super-capacitors, or flywheels without any interruption. The battery backup of most uninterruptible power sources is relatively short (only a few minutes), typically provide about 15 minutes at full load, which allows back-up generators to start in the event of a utility failure. The following devices are typically installed inside UPSs: these are input/output switches, bypass switches, static switches, power modules including the rectifiers and inverters, and their control and communication modules [12].

Data centers houses UPS to supply power to critical server loads during emergency without any power interruptions. The data center UPS uses double conversion method that means the incoming power is rectified by the inbuilt rectifier to a certain DC voltage charging the batteries connected to the DC bus, then the DC voltage is again converted in to supply level AC voltage. Then it can be supplied to the load connected at the output of UPS. These UPS are on-line, meaning the power flows through the rectifier charging the batteries and through the inverter at all times. Figure 2.4 shows the single line diagram of an on-line/double-conversion UPS.

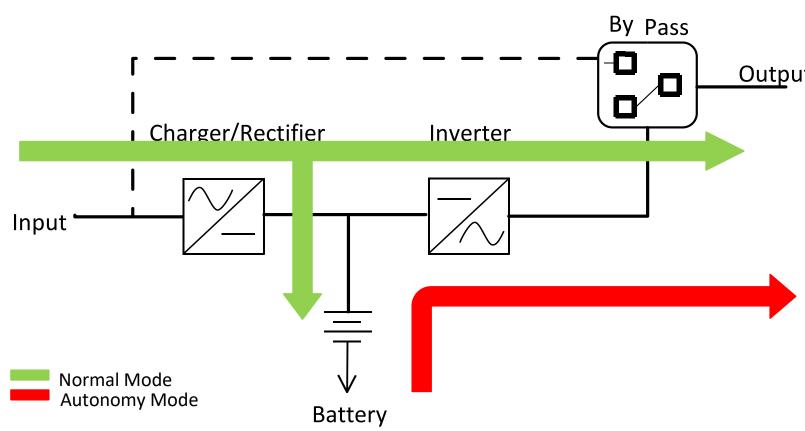


Figure 2.4. On-line double-conversion UPS [L-1].

As shown in Figure 2.4, the green arrow shows the normal operating mode of UPS. The mains supply charges the battery while supplying the load. The red arrow indicates autonomy mode of operation of UPS. In this mode, the mains supply is not available. The battery discharges and supplies the load. Furthermore, a static by-pass is also present in on-line double-conversion UPS. The load can be supplied directly from the mains supply as indicated by the dotted line in figure 2.4. This feature is useful when component(s) of UPS fails. The UPS can be by-passed and taken out for maintenance without disruption in the power supply to the load. This feature is also known as AC UPS which are having two conversion processes that results in reduced efficiency and reliability.

Another type of UPS is introduced which reduces the conversion stages inside it for efficient and reliable operation of the system. This is also known as DC UPS which is mostly applicable for DC distribution system case. The following figure shows a single line diagram of DC UPS.

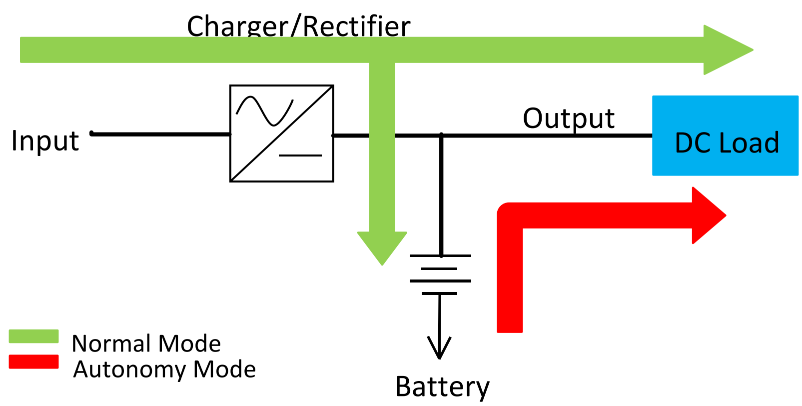


Figure 2.5. DC UPS [L-2]

Figure 2.5 shows a DC UPS indicating its modes of operations. Unlike double conversion AC UPS, a DC UPS has a single conversion feature as inverter is not present. For this, the input AC grid supply is converted to DC voltage and supplied directly to the DC load while charging the batteries. The DC load and batteries are both connected to the DC bus. Also, since the input is AC and the output is DC, static by-pass switch is absent in DC UPSs. DC UPSs are more efficient than AC UPS due to fewer conversion stages, and are more reliable due to lower number of converters in series in the power delivery path. In general depending on the differences described above, throughout this paper, the terms called AC UPS for AC distribution system and DC UPS for DC distribution system has to be used.

Power Supply Unit (PSU)

Another equipment called power supply unit (PSU) converts the supply AC to low-voltage regulated DC power for the internal components of a server or digital storage media. In a data centers server, PSU has an AC-DC converter converts AC input (220V) from AC UPS to DC (12V) before it can be supplied to components of IT load.

2.2.5.3 Data Center Loads

A data center load can be divided into two groups: IT load and supporting infrastructure. IT load comprises of sever load, switches, routers and soon. These are considered critical data center loads that consumes more of total data center load. IT load in data centers are housed in a separate room called server room or data center room where these devices are places in cabinets called server racks.

Other loads such as computer room air-conditioners (CRACs), lighting, and switchgears are known as supporting infrastructure for IT load. After IT load, CRACs has the highest power share in data centers. The function of CRAC is to cool the server room.

2.2.6 Data Center Supplied by Renewable Energy Sources

As described above, to reduce the dependability of data centers in utility powered plants in coming years, the data center industry is faced to integrate renewable energy sources. Among renewable energies, solar energy is the most widely used source of energy. The working principle of an off grid solar PV is described below.

2.2.6.1 Solar/PV Power Working Principle

The solar cells convert sunlight directly into the electricity. The photons are converted into electrons and generate direct current (DC). The principle behind any solar PV cell is to capture and absorb energy of the sun and use in seek of generating usable and beneficial energy. Any other solar PV system is a collection of solar PV cells which convert solar radiation into a useful form of energy (electricity). In the case when the solar system is out of the electric utility , it is vital and quite crucial to the PV system to store the harvested energy from the sun into a storing capacity or what is commonly known as “battery bank” since the electric energy generated by the PV solar panels can't generally be straightforwardly utilized. As the need from the load does not generally meet up or satisfy the solar array capacity, battery banks are largely utilized [13].

A battery backup system is installed between the solar panels and the inverter to store the electrical energy during day time and use it during the night time when sun is not available. Batteries also act as a device to cope up with the intermittent nature of the solar energy. The inverter converts the DC power into AC power. The PV setup is shown in figure 2.6.

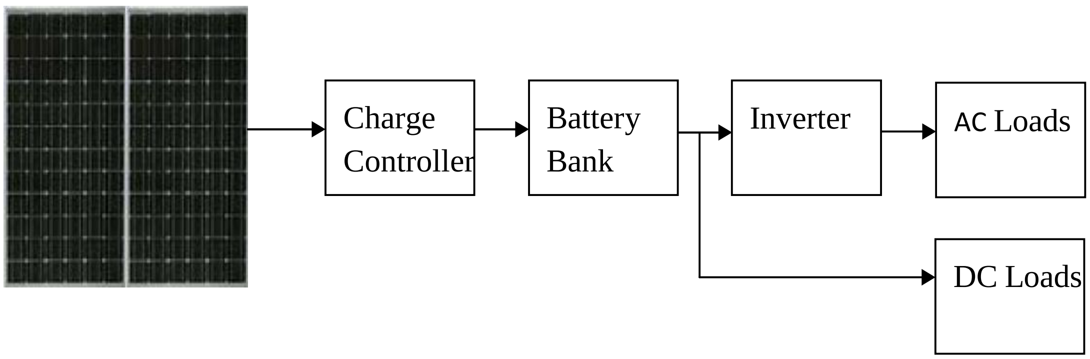


Figure 2.6. Standalone solar system.

A solar PV system/array consists of a large number of PV modules, which in turn is made up of semiconductor device known as solar cell or PV cell that converts sunlight into direct current electricity. Each cell is made from one or two layers of semi-conducting materials, usually Silicon. Power generated from PV panel is not linear since it depends upon the operating voltage. The maximum power point is at the knee of the I-V curve, as shown in figure 2.7. Let I_m and V_m denote the cell current and cell voltage at maximum power point, P_m, then the maximum power can be calculated as the product of I_m and V_m. I_{SC} is the short circuit current through the solar cell when the terminals of the PV module is short-circuited, and V_{OC} is open circuit voltage that is the maximum output voltage achievable when no load is connected.

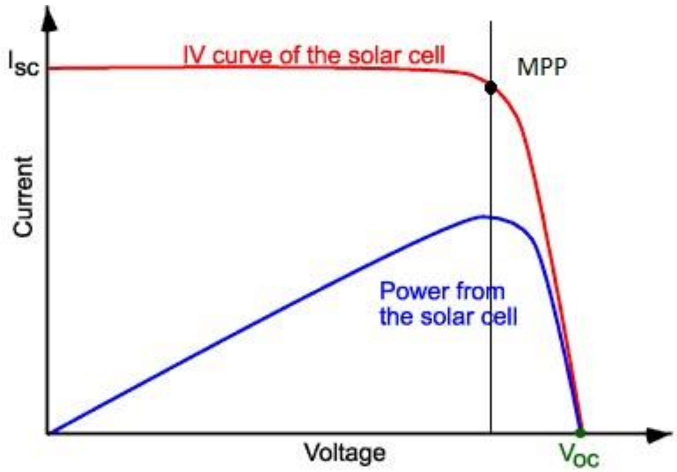


Figure 2.7. I-V Characteristic curve of solar cell

Figure 2.8 shows the I-V characteristic of PV cells differ under different solar irradiance levels. As it can be seen in figure 2.8, the short circuit current depends upon the irradiance and the temperature of cell as well. Most of the PV system employ maximum power point tracker (MPPT). MPPT tracks the optimum operating point for its operation, in this case, the point where the generation is maximum. The working principle of MPPT is it has a feedback system that senses the PV power output and changes the array output voltage until the output power reaches its maximum.

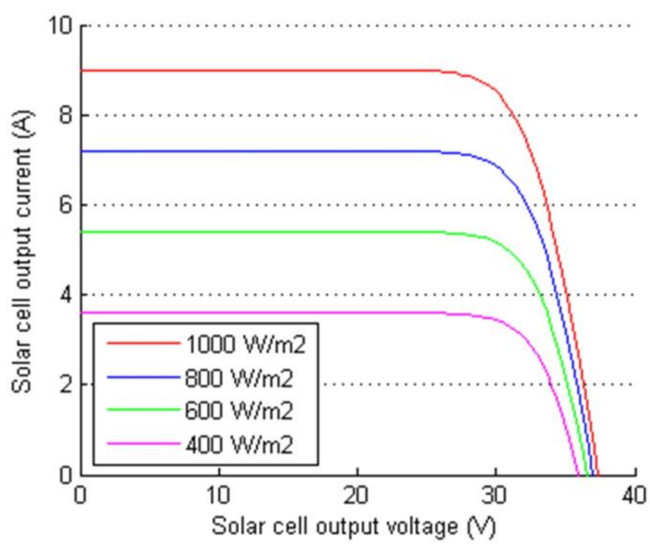


Figure 2.8. I-V curve of a PV module at different irradiance levels.

2.2.7 Basics of Power Electronics Converters

Power electronic converters are devices used to convert a power source into a voltage or current supply that is suitable for the load, as shown in figure 2.9. It involves the integration of power electronic devices and a controller. There are four types of power converters: AC-DC conversion, DC-DC conversion, DC-AC conversion and AC-AC conversion [14].

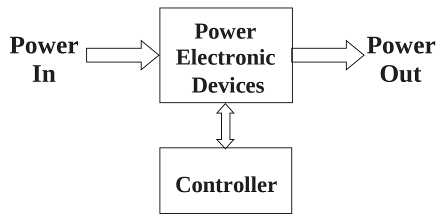


Figure 2.9. Power conversion process [14]

2.2.7.1 AC-DC Conversion

The conversion from AC to DC is often called rectification and the converter used is called a rectifier. For an ideal rectifier, it is expected that the output voltage is a pure DC signal without any ripples and the input current is in phase with the voltage and does not have harmonics. According to the power electronic devices adopted, rectifiers can be divided into uncontrolled rectifiers with diodes, phase-controlled rectifiers with thyristors and PWM-controlled rectifiers with IGBTs or MOSFETs.

2.2.7.2 DC-DC Conversion

A DC-DC converter is used to change the voltage level of a DC source from one to another. According to the relationship between the input and output voltages, a DC-DC converter can be designed to reduce the voltage level, to increase the voltage level, or both. The ratio between the output voltage and the input voltage is called the conversion ratio α. When it is lower than 1, the converter is called a buck converter; when it is higher than 1, the converter is called a boost converter; when it can be higher or lower than 1, the converter is called a buck-boost converter.

2.2.7.3 DC-AC Conversion

A DC-AC converter, also known as an inverter, generates an AC output from a DC source. There are different types of inverters. According to the type of the DC supply, an inverter is known as a current-source inverter (CSI) if the supply is a current source and a voltage-source inverter (VSI) if the supply is a voltage source. Typically, an inverter is a VSI if there is a large capacitor across the DC bus and is a CSI if there is a large inductor in series with the DC supply. According to the type of the inverter output, an inverter is called current-controlled if the output is controlled to be a current source and voltage-controlled if the output is controlled to be a voltage source. Hence, there are current-controlled VSIs and voltage-controlled VSIs, and there are also current-controlled CSIs and voltage-controlled CSIs.

The amplitude of the output of an inverter can be fixed or variable. Moreover, the frequency can be fixed or variable as well, depending on the applications. These can be easily achieved with pulse-width-modulation (PWM) techniques. Note that the main objective of PWM is to change a signal with possibly variable amplitude into a train of pulses with variable widths to drive the switches.

2.2.7.4 AC-AC Conversion

The AC-AC conversion can be performed indirectly via AC-DC-AC with the addition of a DC bus or directly without a DC bus. The indirect AC-AC conversion is basically the combination of AC-DC conversion and DC-AC conversion, as discussed in sections above.

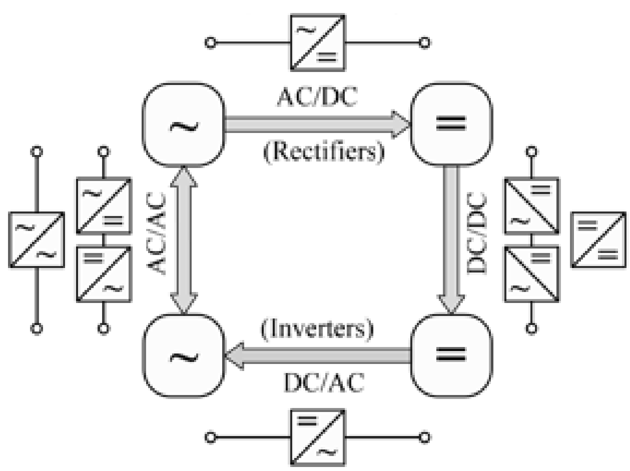


Figure 2.10 Basic types of power electronics converters [15]

CHAPTER - THREE

3. METHODOLOGY

In this chapter, a necessary collected data required for this study have been described and analyzed. The study is based on a data center which is found in Debre Berhan University and its load profile and solar radiation data has been collected. To supply all data center loads using solar energy, all procedures and mathematical equations of solar design/sizing are considered by this chapter. Next the electrical power distribution architecture of existing (AC) system and a proposed solar powered DC distribution would be explained. The preference of DC distribution over an AC distribution and the standard selection of DC voltage for distribution system is also described. In addition, the proposed distribution system could be compared with an existing AC power distribution system in terms of efficiency and reliability. Finally, the mathematical analysis and expressions of data center efficiency and reliability methods are explained.

3.1 Data Collection and Analysis

The data has been collected from Debre Berhan University data center**.** For this study, there are two data's which are necessarily required for system designing and modeling. The first is the data center daily load profile and the next is the solar irradiation data. Both are required for the design/size of solar energy to supply the data center loads. The load profile data has been collected by two ways, one by interviewing the office worker and another is by using the name plate of the equipment's. The solar irradiation data for the selected site were extracted from NASA. Each of the collected data is further described in the next section.

3.1.1.1 Data Center Load Profile

As explained in section 2.2.5 a data center consists both IT load and supporting infrastructures. IT load comprises of server load, switches, and routers and so on. It is a critical or sensitive load of a data center. Other loads such as computer room air-conditioners (CRACs), lighting, and switchgears are known as supporting infrastructure for IT load. Table 3.1 below shows the load profile data for selected study case area.

Table 3.1. Data center load profile

Load	Watts	H/day	Number	Watt – Hr
Air Conditioner	2500	24	1	60000
IT load	120	24	12	34560
Un interruptible Power Supply (UPS)	16000	0.0916	2	2931.2
Lighting	18	12	50	10800
Computer (Desktop)	90	8	4	2880
Security Camera	120	24	1	2880
----	-----	----	----	----
Total daily watt and Watt-Hr/day	**37,320Watt**			**114,051.2Wh/day**

Based on table 3.1, the total power consumption of the electrical service needed to support all the loads in data center are included. It consists of 12 racks for the IT critical loads and each rack contains 10 servers with peak power usage of 120W on the data nameplate. From the table above, estimated energy capacity at full load, is 114,051.2 Wh/day or 114.051 KWh/day.

3.1.2 Solar Resource Assessment of Selected Site

Debre Berhan area gets enough sun for standalone as well as grid-connected photovoltaic systems to operate well. The site location from NASA is shown in figure 3.1 below. Photovoltaic arrays are mainly affected by shading. A shadow of trees can significantly reduce the power output of solar module. Keep in mind that an area may be unshaded during one part of the day, but shaded at another part of the day. This is basically known by observing the site properly. Thus Debre Berhan university data center is installed in one sectional room of a large building and it is free from shading and also gets sun in all times of a day.

Figure 3.1. Debre Berhan University, N/Shewa, Ethiopia map

The area (Location) to be electrified is that Debre Berhan University data center with Latitude 9.65741 and Longitude 39.55071 which is extracted from NASA and has the following Monthly Averaged Radiation (kWh/m^2/day) is indicated in table 3.2.

Table 3.2. Monthly Averaged Radiation (kWh/m^2/day)

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
KWh/m^2/day	6.57	6.45	6.56	6.04	6.51	5.38	5.01	4.78	5.08	6.18	5.68	6.06

From the above table, the maximum average radiation is 6.57 kWh/m^2/day which is gained in January and minimum radiation is 4.78 kWh/m^2/day at August.

3.2 Standalone PV System Design Considerations

The stand-alone electricity generation systems using PV technology has come up as a major and favored way to harness the solar energy due to its multi-dimensional advantages such as energy independence, safety, security, lack of electric bills, easier and timely installation, long-term back-up in case of storage system and power whenever and wherever needed. The stand-alone solar PV system is also an ultimate, convenient and self-sufficient alternative to provide electricity without having a connection to utility grid [16]. The following technical considerations are very important for designing an optimal solar PV system for stand-alone application.

- Estimating electrical energy demand
- Sizing and specifying of photovoltaic module
- Sizing or specifying battery bank
- Sizing or specifying charge controller
- Sizing or specifying an inverter
- Sizing system wiring

The above considerations are important for a standalone solar photovoltaic system design. These all are explained in the following sections.

3.2.1 Estimation of Energy Demand

This is the fundamental step in designing a stand-alone solar PV system for a home or office or any other building to calculate the total energy demand on daily basis. For this purpose, the load requirement of each equipment is measured in watts and the time of use or operation of that appliance is considered in hours. Load and the running time vary from appliance to appliance [16]. The energy consumption of individual load in Wh (watt-hours) is calculated by multiplying the appliance's load power with its time of use and it is expressed in table 3.1.

3.2.2 Sizing and Specifying of Photovoltaic Module

The design method for PV array size is depend on estimated energy demand and the solar radiation. To calculate the size and number of PV modules needed for specific loads, the rated peak-watts produced by the chosen panel has to be required. Thus, the total size of solar panels or PV array against specific load demand is calculated as follows.

$$P_{pv} = \frac{E_{pv}}{G_{min}} \text{ x } 1000\text{w}/\text{m}^2 \qquad (3.1)$$

Where:

P_{pv} is the total power of PV array in watts

E_{pv} is the total energy required from PV array and

G_{min} is the minimum solar radiation of a month occurred in a year

Considering the temperature losses, battery efficiency and wiring losses, the energy for the PV (E_{pv}) is greater than the total energy demand that extracted from the load profile. This energy is expressed in equation 3.2 as follows.

$$E_{pv} = \frac{\text{Energy of the system}}{\text{Combined efficiencies}} \tag{3.2}$$

Hence, depending on the above equations, the total number of modules which are connected in parallel and series would be calculated.

3.2.3 Battery Sizing

To ensure the availability of energy at night and under cloudy conditions, the photovoltaic modules must store energy in some type of storage during the peak sunlight hours. The different types of rechargeable batteries are available in market but the most commonly used type is lead-acid because they are readily available, cost-effective, longevity and more suitable for stand-alone solar electric power systems. The capacity of batteries are expressed in ampere-hour (Ah). The various factors are considered during the selection and sizing of batteries or battery bank. These factors include the appliances total load, inverter size and efficiency, days of autonomy, discharge depth and the battery nominal voltage. However, among all factors, the factor of autonomy days is very important one. These days represents the number of cloudy days in a row that might occur and for which the batteries will need to supply energy to the load. Usually, 2 days is considered as a standard for number of autonomy days. Thus, the battery size or capacity should be increased to 1.5-3 times more to make it oversize rather than undersize [17]. The simplest relationship used to determine the size of batteries or battery bank for a certain load demand is as follows.

$$E_{bat} = \frac{E_t \text{ x days of autonomy}}{\text{DOD x } \eta_{out}} \text{ Wh/day} \tag{3.3}$$

Where:

E_{bat} is battery energy storage capacity

DOD is maximum permissible depth of discharge of the battery

η_{out} is the output efficiency of the battery. Which is η_{out} = battery efficiency (η_B) x inverter efficiency (η_{Inv})

Therefore, battery capacity in ampere - hour is given by

$$C_{bat} = \frac{E_{bat}}{V_{nominal}} \tag{3.4}$$

Where:

C_{bat} is battery ampere - hour capacity

$V_{nominal}$ is the nominal or system voltage which is selected depends on the design bus voltage.

Thus, depending on the above equations, the number of batteries which are connected in series and parallel would be calculated.

3.2.4 Sizing of the Battery Charge Controller

The battery charge controller is required to safely charge the batteries and to maintain longer lifetime for them. It has to be capable of carrying the short circuit current of the PV array and to maintain the DC bus voltage [18]. According to standard practice, the sizing of solar charge controller is to take the short-circuit current (I_{sc}) of the PV array and multiply it by a safety factor of 1.3. The rated load output of the charge controller needs to comply with the sum of all loads connected to the charge controller. The maximum array-to controller current can be estimated as:

$$I_{controller} = N_{parallel} \text{ x } I_{sc} \text{ x } 1.3 \tag{3.5}$$

Where

I_{sc} represents the size of solar charge controller in amperes.

$N_{parallel}$ is the number of parallel connected solar modules.

I_{sc} represents the short circuit current rating of selected PV unit

In general, the primary function of a battery charge controller in a standalone PV system is to maintain the battery at highest possible state of charge while protecting it from over charging by the array and from over discharge by the loads.

3.2.5 Inverter Sizing

The inverter is a device that is used to convert the DC power to an AC power. Some loads like supporting infrastructure loads are operated on AC power. While, the solar modules generates DC power that is stored in batteries. Therefore, an inverter of optimum size is used in between the batteries and AC loads to convert the stored DC power in batteries to AC power to run the AC loads. The used inverter must be able to handle the maximum expected power of AC loads. Therefore, it can be selected as 20% - 30% higher than the rated power of the total ac loads [18]. Thus, the size of inverter is mathematically;

$$P_{inv} = P_{ac\ load}\ x\ \ CF \tag{3.6}$$

Where:

P_{inv} represents the rating of inverter in watt.

CF represents the correction factor for safety whose value is 3 for motor loads and 1.25 for simple and non-motor loads.

$P_{ac\ load}$ represents the total ac electrical load in watt and calculated by summation of the rating $(W)_i$ of all the individual ac loads.

Usually, an inverter is chosen considering different parameters including cost, maintenance requirements, reliability, frequency, voltage regulation and efficiency.

3.2.6 Sizing of System Wiring

The size of cables is very important for stand-alone solar system as they are used to connect the different components of the PV system with each other and to the electrical load. In general, their size depends on the maximum current carrying capacity and should be sufficient in order to minimize the voltage drops and resistive losses. The size of the cable includes the length and cross-sectional area of the cable. The length of the cable is obtained by physically measuring the distance on site between the components of solar system. While, the cross-sectional area (A) of the cable is calculated mathematically as [19]:

$$A = \frac{\rho\ x\ l\ x\ I_{max}}{V_d} \tag{3.7}$$

Where:

ρ represents the resistivity of the conducting wire material in ohm-meters. For copper wire which is 1.724×10^{-8} Ωm,

l represents the length of cable.

V_d represents the maximum permissible voltage drop in cable.

I_{max} represents the maximum current carried by the cable.

For PV solar systems, the cable sizes are especially imperative for sections between: solar panels and batteries; batteries and inverter; inverter and load distribution board. The value of I_{max} will vary from section to section and depends upon the voltage and power rating of their section components [19].

A. Cable size between solar PV array and battery

The following steps can be followed to calculate the conductor size:

Step-1: Determine the maximum DC system voltage

In the DC side of the circuit, i.e. from the PV module side to the combiner box or to the inverter, calculate the maximum DC system voltage (shall not exceed the inverter maximum DC input voltage):

Step-2: Calculate the Maximum DC current

The maximum DC current is defined as 1.25 times the rated short-circuit current I_{sc} (module specification). Where 1.25 is a safety factor for continuous PV system current. For example, if a module had an I_{sc} of 7.5 amps, the maximum current would be $1.25 \times 7.5 = 9.4$ amps. If three strings of modules are connected in parallel, the PV output circuit of the combiner would have an I_{sc} of $3 \times 7.5 = 22.5$ amps. So the maximum current in this circuit would be $1.25 \times 22.5 = 28.125$ amps.

Step-3: Determine percentage cable loss acceptable

Generally, the cable length and the cross-sectional area are chosen in a way that voltage drop between any two sections is within the permissible voltage level. Normally, 2–4 % voltage drop is allowed to calculate the cable length and the cross-sectional area.

Step-4: Calculate the cable length and the cross-sectional area

Once the actual ampacity is found out, it is used to find out the length and size of the cable which is to be used. Alternatively, the cross-sectional area (A) of the cable is given by equation 3.7 above. Based on the above formula, the cross-sectional area (A) of the cable between PV modules to charge controller, battery to the inverter, and between the inverter to the load can be calculated.

B. The cable size between battery to load and inverter:

Considering the length of the cable (l) in meter and the allowable voltage drop in percent (usually less than 10%), the cross-sectional area is determined as follows [19].

The maximum current from battery at full load supply is given by:

$$I = \frac{\text{Inverter kVA}}{\eta_{inverter} \ \text{x} \ V_{system}} \tag{3.8}$$

Here, V_{system} is the minimum possible voltage of the battery. Applying the value of l, V_d, I and ρ in equation 3.7 the cross-sectional area of the cable can be calculated.

C. Cable size between inverter and load:

Assuming the maximum length of the cable for powering the load from the inverter and the allowable voltage drop, the maximum current on the phase is

$$I_{max} = \frac{\text{Inverter kVA}}{\sqrt{3} \ \text{x} \ V_{output}} \quad \text{(For three phase inverter)} \tag{3.9}$$

$$I_{max} = \frac{\text{Inverter KVA}}{V_{output}} \quad \text{(For single phase inverter)} \tag{3.10}$$

The maximum continuous current will be I = 1.25 x I_{max} and with a maximum allowable voltage drop (V_d) applying the values of l, V_d, I and ρ in equation 3.7, the cross-sectional area of the cable between inverter and load can be calculated.

3.3 Mathematical Modelling of Photovoltaic in Simulink

A cell is defined as the semiconductor device that converts sunlight into electricity. A PV module refers to a number of cells connected in series and in a PV array, modules are connected in series and in parallel [20]. In this topic the current-voltage and power-voltage relationship for the single-diode model of a PV cell has to be presented. The single-diode model has been derived from the well-known equivalent circuit for a single photovoltaic (PV) cell.

Development of current-voltage and power-voltage relationship was based on a five-parameter model, which requires data typically available from the manufacturer. Manufacturers typically provide the following operational data on PV panels: the open-circuit voltage (V_{oc}); the short-circuit current (I_{sc}); the maximum power point current (I_{mp}) and voltage (V_{mp}); and the temperature coefficients of open-circuit voltage and short-circuit current. This operational data is required to solve the improved five parameter determination method using MATLAB/Simulink. The model accurately predicts voltage-current (I-V) curves and power-voltage (P-V) curves.

3.3.1 Single Diode Model

The PV module is the interface which converts light into electricity directly. The various factors like temperature, solar irradiance, series and shunt resistance influence the output characteristics of PV cell. The output can be voltage, current, or power. The P-V and I-V characteristics are being plotted by varying the given parameters.

Typically a solar cell can be modeled by a current source and an inverted diode connected in parallel to it. It has its own series and parallel resistance. Series resistance is due to the flow of electrons from N to P junction and parallel resistance is due to the leakage current [21].

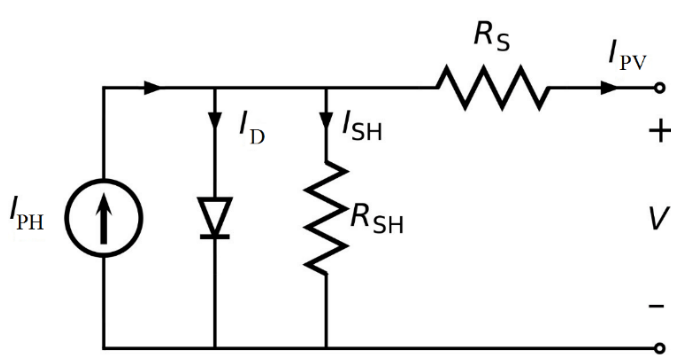


Figure. 3.2. Single diode mathematical model of a PV cell [21]

The equivalent circuit of general model which consist of a photo current (I_{PH}) a diode with diode current (I_D), a parallel resistor expressing a leakage current (I_{SH}) and a series resistor describing an internal resistance to the current flow (I_{PV}), is shown in Figure 3.2.

According to Kirchoff's current law,

$$I_{pv} = I_{PH} - I_D - I_{SH} \tag{3.11}$$

Where I_{PH} is the photo current or irradiance current, which is generated when the cell is exposed to sunlight. I_{PH} varies linearly with solar irradiance for a certain cell temperature. I_D is the current flowing through the anti-parallel diode, which induces the non-linear characteristics of the solar cell. I_{SH} is shunt current due to the shunt resistor R_{SH} branch. Substituting relevant expressions for I_D and I_{SH}, we get the following parameters.

Photo current

$$I_{PH} = \frac{[I_{SH} + ki \text{ x } (T - 298)] \text{ x } G}{1000} \quad . \tag{3.12}$$

Saturation current

$$I_0 = I_{PH} \text{ x } \frac{\left(T/T_n\right)^3 \text{ x } \exp[q \text{ x } E_{g0} \text{ x } \left((1/T_n) - (1/T)\right)]}{n \text{ x } K} \tag{3.13}$$

Reverse saturation current

$$I_{rs} = \frac{I_{SH}}{\exp[(q \text{ x } V_{oc})/(n \text{ x } Ns \text{ x } K \text{ x } T)] - 1} \tag{3.14}$$

Current through shunt resistor

$$I_{SH} = \frac{V + (I_{pv} \text{ x } R_s)}{R_{SH}} \tag{3.15}$$

Output (PV) current

$$I_{PV} = I_{PH} - I_0 \text{ x } [\exp[\frac{(q \text{ x } (V + (I_{PV} \text{ x } R_S)))}{n \text{ x } Ns \text{ x } K \text{ x } T}] - 1] - I_{SH} \tag{3.16}$$

Where:

T_n is the reference temperature = 298 K

T is the module operating temperature in Kelvin

I_{PH} is the light generated current in a PV module (A)

I_0 is the PV module saturation current (A)

K is Boltzman constant = 1.3805×10^{-23} J/K

q is Electron charge = 1.6×10^{-19} C

R_S is the series resistance of a PV module

I_{SH} is the PV module short-circuit current (A)

K_i is the short-circuit current temperature co-efficient at 25 ^{0}C and 1000W/m^2 = 0.0032

E_{go} is the band gap for silicon = 1.1 eV

Ns is the number of cells connected in series

I_{rs} is the cells reverse saturation current at a reference temperature and a solar radiation

n is the diode ideality constant which is 1.3 for polysaccharide type of module.

All the above parameters are considered for a single solar cell model.

3.4 Design Procedure of Solar Powered System

Proceed to the data collection and design consideration of solar PV module, a solar powered DC distribution system is proposed for data center load. The proposed system is designed based on Tier standard and compared with the existing distribution system architecture in terms of efficiency, reliability and cost. The design is based on collected data of the selected case area and follows the following flow diagram to get the expected result of this study.

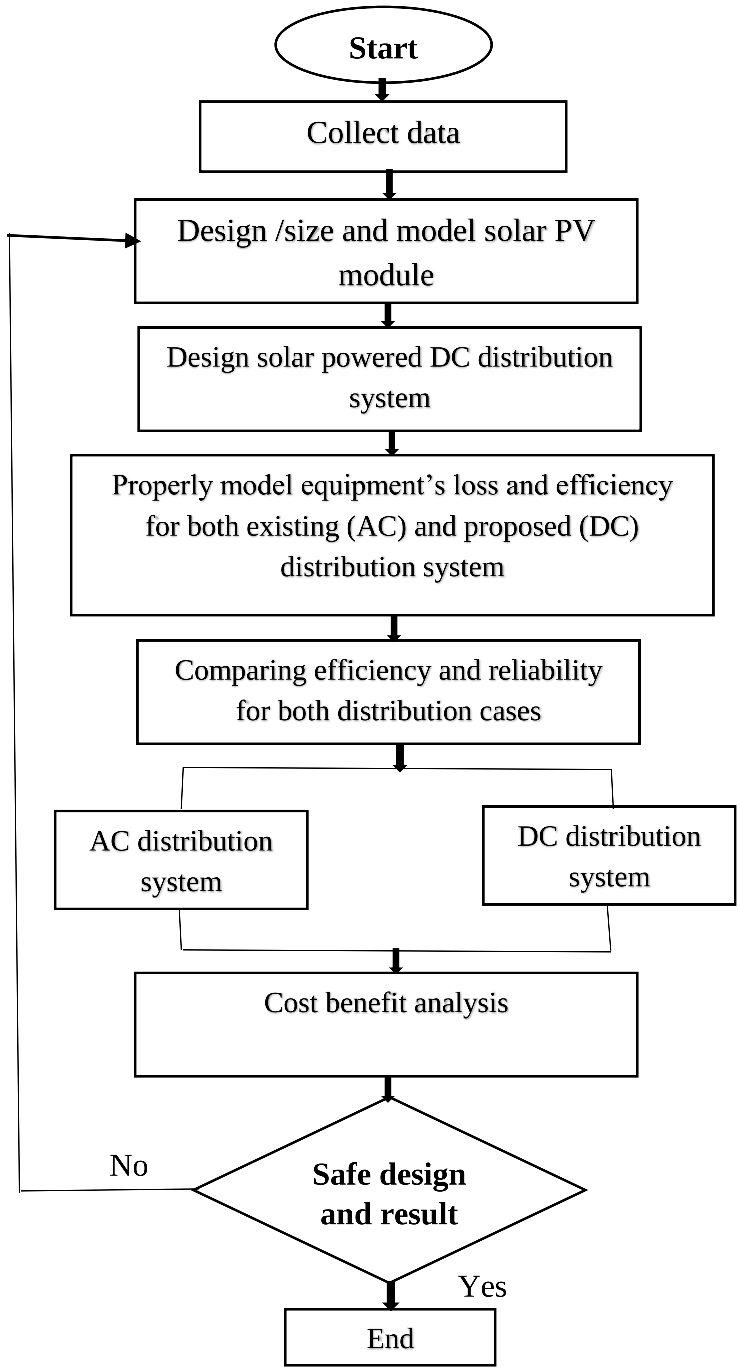


Figure 3.3 Schematic diagram of design procedures

3.5 AC Vs DC Power Distribution System Lay-out

This study is based on two power distribution system model for selected data center electrical power architecture. One is the existing AC power distribution system of the selected case area (Debre Berhan University Data Center) which gets supply from Ethiopian electric utility (EEU) with a nearby diesel generator as a backup power supply system in a case of power outage from the utility system. Another is the proposed datacenter power distribution model with an off grid solar powered 380 V DC distribution system. Figure 3.4 and 3.5 shows the power distribution for AC and 380V DC data centers. Each power distribution model is further explained in the proceeding sections with their main component power loss model.

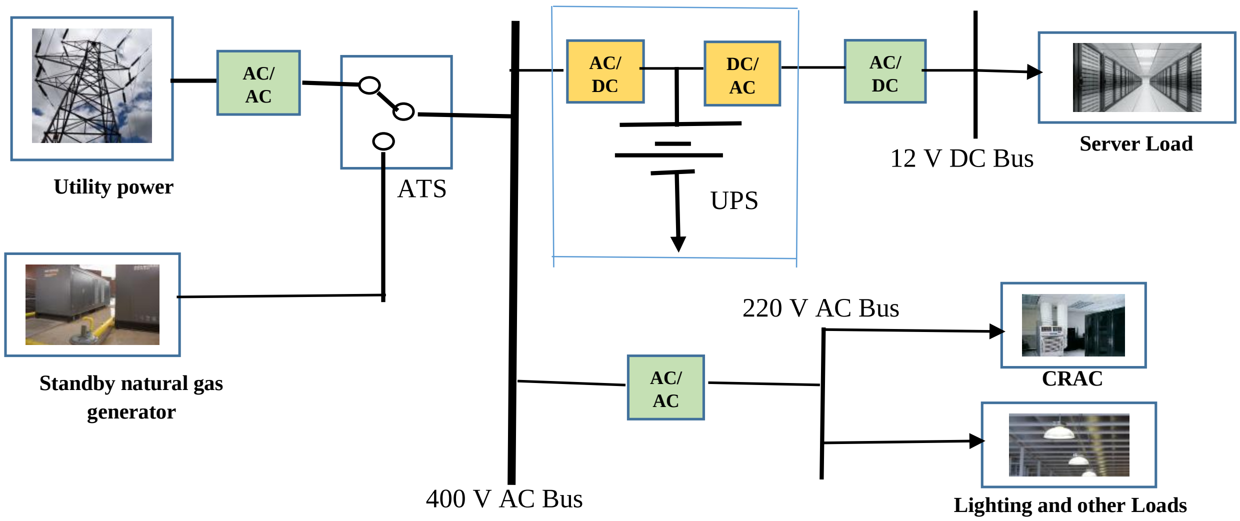


Figure 3.4. AC distribution system model of existing system

As shown in figure above, the medium voltage from the utility is stepped down by distribution transformer to 400V AC at the building entrance. The utility supply which along with the backup generator powers the double conversion on-line AC UPS via Automatic Transfer Switch (ATS). The battery bank is connected between the two converters via a DC bus. There are five different conversion stages including the distribution transformer that causes significant power loss in the distribution path, impacting the overall system efficiency. Reduction in the number of converters is possible by moving to DC distribution system. Figure 3.5 shows solar with diesel generator based DC distribution system model for the selected data center.

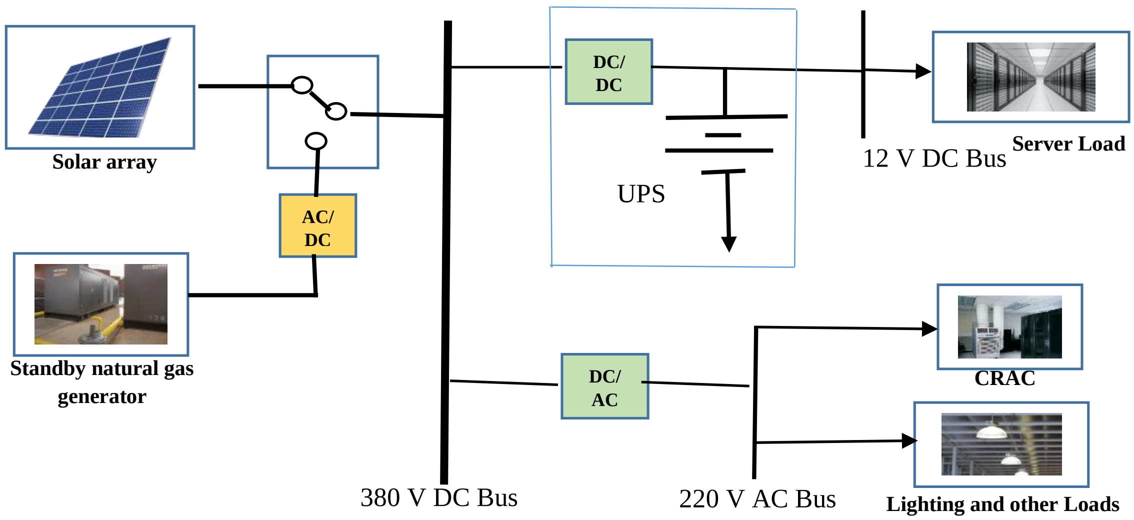


Figure 3.5 Proposed 380V DC distribution system model.

3.6 Why DC Distribution System in Data Center

DC power distribution has been accepted and used in the telecommunications industry for decades. Moreover, the higher voltage DC distribution provides many advantages over AC distribution. The following are some advantages [22].

- Fewer conversion stages in the overall system resulting in higher efficiency
- Longer battery back up without system de-rating
- No harmonic losses and effects on distribution
- No need for load balancing between phases
- Simplified distribution switchgear
- Simplified maintenance
- Conditioned output power quality
- Single global voltage – 380V DC

3.6.1 Voltage Selection for DC Data Centers

One of the most debated topic in modern data centers is the choice of DC voltage level for the most efficient and reliable power distribution. According to international standard, both the European Telecommunications Standards Institute (ETSI) and EMerge Alliance have made standardized 380V DC for power distribution for data center. The studies show that 380V DC is an ideal distribution voltage level for efficient and reliable system operation of data center [23]. As shown in figure 3.5 above, the loads in a data center are both DC type and AC type loads. The IT loads such as servers, switches, routers, UPS systems and security camera are a 12v DC type loads. While the supporting is used to cool cooling and lighting purposes such as CRAC, lamp and desktop computers for display and office applications are a single phase 220v AC type loads. For this proposed study a 380 V DC distribution bus is used as a main supply for both type of loads.

3.7 Data Center Efficiency

The efficiency of a system is expressed as the fraction of its input that is converted to the desired useful output. Anything which else than the useful output is a loss or waste. For data centers, the efficiency is expressed using the following equation.

$$\text{Data center efficiency} = \frac{\text{IT load power}}{\text{Total data center power}} \tag{3.17}$$

As expressed in equation above, data center efficiency is the ratio of power consumed by the IT equipment’s to the total input power. Various metrics to measure data center effectiveness has been discussed in the next section. In real data centers, electrical energy is consumed by devices other than IT loads. Such loads are called supporting infrastructures because they help keeping the IT equipment properly housed, powered, cooled, and protected to perform a better operation.

3.7.1 Data Center Efficiency Metrics

The large portion of energy consumption by data centers is causing a significant impact on the electrical grid and the environment. Hence, there should be metrics to measure data center’s effectiveness. Metrics are used to measure and improve the effectiveness of some value, function or parameter. The mostly used metrics for measuring data center’s effectiveness are Power Usage Effectiveness (PUE), Water Usage Effectiveness (WUE), Energy Reuse Effectiveness (ERE), Data Center Compute Efficiency (DCCE), and Clean Energy Index. PUE is the most common metric used in data centers. The above mentioned metrics are described in the following sections [24].

3.7.1.1 Power Usage Effectiveness (PUE)

PUE is the simple and primarily used metrics in data centers. PUE represents how much of this power is actually used by the IT equipment, in contrast to power used by cooling, lighting and other additional plant within the data center. Ideally, the value of PUE should be 1, a lower PUE value indicates a more efficient data center. PUE is calculated by:

$$PUE = \frac{P_{total}}{P_{ITload}} \tag{3.18}$$

Where,

$P_{total,}$ is the total power consumed by the data center and

$P_{IT\ load,}$ is the power consumed by the IT load.

3.7.1.2 Data Center Infrastructure Efficiency (DCiE)

Data Center Infrastructure Efficiency (DCiE) is a metric used to determine the energy efficiency of a data center. The metrics DCiE is simply inverse of PUE. The ideal value of DCiE is 1. DCiE was developed by Green Grid. DCiE is also expressed as a percentage, is calculated by dividing IT equipment power by total facility power.

$$DCiE = \frac{1}{PUE} = \frac{P_{ITload}}{P_{total}} \tag{3.19}$$

3.7.1.3 Energy Reuse Effectiveness (ERE)

A significant portion of the energy used by a data center is dissipated in the form of heat. The heat generated by the servers can be reused for other purposes. ERE measures the amount of energy reused from a data center which can be calculated by:

$$DCiE = \frac{\text{Total Energy - Reused Energy}}{\text{IT Energy}} \tag{3.20}$$

The theoretical ideal value of ERE is 0, which implies that all of the data center’s input energy is reused.

3.7.1.4 Data Center Compute Efficiency (DCcE)

Server in data centers are designated to perform specific task known as primary services. For example, primary service of an email server is to provide email services when requested. Depending upon the primary service provided by the server, the server compute efficiency can be calculated by:

$$\text{SCE} = \frac{\sum_{i=1}^{n} \text{Pi}}{\text{m}} \text{ x } 100 \tag{3.21}$$

Where Pi is the number of primary service provided by the server, *n* is total number of sample taken over time. Also, for a given data center having *m* servers, DCcE is calculated by averaging the *ScE* values from all servers during the same time period calculated by:

$$\text{DCcE} = \frac{\sum_{j=1}^{n} \text{SCEj}}{\text{m}} \text{ x } 100 \tag{3.22}$$

3.8 Data Center Reliability

Reliability is the probability that a system or component will perform its required functions under stated conditions for a specified period of time. The reliability of a repairable system is commonly measured using two metrics MTBF and MTTR. The reliability decreases with time regardless of the system design. The more robust the system, the higher the probability that the system will perform its intended function successfully [25].

For a constant failure rate λ, the reliability of the system is given by equation 3.23.

$$R(t) = e^{-\lambda t} \tag{3.23}$$

$R(t)$ is also known as the survival function.

3.8.1 Reliability Analysis Terms and Definitions

This section presents the terms and its definitions, and assumptions made for reliability analysis.

3.8.1.1 Failure Rate

The electronic equipment has a constant failure rate over its lifetime and follows an exponential statistical life distribution. The failure rates are assumed to be constant for all of the components given by equation 3.24.

$$\lambda = \frac{1}{\text{MTBF}} \text{ failures/hr} \tag{3.24}$$

Where, MTBF is the mean time between consecutive failures of a system or a component, usually expressed in either hours per failure.

3.8.1.2 Repair Rate

Most components also have an exponential repair distribution. The repair rates of most components denoted by μ (repairs/hr) are assumed to be constant over their lifetime. However, some of the components have a non-constant repair rates. The constant repair rate is given by equation 3.25.

$$\mu = \frac{1}{\text{MTTR}} \tag{3.25}$$

Where, MTTR is the mean time to repair of a failed component.

3.8.1.3 Availability

Availability is the ratio expressed as the percentage of time a system or a component can perform its required function. Availability is a dimensionless quantity given by equation 3.26.

$$\text{Availability} = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}} \tag{3.26}$$

Table 3.3 shows the availability and its resulting downtime. The downtime per year decreases with the number-of-9s. However, availability is not considered a good performance metric for knowing how reliable the power distribution architecture is. Availability of a distribution system does not provide any information about the frequency of outages during a time period of its operation. For two different systems with a similar availability, the frequency of outages will be the only distinguishing factor when these systems are compared. For example, a highly available system with 99.999% availability that failed just once in a year for 5.25 minutes has a much better reliability than a system that failed 157 times for 2 seconds. MTBF provides information about the frequency of outages to expect from a system [25].

Table 3.3. Availability and downtimes [25]

Availability (number of 9s)	Downtime (per year)	Downtime (per day)
1	36.5 days	2.4 hours
2	3.65 days	14.4 minutes
3	8.76 hours	1.44 minutes
4	52.56 minutes	8.66 seconds
5	5.26 minutes	864.3 milliseconds
6	31.5 seconds	86.4 milliseconds
7	3.15 seconds	8.64 milliseconds
8	315.569 milliseconds	0.864 milliseconds
9	31.5569 milliseconds	0.0864 milliseconds

3.8.2 Reliability Analysis Methods

The most commonly used methods to perform reliability analysis of electrical systems are where reliability block diagram method and Monte Carlo simulation method [25].

3.8.2.1 Reliability Block Diagram

In reliability block diagram method, each component is represented by a block with its reliability model given by figures 3.6 and 3.7. The blocks are connected in the same manner as they are connected electrically. The series connected equipment's are represented by series connected blocks as shown in figure 3.6. Let λ_1 and λ_2 represent the failure rates of component 1 and 2. Then, $e^{-\lambda 1t}$ and $e^{-\lambda 2t}$ represent the reliability functions which gives us the individual reliabilities of the components. To calculate the overall reliability of the system shown in figure 3.5, a single equation representing the reliability of the system should be obtained first.

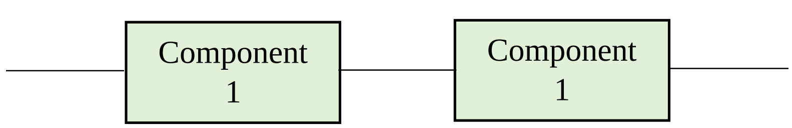


Figure 3.6. Two component series system.

The reliability of two component in a series system is given by equation 3.27. This is called product rule of reliability. In this case, both components should be operating for the system to operate. Failure of any one of the components will result in failure of the whole system.

$$R(t) = e^{-\lambda 1t} \text{ x } e^{-\lambda 2t} = e^{-(\lambda 1 + \lambda 2)t} \tag{3.27}$$

Let's consider two independent components connected in parallel as shown in figure 3.7. In this case, only one component should work for the system to work successfully.

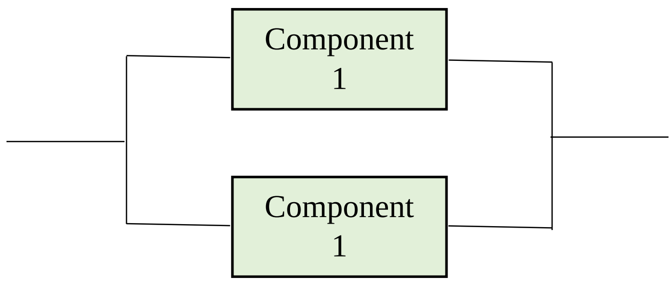


Figure 3.7. Two component parallel system.

The overall reliability of the parallel connected system can be calculated by equation 3.28.

$$R(t) = e^{-\lambda 1t} + e^{-\lambda 2t} - e^{-\lambda 1t} \text{ x } e^{-\lambda 2t} = e^{-\lambda 1t} + e^{-\lambda 2t} - e^{-(\lambda 1 + \lambda 2)t} \tag{3.28}$$

In case of series system, the system reliability will decrease as the number of components is increased. However, in case of the parallel system, the system reliability will increase with the increase in the number of components. Hence, a system with parallel components (or redundant) components will be more reliable than a system with series components. However, the cost of parallel system can be much higher. An electrical system will have both series and parallel connected components. Hence, the complexity in finding equation representing the overall electrical system will increase as the system size increases.

3.8.2.2 Monte Carlo Simulation

Monte-Carlo simulation is a powerful method for reliability modeling of the systems. The method is a powerful tool for obtaining numerical solutions to problems that are very complicated to solve analytically. For example, the reliability solution to a large electrical system using analytical method, such as reliability block diagram (RBD) will be complex. It uses the failure and repair statistical distributions of individual components to model the system behavior. It uses mathematical models to represent a real system. The failure and repair data are provided by the manufacturer. The appropriate distribution for the components can be determined by curve fitting the time to failure (TTF) and time to repair (TTR) data using software packages. The data points for TTF and TTR can be obtained from an equipment use over time. After finding the failure and repair distributions, a Monte Carlo simulation can be performed to model the reliability of the system. Once the failure and repair distributions of all the components are known, a Monte Carlo simulation is performed to model the reliability of the system [25]. Here in this study Monte Carlo simulation using Powertechnic Analyst software was done for reliability analysis to eliminate the problems in reliability block diagram method.

3.8.3 System Failure Consideration

A general reliability analysis is described in [24] is used in this thesis. The inability of the distribution system to supply electrical power to critical IT loads in a data center is counted as a failure. The failure of the IT loads itself is not considered here. Only the failure of power distribution components are considered. The distribution system either existing AC or the proposed DC is said to have failed if there is a loss of power at the PSU DC link of IT load. The reliability of the system at load connection point will be analyzed, as shown in figure 3.8 circled in red.

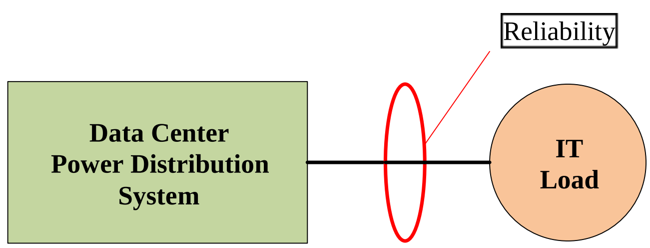


Figure 3.8. Data center point of reliability analysis.

Table 3.4 shows the equipment reliability data. These data's are considered for a good performance metric to know how reliable the power distribution architecture is.

Table 3.4. Equipment reliability data [26]

Component	Inherent Availability (%)	MTBF (hours)	MTTR (hours)
High Quality Supply	99.9705	8030	2
Diesel Generator	99.997423	2000	4
Circuit Breaker	99.999989	1×10^6	2
Bus Bars/Switch Board	99.999210	4.38×10^6	9
Automatic Transfer Switch	99.999950	1×10^6	2
Rectifier	99.990100	20000	2
Inverter	99.990100	20000	2
DC-DC Converter	99.996000	50000	2
Lead Acid Battery	99.9966667	240×10^3	8
Transformer	99.999937	7.8×10^6	6

3.9 Data Center Component Loss and Efficiency Model

The data center's efficiency can be determined empirically by summing up the power consumption of all IT equipment and dividing by the total power input of the data center. This method is simple, but gives an overstated efficiency result of data centers. Another approach is to use manufacturer provided efficiency for the data center main components such as UPSs, inverters, rectifiers and PSUs. Manufacturers provide efficiency data for the data center components.

For power equipment, efficiency is usually expressed as the percent of power out to power in. The prior method use a single efficiency value of the components to calculate data center efficiency. In case of real data center, this approach of efficiency calculations does not provide accurate results. The use of manufacturers' efficiency ratings causes overestimation of efficiency, and as a result it will underestimate the losses. Use of efficiency models that uses a single efficiency value to model the data center components will overstate the overall data center efficiency [27].

3.9.1 Component Loss Model

The accuracy of the data center efficiency estimation depends on the accuracy of the efficiency models of each data center component losses. A component's losses can be computed as the sum of three loss: No-load loss, Proportional Loss and Square-law loss as shown in equation 3.29. The no-load losses are fixed losses independent of the output power. The proportional losses are the losses that vary proportionately with the load (like switching loss in power semiconductors, gate drive loss, core losses in magnetics, etc.). The square losses are the losses that increase with the square of the load current (the I^2R losses) [27].

$$\text{Component's loss} = \text{No-load loss} + \text{Proportional loss} + \text{Square - law loss} \qquad (3.29)$$

Equation 3.29 can be modified using component load as the percentage of the rated active power. Now, the component loss can be computed by using equation 3.30.

$$P_{loss} = K_0 + K_1 L_{\%} + K_2 L_{\%}^2 \qquad (3.30)$$

Where, $L_{\%}$ is the component load as the percentage of its rated active power and K_0, K_1 and K_2 are respectively the no-load, proportional loss and square-law term coefficients that are determined through regression analysis of the loss data provided by the manufacturer at multiple load levels that are available from the manufacturer are 0% (no-load), 25%, 50%, 75% and 100% (full load). The component losses are computed by subtracting the output power from the input power using equation 3.31.

$$P_{loss} = P_{in} - P_{out} \qquad (3.31)$$

The component loss can also be expressed as the percentage of its rated power. By doing so results in equation 3.32.

$$P_l = K_{p0} + K_{p1} L_{\%} + K_{p2} L_{\%}^2 \qquad (3.32)$$

Where,

$$P_1 = \frac{P_{loss}}{P_{rated}} \quad \text{And} \quad K_{pz} = \frac{K_z}{P_{rated}} \quad ; z = 0, 1, 2$$

As the values of the per-unit component losses P_l and the component's per unit load $L_{\%}$ are known, regression analysis is used to determine the values of the loss term coefficients: K_{p0}, K_{p1} and K_{p2}.

3.9.2 Efficiency Model

To build up the efficiency models for the system, let's consider the efficiency of any power component at any instant that can be computed using equation 3.33 [27].

$$\eta = \frac{P_{out}}{P_{in}} \tag{3.33}$$

$P_{in} = P_{out} + P_{los}$, Hence, equation 3.33 can be written as,

$$\eta = \frac{P_{out}}{P_{out} + P_{loss}} \tag{3.34}$$

The load and loss in equation 3.31 can be expressed as the percentage of rated power.

$$\eta = \frac{L\,\%P_{rated}}{L\,\%P_{rated} + P_1 P_{rated}} = \frac{L\,\%}{L\,\% + P_1} \tag{3.35}$$

Substituting the value of P_l from equation 3.32.

$$\eta = \frac{L\,\%}{L\,\% + K_{p0} + K_{p1}L_{\%} + K_{p2}L_{\%}^{2}} \tag{3.36}$$

Equation 3.36 will be used to find out the efficiency model of all the components of the power distribution.

3.10 Energy Efficiency of the System

The energy efficiency of the data center power distribution system for both AC and DC power is reduced to the product of all component efficiencies in the distribution path. For AC data center distribution path at different loading level, it can be calculated using equation 3.37.

$$\eta_{Existing\ system} = \eta_{dist.tr} \times \eta_{ACUPS,} \times \eta_{convertors} \times \eta_{ACPSU} \tag{3.37}$$

Similarly for the proposed DC distribution path the efficiency of the total system at different loading level can be calculated using equation 3.38 as follows.

$$\eta_{Proposed\ system} = \eta_{DC\ UPS}\ x\ \eta_{rectifier}\ x\ \eta_{inverter} \tag{3.38}$$

In the above equation, to calculate energy efficiency, all component efficiencies at multiple load level need has to be calculated.

CHAPTER - FOUR

4. MODELLING AND SIZING OF THE DC SYSTEM

In this chapter first presents the design/sizing and modelling of solar PV system to supply the data center loads has been done. Next the distribution system model of the selected data center for both existing and proposed solar powered system model was presented. In addition, loss modeling of data center's power equipment along with the power distribution path is explained in detail. From the loss models, the efficiency of the components are developed. Finally the methods for reliability calculations are presented in detail.

4.1 Solar PV Design

The first step taken in this design process is to estimate daily electrical demand. Thus, according to table 3.1 the daily estimated energy capacity at full load, is 114,051.2 Wh/day or 114.051 KWh/day.

The following are specifications which have to be considered in a design procedure.

- Design month = August (summer) with lowest average monthly radiation which is 4.78 KWh/m^2/day given in Table 3.2.
- Life span 25 years and above

A typical module is selected for design purpose and its specification also shown in table 4.1 below. The performance of PV modules and arrays is generally rated according to the maximum DC power output and current. Thus, in this study a module is selected with a maximum power of 300 W in which it reduces the installation area by decreasing the designed number of parallel and series connected PV array. Its cost is also relatively cheap than other modules with a similar power rating and it is easily available in Ethiopian market with a life time of more than 25 years.

Table 4.1: Specification of typical PV- module for design purpose (JSSP-24300) [L-3]

Specification	Value
Maximum power current (I_{mp})	8.3 A
Maximum power voltage (V_{mp})	36 V
Max. Power (P_{max})	300 W
Short circuit current (I_{sc})	8.9 A
Open circuit voltage (V_{oc})	44 V

The following constants are also taking into consideration for the general design of PV system. In this case the capacity of PV array to withstand load requirement can be increased according to typical loss percentages in a PV system as follows [28].

- Battery efficiency (%) = ($0.8 < x < 0.85$) for round trip average efficiency of a new battery. Here the maximum efficiency is taken throughout this design steps.
- Typical percentages of the losses in a PV system are
  - ✓ Temperature losses = 0.90
  - ✓ Wiring losses = 0.97
- Combined efficiency = 0.85*0.9*0.97 = 0.74
- Inverter efficiency = 0.9
- Output efficiency, η_{out} = 0.85*0.9 = 0.765
- Depth of discharge, DOD = 0.65

Following it setting nominal voltage ratings for the given stand-alone solar powered data center DC distribution system. For the most efficient and reliable power distribution in modern data centers with standalone PV system case, 380 V is selected as off grid supply of data center loads since 380V has relatively better performance compared to 120V, 48V, 24V and 12V DC distribution systems and considered as a standard.

4.1.1 Step-by-Step Sizing of Components

The following procedures are a step by step methods for which to design/size PV array, Charge controller, Battery capacity and other necessities to supply the proposed system from standalone solar power system.

Step 1: PV- Array Sizing

By using equation 3.1, the peak power from PV array is can be calculated as:-

$$P_{pv} = \frac{114,051.2}{0.74 \ x \ 4.78}$$

$$P_{pv} = \ 32,243.36 \ W$$

By considering fill factor, more commonly known by its abbreviation "FF", is a parameter which, in conjunction with V_{oc} and I_{sc}, determines the maximum power from a solar cell. The FF is defined as the ratio of the maximum power from the solar cell to the product of V_{oc} and I_{sc} so that:

$$fill \ factor = \frac{max. \ power \ from \ solar \ module}{I_{sc} \ x \ V_{oc}}$$

$$fill \ factor = \frac{300}{8.9 \ x \ 44}$$

$$fill \ factor = 0.77$$

$$PV \ array \ (w) \ = \ fill \ factor \ \text{x} \ PV \ array \ (w)$$

$$= \ 0.77 \ \text{x} \ 32,243.36 \ w$$

$$\mathbf{P_{array}} = 24,827.38 \ \text{W}$$

$$I_{pv} = \frac{24,827.38}{380}$$

I_{pv} = 65.34 A, For 380 V system

By selecting the specifications of solar modules with a capacity of 300 watt maximum power as shown in table 3.3, the required number of modules become calculated.

Number of PV modules:

$$\textbf{Parallel}: \quad \frac{65.34}{8.3} = 7.87 \;\approx\; \mathbf{8}$$

Number of PV modules to provide the 380V DC-voltage is:

$$\textbf{Series:}\ \frac{380}{36} = 10.55 \;\approx \mathbf{11}$$

$$\textbf{Total} = 8\,x\,11 = \mathbf{88}$$

Step 2: Battery Sizing

According to equation 3.3 the sizing of battery bank which is required for 2 days of autonomy can be calculated as:

$$E_{bat} = \frac{114,051.2Wh/day\ x\ 2}{0.65\ x\ 0.765}$$

$$= 458,727.8\ Wh/day$$

From equation 3.4 battery ampere - hour capacity can also be calculated as

$$C_{bat} = \frac{458,727.8}{380} \approx \mathbf{1207.2\ Ah}\ \text{For 380 V nominal voltage}$$

Proceed to it by selecting a battery which have 24 V nominal and a capacity of 600 Ah rating of lead acid battery type, the total required number of batteries can be calculated. This battery is selected because it has long life time, very low self-discharge, easy to maintain (maintenance cost is low), easily available in market and it is easy to install and operate.

Number of batteries required:

$$N = \frac{C_{bat}}{rating} = \frac{1207.2}{600} = 2.01 \;\approx \mathbf{2}\ Batteries\ \text{(Select an even number)}$$

Parallel: 2 batteries in parallel

$$\textbf{Series:}\ \frac{380}{24} = \textbf{16 batteries in series}$$

Total number of batteries = 2 x 16 = **32 Batteries**

Step 3: Sizing of Charge Controller

The battery charge controller is required to safely charge the batteries and to maintain longer life. Using the formula shown in equation 3.5, the size of charge controller can be calculated as follows.

$$I_{controller} = 8\ x\ 8.9\ x\ 1.3 \approx \mathbf{92.56\ A}$$

For this study a 24V, 50A, MPPT based solar charge controller have chosen from specifications based on the voltage rating of battery bank. Unlike pulse width modulation (PWM) controller, maximum power point tracking (MPP) based charge controller is the most common type of controller in application because of its simplicity to install and easy compacted with the type of PV panel and battery bank.

$$Number\ of\ \ charge\ controller = \frac{I_{controller}}{50A} = \frac{92.56A}{50A} = 1.85 \approx \mathbf{2}$$

Number of charge controller required = **2 Controllers.**

Step 4: Inverter Sizing

To calculate the inverter size, the total AC power in a data center is 3,760 W as shown in table 3.1. Considering a correction factor 1.25 and using equation 3.6, the inverter power rating can be calculated as;

$$P_{inverter} = 3,760\ x\ 1.25 = \mathbf{4,700\ W}$$

An inverter which can handle the calculated continuous power rating is desirable for the PV system. To allow system expanding, it has to be choose the inverter of output continues power with these feature considerations. So, the specifications of the required inverter will be:

- Output power = 6000 watt
- Input DC voltage = 400 V
- Output = 220V AC , 50 Hz , pure sine wave
- Front panel LED statues indicators
- The selected inverter type is ATO-PSW-60002

Step 5: System Wire Sizing

Cable or conductor of working zone critical to the safe, long-term operation of any electrical system. As explained in section 3.2, the cable sizes are especially imperative for sections between: solar panels and batteries; batteries and inverter or load; inverter and load distribution board. These three section of conductor sizes are calculated below.

i. Cable size between solar PV array and battery:

The DC system voltage from the output of solar array is 380V. To calculate the maximum DC current, considering a safety factor of 125% with 8 strings having a short circuit current (I_{sc}) of 8.9A which is given from specification. Maximum DC current (I_{max}) can be calculated as:

$$I_{max} = 1.25\ x\ 8\ x\ 8.9\ = \mathbf{89\ A}$$

Cable length is assumed to be 25 meter as most modules are installed on the top of the building it is a reasonable assumption [29]. As explained in section 3.2.6, the most acceptable and reasonable voltage drop level (which is <10%) is 2% - 4% and here in this study is assumed to have a voltage drop of 4%. Finally the cross sectional area of the conductor can be calculated using equation 3.7 is as follows. For Aluminum wire which has a resistivity of 2.82×10^{-8} Ωm,

$$A = \frac{\rho \text{ x } l \text{ x } I_{max}}{V_d}$$

$$A = \frac{2.82 \times 10^{-8}\Omega m\ x\ 25m\ x\ 333.75A}{0.04\ x\ 380V}$$

$$\mathbf{A = 4.13\ mm^2 \approx 6\ mm^2}$$

ii. The cable size between battery to load and inverter:

Excluding the panels which are installed on the top of building, the remaining components such as battery bank, charge controller and inverters are placed in door of the data center room to protect them from rain, sun, dust and so on. Debre Berhan university data center have one room with an area of 25m X 10m space. This room is divided in to two parts and it holds inside electrical room in one area and server room in another area. The electrical room is measured an area of 150m^2 and therefore the above designed electrical equipment's would be placed and installed inside. From this the length of an electrical room is 15m and if the spacing between battery bank and invertor is 5m it is acceptable as referred in [29].

Considering the length of the cable (l) as 5 m between battery to inverter or load and the allowable voltage drop is 4 %. In such cases, the cross-sectional area is determined by using equation 3.8 as follows.

The maximum current from battery at full load supply is given by

$$I_{max} = \frac{6000}{0.9\ x\ 24}$$

$$\mathbf{I_{max} = 277.78A}$$

Where V_{system} is the battery system voltage and it becomes 24V. The area of conductor between batteries to inverter can be calculated using equation 3.7 as follows.

$$A = \frac{\rho \text{ x } l \text{ x } I_{max}}{V_d}$$

$$A = \frac{2.82 \times 10^{-8}\Omega m\ x\ 5m\ x\ 277.78A}{0.04\ x\ 24V}$$

$$\mathbf{A = 40.80mm^2}$$

iii. Cable size between inverter and load:

Here there are different AC loads in side data center room and it is better to select the maximum length of the load which are far from the inverter. AC loads such as lighting fixtures and computer display are present in both electrical room and server in this selected case study. The total length of data center room is 25m and its width become 10m. From the total length of the room, and the maximum length of the cable for powering loads from inverter is 25 m. Thus, considering the voltage drop which is 4 % the cross sectional area of conductor can be calculated. The maximum current on the phase for single phase is calculated by using equation 3.9 as follows.

$$I_{max} = \frac{Inverter\ kVA}{V_{output}}$$

$$I_{max} = \frac{6000}{220}$$

$$\mathbf{I_{max} = 27.27A}$$

The maximum continuous current will be $I = 1.25\ xI_{max}$ and with a maximum allowable voltage drop (V_d) applying the values of l, V_d, I and ρ in equation 3.7, the cross-sectional area of the cable between inverter and load can be calculated.

The maximum continuous current,

$$I = 1.25 \text{ x } 27.27$$

$$\mathbf{I = 34.1A}$$

Similarly, the cross-sectional area of the cable between inverter and load becomes;

$$A = \frac{\rho \text{ x } l \text{ x } I_{max}}{V_d}$$

$$A = \frac{2.82 \times 10^{-8}\Omega m\ x\ 25m\ x\ 34.1A}{0.04\ x\ 220V}$$

$$\mathbf{A = 2.73\ mm^2 \approx 4\ mm^2}$$

Once the sizing for different components of the PV system are done by following the above-calculations, a summary table (Table 4.2) can be prepared as follows.

Table 4.2: A summary for PV system component sizing

Component	Description of component	Result
Load	Total estimated load (kW)	37.32
	Total estimated energy(kWh)	114.051
PV Array	Capacity of PV array(kW)	24.83
Number of modules	in series	11
Number of modules	in parallels	8
Total number of modules		88
Battery Bank	Battery bank capacity (Ah)	1207.2
Number of batteries	in series	16
Number of batteries	in parallel	2
Total number of batteries required		32
Inverter	Capacity of the inverter (kW)	4.7
Wire (mm^2)	Between PV modules and batteries	6
	Between battery bank and inverter	50
	Between inverter and load	4

4.2 Modelling of Photovoltaic in Simulink

A photovoltaic system directly converts sunlight into electricity. The basic device of a photovoltaic system is the photovoltaic cell. Cells may be grouped to form panels or modules. Panels can be grouped to form large photovoltaic arrays. An array is a group of panels or modules which are connected in series and/or parallel to form a solar plant. Based on the mathematical equation and parameters of PV cell which are described in section 3.3 the simulation model is explained in the next section.

4.2.1 Simulation Diagram of a Single PV Module Model

The MATLAB/Simulink model of standalone PV module illustrates and verifies the nonlinear voltage, current and power-voltage output characteristics of a one-diode equivalent circuit. The model consists of five parameters such as photo current (I_{ph}), saturation current (I_0), reverse saturation current (I_{rs}), current through shunt resistor (I_{sh}) and output (PV) current (I_{pv}) as shown in figure 4.1 below.

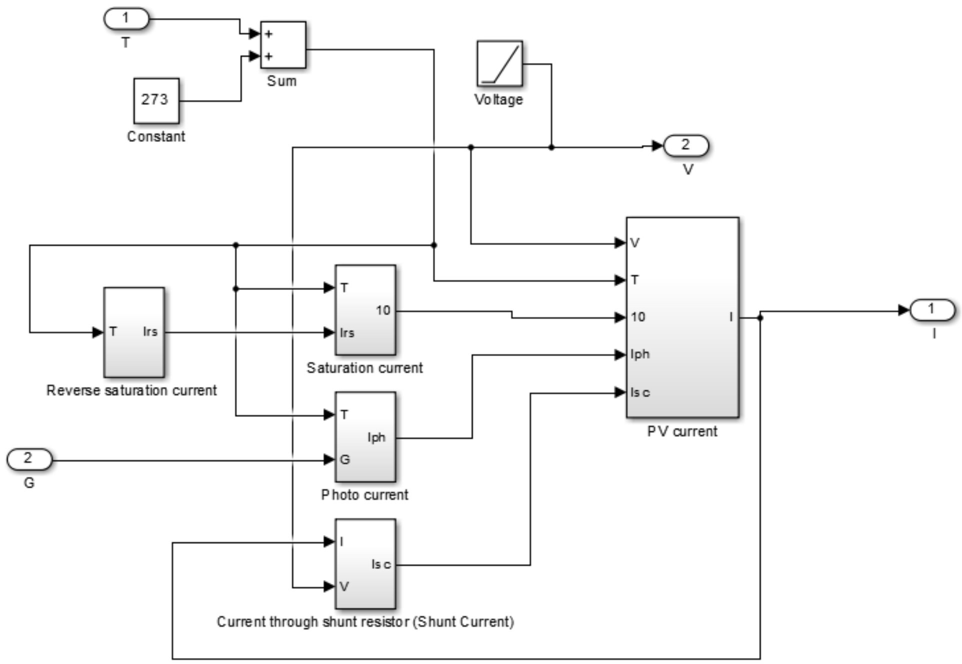


Figure 4.1. Simulink diagram of five parameter single diode PV cell.

Figure 4.1 is drawn with the help of above equations (equations 3.12 through 3.16). A more generalized PV model is built using MATLAB/Simulink as per figure 4.2 to illustrate the nonlinear I-V and P-V output characteristics of PV module. The inputs are the irradiance intensity and ambient temperature. Simulink is a simulation program, which provides a graphical interphase for building models as block diagrams.

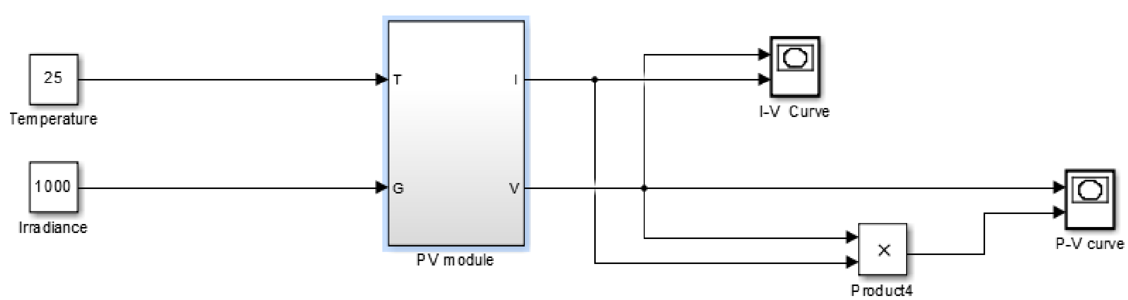


Figure 4.2 Generalized model of a single PV system.

For a PV cell with an ideal I-V characteristic, its open-circuit voltage and short circuit current are given as V_{oc} = 44V and I_{sc} = 8.9A, respectively. Both I–V and P–V output characteristics of generalized PV module are shown in figure 4.3 and 4.4 respectively. The nonlinear nature of PV cell is apparent as shown in the figures, i.e. the output current and power of PV cell depend on the cell's terminal operating voltage and temperature, and solar irradiance as well. It is been observed that with increase of working temperature, the short-circuit current of the PV cell increases, whereas the maximum power output decreases. As much as the increase in the output current is much less than the decrease in the voltage, the net power decreases at high temperatures.

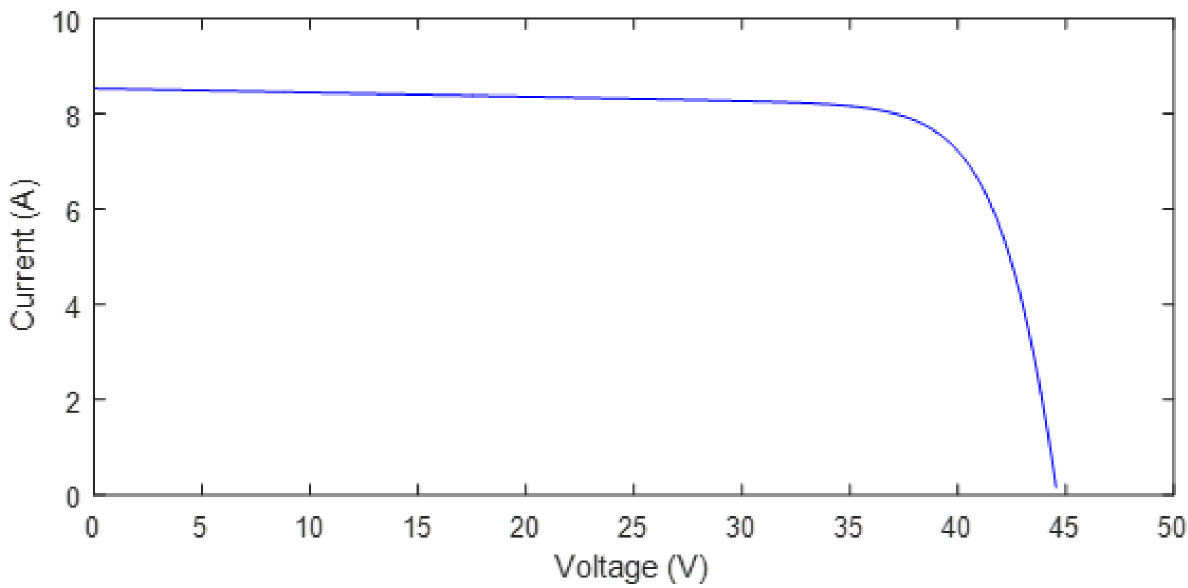


Figure 4.3. I – V output characteristics of the model.

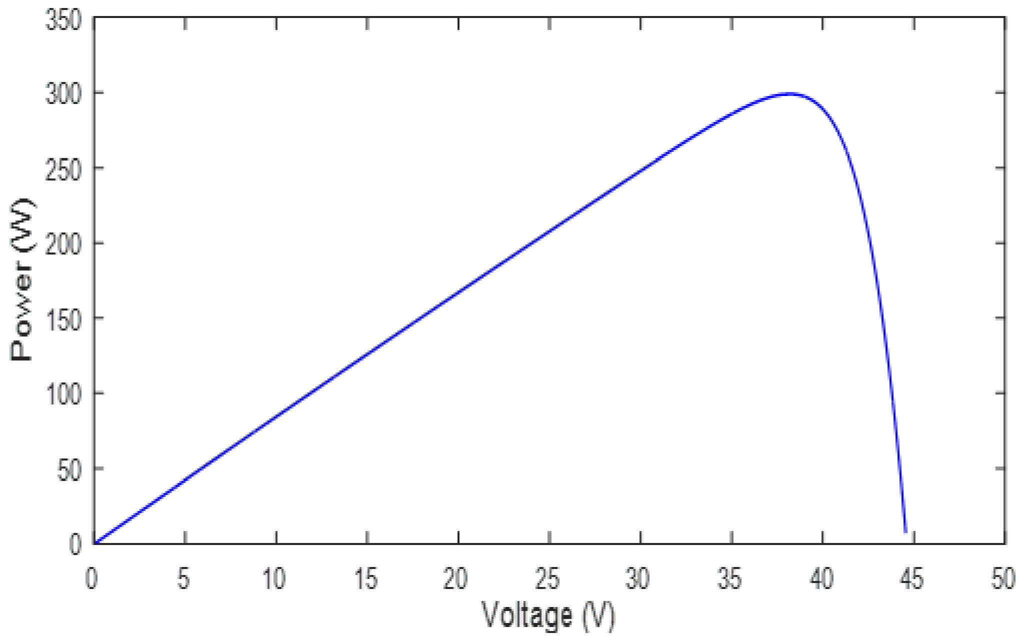


Figure 4.4. P – V output characteristics of the model.

On the other hand, with increase of solar irradiance, the short-circuit current of the PV module increases and the maximum power output increases as well. The reason is the open-circuit voltage is dependent on the solar irradiance, yet the short-circuit current is directly proportional to the radiant intensity. Both I-V and P-V output characteristics of PV array at various irradiance and temperature are carried out by the following diagram.

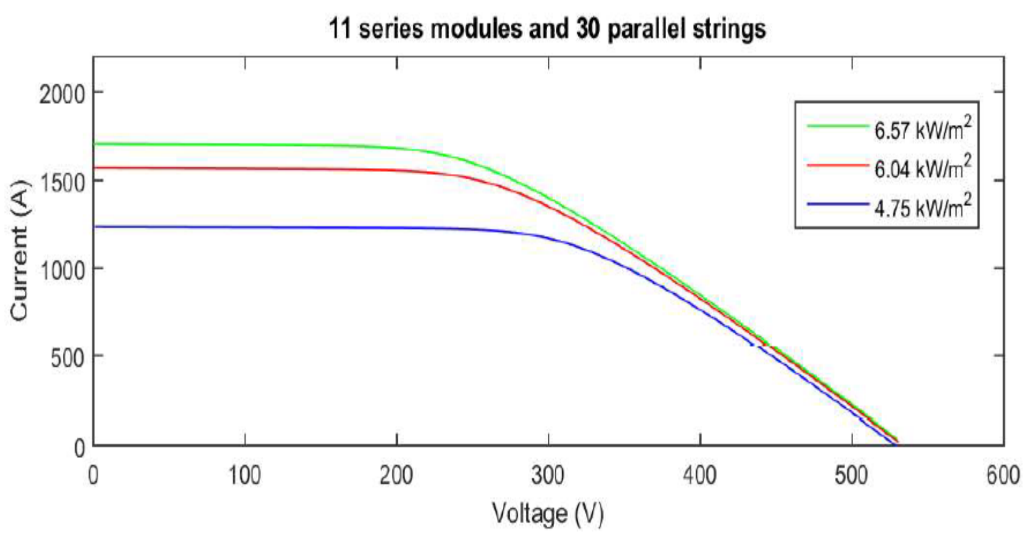


Figure 4.5. I – V output characteristics of solar array for different solar irradiance.

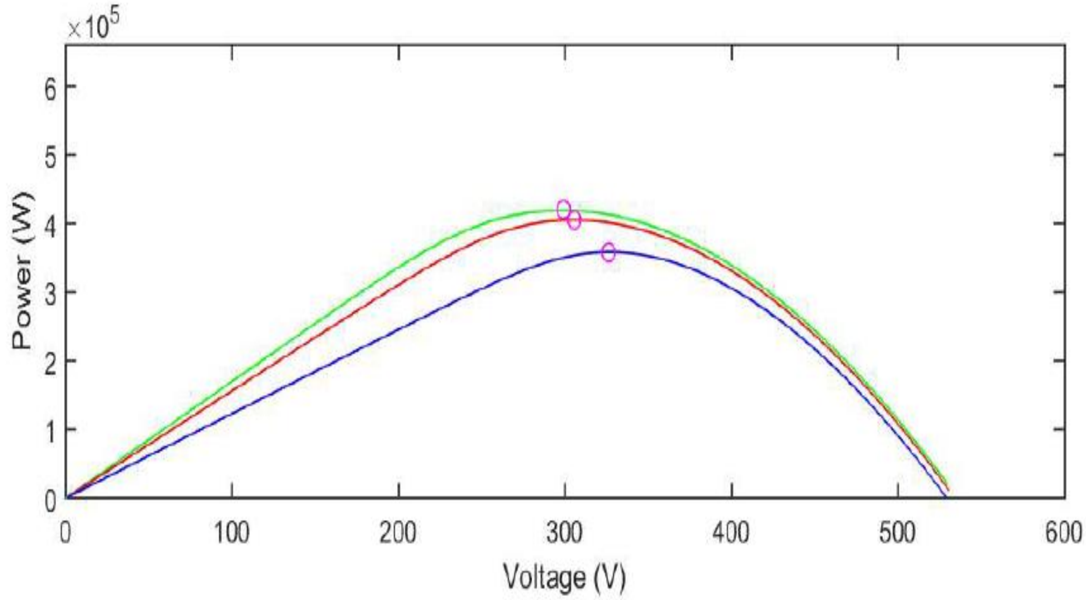


Figure 4.6. P – V output characteristics of solar array for different solar irradiance.

4.3 Data Center Power Distribution Model

Prior to efficiency and reliability modeling, a data center layout model has to be developed. As described in section 3.5, the power distribution model of both existing AC system and the proposed DC system is carried out in the next section. The model is based on Tier two standard. As shown in figure 2.1, a tier 2 type is a data center with redundant capacity components and a single non-redundant distribution path. It has N+1 UPS system and one backup (Diesel is commonly used) generator.

4.3.1 Existing (AC) Power Distribution System of a Data Center

Figure 4.7 shows the single line diagram of existing AC power distribution system for the selected case (Debre Berhan University Data Center) which has one main source from the utility system (EEU) and a diesel generator as aback up source. One distribution transformer are used in this model. The distribution transformer steps down the 15 kV AC bus voltage to distribution level voltage, 400V before connecting to the 400V AC bus of the data center input. As shown in figure 4.7 of AC power distribution architecture, it consists of five converters including the distribution transformer. These converters on the AC power distribution architecture leads to decrease the total efficiency of the system.

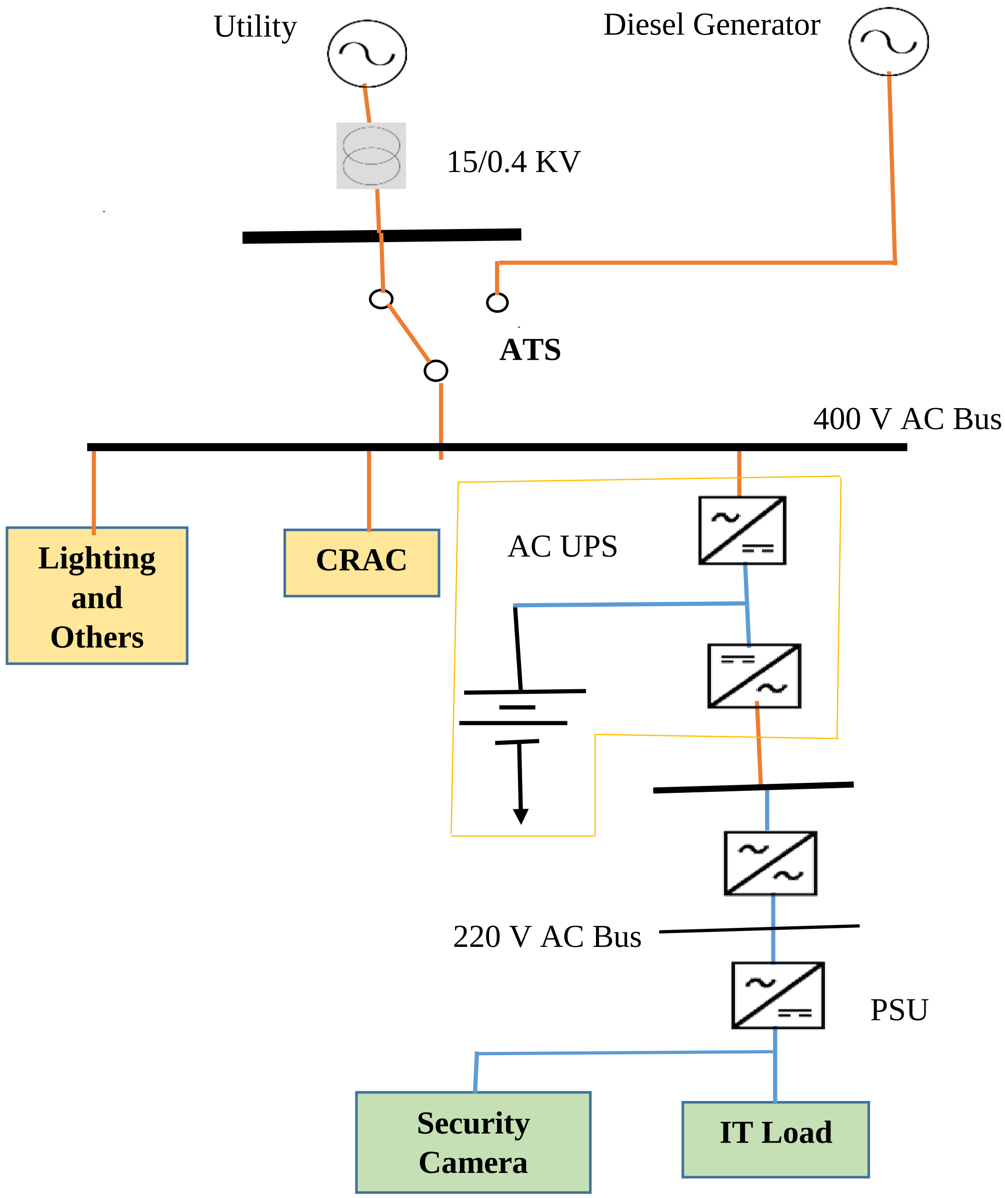


Figure 4.7. Single line diagram of existing data center AC power distribution.

4.3.2 The Proposed 380V DC Power Distribution System Model

The proposed system contains a designed solar array as a main source of supply and one diesel generator as a backup source. The renewable energy source (in this case solar array) is used to replace the utility source in order to independently supply the data center loads to eliminate power interruptions from the utility system. The data center in this study has a load of 37.32 KW power and is designed to have 88 solar panels each having 300 watt power ratings to achieve the required load capacity. Hence, to get a solar plant capacity, 11 solar panels are connected in series to form a string to achieve 380V DC voltage. From a total of 88 solar panels, there will be 8 parallel solar panel strings. These parallel strings are directly connected to the 380 V DC bus bar. Figure 4.8 shows the single line diagram of proposed DC power distribution architecture with 37.32 KW PV supply and a backup diesel generator. From the figure, it consists of three converters and leads to have relatively good efficiency as compared to AC distribution which consists five converters.

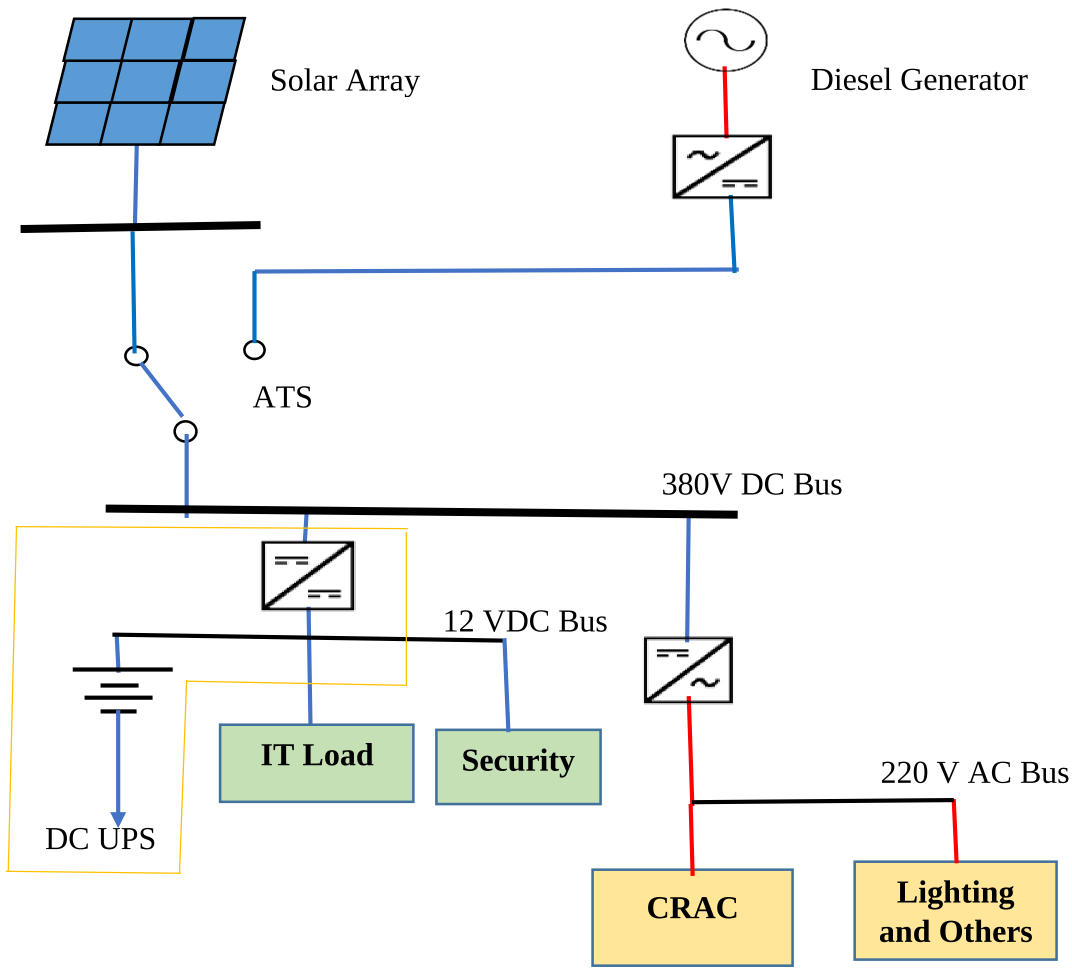


Figure 4.8 Single line diagram of proposed 380V DC distribution system.

4.4 Component Loss and Efficiency Modeling

As described in section 3.9, using the loss model of main components in a data center distribution path, the overall data center efficiency can be estimated. Such component losses are modeled by the preceding sections.

4.4.1 Main Components Loss Model

The accuracy of the data center efficiency estimation depends on the accuracy of the efficiency models of each data center component. From equation 3.32, as the values of the per-unit component losses Pl and the component's per unit load $L_{\%}$ are known, regression analysis is used to determine the values of the loss term coefficients: K_{p0}, K_{p1} and K_{p2}. Component losses P_l and the component's per unit load $L_{\%}$ are provided by the manufacturer at multiple load levels that are 0% (no-load), 25%, 50%, 75% and 100% (full load). The following sections describe the mathematical model of loss and efficiency of main data center components which is provided by this study.

4.4.1.1 UPS Loss Model

The UPS loss data is considered here for both AC and DC type UPS. Loss data of typical double conversion AC UPS was extracted from [30]. The loss data expressed in per unit value at different loadings are shown in table 4.3.

Table 4.3. Measured AC UPS loss data (p.u.) at multiple load levels (p.u) [30]

Load (p.u.)	0.25	0.50	0.75	1.0
Loss (p.u.)	0.0364	0.0631	0.0946	0.1312

A regression analysis (or second order polynomial fit) was done for this loss data and plotted in figure 4.9. It can be seen from the figure that the values of K_{p0}, K_{p1} and K_{p2} for AC UPS loss model are respectively 0.0892, -0.01096 and 0.11465.

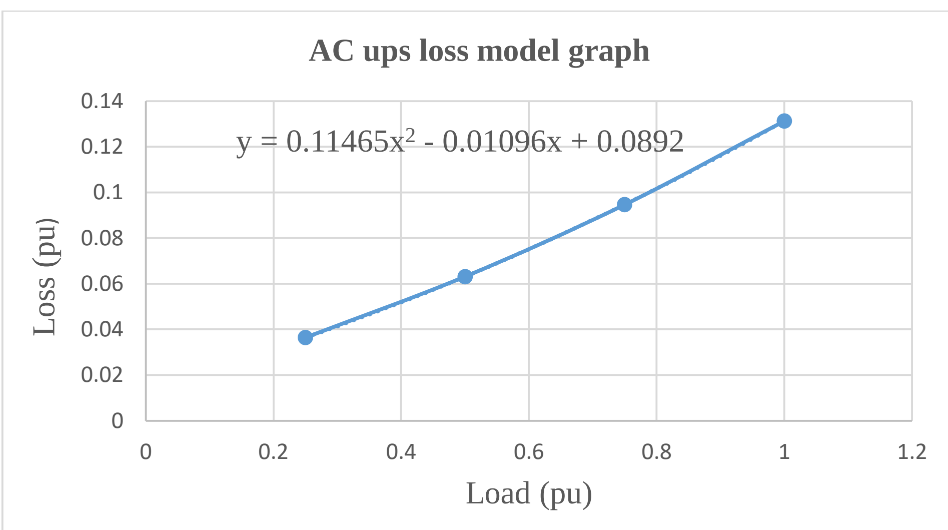


Figure 4.9. Interpolated model of AC UPS losses.

Similarly, loss data of a DC UPS was extracted from efficiency data in [30]. The loss data expressed as percentage of the rated load at different loadings are shown in table 4.4.

Table 4.4. Measured DC UPS loss data (p.u.) at multiple load levels (p.u.)

Load (p.u.)	0.25	0.50	0.75	1.0
Loss (p.u.)	0.01767	0.02576	0.04114	0.06157

A regression analysis (or second order polynomial fit) was again done for this loss data and plotted in figure 4.10 below.

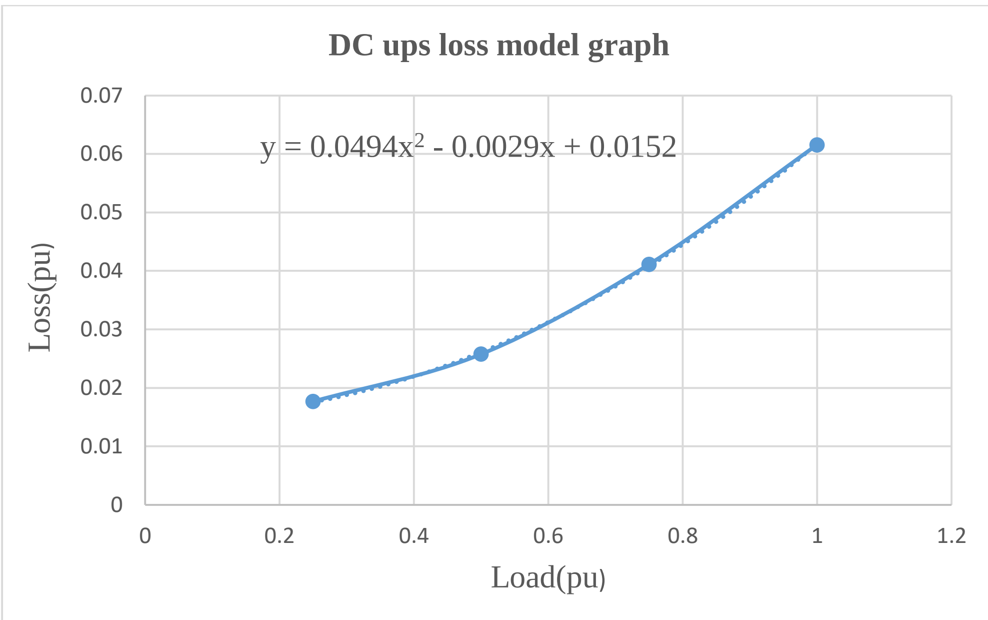


Figure 4.10. Interpolated model of DC UPS losses.

From figure 4.10, it can be seen that the values of K_{p0}, K_{p1} and K_{p2} for DC UPS loss model are respectively 0.0152, 0.029 and 0.0494.

4.4.1.2 PSU Loss Data

The loss data and their second order polynomial fit of AC power supply unit in the model used in this thesis is shown in the following tables and figure. For AC power supply unit, a measured 240V loss data was extracted from [30] which is approximated with 220V supply unit and its polynomial fit is constructed as shown in table below.

Table 4.5. Measured 240V AC PSU loss data (p.u.) at multiple load levels (p.u.) [30]

Load (p.u.)	0.25	0.50	0.75	1.0
Loss (p.u.)	0.0441	0.0365	0.0504	0.0684

The interpolated second order polynomial fit of this AC PSU loss is plotted in the following graph.

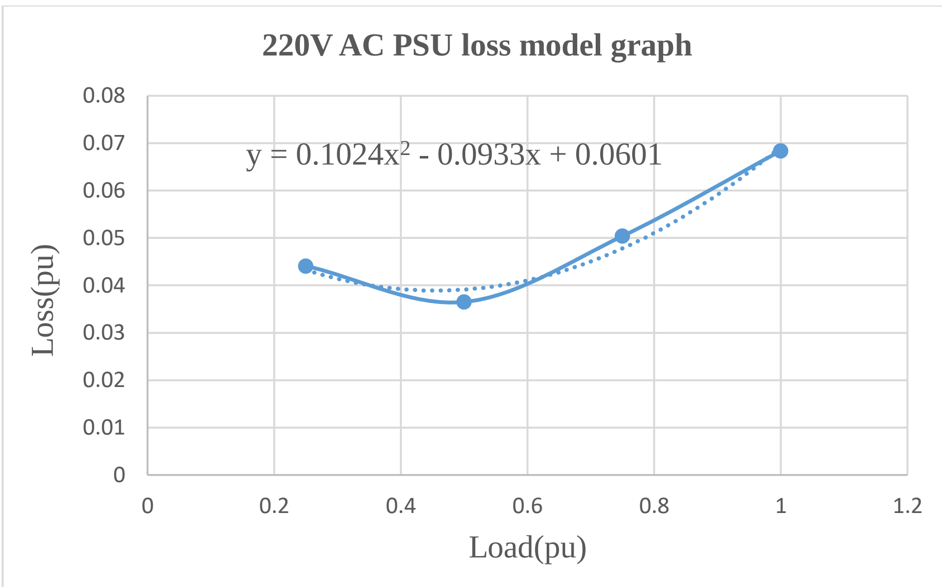


Figure 4.11. Interpolated model of AC PSU losses.

4.4.1.3 PV inverter loss model

The loss data taken for this inverter is a loss data from a 240 V type inverter which is extracted in [31] approximated with 220 V inverter to determine the component loss coefficients as follows.

Table 4.6. Measured PV inverter loss data (p.u.) at multiple load levels (p.u.)

Load (p.u.)	0.25	0.50	0.75	1.0	1.20
Loss (p.u.)	0.03409	0.04765	0.06788	0.09649	0.12597

Based on this data, a regression analysis graph was done as shown in figure below.

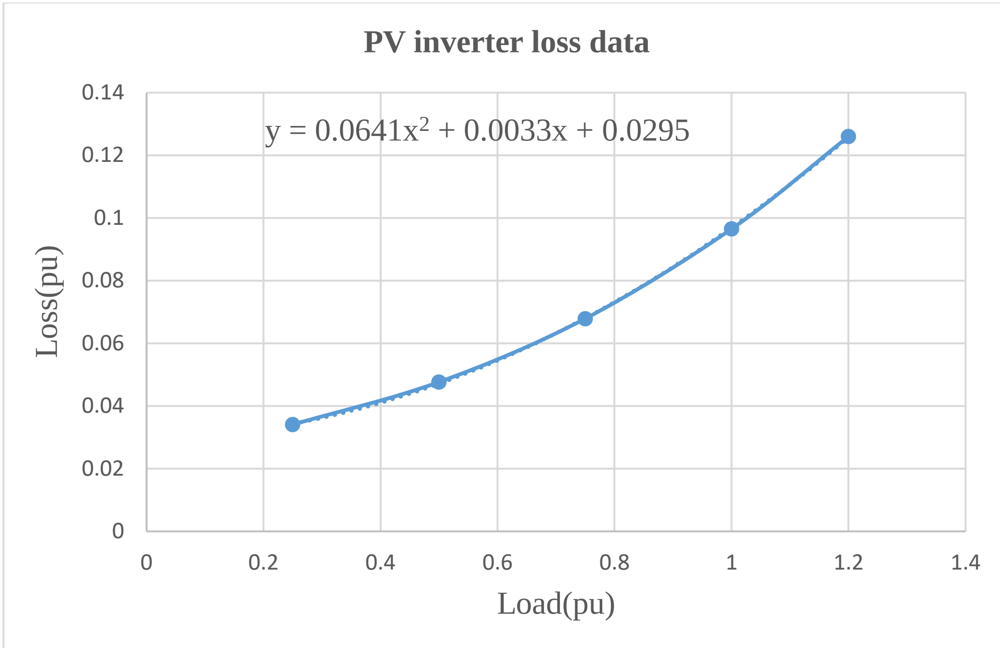


Figure 4.12. Interpolated model of PV invertor losses.

4.4.1.4 Distribution transformer loss model

The loss data of distribution transformer was obtained from [32] and it is shown in table 4.7.

Table 4.7. Measured distribution loss data (p.u.) at multiple load levels (p.u)

Load (p.u.)	Loss (p.u.)
0.10	0.00285
0.15	0.00301
0.20	0.00317
0.25	0.00329
0.30	0.00367
0.35	0.00411
0.40	0.00453
0.45	0.00510
0.50	0.00577
0.55	0.00640
0.60	0.00710
0.65	0.00789

0.70	0.00879
0.75	0.00972
0.80	0.01078
0.85	0.01181
0.90	0.01306
0.95	0.01437
1.00	0.01564

A regression analysis (or second order polynomial fit) was again done for this loss data and plotted in figure 4.13.

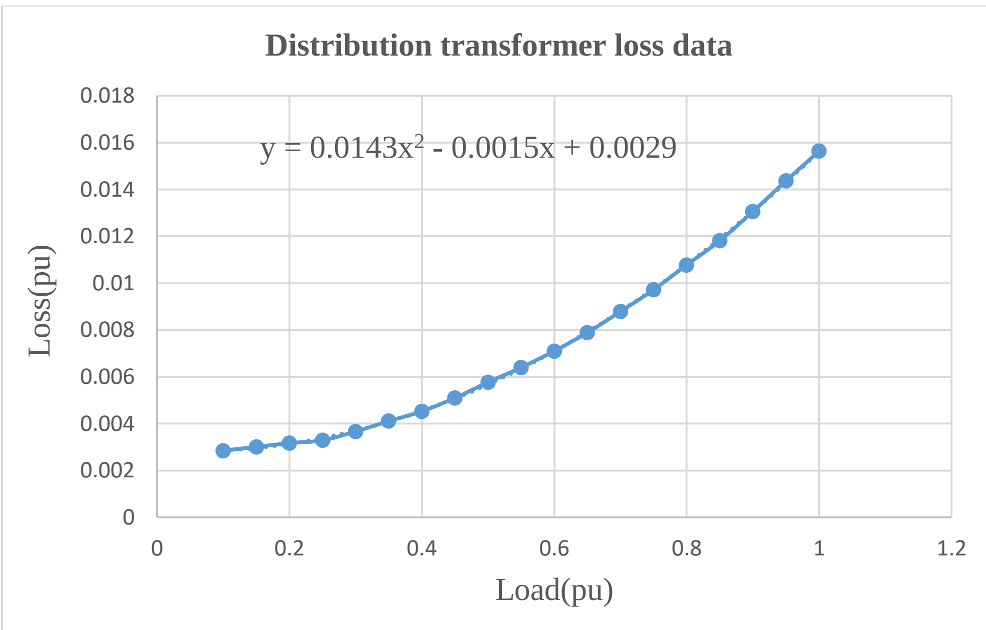


Figure 4.13. Interpolated model of distribution transformer losses.

4.4.1.5 DC Rectifier Loss Model

The loss data of 380V DC rectifier is extracted from [33] and it is tabulated in table 4.8. This loss data is based on a measured 400V DC rectifier and has the following losses which is expressed in per unit value at different loading conditions.

Table 4.8. Measured 380V rectifier loss data (p.u.) at multiple load levels (p.u.)

Load (p.u.)	0.25	0.50	0.75	1.0
Loss (p.u.)	0.0048	0.0118	0.0224	0.0363

Similarly a regression analysis (or second order polynomial fit) was again done for this loss data and plotted in figure 4.14.

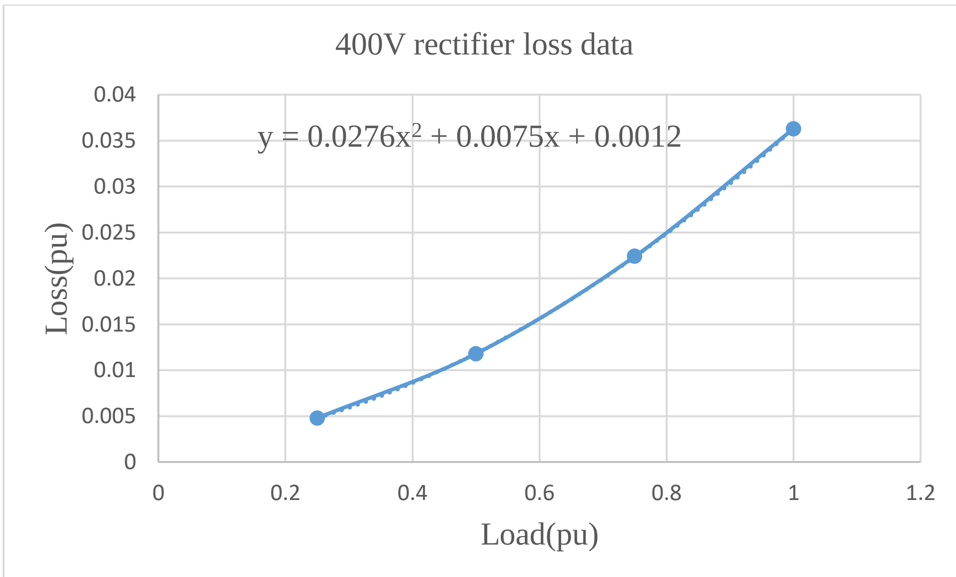


Figure 4.14. Interpolated model of rectifier losses.

4.4.2 Component Loss Coefficients

Regression analysis (or second order polynomial fit) was done for all the loss data listed above. The no-load, proportional and square-law term coefficients for the components are listed in table 4.9.

Table 4.9. No-load, proportional and square-law item coefficients.

Components	Loss item coefficients		
	*Kp*0	*Kp*1	*Kp*2
AC UPS	0.0892	-0.01096	0.11465
DC UPS	0.0152	-0.0029	0.0494
AC PSU	0.0601	-0.0933	0.1024
PV Inverter	0.0295	0.0033	0.0641
Distribution Transformer	0.0029	-0.0015	0.0143
380V DC Rectifier	0.0012	0.0075	0.0276

4.5 Efficiency of the System

Generally the energy efficiency of the data center power distribution system for both AC and DC power is calculated based on the loss data described above and by using equation 3.37 and 3.38 which is derived from section 3.10. The efficiency of the system has to be expressed in terms of load variation in a data center. The common loading levels are 25%, 50%, 75% and at full load (100%). This will be more described in the next chapter.

CHAPTER - FIVE

5. RESULTS AND DISCUSSIONS

This chapter presents the results for efficiency and reliability analysis of AC and 380V DC power distribution in data center. The efficiency analysis was done by comparing the existing system model and the proposed system for different loading conditions. The results for reliability analysis of both AC and DC distribution system model is performed by running Monte Carlo simulation using a software package called Powertechnic Analyst. Finally the cost analysis will be presented in the later section.

5.1 Efficiency Analysis

The efficiency analysis of the data center power distribution lay out can be divided into two cases: Efficiency analysis with existing system and efficiency analysis of proposed 380V DC system.

5.1.1 Efficiency Analysis of Existing Distribution System (Base Case Scenario)

The efficiency analysis results of existing AC distribution systems are presented in this section. It is done by following the different component loss model described in section 4.4. The efficiency analysis of the data center for different load conditions was carried out based on equation 3.36. By considering the efficiency plot of different equipment's used by the existing system at different load conditions, the total efficiency of the AC system is drawn.

Table 5.1 Efficiency data of different components

Components	Efficiency(%) at multiple load level				
	25%	*50%*	*75%*	*100%*	*Average*
AC UPS	73.10	81.90	84.00	84.10	80.775
DC UPS	93.44	95.04	94.84	94.19	94.38
AC PSU	85.27	92.76	94.02	93.53	91.39
DC rectifier	98.12	97.69	97.11	96.50	97.36

PV Inverter	87.93	88.96	91.68	91.17	89.94
Distribution Transformer	98.44	98.87	98.75	98.45	98.63

5.1.1.1 AC UPS Efficiency

Substituting loss data from table 4.1 or loss data points obtained from figure 4.8, efficiency data of main components in the system can be obtained as per table 5.1 above. Figure 5.1 shows the efficiency plot of AC UPS used in this thesis. From the figure, efficiency plot shows that the efficiency decreases significantly at low loads and decreases slowly on increasing the load from medium to high load.

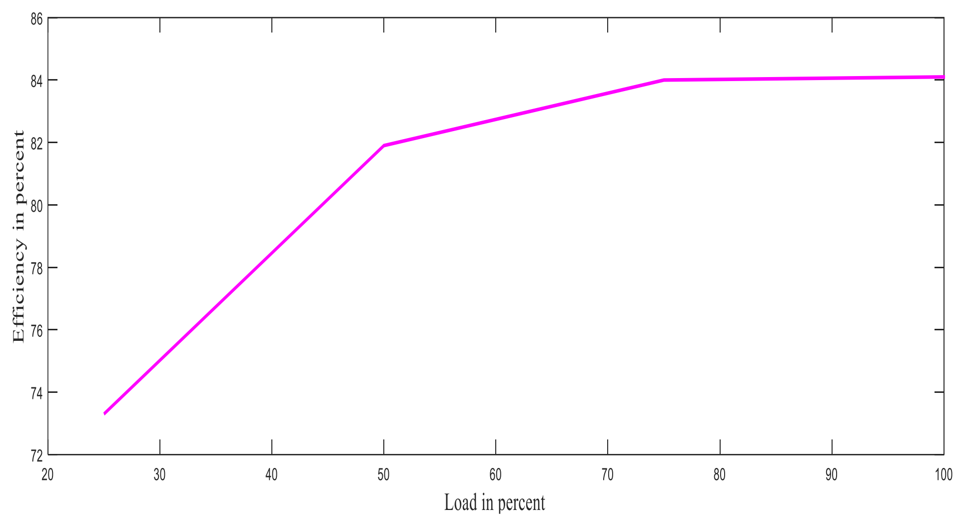


Figure 5.1. Efficiency plot of AC UPS.

As shown in figure 5.1 the minimum efficiency of the AC UPS is 87.28% at 25% load and its maximum efficiency become 88.9% at 50% loading condition. The efficiency is slightly decreased as load increases after reaching the peak loading condition.

5.1.1.2 AC PSU Efficiency

The following figure similarly shows the efficiency plot of an AC power supply unit (PSU) for the existing system configuration. From the result shown, the minimum efficiency is 85.27% at 25% load and its maximum efficiency is around 94.02% at 75% load condition.

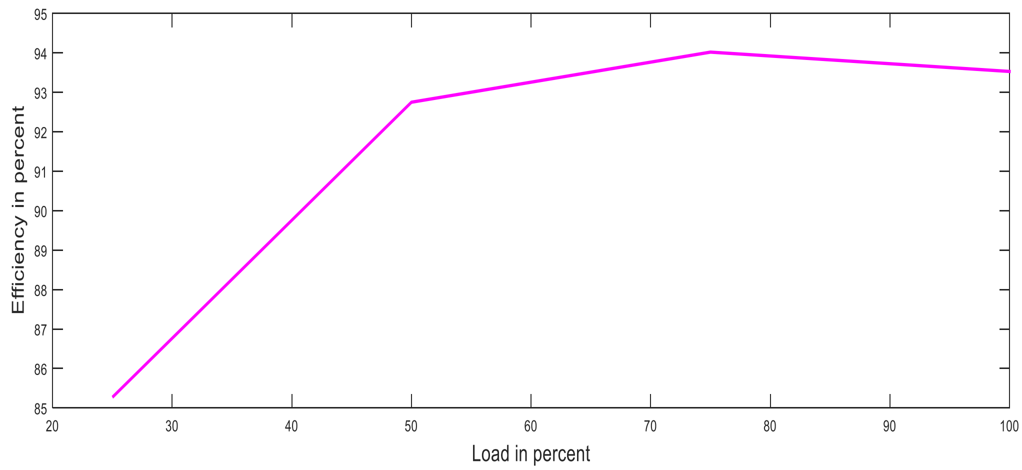


Figure 5.2. Efficiency plot of AC PSU.

5.1.1.3 Distribution Transformer Efficiency

Similarly figure 5.3 shows the efficiency plot of distribution transformer for the existing power distribution system of Debre Berhan University data center. As shown in the figure the minimum efficiency is 98.44 at 25% loading level and maximum efficiency is 98.87 at 50% loading condition. The efficiency is slightly decreased as load increases after reaching the peak (50%) loading condition.

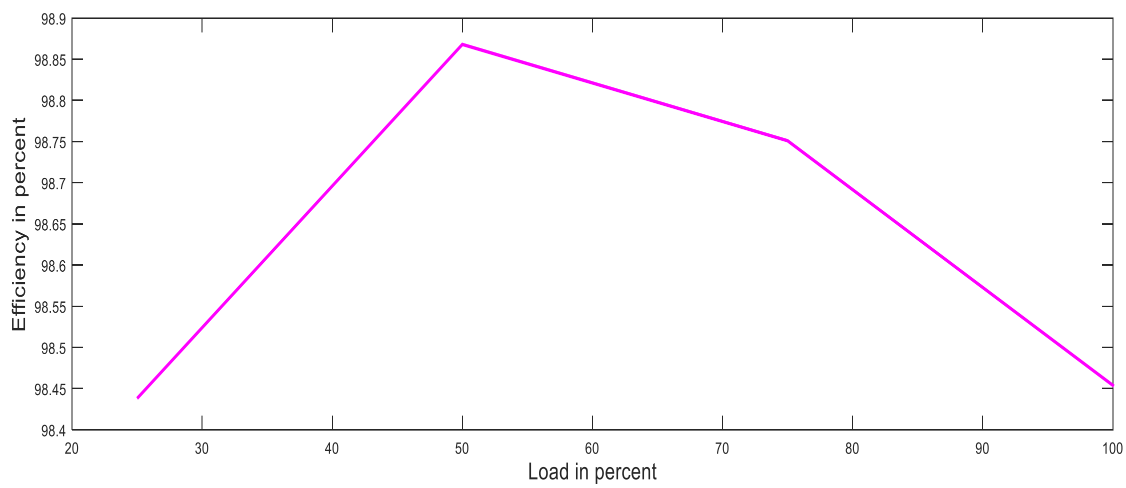


Figure 5.3. Efficiency plot of distribution transformer.

As a result the efficiency of existing AC distribution system of data center in this case study is summarized based on equation 3.37. By following it, the following table is constructed to get the total energy efficiency of the existing AC system.

Table 5.2 Efficiency of the existing AC distribution system

Load (%)	25	50	75	100	Average
Efficiency (%.)	61.4	75.02	77.97	77.44	72.96

Figure 5.4 shows the result of efficiency plot for Debre Berhan University data center power distribution system (existing AC distribution system). From the figure, result shows the minimum efficiency is 61.4% at 25% load and maximum efficiency is 77.97% at 75% load condition. For this case the average efficiency becomes 72.96%.

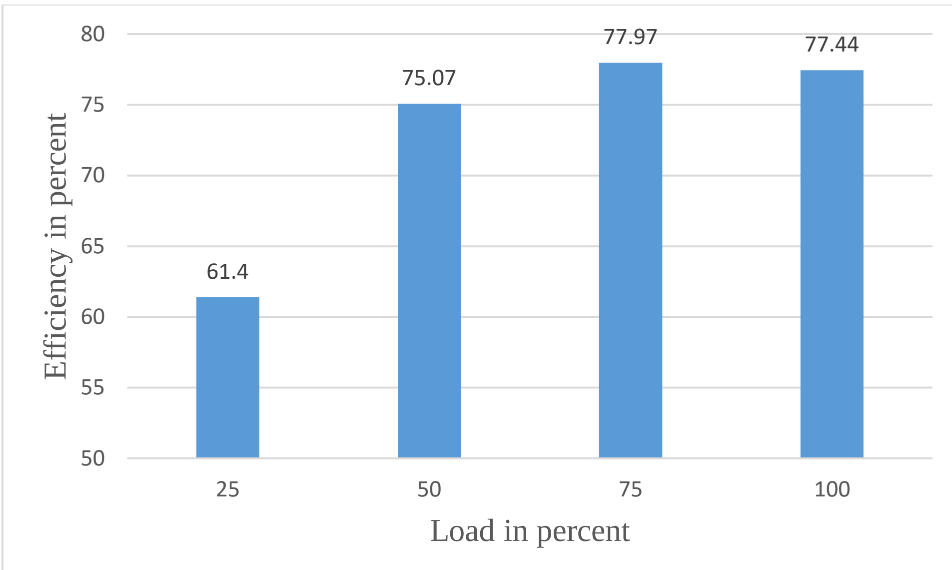


Figure 5.4 Efficiency of existing AC distribution system.

5.1.2 Efficiency Analysis of DC Distribution System (Proposed Case Scenario)

Similarly the efficiency analysis of proposed and designed DC distribution system case is presented based on the single line diagram of figure 4.8 for different load levels. By considering the efficiency plot of different equipment's used by the proposed system at different load conditions, the total efficiency of the system is drawn. The following individual components with their efficiency plot are considered to this proposed system. Following by the individual component efficiency for different loading level and using equation 3.38, the total efficiency of the DC system was constructed.

5.1.2.1 DC UPS Efficiency

Figure 5.5 shows the efficiency plot of DC UPS used in this thesis. As shown in figure, the efficiency plot shows that the efficiency decreases significantly at low loads and decreases slowly on increasing the load from medium to high load.

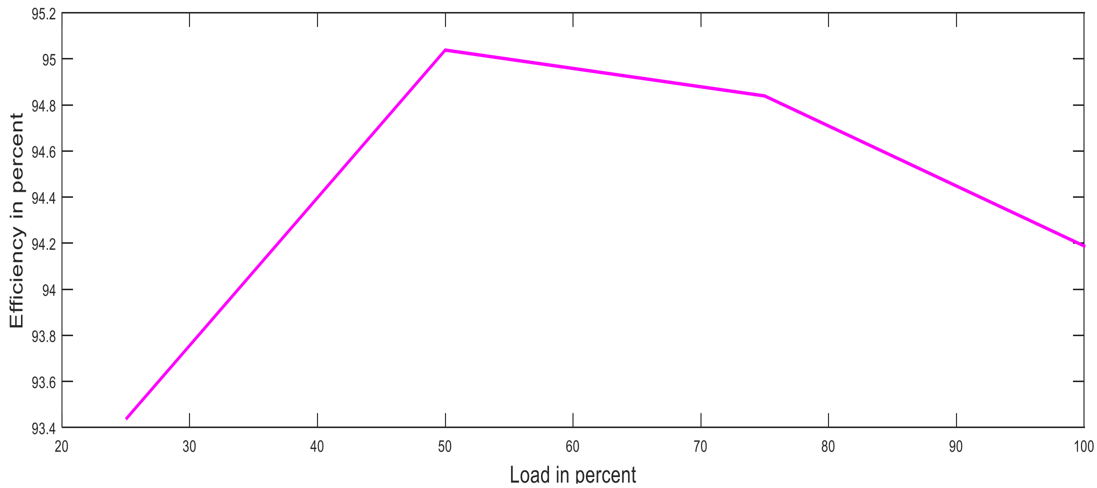


Figure 5.5. Efficiency plot of DC UPS.

As shown in figure 5.5 the minimum efficiency of the DC UPS is 93.4% at 25% load and its maximum efficiency become 95% at 50% loading condition. The efficiency is slightly decreased as load increases after reaching the peak loading condition.

5.1.2.2 DC-AC Converter (inverter) Efficiency

Converter which converts DC input power in to AC output for AC applications like lighting, computer room air conditioner (CRAC), computers and other AC data center loads are required for this proposed system model. Based on the loading condition of the data center, the efficiency result is indicated in figure 5.6 below.

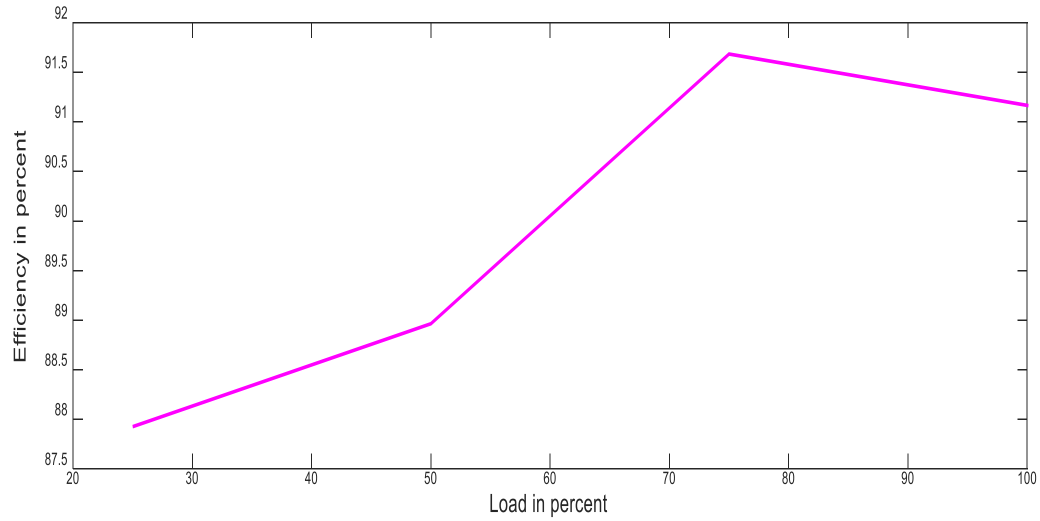


Figure 5.6. Inverter efficiency plot.

From the figure shown, minimum efficiency is 87.93% for 25% load .and maximum efficiency is around 91.68% for 75% load condition.

5.1.2.3 Rectifier Efficiency

Converter which converts AC input power in to DC power output for DC applications especially for servers in the existing system has an efficiency plot as shown in figure below. The efficiency result is based on the loading condition of the data center. As shown in figure 5.7 the minimum efficiency is 96.49% at 100% load level and maximum efficiency is around 98.12% at 25% load. From this it shows that the efficiency rectifier for this system has an inverse relationship with the loading condition. It means that as the load increases, the efficiency of the rectifier decreases.

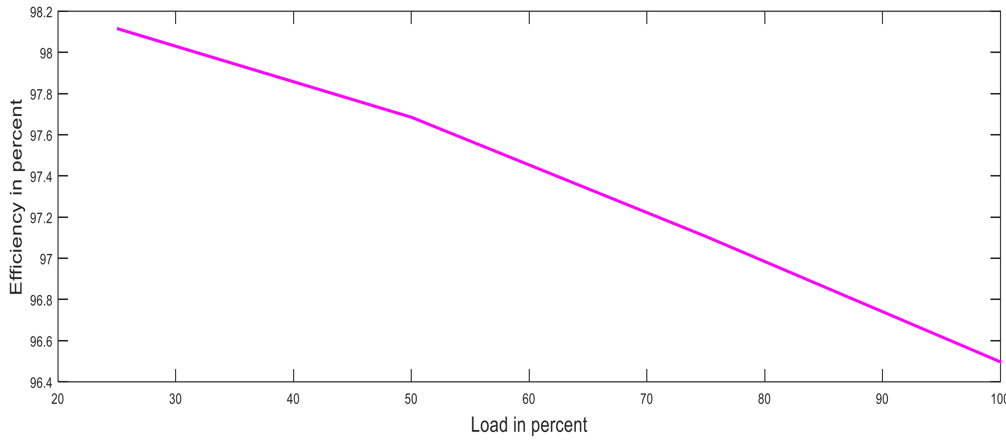


Figure 5.7. Rectifier efficiency plot.

As a result the total efficiency of proposed DC power distribution system is based on the individual component efficiency. In this case, by following equation 3.34 the following table is constructed to get the data points for total efficiency of the proposed system.

Table 5.3 Efficiency of the proposed DC distribution system

Load (%)	25	50	75	100	Average
Efficiency (%.)	80.60	82.59	84.44	82.87	82.63

Figure 5.4 shows the result of efficiency plot for Debre Berhan University data center power distribution system (proposed DC distribution system). From the figure, result shows that the minimum efficiency is 80.6% at 25% load and maximum efficiency is 84.44% at 75% load condition. For this case the average efficiency becomes 82.63%.

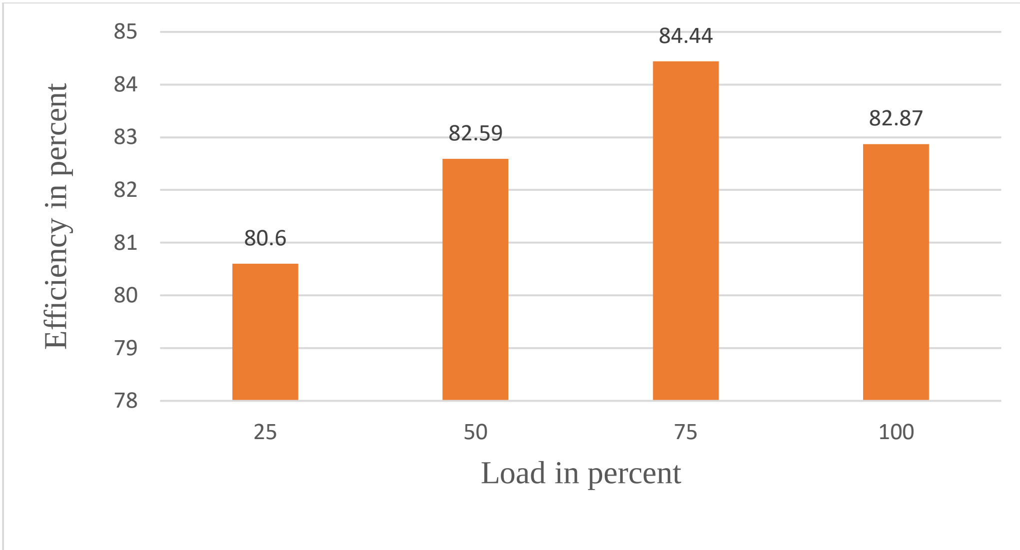


Figure 5.8 Efficiency of proposed DC distribution system.

Generally the figure 5.9 shows the bar graph showing efficiencies of AC and DC power distribution architectures for different loading conditions.

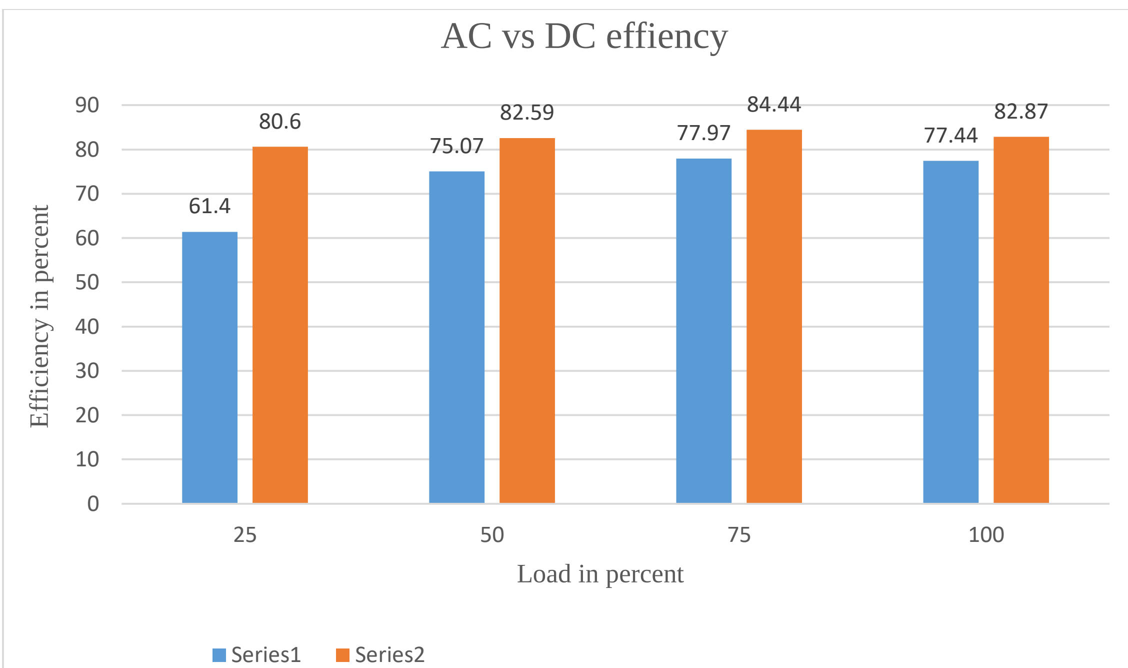


Figure 5.9 Efficiency plot of AC and proposed DC distribution system.

From figure 5.9, results show that an AC distribution system has an average efficiency of 72.96% while a proposed DC distribution system has an average efficiency of 82.63%. From this it shows that, a DC power distribution system is 9.67% efficient than AC power distribution architecture of a selected data center. From the above results, it can be said that 380V DC power distribution system in data centers is more efficient than typical AC power distribution system.

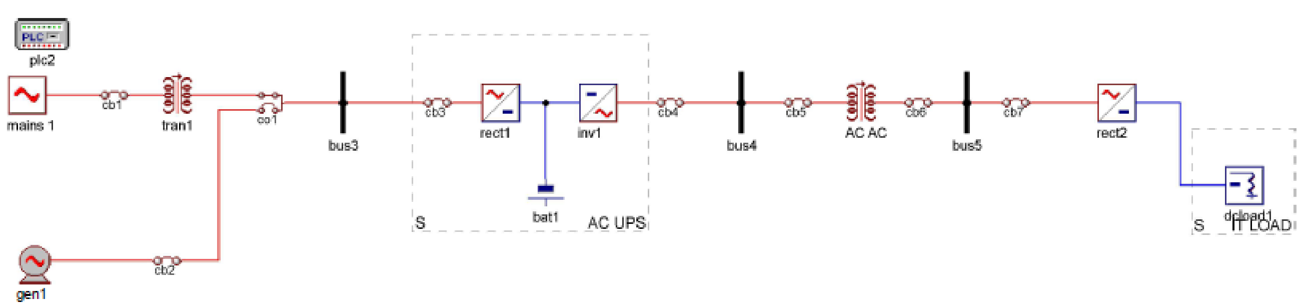
5.2 Reliability Analysis

Both the existing AC and proposed DC distribution system were modeled with their failure and repair data which are taken from table 3.4 using Analyst Enterprise software. The reliability data and the electrical parameters for each component were entered in the software. Two cases were considered for reliability studies for both distribution architecture. One with only a single active UPS and the other with additional UPSs with N+1 redundancy.

5.2.1 Case I: Single Active UPS

The most basic topology for a single UPS connection in the selected data centers with N component redundancy is using a single UPS, with battery banks for UPS. At normal operating condition, the UPS will be operating at 100% load (max). When the UPSs fails, the IT load goes out of service. It requires another power path which needs for maintenance purpose without power interruption. The simulation model and analysis is using Powertechnic Analyst software tool [L-4].

SCHEMATIC



RESULTS

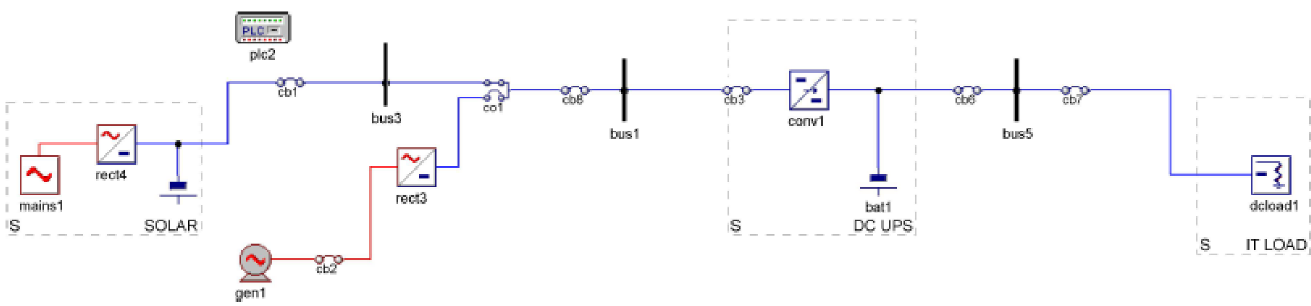
Run Name: run005 Num Runs: 1 Hrs/Run: 200000

Component	NumFailures	MTBF(yrs)	MTTR(hrs)	Av(%)	Unav(min/yr)
IT LOAD	16	1.42675	1.65599	99.98675000	69.63
AC UPS	9	2.5366	1.56607	99.99295117	37.04

Figure 5.10. Simulation model of AC topology.

The working simulation model of existing AC distribution system in a selected data center is indicated in figure 5.10. The simulation was done and, failure rate of AC system was found to be 7.009×10^{-1} failures/year. A simulation model of the proposed 380V based DC distribution is also drawn in figure 5.11 below. The failure rate of the 380V DC distribution system becomes 4.38×10^{-2} failures/year. From these, the failure rate of DC system is 0.0625 times the failure rate of the AC system. Hence, the DC system is more reliable than AC system, as DC systems has higher MTBF, as shown in the result table of figures 5.10 and 5.11.

SCHEMATIC



RESULTS

Run Name: run023 Num Runs: 1 Hrs/Run: 200000

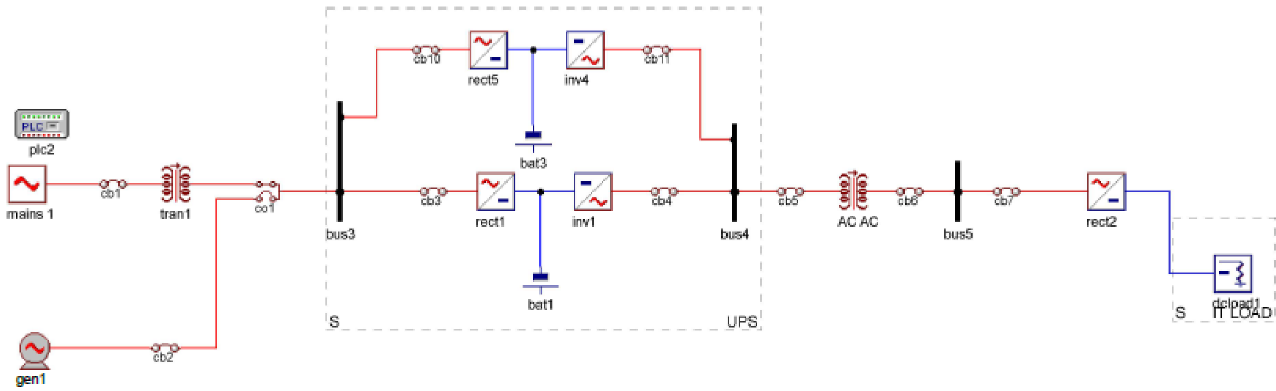
Component	NumFailures	MTBF(yrs)	MTTR(hrs)	Av(%)	Unav(min/yr)
DC UPS	7	3.26106	4.5863	99.98394922	84.37
IT LOAD	1	22.8291	17.0964	99.99145312	44.93
SOLAR	53	0.430653	1.06834	99.97168848	148.80

Figure 5.11. Simulation model of proposed 380V DC topology.

5.2.2 Case II: Multiple Active UPSs with N+1 Redundancy

This topology has an additional UPS in the main path to have N+1 redundancy. Here, two active UPSs are ready to supply the IT load. In this case, each UPS in the path will be operating at 50% load at normal operating condition. One UPS is able to supply the IT load when the other UPS system fail. The UPS system is designed in such a way that a single UPS can handle full data center load. For the distribution path of the IT load to go out of service, when both UPSs have to fail at the same time.

SCHEMATIC



RESULTS

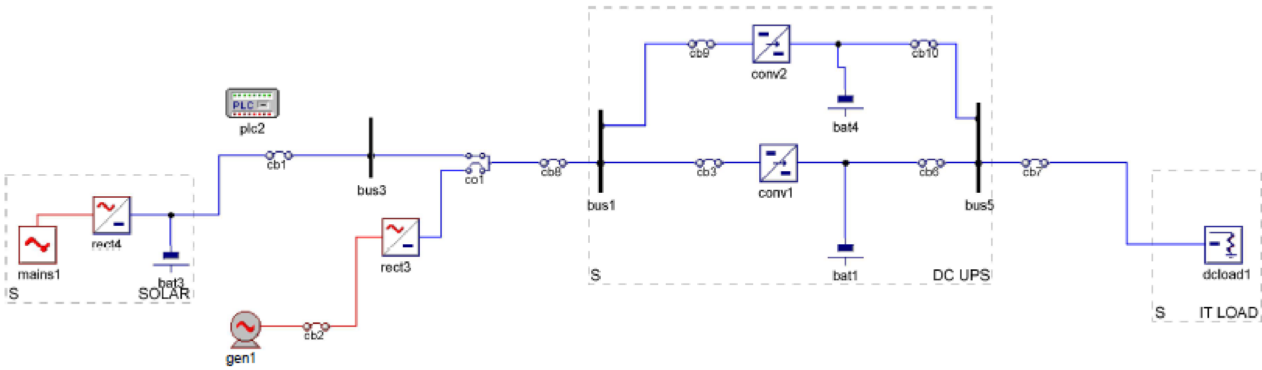
Run Name: run010 Num Runs: 1 Hrs/Run: 200000

Component	NumFailures	MTBF(yrs)	MTTR(hrs)	Av(%)	Unav(min/yr)
UPS	44	0.518682	1.79826	99.96043653	207.94
IT LOAD	6	3.80503	1.26764	99.99619141	19.99

Figure 5.12. Simulation model of N+1 AC topology.

Figure 5.12 shows the working simulation model of N+1 AC distribution system of existing data center. The failure rate of this system was found to be 2.628×10^{-1} failures/year. This result is clearly less frequent than the AC system with a single UPS in the previous case. The failure rate of the DC system with N+1 UPS system in figure 5.13 is 4.38×10^{-2} failures/year, which is similar with that of the DC system with a single UPS as shown in the previous case. The difference in a DC system with single UPS and double UPS system is the reduction of mean time to repair (MTTR) value. In this case (N+1 UPS redundancy), failure rate of the DC system is 0.0.167 times the failure rate of the AC system. In both cases, the mean time to repair (MTTR) of the system is further decreases as the number of redundancy increases as seen from the result tables from figure 5.10 through figure 5.13. From the above result it is clear that the DC system has more reliable than the AC system with a relative lower failure rate and high mean time between failure values.

SCHEMATIC



RESULTS

Run Name: run023 Num Runs: 1 Hrs/Run: 200000

Component	NumFailures	MTBF(yrs)	MTTR(hrs)	Av(%)	Unav(min/yr)
SOLAR	44	0.518801	0.757973	99.98332812	87.65
IT LOAD	1	22.8309	1.19631	99.99939844	3.14
DC UPS	10	2.28291	1.74358	99.99127930	45.82

Figure 5.13. Simulation model of 380V"N+1" DC topology.

From the above it is concluded that, as the level of redundancy in the UPS system was further increased to N+2, N+3 and so on, mean time between failures (MTBF) becomes increased and in contrast the mean time to repair (MTTR) value is decreased. As a result, this shows the reliability of the system becomes further increased.

5.3 Energy Cost Calculation

In this section the Life Cycle Cost (LCC) estimation of the designed stand-alone PV system is discussed. The LCC of an item consists of the total costs of owning and operating an item over its lifetime, expressed in today's money exchange. The costs of a stand-alone PV system include acquisition costs, operating costs, maintenance costs, and replacement costs. All these costs have the following specifications [34]:

- The initial cost of the system (the capital cost) is high.
- There are no fuel costs.
- Maintenance costs are low.
- Replacement costs are low (mainly for batteries).

The LCC of the PV system includes the sum of all the present worth's (PWs) of the costs of the PV modules, storage batteries, battery charger, and inverter, the cost of the installation, and the maintenance and operation cost (M&O) of the system. The lifetime N of all the items is considered to be 25 years, except that of the battery which is considered to be 5 years. Thus, an extra 2 groups of batteries (each of 2 batteries) have to be purchased, after 5 years, 10 years, 15 years and 20 years, assuming inflation rate i of 3% and a discount or interest rate d of 10%. Therefore, the PWs of all the items can be calculated as follows [34]:

- PV array cost (C_{PV}) = \$3.14/w x 88 x 300w = **\$82,896** [35]
- Initial cost of batteries (C_B) = \$0.24/Ah x 600Ah x 32 = **\$4,608** [36]
- The PW of the 1st extra group of batteries (purchased after N = 5 years), C_{B1PW} can be calculated as:

$$C_{BIPW} = C_B \left(\frac{1+i}{1+d} \right)^N \tag{5.1}$$

$$C_{BIPW} = \$4608\ x\ \left(\frac{1+0.03}{1+0.1} \right)^5$$

C_{B1PW} = **\$3,316.92**

- The PW of the 2nd extra group of batteries (purchased after N = 10 years) C_{B2PW}, the 3rd extra group (purchased after N = 15 years) C_{B3PW}, and that of the 4th extra group (purchased after N = 20 years) C_{B4PW} are calculated, using Eq. (5.1), to be **\$2,387.58**, **\$1,718.62** and **\$1,237.10,** respectively.
- Charge controller cost C_C = \$42.49 x 2 = **\$84.98**
- Inverter cost C_{Inv} = **\$1,553.21**
- Installation cost C_{Inst} = 0.1 x 82896 = **\$8,289.6**. [34]
- The PW of the maintenance cost C_{MPW} can be calculated using the maintenance cost per year (M/yr) and the lifetime of the system (N = 25 years). And maintenance cost is taken to be 2% of the total PV cost, which is equal to \$1657.92.

$$C_{MPW} = \left(\frac{M}{yr}\right) x \left(\frac{1+i}{1+d}\right) x \left(\frac{1-\left(\frac{1+i}{1+d}\right)^{N}}{1-\left(\frac{1+i}{1+d}\right)}\right) \tag{5.2}$$

Hence,

$$C_{MPW} = \left(1657.92\right) x \left(\frac{1+0.03}{1+0.1}\right) x \left(\frac{1-\left(\frac{1+0.03}{1+0.1}\right)^{25}}{1-\left(\frac{1+0.03}{1+0.1}\right)}\right)$$

C_{MPW} = **$19,680.82**

Therefore, the LCC of the system can be calculated as the following equation.

$$LCC = C_{PV} + C_{B} + C_{B1PW} + C_{B2PW} + C_{B3PW} + C_{B4PW} + C_{C} + C_{Inv} + C_{Ins} + C_{MPW}. \tag{5.3}$$

Hence,

LCC = $82,896 + $4,608 + $3,316.92+ $2,387.58 + $1,718.62+ $1,237.1 + $84.98 + $1,553.21 + $8289.6 + $19,680.82

LCC = $125,772.83

It is sometimes useful to calculate the LCC of a system on an annual basis. The annualized LCC (ALCC) of the PV system in terms of the present day dollars can be calculated using the following equation.

$$ALCC = LCC\ x \left(\frac{1-\left(\frac{1+i}{1+d}\right)}{1-\left(\frac{1+i}{1+d}\right)^{N}}\right) \tag{5.4}$$

Hence,

$$ALCC = \$125,772.83\ x \left(\frac{1-\left(\frac{1+0.03}{1+0.1}\right)}{1-\left(\frac{1+0.03}{1+0.1}\right)^{25}} \right)$$

ALCC = $9,920.92

Once the ALCC is known, the unit electrical cost (cost of 1 kWh) can be calculated, to be $0.238/kWh, from equation (5.5).

$$Unit\ Electrical\ Cost\ = \frac{ALCC}{365E_L} \tag{5.5}$$

$$Unit\ Electrical\ Cost\ = \frac{\$9920.92}{365\ \text{x}\ 114.051\ KWh/yr}$$

= $0.238/kWh

It is to be noted, here, that this price is very high compared to the current unit cost of electricity in Ethiopia for 15Kv customer is 0.8008 Birr/kWh. That is, (0.8008 Birr/kWh) x ($1/34.09 Birr) = **$0.0235/kWh**. PV energy generation for data center is important due to its better efficiency and reliability to the power distribution system. This price is also free from interruption and fuel cost.

CHAPTER - SIX

6. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

6.1 Conclusion

In this thesis the improvement method of data center's efficiency and reliability has been presented. A 380V solar powered DC power distribution architecture has been proposed to obtain improved efficiency and better reliability in data center power distribution system. The design of solar power for overall data center loads has also been included. The efficiency analysis shows that solar powered DC distribution system is more efficient than the typical AC distribution system at different load levels. Results show that 380V solar powered DC distribution has an average of 9.67% efficient than AC power distribution architecture of a selected data center for different loading level typically 25%, 50%, 75% and at full load (100%). This improvement is due to the reduction of number of convertors and high component efficiency of the proposed DC distribution system for a selected data center.

The reliability analysis of both AC and DC powering option for power distribution in data centers shows that 380V DC distribution system is more reliable than typical AC distribution system up to certain level of redundancy in the UPS systems. As the number of UPSs in each path is increased, the values of reliability for AC system will approach the reliability metrics values of the DC system.

6.2 Recommendation

Based on this thesis work it is recommended that the Ethiopian companies which installs a data center to facilitate their work and business should installed a renewable energy based direct current distribution system to supply all data center loads. This leads to improve the overall efficiency and reliability of the system, especially in all universities of the country. The government of the country should also promote the use of micro grid based renewable energy sources with DC distribution for most DC load types.

For the practical implementation of the work, the selected case area called Debre Berhan University should have to considered this study and update the system based on this work.

6.3 Future Work

A DC distribution system for data center is not widely used in Ethiopia. This research work mainly focus on the design of a DC distribution system with efficiency and reliability improvement for Debre Berhan University data center. A lot of research is already being done in this field. Further research should be done in a micro grid based DC distribution system. The following research future works are important to be considered.

- Research on DC circuit breakers and electrical safety.
- Setting electrical building codes for DC distribution system.
- Fault detection and analysis and protection of DC distribution system to improve the power quality.
- Converting and developing all data center equipment's in to DC equipment's that are compatible with 380V DC distribution system.
- Developing dc plugs, switches ,sockets and circuit breakers
- Integrating other available renewable energy sources with optimized energy management system.
- Further research on data center effectiveness measures by considering the metrics included by this paper and other excluded effectiveness parameters.

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Appendices

Appendix A: MATLAB Code for Efficiency Plot

```
x = [25 50 75 100]

x =

    25    50    75   100

y = [87.28 88.9 88.79 88.4]

y =

   87.2800   88.9000   88.7900   88.4000

plot(x,y)

xlabel('Load in percent')

ylabel('Efficiency in percent')

l = [25 50 75 100]

l =

    25    50    75   100

e = [93.44 95.04 94.84 94.19]

e =

   93.4400   95.0400   94.8400   94.1900

plot(l,e)

xlabel('Load in percent')

ylabel('Efficiency in percent')

x = [25 50 75 100]

x =

    25    50    75   100

y = [87.28 88.9 88.79 88.4]

y =

   87.2800   88.9000   88.7900   88.4000

e = [85.27 92.76 94.02 94.19]

e =
```

```
   85.2700   92.7600   94.0200   94.1900
plot(x,e)
xlabel('Load in percent')
ylabel('Efficiency in percent')
x = [25 50 75 100]
x =
    25    50    75   100
z = [85.68 93.74 95.04 94.44]
z =
   85.6800   93.7400   95.0400   94.4400
xlabel('Load in percent')
ylabel('Efficiency in percent')
x = [25 50 75 100]
x =
    25    50    75   100
 z = [85.68 93.74 95.04 94.44]
z =
   85.6800   93.7400   95.0400   94.4400
 plot(x,z)
xlabel('Load in percent')
ylabel('Efficiency in percent')
>> x = [25 50 75 100]
x =
    25    50    75   100
r = [87.93 88.96 91.68 91.17]
r =
   87.9300   88.9600   91.6800   91.1700
plot(x,r)
```

```
xlabel('Load in percent')

ylabel('Efficiency in percent')

x = [10 20 30 40 50 60 70 80 90 100]

x =

    10    20    30    40    50    60    70    80    90   100

k = [97.19 98.44 98.75 98.87 98.82 98.75 98.66 98.56 98.45 ]

k =

   97.1900   98.4400   98.7500   98.8700   98.8200   98.7500   98.6600   98.5600   98.4500

p = [97.19 98.44 98.75 98.87 98.87 98.82 98.75 98.66 98.56 98.45 ]

p =

   97.1900   98.4400   98.7500   98.8700   98.8700   98.8200   98.7500   98.6600   98.5600
98.4500

plot(x,p)

xlabel('Load in percent')

ylabel('Efficiency in percent')

x = [25 50 75 100]

x =

    25    50    75   100

m = [98.12 97.68 97.11 96.5]

m =

   98.1200   97.6800   97.1100   96.5000

plot(x,m)

xlabel('Load in percent')

ylabel('Efficiency in percent')
```

Appendix B: Backup Diesel Generator Specification

PRAMAC GSW 110	
Main specifications	
Type	Canopied
Standby power LTP	108 kVA
Rated prime power (PRP)	102 kVA
Rated continuous power (COP)	97 kVA
Phases	3
Voltage	400 V
Frequency	50 Hz
Battery charger current	55 A
Circuit breaker	160
Ratio	0 , 97

Caracterisitici tehnice	
Dimensional data	
Length	3000 mm
Width	1150 mm
Height	1680 mm
Dry weight	1690 kg
Additional information	
Fuel tank location	Internal
Fuel tank capacity	340 l
Running time at 100% PRP	15 ,29 h
Running time at 75% PRP	20 h
Measured acoustic power (LWA) at 10 mt	96 ,8 dBA
Noise level at 7 m	71 ,8 dBA
Guaranteed noise level (LWA)	97 dBA
Scale specifications	
Electric protection grade	IP 23
Engine specifications	
Engine manufacturer	Deutz
Model	BF4M1013EC
Stroke	4 , diesel
Fuel	Diesel
Number of cylinders and disposition	4 , inline
Displacement	4760 cm³
Air intake	Turbocharged, CAC
Starting system	Electric
Nominal operating speed	1500 rpm

Speed governor	Mechanical
SAE	n.a.
Flywheel	n.a.
Continuous power COP	86 ,1 kW
Prime power PRP	91 ,1 kW
Lube oil capacity	11 l
Coolant capacity	19 ,7 l
Fuel consumption at 100% PRP	22 l/h
Fuel consumption at 75% PRP	17 l/h
Maximum lube oil consumption at PRP	0 ,3 %
Electric circuit voltage	12 V
Engine derating	1 , 0
Cooling fan	Mechanical

Appendix C: Double conversion AC UPS Specification

Specifications

OUTPUT	
Output Volt Amp Capacity (VA)	40000
Output kVA Capacity (kVA)	40
Output Watt Capacity (Watts)	32000
Output kW Capacity (kW)	32
Power Factor	0.8
Crest Factor	3:1
Nominal Output Voltage(s) Supported	220/380V; 230/400V; 240/415V; 3-Phase Wye
Frequency Compatibility	50 / 60 Hz
Output Voltage Regulation (Line Mode)	+/- 1%
Output Voltage Regulation (Battery Mode)	+/- 1%
Output Receptacles	Hardwire
Output AC Waveform (AC Mode)	Sine wave
Output AC Waveform (Battery Mode)	Pure Sine wave

INPUT	
Rated input current (Maximum Load)	48A/50A/53A
Nominal Input Voltage(s) Supported	220/380V (3ph wye); 230/400V (3ph wye); 240/415V (3ph wye)
Nominal Input Voltage Description	3-Phase Wye, 4 wire (L1, L2, L3, N, G)
UPS Input Connection Type	Hardwire
Input Phase	3-Phase
BATTERY	
Full Load Runtime (min.)	5.5 min. (32kw)
Half Load Runtime (min.)	13 min. (16kw)
Expandable Battery Runtime	Supports extended runtime with optional external battery packs
External Battery Pack Compatibility	BP480V103; BP480V140; BP480V26B; BP480V40C; BP480V55; BP480V78; BP480V200; BP480V300; BP480V400; BP480V500
Expandable Runtime Description	External battery pack wiring is contractor supplied
DC System Voltage (VDC)	+/- 240VDC
Battery Recharge Rate (Included Batteries)	4 hours from 10% to 90%
Battery Replacement Description	Hot-swappable, replaceable batteries

Appendix D: Detail Interruption Report for Substation Feeder which is connected to Debre Berhan University {2011 E.C (2018/19)}.

Table A-1. Debre Berhan Blanket Factory, 15 kV(F-4)

S. NO	Date	Type of fault (relay acted)	Cause of fault	Time								
				Interruption			Reconnection			Difference (Δt)		
				Hrs	min	sec	Hrs	min	sec	Hrs	min	sec
1	03/01/11	EF	Load shad.	10	30	0	12	30	0	2	0	0
2	30/01/11	EF	maintenance	06	30	0	07	30	0	1	0	0
3	30/01/11	EF	,,	08	00	0	09	30	0	1	30	0
4	30/01/11	EF	Bird	11	30	0	13	30	0	2	0	0
5	30/01/11	EF	Load shad.	16	30	0	17	30	0	1	0	0
6	30/01/11	EF	Line broken	11	20	0	12	00	0	0	3	0

7	**30/01/11**	**EF**	**maintenance**	**14**	**30**	**0**	**14**	**50**	**0**	**0**	**20**	**0**
8	**30/01/11**	**EF**	**Fallen tree**	**11**	**30**	**0**	**13**	**40**	**0**	**2**	**10**	**0**
9	**30/01/11**	**EF**	**maintenance**	**01**	**30**	**0**	**03**	**30**	**0**	**2**	**0**	**0**
10	**30/01/11**	**EF**	**Load shad.**	**08**	**30**	**0**	**09**	**30**	**0**	**1**	**0**	**0**
11	**30/01/11**	**EF**	**maintenance**	**08**	**30**	**0**	**10**	**35**	**0**	**2**	**05**	**0**
12	**01/02/11**	**O.C**	**Sheno line**	**12**	**30**	**0**	**14**	**0**	**0**	**1**	**30**	**0**
13	**02/02/11**	**EF**	**Broken line**	**12**	**00**	**0**	**13**	**40**	**0**	**1**	**40**	**0**
14	**04/02/11**	**EF**	**Birds**	**09**	**10**	**0**	**12**	**30**	**0**	**3**	**20**	**0**
15	**05/02/11**	**SC**	**Load shad.**	**08**	**30**	**0**	**09**	**30**	**0**	**1**	**0**	**0**
16	**06/02/11**	**EF**	**maintenance**	**08**	**30**	**0**	**10**	**35**	**0**	**2**	**05**	**0**
17	**06/02/11**	**EF**	**Un known**	**08**	**30**	**0**	**10**	**35**	**0**	**2**	**05**	**0**
18	**10/02/11**	**Loose**	**Load shad.**	**18**	**10**	**0**	**20**	**40**	**0**	**2**	**30**	**0**
19	**11/02/11**	**EF**	**maintenance**	**08**	**30**	**0**	**10**	**35**	**0**	**2**	**05**	**0**
20	**12/02/11**	**OI**	**,,**	**09**	**10**	**0**	**12**	**30**	**0**	**3**	**20**	**0**
21	**13/02/11**	**OC**	**maintenance**	**16**	**20**	**0**	**17**	**50**	**0**	**1**	**30**	**0**
22	**15/02/11**	**OI**	**Un known**	**09**	**10**	**0**	**12**	**30**	**0**	**3**	**20**	**0**
23	**16/02/11**	**OI**	**maintenance**	**06**	**05**	**0**	**07**	**10**	**0**	**1**	**05**	**0**
24	**17/02/11**	**EF**	**Un known**	**14**	**05**	**0**	**14**	**10**	**0**	**0**	**05**	**0**
25	**19/02/11**	**SC**	**Broken line**	**17**	**10**	**0**	**17**	**20**	**0**	**0**	**10**	**0**
26	**22/02/11**	**,,**	**maintenance**	**19**	**0**	**0**	**20**	**0**	**0**	**1**	**0**	**0**
27	**24/02/11**	**OI**	**L. shading**	**12**	**25**	**0**	**13**	**40**	**0**	**1**	**15**	**0**
28	**25/02/11**	**SC**	**Car**	**18**	**10**	**0**	**19**	**20**	**0**	**1**	**10**	**0**
29	**26/02/11**	**EF**	**Birds**	**06**	**30**	**0**	**06**	**35**	**0**	**0**	**05**	**0**
30	**27/02/11**	**EF**	**maintenance**	**07**	**40**	**0**	**07**	**45**	**0**	**0**	**05**	**0**
31	**29/02/11**	**SC**	**maintenance**	**07**	**40**	**0**	**07**	**45**	**0**	**0**	**05**	**0**
32	**30/02/11**	**OI**		**08**	**55**	**0**	**12**	**0**	**0**	**3**	**05**	**0**
33	**02/03/11**	**O.C**	**Unknown**	**10**	**05**	**0**	**10**	**10**	**0**	**0**	**05**	**0**
34	**04/03/11**	**,,**	**Shading**	**12**	**45**	**0**	**13**	**45**	**0**	**1**	**0**	**0**
35	**05/03/11**	**,,**	**Un known**	**14**	**30**	**0**	**14**	**40**	**0**	**0**	**10**	**0**
36	**07/03/11**	**EF**	**Fallen tree**	**12**	**45**	**0**	**13**	**0**	**0**	**0**	**15**	**0**
37	**09/03/11**	**,,**	**Shading**	**07**	**30**	**0**	**12**	**05**	**0**	**4**	**25**	**0**
38	**11/03/11**	**O.C**	**L. shading**	**08**	**15**	**0**	**08**	**20**	**0**	**0**	**05**	**0**
39	**12/03/11**	**EF/SC**	**Un known**	**10**	**25**	**0**	**10**	**28**	**0**	**0**	**03**	**0**
40	**13/03/11**	**,,**	**Shading**	**12**	**45**	**0**	**13**	**45**	**0**	**1**	**0**	**0**
41	**14/03/11**	**,,**	**Un known**	**14**	**30**	**0**	**14**	**40**	**0**	**0**	**10**	**0**
42	**15/03/11**	**EF**	**Fallen tree**	**12**	**45**	**0**	**13**	**0**	**0**	**0**	**15**	**0**
43	**16/03/11**	**,,**	**Shading**	**07**	**30**	**0**	**10**	**40**	**0**	**3**	**10**	**0**
44	**17/03/11**	**OI**	**maintenance**	**08**	**0**	**0**	**12**	**0**	**0**	**4**	**0**	**0**
45	**18/03/11**	**OI**	**Unknown**	**12**	**10**	**0**	**12**	**20**	**0**	**0**	**10**	**0**

46	**19/03/11**	**OC**	**L. Shading**	**19**	**15**	**0**	**20**	**25**	**0**	**1**	**10**	**0**
47	**20/03/11**	**OC**	**Broken phas**	**14**	**40**	**0**	**14**	**50**	**0**	**0**	**10**	**0**
48	**21/03/11**	**EF**	**Un known**	**08**	**45**	**0**	**09**	**20**	**0**	**0**	**35**	**0**
49	**22/03/11**	**EF**	**maintenance**	**18**	**0**	**0**	**21**	**10**	**0**	**3**	**10**	**0**
50	**23/03/11**	**OI**	**’’**	**11**	**10**	**0**	**11**	**20**	**0**	**0**	**10**	**0**
51	**24/03/11**	**OC**	**Shading**	**07**	**50**	**0**	**12**	**40**	**0**	**4**	**50**	**0**
52	**24/03/11**	**„**	**Shading**	**06**	**45**	**0**	**07**	**45**	**0**	**1**	**0**	**0**
53	**25/03/11**	**„**	**Un known**	**14**	**30**	**0**	**14**	**33**	**0**	**0**	**03**	**0**
54	**26/03/11**	**EF**	**Fallen tree**	**06**	**40**	**0**	**06**	**55**	**0**	**0**	**15**	**0**
55	**27/03/11**	**OI**	**L. Shading**	**07**	**30**	**0**	**12**	**05**	**0**	**4**	**25**	**0**
56	**28/03/11**	**„**	**„**	**15**	**45**	**0**	**16**	**45**	**0**	**1**	**0**	**0**
57	**29/03/11**	**„**	**Un known**	**14**	**30**	**0**	**14**	**40**	**0**	**0**	**10**	**0**
58	**30/03/11**	**EF**	**Fallen tree**	**07**	**10**	**0**	**08**	**25**	**0**	**0**	**15**	**0**
59	**05/03/11**	**„**	**Shading**	**08**	**30**	**0**	**11**	**05**	**0**	**2**	**25**	**0**
60	**09/04/11**	**„**	**maintenance**	**03**	**10**	**0**	**04**	**20**	**0**	**1**	**10**	**0**
61	**12/04/11**	**EF**	**Shading**	**18**	**0**	**0**	**20**	**0**	**0**	**2**	**0**	**0**
62	**13/04/11**	**„**	**maintenance**	**10**	**05**	**0**	**13**	**05**	**0**	**3**	**0**	**0**
63	**17/04/11**	**EF/SC**	**Birds**	**18**	**0**	**0**	**20**	**0**	**0**	**2**	**0**	**0**
64	**21/04/11**	**„**	**Broken line**	**07**	**10**	**0**	**11**	**10**	**0**	**4**	**0**	**0**
65	**23/04/11**	**EF/SC**	**L maintenance**	**20**	**0**	**0**	**21**	**30**	**0**	**1**	**30**	**0**
66	**24/04/11**	**„**	**Un known**	**15**	**05**	**0**	**17**	**05**	**0**	**2**	**0**	**0**
67	**28/04/11**	**„**	**maintenance**	**07**	**05**	**0**	**10**	**10**	**0**	**3**	**05**	**0**
68	**02/05/11**	**„**	**Shading**	**08**	**40**	**0**	**12**	**15**	**0**	**3**	**35**	**0**
69	**07/05/11**	**„**	**maintenance**	**07**	**33**	**0**	**09**	**36**	**0**	**2**	**03**	**0**
70	**08/05/11**	**OI**	**maintenance**	**10**	**30**	**0**	**11**	**20**	**0**	**0**	**50**	**0**
71	**09/05/11**	**„**	**Shading**	**14**	**0**	**0**	**14**	**03**	**0**	**0**	**03**	**0**
72	**15/05/11**	**EF/SC**	**Un known**	**12**	**50**	**0**	**13**	**0**	**0**	**0**	**10**	**0**
73	**19/05/11**	**„**	**maintenance**	**09**	**10**	**0**	**12**	**0**	**0**	**2**	**55**	**0**
74	**20/05/11**	**OC**	**Un known**	**11**	**05**	**0**	**12**	**0**	**0**	**0**	**55**	**0**
75	**22/05/11**	**EF**	**Animals**	**16**	**00**	**0**	**16**	**45**	**0**	**0**	**45**	**0**
76	**23/05/11**	**OI**	**Technical fault**	**18**	**00**	**0**	**10**	**40**	**0**	**0**	**40**	**0**
77	**27/06/11**	**EF**	**Un known**	**08**	**20**	**0**	**09**	**30**	**0**	**1**	**10**	**0**
78	**03/06/11**	**OI**	**L.O.L**	**12**	**30**	**0**	**18**	**0**	**0**	**5**	**30**	**0**
79	**04/06/11**	**EF**	**Shading**	**07**	**25**	**0**	**12**	**0**	**0**	**4**	**35**	**0**
80	**05/06/11**	**EF**	**„**	**15**	**05**	**0**	**15**	**55**	**0**	**0**	**50**	**0**
81	**05/06/11**	**EF**	**„**	**18**	**45**	**0**	**22**	**0**	**0**	**3**	**15**	**0**
82	**11/06/11**	**OI**	**maintenance**	**12**	**0**	**0**	**18**	**0**	**0**	**6**	**0**	**0**
83	**12/06/11**	**OC**	**maintenance**	**13**	**45**	**0**	**14**	**10**	**0**	**0**	**35**	**0**
84	**13/06/11**	**EF**	**„**	**14**	**0**	**0**	**15**	**0**	**0**	**1**	**0**	**0**

85	**16/06/11**	**EF/SC**	**,,**	**12**	**20**	**0**	**12**	**55**	**0**	**0**	**35**	**0**
86	**16/06/11**	**O.C**	**Un known**	**16**	**45**	**0**	**18**	**10**	**0**	**1**	**25**	**0**
87	**17/06/11**	**,,**	**Shading**	**09**	**15**	**0**	**12**	**10**	**0**	**2**	**55**	**0**
88	**19/06/11**	**,,**	**,,**	**15**	**0**	**0**	**16**	**0**	**0**	**1**	**0**	**0**
89	**21/06/11**	**EF**	**,,**	**17**	**15**	**0**	**17**	**40**	**0**	**0**	**25**	**0**
90	**22/06/11**	**O.C**	**Un known**	**09**	**45**	**0**	**10**	**55**	**0**	**1**	**05**	**0**
91	**23/06/11**	**,,**	**Feeder O.L**	**10**	**25**	**0**	**11**	**10**	**0**	**0**	**55**	**0**
92	**25/06/11**	**,,**	**L. O.L**	**5**	**0**	**0**	**16**	**0**	**0**	**1**	**0**	**0**
93	**28/06/11**	**EF/SC**	**,,**	**17**	**15**	**0**	**17**	**40**	**0**	**0**	**25**	**0**
94	**02/07/11**	**,,**	**maintenance**	**07**	**0**	**0**	**12**	**0**	**0**	**5**	**0**	**0**
95	**05/07/11**	**EF**	**maintenance**	**08**	**10**	**0**	**12**	**10**	**0**	**2**	**0**	**0**
96	**08/07/11**	**EF**	**Shading pro**	**12**	**30**	**0**	**18**	**0**	**0**	**5**	**30**	**0**
97	**10/07/11**	**EF**	**maintenance**	**07**	**20**	**0**	**12**	**0**	**0**	**4**	**40**	**0**
99	**12/07/11**	**OI**	**Feeder O.L**	**18**	**30**	**0**	**21**	**45**	**0**	**3**	**15**	**0**
100	**16/07/11**	**OC**	**Birds**	**18**	**0**	**0**	**21**	**25**	**0**	**3**	**25**	**0**
101	**17/07/11**	**OI**	**Feeder O.L**	**07**	**0**	**0**	**12**	**0**	**0**	**5**	**0**	**0**
102	**19/07/11**	**O.C**	**L. shading**	**15**	**10**	**0**	**16**	**20**	**0**	**1**	**10**	**0**
103	**20/07/11**	**OI**	**Feeder O.L**	**18**	**0**	**0**	**22**	**10**	**0**	**4**	**10**	**0**
104	**21/07/11**	**EF**	**maintenance**	**11**	**20**	**0**	**13**	**30**	**0**	**2**	**10**	**0**
105	**23/07/11**	**EF**	**Broken line**	**08**	**30**	**0**	**10**	**30**	**0**	**2**	**40**	**0**
106	**24/07/11**	**OI**	**Feeder O.L**	**20**	**00**	**0**	**21**	**45**	**0**	**1**	**15**	**0**
107	**26/07/11**	**OC**	**Birds**	**18**	**0**	**0**	**21**	**25**	**0**	**3**	**25**	**0**
108	**27/07/11**	**OI**	**maintenance**	**09**	**0**	**0**	**10**	**15**	**0**	**1**	**15**	**0**
109	**28/07/11**	**O.C**	**L. shading**	**16**	**10**	**0**	**17**	**20**	**0**	**1**	**10**	**0**
110	**29/07/11**	**OI**	**Animals**	**11**	**0**	**0**	**13**	**10**	**0**	**2**	**10**	**0**
111	**08/08/11**	**EF/SC**	**Un known**	**09**	**20**	**0**	**11**	**30**	**0**	**2**	**10**	**0**
112	**11/08/11**	**EF**	**maintenance**	**06**	**30**	**0**	**09**	**30**	**0**	**3**	**0**	**0**
113	**15/08/11**	**OC**	**Un known**	**11**	**30**	**0**	**11**	**33**	**0**	**0**	**03**	**0**
114	**18/08/11**	**EF**	**L. shading**	**06**	**30**	**0**	**09**	**30**	**0**	**3**	**0**	**0**
115	**20/08/11**	**OC**	**Un known**	**09**	**30**	**0**	**10**	**30**	**0**	**1**	**0**	**0**
116	**22/08/11**	**EF**	**Feeder O.L**	**18**	**30**	**0**	**18**	**55**	**0**	**0**	**25**	**0**
117	**28/08/11**	**OC**	**maintenance**	**09**	**35**	**0**	**10**	**50**	**0**	**1**	**15**	**0**
118	**29/08/11**	**EF**	**Feeder O.L**	**06**	**30**	**0**	**09**	**30**	**0**	**3**	**0**	**0**
119	**01/09/11**	**EF**	**maintenance**	**08**	**0**	**0**	**08**	**24**	**0**	**0**	**24**	**0**
120	**02/09/11**	**,,**	**maintenance**	**08**	**10**	**0**	**09**	**40**	**0**	**1**	**30**	**0**
121	**05/09/11**	**EF**	**’’**	**17**	**10**	**0**	**17**	**40**	**0**	**0**	**30**	**0**
112	**09/09/11**	**OI**	**Shading**	**07**	**0**	**0**	**12**	**0**	**0**	**5**	**0**	**0**
123	**10/09/11**	**OC**	**maintenance**	**08**	**10**	**0**	**12**	**10**	**0**	**2**	**0**	**0**
124	**11/09/11**	**EF**	**Shading pro**	**12**	**30**	**0**	**18**	**0**	**0**	**5**	**30**	**0**

125	**13/09/11**	**EF**	**Shading pro**	**07**	**20**	**0**	**12**	**0**	**0**	**4**	**40**	**0**
126	**23/09/11**	**OI**	**Feeder O.L**	**18**	**30**	**0**	**21**	**45**	**0**	**3**	**15**	**0**
127	**24/09/11**	**OI**	**Feeder O.L**	**18**	**0**	**0**	**21**	**25**	**0**	**3**	**25**	**0**
128	**25/09/11**	**OI**	**Feeder O.L**	**07**	**0**	**0**	**12**	**0**	**0**	**5**	**0**	**0**
129	**26/09/11**	**O.C**	**Un known**	**16**	**10**	**0**	**17**	**20**	**0**	**1**	**10**	**0**
130	**26/09/11**	**„**	**Feeder O.L**	**18**	**0**	**0**	**22**	**10**	**0**	**4**	**10**	**0**
131	**14/09/11**	**OI**	**’’**	**14**	**25**	**0**	**14**	**29**	**0**	**0**	**04**	**0**
132	**15/09/11**	**OC**	**maintenance**	**09**	**20**	**0**	**10**	**20**	**0**	**1**	**0**	**0**
133	**03/10/11**	**„**	**„**	**10**	**30**	**0**	**11**	**30**	**0**	**1**	**0**	**0**
134	**05/10/11**	**„**	**Un known**	**12**	**00**	**0**	**13**	**30**	**0**	**1**	**30**	**0**
135	**08/10/11**	**„**	**Animals**	**13**	**35**	**0**	**13**	**55**	**0**	**0**	**20**	**0**
136	**09/10/11**	**„**	**Feeder O.L**	**18**	**30**	**0**	**19**	**45**	**0**	**1**	**15**	**0**
137	**11/10/11**	**„**	**LOL**	**16**	**30**	**0**	**17**	**30**	**0**	**1**	**0**	**0**
138	**14/10/11**	**EF**	**maintenance**	**18**	**0**	**0**	**19**	**22**	**0**	**1**	**22**	**0**
139	**27/10/11**	**„**	**„**	**08**	**20**	**0**	**09**	**50**	**0**	**1**	**30**	**0**
140	**11/10/11**	**OI**	**Feeder O.L**	**10**	**30**	**0**	**11**	**55**	**0**	**1**	**25**	**0**
141	**16/10/11**	**EF**	**Wind**	**09**	**20**	**0**	**09**	**42**	**0**	**1**	**22**	**0**
142	**18/10/11**	**OC**	**Windy rain**	**08**	**10**	**0**	**09**	**50**	**0**	**1**	**40**	**0**
143	**27/10/11**	**„**	**maintenance**	**08**	**10**	**0**	**09**	**40**	**0**	**1**	**30**	**0**
144	**21/10/11**	**EF**	**’’**	**17**	**10**	**0**	**17**	**40**	**0**	**0**	**30**	**0**
145	**02/10/11**	**OI**	**Shading**	**07**	**0**	**0**	**12**	**0**	**0**	**5**	**0**	**0**
146	**05/10/11**	**OC**	**maintenance**	**08**	**10**	**0**	**12**	**10**	**0**	**2**	**0**	**0**
147	**10/10/11**	**EF**	**Shading pro**	**12**	**30**	**0**	**18**	**0**	**0**	**5**	**30**	**0**
148	**11/10/11**	**EF**	**Shading pro**	**07**	**20**	**0**	**12**	**0**	**0**	**4**	**40**	**0**
149	**23/10/11**	**OI**	**Feeder O.L**	**18**	**30**	**0**	**21**	**45**	**0**	**3**	**15**	**0**
150	**24/10/11**	**OI**	**Feeder O.L**	**18**	**00**	**0**	**21**	**25**	**0**	**3**	**25**	**0**
151	**25/10/11**	**OI**	**Feeder O.L**	**07**	**00**	**0**	**12**	**0**	**0**	**5**	**0**	**0**
152	**26/10/11**	**O.C**	**Un known**	**15**	**10**	**0**	**16**	**20**	**0**	**1**	**10**	**0**
153	**29/10/11**	**„**	**Feeder O.L**	**20**	**00**	**0**	**22**	**10**	**0**	**2**	**10**	**0**
154	**02/11/11**	**OC**	**Un known**	**10**	**30**	**0**	**10**	**34**	**0**	**0**	**04**	**0**
155	**03/11/11**	**„**	**„**	**06**	**30**	**0**	**09**	**30**	**0**	**3**	**0**	**0**
156	**04/11/11**	**EF**	**maintenance**	**11**	**0**	**0**	**12**	**0**	**0**	**1**	**0**	**0**
157	**05/11/11**	**„**	**„**	**12**	**10**	**0**	**13**	**40**	**0**	**1**	**30**	**0**
158	**05/11/11**	**OI**	**Feeder O.L**	**06**	**30**	**0**	**09**	**30**	**0**	**3**	**0**	**0**
159	**07/11/11**	**OI**	**’’**	**14**	**25**	**0**	**15**	**30**	**0**	**1**	**05**	**0**
160	**08/11/11**	**OI**	**L. O.L**	**06**	**30**	**0**	**09**	**30**	**0**	**3**	**0**	**0**
161	**09/11/11**	**OI**	**’’**	**14**	**25**	**0**	**15**	**30**	**0**	**1**	**05**	**0**
162	**10/11/11**	**OC**	**maintenance**	**09**	**30**	**0**	**10**	**30**	**0**	**1**	**0**	**0**
163	**11/11/11**	**„**	**Feeder O.L**	**06**	**30**	**0**	**09**	**30**	**0**	**3**	**0**	**0**

164	12/11/06	EF	maintenance	08	0	0	08	22	0	0	22	0
165	13/11/11	,,	Un known	09	10	0	09	30	0	0	20	0
166	14/11/11	OI	Feeder O.L	15	30	0	16	30	0	1	0	0
167	15/11/11	EF	Wind	16	0	0	16	20	0	0	20	0
168	16/11/11	OC	Windy rain	10	10	0	10	50	0	0	40	0
169	17/11/11	,,	maintenance	09	10	0	09	40	0	0	30	0
170	18/11/11	EF	’’	17	10	0	17	40	0	0	30	0
171	19/11/11	OI	Shading	07	0	0	12	0	0	5	0	0
172	20/11/11	OC	maintenance	08	10	0	12	10	0	2	0	0
173	21/11/11	EF	Shading pro	12	30	0	18	0	0	5	30	0
174	22/11/11	EF	Shading pro	07	20	0	12	0	0	4	40	0
175	23/11/11	OI	Feeder O.L	18	30	0	21	45	0	3	15	0
176	24/11/11	OI	LOL	18	0	0	21	25	0	3	25	0
177	25/11/11	OI	Feeder O.L	07	0	0	12	0	0	5	0	0
178	26/11/11	O.C	Un known	15	10	0	16	20	0	1	10	0
179	02/12/11	,,	Feeder O.L	18	0	0	22	10	0	4	10	0
180	03/12/11	OI	’’	14	25	0	15	30	0	1	05	0
181	04/12/11	OC	maintenance	09	30	0	10	30	0	1	0	0
182	05/12/11	,,	Feeder O.L	11	30	0	12	55	0	1	25	0
183	05/12/11	EF	Un known	13	0	0	14	20	0	1	20	0
184	07/12/11	,,	maintenance	10	10	0	10	50	0	0	40	0
185	08/12/11	OI	Feeder O.L	20	30	0	22	30	0	2	0	0
186	09/12/11	EF	Wind	10	30	0	11	30	0	1	0	0
187	10/12/11	OI	’’	15	25	0	16	30	0	1	05	0
188	11/12/11	OC	maintenance	16	30	0	17	30	0	1	0	0
189	12/12/11	,,	Feeder O.L	17	30	0	19	30	0	2	0	0
190	13/12/11	EF	maintenance	10	0	0	10	20	0	0	20	0
191	14/12/11	,,	maintenance	03	40	0	04	50	0	1	10	0
192	15/12/11	OI	Feeder O.L	05	30	0	06	30	0	1	0	0
193	16/12/11	EF	Wind	10	00	0	10	40	0	0	40	0
194	17/12/11	OC	Windy rain	11	10	0	13	50	0	1	40	0
195	18/12/11	OI	Feeder O.L	07	0	0	12	0	0	5	0	0
196	19/12/11	O.C	Un known	15	10	0	16	20	0	1	10	0
197	20/12/11	,,	Feeder O.L	18	0	0	22	10	0	4	10	0
198	21/12/11	OI	’’	14	25	0	15	30	0	1	05	0
199	22/12/11	OC	maintenance	09	30	0	10	30	0	1	0	0
200	23/12/11	,,	Feeder O.L	05	30	0	06	30	0	1	0	0
201	24/12/11	EF	maintenance	08	0	0	09	30	0	0	30	0
202	25/10/11	,,	maintenance	10	10	0	10	50	0	0	40	0

203	**26/11/11**	**OI**	**Feeder O.L**	**05**	**30**	**0**	**05**	**35**	**0**	**1**	**05**	**0**
204	**27/11/11**	**EF**	**Wind**	**04**	**0**	**0**	**05**	**0**	**0**	**1**	**00**	**0**
205	**29/12/11**	**OC**	**Windy rain**	**08**	**20**	**0**	**09**	**50**	**0**	**1**	**30**	**0**

Appendix E: Ethiopian Electric Utility Demand Tariff for different customers.