ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

School of Electrical and Computer Engineering

DEVELOPMENT AND FEASIBILITY STUDY OF MEDIUM AND LOW VOLTAGE DC DISTRIBUTION SYSTEM

Case Study: 15KV, 1500 KVA and 50 Hz AC distribution system

A thesis submitted to Addis Ababa institute of Technology, School of Graduate studies, Addis Ababa University

In partial fulfillment of the requirements for the degree of Master of Science in Electrical power Engineering

By

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The undersigned certify that he has read and hereby recommend for the acceptance by the Addis Ababa University a thesis entitled: **Development and Feasibility study of medium and low voltage DC distribution system: under the case study of 15 KV, 1500 KVA, and 50Hz AC distribution system**, in partial fulfillment of the requirements for the degree of Masters of Science in Electrical Power Engineering.

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Advisor	Signature	Date

Declaration

I, Shumye Birhan, declare this M.Sc. thesis is my original work and has not been presented for the 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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ABSTRACT

Power distribution system development initially was conceived in the form of DC distribution system. But, due to different drawback of this system and the invention of transformer, it was shifted to AC distribution system. As a result, the manufacturer created AC powered loads to the customers to meet AC generation systems. AC system dominated the market for a long time. Lately, the developments achieved in power electronics area led to further studies in direct current power systems.This research work presents the development and comparative study of DC distribution systems by taking 132/15kV, 20MVA, 50Hz distribution substation system to be extended to MVDC as study of the research. The specific objective of the study is to develop alternative DC distribution system and make a comparative analysis of MVAC and MVDC in terms of power loss, material cost, system efficiency and energy loss cost. carrying capacity of AC and DC distribution system, the total power loss, equipment cost and the system effiecncy was computed and compared each other.

Finally, three DC distribution scenarios were developed and evaluated in terms of power loss, efficiency and cost. Each scenarios were compared not only with the traditional AC system but also with each other. The existing AC distribution evaluation system results in 1989.7 KW power loss, 348,595 USD energy loss cost, 3,094,622 USD materials cost and 90 % overall efficiency. In DC distribution, Scenario A evaluation results in 1610 KW power loss, 282,072 USD of energy loss cost, 2,433,290 USD of materials cost and 91.9 % of overall efficiency. Scenario B evaluation results in 2011.5 KW of power loss, 352,418 USD of energy loss cost, 2,989,308 USD of materials cost and 89.9 % of overall efficiency. Scenario C, The DC structure which consists of DC/AC inverter with its system efficeincy 92.6 %, power loss 1486.5 kw, the energy loss cost of 260,438 USD and equipment cost of 2,989,308 USD were achieved in which it was much significantly less than AC distribution system. As the quantitative results showed, around 500 KW power saving and more than 0.2 million USD momentarily saving have been possibly achieved by using scenario C of DC distribution system as compared to the existing AC distribution system.

Key word: Distribution, Direct Current, Alternative Current, Power loss, Transformer, Converter, Rectifier, Inverter and Feasibility study.

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Finally, I want to thank my parents and friends for their constant inspiration during these years of study.

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A	Ampere
A_c	Conductor cross sectional area
K	Transformer K- factor
P_c	Copper loss
p_i	Iron loss
P_{wdg}	Transformer winding loss
P_{DC}	DC power
P_{AC}	AC power
α	Temperature constant
W_{loss}	Energy loss
f_s	Skin effect factor
f_p	Proximity effect factor
Ω	Ohm
ρ	Resistivity constant
f	Frequency
T	Temperature
D_c	Conductor diameter
t	Time
C	Capacitor
R	Resistor
L	Inductor
L_{df}	Load factor
L_{Lf}	Loss factor
ϕ	Load angle
V_m	Peak voltage
π	Pi (3.14)

LIST OF ABBREVIATION

AAAC	All Aluminum Alloyed Conductor
ACSA	Aluminum Copper Steel Reinforced
AC	Alternative Current
DC	Direct Current
DT	Distribution Transformer
EEP	Ethiopian Electric Power
EEPCO	Ethiopian Electric Power Corporation
FF	Form factor
GTO	Gate Turn ON
GW	Giga watt
HVDC	High Voltage Direct Current
HVAC	High Voltage Alternative Current
HV	High voltage
IEEE-SA	International Electronic Electric Engineers' Standard Association
IEEE	International Electronic Electric Engineers
IGBT	Insulated Gate Bipolar Transistor
K.m	Kilo meter
KW	Kilo Watt
KV	Kilo Volt
KWh	Kilo Watt hour
KVA	Kilo Volt Ampere
LVDC	Low Voltage Direct Current
LC	Inductor Capacitor
LVAC	Low Voltage Alternative Current
LV	Low Voltage
LDC	Load Dispatch Center
LCOE	Levelized Cost of Energy
MW	Mega Watt
MV	Medium Voltage

MVDC	Medium Voltage Direct Current
MVAC	Medium Voltage Alternative Current
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
MVA	Mega Volt Ampere
mm	mili meter
Max.	Maximum
Min.	Minimum
PV	Photovoltaic
RF	Rectification Ratio
R.M.S	Root Mean Square
SCR	Silicon Controlled Rectifier
TUF	Transformer Utilization Factor

CHAPTER 1
INTRODUCTION

1.1. BACKGROUND OF THE STUDY

Energy demands are growing globally with economic growth and the people are concerned with efficiency first for saving some money. Of course energy distribution and studying of efficient Distribution system becomes the most issue of the researchers. Now a days electricity distribution networks construction are mainly of the three and single phase AC systems [4]. Historically, electricity was first commercially transmitted [by Thomas Edison] with a DC power line. DC power is simply the application of a steady or constant voltage across a circuit resulting in a constant current. However, this electrification system was low voltage, due to the inability to step up DC voltage at the time, and thus it was not capable of transmitting power over long distances. The distribution voltage level was the same as the transmission one. It was constructed for only a 100k.m distance of transmission line using 100 KVvoltage level [23].The expansion of electric current in the last centuries has been also the question of one over the other. T. Edison and Westinghouse publically fought over DC versus AC in the War of Currents [6]. In the nineteenth century, AC became the dominant power distribution design because transformers cheaply solved the problem of getting power more than a kilometer from a centralized power station [9].Yet, today, the world faces the paralleled issues of distribution systems. The fast development of power electronic devices has led to have an innovative distribution systems and solve the earlier challenge of voltage conversion. Specially, high voltage Direct current (HVDC) system of transmission was developed back quickly. High voltage Direct current transmission system can include from 230 KV to 500 KV voltage for transmitting power over along distance [23]. This power electronic devices enable also to develop DC distribution systems at medium and low voltage level from the existed AC power generation system. Medium voltage DC distribution (MVDC) system can be developed from AC/DC converter. Even if power electronics are developing quickly and it can give DC transmissions and distribution systems, there was some difficulities and challenges to implement low voltage distribution systems in home. A lot of DC powered loads are coming soon parallel to AC powered loads. All electronic equipments (smart TV, Radio), data centers, resistive loads (different lamps, fluorescent lamps, driers, incandescent lamps, ovens etc.) could be taken as the evidences. On the other hand, most of home loads such as stove, refrigarator, and iron are purely AC powered loads. So, the currently existance of AC and DC run loads was becoming one of the challenge to implement DC distribution system alone. Low voltage DC distribution system (LVDC) can supply only DC loads and without the involment of converters low voltage AC distribution system also can not run both AC and DC powered loads. The research focuses the application and feasibility of medium voltage direct current (MVDC) and low voltage direct current (LVDC) systems by making a comparative analysis with the traditional distribution system (Alternating Current distribution systems).

1.1.1. POWER ELECTRONICS TECHNOLOGY

The world cannot be powered with one simple form of energy. Application of power electronics in power system has been developing very fast. So, this device makes easy to integrate DC bus with AC power and vice versa in an efficient system of configuration. Achievements in power electronis is the development of different converters such as AC/DC rectifier, DC/DC converter and DC/AC inverter. AC/DC rectifier is a capability of Obtaining DC voltages to supply DC powered loads and DC/AC inverter was developed for supplying AC powered loads from DC lines. Electrical power can be genertaed in the form of AC and DC currents. But, the existed system of distribution can not support AC and DC loads without converters. The study is on 132/15 KV, 20 MVA and 50 Hz distribution substation. AC/DC converter would be applied at the secondary portion of the Distribution substation. Since the bench mark of the study is AC distribution system**,** in which the three phase 15 KV must be stepped down to three phase 380 V to be suitable for AC powered loads. This voltage level is commonly used by the loads in the market today. The medium and the low voltage portion of the AC system should be converted to DC system using the appropriate electronic converter switches. On the other hand there are other components that must be incorporated in this research work, the converter’s design, modeling and their simulation are considered as the part of the study. The preliminary design for such a system to supply DC power was formulated using the MULTISM/ MATLAB Software's and they were applied at 15KV AC distribution systems. The AC/DC, DC/DC, and DC/AC converters were constructed to obtain the organized DC distribution structure. The Diode or Thyristor based AC/DC converter was connected to 15KV distribution lines to get DC voltage line. DC/DC converter was applied for stepping down the given medium level voltage to the required voltage level. It should be noted that since 1954 there have been many high voltage DC transmission and distributions systems implemented around the globe with the advent of DC/DC converters, allowing the easy stepping up and down of DC voltages [4]. In most of the studies, NI MULTISM, ETAPS, DIGsilent and MATLAB were the best software to simulate AC/DC, DC/DC and DC/AC converters.

1.1.2. LOW VOLTAGE FOR HOMES AND OFFICE LOADS

Most of the equipments in home and office are AC powered. But, there are some DC powered equipments in office such as desk top computers, LCD TV, scanners, smart bords, printers, fluorescent lamp, battery charger and so on. And some resistive loads like heaters, incandescent lamps and heaters operate with both AC and DC , in which the output power is equal if the RMS values are the same [16]. Today, it is common that supplying those loads from 220 V AC single phase systems. All these loads are low voltage systems either AC or DC voltages.The use of direct current low voltage to homes, offices and commercials would make it possible to have an efficient overall distribution system. This can be achieved by converting the existing AC voltage to DC voltage either internally or externally at the loads. Equipments having internal AC/DC converter can be supplied directly from AC voltage supply. But, there are equipments without AC/DC converters especially in data centers, telecom equipments and so on. Telecom equipments and data centers mostly powered from 48 V DC line [16]. This 48 V line was obtained from 220 V AC distributor using AC/DC rectifier. Small AC/DC rectifier installed near by the loads. Since the study aims to convert the medium AC distribution networks into DC distribution system continuing with same manner to low voltage levels and supplying this voltage by any means to any load. The most achievable technique is using AC/DC rectifier on the medium voltage level, DC/DC converter to obtain low voltage DC and central DC/AC converter in a village. Similarly, this network system would be compare and contrast with not only the old AC distribution system but also with the above optional techniques.

1.2. PROBLEM STATEMENT

The existed AC distribution systems have so many drawbacks as compared to DC distribution systems [5], [6]. The presence of inductance and capacitace in the system enable to have a continous active and reactive power loss when no load on the lines. Skin effect and proximity effect increases its power loss. In AC distribution system, feeders are drawn in three lines. But, in DC distribution systems feeders are constructed with two lines. As a result, there is a significance difference on the cost of wires, poles and other equipments. On the other hand, the widespread development of low voltage DC devices and systems, as well as large scale MVDC systems and no DC-based substructure exists to efficiently connect the two together.The gradual reduction in cost of converters and the rise of DC powered devcies encourage the development of DC distribution systems. The material consumption, power loss, efficency and energy loss costs are the variable for the comparative study.

1.3. OBJECTIVE

1.3.1. General Objective

The general objective of the thesis work is to develop the alternative DC distribution system and comparative analysis with the existing AC distribution system.

1.3.2. Specific Objective

- Extensive literature review about AC and DC distribution systems.
- Identify the various DC distribution components and DC powered loads.
- Model and Develop the MVDC and LVDC distribution system structures.
- Make comparative analysis of MVDC distribution that of MVAC distribution systems using power loss, energy loss cost, material cost and system efficiency as a comparative variable.

- Make comparative analysis of MVDC power delivery system with that of MVAC distribution system.
- Analyze optional LVDC implementation techniques.
- Identify ways of incorporating DC distribution system in existing distribution system structure.
- Verify economic benefits of DC distribution systems.
- Identify efficiency of the dedicated DC distribution system scenarios.

1.4. METHODOLOGY

A. Data Collection: - The first step of the research process was gathering data on the existing distribution networks. Primary data would be collected from Ethiopian electric power corporation. The data being collected include transformers and other network components, peak demands, cable types and sizes at the MVAC and LVAC voltage level in which they are used in Ethiopian electric grid distribution system.

B. Literature Review: -So many public papers were reviewed and summarized as how much they are related and helpful with this research work. Basically, literatures on Low voltage DC for home appliances, office and for other organizations were reviewed. To analyze the power loss on MVAC distribution system medium voltage transformer loss was referred to compare the result obtained from this study. Different MVDC and LVDC distribution system implementation techniques were checked from Literatures. MVAC distribution system was performed for better understanding of the draw backs. And information on MVDC distribution system was collected enough in order to see the most related and supportive works done in the last few years.

C. Demand /load type assessment: -This was used to model LVDC and LVAC distribution system at the customer side and also it is used to identify the DC and AC load types. To determine the power quantitative values the possible load types and rating values were assessed and were kept in tabular form.

D. **Data analysis:-**the collected data was analyzed to evaluate the comparative parameter variables, like the power loss across the equipments, equipment operational costs and system efficiency. The values of these data like peak load, average load, different electrical rating values, standard values have been seen for the appropriate model of AC and DC distribution system.

E. **Modeling and Designing: -**After data analysis, the existing AC distribution system has been technically evaluated and the DC system components were modeled and designed to develop the new DC distribution scenario. MVDC and LVDC structure development were carried out component by component. As a result MVDC distribution system feasibility would be easily studied. On the LVDC distribution side, it was modeled depend on the data obtaining from EEPCO and the standards used in reviewed papers. The total power or the capacity of the network is determined by assessing the loads in different ways. It is considered the possible types of loads in home, office and in some organizations like school, clinic and religious purposes. Finally the types of appliances, ratings, their operating hours, total power and total energy consumed was putted in tabular form. Depend on this result, MVDC and LVDC network structure was configured. The DC distribution part was obtained from the existing MVAC distribution network. Then, the cost benefit analysis of the two distribution systems were carried out to delineate the most feasible distribution structure. Cost breakdown was made for each component of AC and DC distribution systems to determine the partial investment cost of both systems. Finally, the equipments and materials cost summary have been made for each distribution systems.

F. **Simulation results and discussions:-** the transformer secondary voltage, AC/DC, DC/DC and DC/AC converters voltage value were simulated using the MATLAB, NI MULTISM and ETAPS software. The low voltage loads would be supplied by using central inverter. The most accurate inverter output simulation result was made to entertain the variety of load voltage ratings.

G. **Conclusion**: - Conclusion was made depending upon the mathematical analysis and simulation results. The comparison analysis was not drawn on the single design and simulation results rather it consists diferent component by component comparative studies with respect to AC distribution system.

1.5. SCOPE OF THE STUDY

The study focuses on medium voltage and low voltage DC distribution system. The scope of the research include:-

- Analysis and Economical evaluation of the existing AC distribution system.
- DC distribution component Modeling, simulation and system development.
- Technical performance evaluation of DC distribution in terms of efficiency, power loss, energy loss cost and equipments and materials cost.
- Comparative study of AC and DC distribution systems.

The study covers the comparative analysis and feasibility study of medium and low voltage DC distribution system. Matlab and NI multism software is used to simulate the model designed

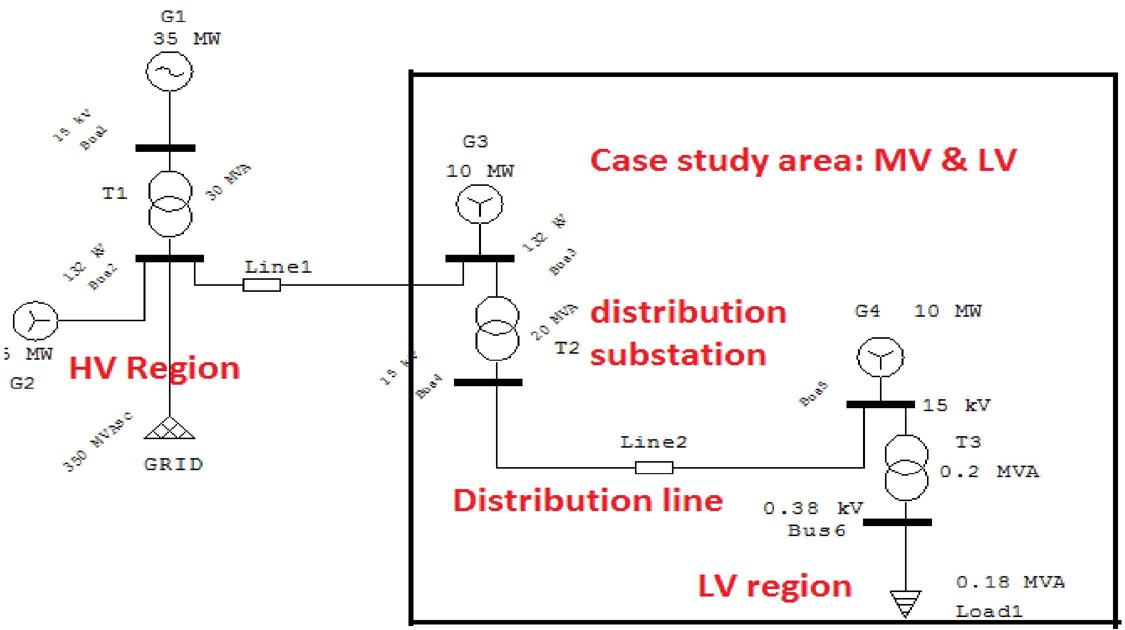


Figure 1. 1The case study and boundary of the research

1.6. OUTLINE OF THE THESIS

Chapter 1:- Describes the theoretical part and the background, and gives the general introduction of the AC and DC distribution systems.

Chapter 2:- In this chapter different research papers are being reviewed to identify and assess the development of the technology in DC distribution.

Chapter 3:- In this chapter different data are collected and analyzed in order to develop the model for simulation. AC data was collected from EEPCO and UEAP office to relate the research to practical application. Using the data collected, the existing AC distribution system will be evaluated in terms of power loss, equipment and materials cost and system efficiency.

Chapter 4:- Different DC distribution system scenarios would be modeled and compared with the evaluation results in chapter three.

Chapter 5:- This chapter describes the simulation of the designed DC distribution system, using NI Multism and MATLAB Simulink software. Some system components have been also simulated using advanced electronic software (NI MULTISM).
Chapter 6:- This chapter presents the conclusion, recommendation and future works depend on the outcomes obtained in chapter five.

CHAPTER 2

LITERATURE REVIEW

2.1. INTRODUCTION

Currently, various studies were being conducted to evaluate the feasibility of medium and low voltage direct current systems. Specifically, low voltage DC distribution system for homes, residential and commercial loads were studied so many times. Medium voltage DC distribution system feasibility also was studied in terms of certain parameters. Some of the relevant papers have been reviewed below.

2.2. LOW VOLTAGE DC DISTRIBUTION SYSTEM

Kristof Engelen, Erik Leung Shun, Pieter Vermeyen, Ief Pardon, Reinhilde D'hulst, Johan Dreiser, Ronnie Bell Mans [13] with their paper entitled "The Feasibility of Small Scale Residential DC Distribution Systems", conducted topological design, buffering of the DC bus, efficiency analysis of small-scale dc distribution systems. The efficiency of power electronic converters was discussed and the line losses were estimated based on a heuristic model of the power consumption for a typical home.

Y. Arafat and M. Amin [27] with the paper entitled 'Feasibility study of low voltage DC house and compatible home appliance design" presented how low voltage DC distribution network minimizes conversion losses by using highly efficient DC to DC converter to run some of the DC appliances. The authors postulated that the devices used in households or offices require low power that are possible to be connected directly to the low voltage DC distribution system by removing the AC to DC conversion stage. Defined voltage levels are tested for commercial equipments and residence appliances. 12V, 24V and 48V are some of the input voltage levels designed for those appliances. Because of the low voltage DC appliances have demand of higher currents, it makes feeder losses considerable. So, the overall efficiency of the appliance becomes low.

2.3. DC LOAD ANALYSIS

Giovanna postiglione [9] with the paper entitled "DC distribution system for homes and office" describes the various possible types of the loads used in home in European standard. The loads are described as resistive, inductive and electronic with their consumption ratings.

2.4. DC DISTRIBUTION SYSTEM FOR HOME

Y. Arafat & M. Amin [27] with the paper entitled "Feasibility study of low voltage DC house and Compatible home appliance design 2011" discussed how many household appliances operate internally on DC voltage with supply of 230V AC being converted to DC voltage internally. The proposed DC system was developed from this AC voltage. To connect the DC distribution system with the existing AC system an additional AC to DC converter was required which brought an additional lose for the system. As mention before, many household appliances operate internally on DC voltage because of the presence of this AC/DC converter. In this paper the loads could be connected directly to 48 V DC supply without any conversion. The system was adopted using efficient DC/DC converter.

Giovanna postiglione [9] with the paper entitled "DC distribution for home and office". The research work focused on the analysis of the AC distribution system and replacing the system with DC distribution system. Different DC voltage levels were evaluated for the home and office loads. AC and DC devices were investigated. Finally the expected advantageous of the DC system and the draw backs of the old system were stated and compared.

[3] with the paper entitled "DC circuits for lighting in commercial buildings" presents analysis of DC system for lighting loads. This paper discusses the economic feasibility of DC circuits for business building lighting systems that were powered by central power supplies and usual AC grid electricity or by onsite solar photovoltaic (PV) arrays with battery back-up.

2.5. MVDC DISTRIBUTION SYSTEM

D. Nilsson and A. Sandino [4] with the paper "Efficiency Analysis of Low and Medium Voltage DC Systems" presented sustainability aspects of connected DC power delivery in low and medium voltage distribution systems. The efficiency of AC system, DC system and mixed AC-DC system models were calculated and compared. It was shown that under the assumption of a substantial reduction in semiconductor losses, the total system losses were decreased using DC voltage system.

Einar Palmi Einarsson and Beng tolof Wickbom [8] with the research entitled "Modeling for Steady State and Transient Analysis of Low Voltage dc Systems", presented the low-voltage residential and commercial loads when supplied with DC power. Their steady-state and transient behavior are studied. Laboratory measurements were carried out on various loads that were categorized as resistive, rotating and electronic loads. From these measurements, it was possible to characterize the steady state behavior of loads. Load sensitivity to voltage variations, in particular voltage dips, with DC supply and then compared with the result to the same voltage variation in AC.

Brandon Michael Grainger [2] with the paper entitled "Medium voltage DC network modeling and analysis with preliminary studies for optimized converter configuration through PSCAD simulation environment", introduced initial design and simulation model of the MVDC network concept containing renewable generation, power electronic converters, and induction machine loads. Each of the equipment are modeled in PSCAD and validated analytically. Finally, the equipments were assembled together into a meshed system to perform traditional preliminary studies on the overall power system including wind speed adjustments, load energizing, and fault-clearing analysis to evaluate operational phenomena such as overvoltage conditions, system stability issues, and other unexpected system conditions.

Matthew J Korytowski [15] with the paper entitled "Comparative analysis of medium voltage DC and AC network infrastructure models" provided a comparative analysis of the MVAC and MVDC. The preliminary design for such a system to supply DC power was created using the PSCAD software package. The system utilizes a medium voltage DC bus rated at 20kV with a set of interconnected loads and generation. The DC system, while complicated with its wide array of power electronic converters, grants the ability to control power flow into the system from the different generation sources and to the loads. The designed system of DC distribution system, different generation stations coming on a single center as shown in Fig. 2.2

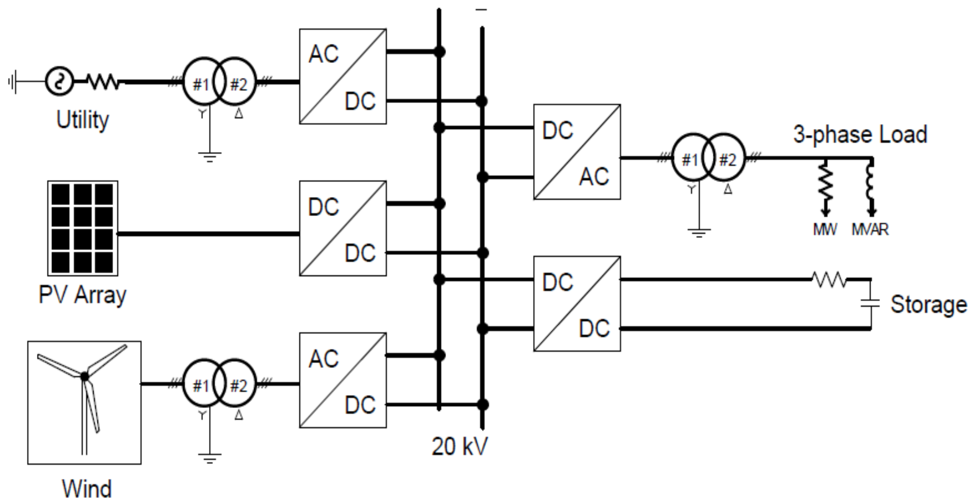


Figure 2. 1MVDC bus system of interconnected distributed generations

D.M. Larruskain1, I. Zamora1, A.J. Mazón1, O. Abarrategui1, J. Monasteries [6] with the paper entitled "Transmission and Distribution Networks: AC versus DC', presented a comparative study between AC and DC transmission system technology. Economical, technical and environmental considerations of the AC and DC power flow were also studied. The paper reviewed the underlying technology and discussed the HVDC systems from a design, construction, operation and maintenance points of view.

2.6. DC /DC CONVERTER FOR MVDC DISTRIBUTION

Stephan Kenzelman [22] with the paper entitled "DC to DC converter for DC distribution and collection of networks". In this paper the DC/DC converter used as a bridge in DC distribution system among different generation farms like wind, solar and other generation sources connected to the DC grid to supply AC loads by converting the distribution line into AC system with the help of inverter. The most important thing from this research work is DC to DC converter used for high voltage distribution system.

F. Krismer and J. W. Kolar [23] with the paper entitled "Medium-Voltage High-Frequency DC-DC Converter" describes the efficiency of DC-DC converter for the application of DC medium voltage. This DC/DC converter transfers power between medium voltage input up to 28kv and low voltage output from 650V to 700V. The level of DC voltages can able to transform over a long distance like transformer. Under this paper the study focused on the mechanism of stepping down of the given DC voltage level in to the required level.

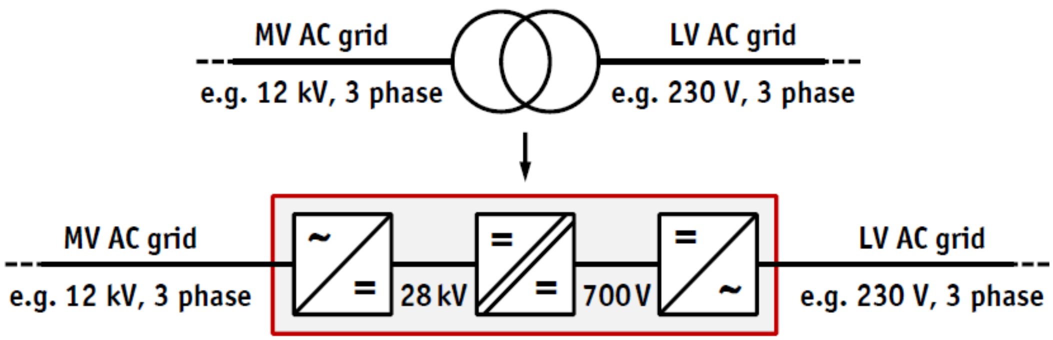


Figure 2. 2 DC-DC converter in between AC voltages

From the above figure the system was studied just to transform the power in the form of DC voltage in order to minimize the power loss. But, at the end the loads were supplied by AC voltage by applying inverter. The high DC voltage was inverted into low AC voltage DC /AC inverter for home loads

Tero Kaipia, Pasi Salonen, Jukka Lassila, Jarmo Partanen [23] with the paper entitled "possibilities of the low voltage dc distribution systems''. It identified the possible structure of medium voltage implementation. The study is started by converting the 20 KV AC voltage into 15 KV DC voltage distribution line. Since most of the home loads are AC powered, it needs the inversion of this DC voltage back into AC voltage line. The inverter were installed for each village as a station. This DC-AC inverter used as the feeder for each village. So every home loads got the AC power from the inverter station. The most important thing from this paper was only the implementation of DC distribution system in medium voltage level via the inverter.

CHAPTER 3

DATA ANALYSIS AND TECHNICAL EVALUATION OF EXISTING AC DISTRIBUTION SYSTEM

3.1. INTRODUCTION

Since the high voltage distribution network is not the part of the study, it can be started from Medium voltage AC distribution system analysis. It consists of a distribution substation transformer located with in a radius of 30 to 80 k.m distance from the low voltage stepdown transformer. For this research work, 15 kV is selected as MV voltage level based on the standard used by Ethiopian Power Utility. MV network can be constructed either from two winding or three winding transformers. Some substations are built as 132/45/15 KV with three winding transformer. The two winding transformers (33/15kv, 66/15KV or 132/15KV) are located at distribution substation. This voltage level can extend for a distance of up to 25 k.m without any voltage compensation. The overhead line is connects to the step down transformer at both ends as shown in figure 3.1 which consists of the distribution substation transformer, the overhead line, and the MV/LV transformer and the feeder lines. The first transformer (HV/MV) converts the high voltage level to medium voltage level and the second transformer (MV/LV) steps down to a voltage level used by end users or customers (to 380V or 400V). The input data that should be collected and analyzed for this research work are the parameter value of HV/MV transformer, MV/LV transformer and the distribution overhead line. The important parameter include load carrying capacity, voltage level, current rating, conductor profile, iron and copper loss of each transformer.In this research, the study begins by anlyzing power loss of this equipments and comparing with DC distribution system.

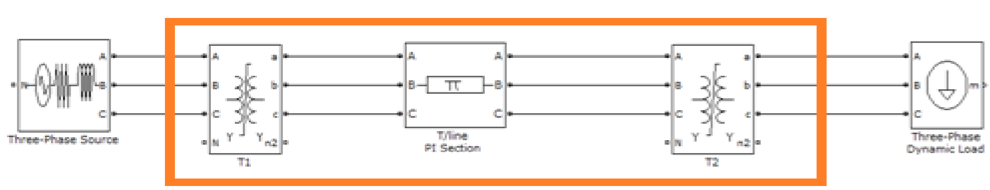


Figure 3. 1MVAC distribution network boundary for the study

3.2. THREE-PHASE HV/MV DISTRIBUTION TRANSFORMER

The most important element for this portion of analysis is the distribution transformer. This Distribution Transformer provides the voltage transformation in the electric Power distribution network system, stepping down the voltage used in the distribution lines to the level used by end users [23]. Transformer is an electric energy conversion device, since the energy received by the primary winding is converted to useful electrical energy in the other circuits (secondary winding circuit). The energy conversion or the amount of the output is depending on its efficiency. There is some power loss dissipated or absorbed by its internal resistive and inductive components. The thesis work starts from the analysis of AC system in which the step down transformer is found as the first component of the system. Medium voltage AC distribution is constructed from distribution substation (HV/MV step down transformer), distribution line, and further steps down which supplies power to end users. Since there are two types of transformers used in the network a separation analysis of each type of transformer is conducted.

3.2.1 Power loss evaluation using analytical techniques

The medium voltage level distribution transformers have different ratings. According to IEEE-SA C-57 standard, one DT can be in among the followings.

Table 3. 1 Distribution transformer rating standards

S .No	Voltage conversion levels	Possible type MVA rating
1.	132/15kV	20, 31.5
2.	132/33 kV	20, 25, 45
3.	132/45 kV	17, 20, 25
4.	230/132 kV	50, 100, 150,200
5.	132/66 kV	30, 45, 50, 100
6.	132/45/15 kV	17, 20, 31.5
7.	230/45 kV	31.5, 35, 50

The data in Table 3.1 was collected from the existing Ethiopian MVAC distribution substation. Basically, the loss of the transformer are the copper loss and iron loss. The copper loss depends significantly on the internal copper resistance and the current rating passing through it, whereas the core loss is dependent on the value of voltage supply and assumed constant and are often referred to as ″no load losses″. Transformer power loss can be determined in two ways. The first one is actual measurements in which the power loss is measured by installing the meter at each distribution transformer. The second method od power loss calculation is Analytical method. Using transformer rating, full load and standards the total winding loss can be computed.The losses on a single DTs can be summarized as below.

$$DT\ LOSSES = IRON\ LOSS + WINDING\ LOSS$$

$$WINDING\ LOSS = STRAY\ LOSS + COPPER\ LOSS$$

The distribution substation data in Addis Ababa, Ethiopia was considered to obtain the available information for the power loss analysis. Transformer's data are obtained from Ethiopian load dispatch center (LDC). The analysis is on 132/15 KV transformer and on 15 KV line.

Table 3. 2 Three phase HV/MV distribution transformer feeder data

Bus Voltage	DTS	KVA ratings	Network name or Feeders
15KV bus bar	132/15 KV	20MVA 31.5MVA	Dairy farm line 1, cotebe, kebena, Bole and CMC line
33KV bus bar	132/33 KV	16MVA	Sendafa (3 feeders)
45KV bus bar	132/45 KV	16MVA	Addis East I (3 feeders)
132KV bus bar	230/132 KV	------------	Legetafo (3 feeders)

From the above Table 3.2, this research feasibility study focuses on 15kV bus bar which was selected to be compared with the DC distribution system. But, for general understanding of DT's loss, the data of all was taken and the loss of each was determined. The following tables 3.4, 3.5, and 3.6 show load data of each feeder lines. These feeders' data contain a monthly average peak load of each substation in 24 hours. And also the average hourly data is obtained from peak value of each hourly load recorded.

Table 3. 3 132/15 KVfeeder line load data

Time	Feeder1	Feeder2	Feeder3	Feeder4	Feeder5	MW
0	1.8	1.3	4.9	3.7	2.8	14.50
1	1.9	1.3	5.2	3.4	2.7	14.50
2	1.8	1.3	4.9	3.7	2.8	14.50
3	1.9	1.3	5.2	3.4	2.7	14.50
4	1.8	1.3	4.9	3.7	2.8	14.50
5	1.9	1.3	5.2	3.4	2.7	14.50
6	1.8	1.4	5.8	4	3	16.00
7	1.8	1.4	5.8	4	3	16.00
8	1.8	1.4	5.8	4	3	16.00
9	1.8	1.4	6	4.3	3.1	16.60
10	2.1	1.4	6	4.3	3	16.80
11	1.9	1.3	6.2	4.5	3.1	17.00
12	2.1	1	6.3	4.4	3.2	17.00
13	2.1	1	6.3	4.4	3.2	17.00
14	1.9	1.3	5.2	3.4	2.7	14.50
15	1.8	1.3	4.9	3.7	2.8	14.50
16	1.6	1.4	5.1	3.8	2.9	14.80
17	1.8	1.3	5.4	3.7	3.2	15.40
18	1.9	1.4	6.2	4	3.6	17.10
19	1.8	1.4	7.3	4.3	4.2	19.00
20	1.8	1.4	7.3	4.3	4.2	19.00
21	1.8	1.4	7.3	4.3	4.2	19.00
22	1.9	1.3	6.2	4.5	3.1	17.00
23	2.1	1	6.3	4.4	3.2	17.00
Average	1.87	1.30	5.82	3.98	3.13	16.11

From the table 3.3 the most important parameters are the peak load, average load, maximum load and minimum load within 24 hours. KVA (average), could be calculated by summing all recorded hourly data, and then divided by the specified period.

KVA_{avg} =16.11MW, KVA_{peak} = 19MM, KVA_{max} = 19MW and

and KVA_{min} = 14.5MW

Figure 3. 2 Graphical representation of 132/15KV DT load data curve

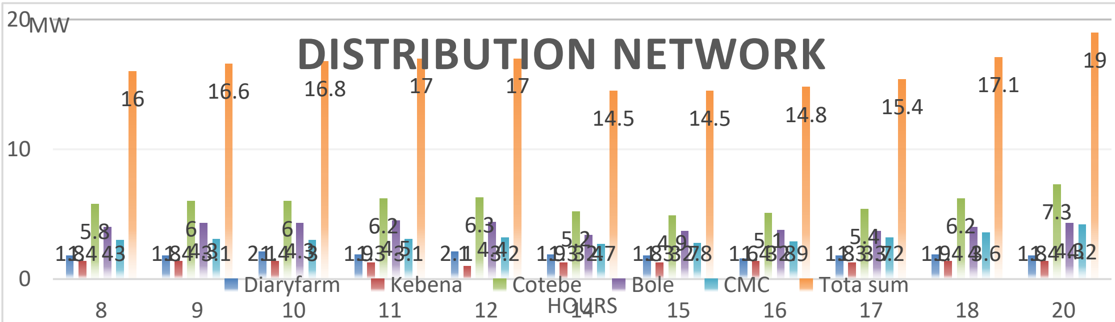


Table 3. 4 132/33 KV line load data

33KV bus bar 16MVA, 132/33kV transformer			
Sendafa			
R	S	T	MW
36	38	35	1.9
40	48	41	2.15
38	38	38	1.9
38	39	39	1.95
38	39	39	1.95
27	27	28	1.4
25	27	27	1.35
30	31	30	1.55
35	37	34	1.85
34	37	34	1.85
39	40	39	2

Table 3. 5 132/33 KV line load data

45KV bus bar 16MVA, 132/45kV transformer			
Addis East I			
R	S	T	MW
95	93	98	7.2
104	103	109	8
106	106	110	8.1
107	107	112	8.1
109	108	111	8.1
89	89	91	6.7
82	83	84	6.1
85	84	87	6.3
96	94	97	7.1
103	102	106	7.7
110	107	112	8.2

The last two tables contain the 33kv and 45kv bus bar load data. Since this portion of the network is not the part of the case study, it can be ignored from the analysis. Now the designed parameters to assess the power loss of DT are load factor, loss factor and K-factor of the given transformer [21].

Load factor – it shows that the amount of average load as compared to the maximum load connected to the transformer. So, it is the ratio of Average load to the maximum load in KVA.

$$load\ factor\ (L_{df}) = \frac{Average\ load\ value\ (average\ KVA\ value\ )}{maximum\ KVA\ value} \qquad 3.1$$

From the data obtained in table 3.3. 132/15KV distribution transformer, the average and maximum load are 16.11MW and 19MW respectively.

$$load\ factor\ (L_{df}) = \frac{16.11MW\ )}{19MW} = 0.8479, \text{Or} = 84.79\%$$

K-factor – it is the ratio of the minimum and maximum demand ratio of the distribution transformer.

$$K = \frac{KVA\ min}{KVA\ max}(as\ per\ the\ load\ curve) \qquad 3.2$$

Similarly, from the data obtained in table 3.3 the minimum and maximum demand data of 132/15KV distribution transformer are 14.5MW and 19MW respectively.

$$K = \frac{14.5MW}{19.00MW} = 0.7634, 0r = 76.34\%$$

Loss factor - It describes the average electrical energy losses for electricity transmitted during period T. Ideally, to calculate the load losses it would be necessary to integrate the squares of all momentary ratios of actual load to the rated load [27]. As the formula indicates, the loss factor could be determined from load and k- factor calculated above.

$$loss\ factor\ (L_{LF}) = L_{df}^2 + 0.23\ (L_{df} - K)^2 \qquad 3.3$$

$$L_{Lf} = 0.8479^2 + 0.23\ (0.8479^2 - 0.7634)^2$$

$L_{Lf} =$ 0.7209, or = 72.09%

As a result, the summary of factors which could be used for the analytical calculation of 132/15KV DT power loss. General power losses in any transformers which affects the output significantly.

Table 3. 6 Summary of value of factors

Factor type	Load factor	K-factor	Loss factor
Symbol used	L_{df}	K	L_{LF}
Value	0.8479	0.7634	0.7209

Iron loss (standby loss or no load loss):- it is commonly known as "No load losses, excitation losses or core loss" which is taking place in iron /core part comprising of hysteresis Losses and eddy current losses in the Core considered to be constant throughoutthe life time of the transformer irrespective of theirloads [27]. This kind of loss on DT was determined depend on the manufacturers' data sheets. It can be also obtained from the standards in general for any kind of transformers. For this thesis work data analysis to obtain the iron and copper loss of 132/15KV distribution transformer, IEEE-SA C57-12.90 2001.Standardwas referred which describes the measurement of no load loss and copper loss. The following table indicates the standard transformers with their no load and full load copper losses. Generally the no load loss should be less than 1% the total loss and this percentage always should be checked when the efficiency of any transformer be determined [20].

Table 3. 7 Standard MV copper and iron transformer losses

s.no.	Transformer rating (KVA)	P_i(watt)	P_C(watt)
1.	100	350	2500
2.	200	570	3300
3.	315	800	4600
4.	500	1100	6500
5.	1000	1800	11000
6.	2000	3000	20000
7.	5000	3700	37000
8.	10000	6200	63150
9.	20000	12550	156500
10.	25000	13550	110000

According to the lists shown on the table 3.7, the 132/15KV, 20MVA the stand by (iron loss) is 12.55KWand the full load loss is 156.5KW. Finally, the total power loss was determined from the analytical calculation of the total winding loss and stand by loss of this medium range transformer.

Winding loss (load loss): - this kind of loss which is occurred on transformer winding components. It is a function of load current passing through it. As a function of load current, can be divided into copper loss ($3I^2R$) and stray losses. The stray losses are caused by eddy-currents that produce stray electromagnetic flux in the windings, core, core clamps, magnetic shield and other parts of the transformer [27]. This winding loss depends on the maximum loading and the copper loss of the transformer as shown on the mathematical formula 3.4.

$$P_{wdg} = P_c \left(\frac{KVA\,max}{KVA\,Total}\right)^2 * (L_{LF}) \quad 3.4$$

$$L_{LF} = L_{df}^2 + 0.23\,(L_{df} - K)^2$$

$$P_{wdg} = P_c[(\frac{KVA\,max}{Tr.KVA\,Total})^2 * \left(0.8479 * 0.8479 + 0.23\,(L_{df} - K)^2\right)$$

$$P_{wdg} = P_c[(\frac{19.0KW}{20KVA})^2 * (0.8479 * 0.8479 + 0.23\,(0.8479 - 0.7634)^2)$$

$$P_{wdg} = 0.6847P_c$$

P_c –full load copper loss which can be determined from international standards or can be taken from manufacturer data sheets of 132/15kv, 20MVA distribution transformer.

$$P_{wdg} = 0.6847 * 156500watt$$

$$P_{wdg} = 107.16kw$$

Other losses: - those losses might be occurred due to load unbalance, oil leakage, loss of life, lack of maintenance, improper up keep of distribution boxes, and joints loose connections. Generally the value is less than 1% of total energy input to the system [IEEE-SA C57-12.90-2001].

Finally, the distribution transformer power loss calculation using analytical method can concluded as

$$\boldsymbol{P_{total\ loss} = P_i + P_{wdg} + P_{others}}$$

Where $\boldsymbol{P_i} - iron\ loss\ P_{wdg} - winding\ loss\ ,\ P_{others} -$ Others

$$\boldsymbol{P_{total\ loss} = 12.55}\ \text{KW} + \boldsymbol{107.16}\ \text{KW} + (\boldsymbol{0.01 * 20,000\ kw}) = \boldsymbol{319.71}\ \text{KW}$$

The theoretical efficiency of the MV/LV transformer became 98.4%, but, practically, a given transformer efficiency does not exceed 97%. With this efficiency the power loss becomes 0.03*20,000KW= 600KW. This could be the maximum value. For the sake of Fairness computation let's take the average value (459.6KW).

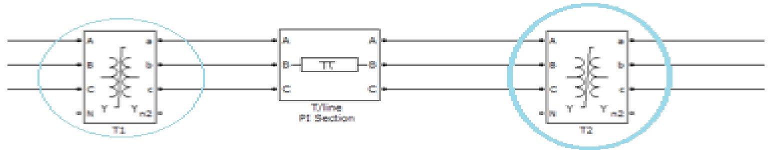


Figure 3. 3 MVAC distribution network power loss calculation

3.3. OVERHEAD DISTRIBUTION LINE (FEEDERS)

For medium AC distribution system the π- type three phase Lines is used to model the medium voltage distribution line. The main MV line shall be constructed with AAAC 95 mm^2. The study is depend on the 15KV voltage line. The main components of the medium voltage distribution lines are reactors, filters, arrestors, and insulators. This components were considered as the same in both systems of distributions for simplicity of power delivery and loss comparison. Under MVAC distribution system, the maximum distance from the distribution substation to that of the distribution transformer location is up to 25 k.m which carries 1500 KVA power. The cable size for different distribution voltage level is obtained by referring the IEEE standards and the existing type of conductors used by Ethiopian Electric Corporation or building installation code. The power loss analysis and power distribution via the overhead line depend on the characteristics of the magnetic field around the conductor. The two basic phenomenas are skin effect and proximity effect. Sine the basic comparision elements in DC and AC distribution systems is the power loss, the study focuses where the cause comes from and analyzed the significance difference in terms of the AC and DC resistance.

3.3.1. Skin effect on AC resistance

Skin effect is the development of current to flow on the boundary of the wire so that the current density is greater at the surface than at the core [35]. This means that the total available space of the wire is not used to carry the electrical power. It can be expressed in terms of the word skin depth which decreasess its value as frequency decreseses. Consequently, the cross sectional area increases which directly alters the conductor resistance. This effect is produced by the eddy currents induced by the magnetic field generated by the alternating current. The change in the AC resistance of the conductor due to skin effect can be evaluated using the ratio of AC resistance to DC resistance by considering different techniques. But, the most widely used approximated formula to compute the AC resistance is probably the one establishedin the IEC 60287-1-1 international standard [34] which is indicated in the following subsquent formulas.

$$R_{ac} = R_{dc}(1 + f_s)\ [\Omega/m] \quad 3.5$$

Where f_s – skin effect factor and it can be calculated using the formula shown below.

$$f_s = \frac{x_s^4}{192+0.8x_s^4}\ where\ x_s^4 = \left(\frac{8\pi f k_s}{R_{dc}10^7}\right)e2 \quad 3.6$$

The obtained skin effect value can be applicable for $x_s \leq 2.8$ and ks=1 for stranded conductor from the indicated international standard (IEC 60287-1-1). To evaluate this skin effect, first the DC equivalent resistance should be calculated.

$$R_{dc} = \frac{\rho}{A}[1 + \alpha(T - T_o)]\ (\Omega/m) \quad 3.7$$

Where $\rho - the\ resitivity\ of\ copper\ conductor\ at\ room\ temperature,$

$Ac - is\ the\ cross\ sectional\ area,$

$\alpha - \ is\ the\ temperature\ cofficient\ and$

$T - T_o\ change\ of\ temperatur$e.

But, assume that there is no temprature change which is at 20^{o}c. So the DC resistance is depend on only its cross sectinal area and its resistivity constant. But, it can be obtained from manufacturers' data sheet. (AAAC DIN 48201 part 6 was referenced for DC resistance at room temperature)

$$R_{dc} = \frac{\rho}{Ac}\ (\Omega/m) \quad 3.8$$

3.3.2. Proximity effect on AC resistance

Beside with skin effect, proximity effect is a mutual challenging found in distribution and transmission line. It can be defined as the crossing magnetic field from one conductor to another close conductor [34]. The major causes of proximity effect are closeness of the wires, bends in the wire, skin effect and frequency noise. Proximity effect can able to cause a power loss or the increament of the AC resistance of the conductor with a factor f_p which is shown in the formula below.

$$R_{ac} = R_{dc}(1 + f_p)\ [\Omega/m] \quad 3.9$$

$$f_p = \frac{x_p^4}{192+0.8x_p^4}\ where\ x_p^4 = \left(\frac{8\pi f k_p}{R_{dc}10^7}\right)e2 \quad 3.10$$

3.3.3. Skin and proximity effect on AC resistance

In a given equally spaced solid round three conductor distribution overhead copper line, there will be the skin effect and proximity efffect on the AC resistance of the system simultaneously.As a result the cumulative effective on AC resistance can be calculated using equation 3.12.

$$R_{ac} = R_{dc}\left(1 + f_s + f_p\right)\ [\Omega/m] \qquad 3.11$$

In the case of three parallel conductors carrying three-phase currents, the IEC 60287-1-1 standard models the following formula to determine the proximity effect factor (f_p) is used.

$$f_p = \frac{x_p^4}{192+0.8x_p^4}\left({D_c}/{s}\right) e2 \left[0.312\left({D_c}/{s}\right) e2 + \frac{1.18}{{x_p^4}/{\left(192+0.8X_p^4\right)}^{+0.27}}\right] \qquad 3.12$$

Where Dc- diameter of the conductor and S- distance between two conductors.

Concentric lay stranded Aluminum Alloy Conductors (AAAC) are made out of high strength Aluminum-Magnesium-Silicon Alloy [35]. The solid AAAC95m.m^2 (all almunium alloyed conductor) overhead line profile at 20^{o}c temprature and 50Hz frequency can be summarized in table 3.10. from IEC international standard, there is no conductor with this cross sectional area (95m.m^2). it approximated to 100m.m^2 conductor specification.

Table 3. 8 different overhead lines' data type and their source

parameter types	Value and data source
Cross sectional area (A)	95m.m^2 (DIN 48201part 6)
Diameter of the conductor (D_c)	12.5m.m (DIN 48201part 6)
Clearance between lines (s)	60c.m (EEPCO)
Resistivity constant (ρ)	1.72x10^{-8} (aluminium ⁻conductor)
Structure constant (k_p =k_s)	1 (stranded conductor)

The skin effect and proximity effct factors was calculated depend on the data shown in Table 3.10. and its summary of evaluation is shown in Table 3.11

Table 3. 9evaluation of skin and proximity effect factor

Effects	*Formula*	*Value calculated*
DC resistance	$R_{dc} = \frac{\rho}{A}\ (\Omega/m)$	$0.3085\ \Omega/k.m$
Skin effect factor	$x_p^4 = \left(\frac{8\pi f k_p}{R_{dc}10^7}\right)e2$	*0.041*
	$f_s = \frac{x_p^4}{192 + 0.8x_p^4}$	*0.00021*
Proximity effect	$f_p = \frac{x_p^4}{192 + 0.8x_p^4}\left({}^{D_c}/_{s}\right)e2\left[0.312\left({}^{D_c}/_{s}\right)e2 + \frac{1.18}{{}^{x_p^4}/_{(192+0.8X_p^4)} + 0.27}\right]$	*0.0023*
Total effect	$f_s + f_p$	*0.00251*
${}^{R_{ac}}/_{R_{dc}}$	$1 + f_s + f_p$	*1.00251*

3.3.4.Power loss comparison Analysis on overhead lines

Power loss determination on the medium AC network basically depends on the current rating through the conductor and the resistive characteristics of the material used. For this research work, it is tried to compare the power loss of MVAC and MVDC on 15 KV voltage distribution overhead lines. It can be computed and compared using the AC and DC resistance values which is obtained in equation 3.10.

- AC resistnace calculation from Dcresistance, skin and proximity effect

AC Resistance = 1.00251* DC resistance ohm per kilometere *distance

R_{ac} =1.00251 * 0.3085 ohm/k.m *25 k.m = 7.732 ohm

R_{dc} = 0.3085ohm/k.m * 25 k.m= 7.71 ohm

To determine the power loss across overall the distribution line , first the rating current should be calculated in both AC and DC distribution systems.From Table 3.11 to distribute 20 MW power from substation through AAAC95mm^2, 1500 KVA overhead distribution line, 14 feeders were required for both AC and DC distribution system. 1081 KW power was dissipated over the AC distribution line. But, 392 KW power was lost in over DC distribution line.

Table 3. 10 comparision of power loss in MVDC and MVAC overhead lines

Parameter type	AC distribution	DC distribution
Substation power	20MW	20MW
Distribution power/line	1500KVA	1500KVA
Overhead line voltage	15KV	25 KV
Rated current	57.7A	60 A
Total feeders (overhead lines)	14	14
Resistance	7.732 ohm	7.710 6ohm
Power loss/distribution line	77.23 kw	28 kw
Total power loss	1081 KW	392 KW

Skin and proximity factors contribute something for such power loss difference. So this is the reason why MVDC is better than MVAC with regard to the power loss of a given distribution network lines. The operational cost will be calculated in chapter four for the sake of comparision.

3.3.5. Power delivery capacity on overhead line

The power delivery capacity of the overhead line from the HV/MV to the MV/LV distribution transformer in both AC and DC cases was analyzed and compared to take which one will be economical over the other with regard to their efficiency. The power delivery analysis of MVDC distribution system for the same size and powercarrying capacity conductor were analyzed as below.

Average AC power delivery to the load

$$P_{AC} = \mathrm{S}\cos\emptyset \quad where\ S = complex\ power\ delivery, \emptyset - load\ angle$$ [12]

It could be written in the form of line to line voltage and the line current.

$$P_{AC} = \sqrt{3}V_{LL}I_L\cos\emptyset = \sqrt{3}V_{LL}I_{Max}\cos\emptyset$$

Average DC power delivery to the load

$$P_{DC} = V_{dc}I_{DC}\ but,\ V_{dc} = \frac{3\sqrt{3}}{\pi}V_{R.M.S}, \qquad P_{DC} = \frac{3\sqrt{3}}{\pi}V_{R.M.S}I_{DC}$$

$$V_{R.M.S} = \sqrt{\frac{9}{\pi}\int_{\pi/3}^{2\pi/3} V_s^2\left(\frac{1-\cos 2\omega t}{2}\right)d\omega t} = \sqrt{\frac{9}{\pi}Vs^2\left[\frac{\pi}{6}+\frac{\sqrt{3}}{4}\right]} = \sqrt{Vs^2\left[\frac{3}{2}+\frac{9\sqrt{3}}{4\pi}\right]}$$

$$V_{R.M.S} = 1.6554V_{LL}$$

$$P_{DC} = \frac{3\sqrt{3}}{\pi} * 1.6554V_{LL} * I_{DC} = 2.738\,V_{LL}I_{DC}$$

Note that, the current was taken as the maximum capacity of the line. So, the DC equivalent current is equal to the r.m.s value of the line current. ($I_{DC} = I_L = \frac{I_{max}}{\sqrt{2}}$)

$$\frac{P_{DC}}{P_{AC}} = \frac{2.738\,V_{LL}I_{Max}}{\sqrt{3}V_{LL}\sqrt{2}I_{Max}\cos\emptyset} = \frac{1.12}{\cos\emptyset} \qquad 3.13$$

From the above mathematical model of power delivery capacity in DC distribution overhead line is more than the power delivery capacity of AC distribution system for maximum power factor in which unity power factor is considered, the power delivery in DC distribution system is 1.12 times the AC distribution system.

3.4. THREE PHASE MV/LV DISTRIBUTION TRANSFORMER

This is the second transformer under the study. The possible rating of this transformer depend on the standards used for low voltage distribution transformers are 15/0.38kv (UEAP), 11/0.4, 20/0.4KV with power rating 200KVA, 100KVA, 50KVA and 25KVA.200KVA, 15kv/ 0.38kv transformer was selected for comparative study and its power loss was analyzed.

Table 3. 113Φ MV/LV Distribution transformer data sheets

Windings	Voltage (KV)	Resistance (ohm)	Inductance (mH)	Power carrying capacity (KVA)
Primary winding	15	14.75	0.131	25, 50, 100, 150 and 200
Secondary winding	0.38	0.0062	0.067	

The core power loss was more significant in low rating transformers rather than the big transformers. The normal core loss was minimum as compared to the nominal power rating of the big transformers like 10MVA, 100MVA, 200MVA and so on [25].

3.4.1. Power loss Evaluation using analytical technique

Since there was no any load data measurement at the low voltage distribution transformer, the load data and its distribution should be estimated using load assessment and estimation mechanisms. First the possible load types and quantities should be assessed in sample area or village by considering as much as possible all the type of the loads. The load assessment was carried out by considering the common loads with their rating and estimating the energy consumed by estimating the working hours. From the assessment 191.6KW power was obtained and the total 1011KWH energy consumption was estimated. As a result, the standard transformer that must be installed was 200KVA, 15/0.38kv.Losses in this distribution transformers account for almost one third of overall transmission and distribution losses [25].Transformer losses occur due to both copper and core losses. An increase in loading will result in an increase of current flow and correspondingly greater amount of loss in the transformer. Similarly, by calculating the maximum, minimum and average load of the LV transformer, it was possible to determine the total power loss from the three transformer factors. The maximum, minimum and average load was determined as 169.4KW, 17KW, and 44.5KWrespectively. The transformer factors were computed from the load status values. [Take the iron loss and copper loss value from table 3.7].

$$load\ factor\ (L_{df}) = \frac{43.5\ KW}{169.4\ KW} = 0.2568$$

$$K-\ factor\ (K) = \frac{17\ KW}{169.4\ KW} =\ 0.1$$

$$loss\ factor\ (L_{LF}) = 0.325 * 0.325 + 0.23\ (0.325 - 0.1)^2 = 0.267$$

$$P_{wdg} = P_c * [(\frac{KVA\ max}{Tr.KVA\ Total})^2\ * (L_{df}^2 + 0.23 *\ (L_{df} - K)^2)$$

$$P_{wdg} = 3300w * [\left(\frac{129.4}{200}\right)^2\ * (0.267) =\ 632.1\text{watt}$$

The 200KVA, 15/0.38KV single transformer loss was determined as

$$P_{total}\ = 632.1 + 350 +\ 0.01 * 20000VA\ =\ 2982.1\text{watt}\ = 2.982\ \text{KW}$$

The total number of LV transformer supplied from 15KV buss line could be calculated from the ratio of the total capacity of 132/15KV, 20MVA substation power rating to the total rating of 15/0.38KV, 200KVA rating. The ratio becomes 100. This means, one hundred LV transformers were required to transfer 20MVA power to the load. The grant total power loss across all the LV transformers became 298.2KW. From the above result the nominal efficiency 132/15KV transformer can be determined from its nominal input and output. Its nominal input power 20MVA and the calculatedoutput power can be obtained as.

20000KVA-298.2KVA= 19701.8KVA.

$$efficiency = \frac{p_{output}}{p_{input}} X100\%$$

$$efficiency = \frac{20000kw - 298.2kw}{20000kw} X100\%$$

$$efficiency = 98.5\%$$

Practically, from [18] the maximum transformer efficiency does not exceed 97%. So, the number is around the actual value. Since it is a feasibility study as compare with DC system taking the maximum value assures the right way comparison. Similarly, the individual LV transformer (15/0.38KV, 200KVA & 50Hz) efficiency becomes

$$efficiency = \frac{200kVA - 2.98KVA}{200kVA} X100\%$$

$$efficiency = 98.5\%$$

Theoretically, the expected power loss of the power transformer 0.03*20000KW= 600KW, for the fairness of comparison analysis let's take the average of the maximum and minimum power loss of the 200KVA transformer.

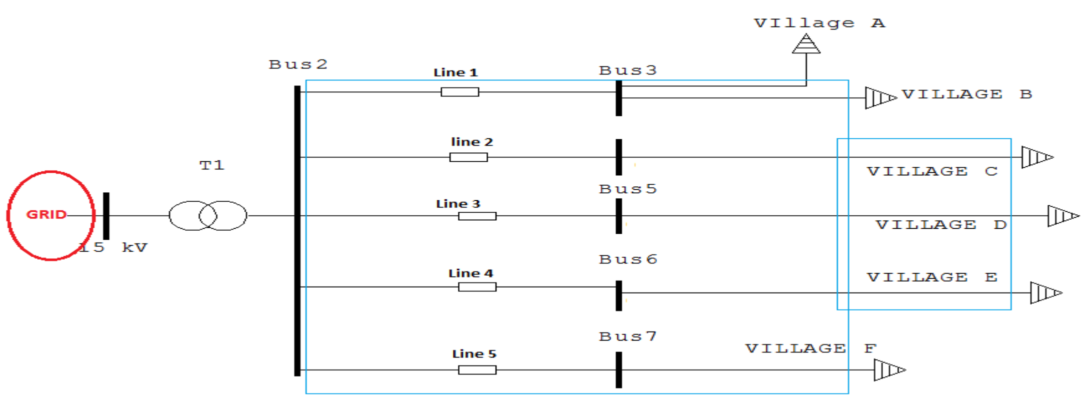


Figure 3. 415KV voltage distribution system

$$P_{avg}(loss) = \frac{298.2\text{KW} + 600\text{KW}}{2} = 449.1\ KW$$

The overall power loss on the distribution transformer can be estimated in the form of minimum, average and maximum value which were 298.2KW, 449.1KW and 600KW respectively. The average power loss (449.1KW) would be taken for comparision.

CHAPTER 4

DC DISTRIBUTION COMPONENT MODELING AND DESIGN

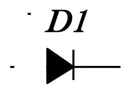
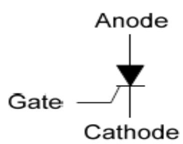
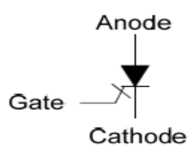
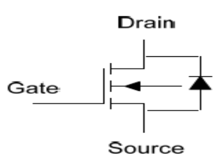
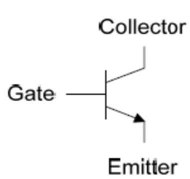
4.1. INTRODUCTION

Development of DC distribution structure can be started from Medium voltage DC distribution network. It should be achieved by modeling of the components like AC to DC converter (rectifier), AC filters, DC cables/ lines, DC/ DC converters and DC/AC inverters. The MVDC distribution system was supplied from 132/15 kV (stepped down transformer). The 15kv AC voltage was rectified to the appropriate DC voltage level. So, the MVDC distribution network was designed and simulated using the Matlab and NI-Multism software. The power loss on the equipments and power distributed to the dedicated load was computed to study its feasibility as compared to the MVAC distribution networks. The material cost in both systems and energy loss cost were evaluated and compared. In order to enter to the DC system of distribution the conversion analysis should be seen first.

4.2. AC/DC RECTIFICATION

The process of converting from AC voltage to DC voltage is commonly known as Rectification and the device which can do this is called rectifier. All characteristics, efficiency and the device cost directly affectthe development of MVDC network system. Now, the case study of the research work is 15 KW, 1500 KVA and 50Hz distribution substation. So, the development of MVDC was by converting 15 KV line to line voltage into the appropriate DC value. There are different electronic devices or switches used for AC/DC conversion (electrification). These converters are applicable and designed for different tasks with different power ranges. Table 4.1. shows different converters with their specification. The converters IGBT and power MOSFET are mostly applied to low and medium power level rating conversion. Power MOSFET is the most fast switching device which can be applied to telecommunication systems [4]. The study is focused on how DC voltage is developed from Medium AC voltage to transfer power in kilo wat level to the dedicated load.

Table 4. 1different converting devices and their character

Device type	Symbol	Application	Power rating maximum
Diode		Medium and high power Uncontrolled rectification	0.1-100MW, At standard frequency
SCR		High power and multi megawatt power system, complex control mechanism	0.1-1GW <100HZ frequency
GTO		High power, multi megawatt traction, special control mechanism	1-100 MW <500HZ frequency
Power MOSFET		Switching mode power supplies and for small power actuators /devices	Up to 10 KW <1MHz frequency
IGBT		Medium power industrial derives , machine control Inverter , converter and active filters	Up to 500KW <100KHz frequency

From Table 4.1 all the converters are listed with their specification. Solid diode and thyristor can be lied as a candidate due to their power ratings. To select the best converter for the study, there must be performance evaluation of each converter. Form factor, Ripple factor, rectification ratio and transformer utilization factor are the performance parameters of converters.The mathematical definition and value of these term were showed and calculated numerically in equation 4.1, 4.2, 4.3 and 4.4 rspectively.

Form factor (FF):- it is the ratio of the root mean square voltage of the input (V.r.m.s) to DC voltage developed. This factor helps to determine the other performance parameter values.

$$\text{FF} = \frac{V_{r.m.s}}{V_{DC}} \tag{4.1}$$

Ripple factor: This shows quality of rectification, smoothness of the voltage waveform at the output of the rectifier. The *RF* is defined as the ratio of the effective AC component of the load voltage versus the DC voltage:

$$RF = \frac{\sqrt{V_{r.m.s}^2 - V_{DC}^2}}{V_{DC}} = \frac{\Delta V_{r.m.s}}{V_{DC}} \tag{4.2}$$

$$RF = \sqrt{FF^2 - 1}$$

Rectification ratio (ɳ): it is also known as rectification efficiency (ɳ), this performance parameter can be referred as converting efficiency of the switching device.

$$ɳ = \frac{P_{DC}}{P_{DC} + P_{loss}} = \frac{1}{FF^2} \tag{4.3}$$

Where- $P_{DC} - DC\ output\ power, P_{loss} - switching\ device\ power$

Transformer Utilization factor (*TUF*):- this factor is used to adjust the rectifier AC input voltage to a level suitable for the required application.

$$TUF = \frac{P_{DC}}{effective\ transformer\ KVA\ rating} \tag{4.4}$$

4.2.1. Solid diode based rectification

The rectification process of the system could be shown in one line diagram. The source voltage from the HV/MV transformer is connected to the rectifier, as a result DC Medium voltage can be obtained from this rectifier. Figure 4.1 shows the one line diagram of the rectifier circuit.

Three phase AC source voltage V_s (t) is given in the following three equations. The source voltage (V_S) is the secondary voltage of the distribution transformer.

$$V_{an} = V_m \sin(\omega t) \quad 4.5$$

$$V_{bn} = V_m \sin(\omega t - 120) \quad 4.6$$

$$V_{cn} = V_m \sin(\omega t + 120) \quad 4.7$$

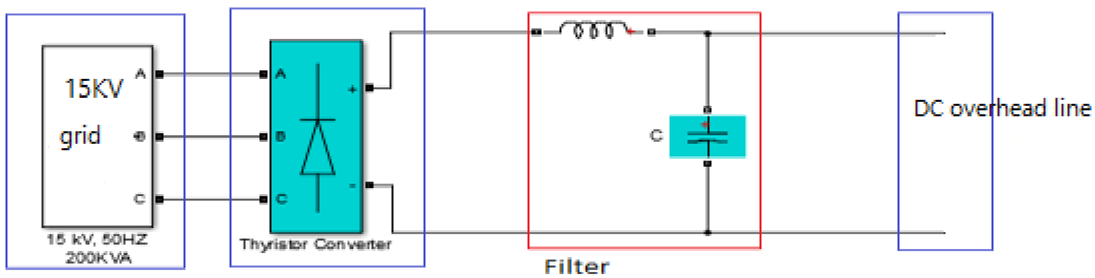


Figure 4. 1 AC/DC rectification.

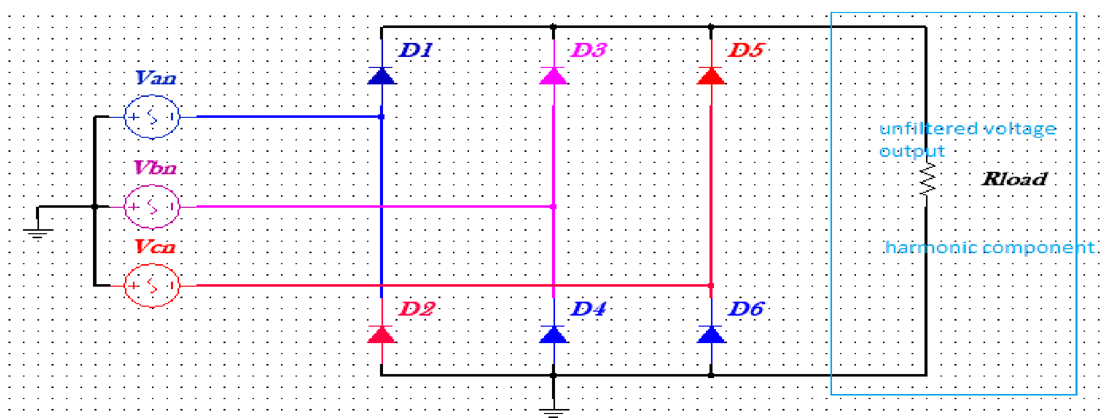


Figure 4. 2 uncontrolled six pulse bridge rectification

The input voltage to the rectifier is the line to line voltage voltage in the form of r.m.s.

$$V_{ab} = \sqrt{3} V_m \sin(\omega t + \frac{\pi}{6})$$

$$V_{ab} = \sqrt{3} V_{an} \angle 30$$

$$V_{an} = \frac{V_{ab} \angle -3}{\sqrt{3}} = \frac{15000}{\sqrt{3}} \angle -30 = 8660\ volt = 8.66kv$$

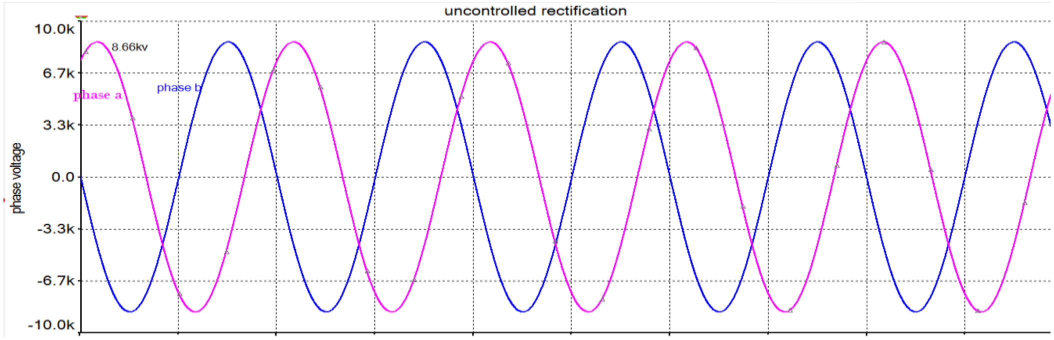


Figure 4. 3phase voltage wave form on phase a and b

$$V_{R.M.S} = \sqrt{\frac{1}{T}\int_0^T {V_s}^2 d\omega t} \qquad 4.8$$

From this r.m.s formula, the single phase r.m.s value can be obtained,

$$V_{R.M.S} = \sqrt{(\frac{1}{2\pi}\int_0^{2\pi} {V_m}^2 \sin^2 \omega t)\, d\omega t}$$

$$V_{R.M.S} = \frac{V_{an}}{\sqrt{2}} = \frac{8660V}{\sqrt{2}} = 6123.5\text{V}$$

Now, the R.M.S voltage can be converted into line to line net voltage using the formula Given below.

$$V_{ab} = \sqrt{3}V_{an}\angle 30 = \sqrt{3}V_{rms}\sin(\omega t + 30) \qquad 4.9$$

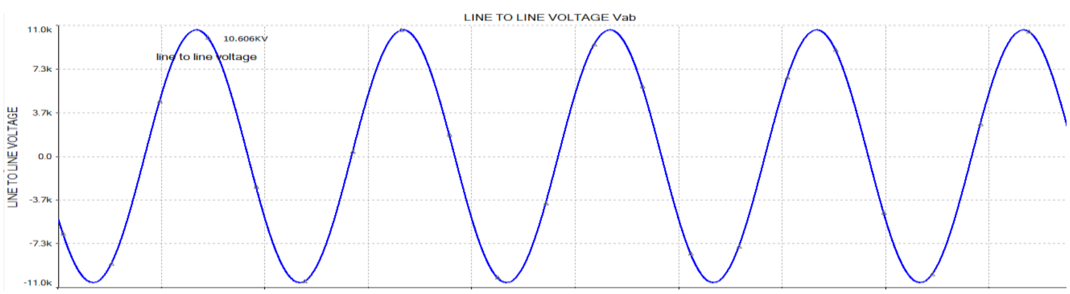


Figure 4. 4 Line to line voltage of 15kv Distribution line

But, for simplicity of analysis the developed DC voltage from the six pulse diode can be considered in terms of the source voltage (Vs) in general. This voltage value is in between two lines (line to line). It is converted into r.m.s value to supply the rectifier. Because any rectifier device changes AC voltage to DC voltage by taking this line to line voltage in terms of R.M.S.Then the converter would be supplied by tapping the 15KV voltage terminal. As it is shown in figure 4.6 the voltage is puerly sinusoidal. It is free from distortion.

$$V_{DC} = \frac{2}{2\pi/3}\int_{\frac{\pi}{3}}^{\frac{2}{3}\pi}\sqrt{3}\,V_s \sin\omega t d\omega t \qquad 4.10$$

$$V_{DC} = \frac{3\sqrt{3}}{\pi}V_s[-\cos{}^{2\pi}/_{3} + \cos{}^{\pi}/_{3}] = 1.6548\,Vs$$

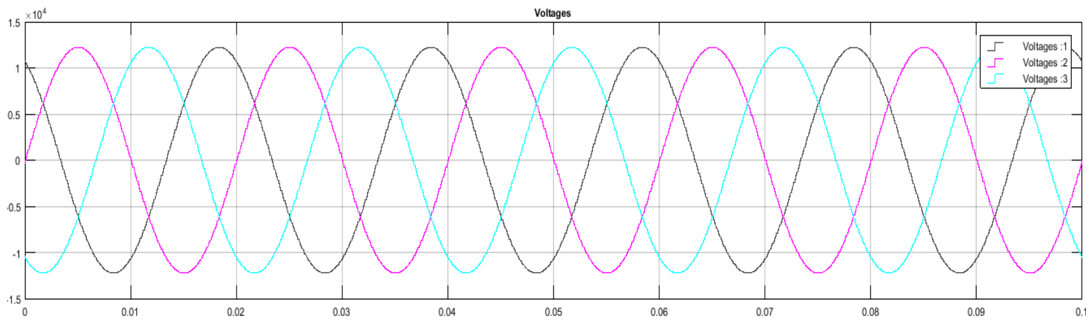


Figure 4. 5 purely sinusoidal wave form of the 15KV distribution line

The root mean square value (R.M.S) the three phase rectifier conduction system

$$V_{R.M.S} = \sqrt{\frac{1}{2\pi/_3}\int_{\pi/_3}^{2\pi/_3}(\sqrt{3}V_s\sin\omega t)^2 d\omega t} = \sqrt{\frac{9}{\pi}\int_{\pi/_3}^{2\pi/_3}Vs^2 sin^2\omega t d\omega t}$$

$$V_{R.M.S} = \sqrt{\frac{9}{\pi}\int_{\pi/_3}^{2\pi/_3}V_s^2\left(\frac{1-\cos 2\omega t}{2}\right)d\omega t} = \sqrt{\frac{9}{\pi}Vs^2[\frac{2\pi/_3}{2} - \frac{\pi/_3}{2} + \frac{\sin 4\pi/_3}{4} + \frac{\sin 2\pi/_3}{4}]}$$

$$V_{R.M.S} = \sqrt{\frac{9}{\pi}\int_{\pi/_3}^{2\pi/_3}V_s^2(\frac{1-\cos 2\omega t}{2})d\omega t} = \sqrt{\frac{9}{\pi}Vs^2[\frac{\pi}{6} + \frac{\sqrt{3}}{4}]} = \sqrt{Vs^2[\frac{3}{2} + \frac{9\sqrt{3}}{4\pi}]}$$

$$V_{R.M.S} = 1.6554V_S \qquad 4.11$$

The performance parameter values can be evaluated using equation 4.10 and 4.11.

Table 4.2 shows that the performance parameter values of solid diode six pulse rectification.These value would be compared with the performance parameter value obtained from SCR based rectification upcoming next.

Table 4. 2 Solid diode rectification performance parameter values

Performance parameter type	Value
Ripple factor	0.0004 (0.04%)
Form factor	1.0004
Rectification ratio	0.99
Transformer utilization factor	0.952

4.2.2. Thyristor based rectification

The full wave controlled rectifier is constructed from the three terminal electronic switching device commonly known as silicon controlled rectifier (SCR). The other name of this switch is thyristor. As it was tried to show before, this switch could be applied on the medium voltage level conversion. The MVDC three phase full wave controlled rectification (MVDC thyristor) which is shown below, consists six thyristor were operated alternatively to rectify the full wave sinusoidal voltage.

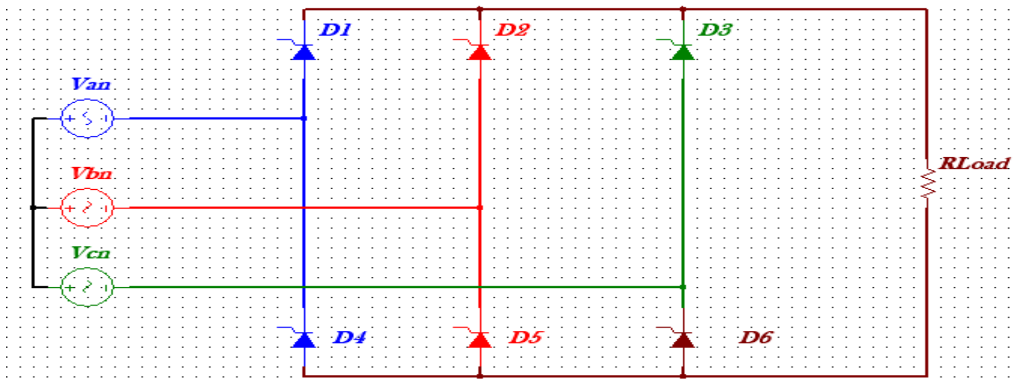


Figure 4. 6 Thyristor based rectifier

The voltage output from unfiltered silicon controlled rectifier can be obtained using the mathematical integral formula shown below. This voltage is ultimately the average value of distorted voltage.

$$V_{DC} = \frac{1}{T}\int_0^T V_{ab}\, d\omega t \qquad 4.12$$

$$V_{dc} = \frac{3}{\pi}\sqrt{3}V_s \cos\alpha \qquad 4.13$$

$$\text{Or, } V_{dc} = \frac{2}{\pi/3}\int_{\alpha}^{2\pi/3} \sqrt{3}V_s \sin(\omega t + \pi/6)\, d\omega t$$

$$V_{dc} = \frac{3\sqrt{3}}{\pi} V_S \left[1 + \cos\left(\alpha + \frac{\pi}{6}\right)\right] \qquad 4.14$$

The root mean square value of the voltage from six pulse SCR rectification:

$$V_{R.M.S} = \sqrt{\frac{1}{2\pi/3}\int_{\alpha}^{\pi/3+\alpha} (\sqrt{3}V_s \sin\omega t)^2 d\omega t}$$

$$V_{R.M.S}\,(\alpha) = \sqrt{3}V_s\sqrt{1+\frac{3\sqrt{3}}{2\pi}\cos 2\alpha} \quad 4.15$$

The performance parameter of the SCR rectification can be evaluated as function of the firing angle. So, thyristor based rectification needs a special control mechanism like Microcontroller to have an excellent performance parameter values. But, from the mathematical model evaluation of performance is posible it can be compared with the solid diode rectification perfomance parameter values.

$$FF(\alpha) = \frac{\pi}{3\cos\alpha}\sqrt{1+\frac{3\sqrt{3}}{2\pi}\cos 2\alpha} \quad 4.16$$

$$\eta(\alpha) = (\frac{1}{FF(\alpha)})^2 = \frac{9}{\pi^2}cos^2\alpha\frac{1}{1+\frac{3\sqrt{3}}{2\pi}\cos 2\alpha} \quad 4.17$$

$$RF(\alpha) = \sqrt{FF^2-1}$$

$$RF(\alpha) = \sqrt{\frac{\pi^2}{9cos^2(\alpha)}\left[1+\frac{3\sqrt{3}}{2\pi}\cos\alpha\right]-1} \quad 4.18$$

By taking the maximum and minimum value of the firing angle, the performance parameter values can be evaluated and approximated. Using equation 4.13, 4.14, 4.15 and 4.16 the performance parameter values were obtanined in Table 4.3. the value of the controlled angle is setted at zero and 90 degree.

Table 4. 3 SCR based rectification performance parameter evaluation

Performance test type	$\alpha \cong 0$	$\alpha \cong 90$
Ripple factor	0.967	Invalid
Form factor	1.387	Invalid
Rectification ratio	Very good	Very Low
Tr. Utilization factor	Very good	Very Low

From table 4.3 and table 4.4. the solid diode rectificaion and thyristor based rectification can be compared with regard to their ripple factor and rectification ratio. The ripple factor and rectification ratio (efficency) in the case of solid diode based rectification were 0.04% and 99% respectively. But, in the case of SCR is 3.3% and very good efficency respectively. As a result, solid diode based rectification is used to convert the MVAC voltage to MVDC voltage in MVDC distribution network model.

4.3. MVDC DISTRIBUTION STRUCTURE

This network model is developed from the three phase AC source supply (15KV distribution line) and using medium power six pulse solid diode bridge rectifier. First, the input or the source voltage was checked for assuring that might be purely sinusoidal wave form generation. The three phase 132/15 KV transformer's out put terminal is directly connected with the solide diode rectifier to develop medium voltage in DC system. The immediate rectification output voltage can be computed using the mathematical model in equation 4.11 approximately 25 KV was obtained. This voltage level will be simulated using NI multism. So, this is the medium voltage level at at MVDC network system. Inorder to get a purified 25 KV, LC filter is connected next to the rectifier. Figure 4.8 shows the MVDC distribution system model circuit.

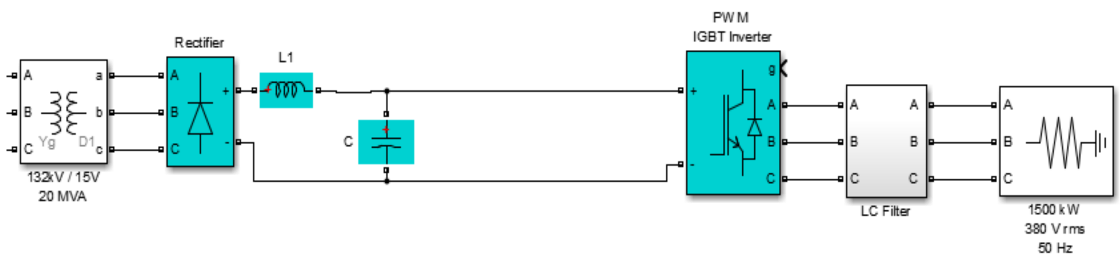


Figure 4. 7 MVDC distribution system model circuit

The MVDC distribution system feeder voltage can be calculated using the mathematical model in equation 4.10.

$$V_{DC} = \frac{2}{2\pi/3}\int_{\frac{\pi}{3}}^{\frac{2}{3}\pi} \sqrt{3}V_s \sin\omega t d\omega t$$

$$V_{DC} = \frac{3\sqrt{3}}{\pi}V_s[-\cos {}^{2\pi}/_3 + \cos {}^{\pi}/_3] = \frac{3\sqrt{3}}{\pi}V_s = 1.6548V_s$$

$$V_{DC} = 1.6548 * 15 = 25\ KV$$

The DC feeder was designed to carry 1500KVA power using 25 KV medium voltage level.

4.3.1. AC/DC rectifier harmonic filter

Filters are basically used for smoothing out the distorted or harmonic contained voltage. Harmonic is the additional constant signal value to the fundamental voltage or current. Electronic devices themselves are the source of harmonics. DC voltage generation from AC voltage source depends on this electronic devices or converters. As a result, these devices produces unwanted signals incorporated with the main message signal (voltage and current). In order to attenuate or remove this unwanted voltage or current signal from the fundamental voltage or current value; most of the time filter is added at the output terminal of the electronic devices. Filters could be designed in different broad ways. Actually, filters consist the passive parameters (inductor and capacitor). Accordingly, they can be categorized as capacitor, inductor and capacitor- inductor filters [23]. Filters were also classified based onthe type of input element used which can be either inductor or capacitor. Inductor input filters are selected in higher power networks. This inductor eliminates variation in current by holding the load current. But, capacitor input filters have the ability to avoid external electromagnetic effects on the current and voltage on the on and off situations of the rectifier and it was not suitable for high power application [19]. The MVDC distribution network with an inductive-capacitor output filter shown in figure 4.7.

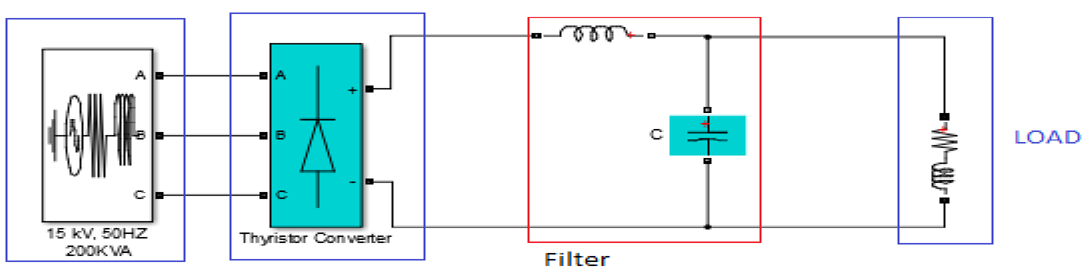


Figure 4. 8 MVDC Network with filters

Ripple is defined as the ratio of the effective AC component of the load voltage versus the DC voltage.

$$Rf = \frac{\Delta V}{V_s} \quad 4.19$$

Where ΔV change in output voltageV_s the voltage source in R.M.S.

Inductor-capacitor filter was selected for this model of MVAC rectification. A capacitor inductor filter is used to improve the filtering action of rectified voltage and current. We saw in above sections that the capacitor alone or the inductor alone cannot perform the filter action satisfactorily. However, if both the capacitor and inductor are combined, they produce high quality dc voltage and current. Different inductor – capacitor values were tried to adjust the smoothing voltage variation values.

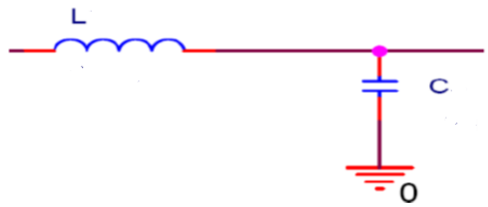


Figure 4. 9 inductor- capacitor AC/DC rectifier filter

To design the filter with ripple factor value 0.04%, select the capacitor value arbitrarily, then varying the inductor value until obtaining the minimum ripple factor by trial and error method. 2.5mF capacitor and 500Ω resistor were selected to be fixed parameters. The voltage deviation was tested at 2.2mH, 5mH, 10mH, 15mH, 20mH, 25mH and 50mH inductor values. The ripple voltage was determined from the equation 4.19. Filter having ripple factor less than 3% is best rectification [32]. By selecting the appropriate values of parameters, the given filter can be designed.

Table 4. 4 AC/DC converter filter parameter value

C (mF)	L (mH)	R (Ω)	$V_{min.}$ (V)	$V_{max.}$(V)	ΔV	Ripple (R_f)
2.5	2	500	52.9	67.2	14.3	0.14
2.5	10	500	53.8	62.2	8.4	0.083
2.5	20	500	57.2	62.2	5	0.049
2.5	30	500	58.8	60.2	2.4	0.024
2.5	50	500	58.8	59.8	1.1	0.011
2.5	100	500	58.8	59.7	1.1	0.011

4.4. LVDC DISTRIBUTION STRUCTURE

Low voltage DC distribution system wasconstructed from the MVDC distribution system by using either DC/DC converter or DC/AC inverter. DC/DC converter should be used to construct the LVDC distribution line. In this case, the medium voltage distribution contains DC/DC converter which steps down the given MVDC voltage level (17.5 KV) to the required low voltage level (LVDC).

4.4.1. Load type assessment and demand estimation

The consumption values and types of the loads taped from distribution transformer (15/0.38 KV) should be assessed before modeling and obtaining the LVDC structure components. These loads may be residential, commercial and industrial. From the assessment AC and DC powered loads are summarized with their voltage ratings. This value is not the accurate one, it is the estimation just to know the capability of the DC distribution component on the market (rectifier, chopper, and inverter size). The selection of DC structure components depends on this estimation value. The load estimation summary is shown on Table 4.5 which is obtained from appendix A.

Table 4. 5 home, commercial and residential demand estimation summary

Target area	Types of Appliances	Unit (k.w)	Quantity (number)	Total load (In KW)	Working Hrs. per day	Kwh/d
loads				191.6 kw		1011kwh/d

The need for assessing the load type and estimating the demand was to address the appropriate DC distribution structure and to determine the size of the system. From Appendix A the total power and energy consumption estimated within 24 hours were 191.6 KW and 1011kwh/d respectively. The demand estimation (191.6 KW) assures that the power carrying capacity of LV transformer (15/0.38 KV) was 200 KVA. The load assessment in type was performed for identifying how much loads can be supplied from AC distribution system without modification and how much the existing loads are DC powered. So the study of power supply technique were by considering the loads indicated in appendix D and appendix A.

4.4.2. Modeling of DC/ DC voltage converter

Basically, DC/DC converter is mostly designed from inductor, capacitor and resistor. The combination elements give the second order transient circuits. The whole analysis can be carried out by applying second order differential equations. The resistor is used to drop down the source voltage into the required low voltge level. And the capacitor - inductor components keeps the voltage and current constant respectively. Figure 4.9represents DC to DC converter. The mathematical model and analysis were performed and the required low voltage level was designed.

$$-V_s + R_1 i_L + \frac{Ldi_L}{dt} + V_c(t) = 0 \qquad 4.20$$

Where $V_c(t) =$ the voltage across the capacitor

$\frac{Ldi}{dt} =$ the voltage across the inductor

$V_s =$ The voltage to be stepped down

Now from the figure the current is divided in to two components. Load current and the capacitor current which passing through the capacitor. So, the input current can be represented using this two currents.

$$i_L = c\frac{dV_c(t)}{dt} + \frac{V_c(t)}{R_2} \qquad 4.21$$

Where $c\frac{dV_c(t)}{dt}$ the capacitor charging current and $\frac{V_c(t)}{R_2}$current outgoing to the load.

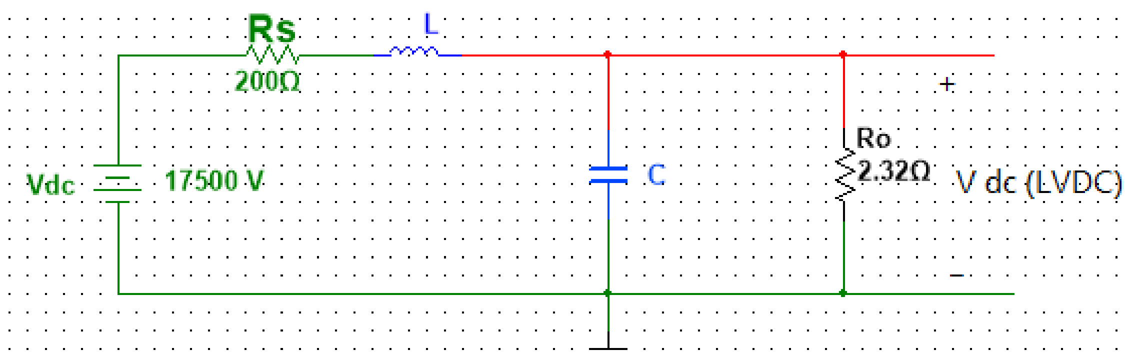


Figure 4. 10 DC to DC voltage converter Model

The general equation can be obtained by combining equation 20 and 21.

$$\frac{d^2V_c(t)}{dt^2} + \frac{R_1}{L}\frac{dV_c(t)}{dt} + \left(\frac{1}{LC} + \frac{R_1}{LCR_2}\right)V_c(t) = V_s \qquad 4.22$$

This equation can be solved using general approach of higher order differential equations and its solution has two components. The first one is purely DC voltage value and the second one is exponentially decaying value. The exponential decaying value will be die out after a certain cycles of operation. During the steady state condition, only the DC component will be present on the output. The solution of the above equation becomes.

$$V_c(t) = K_o + K_1 e^{-B1t} + K_2 e^{-B2t} \qquad 4.23$$

The decaying component solution

$$V_c(t) = K_1 e^{-B1t} + K_2 e^{-B2t}$$

Where K_0, K_1 and K_2 are the conversion constants. The three variables can be solved by using the steady state condition of the circuits. The first constant show that the ultimate DC component present throughout the operation. At steady state the capacitor stored full of charges and the inductor doesn't hold any current. As a result the overall current coming from the source totally passed to the load.

$$B_{12} = -\frac{R_1}{L} \pm \sqrt{\frac{R1^2}{L^2} - 4(\frac{1}{LC} + \frac{R1}{LCR2})}$$

The value of these constants does not affect the steady state value of the inductor current and capacitor voltage. Because the current and the voltage at infinite time the all decaying component becomes zero. The most important parameter to design the required voltage level is the constant K_0.

$$K_o = \frac{V_s}{\frac{1}{LC}+\frac{R_1}{LCR2}}\ ,\ {}^{V_s}/_{K_o} = {}^{1}/_{LC} + {}^{R_1}/_{LCR_2} \qquad 4.24$$

The value ${}^{V_s}/_{K_o}$ could be known. So, the parameters that should be determined are the passive component (resistors, capacitor, and the inductor value). The input voltage is 25 kv and lets consider the DC/DC output voltage is 400 V. Then, ${}^{V_s}/_{K_o}\ becomes\ {}^{25\ kv}/_{200\ v} = 125.$ Therefore, the following mathematical relationship was taken to determine R_1 and R_2.

$${}^{1}/_{LC} + {}^{R_1}/_{LCR_2} = 125$$

The contribution of the capacitor and the inductor was to decay out or die out the additional voltage values like harmonics. So, the multiplication result can be set as unity (LC≅1). The equation becomes as R_1 was the variable parameter and R_2 the load current determinant factor.

$$1 + {}^{R_1}/_{R_2} = 125\ \rightarrow R_1 = 124\ R_2$$

From this equation the DC/DC converter output depend on the load resistance. The input resistance is constant. For example, 2.3 ohm resistive load needs 200 ohm resistance value in DC/DC converter to have 200 V. So, from DC/DC voltage converter multiple level of DC voltage can be obtained (12v to 400 Volt).

4.4.3. Three phase voltage source inverter modeling

To model a given inverter, different books and literatures were reviewed. From table 4.1 the converter types and their characteristics were stated. Among those converters, IGBT based inverter was selected. Using the IGBT device, six-pulse bridge PWM inverter was modeled as in figure 13. The input DC voltage was supplied in bipolar form. The general principle of operation was stated as three paired leg switches (Q1 and Q4, Q3 and Q5, Q2 and Q6) never operate at the same time to prevent short circuit across the link [21]. As a result voltages of the output depend on the line current polarity.

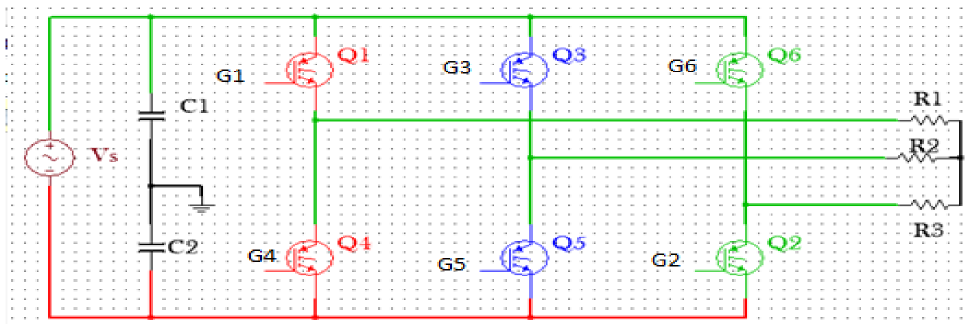


Figure 4. 11 six pulse bridge inverter Model

There would be eight possibility conduction conditions of the six switches. The control generator was connected at each gate terminals [G_1, G_2, G_3, G_4, G_5 and G_6]. The eight state was shown in table 4.6. Among the eight states, 7 and 8 produced zero output voltage because of the current circulate freewheel either through the upper or lower legs. The remaining six states produced pulsed AC output voltages. To generate 120^0 out of phase AC voltage, sinusoidal pulse width modulation was used. The sinusoidal AC control voltage supplied to the gate of the six pulse bridge inverter shown on figure 4.11.

Table 4. 6 operating principle of three phase inverter

State	On switches	Off switches	V_{an}	V_{bn}	V_{ab}	Remarks
1	1,2, 6	3, 4, 5	v	0	V	Half peak
2	2,3,1	4, 5, 6	v	-V	2V	Positive peak
3	3,4, 2	1, 5, 6	0	v	v	Positive half peak
4	4,5,3	1, 2, 6	-v	0	-v	Negative half peak
5	5,6,4	1, 2, 3	-V	-v	-2V	Negative peak
6	6,1,5	2, 3, 4	0	-v	v	Positive half peak
7	1,3,5	2, 4, 6,	0	0	0	No output
8	4,6,2	1, 3, 5	0	0	0	No output

So there would be comparable inputs which are the normal DC output and the sinusoidal input at the gate. As a result, 120^0 out of phase AC line to line voltage was developed on the load. Normally, the amplitude of the output voltage was controlled by the DC input voltage which was supplied in pulse form. From DC to DC voltage converter output voltage was obtained and this voltage is supplied to the central inverter, by grounding centrally (-200, 200) or by making the DC-DC converter output is 400V. The most important advantage from three phase inverter was no even harmonics and the odd harmonics were eliminated each other. Because, the amplitude were the same and the phase angle was the multiple of three. Consequently, it became the same as the fundamental signal phase angle.

$$V_{an(N=9)} = V_{an(9)} \sin 9\omega t$$

$$V_{bn(N=9)} = V_{bn(9)} \sin 9(\omega t - 120) = V_{bn(N=9)} = V_{bn(9)} \sin(9\omega t - 1080)$$

$$V_{bn(N=9)} = V_{bn(9)} \sin 9\omega t$$

The inverter output voltage: - $V_{ab\,(N=9)} = V_{an} - V_{bn} = 0$

The harmonic component output voltage on the load became zero because $V_{an} = V_{bn}$ at any harmonic level. To simulate three phase inverter output, two three level bridge inverter with linear transformers were used. The pulse width modulation controls each bridge output. The advantage of this linear transformer based bridge inverter was to eliminate the harmonics by holding the current on its winding. The standard three phase 380 /400 V output voltage were obtained.

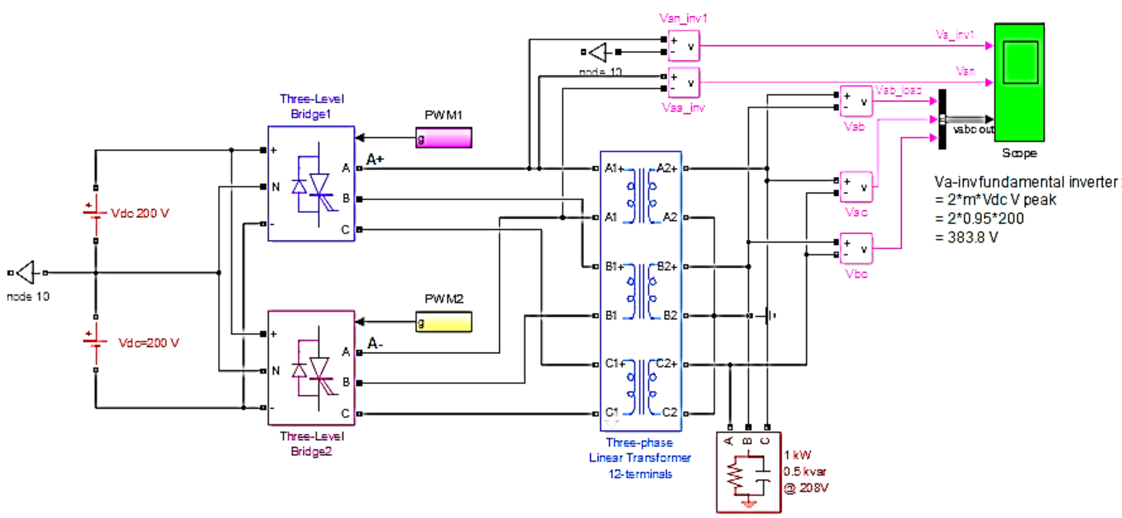


Figure 4. 12 Central three- stage PWM Inverter system design

4.4.4. Inverter selection

Previously, there were a lot of challenges to implement DC distribution system on ground. Because, high power application central inverters have not been developed to fit the required amount of demands. Today, there are several types of inverters on the market which can supply up to 1MW power. In this part of the study inverter was selected from the market depend on the designed parameter values on the previous section. This designed parameter value was -+200V DC input, 200KVA power rating, 400V AC output and IGBT based three level bridge inverter. So, inverters which could fit this specification were searched from the market. Some inverters obtained from websites and international manufacturers summarized in table 4.7 with their specification. Totally, the nine different standard inverters' specification was tried to have seen.

Table 4. 7 summary of inverter types with their specification

s.no	Name /type/product name	Specification
1	Consul pelican 3000 Indian	400KVA, 415V (Indian standard) AC sine wave IGBT based.
2	Kevin DSP sine wave	60KVA, 360V, pure sine wave, IGBT based.
3	Delta SOLVIA CL 600AP	675A, 330V, IGBT based inverter
4	Unlined Leo power	300KVA, IGBT based pure sine wave
5	Unique max. Unique.	50KVA, 400V, IGBT based pure sine wave
6	SOCOMECS SUNSYS P100TR.	120KVA, 900V, IGBT based, grey colored, 97.5% efficiency.
7	PVS800-57-0500kW-A, ABB inverter	500KVA, 230V & 400VAC output, 400-900V DC input, IGBT based, 98.6%& 98.2%. <3%
8	PVS800-57-0250kW-A ABB inverter.	250KVA, 230V & 400V AC output, 400-900V DC input, IGBT based, 98.0% & 97.6 %. <3%
9	Sunny central 250U/500U	250KW, 500KW, weighted efficiency 97%-98.6% with integrated isolation transformer,

Among the inverters listed in table 4.7 PVS800-57-0250kW-A ABB inverterwas best fit able to the designed parameter values. Their power rating, voltage and efficiency are well specified. Secondly, unique max. Unique inverter which has 50KVA power output, 400V AC pure sinusoidal voltage output and it is IGBT based controller. This inverter is not as good as ABB inverter. Because of its power rating and unknown efficiency. Thirdly, Consul Pelican 3000 inverter was nice with regard to its power rating and voltage. But, its voltage output was designed in Indian voltage standard which is 415V AC three phase output. Finally, ABB inverters were selected as candidates for final selection. It is better to evaluate according to their price and efficiency. According to its efficiency, power rating and output voltage PVS800-57-0500kW-A, ABB inverter is selected for the general structure of the MVDC distribution system.

4.5. DEVELOPMENT OF DC POWER SUPPLY MECHANISM

After developing MVDC distribution system network, the most important issue is how can able to supply the existing AC and DC loads. From the assessment of load types in Table 4.6 currently most of the loads were AC powered and some of them were DC powered. Three possibilities (options) were studided to supply these LV variable loads. These options are direct DC supply, using DC/DC and DC/AC converters and using Central inverters. Their feasbility comparision with the tradational system of distribution was summarized in table 4.11, 4.12 and 4.13. power loss, energy loss cost, material consumption and the over all system efficency was the comparing variables.

4.5.1. Direct DC supply Senario

This mechanism must be achieved by supplying the loads directly from DC/DC converter. As it is shown in figure 4.12 the overall distribution system cosists of AC/DC rectifier, DC feeder and DC/DC converter. The main functuion of this DC- DC converter is providing an equivalent DC voltage for the existing AC and DC powered loads. It can be performed by obtaining the peak and the square root mean value of the AC voltage [8]. 230 V and 220 V are the two standard single phase AC voltages. Their peak and square root mean value can be the DC equivalent voltage. **326V DC voltage source** – becuase it is the peak voltage value of 230V AC voltage. All appliances rated with 230V AC voltage can be supplied with 326 Vand 156 VDC voltage. Similarly, all appliances rated with 220 V AC voltage can be supplied with 156V and 310 V DC voltage. Telecommunication equipments, electronic loads and data centers can be powered from 48 V DC line which is already exists in the system. According to those equivalent DC voltage levels, atleast five DC/DC converters should be required to entertain all the loads. The most important difficult things to configure this senario can be summarized as in the following main points.

- Different DC loads have no fixed standard voltage value like AC loads.
- To supply AC powered loads with DC source, every AC powered equipments needs equivalent DC voltage level. The distribution structure will consist different DC voltage level which needs multiple number of DC/DC converter.

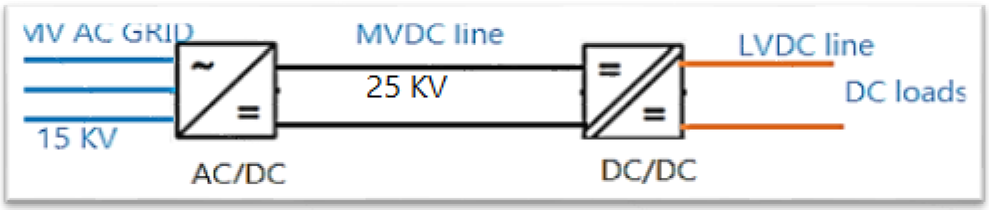


Figure 4. 13 Direct DC supply senario

4.5.2. Using DC/DC and DC/AC converters

In this senario the distribution system is developed from AC/DC rectifier, DC feeder, DC/DC converter and DC/AC inverter. The model diagram is shown in figure 4.13. The system provides LVDC and LVAC distribution line using DC/DC converter and DC/AC inverter respectively. The required DC voltage can be obtained from DC/DC converter to supply DC loads and the current operating LVAC volatge (380/400 V) can be brought back using DC/AC inverter. As a result, all the loads existed today can be supplied from this inverter output without any modification. The system feasibility summary with regard to power loss, energy loss cost, material consumption and system efficiency is shown in Table 4.13.

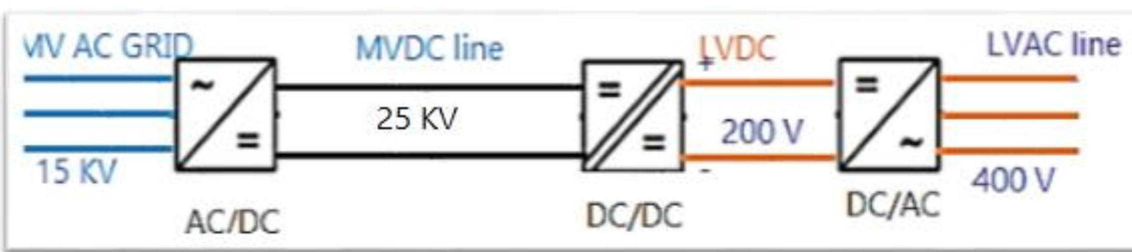


Figure 4. 14 DC supply using chopper and inverter

4.5.3. Using DC/AC central inverter

As shown in figure 4.14, the distribution system was developed from AC/DC rectifier, DC feeder and DC/AC inverter.Based the previous load type assessment, most of the loads in the market were AC powered. This mechanism is constructed for supplying of all the existed loads without modification. The selected inverter (PVS800-57 0500kW-A, ABB inverter) in section 4.2.4 can provide 500 KW with 380 V/ 400 V AC three phase voltage or 220 V/ 230 V AC single phase voltage. Installing such type of inverter centerally can minimize the cost of multiple converters used in the previous senario. Its feasibility study comparing with the tradational distribution system and with the other two DC supply mechanisms were summarized in Table 4.14.

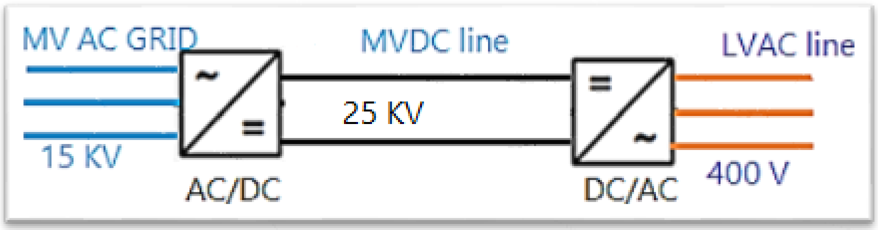


Figure 4. 15 DC supply using DC/AC central inverter system

4.6. COMPARATIVE ANALYSIS AND FEASIBILITY STUDY

4.6.1. Equipment and material cost analysis

The material cost for system configuration is also called investment cost. The most significance equipments and materials under feasibility study of MVDC distribution system were the transformers, rectifiers, choppers, inverters, the number of poles and conductors. These equipments and materials cost can able to make a direct influence on the cost comparison. UEAP (universal Electric Access program) and Ethiopian electric distribution system were taken as references to evaluate the material consumption in AC distribution system. The quantitative value of materials was determined based on the selected case study (20 MW, 15 KV, and 50 Hz distribution substation). The materials' unit price was taken from UEAP material cost breakdown prepared in 2014 and cross checked with the international online market costs. The basic materials list, specification, quantity, unit price and total price of AC and DC distribution system were summarizedin table 4.8 and 4.9 respectively.

According to UEAP distribution system, the separation between two poles is 50-70 meter. This distance basically depends on distribution location situation (urban and rural), road complexity. Most of the time 11m pole with 60 m gap is used for urban MVAC distribution system. 15 KV distribution line can be stretched over 25 km distance without voltage componsation. In the case of DC distribution system, material consumption depends on the rectifier power carrying capacity.

Table 4. 8 MVAC distribution equipment costs

Equipment type	Specification /type	Quantity	Unit cost ($)	Total price ($)
MV transformer	132/15KV, 50HZ, 20MVA	1	69,546	69,546
LV transformer	15/0.38KV,50HZ, 200KVA	100	2000	200,000
Filter	DC filter	14	334.4	33,440
Cables/wire	AAAC95mm in meter	1,050,000	0.764	802,200
	AAAC50mm in meter	350,000	0.466	163,210
Poles	Wooden 11m height	417*14	312.8	1,826,126
Total cost			$3,094,622	

Since 1500KVA power rating rectifier was selected to deliver 20MW power on the recommended DC distribution line, fourteen(14) bridge rectifiers, fourteen choppers (14), fourteen filters (14)and fourty two (42) central inverters have to be used. The power deleviry across the distribution, the number of poles required and distance between poles were considered as the same as the AC distribution system.

Table 4. 9 Equipments cost for DC distribution system

Equipment	Specification/type	Quantity	Unit price ($)	Total price ($)
Rectifier	1500KVA, Bridge rectifier	14	4500	63000
Chopper	LC filter based chopper	14	334.4	4,682
Filter	AC filter /compensator	14	334.4	4682
Inverter	PVS800-57-0500kW-A	42	13,350	560,700
Cables	AAAC95mm in meter	25,000*2*14	0.764	534,800
Pole	Wooden, 11meter height	417*14	312.8	1,826,126
Total cost			2,993,990	

4.6.2. Equipment Energy loss cost

Actually, the determinant parameter for the energy loss cost is the total power loss during operation. The power loss in each equipments (transformers, overhead lines, rectifiers, choppers, and inverters) should be calculated.The values of Levelized electrical energy cost rating in terms $/kWh can be taken from well-known standards.The American energy cost rating standard was taken for the calculation. Actually, they charge $0.02 to $0.19 per KWh for large hydro power generation and $0.02 to $0.27 per KWh for small power generation [30]. Since Ethiopia have large hydro power generation system and similiar levelized energy cost with the American, the first one is selected for comparison and energy computation study. So levelized cost of energy for all equipments $0.02/kwh is considered. Since it is common for all equipments, the value does not matter the comparision analysis.

A. Transformer loss cost: -Transformer power loss in AC distribution system was calculated in chapter three. The sum of the power of of each transformer in distribution became 908.7 KW. So the annual energy lost can be calculated as 908.7 KW*8760 hours which is equal to 7,960,212 KWh. Energy loss Cost = Energy loss * Levelized cost of energy = W_{loss} *LCOE

$$\text{Energy loss cost} = 7{,}960{,}212\text{KWH} * \$0.02\ /\text{KWH} = \$159{,}204.2/\text{year}$$

B. **Overhead line (feeder) loss: -**The power carrying capacity of the single feeder in AC distribution and DC feeder is 1500 KVA. Both systems have fourteen feeders. The power loss comparision was analyzed by considering the skin effect, proximity effect, power carrying capacity and voltage rating. 1081 KW power on MVAC feeders and 392 KWpower on DC feeders was lost. So, 689 kw was lost becuase of it is AC distribution system. This lost power can be converted in terms of energy loss cost.

Case a: AC overhead line with 15kv voltage level

The total energy lost in a year becomes 1081 KW*8760Hr.which is 17,418,384 KWh.

Energy loss cost = Energy loss * Levelized cost of energy = W_{loss} *LCOE

$$\text{Energy loss cost} = 1081\ \text{KW} * 8760 * \$0.02\ /\text{KWH} = 189{,}391\ \$\ /\text{year}$$

Case b: DC overhead line with 25 KV voltage level

The total energy lost in a year becomes 392 KW*8760Hr. which is 3,433,920 KWh.

Energy loss cost = Energy loss * Levelized cost of energy = W_{loss} *LCOE

$$\text{Energy loss cost} = 3{,}433{,}920 * \$0.02\ /\text{KWH} = \$\ 68{,}678\ /\text{year}$$

C. **Rectifier Loss**: **-** buffalo power electronic center specifies different rating group of rectifiers [30]. Generally named as industrial rectifiers. Some of the specified group mates were R300 rating and R20SI rating. The first group having the power rating from3-300kw and the second group having the rating 500-3000kw. The standard rating of this group rectifiers are 500kw, 750kw, 1000kw, 1500kw and 3000kw. For MVDC implementation 1500KVA R20SI group industrial application rectifier was selected. The full specification of this device were stated [30]. According to this rating value the total rectifier required to implement 20MVA power capacity is fourteen. From its efficiency [97.7%] and the no load loss of this device was specified as 1% of the nominal rating of the R20SIrectifier rating.

Total power loss =(0.023*1500KVA+0.01*1500kw)*14 which was 693KVA.

The Energy loss across the MVDC distribution = 693kw*8760h = 6,070,680kwh

Energy loss cost = Energy loss * Levelized cost of energy = W_{loss} *LCOE

Energy loss cost = $0.02/kwh*6,070,680kwh = $121,413.6

D. DC/DC converter loss: -there are different and efficient choppers in the market. ABB can made different level DC/DC converters. For this feasibility study, the DC/DC converter with its efficiency 92.0% was taken for comparision of the energy loss cost analysis. To cover the whole 20MVA power network 14 DC/DC converters should be available. The total power loss of the grand total chopper across the whole distribution can be obtained by multiplying by 14 of the individual which became (0.015*1500KVA+0.01*1500kw)*14 which was 525KVA.

The Energy loss across the MVDC distribution = 525kw*8760h = 4,599,000 kWh

Energy loss cost = Energy loss * Levelized cost of energy = W_{loss} *LCOE

= $0.02/kwh*4,599,000 kWh

Energy loss cost = $91,980

E. Inverter loss:-the selected central inverter was PVS-800-57-0500KW-A. the manufacturer data sheet showed the device specification as shown in appendix A, efficiency 98.2%, power rating 500kw, standby loss (no load loss) 65w, and power consumption for its own operation 490w.

Power loss = standby loss + load loss =65w+490w+0.018*500kw= 9.56kw

Energy loss = power loss * operating hours

= 9.56kw*8760/year

= 83745.6kwh

The annual energy lost (W_{loss}) = 83745.6kwh

Energy loss Cost = Energy loss * Levelized cost of energy = W_{loss} *LCOE

Energy loss Cost = 83745.6kwh *$0.02/KWH*42 = $70,346.34/year.

4.6.3. Feasibility comparison summary

The comparison summary of AC distribution system with DC distribution system is shown in table 4.10. In this summary, thedistribution is divided into four groups (MVAC, MVDC, LVAC and LVDC). Under medium voltage level distribution the total power loss, energy loss cost and material cost was considered. Similarly, in low voltage distribution system the gross total power loss, energy loss cost and material cost were the part of the comparision. The feasibility conclusionof each distribution system was summarized in terms of these parameters.

Table 4. 10 feasibility summary of AC and DC distribution system

Comparison variables	MVAC	LVAC	MVDC	LVDC
Substation capacity	20 MW		20 MW	
Voltage level	15 KV	220/380V	25 KV	200V/400 V
Distribution power	1500 KVA	200KVA	1500 KVA	500 KVA
Number of feeders	14	100	14	42
Distribution distance	25 k.m	0.81k.m	25 k.m	0.81k.m
Total Power loss	1989.7 KW		1486.5 KW	
Overall efficiency	90 %		92.6 %	
energy loss cost / year	$ 348,595		$ 231,001	
Cost of materials	$3,094,622		$ 2,993,990	
Grand total cost	$ 3,443,217		$ 3,224,991	
Feasibility deduction	Not feasible	Feasible	Feasible	Feasible

According to the result obtained in table 4.10, only the MVAC system is not feasible in all comparision parameters. As a result, 92.6 % efficent MVDC distribution system can be developed using material cost of 8,183,357 USD. But, these comparison analysis is not enough to obtain the most efficent and less cost DC ditribution system. Each DC supply senarios should be compared each other and with AC distribution systems. The three DC supply mechanisms should be summarized in a similar fashion. This posibilities have been shown in table 4.11 , 4.12 and 4.13. and they are compared with the result in AC distribution obtained in table 4.10.

Table 4. 11 Senario A: DC distribution using AC/DC and DC/DC converter only

Senario	AC/DC rectifier	DC feeders (overheadline)	DC/DC converter	Load	Total
Power loss	693 kw	392 KW	525kw		1610 KW
Energy Loss cost	$121,413.6	$68,678.4	$91,980		$282,072
Eqipment cost	$63000	$$2,365,608	$4,682		$2,433,290
Efficiency	97.7%	98 %	92.0%		91.9 %

Table 4. 12 Senario B: DC distribution using AC/DC, DC/DC and DC/AC

Senario	AC/DC converter	DC overhead line	DC/DC converter	DC/AC Inverter	Total
Power loss	693kw	392 KW	525kw	401.5kw	2011.5 KW
Energy Loss cost	$121,413.6	$68,678.4	$91,980	$70,346	$352,418
Eqipment cost	$63000	$2,365,608	$4,682	$560,000	$2,993,990
Efficiency	97.7%	98 %	92.0%	98.2%	89.9% %

Table 4. 13 Senario C: DC distribution using DC/AC inverter

Senario	AC/DC converter	DC overhead line	DC/AC inverter	AC/DC loads	Total
Power loss	693kw	392 KW	401.5kw		1486.5 kw
Energy Loss cost	$121,413.6	$68,678.4	$70,346		$260,438
Eqipment cost	$63000	$2,365,608	$560,000		$2,989,308
Efficiency	97.7%	98 %	98.2%		92.6 %

4.6.4. Graphical Representation of Feasibility Summary

The feasibility summary with respect to the comparative parameters (power loss, energy loss cost, material cost and system efficiency) can be represented graphically. Each DC distribution senarios including AC distribution system versus the parameter values was represented in graph. These graphs clearly showed that the comparative systems developed with their feasibility values when they are compared each other.

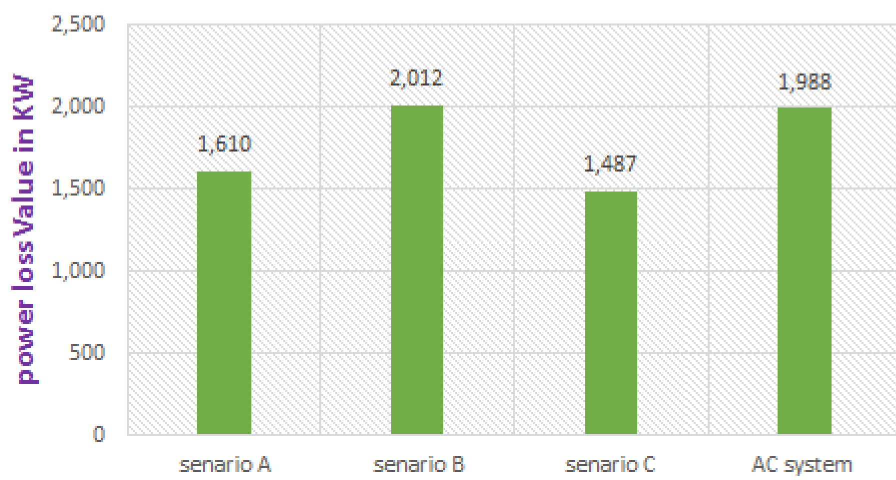


Figure 4. 16 power loss comparision

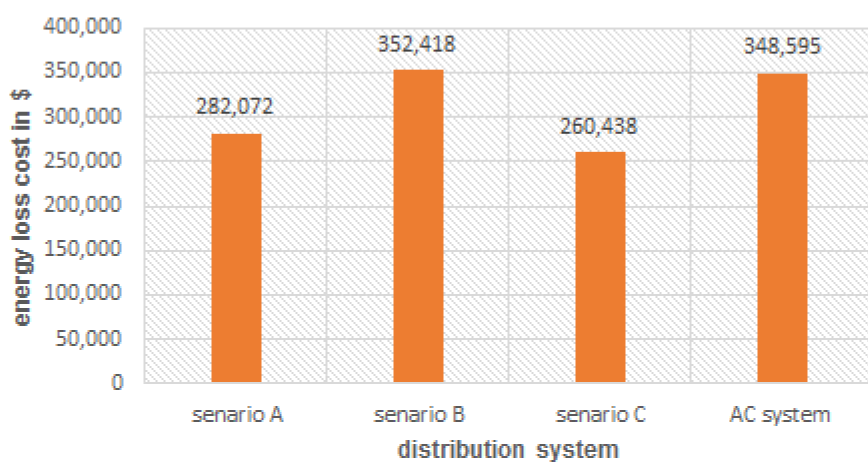


Figure 4. 17 energy loss cost comparison

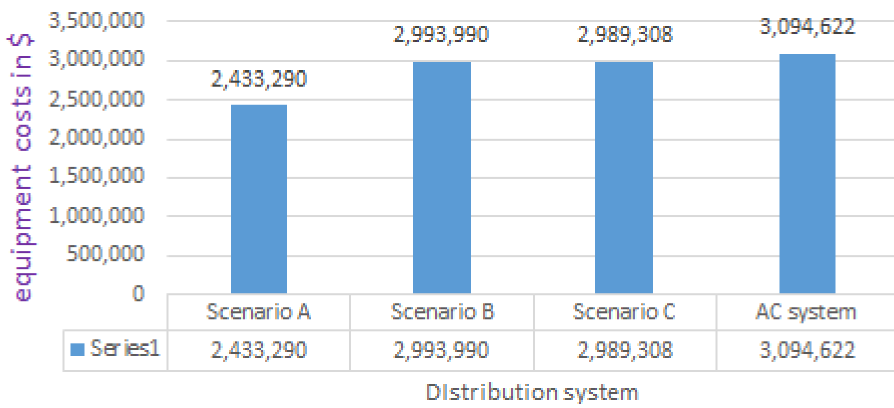


Figure 4. 18 materials cost comparision

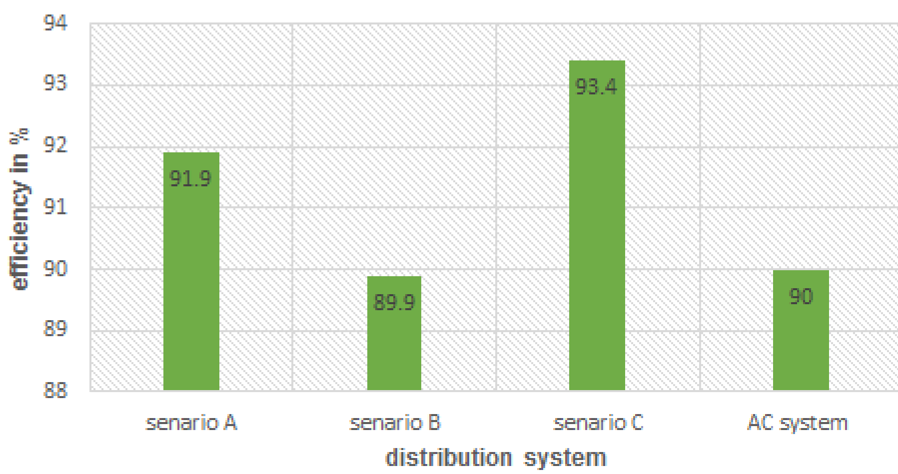


Figure 4. 19 system efficiency comparion

4.6.5. General systems description

Senario A: The model diagram representation of this senario is shown in figure 4.12 which represents direct DC supply mechanism. As stated before, it was developed for providing LVDC distribution system to LV loads.When its feasibility condition compared with AC distribution system with regard to equipment cost, energy loss cost and power loss, it has better feasibility result. But, when it is compared with regard to its efficency, it is not as feasible as AC distribution system.

Senario B: This DC distribution system was constructed from AC/DC rectifier , DC/DC converter and DC/AC inverter. The system model diagram is shown in figure 4.13. The structure provides the posibility of supplying AC and DC loads separately. DC loads can be connnected to DC/DC converters and AC loads can be supplied from inverter output. The feasibility summary of this DC structure indicates that it is not feasible with regard to its system power loss, efficiency and energy loss cost as shown in figure 4.15, 4.16, and 4.18. But, it is more feasible than the AC distribution systemwith regard the material consumption.

Senario C: The system model diagram was shown in figure 4.14 AC/DC rctifier, DC feeder and DC/AC inverter are the basic components of the structure. The structure enables that all existing loads in the market can be supplied from this structure without any load modification. The graphical representation of feasibility summary shows that it is the most feasible DC structure in all comparative parameter values. It has less power loss, energy loss cost, material cost and high efficiency. Its comparative parameter results are 1487 KW distribution power loss, $260,438 enrgy loss cost and 92.6 % system efficiency. Finally, this most feasible DC structure's one line diagram is developed as shown in figure 4.19.

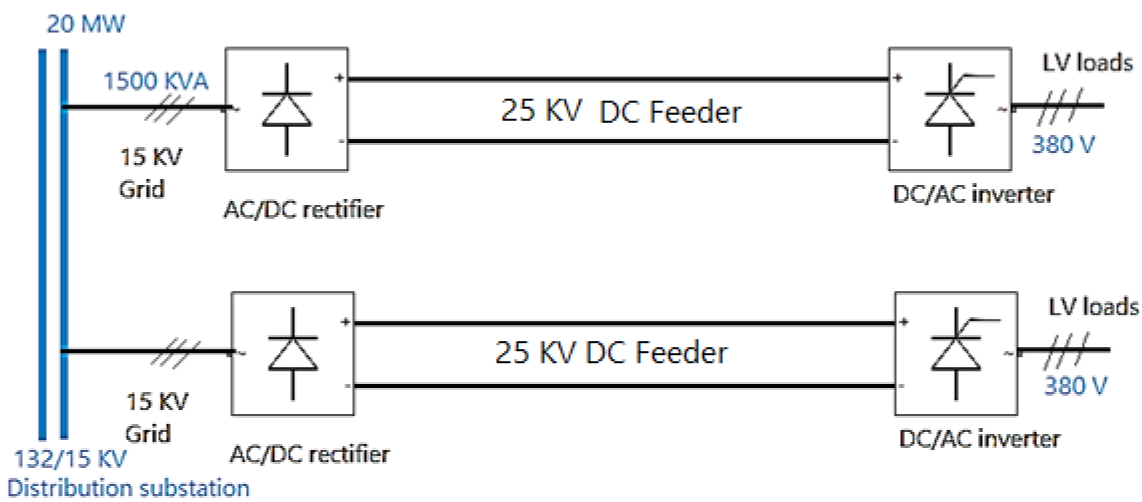


Figure 4. 20 General MVDC distribution system layout

CHAPTER 5

SIMULATION STUDIES AND DISCUSIONS

5.1. INTRODUCTION

In this chapter, different simulation results were displayed and discussed in detail. The input for the design was taken from 132/15kv distribution transformer. This transformer were the main component of MVAC distribution. Its total power loss analysis was done in chapter 3. The most important parameters of this transformer was the secondary winding output voltage (15 KV). The three phase sinusoidal wave form of 15 KV line to line voltage is simulated with Matlab Simulink software to check its puerly sinusoidalilty Figure 5.1, and 5.2, shows that the three phase pure sinusoidal wave form of the input voltage and current in root mean square forms. The line to line voltage was 15KV which is peak voltage of the distribution line. But, the root mean square value as calculated in chapter four it was Figure 5.1 assured this voltage quantity. Additionally, the software gives the related current value on the distribution line. Since the input voltage is peak line to line voltage and the rectifier needs to be supplied from line to line in R.M.S value, it should be converted to the equivalent line to line r.m.s voltage values.Phase A and phase B was considered as the input voltage of the rectifier and simulated as shown in figure 5.3.

5.2. SIMULATION STUDIES

To simulate medium voltage AC conversion to medium voltage DC, solid diode bridge rectifier was used. This converting device was selected due to its better performance values which was good as compared to the controlled rectification. Because one of the objective of the research is developing a new DC distribution system voltage for a comparative study with AC distribution system.So, 10.6kv voltage was supplied to thisrectifier in order to obtain 25 KV MVDC voltage from the distribution transformer. This input voltage should be simulated first to check its pure sinusoidalityand has to be harmonic free 25 DCvoltage which is shown on figure 5.1 and 5.2. the simulation rsult showed that it is purely sinusoidal.Both the input current and voltage was harmonic free.

This pure voltage and current would not be the cause of the distortion on the rectifier output.

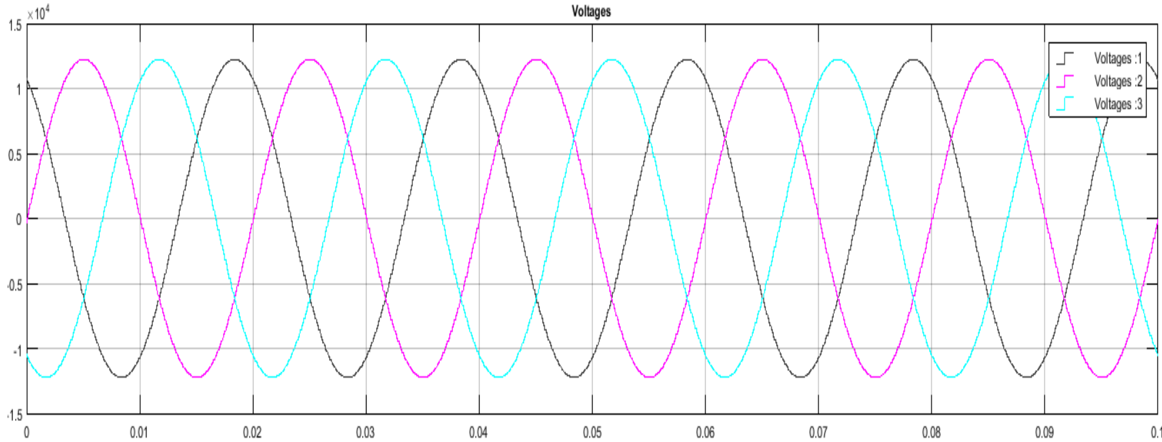


Figure 5. 1Three phase AC rectifier input voltage wave form

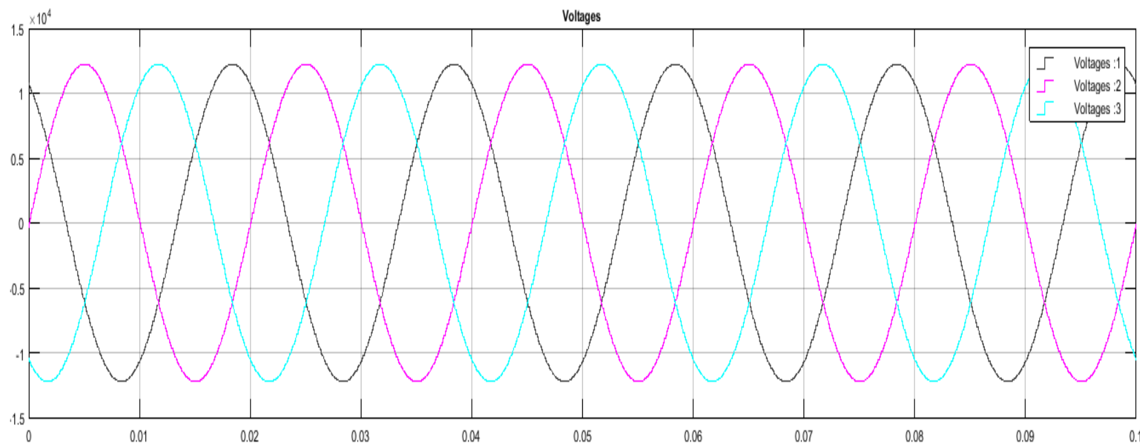


Figure 5. 2There phase AC rectifier input current wave form

On the other hand, the source voltage was analyzed in terms of r.m.s voltage and then the line to line voltage in r.m.s value was calculated.The measurement were taken at the secondary winding terminal of 132/15KV transformerusing matlab simulik software in whichthe result is shown in figure 5.3. Since the rectifier needs the r.m.s value input voltage, the line to line peak voltage should be converted. The peak to peak voltage (15 KV) was displayed with its single phase voltage value (8.66 KV).. The blue printed line is the line to neutral voltage and the other one is the line to line peak voltage which is clearly shown in figure 5.4.

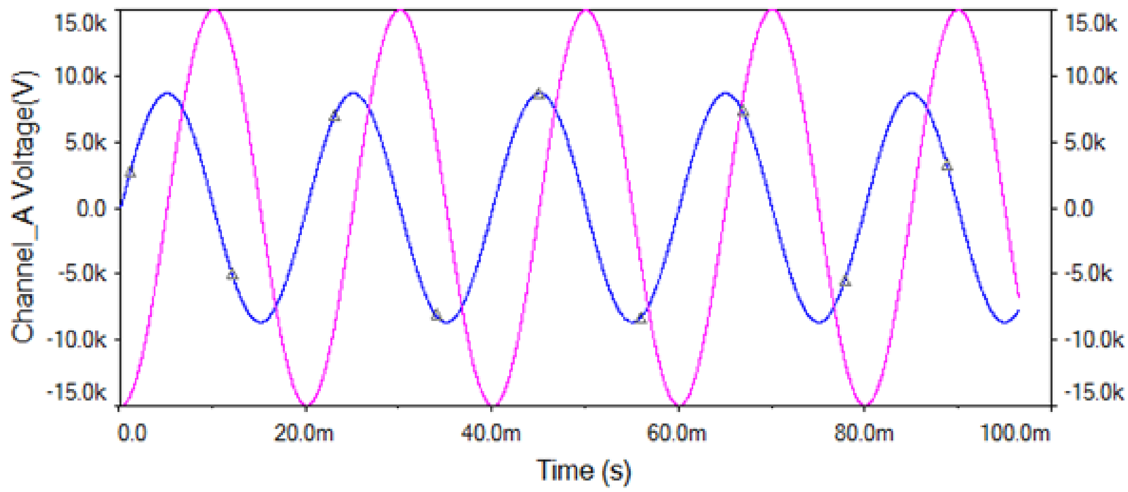


Figure 5. 3 phase a peak and its R.M.S voltage wave form

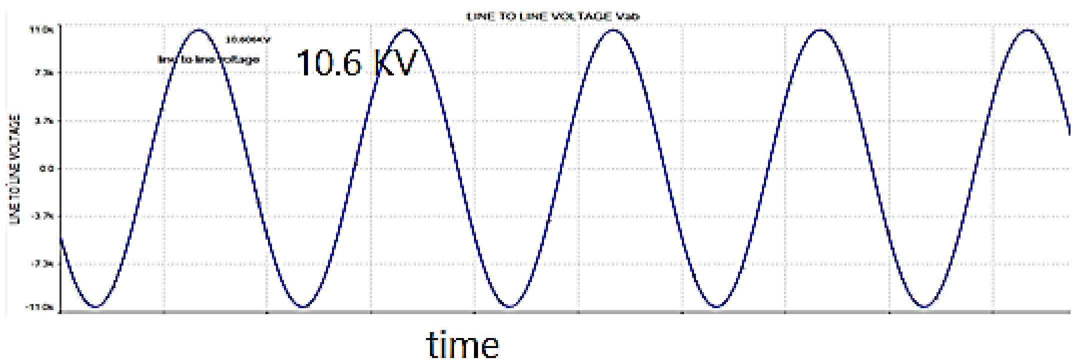


Figure 5. 4 Three phase AC rectifier phase a and b voltage wave form

From the circuit diagram in figure 4.1 the conducting principle of the solid diode rectifier can be seen from the paired diodes. Let's consider D_1 and D_4 conduct at the same time for 30^0 duration by taking phase A and B as an input voltage because it is the most positive and negative among the three phase voltages. Consequently, V_{AB} was generally the input voltage. D_3 and D_6 conduct next to phase A and B by taking phase B and C as an input voltage. The deriving input voltage becomes V_{BC}. Finally, phase C and phase A were compared each other. As a result phase C was more positive than phase A or phase C supplied at the positive leg and phase a supplied at the negative leg of the bridge. So V_{CA} should be the deriving input voltage of the operation of D_5 and D2 at the time. To develop distortion free DC voltage from rectifiers, for main simulations were carried out. The first simulation result was obtained from directly from the rectifier without any filter. This simulation result was showed in figure 5.6. It was a square wave form. This voltage could not able to supply to because it is a pure DC standard voltage. The second simulation result was obtained from rectifiers with an inductive filter which is shown in figure 5.5. This simulation result shows that how DC voltage can be developed from converters using filters. In figure 5.7, simply different value of inductor is used to display the voltage with ripples. The last rectification process was ripple mitigation using LC filter.

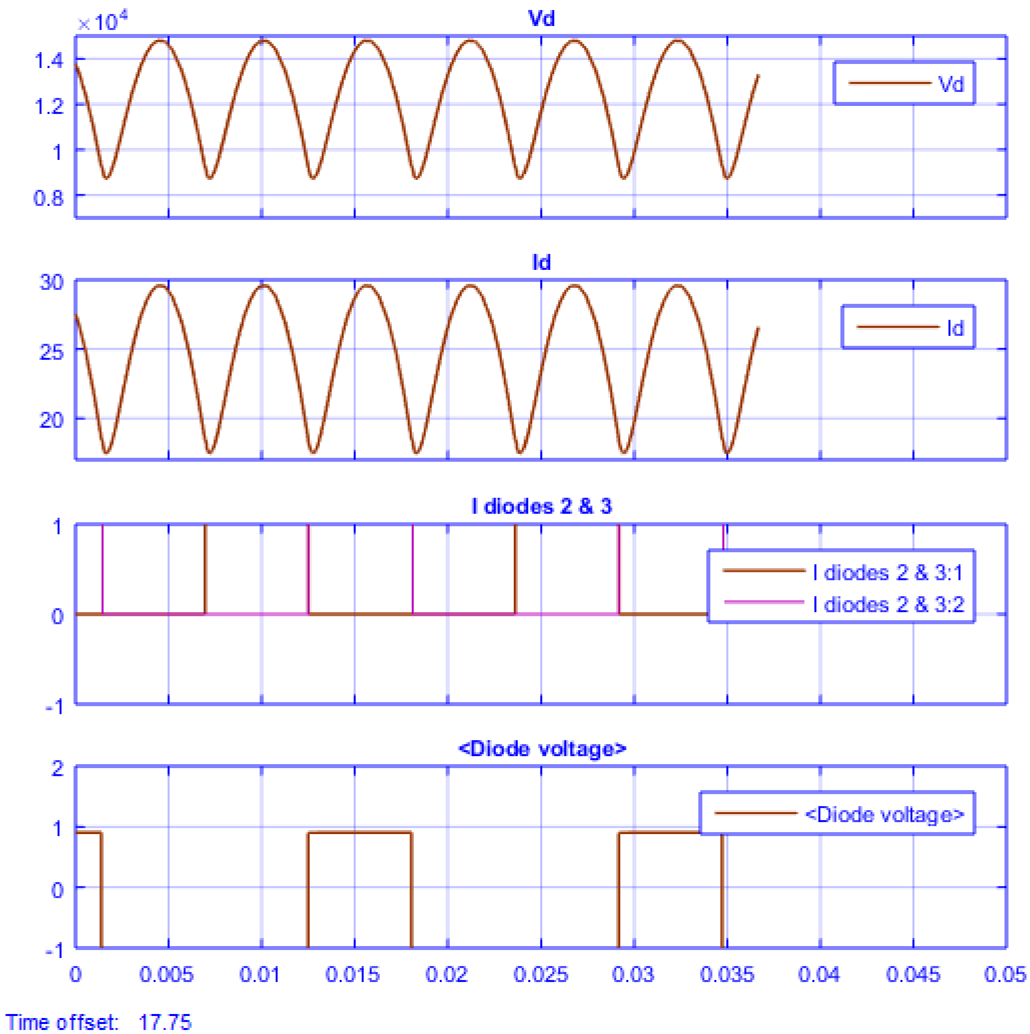


Figure 5. 5 AC/DC converter output voltage with inductive filter

The immediate output of the rectifier from the purely sinusoidal input voltage without filtering was shown in figure 5.6. The voltage wave form needs smoothing out to obtain medium level DC voltage. This voltage output obtained from the peak to peak 15 KV supply to the six pulse bridge diode rectifier. On figure 5.8- 5.13 the amount of the ripple can be displayed at the capacitor out of the rectifier. This voltage value of the distortion component was estimated as 0.04%. The voltage variation at the output of the AC/DC rectification can be eliminated using filters.

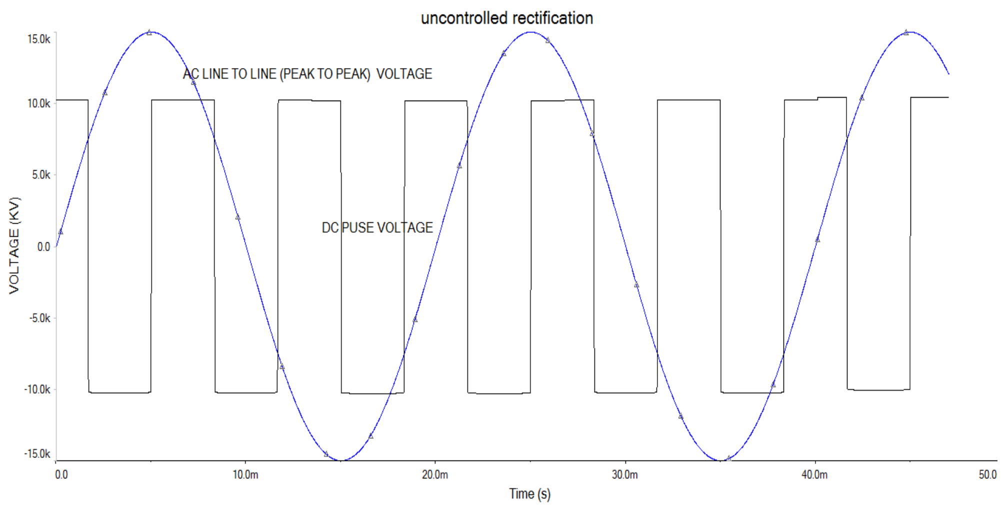


Figure 5. 6 rectification without filter

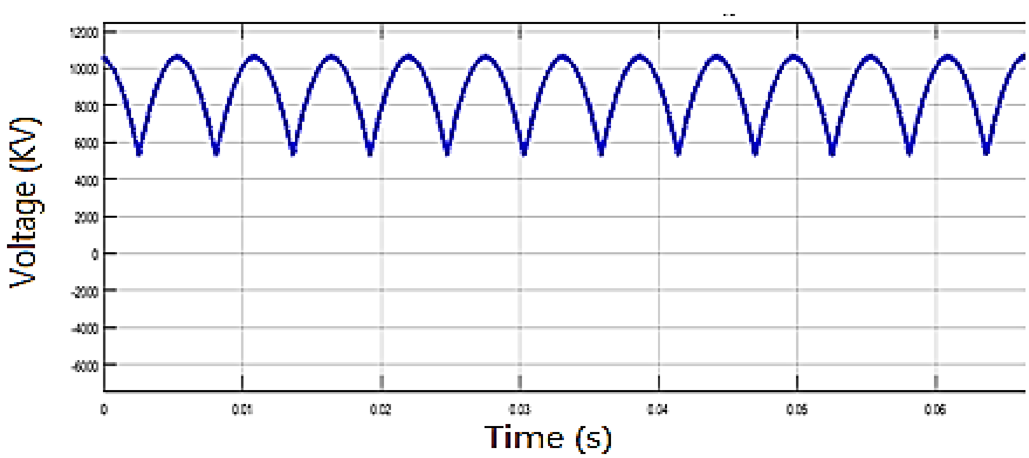


Figure 5. 7 AC/DC converter output voltage with inductive filter

5.2.1. AC/DC Rectifier Filter Result

To develop undistorted pure DC voltage from AC/DC rectifier, filter is connected to its output terminal. As shown the circuit diagram in figure 4.7, inductor-capacitor filter is to develop pure 25 KV DC voltage. Assuming the resistor and the capacitor is fixed and varying the value of the inductor until the distorted voltage is smoothed out. These different parameter values were summarized in table 4.4 and the different simulation results for different inductor value was shown in figure 5.8- 5.13. Since the data which showed in table 4.4. Clearly indicates that the difference of each voltage deviation, it does not need to display all the voltage wave forms.

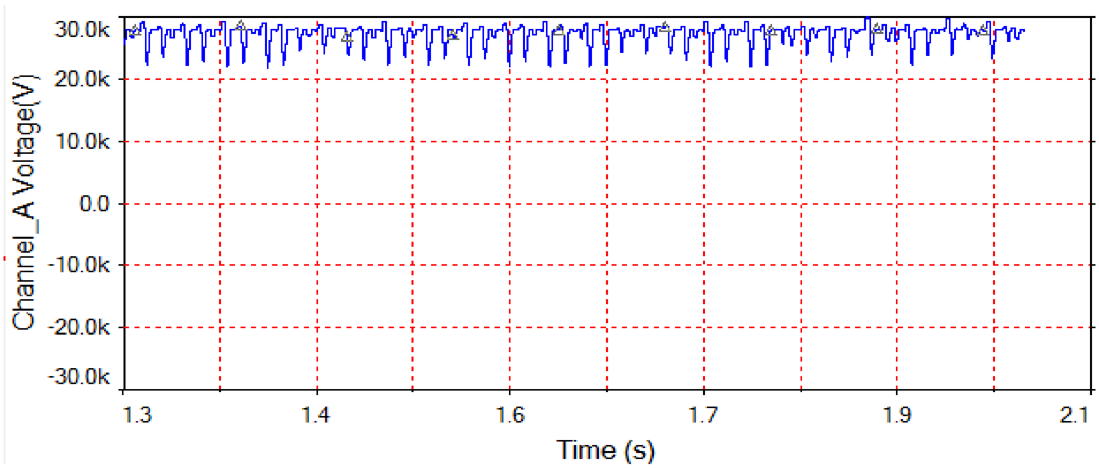


Figure 5. 8 the output voltage at L=2mH and C= 2.5mF

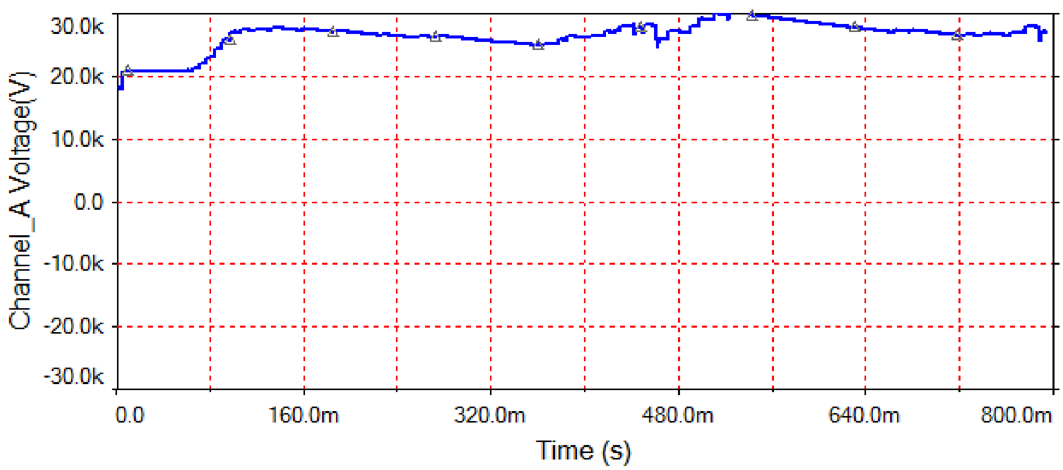


Figure 5. 9 the output voltage at L= 10mH and C= 2.5mF

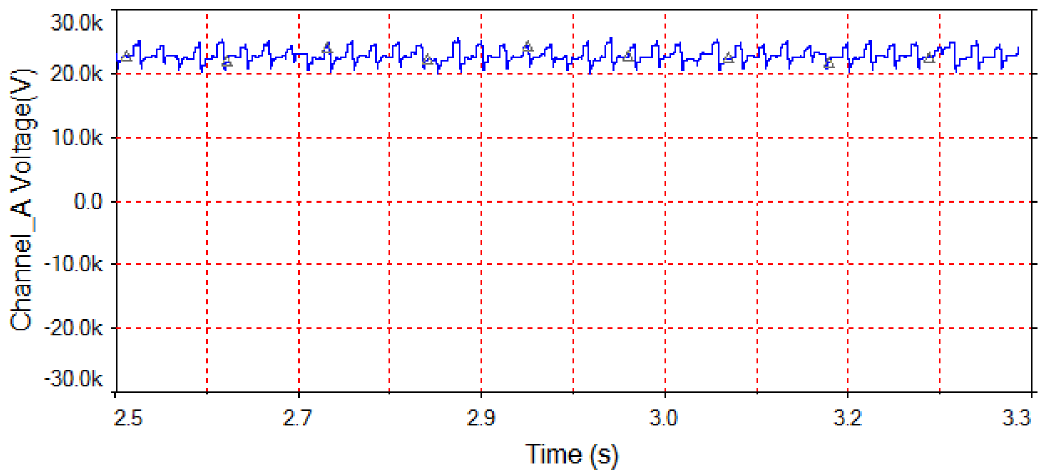


Figure 5. 10 the output voltage at L= 20mH and C= 2.5mF

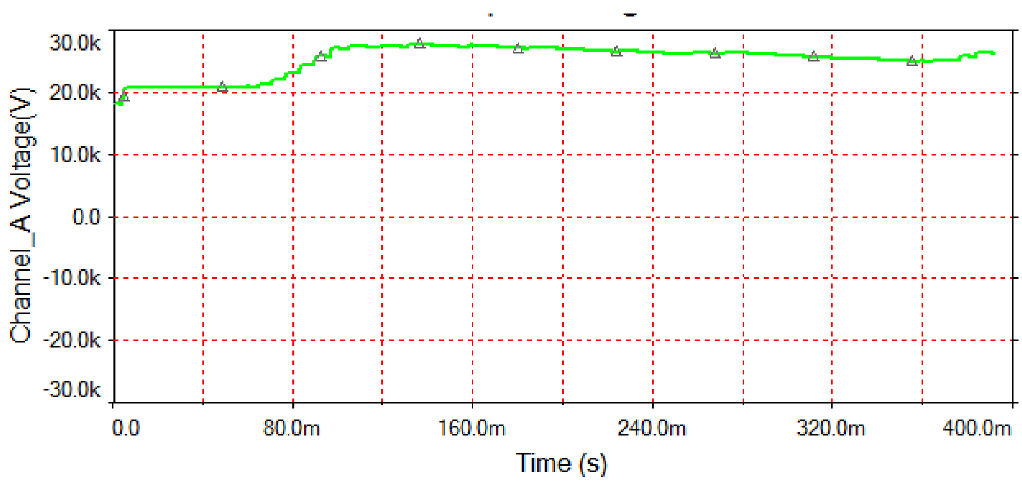


Figure 5. 11 the output voltage at L= 30 mH and C= 2.5 mF

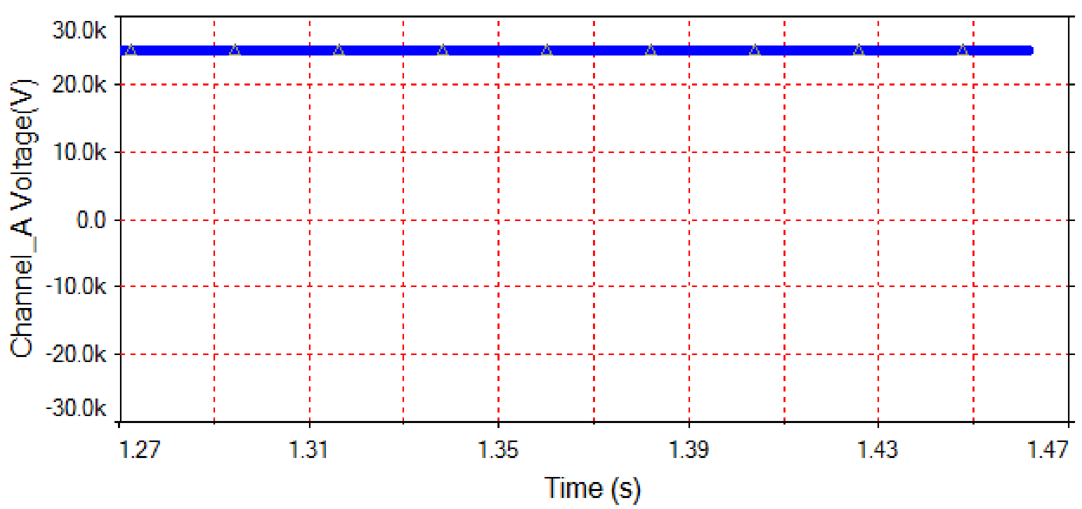


Figure 5. 12 the output voltage at L= 50 mH and C= 2.5 mF

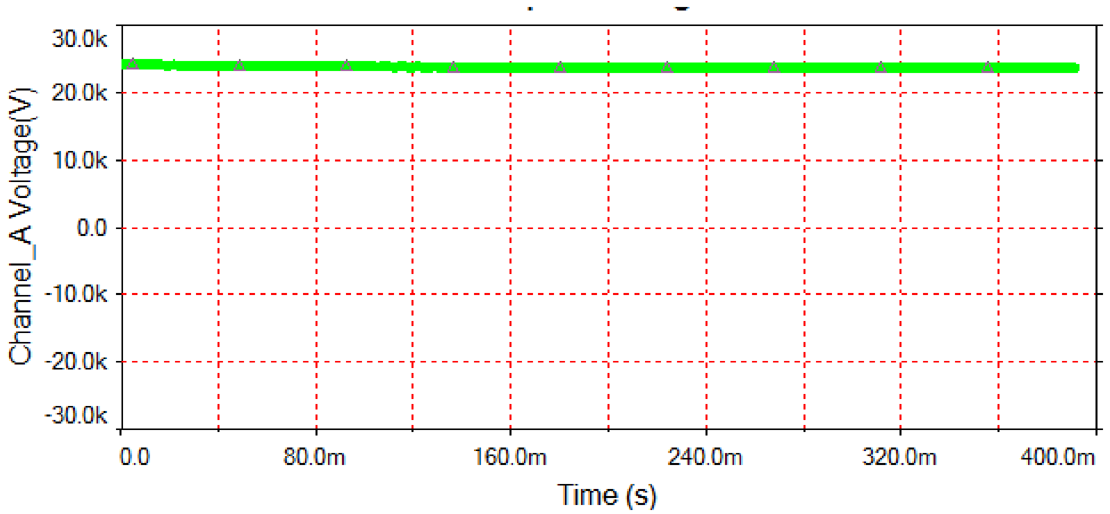


Figure 5. 13 the output voltage at L= 100mH and C= 2.5mF

From filter simulation result, when the difference of the capacitor and inductor value increases, the voltage deviation or variation decreases. Theoretically the ripple factor as calculated before in table 4.2 it can be 0.04% but from this AC/DC converter filter design the ripple factor was 0.011% from 2.5mF and 50 mH-100 mH which is shown in figure 5.13, 0.024% from 2.5mF and 30mH in figure 5.9, 0.049% from 2.5mF and 20mH in figure 5.10, 0.083% from 2.5mF and 10 mH in figure 5.11 and 20mH and 0.14% from 2.5mF and 2mH in figure 5.12. The increment of inductor value was up to the minimum ripple values was achieved. The inductor value above 50 mH gave the same ripple factors and the pure DC voltage was obtained. The difference of the wave forms between figure 5.8 and figure 5.13 clearly shows that how the ripples can be cleared using LC filters.

5.2.2. DC-DC converter simulation result

The MVDC distribution system might be implemented with DC/DC converter commonly known as chopper. The DC/DC converter was constructed the three passive parameters of circuits which are resistor, inductor and capacitor which is step- down DC transformer or buck converter. So this DC circuit supplied from the two MVDC line then converted into LVDC system. From figure 4.8 the MVDC circuit using 100 mH inductor and 2.5 mF capacitor of the filter component 25 KV medium voltage was generated as shown in figure 5.3. This voltage could not supply all existing loads on ground. Because of this DC/ DC buck converter should be used to develop LVDC system. MVDC/LVDC converter circuit model shown in figure 4.10 simulation result was shown on figure 5.4. This voltage value was obtained from the resistive and inductive input and capacitive output circuit.

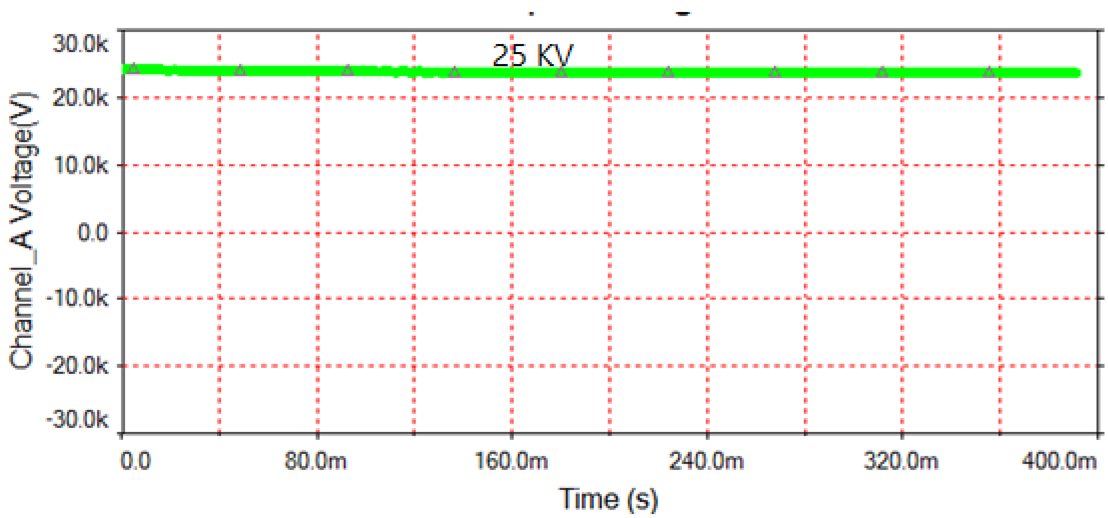


Figure 5. 14 AC/DC converter output voltage with filter

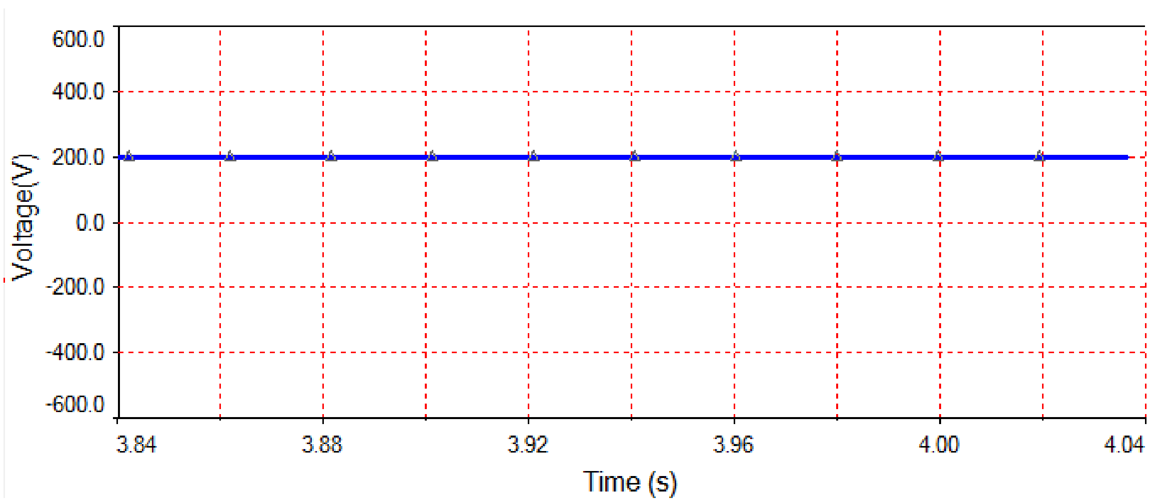


Figure 5. 15 DC/DC converter output voltage

5.2.3. DC/AC inverter simulation result

To supply all the existed loads without any modification, central inverter has been used in DC distribution systems. Inverters produce AC power output from DC power input using different circuit designs and configurations. For this thesis work IGBT based ABB 500 KW inverter was configured with linear transformers to generate purely sinusoidal three phase AC voltage. Actually, to obtain single phase AC voltage, 200V DC input could be used with single IGBT inverter and single linear transformer. Bipolar 200 V DC voltages were supplied to two IGBT based inverters. Operating in parallel. From figure 4.11 central bridge inverter having linear paired windings like a transformer in which their input terminals are connected directly with the two bridge inverters and the output terminal of each winding were connected with the voltmeters via the assumed load. The purpose of these linear transformers were to smoothing out the output current by holding and realizing the input current. Because, they are constructed purely from coils or windings with 1:1 turn ratio. Such type of transformers is called linear transformers.

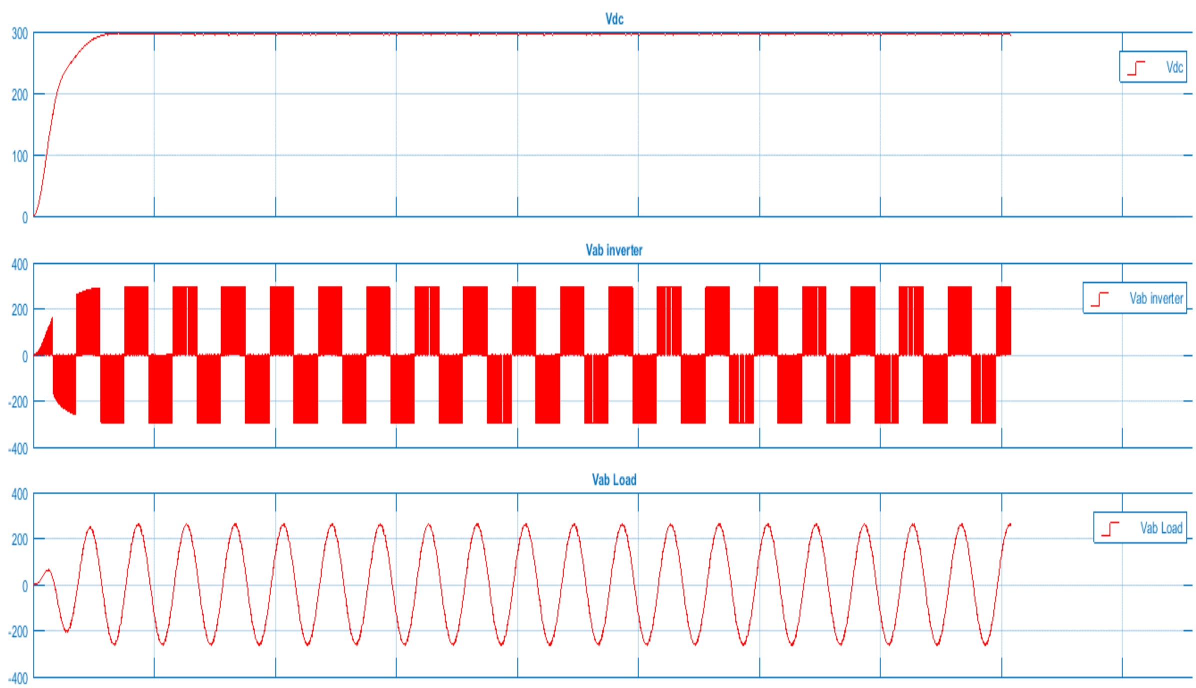


Figure 5. 16 DC/AC inverter single phase output voltage

Three voltmeters were connected with each linear transformers to measure the line to line three phase output AC voltage. The three voltmeter readings were displayed within a single scope meter. The circuit diagram of central inverter in figure 4.11 simulation result has been displayed in figure 5.17. The output wave form indicated that the development of the line to line AC voltage from bipolar 200 V DC voltage input using single scope meter. As shown on the figure 5.17, the purely sinusoidal line to line voltage was developed from the two linear transformers. So, to generate the line to line voltage one volt meter should be connected with two terminals of different linear transformers. V_{ab} was developed from the first and the second transformer, V_{ac} was developed from the first and third linear transformer and finally, V_{bc} was obtained from the second and third transformers. The standard three phase line to line voltage were Simulated as shown in figure 5.16. As stated before, the line to line voltage itself is a sinusoidal wave form. The single line to line voltage (V_{ab}) was displayed as a sample. Finally, the three phase line to line were displayed simultaneously with in a single scope meter. The simulation results show that the development of the most common standard three phase purely sinusoidal voltage (380/400) from DC/AC central inverter as the best choice.

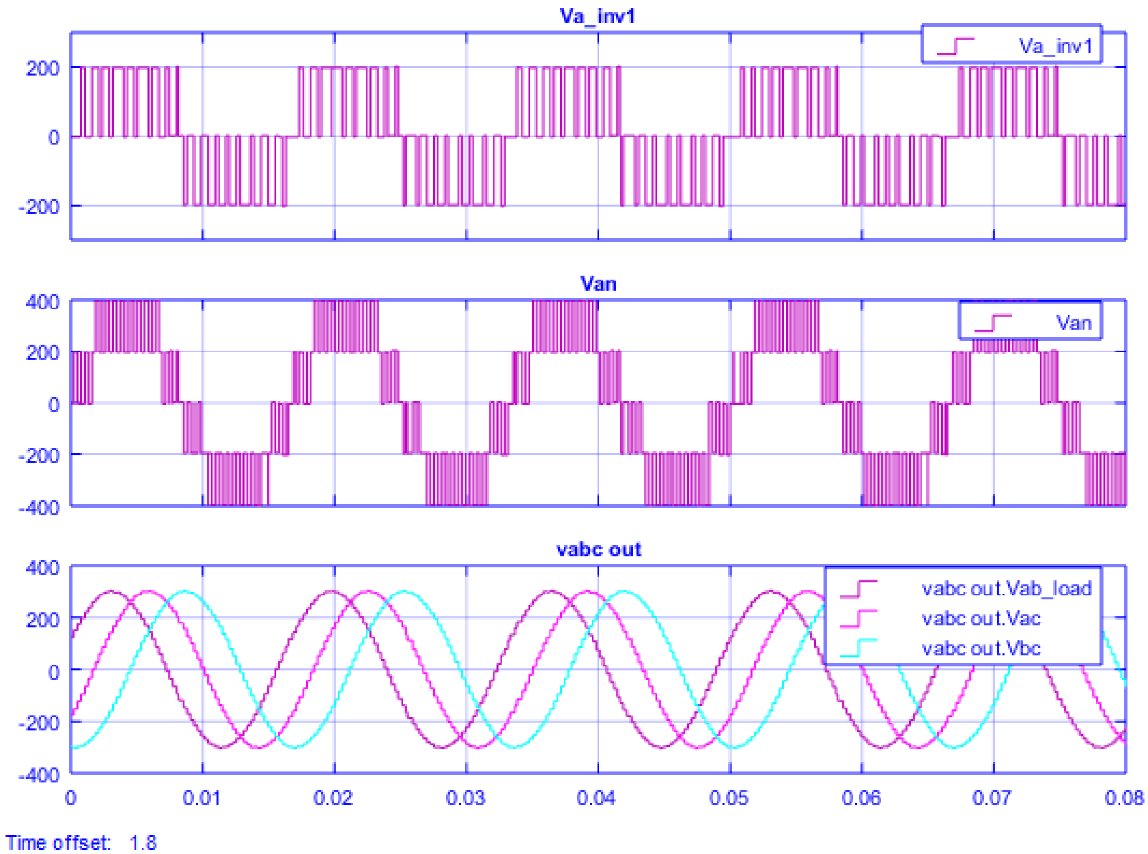


Figure 5. 17 DC-AC inverter three phase output voltage

5.3. RESULT DISCUSSIONS

The development of DC distribution structure was performed by modeling and designing system components. The voltage through the rectifier, filter, DC/DC converter and inverter was simulated using Matlab Simulink and NI Multism soft wares. AC/DC Rectification was performed by supplying 15 KV line to line voltage and the output voltage obtained with and without filters. The output voltage from the solid diode rectifier without filter was square wave form (figure 5.6) which has high ripple components and the voltage output with inductive filter was a rectified sinusoidal voltage having ripple components (figure 5.7).The full rectification process was performed with LC filters. Evaluation of ripples at the output voltage was measured using trial and error methods. The capacitor inductor filter mitigates the ripple components of the output voltage. The ripple effect was measured by using 2.5mF capacitor and 500 ohm resistor as a fixed value and varying the inductor value from 2 mH to 100 mH. When the value between the capacitor and inductor increases, the ripple factor becomes less and less. From simulation result in figure 5.8 and figure 5.13, the ripple factor difference in between the two was observed. 0.14% and 0.011% were the respective results. Using the output simulation result in figure 5.13, a DC voltage having a very irrelevance ripple component can be developed. 17.5KV was obtained from mathematical model and the circuit diagram in figure 4.1. This voltage level was cheked with NI multism software as shown in figure 5.14. This MVDC voltage can be distributed over 30-80k.m distance without any voltage compensation [15].

One of the serious part of study was how can this medium voltage level could be supplied to low level voltage rated loads. Actually, it is obvious that one or two DC low voltage loads can be supplied using buck converter. The medium voltage level should be converted into the appropriate low voltage level to connect with loads. The simulation result from figure 4.15 shows that the capability of obtaining 200 V DC from 25 KV using circuit diagram in figure 4.9. But, this voltage level could not able to entertain all types of loads in the market. As a result, central high power application inverter in figure 4.11 was taken as a solution and the standard 380 V AC voltage was simulated in figure 5.16 and figure 5.17. This voltage level is suitable for all low voltage rated loads. Any required low voltage level can be obtained from figure 4.11 by changing the input DC voltage level.

CHAPTER 6

CONCLUSIONS, RECOMMENDATION AND FUTURE WORK

6.1. CONCLUSIONS

In order to investigate the profits of a DC distribution system in power system networks, a comparison between MVDC and MVAC should be made to know the advantages and disadvantages of both approaches. This research investigates alternative DC distribution structures and comparative study outcomes. DC distribution components like rectifiers, filters, choppers and inverters were modeled and designed to develop the required DC distribution system and for parameter evaluations. 25 KV DC distribution system was obtained using DC/DC or using DC/AC converter. Loads can be supplied either by Direct DC supply from DC/DC converter or from DC/AC inverter with 380 V/400 V voltage rating. Then, it is compared with the existing15 KV MVAC distribution system with respect to power loss, energy loss cost, material consumption and system efficiency. The 15 KV AC distribution network comparative parameter evaluation was performed on its transformers and feeders. The power loss on each transformer and overhead lines was analysed. The MV and LV transformers power lost has been quantified as 908.7KW using analytical techniques. Similarly, the power loss comparison on the overhead line of medium voltage distribution system was computed by considering skin and proximity effects. The total power loss across the AC system was 1989.7 KW. It can be conclude that more power could be dissipated on 15 KV AC distribution overhead line than 25 KV DC distribution system. But, a DC distribution system which is constructed using AC/DC, DC/DC and DC/AC, was not feasible with respect to system power loss because of triple electronic devices present in the system.

Correspondingly, the cost comparative analysis of the MVDC and MVAC distribution system was investigated from the most significant components and energy loss cost of each system. The common materials' cost in AC distribution system such as transformers, cables, poles and filters were taken from Ethiopian electric distribution systems usage and UEAP and the basic power electronic equipments and cables were considered to evaluate the investment cost of DC distribution systems. In all DC configuration situations, the material consumption is smaller than materials' cost in AC distribution systems. But, the equipments operational cost in DC distribution system using the scenario AC/DC rectifier, DC/DC converter and DC/AC inverter is not better achievable due to multiple converter losses. As a result, DC distribution is not recommended using all those electronic converters at the time. Generally, development of MVDC distribution system using AC/DC rectifier and DC/AC converter is economically best scenario in both material cost and equipments operational cost.

The other comparative variable to investigate the most feasible distribution system is the system overall efficiency. Actually, the traditional distribution system efficiency was evaluated from the total power loss in the system and the input power from distribution substation (132/15 KV). So, the 15 KV AC distribution systems is 90% efficient. Three different efficient DC distribution systems are developed. The scenario using AC/DC rectifier and DC/AC converter is constructed with 92.6 % efficiency. It can be possible developing DC distribution system with better efficiency than 90%.

Finally, the research investigates MVDC distribution system using central inverter as a best choice and also it is a solution for LVDC distribution system. By taking high power application inverter centrally, the existing AC and DC loads can be supplied without any modification. Scenario C, The DC structure which consists of DC/AC inverter with its system efficeincy 92.6 %, power loss 1486.5 kw, the energy loss cost of 260,438 USD and equipment cost of 2,989,308 USD were achieved in which it was much significantly less than AC distribution system. As the quantitative results showed, around 500 KW power saving and more than 0.2 million USD momentarily saving have been possibly achieved by using scenario C of DC distribution system as compared to the existing AC distribution system.

This distribution system is cost-effective solution with better efficiency which can replace medium voltage AC distribution structures at normal distribution powers. The new MVDC distribution system was feasible with respect to all comparative variables (efficiency, power loss, material cost and energy loss cost). The reason behined was severe estimation of power electronic device costs before is ultimately and constantly decreasing now.

6.2. RECOMMENDATIONS

In the previous few decades, there were a number of challenges to implement DC distribution systems at medium and low voltage levels. The converters'expensive cost, low power carrying capacity, high energy loss cost and the harmonics were some of the challenges. Today these all difficulties are not the issue for DC distribution development. Efficient, high power carrying capacity and less cost electronic devices such as rectifiers, choppers and inverters are joining the market. The existing AC distribution system penalizes the customers and the electric power companies by losing more power. DC devices are widely coming to the system. It is strongly recommend that the whole system of distribution should be replaced by DC distribution technology to get better cost benefit and to have best efficient system.

6.3. FUTURE WORK

Depend on the discussions and the outcomes presented, upcoming works in the DC development and feasibility research should include on the following important issues.

- Development of optimum DC voltage level: - in this project central inverter was taken as a solution for LV loads. But, Future works can incorporate the development of optimal LVDC level for LV loads.
- Transient state study for DC distribution system: - since the transient condition was not the part of this thesis work, the degree of severity during fault condition in DC distribution can be analyzed as compared to AC distribution system. The efficiency of DC breakers for protection of MVDC and LVDC systems should be seen as compared to the AC breaker systems.
- MVDC and LVDC grid structure Development for integration of Distributed generation (DG) systems: - the DC power plants such as photovoltaic cells, fuel cells and others are good to interconnect with DC buses.

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Appendix A

Load assessment and demand estimation

Target area	Type Appliances	Wattage in (kW)	Quantity	Total load	Working Hours	Kwh/ day
Home Loads	Lighting(CFL)	0.027	300	8.1	5	40.5
	Radio/tape	0.015	300	4.5	8	36
	Mobile charger	0.015	300	4.5	0.25	1.125
	Stove	0.8	50	40	2	80
	Electric mithad	4.4	15	66	1	66
	TV (21”)	0.065	200	13	8	104
	Mill grill	11	2	22	8	176
Pr. School Society and com. Loads	Class lighting	0.011	100	1.1	3	3.3
	Refrigerator	0.080	200	16	24	384
	Stove	0.80	2	1.6	8	12.8
	TV (21”)	0.065	8	0.52	4	2.08
	Radio /tape	0.015	100	1.5	8	12
	Mob. Charger	0.025	10	0.25	0.25	0.06
	Copy machine	0.020	25	0.5	6	3
	Speaker	0.015	1	0.015	1	0.015
	desk top	0.080	100	8	7	72
	Printer	0.060	50	3	2	6
Clinical Loads	Lighting(CFL)	0.011	50	0.55	12	6.6
	Microscope	0.030	6	0.18	10	1.8
	TV (21”)	0.015	1	0.015	10	0.15
Religious Purpose	Lighting (CFL)	0.011	15	0.165	12	1.98
	Loud speaker	0.015	1	0.015	6	0.09
	Musical inst.	0.035	1	0.035	3	0.105
Total loads				191.6KW		1011 KWH

Appendix B

Technical demand estimation at LV transformer

	AM												PM											
Appliance		2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5		7	8	9	10	11	12
Home light																								
Radio/tape																								
Charger																								
Stove																								
Ele. Mithad																								
mill grinder																								
TV-21’																								
Class light																								
Tel. home																								
Fridge																								
TV-21’’																								
Radio /tape																								
Telephone																								
Charger																								
Copy mach.																								
Speaker																								
Desk top																								
Printer																								
c/light																								
Fridge																								
Microscope																								
Clinic TV																								
Rel. light																								
Speaker																								
Musical/ins																								
Tot .load	**57.8**	**58.4**	**63.5**	**60.7**	**25.18**	**35.3**	**35.9**	**169.4**	**60.1**	**60**	**59.3**	**18.15**	**72.34**	**76.7**	**32**	**31**	**24.2**	**24.2**	**17**	**17**	**17**	**17**	**17**	**18**

Appendix C

Different inverter types and specification

Technical data and types

Type designation PVS800-57	-0100kW-A 100 kW	-0250kW-A 250 kW	-0315kW-B 315 kW	-0500kW-A 500 kW	-0630kW-B 630 kW	-0875kW-B 875 kW	-1000kW-C 1000 kW
Input (DC)							
Maximum input power ($P_{PV, max}$) [1]	120 kWp	300 kWp	378 kWp	600 kWp	756 kWp	1050 kWp	1200 kWp
DC voltage range, mpp ($U_{DC, mpp}$)	450 to 825 V	450 to 825 V	525 to 825 V	450 to 825 V	525 to 825 V	525 to 825 V	600 to 850 V
Maximum DC voltage ($U_{max (DC)}$)	1000 V	1000 V	1000 V	1100 V	1100 V	1100 V	1100 V
Maximum DC current ($I_{max (DC)}$)	245 A	600 A	615 A	1145 A	1230 A	1710 A	1710 A
Number of protected DC inputs	1 (+/-) /4 [2]	2, 4, 8 (+/-)	2, 4, 8 (+/-)	4 to 15 (+/-)	4 to 15 (+/-)	8 to 20 (+/-)	8 to 20 (+/-)
Output (AC)							
Nominal power ($P_{N(AC)}$) [3]	100 kW	250 kW	315 kW	500 kW	630 kW	875 kW	1000 kW
Maximum output power [4]	100 kW	250 kW	345 kW	600 kW	700 kW	1050 kW	1200 kW
Power at cosφ = 0.95 [3]	96 kW	240 kW	300 kW	475 kW	600 kW	830 kW	950 kW
Nominal AC current ($I_{N(AC)}$)	195 A	485 A	520 A	965 A	1040 A	1445 A	1445 A
Nominal output voltage ($U_{N(AC)}$) [5]	300 V	300 V	350 V	300 V	350 V	350 V	400 V
Output frequency	50/60 Hz	50/60 Hz	50/60 Hz	50/60 Hz	50/60 Hz	50/60 Hz	50/60 Hz
Harmonic distortion, current [6]	< 3%	< 3%	< 3%	< 3%	< 3%	< 3%	< 3%
Distribution network type [7]	TN and IT	TN and IT	TN and IT	TN and IT	TN and IT	TN and IT	TN and IT
Efficiency							
Maximum [8]	98.0%	98.0%	98.6%	98.6%	98.6%	98.7%	98.8%
Euro-eta [8]	97.5%	97.6%	98.3%	98.2%	98.4%	98.5%	98.6%
Power consumption							
Own consumption in operation	310 W	310 W	310 W	490 W	490 W	650 W	650 W
Standby operation consumption	60 W	60 W	60 W	65 W	65 W	65 W	65 W
External auxiliary voltage [9]	230 V, 50 Hz	230 V, 50 Hz	230 V, 50 Hz	230 V, 50 Hz	230 V, 50 Hz	230 V, 50 Hz	230 V, 50 Hz
Dimensions and weight							
Width/Height/Depth, mm (W/H/D)	1030/2130/690	1830/2130/680	1830/2130/680	2630/2130/708	2630/2130/708	3630/2130/708	3630/2130/708
Weight appr. [10]	550	1100	1100	1800	1800	2320	2320

Appendix D

Load type assessment and their voltage rating

Home /residential appliances			Commercial/electronic loads		
Equipments	AC or DC powered	Voltage Value	Light	AC / DC powered	6-48V DC, 230 V AC
Lighting	Both possible	Different values	Computer	DC powered	6-24V
Stove	AC powered	230/380 V	Fax	DC powered	6-36V
Refrigerator	AC powered	230V	Printer	DC powered	6-48V
Television	DC powered	12-48V	Copy machine	AC powered	230V
Cooker	AC powered	230 (1ϕ), 380 (3ϕ)	Bind machine /laminating	DC powered	24-48V
Radio /tape	Both possible	24-48V, DC 230 V AC	Data centers/telecom equipments	DC powered	6-48V DC
computer	DC powered	6- 24V	**Industrial common appliances**		
Iron	AC powered	230V	Equipments	AC/DC powered	Voltage value
Heater	AC powered	48 V DC 230V AC	Lighting	AC powered	220V(1ϕ)
Air Conditioner	AC powered	230V AC	AC motors, synchronous machines, drier machines	AC powered	380V (3ϕ)
Washing machine	AC powered	220 V	Actuators, mixers, washing, baking and other machines	AC powered	380V (3ϕ)
Boiler	AC powered	230v	Refrigerators	AC powered	220V(1ϕ)