ADDIS ABABA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

ADDIS ABABA INSTITUTE OF TECHNOLOGY

ELECTRICAL AND COMPUTER ENGINEERING DEPARTMENT

STUDY TO UPGRADE EXISTING HVAC TRANSMISSION LINE TO HVDC : CASE OF EPP’s HV TRANSMISSION LINES

A Thesis Submitted to the School of Graduate Studies of Addis Ababa

University in Partial Fulfillment of the Requirements for the Degree of

Masters of Science in Electrical Engineering (Electrical Power Engineering)

By EKRAME WORKU

Advisor : Dr.-Ing. GETACHEW BIRU WORKU

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Declaration

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

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Place: Addis Ababa

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

Dr.-Ing.Getachew Biru	________________________
Advisor's Name	Signature

Dedication

... to my beloved Family

My Parents

and

Siblings....

... for their incomparable support in all of my academic achievements!

Acknowledgement

First of all, I would like to thank the Almighty God for his provision of Grace to complete the entire work.

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Finally to Family and Friends who encouraged me and showed me great affection throughout this thesis work, my sincere thank is here, Thank you all.

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Abstract

The increased demand for electrical energy due to increased industrialization and population growth of Dire Dawa and nearby cities has become a challenge to supply adequate power using the national grid to Eastern region of Ethiopia. One reason for these power shortages is the insufficient current carrying capacity of existing high voltage alternating current, (HVAC), transmission lines supplying the area. High voltage direct current (HVDC) transmission lines are a possible solution as they provide more power than HVAC lines.

New parallel HVAC lines, or converting the existing HVAC line to HVDC lines are possible solutions to improve power delivery in the area. This thesis investigates the technical feasibility of upgrading existing HVAC lines to HVDC. This option allows the power transmission rating to be more than doubled and the specific transmission losses to be substantially reduced without having to widen the right-of-way. What is more, such conversions cost only a one third the cost of building a new line. Thus main contribution of this thesis work is the evaluation of a HVDC system including study of technical compatibility of existing system conversion to HVDC as a solution to overcom power delivery shortages to Eastern region of Ethiopia.

From the technical performance the bipolar HVDC lines has a loss as much as 69.75% lower compared to the existing transmission lines and the monopolar HVDC line has a loss as much as 83.02% lower compared to the existing transmission lines. On the other hand, the transmission powers of the bipolar HVDC line at ± 500 kV increase by 217% and the monopolar HVDC line at ± 500 kV increase by 75.8% from the power transfer capacity of the existing HVAC line. From the cost analysis the cost of conversion is approximately 36% of cost of new HVAC line. Moreover, conversion of the existing transmission line to DC line is both financially and economically feasible.

Key Words: HVAC, HVDC,LLC,HVDC control, Transmission line efficiency, corona loss, investment cost, internal rate of return.

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Acronyms

HVDC/hvdc	High Voltage Direct Current
HVAC/hvac	High Voltage Alternate Current
DC/dc	Direct current
AC/ac	Alternate Current
pu	Per Unit
A	Amper
V	Volt
MW	Mega Watt
KW	Kilo Watt
MVAR	Mega Volt Amper Reactive
F	Farad
H	Henry
K/k	kilo
KM/km	kilo meter
OH	Over Head
TL	Transmission line
EEP	Ethiopian Electric Power
ESIA	Environment and Social Impact Assessment
LC	Line Commutation
LCC	Line Commutated Converters
VSC	Voltage Source Converter
RoW	Right of Way
RAP	Resettlement Action Plan
NPV	Net Present Value
B/C	Benefit Cost Ratio
IRR	Internal Rate of Return

CHAPTER ONE

INTRODUCTION

1.1 Introduction

In general, a transmission line is a device for the transfer of electric energy. It can transfer the energy over long or short distances, and at different voltages. Transfer of electrical energy over very long distances calls for a trunk line with high voltages. The Ethiopian electric grid system consists of five principal levels of transmission voltages: 400, 230, 132, 66 and 45 KV. The 400 and 230 KV high voltage (HV) transmission lines are the backbone of the system connecting the generating stations of Finchaa, MelkaWakena, Gilgel Gibe-I, Gilgel Gibe-II,Tekeze to the major load centers (Addis Ababa) at Gefersa, Kaliti and Sebeta substations respectively. These substations are also interconnected through double circuits of 132 KV and single circuits of 230 KV making a complete ring at 132 KV and a partial ring at 230 KV around Addis Ababa. The 230-KV system further extends from Addis Ababa about 400KM eastward to Dire Dawa, south to MelkaWakena and about 1000 KM towards the west and north.

There are a number of 132 KV lines in the system either being the major distributors of electricity from the 230 KV system or the major interconnecting lines of generating stations to the system as that of Koka, Awash-II & III and Tis Abay-II. The 66 and 45 KV transmission lines are also used to distribute bulk powers transmitted mainly by 132 and 230 KV transmission lines. The 45 KV systems are being phased-out in favor of the 66 KV systems.

Ethiopia's widely distributed population has led to the development of an extensive transmission network. Bulk energy transfer is effected at transmission voltage levels of 400, 230 and 132 kV and sub- transmission voltage levels of 66 and 45 kV in both the ICS and SCS.

The present network consists of about 10,397 km of transmission lines in total

Table 1.1: Summary of Existing High Voltage Transmission Lines [7]

No.	Voltage Level (kV)	Total (km)
1	400 kV Transmission Line	686.70
2	230 kV Transmission Line	3,286.29
3	132 kV Transmission Line	4,316.15
4	66 kV Transmission Line	1,835.11
5	45 kV Transmission Line	273.16
EEP Total		10,397.2

Based on the Distributed Load Forecast, the peak demand at transmission substation level will have reached 3935 MW (excluding exports) by 2017, which is a 56 percent increase on the 2015 level [7]. Appendix-1 lists the transmission projects required to meet this level of demand whilst complying with the planning criteria. Due to this the Ethiopian Federal government is now undertaking extensive generation and transmission system expansions. Among the transmission expansion by 2020 is Completion of a 400 kV ring around Addis Ababa by constructing a 400/230 kV substation at Cotobie II (Legetafo) and interconnecting it with Sululta and DebreZeit with extension of the 400 kV network to Hurso and in the Eastern region.

According to the future load demand forecast of the eastern region of the grid, there are many load demand both industrial and agricultural at Hurso which request power demand around 545.3MW at Hurso and nearby town. The major loads are industries in Diredawa which require about 150MW power, Jigjiga irrigation requires about 80MW and export to Djibouti which requires about 85MW. There is also the railway project with power demand of around 15MW.

The existing HVAC transmission line from Koka to Hurso is a double circuit 230KV line. HVAC transmission lines have an inherent design inefficiency whereby the conductor current carrying capability remains largely unused. With increasing system voltages and the consequential increase in conductor bundles this design inefficiency worsens because loss is I^2R. When the same transmission line is converted to carry direct current, the full conductor current carrying capability can be fully employed.

The net result is much higher power transfer, more economic utilization of existing assets and removal of the need for new power line routes, rights of way and servitudes. HVDC also introduces many key technical and economic benefits such as lower power losses for bulk power transfer, creation of asynchronous power systems and advanced controllability of large power systems having both speed of response and intelligence of control. The study presents the results of investigations into the power transfer constraints of, and the benefits of converting HVAC transmission lines to HVDC transmission lines.

Cost effective higher current rated power electronic technology makes possible the conversion of high voltage AC circuits to high voltage DC. This strategy yields greater power transfers by using the same physical power line and installed conductor cross sectional area. The conversion strategy is being developed and promoted because of limited availability of new power line servitudes, to overcome transmission congestion and bottlenecks in interconnected power networks; to recycle existing assets for greater power transfer efficiency, to promote bi-directional power transfer under different system operating conditions, to promote electrically separate power islands within a greater and growing interconnected power system thereby enhancing power system stability and controllability and to introduce the new technology HVDC control computers for rapid real time ancillary services energy management.

In this thesis a study has been conducted to evaluate the conversion of existing HVAC transmission line to HVDC for increased power capacity in terms of technical and financial parameters and an alternative design has been presented for further considerations.

1.2 Statement of the Problem

The electric energy generated in Ethiopia from the main hydropower plants is transported through high voltage transmission lines rated 45, 66, 132, 230 and 400 kV. The 400 kV transmission lines of 685.71 km were constructed and commissioned recently while 500kV and DC lines are being considered as part of the five year plan. The total length of the existing transmission lines is about 10884.23 km. Regional interconnections with neighboring countries including Djibouti, Sudan and Kenya are under the construction and procurement phases.

The Djibouti interconnector comprises a 283 km, 230 kV double circuit line from Dire Dawa in Ethiopia to PK12 substation in Djibouti. Dire Dawa is in the Eastern region of Ethiopia and is connected to Koka substation to the south east of Addis Ababa via a 352 km double circuit 230 kV line from Koka to Hurso. The transmission system is therefore particularly weak at Dire Dawa. There is a diesel fired power plant at Dire Dawa, however this has limited capacity for providing voltage support. Hence, there are issues with energizing the interconnector at periods of low demand in Ethiopia, and there is limited power transfer capacity during peak times in Ethiopia. To address this problem EEPCo planning department is currently conducting a study which involves the introduction of a new double circuit 400 kV line from Debrezeit to Hurso (near Dire Dawa). The length of these transmission lines from Debrezeit to Hurso is about 387 km.

Power transfer to Djibouti and Eastern region will be significantly improved by reinforcement of the existing Koka – Dire Dawa line. In this thesis it is proposed that the existing 352 km double circuit 230 kV line from Koka - Hurso converted to 500KV bipolar HVDS transmission system. The experience of several countries was taken into account to create the scenarios used in this research due to the fact that previous work to convert existing high voltage alternating current (HVAC) transmission line to high voltage direct current (HVDC) hasn't been made in the country. Using Line commutated converter (LLC) technology option appears to fit in bulk power transmission from large concentrated hydropower. On the other hand, Voltage source converter (VSC) seems to suit offshore wind farms and remote land-based wind farms, sometimes at a moderate distances from load centers but inaccessible to present HVAC grids.

1.3 Objective

1.3.1 General Objectives

The general objective of this thesis is to study and evaluate the possibility of increasing the performance and efficiency of the transmission line by upgrading the existing HVAC transmission line to HVDC for increased power rating.

1.3.2 Specific Objectives

Particularly, the thesis focuses on

- Identifying and evaluating the problems related to the existing HVAC transmission line.
- Evaluating the transmission line performance & capacity by upgrading HVAC transmission line to HVDC.
- Designing the HVDC line in a way that permits fully controllable, fast and accurate power flow with reduced Corona & radio frequency interference losses.
- Comparing the performance characteristics of the existing HVAC transmission line with the new suggested HVDC line and including the cost aspects.

1.4 Methodology

The design methodology is based on the concept whereby a transmission line is designed as a system made of components such as foundation, supports, conductors, insulators and other hardware. It is assumed the new design will retain the existing structure and layouts for the conversion.

Data Collection: The data collection is the basis for this study. Relevant data’s has been collected from the power company EEP. These data’s include National grid data’s.

Investment cost of HVAC is also collected from EEP's Planning Department. The technical data are obtained from national and international standards.

Design of main components of HVDC: Design of system components of the bipolar HVDC transmission system is made to fulfills the N-1 contingency criteria. The transmission line is designed based on IEEE Standard for Calculating the Current-Temperature of Bare Overhead Conductors. And the smoothing reactor is designed based on IEEE Standard General Requirements and Test Code for Dry-Type and Oil-Immersed Smoothing Reactors for DC Power Transmission. The harmonic filters are designed to fulfill the standards set by ABB group which is the worldwide HVDC equipment supplier.

Simulation and Result: The network analysis is maid for the four different transmission lines cases to see which option give better solution for increased power delivery. The design of the converted transmission line and related performance improvement are also shown The simulation results have been compared with the standards that are stated in each section of the thesis work.

Comparison of HVDC with HVAC: Comparison of the two transmission line options is carried out based on the investment cost and technical performance parameters i.e. Transmission line efficiency, voltage drop and corona loss. And finally financial and economic feasibility of the converted transmission line is conducted based of discounted cash flow analysis.

1.5 Thesis Layout

This thesis is organized into six chapters.

Chapter 1 is an introductory part giving background of the study. The basic problem to be investigated is described. The objectives of the thesis work are stated. Finally the Methodologies are described briefly.

Chapter 2 deals with the theoretical back ground of the thesis work. Under this chapter main features of conversion HVAC to HVDC is discussed. Also comparison of HVDC and HVAC is discussed in terms of cost and technical performance. Organization and operation of HVDC is discussed and definition of system components is stated.

Chapter 3 deals with the basic design of the conversion of the existing transmission line to HVDC in terms of conductor, insulation, electric field, and tower configuration followed by designing of main components of the HVDC converter station which are converters, converter transformer, AC filters and smoothing reactors. Beside this, Algorithm of the controller is also presented.

Chapter 4 covers the network analysis for the four different cases of transmission lines on the PSS/E software. Based on this software and with the system grid load forecast, load flow analysis, short circuit analysis and steady state stability analysis is shown for the proposed transmission lines.

Chapter 5 deals with economical and technical comparison of HVDC with HVAC. In the technical aspect, performance parameters like transmission line efficiency, voltage drop, and corona loss are calculated to find out which transmission system has better performance.

In the economical aspect the investment of the converted and new transmission line is covered and the saving in million US$ is calculated to choose which transmission system is better to implement. Also the financial and economic feasibility of the converted transmission line is included.

Chapter 6 deals with the relevant conclusions and recommendations drawn from the study.

CHAPTER TWO

LITERATURE REVIEW AND THEORETICAL BACKGROUND

Numerous studies have been carried out in the past to investigate ways of converting AC lines to HVDC lines. This technique allows the power transmission rating to be more than tripled and the specific transmission losses to be substantially reduced without having to widen the right-of-way. What is more, such conversions cost only a third to half the cost of building a new DC line [3]. Some of the studies done in the area of converting AC lines to HVDC lines are described below.

2.1 Historic Background of HVDC

The transmission and distribution of electrical energy started with direct current. In 1882, a 50-km-long 2-kV DC transmission line was built between Miesbach and Munich in Germany. At that time, conversion between reasonable consumer voltages and higher DC transmission voltages could only be realized by means of rotating DC machines.

In an AC system, voltage conversion is simple. An AC transformer allows high power levels and high insulation levels within one unit, and has low losses. It is a relatively simple device, which requires little maintenance. Further, a three-phase synchronous generator is superior to a DC generator in every respect. For these reasons, AC technology was introduced at a very early stage in the development of electrical power systems. It was soon accepted as the only feasible technology for generation, transmission and distribution of electrical energy.

However, high-voltage AC transmission links have disadvantages, which may compel a change to DC technology:

- Inductive and capacitive elements of overhead lines and cables put limits to the transmission capacity and the transmission distance of AC transmission links.
- This limitation is of particular significance for cables. Depending on the required transmission capacity, the system frequency and the loss evaluation, the

achievable transmission distance for an AC cable will be in the range of 40 to 100 km. It will mainly be limited by the charging current.

- Direct connection between two AC systems with different frequencies is not possible.
- Direct connection between two AC systems with the same frequency or a new connection within a meshed grid may be impossible because of system instability, too high short-circuit levels or undesirable power flow scenarios.

Engineers were therefore engaged over generations in the development of a technology for DC transmissions as a supplement to the AC transmissions.

Figure 2.1: ±5 HVDC transmission line [17].

2.1.1 Line-Commutated Current Sourced Converters

The invention of mercury arc rectifiers in the nineteen-thirties made the design of line-commutated current sourced converters possible. In 1941, the first contract for a commercial HVDC system was signed in Germany: 60 MW were to be supplied to the city of Berlin via an underground cable of 115 km length. The system with ±200 kV and 150 A was ready for energizing in 1945. It was never put into operation.

Since then, several large HVDC systems have been realized with mercury arc valves. The replacement of mercury arc valves by thyristor valves was the next major development. The first thyristor valves were put into operation in the late nineteen-seventies. The outdoor valves for CahoraBassa were designed with oil-immersed thyristors with parallel/series connection of thyristors and an electromagnetic firing system. Further development went via air-insulated aircooled valves to the air- insulated water-cooled design, which is still state of the art in HVDC valve design.

The development of thyristors with higher current and voltage ratings has eliminated the need for parallel connection and reduced the number of series-connected thyristors per valve. The development of light-triggered thyristors has further reduced the overall number of components and thus contributed to increased reliability. Innovations in almost every other area of HVDC have been constantly adding to the reliability of this technology with economic benefits for users throughout the world.

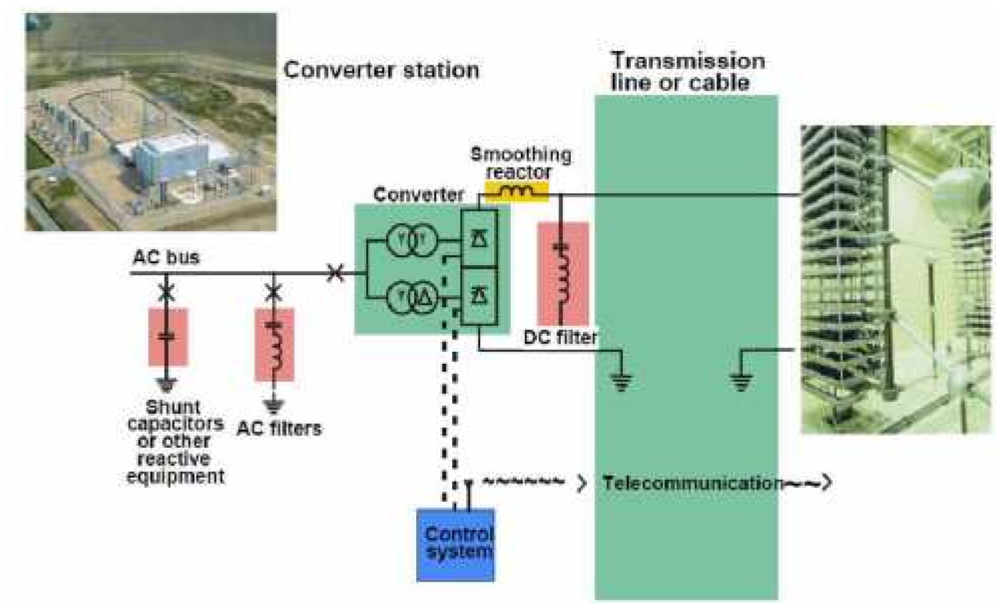


Figure 2.2: LCC-HVDC (converter station and thyristor valve) [39].

2.1.2 Self-Commutated Voltage Sourced Converters

Voltage sourced converters require semiconductor devices with turn-off capability. The development of Insulated Gate Bipolar Transistors (IGBT) with high voltage ratings have accelerated the development of voltage sourced converters for HVDC applications in the lower power range. The main characteristics of the voltage sourced converters are a compact design, four-quadrant operation capability and high losses.

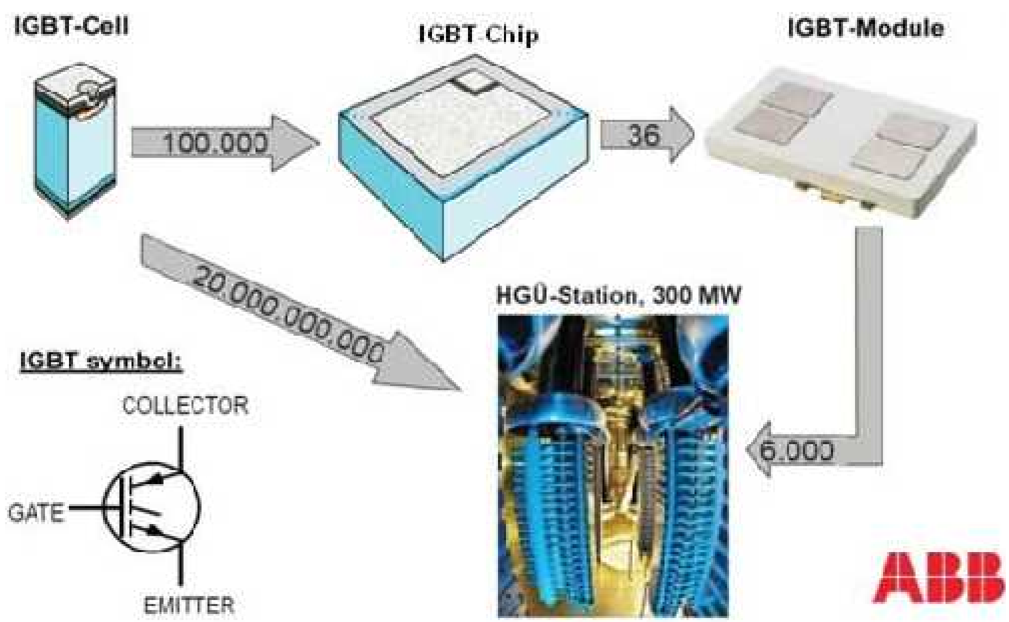


Figure 2.3: IGBT symbol and representation of a valve from IGBT cells [39].

2.2 HVDC System Configurations and Components

HVDC links always require rectifiers/inverters to connect to AC grids. This is necessary for converting the alternating AC voltage to a constant DC voltage. These rectifiers and inverters are referred to as converters [2]. For a DC transmission link, there is typically one converter at each end of the link . HVDC systems have the ability to rapidly control the transmitted power. Therefore, they have a significant impact on the stability of the associated ac power systems. An understanding of the characteristics of the HVDC systems is essential for the study of the stability of the power system. More importantly, proper design of the HVDC controls is essential to ensure satisfactory performance of the overall ac/dc system [1].

2.2.1 Configuration of HVDC system

Many different types of HVDC configurations exist, Some of them are introduced here:

I. Back-to-back HVDC system

Figure 2.4 shows the back-to-back HVDC system. In this configuration, two converter stations are built at the same place, and there is no long-distance power transmission in the DC link. It is the common configuration for connecting two adjacent asynchronous AC systems. The two AC systems interconnected may have the same or different nominal frequencies, i.e. 50 Hz and 60 Hz.

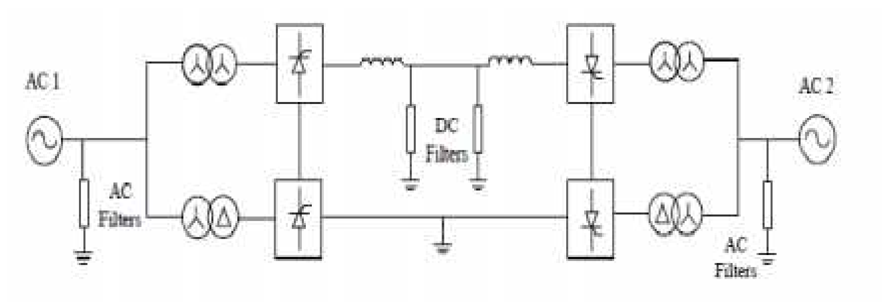


Figure 2.4: Back-to-back HVDC system [38].

II. Monopolar HVDC system

Figure 2.5 illustrates a monopolar HVDC system. In this case, the two converter stations are separated by a single pole line with a positive or a negative DC voltage. The ground is used to return current. Furthermore, submarine connections for many transmission systems used monopolar configuration.

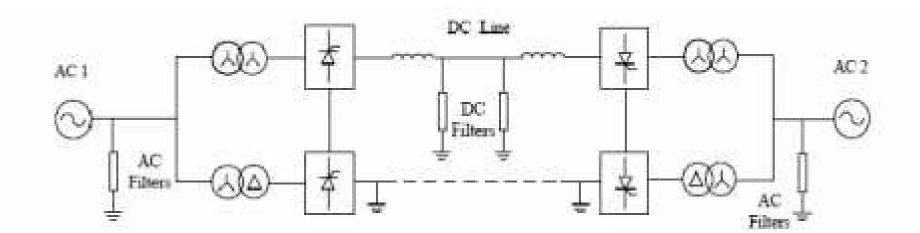


Figure 2.5: Monopolar HVDC system [38].

III. Bipolar HVDC system

Figure 2.6 shows Bipolar HVDC system, which is the most commonly used configuration. Most overhead line HVDC transmission systems use the bipolar configuration [40].

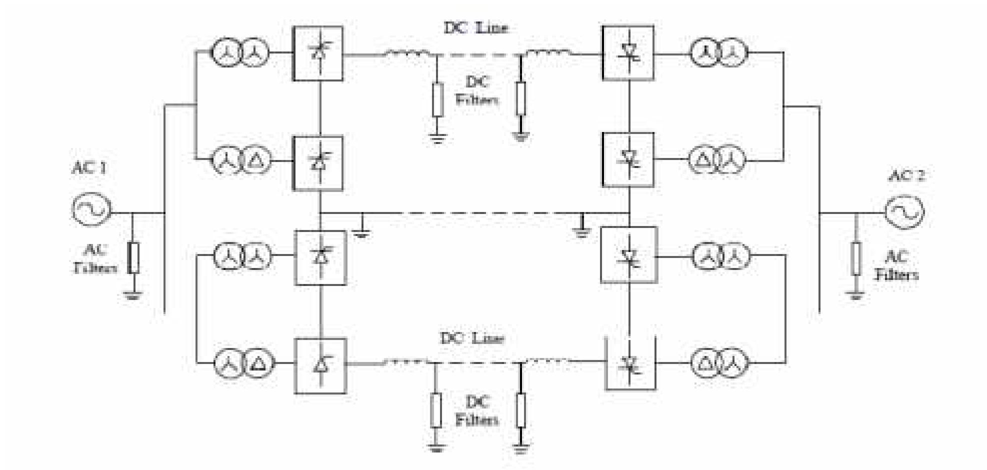


Figure 2.6: Bipolar HVDC system [38].

As shown in the figure the bipolar system is essentially two monopolar systems connected in parallel. The advantage of such system is that one pole can continue to transmit power in the case of a fault on other one. Each system can operate separately as an independent system with the earth return. Both poles have equal currents since one is positive and one is negative, so the ground current is theoretically zero, or in practice, the ground current is within a difference of 1% [40].

IV. Multi-terminal HVDC system

Figure 2.7 illustrates a multi-terminal HVDC system, which is more than two sets of converter stations. The three or more HVDC converter stations are separated by location and interconnected through transmission lines or cables. In the example shown in Figure 2.7, converter stations 1 and 3 operate as rectifiers and converter 2 operate as an inverter.

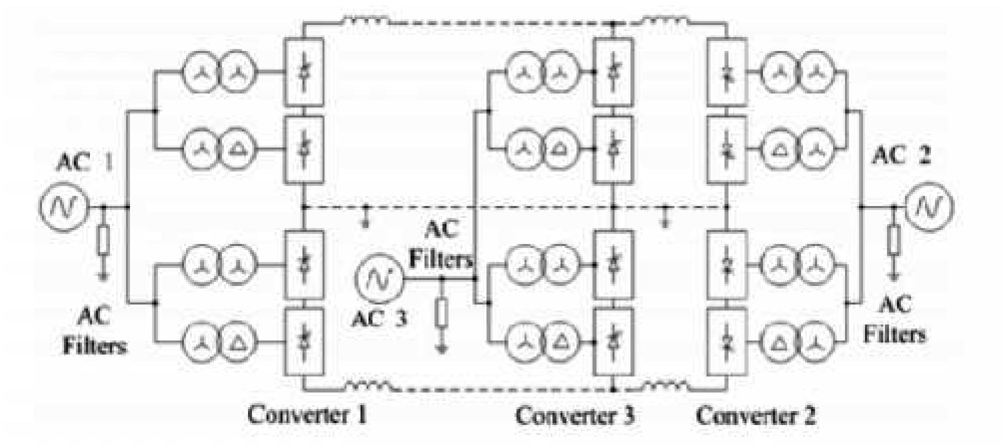


Figure 2.7: Multi-terminal HVDC system [41].

2.2.2 Components of HVDC transmission system

The main components associated with an HVDC system are shown in Figure 2.8, taking a bipolar system as an example. The components for other configurations are essentially the same as those shown in the Figure 2.8. The following is a brief description of each component.

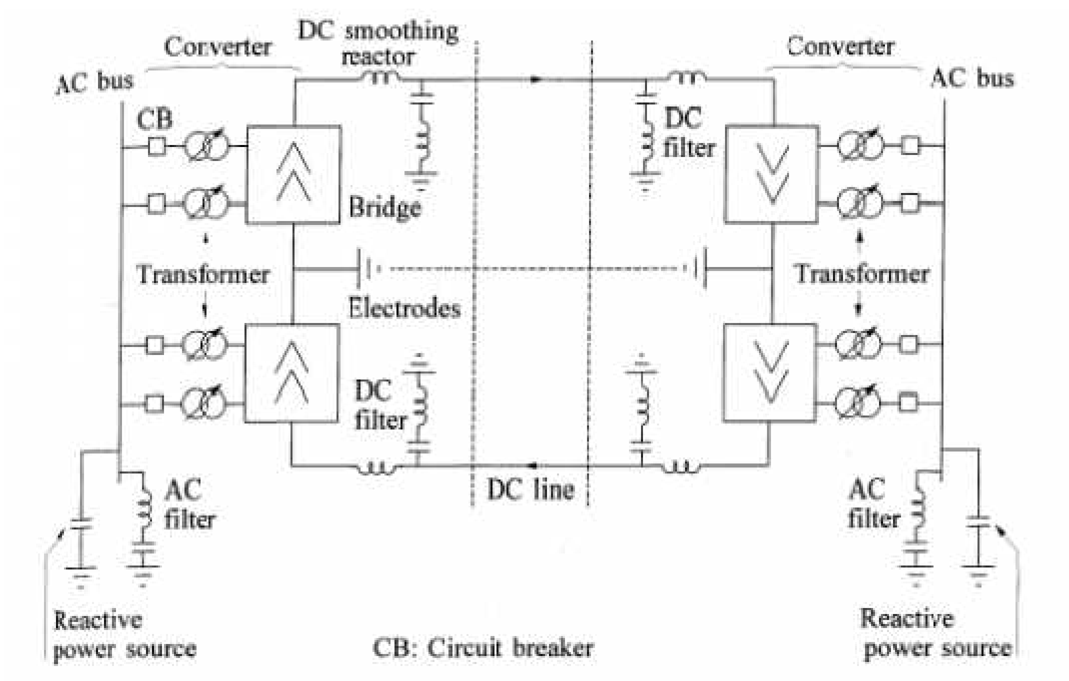


Figure 2.8: A schematic of a bipolar HVDC system [1].

Converters : They perform ac/dc and dc/ac conversion, and consist of valve bridges and transformers with tap changers. The valve bridges consist of high-voltage valves connected in a 6-pulse or 12-pulse arrangement. The converter transformers provide ungrounded three-phase voltage source of appropriate level to the valve bridge. With the valve side of the transformer ungrounded, the dc system will be able to establish its own reference to ground, usually by grounding the positive or negative end of the valve converter.

Smoothing Reactors : These are large reactor having inductance as high as 300mHz connected in series with each pole of converter station. They serve the following purposes;

- Decrease harmonic voltages and currents in the dc line.
- Prevent commutation failure in inverters.
- Prevent current from being discontinuous at light load.
- Limit the crest current in the rectifier during short-circuit on the dc lin.

Harmonic Filters : Converters generate harmonic voltages and currents on both ac and dc sides. These harmonics may cause overheating of capacitors and nearby generators, and interference with telecommunication systems. Filters are therefore used on both ac and dc sides.

Reactive Power Supplies : DC converters inherently absorb reactive power. Under steady-state conditions, the reactive power consumed is about 50% of active power transferred. Under transient conditions, the consumption of reactive power may be much higher. Reactive power sources are therefore provided near the converters. For strong ac systems, these are usually in the form of shunt capacitors. Depending on the demands placed on the dc link and on the ac system, part of the reactive power source may be in the form of synchronous condensers or static var compensators. The capacitors associated with the ac filters also provide part of the reactive power required.

Electrodes : Most dc links are designed to use earth as a neutral conductor for at least brief periods of time. The connection to the earth requires a large-surface-area conductor to minimize current densities and surface voltage gradients. This conductor is referred to as an electrode. As discussed earlier, if it is necessary to restrict the current flow through the earth, a metallic return conductor may be provided as part of the dc line.

DC Lines : They may be overhead lines or cables. Except for the number of conductor and spacing required, dc lines are very similar to ac lines.

AC Circuit Breaker : For clearing faults in the transformer and for taking the dc link out of service, circuit-breakers are used on the ac side. They are not Used for clearing dc faults, since these faults can be cleared more rapidly by converter control.

2.3 Operation of a Converter

A converter performs ac/dc conversion and provides a means of controlling the power flow through the HVDC link. The major elements of the converter are the valve bridge and converter transformer. The valve bridge is an array of high-voltage switches or valves that sequentially connect the three-phase alternating voltage to the dc terminals so that the desired conversion and control of power are achieved. The converter transformer provides the appropriate interface between the ac and dc systems [1].

In the following section the basic operation of a Line Commutated Converter is presented. Line Commutated Current Source Six Pulse Bridge Converter and associated voltage and current wave shapes, considering the periods of firing delay and overlap angles is shown in Figure 2.9.The conversion of current between the AC side and the DC side is accomplished by transferring direct current in sequence from the valve, such that the DC current flows as blocks of AC current in the transforming windings. With line commutation, the AC voltage at both rectifier and inverter must be provided by the AC networks at each end and should be three phase and relatively free of harmonics.

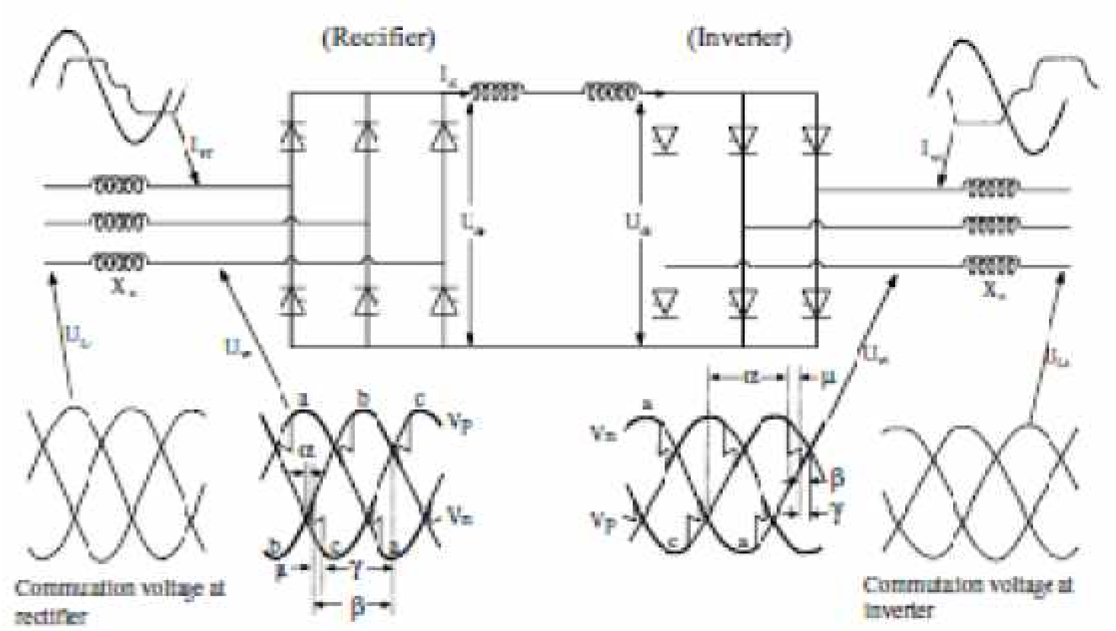


Figure 2.9: Operation Characteristics of a Line Commutated Current Source HVDC System [37]

Figure 2.9, shows the influence of the transformer´s commutation reactance on the waveform, at the rectifier and inverter. The current flow through a conducting valve does not change instantaneously as it commutates to another valve because the transfer is through the transformer winding.

All the valve current contributions result in a direct current which is transferred from the DC side through the DC reactor, and is relatively flat because of the inductance of the DC reactor.

A 12-pulse converter consisting of two six-pulse bridges in series, one supplied by three-phase AC voltage from Y secondary and the other a Δ secondary of a converter transformer is shown in Figure 2.10. The typical waveforms show a change from maximum positive DC voltage to approximately 70%, then to –70% and then to the maximum negative of about –90%. [35]

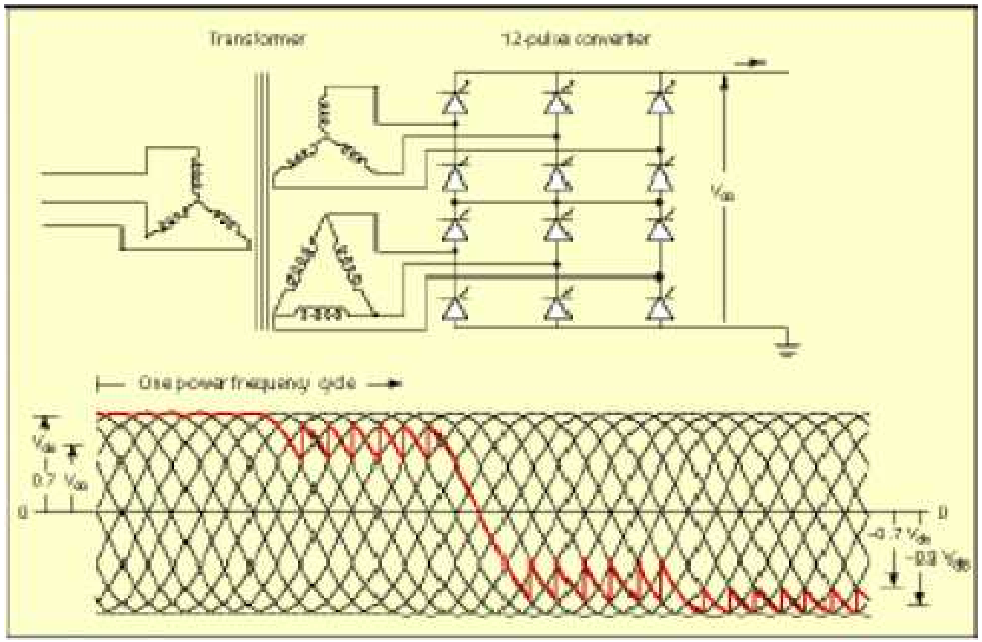


Figure 2.10: 12-pulse converter consisting of two six-pulse bridges in series [35]

The output DC voltage obtained from a twelve-pulse bridge by switching twelve valves is shown in Figure 2.10. The sequence shows the converter operating first as a rectifier at its maximum positive voltage, then at a voltage reduced by delaying the firing angle, then at a negative voltage with a delay angle exceeding 90 degrees (inverter operation), and finally, at maximum negative voltage.

2.4 Main Features of AC to DC Conversions

a) Tower design

The scope of such a conversion, as it is understood here, covers changes to the conductor arrangement on the tower, the insulator assemblies and the configuration of the conductor bundle, but not to the actual tower structure or to the number of towers (ie, no additional towers have to be erected). As a starting point, it is assumed that the existing overhead conductors will be re-used, although this will depend on their condition. Re-use of the existing conductors has the advantage that the load that the weight of the conductors exerts on the towers does not change. Even so, it may be necessary to reinforce the towers if the conductors have to be hung higher.

b) Phase-to-ground clearance

Although none of the international standards committee, such as the CENELEC, have as yet specified phase-to-ground clearances for DC lines, a recommendation of the EPRI in the USA [9] provides some help. An important parameter for specifying the clearances is the maximum overvoltage occurring. Field experience shows that, due to the advanced controls being used today for HVDC schemes and because of the resulting insulation coordination, over voltages to earth of no more than 1.7 to 1.8 pu can be expected in the worst case. According to [9], clearances of at least 2.2 m for a transmission voltage of 500 kV and 3.1 m for 600 kV are needed.

If, for example, a 400-kV AC line is converted to an HVDC bipole rated at ±500 kV, the design voltage to earth will increase by the factor 1.46. According to ground clearance (ie, between conductor and cross-arm) should be at least 2.26 m for AC systems with a maximum operating voltage of 420 kV and a basic insulation level (BIL) of 950 kV. It is therefore possible in principle to convert from AC to DC with a higher design voltage without having to change the structural design of the tower.

c) Surface voltage gradient

Unlike AC lines, DC lines are characterized by the following phenomena [7]:

- • Steady-state ionization forms around the conductors.
- The emitted ions create a space charge around the conductors.
- The most severe radio interference occurs in dry weather conditions.

The space charge acts like a screen and reduces the maximum surface voltage gradient of the conductors. In contrast, the effect of the space charge close to earth is to strengthen the electric field. Corona discharge is always caused by the ionization of neutral air molecules colliding with free electrons accelerating in the electric field. Because of the different velocities at which the positive and negative ions travel, two very different types of corona discharge occur in the region around the conductors. Negative corona discharges occur with a high repetition rate and small discharge amplitudes. Positive corona discharges occur less often, but exhibit higher amplitudes. By neglecting the space charge effect, a theoretical value can be calculated for the surface voltage gradient of DC lines in dry weather conditions using the same method as for AC lines.

The surface voltage gradient of overhead transmission lines has to be dimensioned according to the permitted radio interference. The electric field intensities recommended for AC lines take account of a 10 dB increase in radio interference when it rains. With DC lines, the radio interference decreases when it is raining. This justifies increasing the electric field intensities for DC lines in comparison with AC lines. Providing the usual limits are introduced to prevent radio interference, the contribution made by corona discharge to the total transmission losses will be negligible.

d) Creepage distances

According to CIGRE SC 33-WG04, a conservative approach to the problem of creepage distances for DC voltage would be to increase the specific values for AC voltage by a factor of 2. This results in values of about 4.2 cm/kV for lines in a moderately polluted environment. The reserve included in this figure is ample; for example, the ± 600-kV Itaipúbipole line in Brazil has insulators designed with a specific creepage distance of 2.7 cm/kV.

e) Electric and magnetic fields

The health risk for people living or working within the low-frequency fields produced by power transmission lines is a concern which national and international committees have addressed through an agreement on field values. These values satisfy even the most critical safety criteria, and providing they are observed such electromagnetic fields cannot be considered a hazard to health.

Some of the new data are also used as a basis for legislation. The German federal government, for example, issued a decree in December 1996, based on the recommendations of the International Radiation Protection Association [8] and the German Radiation Protection Commission, which specifies mandatory limits for fields generated by low-frequency systems such as overhead transmission lines. The systems are to be built and operated in such a way that the fields do not exceed the limits given in Table 2.1.

Table 2.1: Limit for-frequency electric and magnetic fields [3]

Frequency (Hz)	Electric field (kV/m)	Magnetic field (μT)
50	5	100
$16^{1/2}$	10	300

No German legislation exists as yet for DC magnetic fields. However, the tentative standard DIN VDE 0848-4/A3 [3] gives limits which take account of the need to protect even highly sensitive people from such fields is given in Table 2.2.

Table 2.2: Limit for DC electric magnetic fields (rms values) [3]

Limit for DC electric magnetic fields (rms values) [3] Electric field (kV/m)	Magnetic field (μT)
20	21,200

f) Conversion procedure

In the case of multiple-system lines, some of the tower designs in use allow conversion in stages, so that transmission can be continued over that system not actually affected by the work being carried out. Conversion in stages allows step-by-step matching to growing power demand and reduces the time until start-up of transmission at the increased power level, translating into lower capital investment. This approach helps to raise the energy availability of the line during the conversion.

During the replacement of the first AC system by the first HVDC bipole, the two DC cables are positioned one above the other on one side of the tower. Since the field strengthening effect of the space charge below the positive conductor is much lower than below the negative conductor, it is an advantage to fix the positive conductor to the lower cross-arm. The next step is to replace the second AC system by the second HVDC bipole. Exchanging the polarities of the conductors vis-à-vis the first bipole will reduce the field intensities in the vicinity of the earth (soil) but increase the electric field at the surfaces of the conductors. If the polarities are left the same, this effect is reversed. The best arrangement for the conductor polarities therefore has to be decided from case to case.

2.5 Comparison of AC and DC Transmission

2.5.1 Advantages of HVDC

(a) **More power can be transmitted per conductor per circuit.**

The capabilities of power transmission of an ac link and a dc link are different. For the same insulation, the direct voltage V_d is equal to the peak value (√2 x rms value) of the alternating voltage V_d.

$$V_d = \sqrt{2}V_a \qquad (2.1)$$

For the same conductor size, the same current can transmitted with both dc and ac if skin effect is not considered.

$$I_d = I_a \qquad (2.2)$$

Thus the corresponding power transmission using 2 conductors with dc and ac are as follows;

dc power per conductor $P_d = V_d I_d$ (2.3)

ac power per conductor $P_a = V_a I_a \cos\varphi$ (2.4)

The greater power transmission with dc over ac is given by the ratio of powers.

$$\frac{P_d}{P_a} = \frac{\sqrt{2}}{\cos\varphi} = \begin{cases} 1.41 \text{ at p.f} = \text{unity} \\ 1.768 \text{ at p.f} = 0.8 \end{cases}$$

In practice, ac transmission is carried out using either single circuit or double circuit 3 phase transmission using 3 or 6 conductors. In such a case the above ratio for power must be multiplied by **2/3** or by **4/3**.

In general, we are interested in transmitting a given quantity of power at a given insulation level, at a given efficiency of transmission. Thus for the same power transmitted P, same losses P_L and same peak voltage V, we can determine the reduction of conductor cross-section A_d over A_a.

Let Rd and Ra be the corresponding values of conductor resistance for dc and ac respectively, neglecting skin resistance.

For **dc** current $= \frac{P}{V_m}$

power loss $P_L = (P/V_m)^2 R_d = (P/V_m)^2 \cdot (\rho l/A_d)$ (2.5)

For **ac** current $= \frac{P}{(V_m/\sqrt{2}) \cos\varphi} = \frac{\sqrt{2}P}{V_m \cos\varphi}$

power loss $P_L = \left[\sqrt{2}P/(V_m \cos\varphi)\right]^2 R_a$ (2.6)

$$= 2(P/V_m)^2 \cdot (\rho l/A_a \cos^2\varphi)$$

Equating power loss for dc and ac

$$(P/V_m)^2 \cdot (\rho l/A_d) = 2(P/V_m)^2 \cdot (\rho l/A_a \cos^2\varphi)$$

This gives the result for the ratio of areas as

$$\frac{A_d}{A_a} = \frac{\cos^2\varphi}{2} = \begin{cases} 0.5 \text{ at p.f.} = \text{unity} \\ 0.32 \text{ at p.f.} = 0.8 \end{cases} \quad (2.7)$$

The result has been calculated at unity power factor and at 0.8 lag to illustrate the effect of power factor on the ratio. It is seen that only one-half the amount of copper is required for the same power transmission at unity power factor, and less than one-third is required at the power factor of 0.8 lag.

(b) **Use of Ground Return Possible**

In the case of HVDC transmission, ground return (especially submarine crossing) may be used, as in the case of a monopolar dc link. Also the single circuit bipolar dc link is more reliable, than the corresponding ac link, as in the event of a fault on one conductor, the other conductor can continue to operate at reduced power with ground return. For the same length of transmission, the impedance of the ground path is much less for dc than

for the corresponding ac because dc spreads over a much larger width and depth. In fact, in the case of dc the ground path resistance is almost entirely dependent on the earth electrode resistance at the two ends of the line, rather than on the line length. However it must be borne in mind that ground return has the following disadvantages. The ground currents cause electrolytic corrosion of buried metals, interfere with the operation of signaling and ships' compasses, and can cause dangerous step and touch potentials.

(c) **Smaller Tower Size**

The dc insulation level for the same power transmission is likely to be lower than the corresponding ac level because of less potential stress for same working voltage. . Also the dc line will only need two conductors whereas three conductors (if not six to obtain the same reliability) are required for ac. Thus both electrical and mechanical considerations dictate a smaller tower. Right-of-Way of typical dc and ac transmission line structure for approximately 2000 MW [29].

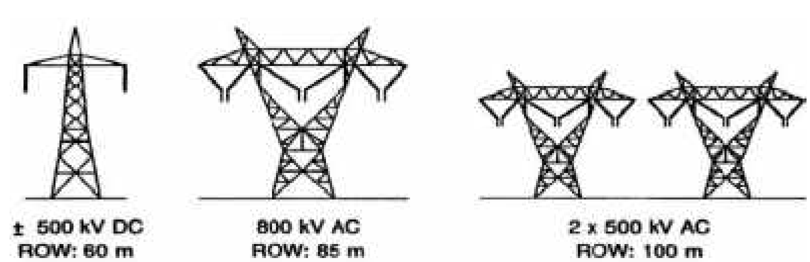


Figure 2.11: Right-of-Way of typical dc and ac transmission line [29].

(e) **No skin effect**

Under ac conditions, the current is not uniformly distributed over the cross section of the conductor. The current density is higher in the outer region (skin effect) and result in under utilization of the conductor cross-section. Skin effect under conditions of smooth dc is completely absent and hence there is a uniform current in the conductor, and the conductor metal is better utilized.

(f) **Less corona and radio interference**

Since corona loss increases with frequency (in fact it is known to be proportional to **f+25**), for a given conductor diameter and applied voltage, there is much lower corona loss and hence more importantly less radio interference with dc. Due to this bundle conductors become unnecessary and hence give a substantial saving in line costs. Tests have also shown that bundle conductors would anyway not offer a significant advantage for dc as the lower reactance effect so beneficial for ac is not applicable for dc.

(g) **No Stability Problem**

The dc link is an asynchronous link and hence any ac supplied through converters or dc generation do not have to be synchronized with the link. Hence the length of dc link is not governed by stability. In ac links the phase angle between sending end and receiving end should not exceed 30^{o} at full-load for transient stability (maximum theoretical steady state limit is 90^{o}).

Note: $\theta = \omega\sqrt{I_{\iota}}\,p\epsilon \qquad = (2\pi \times 50)(3 \times 10^{5})r \quad / k$

$$\approx (2 \times 180 \times 50)(3 \times 10^{5}) \approx 0.06^{c} / k$$

The phase angle change at the natural load of a line is thus 0.6^{o} per 10 km. The maximum permissible length without compensation ≈ 30/0.06 = 500 km. With compensation, this length can be doubled to 1000 km.

(h) **Asynchronous interconnection possible**

With ac links, interconnections between power systems must be synchronous. Thus different frequency systems cannot be interconnected. Such systems can be easily interconnected through HVDC links. For different frequency interconnections both convertors can be confined to the same station. In addition, different power authorities may need to maintain different tolerances on their supplies, even though nominally of the same frequency. This option is not available with ac. With dc there is no such problem.

(i) **Lower short circuit fault levels**

When an ac transmission system is extended, the fault level of the whole system goes up, sometimes necessitating the expensive replacement of circuit breakers with those of higher fault levels. This problem can be overcome with HVDC as it does not contribute current to the ac short circuit beyond its rated current. In fact it is possible to operate a dc link in "parallel" with an ac link to limit the fault level on an expansion. In the event of a fault on the dc line, after a momentary transient due to the discharge of the line capacitance, the current is limited by automatic grid control. Also the dc line does not draw excessive current from the ac system.

(j) **Tie line power is easily controlled**

In the case of an ac tie line, the power cannot be easily controlled between the two systems. With dc tie lines, the control is easily accomplished through grid control. In fact even the reversal of the power flow is just as easy.

2.6 Inherent problems associated with HVDC

(a) **Expensive convertors**

Expensive Convertor Stations are required at each end of a dc transmission link, whereas only transformer stations are required in an ac link.

(b) **Reactive power requirement**

Convertors require much reactive power, both in rectification as well as in inversion. At each convertor the reactive power consumed may be as much at 50% of the active power rating of the dc link. The reactive power requirement is partly supplied by the filter capacitance, and partly by synchronous or static capacitors that need to be installed for the purpose.

(c) **Generation of harmonics**

Convertors generate a lot of harmonics both on the dc side and on the ac side. Filters are used on the ac side to reduce the amount of harmonics transferred to the ac system. On the dc system, smoothing reactors are used. These components add to the cost of the convertor.

(d) **Difficulty of circuit breaking**

Due to the absence of a natural current zero with dc, circuit breaking is difficult. This is not a major problem in single HVDC link systems, as circuit breaking can be accomplished by a very rapid absorbing of the energy back into the ac system. (The blocking action of thyristors is faster than the operation of mechanical circuit breakers). However the lack of HVDC circuit breakers hampers multi-terminal operation.

(e) **Difficulty of voltage transformation**

Power is generally used at low voltage, but for reasons of efficiency must be transmitted at high voltage. The absence of the equivalent of dc transformers makes it necessary for voltage transformation to carried out on the ac side of the system and prevents a purely dc system being used.

(f) **Difficulty of high power generation**

Due to the problems of commutation with dc machines, voltage, speed and size are limited. This can comparatively lower power can be generated with dc.

2.5.2 Economic Comparison

The HVDC system has a lower line cost per unit length as compared to an equally reliable ac system due to the lesser number of conductors and smaller tower size. However, the dc system needs two expensive convertor stations which may cost around two to three times the corresponding ac transformer stations. Thus HVDC transmission is not generally economical for short distances, unless other factors dictate otherwise. Economic considerations call for a certain minimum transmission distance (break-even distance) before HVDC can be considered competitive purely on cost.

Estimates for the break even distance of overhead lines are around 500 km with a wide variation about this value depending on the magnitude of power transfer and the range of costs of lines and equipment. The breakeven distances are reducing with the progress made in the development of converting devices.

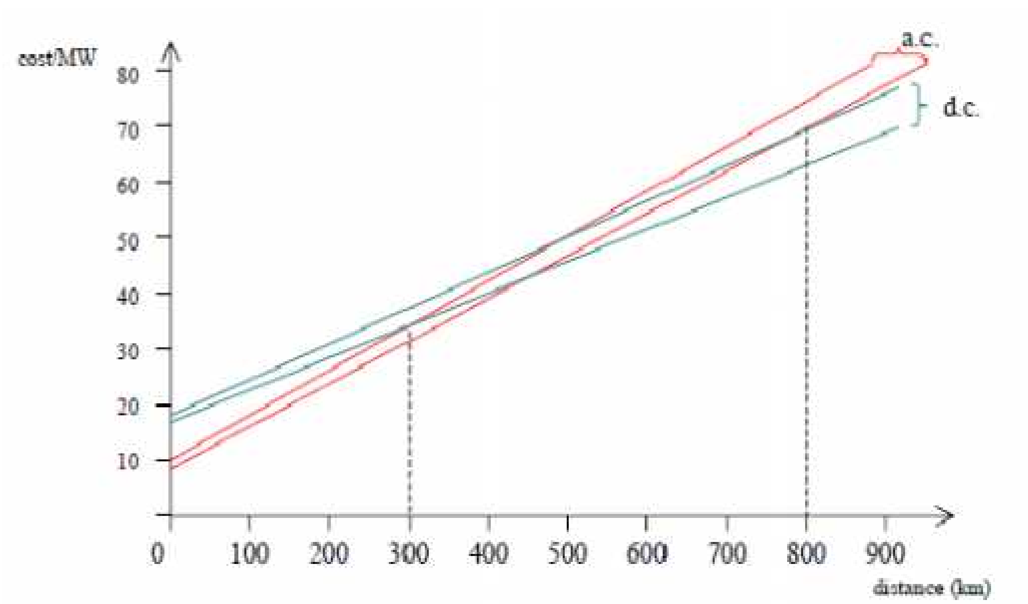


Figure 2.12: Break-even distance for dc transmission [42]

Figure 2.12 shows the comparative costs of dc links and ac links with distance, assuming a cost variation of ± 5% for the ac link and a variation of ± 10% for the dc link.

For cables, the break-even distance is much smaller than for overhead lines and is of the order of 25 km for submarine cables and 50 km for underground cables.

2.7 Current Literature Reviews

K. Halsan and D. Loudon, made a study on feasibility of upgrading 300 kV AC Lines to DC based on increasing the capacity of existing transmission lines by utilizing existing lines, which are already accepted by the public, in a more efficient way by increasing their power transfer capacity. In their study they evaluated several alternative technologies are at hand for increased capacity of existing AC lines, such as current or voltage up rating. However, in many cases, the most efficient way of increasing the capacity of AC lines is conversion to DC operation. In feasibility studies they have carried out , they indicated that the power capacity of a single circuit transmission line may increase by 50 to 100% through conversion to DC. For a completely converted double-circuit line, the increase may be 150 to 200%. However, the potential increase depends on the dimensions of the existing line and the pollution conditions [44].

Dr. Michael and Gernot, made a study on converting HVAC transmission lines to HVDC for higher transmission ratings. In their study they showed that one way of avoiding transmission bottlenecks caused by a shortage of suitable right-of-ways is to convert overhead power lines from AC to DC. They have found that this option allows the power transmission rating to be more than tripled and the specific transmission losses to be substantially reduced without having to widen the right-of-way. What is more, such conversions cost only a third to half the cost of building a new DC line. Several examples of 330-kV AC line conversions illustrate these benefits. Finally they showed that existing overhead AC lines can be converted to overhead HVDC lines. For transmission voltages of ± 500kV, such a conversion can increase the AC power level by a factor of more than 2.5 for the same current density. This presumes re-use of the existing conductors and an unchanged tower design. The specific transmission losses are reduced by more than half. On the environmental aspect they showed that roughly estimated cost of conversion would in the best case be equal to only something more than one third of the cost of building a new DC line in compliance with the regulations in force today. The cost will be higher when the existing conductors are so old that they cannot be re-used [3].

K. Pawani and B. Sachidan and , made a study on challenges of HVDC and its prospects. In their study they showed prospects and technical challenges for the future HVDC super grids based on comprehensive overview of different sub-module implementations of multilevel module convertor. Finally they showed an overview of short circuit behavior of the modular multilevel converter, as well as a discussion on the choice between cables or overhead lines [45].

D.M Larruskain and I. Zamora, made a study on transmission and distribution networks comparing AC and DC. They found a need for study as construction of new overhead electric lines are increasing difficulty, thus there is a need to look at alternatives that increases the power transfer capability of the existing right of way. In their study they showed that it is technically feasible to achieve a substantial power upgrading of existing AC lines through their conversion for use with DC, by using the same conductors, tower bodies and foundations, but with changes in tower head and insulation assemblies. They have found that when using existing AC lines to transmit DC power, the lines are already built, so that cost can be saved. The distribution networks cost is lower than the transmission ones, because of the lower voltage level applied to the semiconductor cost. Finally they showed that DC transmission has many more advantages, such as stability, controlled emergency support and no contribution to short circuit level [16].

Lars Weiners in his study of bulk power transmission at extra high voltages made a general comparison of HVDC vs. EHVAC power transmission, the design of the transmission lines and the related investment costs are of great importance. In his study he showed the differences in the design of line insulation and conductor configuration, and its influence on the mechanical loads. For the line insulation, air clearance requirements are more critical with EHVAC due to the nonlinear behavior of the switching overvoltage withstand. Also he showed that the corona effects are more pronounced at AC voltage, therefore, larger conductor bundles are needed at higher system voltages. The mechanical load on the tower is considerably lower with HVDC due to less number of subconductors required to fulfill the corona noise limits. Finally he showed that the high transmission capacity of the HVDC lines, combined with lower requirements on conductor bundles and air clearances at the higher voltage levels, makes the HVDC lines very cost efficient compared to EHVAC lines. The cost advantage is even more pronounced at the highest voltage levels [33].

Baljit Singh and Gagandeep Sharma, made a study on the merits of EHVDC over EHVAC. In their particular system Study, they showed that there is substantial increase in the load ability of the line. The line is loaded to its thermal limit with dc current. No modification is required in the size of conductors, insulator strings and towers structure of the original line. Finally they showed that by converting EHVAC line into EHVDC, we can improve the transmission capacity of the line by the factor of three or more without altering the physical equipments [43].

CHAPTER THREE

BASIC DESIGN AND MAIN COMPONENTS OF HVDC CONVERSION OF HVAC

In general, the cost of converting from AC to HVDC will depend upon the type of AC system involved. This thesis look at the conversion of 230-kV AC lines in Ethiopia and give a good idea of the technical consideration and cost of such conversions. More thorough investigations are needed to determine the exact cost of an actual project.

To obtain a rough estimate of the cost, it is assumed that the tower of the Koka–Hurso double-circuit line is converted to 1000MW HVDC bipoles with a transmission voltage of ± 500 kV. The towers carry conductor type of single ACSR “MALLARD” (DC resistance of conductor = 0.0717 Ω/km), which are to be re-used if possible.

3.1 Major Considerations for Conversion

In general, basic parameters such as power to be transmitted, distance of transmission, voltage levels, temporary and continuous overload, status of the existing network, environmental requirements etc. are required to initiate a design of a HVDC system conversion [16].

The design criteria for conversion of AC transmission lines to DC can be divided into electrical and mechanical aspects, both having considerable effects on the investment and operation costs. The power transmission capacity determines the voltage level and the number of poles. Other aspects are emergency loading capability and reactive power compensation of lines.

The insulation performance is determined by the overvoltage levels, the air clearances, the environmental conditions and the selection of insulators. The requirements on the insulation performance affect mainly the investment costs for the conversion.

The corona performance influences heavily on the design of the conductor bundles and, subsequently, on the mechanical forces on the towers from wind of the conductors. Any constraints on the electric fields at the ground level will, however, primarily influence the costs for the right-of-way.

The mechanical loading, and hence the investment cost of towers reinforcement, insulators and conductors, depends mainly on the status of the existing network, design of the conductor bundles and the climatic conditions.

The major consideration for conversion are as follows;

- Phase conductor arrangement for HVDC bipolar line
- Corona loss
- Surface voltage gradient
- Insulation for 500kV HVDC line
- HVDC Electric field
- Tower design
- Converter station design

3.2 Selection of Phase Conductor of HVDC Bipolar Line

Phase conductor should be designed well to fulfill the following assumptions:

- To provide satisfactory radio interference (RI), audible noise (AN) and corona loss performances;
- To transfer a maximum design power of 1000 MW at +/- 500 kV nominal voltages on bipolar line without neutral conductor;
- To transfer continuously the specified maximum power under N-1 contingency for the pole operation over ground return, tentatively adopted at 1000 MW;
- To provide safety of the line, considering the mechanical loads from wind.

The optimal conductor selection process is complex and the choice of suitable conductor (and sub conductors) depends on the operating voltage, the power to be transmitted and the acceptable voltage drop and losses in the conductor. Thereafter, radio interference, audible noise and corona losses need to be evaluated to find the optimum conductor bundle.

3.1.1 Voltage drop considerations

For a single conductor configuration, maximum power to be transferred with 10% drop restriction voltage, resulted from [25]:

$$P_m = \frac{V^2}{1 \times R_x \times L} \tag{3.1}$$

Where: V = Setting end voltage, pole to ground, in our case 500 kV

R_x = DC resistance of the conductor in Ω / km

L = Distance in km

To transfer 1500 MW per one pole, with maximum 10% drop voltage the pole resistance must be less than:

$$R_{x(m\quad)} = \frac{V^2}{10 \times P_m \times L} = \frac{500^2}{10 \times 1000 \times 352} = 0.071022\Omega$$

or $0.071022 \times 3 = 0.213066\Omega$ per conductor in case of 3 conductors per pole (bundle).

Accordingly, conductors with electrical resistances lower than 0.213066Ω should be selected for the HVDC bipole transmission line. The existing HVAC line carry conductor type of single ACSR “MALLARD” with dc resistance of conductor = 0.0717 Ω/km, which is much lower than 0.213066Ω, There for existing HVAC line conductor will be re-used.

3.1.2 Surface voltage gradient

The interference (RI), audible noise (AN) and corona loss performances depend on the conductor surface voltage gradients of the candidate conductors, i.e. as the surface voltage gradient decreases RI, AN, and corona loss are also deceases.

Taking into account different bundle arrangements the following line geometry is considered as per the existing OH transmission line tower geometry:

- 16 m pole spacing
- 11 m conductor above ground level.

Calculations of Voltage Gradients for HVDC transmission line conductor is given by [28]:

$$D = \frac{S}{\sin(\pi/n)}$$

$$deq = D\left(\frac{n \times d}{D}\right)^{1/n} \quad (3.2)$$

$$F = \left(1 + \left(\frac{2H}{P}\right)^{2}\right)^{\frac{1}{n}}$$

$$T = \frac{4H}{deq}$$

$$G_a = \frac{2V}{n \ln(T/F)} \quad (3.3)$$

$$G_m = G_a\left(1 + \frac{d(n-1)}{D}\right)$$

Where : V = dc pole voltage with respect to ground (kV)

S = Conductor Spacing (m)

H = Mean height of conductor (m)

P = Pole to Pole spacing (m)

n = Number of Conductor

d = Conductor Diameter (mm)

D = Bundle Diameter (m)

deq = Equivalent bundle diameter (m)

Gav = Average Conductor Gradient (kV/cm)

Gmax = Max. Conductor Gradient (kV/cm)

Conductor surface voltage gradients of a pole of 3 and 4 Sub-conductors for the above conductor having a resistance 0.0717 Ω/km are calculated and shown in Table 3.1. As the number of conductor in a bundle increases the performance of the conductor concerning corona loss, RI, TVI decreases since the surface voltage gradient decreases as the number of conductors in a bundle increases. To achieve satisfactory corona effects, multiple conductor bundles instead of single conductors may have to be used [24].

It is common practice for EHV lines to use more than one conductor per phase, a practice called bundling. Bundling reduces the electric field strength at the conductor surfaces, which in turn reduces or eliminates corona and its results: undesirable power loss, communications interference, and audible noise. Bundling also reduces the series reactance of the line by increasing the Geometric Mean Radius (GMR) of the bundle [17].

Table 3.1: Conductor surface voltage gradients of a pole of 3 and 4 Sub-conductors for +/- 500 KV line.

Codename ACSR	Bundle spacing, S(m)	Diameter (mm)	Conductor in bundle	
			3	4
Mallard	0.455	28.96	27.34	22.12

When the AC system overhead lines are to be re-used, the most effective way to reduce the surface voltage gradient of the DC lines is to increase the number of sub-conductors and place the conductors further apart. In the case of triple bundles, the combination of these two measures leads to an acceptable maximum electric field of 27.34 kV/cm for a DC voltage of 500 kV [3]. Triple bundles allow full re-use of the existing overhead lines.

When quadruple bundles are used, the surface voltage gradient can be reduced to 22.12 kV/cm. This design is an option when the power to be transmitted is higher than about 2,300 MW. However it requires 25% more conductor materials. The surface voltage gradient would rise to 26.5 kV/cm, close to the value for triple bundles and a DC voltage of ±500 kV.

3.1.3 Maximum Power to be Transferred

The assumptions for checking the conductors with respect to their thermal behavior (steady state) are [7]:

- Highest ambient temperature 41°C
- Highest conductor temperature 85°C
- Maximum solar radiation 1100 W/m2
- Wind velocity 0.3 m/s
- Altitude 2000 m

The carrying capacities of 3-bundles in case of 0.3 m/s wind velocity are shown below.

Table 3.2: Pole carrying capacity, 0.3 m/s wind velocity(see the thermal current carrying capacity of the conductors in Annex 3)

Conductor type ACSR:	**Conductor carrying capacity (A)**	**Pole carrying capacity (MW)** 3 conductors in bundle
Mallard	**887**	**1330**

For the bipolar line the current transmitted by each pole becomes (500 M /500k , i.e. 1k and the current of each sub conductors will be 333.33A. During one pole outage, the current ratings of each of the remaining conductor reaches 666.66A, so the conductors type in Table 3.2 can satisfy the N-1 contingency criteria since the calculated thermal power rating of the conductors is above 1000 MW.

3.3 Insulation for HVDC Line

The requirements on HVDC insulators are higher than for the AC case when compared on the basis of rms voltage level. This is due to the attraction of pollution particles, which is an effect of the DC electric field surrounding the insulators.

Composite insulators are becoming an attractive alternative for HVDC, even in areas with a low pollution level. Present service experience indicates that composite insulators provide a viable alternative for both HVAC and HVDC lines.

Examples of actual insulator lengths used on operating lines and test lines for HVAC and HVDC are shown in Figure 3.1.

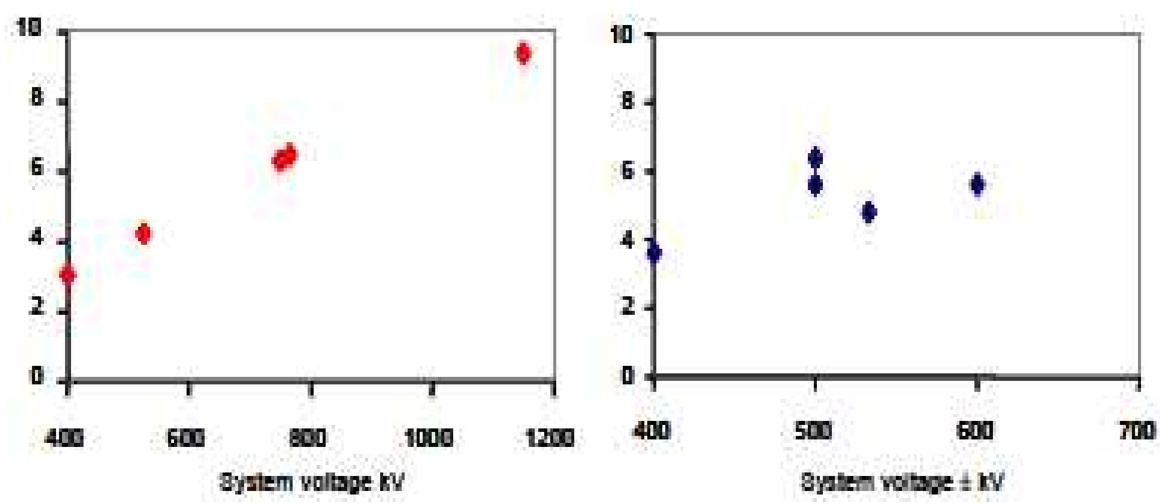


Figure 3.1: Actual insulator lengths in meter at different system voltages for HVAC and HVDC [33]

3.2.1 Over-Voltages

The four ways in which over-voltages can occur on a transmission system due to the lightning are [25]:

- direct strokes to a conductor (shielding failure)
- rise in potential of tower steelwork (back flashover)
- electromagnetic induction
- electrostatic induction.

For the HVDC line considered in this thesis the insulator sets should fulfill the requirements for ± 500kV HVDC systems, i.e. a Basic Insulation Level BIL - 1300 kV (lightning impulse withstand voltage) given in Appendix 4. The polymer composite insulator of the Koka-Hurso HVAC line has a minimum dry lightning withstand voltage of 1410kV [31]. This shows that the existing insulator sets can be reused for the HVDC line in this thesis with increased in insulation length.

3.2.1 Creepage Distance

The creepage is defined as shortest distance on the surface of an insulating material between two conductive elements. Figure 3.2 shows creepage distance for an insulating material. The long rod polymeric composite insulators of the Koka-Hurso HVAC OH has a specific creepage distance of 3.1 kV/cm [31]. This figure gives ample reserve for the ±500kV bipolar HVDC line in this thesis; as the ±600kV Itaipú bipole line in Brazil has insulators designed with a specific creepage distanceof 2.7 cm/kV [3].

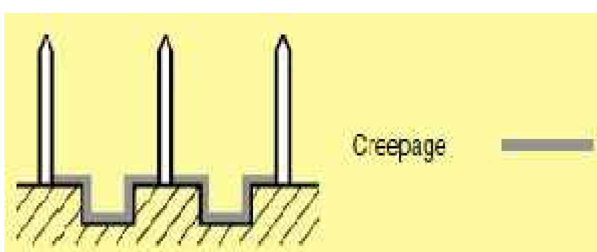


Figure 3.2: Creepage distance [33]

3.2.2 Calculation of Insulation Length

For a given insulation length, the ratio of continuous working withstand voltage is as indicated below;

$$k = \frac{V_{d\ (w)}}{V_a} \tag{3.4}$$

Were : $V_{d\ (w)}$ = DC withstand voltage and V_a = AC withstand voltage

Various experiments on outdoor DC overhead-line insulators have demonstrated that due to unfavorable effects there is some precipitation of pollution on one end of the insulators and a safe factor under such conditions is k=1. However if an overhead line is passing through a reasonably clean area, k may be as high as √2,corresponding to the peak value of rms alternating voltage.

A line has to be insulated for over-voltages expected during faults, switching operations, etc. AC transmission lines are normally insulated against over-voltages of more than 4 times the normal rms voltage. This insulation requirement can be met by insulation corresponding to an AC voltage of2.5 to 3 times the normal rated voltage [16].

$$k_1 = \frac{IL_a}{E_p} = 2.5 \tag{3.5}$$

Where : IL_a = AC insulation level and E_p = rated AC voltage

On the other hand with suitable convertor control the corresponding HVDC transmission ratio is shown below;

$$k_2 = \frac{IL_d}{V_d} = 1.7 \tag{3.6}$$

Where : IL_d = DC insulation level and V_d = rated DC voltage

Thus for a DC pole to earth voltage V_d and AC phase toearth voltage $E_p$the relations becomes,

$$In \qquad r = \frac{L_{ac}}{L_d} \tag{3.7}$$

Were : L_a = insulation length required for each AC phase and

L_d = insulation length required for each DC pole

and substituting (3.4), (3.5) and (3.6) equations, we obtain equation (3.8) for the insulation ratio.

$$In \qquad - r = \left(k \times \frac{k_1}{k_2}\right)\frac{E_p}{V_d} \tag{3.8}$$

Therefore, calculation of insulation length for the HVDC OH line;

$$In \qquad r = \left(1 \times \frac{2.5}{1.7}\right)\frac{230/\sqrt{3}}{500} = 0.391$$

$$L_d = \frac{L_a}{In \qquad r}$$

$$L_d = \frac{2.6}{0.391} = 6.6m$$

The line insulation length is approximately the same for each type of DC tower. The figure chosen (i.e 6.6m) for the specific creepage distance is the maximum value stipulated for a moderate level of pollution.

3.2.3 Air Clearance Requirements

The insulation performance of transmission lines depends on several factors which are somewhat different for HVAC and HVDC. The air clearance requirement is a very important factor for the mechanical design of the tower.

With HVAC, the switching overvoltage level is the decisive parameter. The diagram shows typical required air clearances at different system voltages for a range of switching overvoltage levels between 1.8 and 2.6pu of the phase-to-ground peak voltage. The required distance shows an exponential behavior with respect to the system voltage.

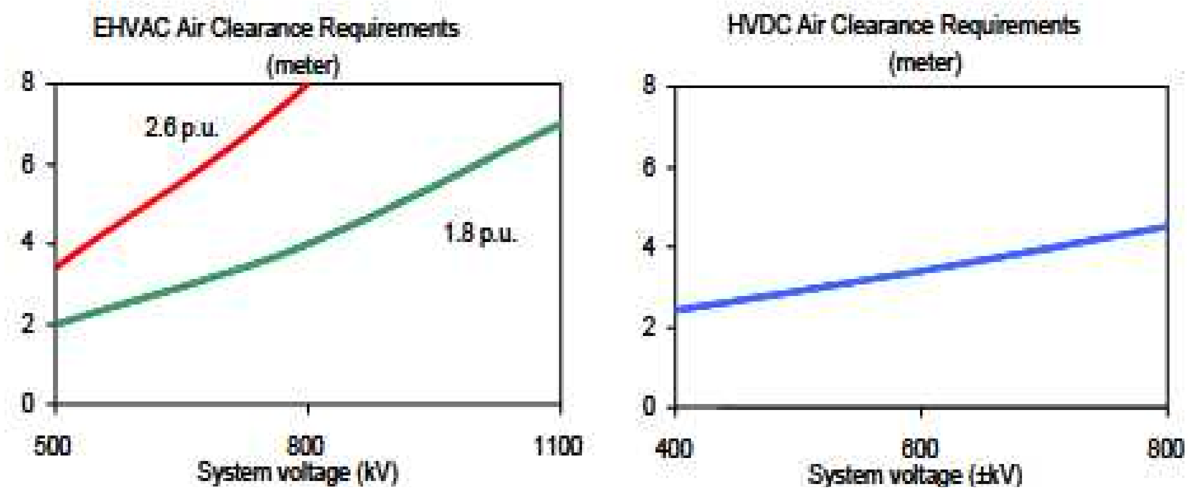


Figure 3.3: Air Clearance requirements for EHVAC and HVDC for different system voltages[33].

With HVDC, the switching over-voltages are lower, in the range 1.6 to 1.8pu, and the air clearance is often determined by the required lightning performance of the line. Typical clearances are shown in Figure 3.3 for different system voltages.

When comparing HVDC and EHVAC line with regard to air clearances, it is clearly seen that the requirement increases rapidly with the system voltage level for the HVAC lines. This is due to the close connection between the system voltage and the switching overvoltage levels. With HVDC, on the other hand, the required air clearances at higher system voltages are considerably smaller than with HVAC.

According to [3] and as shown in Figure 3.3 for the ±500kV bipolar HVDC line an air clearance of at least 2.2m is required. The existing 230kV Koka-Hurso HVAC line have an air clearance of 2.6m. The air clearance given on the existing HVAC line is ample for use in HVDC operation.

3.4 HVDC Electric Field

The direct current field has its particularities which make it different from the alternative current field. This field is a stationary one and its parameters are constant in time, but they could be variable in space. Since the different phenomena result in different field effects, these fields are defined as follows:

- The “electrostatic field” is the field surrounding an energized conductor.
- The “space charge field” is peculiar to DC conductors energized to voltages above the level required for the ionization of air. Some of the ions formed in the region of conductor migrate to earth and in effect reduce the resistance of free space. As result, the gradient at the ground plane is increased.
- “Electric field” refers to the total effect (electrostatic and space charge)The space charge has various effects on persons or objects near a direct current line, from which three conditions where described below:

3.3.1 Possible Situations Involving Persons and Objects Near a DC Transmission Line

The most common situation for person who work under or adjacent to HVDC lines for a standing person the resistance-to-ground given by the type and condition of his footwear vary from 60 to 400 MΏ (for common commercial footwear). The common practice shows that a potential of 800 V could be attained for a person walking beneath the500 kV HVDC line.

The “awareness” situation (movement of fine body hairs due to the field) could appear when the shoes have sufficient insulation to attain a potential of 12V to ground.

Nevertheless, the common practice shows that a person would not be aware of the field under this situation.

3.3.2 Calculation of Direct Current Field

The electric field from a DC line is a random variable. In warm and humidor foul weather a charge sheath forms around the conductor which decreases the electric field near the conductor and therefore increases the ground level field. A DC electric field is less bothersome to work in than an AC electric field of the same level. The magnetic field from the DC line is constant(except perhaps for a small ripple component), and is usually much smaller than the earth’s magnetic field due to the fact, that existing limits to magnetic field exposure are much higher than the exposure that would be encountered under an HVDC transmission line[33]. As result there is no controversy about health effects from the DC line magnetic field, and is usually not calculated.

The maximum direct field above soil was in accordance with Transmission Line Reference Book – HVDC to +/- 600 kV, published by Electric Power Research Institute, Palo Alto, USA, [9].

The electrical field calculated for different values of the distance to ground of the conductors is shown in Figure 3.4. This will enable the selection of the most convenient distance to ground in the respect of tower height (weight) versus the line corridor spacing.

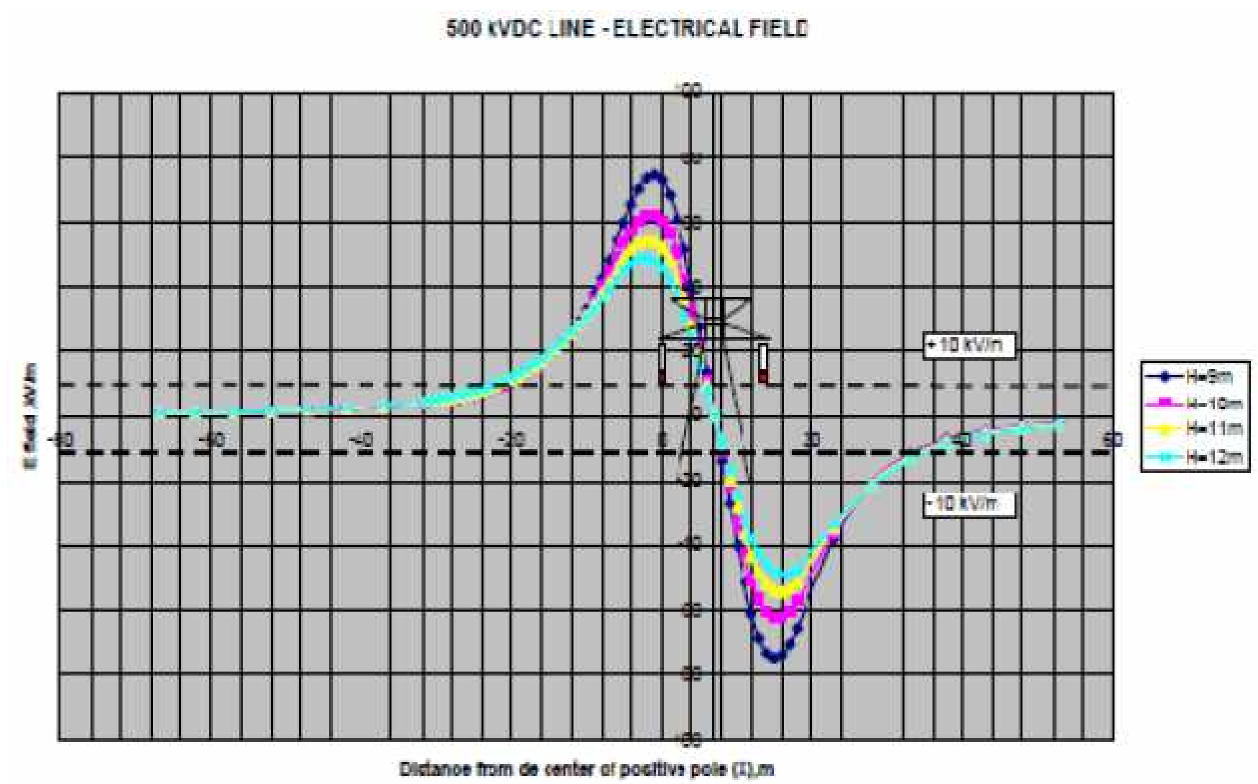


Figure 3.4: HVDC lines - Electric field distribution [25].

Form Figure 3.4 it can be observed that the value of the field of 10 kV/m, as electric field accepted in the line corridor, recommended by EPRI, is reached at about20 m from the center line, for a conductor height above the soil level of11 m which will be the ground clearance of HVDC line. In this respect the value of 40 m line corridor [31] of the existing transmission line is fulfilled.

3.5 Tower Design

The conversion covers changes to the conductor arrangement. The existing Koka-Hurso double circuit 230 kV, 3-phase OH line carry conductor type of single ACSR “MALLARD” conductor on self supporting, tapered configuration, vertical formation galvanized steel lattice towers with each leg having a separate footings of pad and chimney concrete type, from existing Koka substation to Hurso substation. The converted HVDC OH line will have a double pole configuration with + pole and – pole suspended on the upper cross-arms at same level. Re-use of the existing conductors has the advantage that the load that the weight of the conductors exerts on the towers does not change.

In order to utilize the cross-arms of the towers of the Koka-Hurso double-circuit line for a DC voltage of ±500 kV, the distance between the conductors and the tower structures has to be fixed ,The minimum clearance between the conductors and the tower cross-arm is 6.1 m. These figure lie well above the minimum clearance recommended in [9],even for a DC voltage of 600 kV.

The higher conductor voltage and longer insulator assemblies of the DC lines calls for a larger line-to-ground clearance. The total height of the existing tower is 47.25m. This figure much higher than the total height recommended in [25], for DC voltage of 500KV. Therefore the OH line-to-ground clearance will be raised from 7m to 11m without raising the tower. The tower configuration is shown in Figure 3.5.

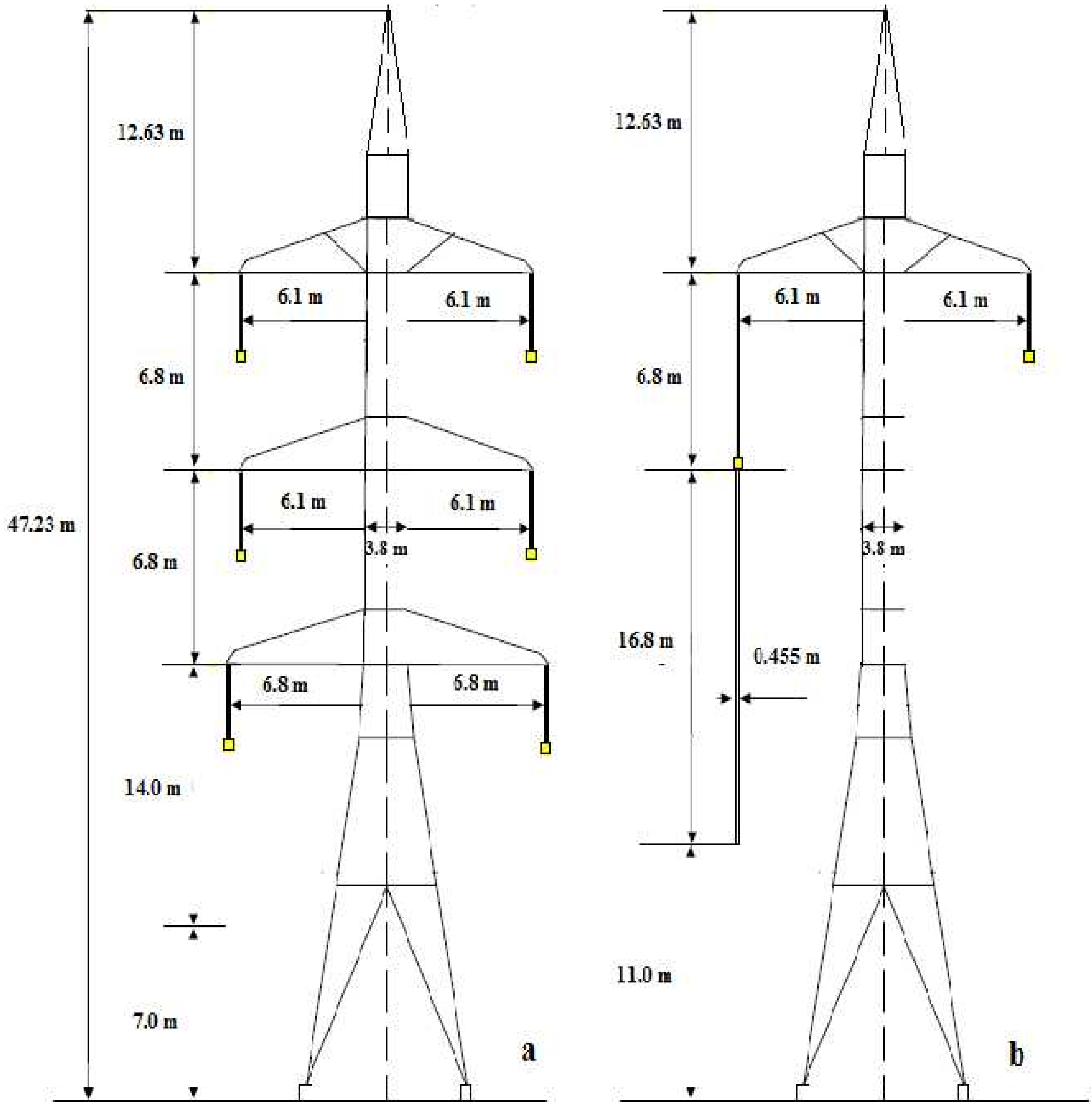


Figure 3.5: Tower configuration of the Koka-Hurso line before and after conversion

a. Before: 230kV double circuit HVAC line with sing
b. After: ±500kV HVDC double bipole with triple bundles

3.6 LCC Converter Design

To fulfill N-1 contingency criteria, the converters should have a continuous and a short term overloading capability in the range of 10% to 30% [17].

3.6.1 The Total reactive Power Consumed by the Inverter

The total power transfer capacity of the converted +/-500KV OH line is 1000MW and each pole has been designed to have capacity of 500MW. Each converter consumes a reactive power that increases with increasing power. With normally acceptable rectifier ignition delay angle (alpha) of 15 to 25 degrees and inverter extinction advance angle (gamma) of 15 to 25 degrees a converter consumes reactive power which is 50 % to 60 % of the real power transmitted [1]. Shunt capacitor banks is used to provide the reactive power needed by the converters. Part of the reactive power required is provided by the capacitor associated with the ac filters.

For the project under study, during faulty conditions the reactive power consumed by the converters is 600 MVAR which is 60% of 1000 MW power (rated power of the bipolar line) and this reactive power supply will be installed at Koka and Hurso bus bars partly in the form of shunt capacitor banks and the remaining in the form of shunt ac filters.

3.6.2 Commutation Reactance of the Rectifier and Inverter

Commutation reactance is the reactance due to commutation overlap and it accounts for the voltage drop in the converters. Because of the inductance Lc present at the ac-terminals the phase currents cannot change instantaneously. Therefore, the dc current requires a finite time to transfer from one phase to another. This phenomenon is called commutation overlap. In HVDC systems the commutation reactance is assumed to be the leakage reactance of the converter Transformer [4].

The rectifier, however, has a minimum α limit of about 5° to ensure adequate voltage across the valve before firing. In the case of thyristors, the positive voltage appearing across each thyristor before firing is used to charge the supply circuit providing the firing pulse energy to the thyristor. Therefore, firing cannot occur earlier than about $\alpha = 5^{o}$. Consequently, the rectifier normally operates at a value of α within the range of 15^{o} *to* 25^{o} so as to leave some room for rectifier voltage to control dc power flow [3]. Since a too small value of the extinction angle γ will make the converter too vulnerable for commutation failures, it should never decrease below a certain minimum value γ_{m} ($\approx 17^{o}$) [13]; values between 15^{o} *to* 25^{o} are typically used [15]. In normal operation, the overlap angle is less than 60^{o} ; typically full-load values are in the range of 15^{o} *to* 25^{o} [3]. The alpha-min-in-inverter mode characteristic is typically about 100-110 degrees, and is required to limit any excursions (even transiently) of the inverter into the rectifier mode of operation. Furthermore, the value of $100^{o} - 100^{o}$ ensures a minimum dc voltage at the inverter during a fast start-up of the dc link with $I_d = 0$.

Rectifier commutating reactance

The DC voltage output depends on the type of rectifier. The no load direct voltage, V_d can be obtained by [3]

$$V_d = V_d \left(\frac{c \quad \alpha + c \quad \delta}{2}\right) \tag{3.9}$$

$$\delta = \alpha + \mu$$

For $\alpha = 15^{o}$ and $\mu = 15^{o}$

$$500 = V_d \left(\frac{\cos(15) + \cos(30)}{2}\right)$$

$$V_d = 545.866\ K$$

$$V_d = V_d \ c \ \ \alpha - \Delta V_d \tag{3.10}$$

$$\Delta V_d = V_d \ c \ \ \alpha - V_d = 27.266\ K$$

$$\Delta V_d = B R_c \ I_d \tag{3.11}$$

The line current of the HVDC line I_d can be obtained from the following equation[30];

$$I_d = \frac{D \qquad P_i}{S\ ne \qquad d\ V} \tag{3.12}$$

$$I_d = \frac{500M}{500k} = 1k$$

A 12-pulse bridge circuit comprises two 6-pulse bridges. Hence $B = 2$

$$R_C = \frac{\Delta V_d}{BI_d}$$

$$= \frac{27.266K}{2 \times 1K} = 13.633\Omega$$

$$X_c = \frac{\pi R_C}{3} \tag{3.13}$$

$$= \frac{\pi \times 13.633}{3} = 14.276\ \Omega/pha$$

Inverter commutating reactance

$$V_d = V_d \quad \frac{(c \quad \gamma + c \quad (\gamma+\mu))}{2} \tag{3.14}$$

For $\gamma = 17^{\circ}$ and $\mu = 15^{\circ}$ (to have a small commutating voltage drop)

$$500 = V_d \quad \frac{(c \quad (17) + c \quad (32))}{2}$$

$$V_d = 554.215\ K$$

$$V_d = V_d \quad c \quad \gamma - \Delta V_d \tag{3.15}$$

$$\Delta V_d = V_d \quad c \quad \gamma - V_d = 29.998\ K$$

$$\Delta V_d = BR_C\ I_d \tag{3.16}$$

$$\Delta R_C = \frac{\Delta V_{di}}{BI_d}$$

$$= \frac{29.998K}{2 \times 1K} = 14.999\Omega$$

$$X_c = \frac{\pi R_C}{3} \tag{3.17}$$

$$= \frac{\pi \times 14.999}{3} = 15.706\ \Omega/pha$$

The bipolar line has a capacity of 1000 MW so that each pole is rated to 500 MW. Each pole is composed of 12 Pulse converters on each side of the transmission line. The 12-pulse converters are composed of two 6-pulse converters connected in series having each a capacity of 250 MW. Pole to ground voltage rating of the 12-pulse converter is 500 kV so that the 6-pulse converters are rated to 250 kV and 1 kA (i.e. 250MW/250kV).The values listed in Table 3.7 are for 6 pulse converter. The HVDC system intended to carry 1000 MW power employs 8 such kind of converters for the bipolar line.

Table 3.3: Summary of six pulse bridges component values.

Parameters	Rated values
Alpha, α	15^0
Extinction angle, γ	17^0
Commutation angle, μ	15^0
Commutation reactance, X_C (Rectifier)	14.276Ω
Commutation reactance, X_C (Inverter)	15.706Ω
Rated voltage (kV)	250kV
Rated current (kA)	1kA
Rated power (MW)	250MW

3.7 Converter Transformer Design

All HVDC systems need transformers, but how these are arranged can vary quite substantially between projects depending on the specification of the project. The HVDC transformer configuration of an individual project is unique to the project and determined by the sheer size of transformers in relation to the limitations in the transport infrastructure between the place of manufacture and the HVDC converter station.

The main driver behind size of the converter transformer is the rated power, which is a direct consequence of HVDC-transmission power capability and the transformer topology [13].

The converter transformers are mostly of conventional design. The standard 12-pulse converter configuration can be obtained with any of the following arrangements [13, 25]:

- Six single phase two-winding transformers;
- Three single phase three-winding transformers;
- Two three-phase two-winding transformers.

Selection of the converter transformer bank is primarily dependent on the maximum weight that can be transported to the site and the spare part policy. If the selected route has a limitation of 200 tones, only single-phase two-winding transformers are suitable which have a transport weight of about 170 tones for a 500 MW pole [25]

According to Figure 3.3, The RMS value of the transformer secondary current (total and not just the fundamental frequency component) I_{Tl} is given by

$$I_{Tl}^2 = \frac{1}{T}\int_0^T i^2(t)d \tag{3.18}$$

$$I_{Tl}^2 = \frac{1}{\pi}\int_{-\pi/2}^{\pi/2} i^2(t)d$$

$$I_{Tl}^2 = \frac{1}{\pi}\int_{-\pi/3}^{\pi/3} i^2(t)d = \frac{2}{3}i_d^2$$

$$I_{Tl} = \sqrt{\frac{2}{3}}\,i_d \tag{3.19}$$

The RMS value of the line-to-neutral transformer secondary voltages is given

$$E_L \ \frac{\pi}{3\sqrt{6}}V_d \tag{3.20}$$

Transformer **volt-ampere rating** is given by 3-phase rating [1]

$$M \quad r \quad = 3E_L \; I_{T} \tag{3.21}$$

$$M \quad r \quad = 3\left[\frac{\pi}{3\sqrt{6}}\right] V_d \; \sqrt{\frac{2}{3}} I_d$$

$$M \quad r \quad = \frac{\pi}{3} V_d \; I_d$$

where : V_d =ideal no-load direct voltage

I_d =rated direct current

3.7.1 Rectifier Side Ratings of Converter Transformer

The MVA rating of the rectifier (6-pulse converter) side converter transformer is given by [1].

$$M \quad r \quad = \frac{\pi}{3} \times V_d \quad \times I_d$$

I_d is *1KA,* $V_d \quad = 272.933\,K$ (previously calculated)

$$M \quad r \quad = 285M$$

The primary side voltage is known. And the secondary voltage is given by

$$V_d \quad = \frac{3\sqrt{2}}{\pi} E_L$$

$$E_L \; (S \qquad) = 202.101K$$

The primary line to line voltage is $230k$ at the Koka bus bar. So the transformer is rated at $230/202.101\,k$ (i.e. step-down transformer).And the transformer turns ratio T becomes $202.101/230\,k$, which is 0.8.

3.7.2 Inverter Side Ratings of Converter Transformer

The MVA rating of the inverter (6-Pulse converters) side converter transformer for I_d = $1k$ and $V_d \quad = 277.107k$ becomes:

$M \quad _{r} \quad = 290.185M$

The secondary side voltage is known. And the primary voltage is given by

$$V_d = \frac{3\sqrt{2}}{\pi} E_L$$

$$E_L \ (p \qquad) = 205.192k$$

The secondary line to line voltage is 230 kV at the Hurso side of the transmission line. So the transformer should be rated at $205.192/230\,k$ (i.e. step-up transformer).And the transformer turns ratio T become $230/205.192\,k$ which is 1.1.

Since eight 6-pulse converters are needed for the conversion process at the rectifier and inverter sides of the bipolar transmission line, A total of twenty-four 100MVA single phase two-winding transformers are needed for the bipolar line. Each pole have six single phase two-winding transformers at Koka side of the transmission line and six single phase two-winding transformers at Hurso side of the transmission line.

3.8 AC Side Harmonic Filters Design

The use of two bridges (either in parallel or series on the dc side), one with a star–star and the other with delta–star or star–delta transformer (i.e. with a 30^o phase shift between them), will inject only harmonic currents of orders $n = 12k \pm 1$ into the ac system. Figure 3.6 illustrates the Harmonic spectrum of the double bridge 12-pulse configuration.

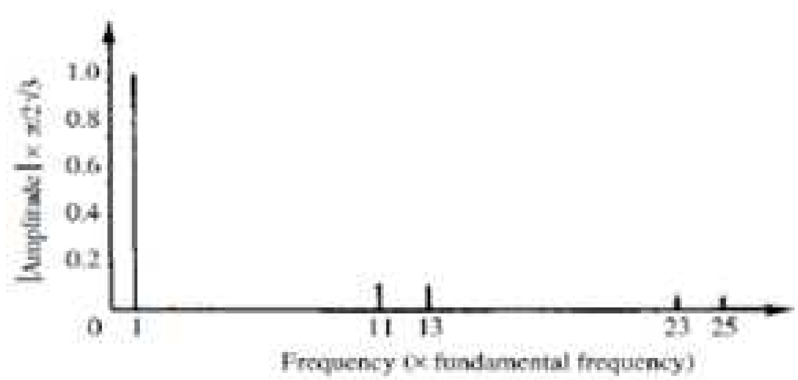


Figure 3.6: Frequency-domain representation of 12-pulse operation [36]

A typical filter system for 12 pulse converter terminal is shown in Figure 3.7. The filter impedance is minimum at 11^{th} and 12^{th} harmonics resulting from the two series resonance tuned branches. The high pass filter maintains low impedance for higher harmonic frequency. This filter is used to eliminate, at the same time, a range of harmonic frequencies rather than implementing a single tuned filter for each high order harmonics.

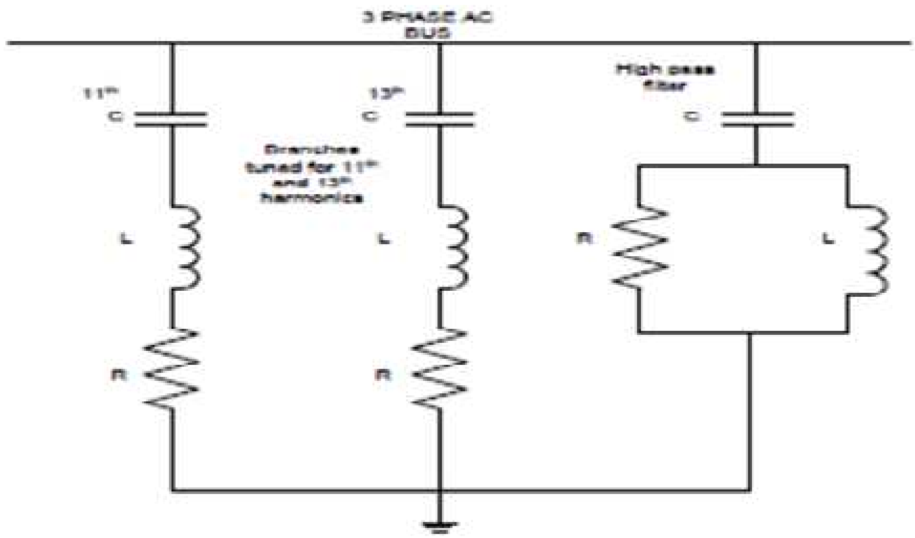


Figure 3.7: Typical filter system configurations [36].

3.8.1 Design of Tuned Filters

A single tuned filter is a series RLC circuit tuned to the frequency of one harmonic (generally a lower characteristic harmonic). Its impedance is given by

$$Z_1 = R + j\left[\omega \quad - \frac{1}{\omega}\right] \tag{3.22}$$

Which at the resonant frequency (fn) reduces to R. There are two basic design parameters to be considered prior to the selection of R, L and C. These are

(a) The quality factor (Q) , and

(b) The relative frequency deviation (δ)

Quality factor (Q):

The quality of a filter (Q) determines the sharpness of tuning and in this respect filters may be either of a high or a low Q type. The former is sharply tuned to one of the lower harmonic frequencies (e.g. the fifth) and a typical value is between 30 and 60. The low Q filter, typically in the region of $0.5 - 5$, has low impedance over a wide range of frequency. When used to eliminate the higher-order harmonics (e.g. 17^{th} up wards) it is also referred to as a high-pass filter [36].

The relative frequency deviation (δ): The extent of filter detuning from the nominal tuned frequency is represented by a factor δ. This factor includes various effects:

i. variations in the fundamental (supply) frequency;
ii. variations in the filter capacitance and inductance caused by ageing and temperature; and
iii. Initial off-tuning caused by manufacturing tolerances and finite size of tuning steps.

For a capacitor temperature coefficient 0.05% per degree Celsius, the inductor temperature coefficient 0.01% per degree Celsius and ambient temperature $40^{\circ}C$ causes the same detuning as a change of system frequency of 1% [6, 38]. Therefore δ is often expressed as

$$\delta = \frac{\Delta f}{f_n} + \frac{1}{2}\left[\frac{\Delta L}{L_n} - \frac{\Delta C}{C_n}\right] \tag{3.23}$$

$$\delta = \frac{1}{100}[1 + 0.5(0.05 \times 40 + 0.01 \times 40)]$$

$$\delta = 0.022$$

Let the ac system impedance be of any magnitude but its phase angle restricted to □ $< 75^{\circ}$ at any frequency. The optimum Q (giving the lowest harmonic voltage) is then obtained from equation stated below, i.e. □ $= \pm 70^{\circ}$ electrical degree for $11 \leq n \leq 15$ according to CIGRÉ WG 14.30 [37].

$$Q = \frac{c\ \ (\square/2)}{2\delta} \qquad (3.24)$$

$$Q = \frac{c\ \ (\square) + 1}{2\delta\, s\ \ (\square)}$$

So,

$$Q = \frac{c\ \ (70) + 1}{2 \times 0.022 \times s\ \ (70)}$$

$$Q = 32$$

The reactance of inductor or capacitor in ohms at the tuned frequency is

$$X_o = \omega_n L = \frac{1}{\omega_n C} = \sqrt{\frac{L}{C}} \qquad (3.25)$$

$$C = \frac{1}{\omega_n X_o} = \frac{1}{\omega_n R} \qquad (3.26)$$

$$L = \frac{X_o}{\omega_n} = \frac{R}{\omega_n} \qquad (3.27)$$

$$Q = \frac{X_o}{R} \qquad (3.28)$$

Where,

$$\omega_n = \frac{1}{\sqrt{L}} \qquad (3.29)$$

3.8.2 Design of Damped Filters

A damped filter provides low impedance for a wide spectrum of harmonics without the need for subdivision of parallel branches, which increases switching and maintenance problems. The behavior of damped filters has been described with the help of two parameters [38].

$$f_o = \frac{1}{2\pi} \qquad (3.30)$$

$$m = \frac{L}{R^2 C} \tag{3.31}$$

Where : f_u = 17*(i.e.* 17^{th}*order harmonic) times fundamental frequency* (05H)

f_u = 17 × 50H

Typical values of m are between 0.5 and 2 [38].

The total filter capacitance is now given by [37]

$$C = \frac{Q^f}{2\pi \ V^2}\left(1 - \frac{1}{n^2}\right) \tag{3.32}$$

Where: f = is the fundamenta frequency in Hz

V = is the bus voltage in kV where the filters are going to connect.

n = Harmonic order n

A typical converter will consume reactive power between its 50%-60% of its MW rating [1].The demanded reactive power of an HVDC converter becomes600MVAR(60% of 1000MW) According to [1] about 30% would be in filter form divided among the 11th, 13thand high pass filters.

Therefore,

$$Q^f = 0.3 \times 600M$$

(3.33)

$$Q^f = 180M$$

And the remaining 420 MVAR will be installed as Shunt Capacitor on the same bus bar at Koka and Hurso bus bar.

3.8.3 Harmonic Filters at the Koka and Hurso Bus Bar

Harmonic filters are used to keep the harmonic contribution of large nonlinear plant components such as HVDC converters under control, normally by the connection of passive filters. As the two bus bars have similar voltage rating of 230kV they will have the same harmonic filter. The components of a single tuned filters is evaluated below.

$$C_1 = \frac{Q_1^f}{2\pi \quad V^2}\left(1 - \frac{1}{n^2}\right)$$

$$C_1 = \frac{60}{2\pi \times 50 \times 230^2}\left(1 - \frac{1}{11^2}\right)$$

$$C_1 = 3.5804 \times 10^{-6} F = 3.5804\mu$$

$$L_1 = \frac{1}{(2\pi \quad)^2 C_1}$$

$$L_1 = \frac{1}{(2\pi \times 50 \times 11)^2 3.5804 \times 10^{-6}}$$

$$L_1 = 2.3363 \times 10^{-2} H$$

$$R_1 = \frac{2\pi \quad L_1}{Q}$$

$$R_1 = \frac{2\pi \times 50 \times 11 \times 2.3363 \times 10^{-2}}{32}$$

$$R_1 = 2.5230 \times 10^{-4}\Omega$$

The same procedure for the 13th harmonic filter

$$C_1 = 3.5889\mu$$

$$L_1 = 1.6705 \times 10^{-2} H$$

$$R_1 = 2.1320 \times 10^{-4}\Omega$$

The damped arm components are found from equations (3.11) and (3.12). By choosing $m = 1$and $f_o = 17 \times 50 = 850H$ Since C has been fixed above (i.e3.5804μ), the resulting values of inductor (L) and resistor (R) are $0.009791H$and 52.296Ω, respectively.

3.9 Smoothing Reactor Design

Smoothing reactor main functions are as follows [10];

- Prevention of intermittent current
- Limitation of the DC fault currents
- Prevention of resonance in the DC circuit
- Reducing harmonic currents including limitation of telephone interference

Prevention of intermittent current

The intermittent current due to the current ripple can cause high over-volt-ages in the transformer and the smoothing reactor. The smoothing reactor is used to prevent the current interruption at minimum load.

Limitation of the DC fault current

The smoothing reactor can reduce the fault current and its rate of rise for commutation failures and DC line faults. This is of primary importance if a long DC cable is used for the transmission. For an overhead line transmission, the current stress in valves is lower than the stress which will occur during valve short circuit.

Prevention of resonance in the DC circuit

The smoothing reactor is selected to avoid resonance in the DC circuit at low order harmonic frequencies like100 or 150 Hz. This is important to avoid the amplification

effect for harmonics originally from the AC system, like negative sequence and transformer saturation.

Reducing harmonic currents including limitation of telephone interference

Limitation of interference coming from the DC overhead line is an essential function of the DC filter circuits. However, the smoothing reactor also plays an important role to reduce harmonic currents acting as a series impedance.

3.8.1 Sizing of the Smoothing Reactor

The transmission capability of an HVDC link is defined by its rated dc system voltage and the continuous dc current. It is a general practice to require about *20%* over current capability above rated current for limited duration (1-2hours) [1]. The smoothing reactor must be designed to meet these loading requirements.

One criteria used on the choice of the optimal size of a dc smoothing reactor based on the acceptable performance of the reactor, is the so-called S_i − factor as per [27]

$$S_i = \frac{V_d}{L \times I_d} \tag{3.34}$$

Where : V_d = The rated dc voltage of a smoothing reactor is the maximum continuous dc voltage, pole- to- ground, that will be experienced by the smoothing reactor in kV.

I_d = The rated dc current of a smoothing reactor is the maximum continuous dc current at rated conditions in kA.

L = dc side inductance in mH

$L = 3.5L_T + L_d$,

Where : L_T = converter transformer inductance

L_d = Smoothing reactor inductance

The value of S_i varies between $0.23ms^{-1}$ to $0.95ms^{-1}$[27]. So, the size of the smoothing reactor, L_d. For $V_d = 500k$, $I_d = 1k$, and L_T = 14mH is

For S_i = $0.23ms^{-1}$

$$0.23ms^{-1} = \frac{500k}{(3.5 \times L_T + L_d)\left(1k \quad + (0.2 \times 1k \quad)\right)}$$

L_d = *513.59mH*

For S_i = $0.95ms^{-1}$

$$0.95ms^{-1} = \frac{500k}{(3.5 \times L_T + L_d)\left(1k \quad + (0.2 \times 1k \quad)\right)}$$

L_d = *125.31mH*

Accordingly a standard inductance value of 130mH is selected. While the current and voltage rating of the smoothing reactor can be specified based on the data of the DC circuit, the inductance is the determining factor in sizing the reactor. Taking all design aspects into account, the size of smoothing reactors is often selected in the range of 100 to 300mH for long distance DC links and 30 to 80mH for back-to-back stations [10].

3.8.2 Arrangement of the Smoothing Reactor

In an HVDC long-distance transmission system, it seems quite logical that the smoothing reactor will be connected in series with the DC line of the station pole. This is the normal arrangement. However in back-to-back schemes, the smoothing reactor can also be connected to the low-voltage terminal.

3.10 HVDC Controllers Designs

An HVDC transmission system is highly controllable. Its effective use depends on appropriate utilization of this controllability to ensure desired performance of the power system. With the objectives of providing efficient and stable operation and maximizing flexibility of power control without compromising the safety of equipment, various levels of control are used in a hierarchical manner [1].

3.10.1 Controls Algorithm

There are 3 major configurations of converter controls [24].

Control configuration 1:

- Rectifier in dc current control
- Inverter in gamma control

Control configuration 2:

- Rectifier in dc current control
- Inverter in dc voltage control

Control configuration 3:

- Rectifier in dc voltage control
- Inverter in dc current control

The control configuration 1 was used for historically first HVDC projects. The second configuration is typical for modern HVDC transmissions with overhead dc lines or comparatively short cables. For HVDCs with a long cable the control configuration 3 is very likely to be implemented. Control configuration 2 is used for this thesis.

Accordingly to the selected control configuration, some parameters of controls must be adjusted as it is shown below.

Converter controls

Controls of both converters can be simulated based on the same structure, which includes 3 controllers, namely:

- DC current controller
- DC voltage controller
- Gamma controller.

The basic converter control configuration is shown in Figure 3.7.

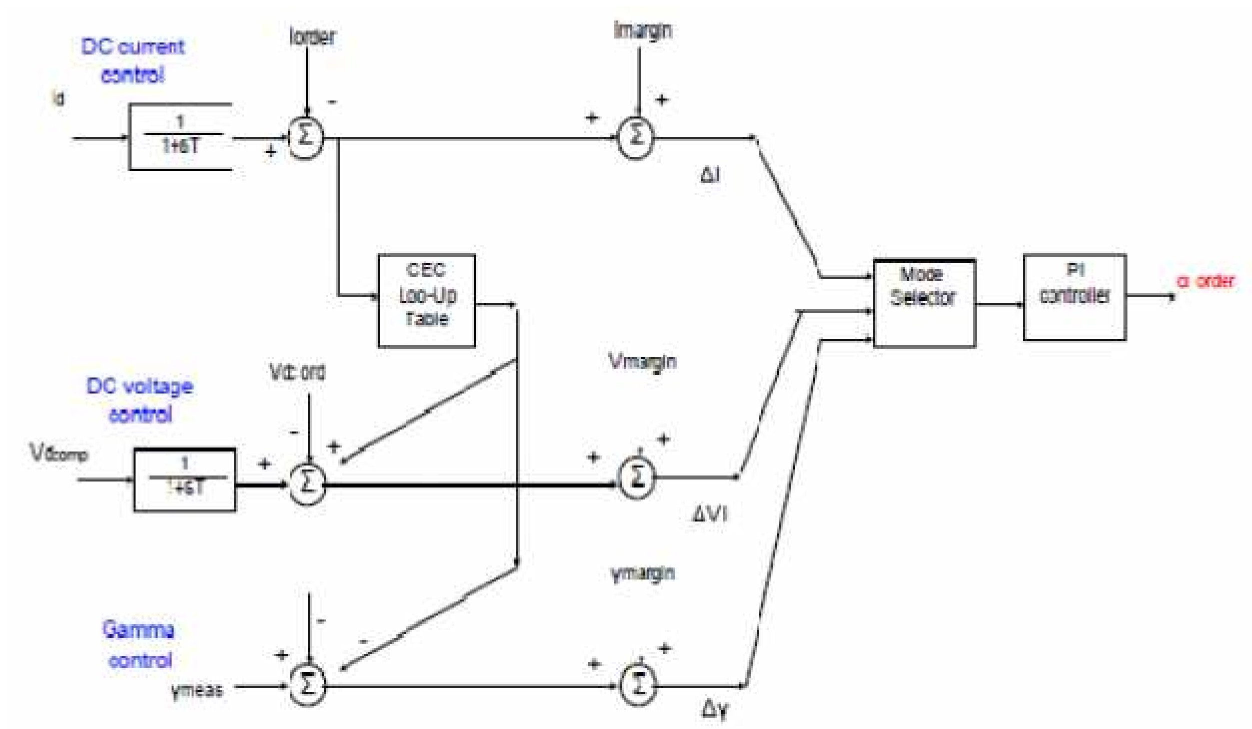


Figure 3.8: Converter Control Configuration [24].

The outputs of dc current, dc voltage, and gamma controllers are used as inputs for the mode selector, which is a maximum signal selector for the rectifier and minimum signal selector for the inverter. The selected signal is processed by the PI-controller whose output is the alpha angle order (α order).

To avoid steady-state instability in situations when, due to ac voltage fluctuations on both sides, rectifier sits on its minimal alpha limit and the inverter is in gamma control, additional signals proportional to the dc current error are added to the outputs of the dc voltage and gamma controllers. The Current Error Control (CEC), shown in Figure 3.8, is supposed to favorably change the slope of the converter characteristic around the steady-state operating point. The CEC contribution is determined by non-linear gains that are represented by hard-coded look-up tables in the model.

The Voltage Dependent Current Order Limit (VDCOL) is shown in Figure 3.9.This is based on the generic Vd-Id characteristics.

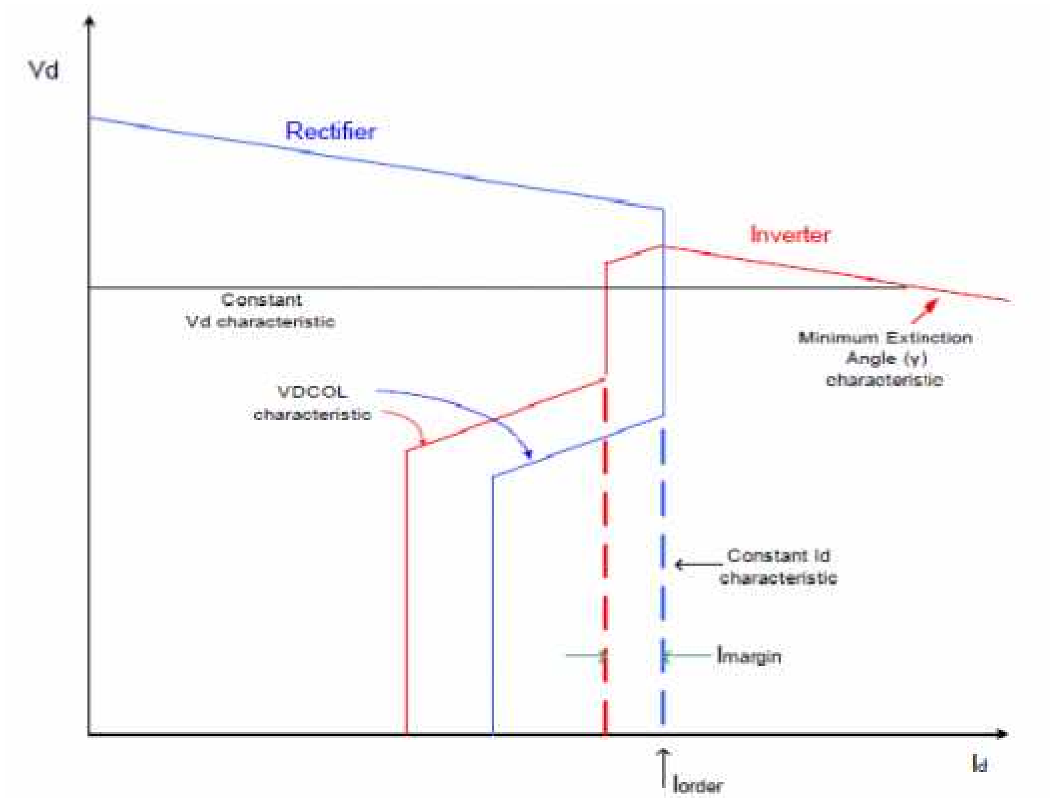


Figure 3.9: VDCOL control [24].

The compounded dc voltage is processed through a lag block and multiplied by a non-linear gain. The time constant of the former is set to up or down value depending on whether the dc voltage is increasing or decreasing. The non-linear gain (which represents the Vd-Id characteristics) is simulated using lookup tables, one for rectifier and another for inverter. The output of the VDCOL (which is a current limit) is compared with the current order, and the minimum of the two is used as an input to the dc current controller.

3.11 HVDC Link Model

Figure 3.9 shows the converter concept for the HVDC conversion of the Koka-Hurso HVAC transmission line with 12-bridge converters and 100MVA single-phase two-winding transformers.

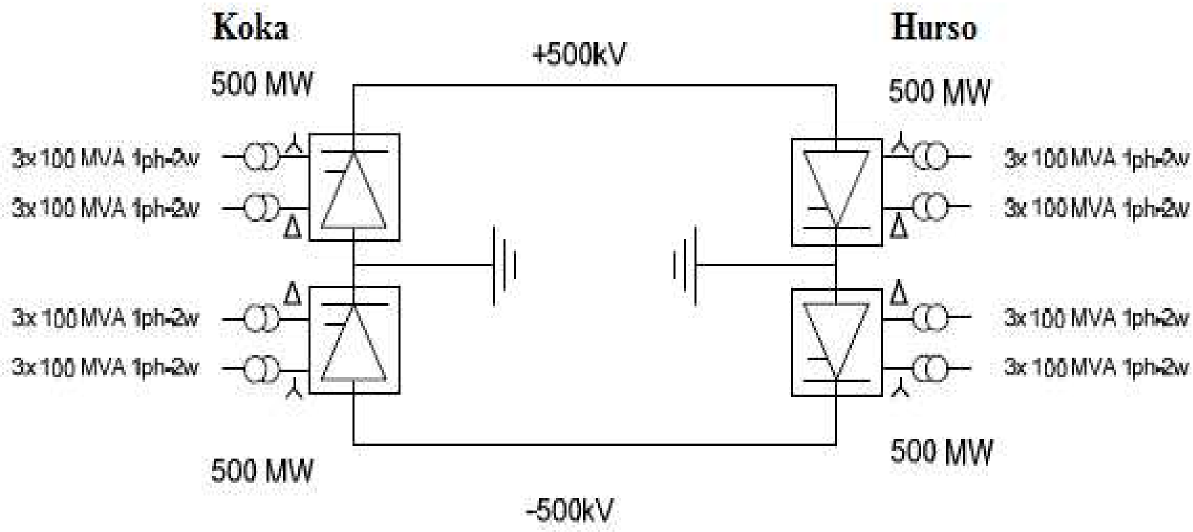


Figure 3.9: Proposed HVDC link

The conversion of HVDC transmission line will be about 352km from Koka 230kV HVAC substation to Hurso 230kV HVAC substation. The HVDC scheme will be a converter bipole configuration (+500 kV pole and -500 kV pole) with a rated capacity of 2 x 500 MW.

The HVDC scheme will allow power exchange of 1000 MW in both directions. The main direction, however, will be from Koka to Hurso. From Hurso converters station the power shall be transmitted into the Easter region of the national grid for the supply of Dire Dawa, nearby cities of Dire Dawa and Djibouti.

The ±500 kV transmission line will have a transmission capacity of 1000 MW and a total length about 352 km. In this thesis the studies and design of the Koka-Hurso conversion will ensure that the conversion will be fully functional and will be able to transfer 1000

MW, as required. In this respect the thesis will consider the status of the networks for year 2017. The HVDC link and converter are summarized in Table 3.4.

Table 3.4: Summary of HVDC link and converter

Parameter	**Unit**	**Rectifier**	**Inverter**
Converter(6-pulse bridge)			
Rating	MVA	250	250
Control	-	DC current	DC voltage
Nominal firing angle	degrees	15	17
Converter transformer			
Rating	MVA	6x100	6x100
AC shunt capacitors			
Number of banks	-	2	2
Rating per bank	MVAr	150	150
Smoothing reactor			
HVDC link			
Rated DC power	MW	1000	1000
Number of pole	-	2	2
Number of 6-pulse bridge	per pole	2	2
Smoothing reactor	mH/pole	130	130
Master control	-	Constant power	

CHAPTER FOUR

RESULT AND SIMULATION

To deliver power to the Eastern region network analysis of four different systems was conducted to find out its impact on the system and to asses which system better supply power for the demand. This involves modeling of transmission line and further integrating this model into the network model of the Ethiopian system. The other most important issues in network analysis are future network development plan of the system, and supply and demand balance of the system. After all the necessary assumptions are made and system model is created, system performance is checked against the planning criteria of the Ethiopian system.

Network analysis of the system is done by the power system analysis software (Power System Simulation for Engineers) PSS/E version 31. PSS/E is a package of programs for studies of power system transmission network and generation performance in both steady state and dynamic conditions. Based on this software and with the system grid load forecast, load flow analysis and steady state stability analysis was conducted for the proposed transmission lines.

4.1 Development of a strategy for upgrading power transfer capacity

From the statement of the problem on the first captor a need was found to develop a strategy in the form of a flow chart to guide EEP in their approach (methodology) to decide on a solution to increase the power delivery to Eastern region of the national grid. Load flow analysis of three possible transmission line solutions where simulated and each of their pros and cons where highlighted.

The case specific studies involving HVAC and HVDC lines are conducted to demonstrate their effectiveness as solutions to meet the increased power demand. The flow chart in Figure 4.1 shows the developed strategy to deal with the problem encountered.

The first possible solution is to add a 400KV HVAC transmission line as proposed by EEP in parallel with the existing one. The second solution is to convert the existing HVAC transmission line with an HVDC bipole scheme.

The third solution proposed is to operate converted HVDC line in mono-polar mood at the first stage of operation. The HVDC line can be operated in bipolar mood at the second stage in the future as load demand increase.

Now questions are asked for each of the possible solutions: Does the two HVAC parallel lines meet the demand ? Likewise, does an HVDC bipolar system provide adequate power delivery ? Also, will operating the HVDC bipole system in mono-polar mood provide the solution ?

If the answers to these questions are yes, then the increased load demand is met and any of these can be implemented. However, other factors need to be considered before making any decision, namely .

The factors needed to be considered are:

- Technical aspect
- Economical aspect

Once these scenarios have all been evaluated, the best solution will be selected as the solution and the strategy ends.

To prove the effectiveness of this developed strategy (flow chart), four different case studies are conducted to evaluate solutions and point out some of the considerations associated with each solution.

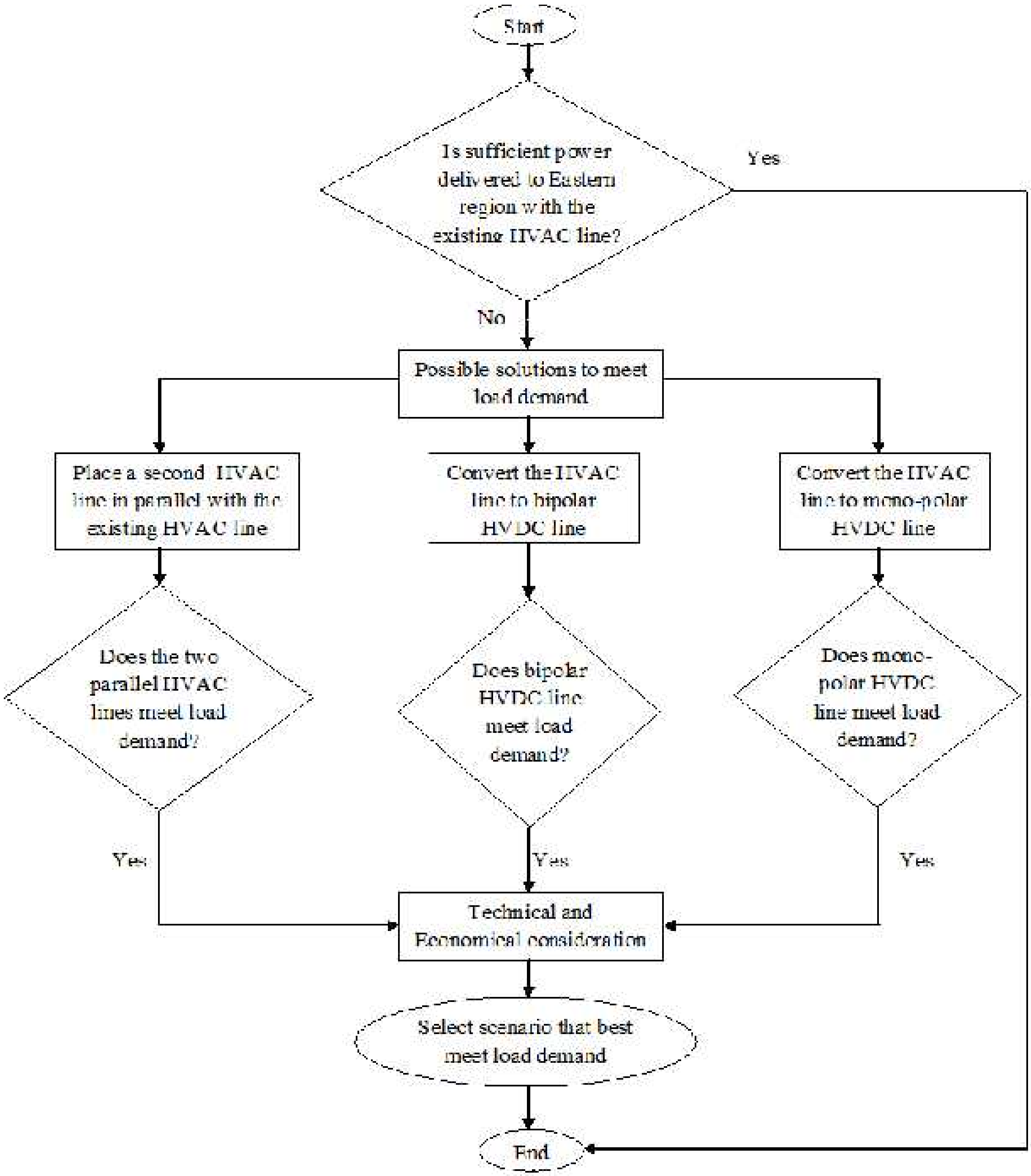


Figure 4.1: Strategy for upgrading existing HVAC line for increased power transmission

4.2 Case studies

Four different case studies have been analyzed to evaluate and demonstrate the application of the developed strategy. Figure 4.2 illustrates the sequence of the four case studies conducted to present a visual insight.

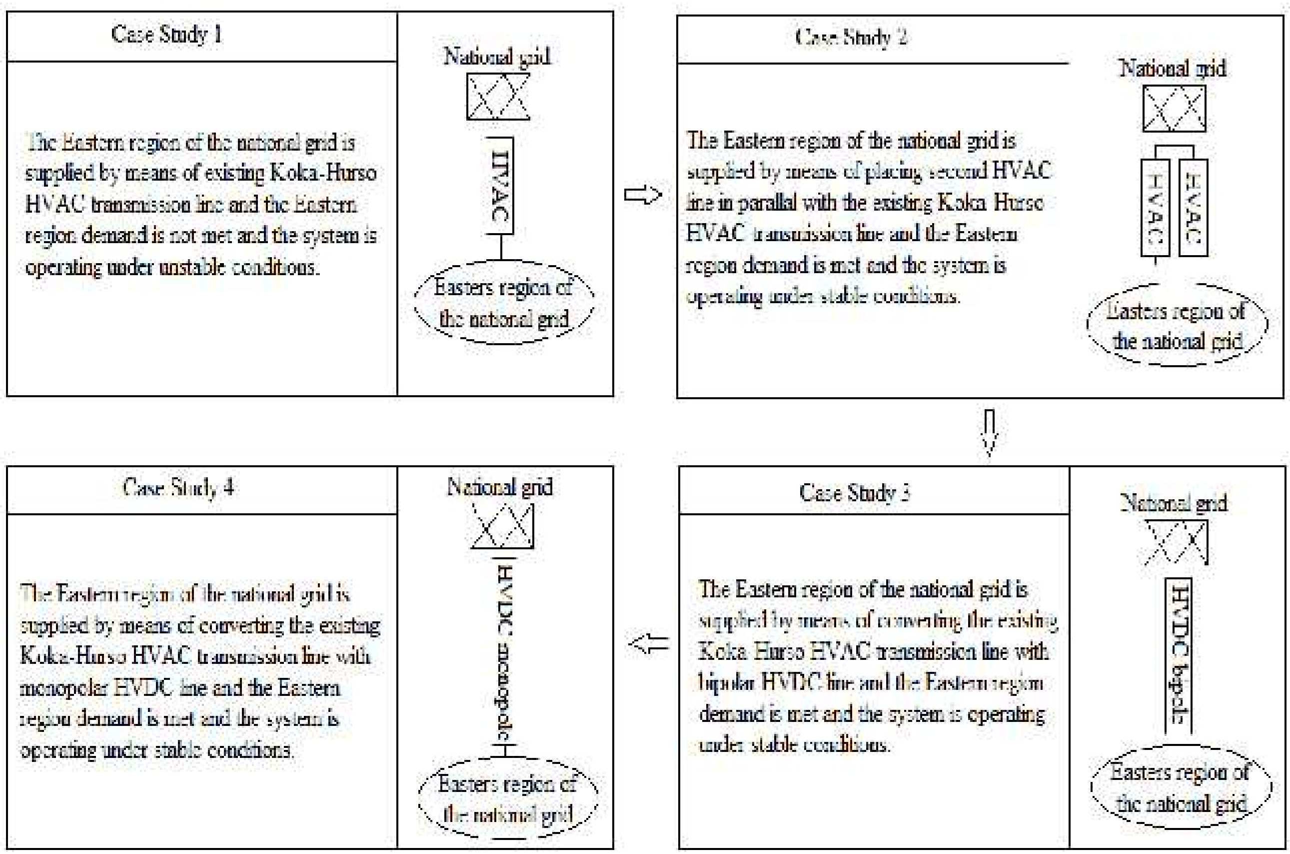


Figure 4.2: Case study sequence

Case study 1

In case Study 1, the Eastern region of the national grid is supplied by means of the existing double circuit 230kV Koka-Hurso HVAC transmission network as shown in Figure 4.3.

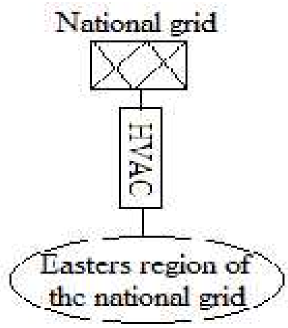


Figure 4.3: Case study 1

For evaluation of the developed strategy in Figure 4.1, Case study 1 was utilized to portray a unstable system. Meaning the existing HVAC transmission line is not adequately supplying power to the Eastern region of the national grid.

Case study 2

In Case study 2 the first possible solution is evaluated as suggested in Figure 4.1. This solution considers the parallel operation of two HVAC transmission lines and this is shown in Figure 4.4.

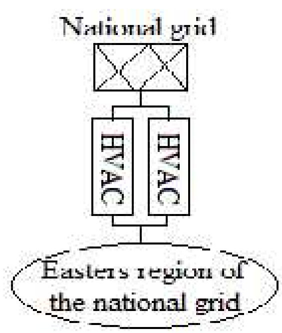


Figure 4.4: Case study 2

In Case study 2, additional parallel identical line is put in place as the a single transmission line was inadequate to supply the Eastern region. The advantage of such a system is that if the one line is out of commission then at least some of the load demand can be met. Parallel HVAC operation is evaluated to solve the power delivery problem highlighted in Case study 1.

Case study 3

The second possible solution indicated in the developed strategy, is to convert the HVAC line in Case study 1 with an HVDC bipolar line as shown in Figure 4.5.

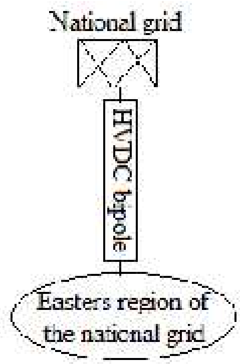


Figure 4.5: Case study 3

From the literature review HVDC was pointed out as a good alternative to that of HVAC lines. The objectives was to convert the double circuit HVAC which is inadequate to supply the Eastern region with power with a bipolar HVDC system.

Case Study 4

The third possible solution that needs to be explored to increase the power delivery to Eastern region is operating the converted HVDC bipolar line in mono-polar mood as shown in Figure 4.6.

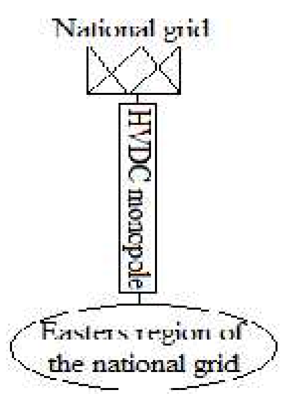


Figure 4.6: Case study 4

This scenario has the advantage that the HVDC bipolar line can be constructed in stages. The first stage would be replacing the first bipole by the year 2017 and operate it as monoplar HVDC. And in the future when the load increase furthermore the second bipole will be constructed . This will decrease the loss caused by the impedance exerted by the second bipole.

4.3 PSS/E Load Flow Modeling Data

The PSSE software perform load flow analysis in two methods, the Gauss-Seidel method and Newton-Raphson method. The Gauss-Seidel method is more effective when there are less number of busses are involved where as the Newton-Raphson method is more effective when more number of busses are involved. Therefore, in this thesis the Newton-Raphson method was used for simulation on the PSS. The convergence tolerance is met for the first 20 iteration. Hence, if the system does not converge before the 20th iteration it may lead to system blow up as the iteration limit exceeded and the system is not stable under steady state operation.

The summary table with the data used for each of HVAC and HVDC transmission lines is given in Table 4.1 and Table 4.2 respectively.

Table 2.1: Power flow parameters of HVAC lines

Voltage (kV)	Conductor	Tower Config.	No. Cond	Positive Sequence			Zero Sequence			Thermal rating			SIL
				R	X	B	R0	X0	B0	Con-ductor	Circuit		Circuit
				Ω/km	Ω/km	μS/km	Ω/km	Ω/km	μS/km	A	A	MVA	MW
230	Mallard	Double	1	0.0861	0.4092	2.8124	0.3163	1.1590	1.8496	687	687	274	139
400	Twin ASTER 851	Double	2	0.0244	0.3096	3.7509	0.2634	0.9123	2.3683	968	1936	1342	560

Table 3.2: Power flow parameters of HVDC lines and converters

(a) Lines:

Line Name	Control Mode	Rdc-Ohm (ohms)	Rcmp-Ohm (ohms)	Delti (pu)	Setval (amps orMW)	Vschedule (kV)	Dcvmin (kV)	Vcmode (kV)	Metered (Rect/Invr)	CCC Itmax	CCC Accel
LINE 1	Power	8.413	4.206	0.1	1000	500	0	300	1	20	1
LINE 2	Power	8.413	4.206	0.1	1000	500	0	300	1	20	1

(b) Converters:

Type	Bus Number	Bus Name	Max Firing Angle (deg)	Min Firing Angle (deg)	Bridges In Series	Primary Base Voltage (kV)	Com R (ohms)	Comm X (ohms)	Meas Bus	Trans Ratio (pu)
Rectifier	84016	KOKA230.00	15	5	2	230	0	14.276	0	0.8
Inverter	90	HURSO230.00	17	17	2	230	0	15.706	0	1.1

Type	Tap Setting (pu)	Max Tap Setting (pu)	Min Tap Setting (pu)	Tap Step (pu)	X of CCC (ohms)	AC Tx From Bus	AC Tx To Bus	AC Tx Id
Rectifier	1.125	1.15	0.9	0.00625	0	0	0	1
Inverter	1.0438	1.15	0.9	0.00625	0	0	0	1

4.4 Load Flow Analysis

Load flow analysis of the system is done for peak loading condition of the system when the four different transmission lines option becomes operational by the year 2017. Note that in the coming years the system load keeps on growing.

4.4.1 Peak Load Flow Analysis of Case Study 1

The network analysis conducted in PSSE for the existing Koka-Hurso 230kV double circuit line are summarized in Tables 4.3 and 4.4. The actual detail report of the simulation is shown in Annex 6.1. The load flow analysis report of PSSE for the existing transmission line and nearby buses is recapitulated in the Figure 4.7 below.

Table 4.3: Power results

From Bus		To Bus		Voltage level	Sending End Power Flow	Receiving End Power Flow
Bus No.	BUS Name	Bus No.	Bus Name	KV	MW	MW
211001	KOKA	203004	HURSO 230	230	142.2	126.8
211001	KOKA	203004	HURSO 230	230	142.2	126.8

The power at the sending end (Koka) is 184.4MW and power at the receiving end (Hurso) is 126.8MW in each lines. This shows a power loss of 15.46MW on each line with 30.92MW total loss of both lines. The loss accounts for 16.76% of the total Power transferred by the lines. Furthermore, the PSS/E report in Annex 6-1 shows a mismatch of 24.4MW. Also the iteration limit was exceeded as load flow analysis does not converge until after the 20th iteration, which lead to blow up during the simulation.

Table 4.4: Voltage profile of buses

Bus No.	BUS Name	Base Voltage	Bus Voltage (PU)
211001	KOKA	230	0.989
203004	HURSO	230	1.000

The steady state voltage criteria for Ethiopia under normal operating condition is between 0.95pu to 1.05pu. Under operating conditions following a single contingency (N-1) the voltage criteria becomes 0.9pu. The voltage at Koka bus is 0.996pu and Hurso is 0.957pu which fulfils planning criteria.

From Table 4.3 it can be seen that the voltage are 229.1 kV at the sending end (Koka bus) of the transmission line and 220.1 kV at the receiving end (Hurso bus), this means there is a voltage decrease of 9 kV. This decrease in voltage is caused by the 43MVAr reactive power absorbed by the line.

From the results obtained in Case study 1, there is a loss of 61.76% and a mismatch of 24.4MW. Furthermore, the load flow analysis does not converge which indicates that the transmission line is not stable under steady state operation and thus the power delivery to the Easters region of the national grid should be increased.

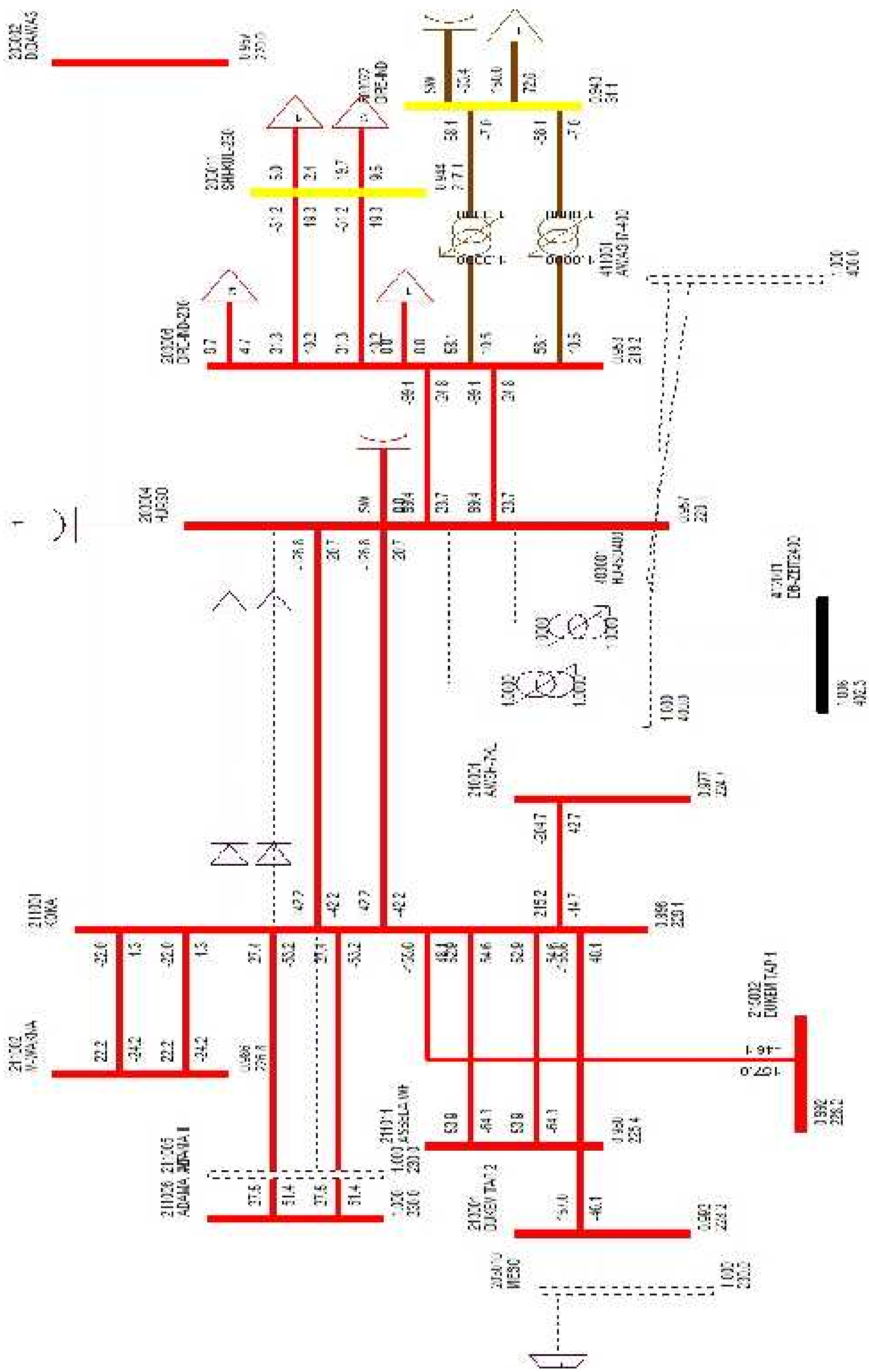


Figure 4.7: Load flow result of case study 1

4.4.2 Peak Load Flow Analysis of Case Study 2

The network analysis conducted in PSSE for the parallel HVAC transmission lines are summarized in Tables 4.5 and 4.6. The actual detail report of the simulation is shown in Annex 6.2. The load flow analysis report of PSSE for the parallel HVAC transmission line and nearby buses is recapitulated in the Figure 4.8 below.

Table 4.5: Power flow

From Bus		To Bus		Voltage level	Sending End Power Flow	Receiving End Power Flow
Bus No.	BUS Name	Bus No.	Bus Name	KV	MW	MW
211001	KOKA 230	203004	HURSO 230	230	67.8	64.2
211001	KOKA 230	203004	HURSO 230	230	67.8	64.2
412001	DB-ZEIT 400	403001	HURSO 400	400	183.9	181.5
412001	DB-ZEIT 400	203001	HURSO 400	400	183.9	181.5

The power at the sending end of Koka 1 and Koka 2 are 67.8MW each, power at the sending end of Debrezeit 1 and Debrezies 2 are 183.9MW each, power at the receiving end of Hurso 1 and Hurso 2 is 64.2MW each, and power at the receiving end of Hurso 3 and Hurso 4 is 181.5MW each. This shows a power loss of 3.56MW on each line from Koka to Hurso and a power loss of 2.44MW on each line from Debrezeit to Hurso with 12.8MW total loss of all the four lines. The loss accounts for 2.41% of the total Power transferred by the lines. The PSS/E report in Annex 6-2 shows no mismatch, which means supply demand balance was meet. Also the system converges at the 9th iteration, which means the system met convergence tolerance.

Table 4.6: Voltage profile of buses

Bus No.	BUS Name	Base Voltage	Bus Voltage (PU)
211001	KOKA 230	230	1.022
203004	HURSO 230	230	1.021
403001	HURSO 400	400	1.032
412001	DB-ZEIT 400	400	1.025

From Table 4.5 it can be seen that the voltage are 235.1 kV at the sending-end of Koka bus , 412.6 kV at the sending-end of Debrezeit bus, and 234.9 kV at the receiving-end of Hurso bus, this means there is a voltage decrease of 0.2 kV. This decrease in voltage is caused by the 87.6MVAr reactive power absorbed by the line. The voltage at Koka bus is 1.022pu, Debrezeit bus is 1.032pu, and Hurso is 1.021pu which fulfils planning criteria.

From the results obtained in Case study 2, there is a loss of 2.41% and there is no mismatch of power. Furthermore, the load flow analysis converge at the 9th iteration and met convergence tolerance which indicates that the transmission line is stable under steady state operation and thus adequate power is delivery to the Easters region of Ethiopia.

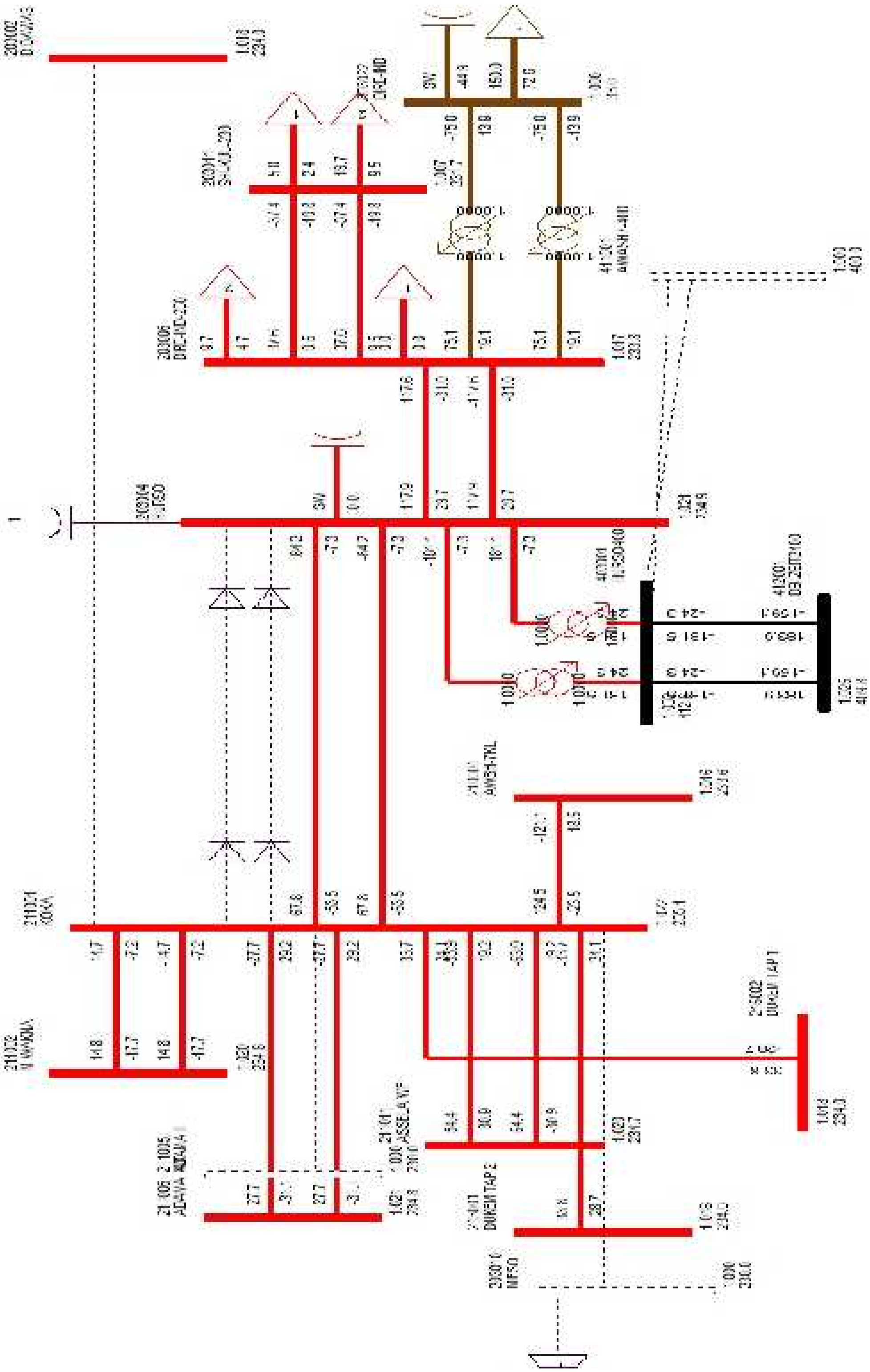


Figure 4.8: Load flow result of case study 2

4.4.3 Peak Load Flow Analysis of Case Study 3

The network analysis conducted in PSSE for the converted HVDC bipolar transmission lines are summarized in Tables 4.7 and 4.8. The actual detail report of the simulation is shown in Annex 6.3. The load flow analysis report of PSSE for the converted HVDC bipolar transmission line and nearby buses is recapitulated in the Figure 4.9 below.

Table 4.7: Power flow

From Bus		To Bus		Voltage level	Sending End Power Flow	Receiving End Power Flow
Bus No.	BUS Name	Bus No.	Bus Name	KV	MW	MW
211001	KOKA 230	203004	HURSO 230	500	450	440.7
211001	KOKA 230	203004	HURSO 230	500	450	440.7

The power at the sending end (Koka) is 450MW and power at the receiving end (Hurso) is 440.7MW in each lines. This shows a power loss of 9.28MW on each line with 18.56MW total loss of both lines. This loss accounts for 2.06% of the total Power transferred by the lines. The large amount of loss is due to the impedance exerted by the second line. Furthermore, the PSS/E report in Annex 6-3 shows no mismatch, which means supply demand balance was meet. Also the system converges at the 12th iteration, which means the system met convergence tolerance.

Table 4.8: Voltage profile of buses

Bus No.	BUS Name	Base Voltage	Bus Voltage (PU)
211001	KOKA 230	230	0.951
203004	HURSO 230	230	1.000

From Table 4.7 it can be seen that the voltage are 218.2 kV at the sending-end (Koka bus) of the transmission line and 230 kV at the receiving-end (Hurso bus), this means there is a voltage increase of 11.8 kV. This increase in voltage is caused by the

504.6MVAr reactive power supplied by the transmission line. The voltage at Koka bus is 0.951pu and Hurso is 1pu which fulfils planning criteria.

From the results obtained in Case study 3, it is important to notice that the power transmitted (900MW) is almost twice the power transmitted in Case study 2 (503.4MW). There is a loss of 2.06% and there is no mismatch of power. Furthermore, the load flow analysis converge at the 12^{th} iteration and met convergence tolerance which indicates that the transmission line is stable under steady state operation and thus adequate power is delivery to the Easters region of Ethiopia.

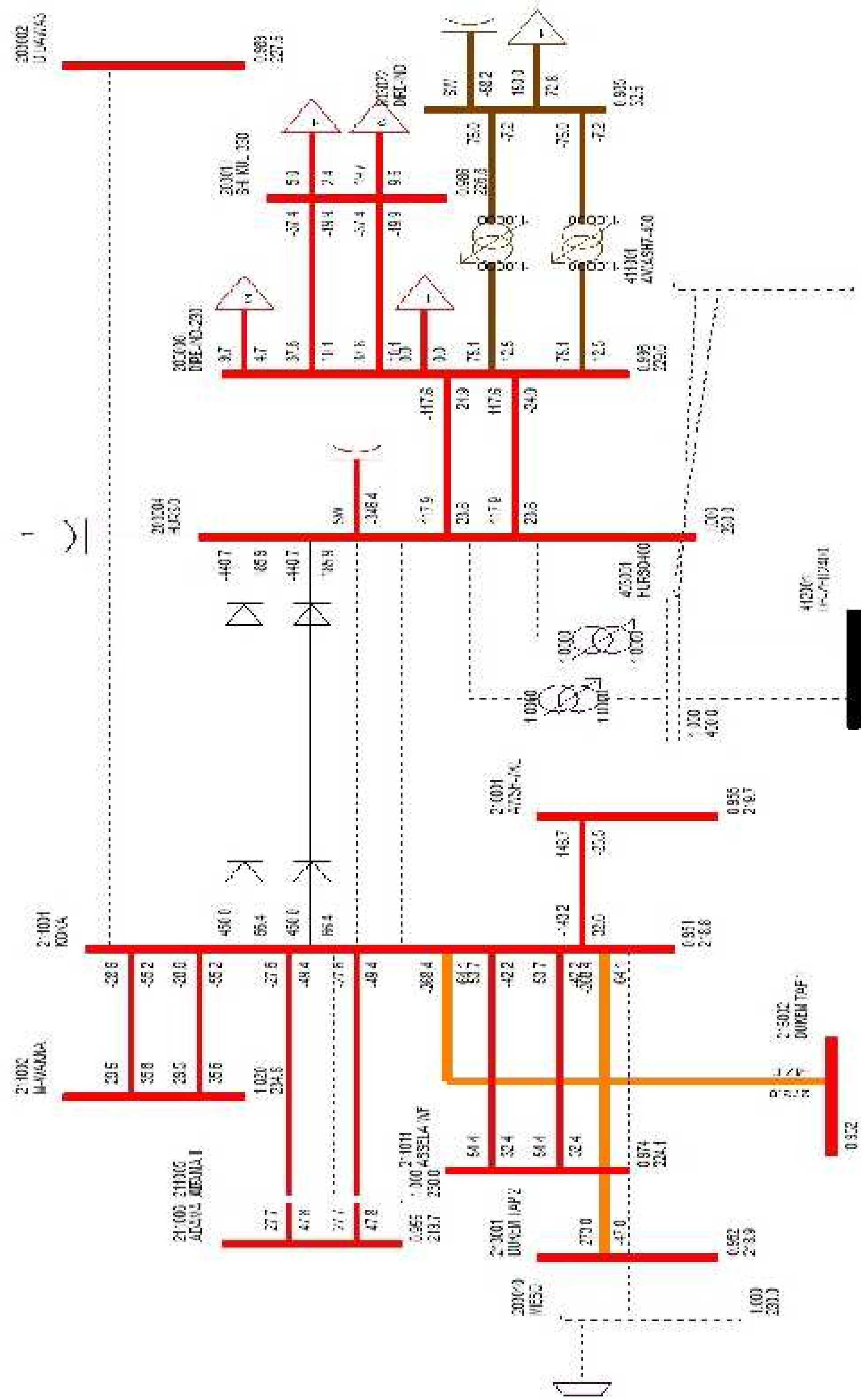


Figure 4.9: Load flow Result of Case study 3

4.4.4 Peak Load Flow Analysis of Case Study 4

The network analysis conducted in PSSE for the converted HVDC monopolar transmission line is summarized in Tables 4.9 and 4.10. The actual detail report of the simulation is shown in Annex 6.2. The load flow analysis report of PSSE for the converted HVDC monopolar transmission line and nearby buses is recapitulated in the Figure 4.10 below.

Table 4.9: Power flow

From Bus		To Bus		Voltage level	Sending End Power Flow	Receiving End Power Flow
Bus No.	BUS Name	Bus No.	Bus Name	KV	MW	MW
211001	KOKA 230	203004	HURSO 230	500	500	489.2

The power at the sending end (Koka) is 500MW and power at the receiving end (Hurso) is 489.2MW. This shows a power loss of 10.79MW which is the lowest loss in all the four cases. This loss accounts for 2.1% of the total Power transferred by the line. Furthermore, the PSS/E report in Annex 6-4 shows no mismatch, which means supply demand balance was meet. Also the system converges at the 9th iteration, which means the system met convergence tolerance.

Table 4.10: Voltage profile of buses

Bus No.	BUS Name	Base Voltage	Bus Voltage (PU)
211001	KOKA 230	230	0.989
203004	HURSO 230	230	1.000

From Table 4.9 it can be seen that the voltage are 227.5 kV at the sending-end (Koka bus) of the transmission line and 230 kV at the receiving-end (Hurso bus), this means there is a voltage increase of 2.5 kV. This increase in voltage is caused by the 263.1MVAr reactive power supplied by the line. Koka bus has voltage of 0.989pu and Hurso bus has voltage of 1pu which fulfils planning criteria's.

From the results obtained in Case study 4, it is important to note that the power transmitted (500MW) is almost twice the power transmitted in Case study 1 (284.4MW). The loss is extremely reduced which is 1/3 of the loss of the existing line and there is no mismatch of power. Furthermore, the load flow analysis converge at the 16th iteration and met convergence tolerance which indicates that the transmission line is stable under steady state operation and thus adequate power is delivery to the Easters region of Ethiopia.

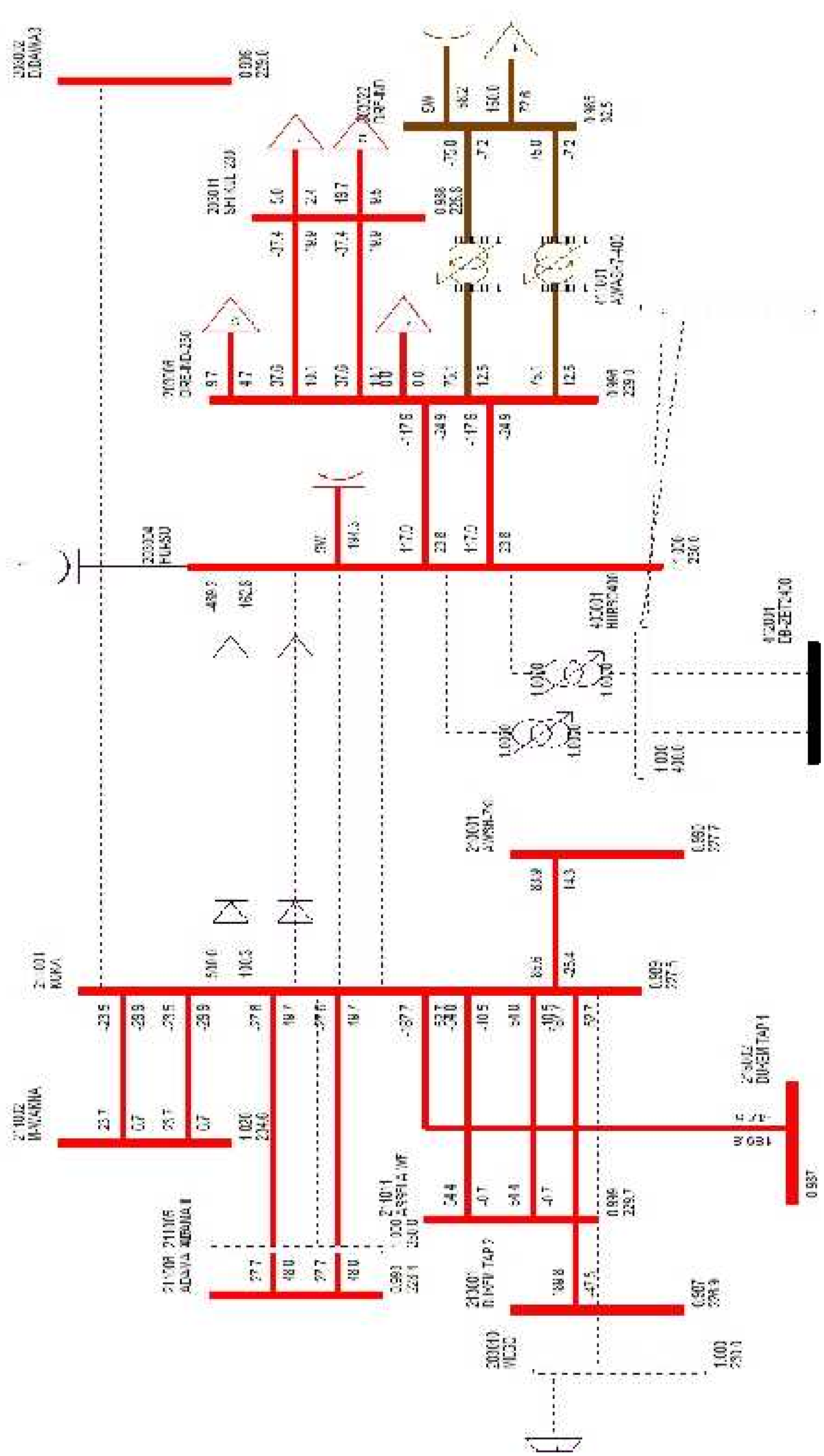


Figure 4.9: Load flow Result of Case study 4

Table 4.11 below summarizes the simulation result for network analysis conducted on the four different transmission lines with the PSSE software.

Table 4.11: Summery of result

Description	Case Study 1 Existing HVAC transmission line	Case Study 2 Parallel HVAC transmission line	Case Study 3 Converted HVDC bipolar transmission line	Case Study 4 Converted HVDC Monopolar transmission line
Bus Voltage	230KV	230kV and 400kV	500kV	500kV
Total Power Transmitted	2894.4MW	503.4MW	900MW	500MW
Power Loss	30.92MW	12.8MW	18.56MW	10.79MW
Load Mismatch	24.4MW	Non	Non	Non
Convergence Tolerance	Does not met convergence tolerance	Met convergence tolerance at the 9^{th} iteration	Met convergence tolerance at the 12^{th} iteration	Met convergence tolerance at the 16^{th} iteration
Steady State Stability	Not Stable	Stable	Stable	Stable
Met Eastern Region load demand	No	Yes	Yes	Yes

CHAPTER FIVE

TECHNICAL AND ECONOMICAL COMPARISON OF HVDC VERSUS HVAC

Bulk power could be transferred using HVDC or HVAC transmission system from a remote generating station to the load center. Before implementation of those transmission lines, total cost and technical comparisons between ac and dc alternatives has been conducted [29].

From the technical comparison point of view, each transmission line has been evaluated based on comparative parameters, like transmission line efficiency, and corona loss, to come up with an optimal transmission line.

In order to compare the cost, all main system components must be taken into consideration. For the dc alternative, investment cost of converter terminals, ac input/output equipment, filters, and the interconnecting transmission line is accounted. For the ac alternative, investment cost of related project in the country was considered.. The assumptions used for comparison HVAC with HVDC are the four Case studies illustrated in previous section.

5.1 Technical Aspect

5.2.1 Transmission System Efficiency

While designing a transmission line care must be taken on the loss of power within a transmission system to maintain the efficiency of the transmission system within desirable limit. This section covers comparison of the converted HVDC with the existing HVAC transmission systems as well as the new proposed parallel HVAC transmission line in terms of the power loss of each transmission line. So the overall transmission system efficiency evaluation is to see which transmission system has better performance in terms of delivering power to the Eastern region of the national grid.

The existing transmission line employs double circuit 230kV HVAC line from Koka to Hurso with a total length of about 352km. To meet the increased load demand EEP proposed placing a parallel double circuit 400kV HVAC line from Debrexzeit to Hurso with a total length about 387km.

On the other hand in this thesis conversion of the existing HVAC line to ±500kV HVDC bipole transmission line is proposed as a viable. Each pole has two rectifiers at the sending end and two inverters at the receiving end that are used for the conversion of voltage from ac to dc and then back to ac respectively. Each converter has converter transformers used to step up and down the voltage levels as per the design requirements.

Depending on the overall transmission system components, the performance of the transmission system with respect to power losses has been evaluated to determine which transmission system (case study) is best performing.

Case study 1

From the PSSE simulation study of the existing HVAC transmission line, the power at the sending end of the transmission line is $284.4M$ and the power at the receiving end of the transmission line is $253.6M$. So, the power loss in the transmission line is $30.8M$. The efficiency of the existing $230K$ transmission line becomes;

$$\eta_T = \frac{R \qquad e \quad P}{S \qquad e \quad P} \tag{5.1}$$

$$\eta_T = \frac{253.6M}{284.4M} = 0.89$$

The transmission line efficiency of Case study 1 without coronal loss is 89%.

Case study 2

From the PSSE simulation study of the two parallel HVAC transmission line, the power at the sending end of the transmission line is $503.4M$ and the power at the receiving end of the transcription line is 490.6M . So, the power loss in the transmission line is 8M . The efficiency of the two parallel HVAC transmission line;

$$\eta_T = \frac{R \qquad e{:} \quad P}{S \qquad e \quad P}$$

$$\eta_T = \frac{490.6M}{503.4M} = 0.97$$

The transmission line efficiency of Case study 2 without coronal loss is 97%.

Case study 3

From the PSSE simulation study of the converted HVDC bipole transmission line, the power at the sending end of the transmission line is 900M and the power at the receiving end of the transmission line is 881.4M . So, the power loss in the transmission line is 18.56M . The large amount of loss is due to the impedance exerted by the second bipole line. The efficiency of the converted HVDC bipole transmission line becomes;

$$\eta_T = \frac{R \qquad e{:} \quad P}{S \qquad e{:} \quad P}$$

$$\eta_T = \frac{900M}{881.4M} = 0.97$$

The transmission line efficiency of Case study 3 without coronal loss is 97%.

Case study 4

From the PSSE simulation study of the converted monopolar HVDC transmission line, the power at the sending end of the transmission line is 500MW and the power at the receiving end of the transmission line is 489.2M . So, the power loss in the transmission line is 10.8M . The efficiency of the converted monopolar HVDC transmission line becomes;

$$\eta_T = \frac{R \qquad e: \quad P}{S \qquad e: \quad P}$$

$$\eta_T = \frac{500M}{489.2M} = 0.99$$

The transmission line efficiency of Case study 4 without coronal loss is 99%.

5.2.2 Corona Loss Calculations

Corona is defined as a ‘luminous discharge due to ionization of air surrounding a conductor caused by a voltage gradient exceeding a certain value’. Corona occurs when a high value of electric field strength at a conductor surface causes the air to become electrically ionized and to conduct.

The real power loss due to corona, called corona loss, depends on meteorological conditions, particularly rain, and on conductor surface irregularities. Losses due to corona are usually small compared to conductor I^2R loss.

AC corona losses are important to the design of the conductor bundle. With only a few $K \quad /k$ of loss in fair weather, the level may increase 10-100 times during conditions of rain or hoarfrost and may reach several hundred kW/km. DC corona losses are, however, of less concern to the design of the conductor bundles, since the increase during rain or hoarfrost is much smaller than with ac, only about 2-3 times [15].

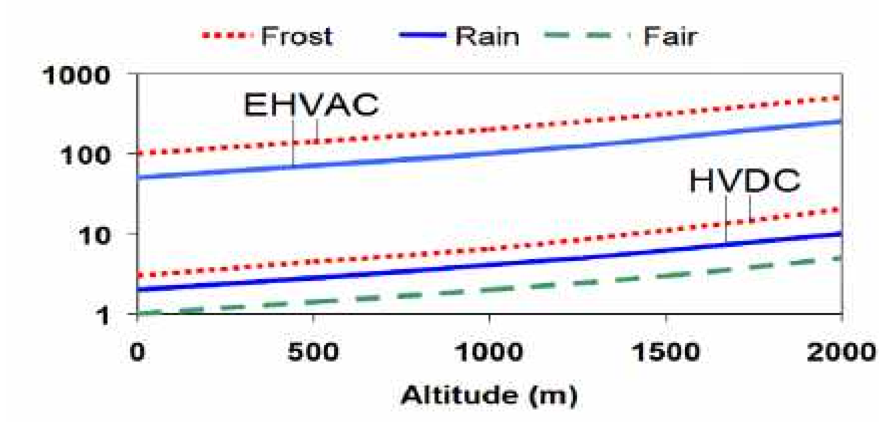


Figure 5.1: Comparison of EHVAC and HVDC Corona Losses as a Function of Altitude and Weather [21].

The power loss due to corona for HVDC can be expressed [26]

$$P_L = \left(2V(k+1)K_c \times n \times r \times 2^{0.2\ (g-g_0)}\right) \times 10^{-3}\, k\ \ /c \qquad -k \qquad (5.2)$$

where : V =is the pole to ground voltage in kV V

n =is the number of subconductors n

r =is the radius of each subconductor in cm r

g =maximum conductor surface gradient at operating voltage (in kV/cm) g

$g_0 = 22 \times \delta\, k\ \ /c$ where δ = relative air density

K_c =conductor surface coefficient which varies from less than 0.15 for smooth, clean conductor to more than 0.35for conductor with imperfections

$k = (2/\pi)\tan^{-1}(2H/S)$

H =mean height of conductor

S =pole spacing

The relative air density δ is given by [30]

$$\delta = \frac{2.9\ \ P}{2\ \ \ +T} \qquad (5.3)$$

where : P =barometric pressure in kilo-Pascal's

T =temperature in centigrade

The maximum gradient g is given by [30]

$$g = \frac{(1+(n-1)(r/R))V}{n\ \ \ \frac{2H}{(n\ \ R^{n-1})^{1/n}\left((2H/S)^2+1\right)^{1/2}}} \qquad (5.4)$$

Where, R = radius of the circle passing through the centers of all sub-conductors in a bundle, in cm.

The corona loss evaluation of HVDC is started by having the following data.

Table 5.1:Conductor configuration and Rated values of HVDC transmission System [7,3]

Items	Unit	Values
Rated voltage (V)	kV	500
Radius of each sub conductor (r)	cm	2.896
Distance between sub conductors in bundle (S)	cm	45.5
Pole spacing (a)	cm	1600
Min height of conductor above ground (h)	cm	1100
Number of sub conductors in bundle (n)	-	3
Barometric pressure	kpa	73.749
Temperature	^{0}C	40

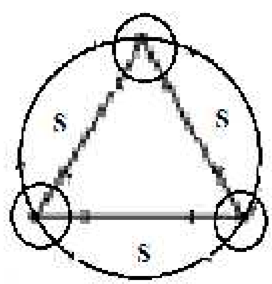


Figure 5.2: Configuration of a phase conductor having 3 sub conductors.

$$s \quad \theta = \frac{(S/2)}{R} \tag{5.5}$$

$$s \quad 60^{c} = \frac{(45.5/2)}{R}$$

$$R = 26.26c$$

$$g = \frac{\left(1 + (n - 1)(r/R)\right)V}{(n\ \ )ln\left(\frac{2H}{\left(n\ \ R^{(n-1)}\right)^{1/n}((2H/S)^2+1)^{1/2}}\right)}$$

$$g = \frac{\left(1 + (3 - 1)(2.896/26.26)\right)500}{(3 \times 2.896)ln\left(\frac{2\times 1}{\left(3\times 2.8\ \ \times 2\ .2\ \ ^{(3-1)}\right)^{1/3}((2\times 1\ \ \ /1\ \ \ )^2+1)^{1/2}}\right)}$$

$$g = 24.94\, k\ \ /c$$

And

$$\delta = \frac{2.92P}{273 + T}$$

$$\delta = \frac{2.92 \times 73.749}{273 + 40^{c}}$$

$$\delta = 0.688$$

$$g_o = 24.94 \times \delta\, k\ \ /c$$

$$g_o = 17.158\, k\ \ /c$$

$$k = (2/\pi)\, t\ \ ^{-1}(2H/S)$$

$$k = (2/\pi)\, t\ \ ^{-1}(2 \times 14/11)$$

$$k = 0.762$$

Corona loss per pole per km is

$$P_{lo} = \left(2V(k + 1)K_c n\ \ \times 2^{0.2\ \ (g-g_o)}\right) \times 10^{-3}\, k\ \ /p\ \ \ - k$$

$$P_{lo} = \left(2 \times 500(0.762 + 1)0.15 \times 3 \times 2.896 \times 2^{0.2\ \ (2\ .9\ -1\ .1\ \ )}\right) \times 10^{-3}\, k\ \ /p\ \ \ - k$$

$$P_{lo} = 8.8\, k\ \ /p\ \ \ - k$$

For a total length of the line per phase

$$P_{lo} = (8.8\, k\ \ /p\ \ \ - k\ \ ) \times 352k$$

$$P_{lo} = 3.097\, M\ \ /p$$

For a total length of the transmission line, the total corona loss of the bipolar line (i.e. 2 poles)

$$P_{lc} = (3.097\,M\ \ /p\ \ ) \times 2p$$
$$P_{lc} = 6.194M$$

or,

$$P_{lc} = 0.61\%$$

The power loss due to corona for HVAC 230kV line

Calculations of Voltage Gradients for HVAC based on [26]

$$E = \left(\frac{V}{\sqrt{3}}\right)\frac{\beta}{\left(r\ \ \left(\left(\frac{a}{R_e}\right)\left(\frac{2h}{\sqrt{4h^2+a^2}}\right)\right)\right)} \tag{5.6}$$

where,

$$\beta = \frac{\left(1+(n-1)\frac{r}{R}\right)}{n} \tag{5.7}$$

$$R_e = R\ \ \sqrt{\frac{n}{R}} \tag{5.8}$$

$$R = \frac{S}{2\,s\ \ \frac{\pi}{n}} \tag{5.9}$$

E = Conductor Surface Voltage Gradient (kV/cm)

V = Rated Voltage (kV)

β = Factor for Multiple Conductors

r = Radius of Conductor (cm)

R = Outside radius of bundle (cm)

R_e = Equivalent Radius of bundle conductor (cm)

S = Distance between Component conductor centers (cm)

A = Phase Spacing (cm)

H = Height of conductor above ground (cm)

n = Number of component conductors in bundle

Table 5.2: Conductor configuration and rated values for HVAC transmission System [31]

Items	Unit	Values
Rated voltage (V)	kV	230
Radius of conductor (r)	cm	2.896
Distance between component conductor centers (S)	cm	45.5
Phase spacing (a)	cm	680
Height of conductor above ground (h)	cm	700
Number of component conductor in bundle (1)	-	1

First find out side radius of the bundle which is given by

$$R = \frac{S}{2 s \quad \frac{\pi}{n}}$$

$$R = \frac{45.5}{2 \times s \quad \frac{\pi}{1}}$$

$$R = 22.75c$$

Factor for Multiple Conductors

$$\beta = \frac{\left(1 + (n-1)\frac{r}{R}\right)}{n}$$

$$\beta = \frac{\left(1 + (1-1)\frac{2.8}{2\ .7}\right)}{1}$$

$$\beta = 1$$

Equivalent Radius of bundle conductor

$$R_e = R\sqrt{\frac{n}{R}}$$

$$R_e = 22.75 \times 1\sqrt{\frac{1 \times 2.896}{22.75}}$$

$$R_e = 8.1168c$$

The Conductor Surface Voltage Gradient become

$$E = \left(\frac{V}{\sqrt{3}}\right)\frac{\beta}{\left(r\ln\left(\left(\frac{d}{R_e}\right)\left(\frac{2h}{\sqrt{4h^2+d^2}}\right)\right)\right)}$$

$$E = \left(\frac{230}{\sqrt{3}}\right)\frac{1}{\left(2.896\ln\left(\left(\frac{6}{8.1}\right)\left(\frac{2\times7}{\sqrt{4\times7^2+6^2}}\right)\right)\right)}$$

$$E = 10.61\mathrm{kV/cm}$$

The disruptive critical corona voltage of four bundle conductors can be obtained by [29,32]

$$V_c^b = Em_o\delta\left(\frac{4}{\left(1+\frac{4.2\ r}{s}\right)}\right)r\ln\left(\frac{G}{D_s^b}\right) \tag{5.10}$$

Known values

$\delta = 0.688$

$E = 1061\mathrm{kV/cm}$

$m_o = 0.8$

$$GMD = \sqrt[3]{a_1 \; a_2 \; a_3}$$

$$GMD = \sqrt[3]{6.8 \times 6.8 \times 13.6}$$

$$GMD = 8.56746m$$

$$D_s^b = 1.09\sqrt[4]{rS^2}$$

$$D_s^b = 1.09\sqrt[4]{0.02896 \times 0.455^2}$$

$$D_s^b = 0.2491m$$

Where, a_1 , a_2 , and a_3 are the respective phase to phase distances

The disruptive critical corona voltage of four bundle conductors can be obtained by

$$V_c^b = 10.61 \times 0.8 \times 0.688 \left(\frac{4}{\left(1+\frac{4.2 \times 2.8}{4 \; .5}\right)}\right) r\ln\left(\frac{8.5}{0.3}\right) \qquad (5.11)$$

$$V_c^b = 177.96kV$$

The corona loss for high voltage ac transmission line is given by [39]

$$P_{lc} = \frac{2}{\delta}(f + 25)\left(\frac{R}{a}\right)^{1/2}\left(V_p - V_c^b\right)^2 \times 10^{-5}\, kW/circuit - km \qquad (5.12)$$

Known values

$$V_p = \frac{230}{\sqrt{3}} = 132.791kV$$

$$V_c^b = 177.96kV$$

$$\delta = 0.688$$

$$f = 50Hz$$

$$R = 22.75cm$$

$$a = 680cm$$

$$P_{lc} = \frac{241}{0.688}(50+25)\left(\frac{22.75}{680}\right)^{1/2}(132.791-177.96)^{2}$$
$$\times 10^{-5}\ \text{kW/circuit} - \text{km}$$

$$P_{lc} = 98.04\ \text{kW/circuit} - \text{km}$$

For 2-circuit line

$$P_{lc} = (98.04\ \text{kW/phase} - \text{km}) \times 2 - \text{circuit}$$
$$P_{lc} = 294.12\ \text{kW/km}$$

For a total length of the double circuit transmission line, the total corona loss of the HVAC transmission line is.

$$P_{lc} = (196.08\,k \quad /k \quad) \times 352k$$
$$P_{lc} = 69.02M$$

or,

$$P_{lc} = 25.18\%$$

In rain weather condition for altitude of 2000m, the typical corona loss (kW/km)for HVAC and HVDC is more than $100\,k \ /k$ and $9\,k \ /k$ respectively [15]. The HVAC transmission line has $98.04\,k \ /k$ corona loss and the HVDC transmission line has $8.8\,k \ /k$ corona loss which are both below the standard Values.

The total corona loss of the existing HVAC transmission line is $69.02\,M \ /k$, for the HVDC bipolar transmission line, the total corona loss is $6.194\,M \ /k$, and for the HVDC monopolar transmission line, the total corona loss is $3.097\,M \ /k$. So that the corona effects such as radio interference, television interference and audible noise become much lower in the converted HVDC line than the existing HVAC line and thus HVDC transmission line has an very less impact to the Environment.

From previous calculation, without considering the corona loss, the total power loss obtained for the existing HVAC is $12.8M$ and for HVDC is $18.56M$. The overall power loss of the existing HVAC transmission system becomes 81.82*M* and for HVDC biolar the overall power loss becomes 24.75*M* . For the HVDC monopolar operation the overall power loss becomes 13.89*M* .

The overall efficiency of the existing HVAC transmission line becomes 83.7%, and the loss is 16.25%. For HVDC bipolar the overall efficiency of the transmission line becomes 97.25%, and the loss is 2.75%. And for the HVDC monopolar operation the overall efficiency of the transmission line becomes 97.22%, and the loss is 2.77%. So, from the efficiency calculations 57.7*M* power can be saved if ±500 kV bipolar HVDC transmission line is implemented and 67.9*M* power can be saved if ±500 kV monopolar HVDC transmission line is implemented meeting the demand to the Eastern region of the national grid.

5.2.3 Comparison and Analysis of Case Study Results

In all case studies the load considered is the increased load demand for the year 2017 in the Eastern region of the national grid.

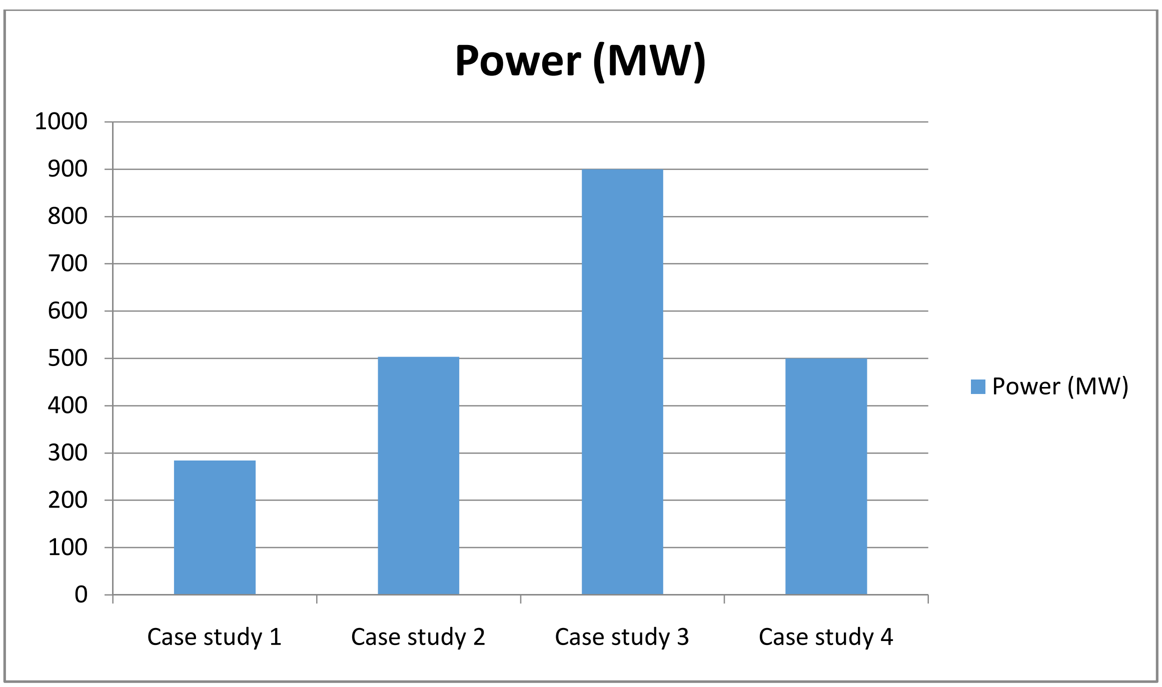


Figure 5.3: Real power delivered by the line

In Case study 1 the existing overhead line only supplies 284.4 MW, which is not enough to meetthe load demand in the Easter region of Ethiopia. In Case study 2 the power transmitted across the parallel overhead line increases to 503.4 MW, which meets the load demand in the Eastern region. From Figure 4.7 it can be seen that the parallel combination of the AC lines delivers the same amount of power to that of in Case study 4. In case study 4 the existing line is converted to a monoplar DC line. With bipolar HVDC transmission line the real power delivery is controlled via it scontrol system. The power transmitted is controlled to deliver 1000 MW and from Figure 4.7 it is seen that only 900MW is delivered. This is due to the loss caused by the impedance exerted by the second line of the bipole.

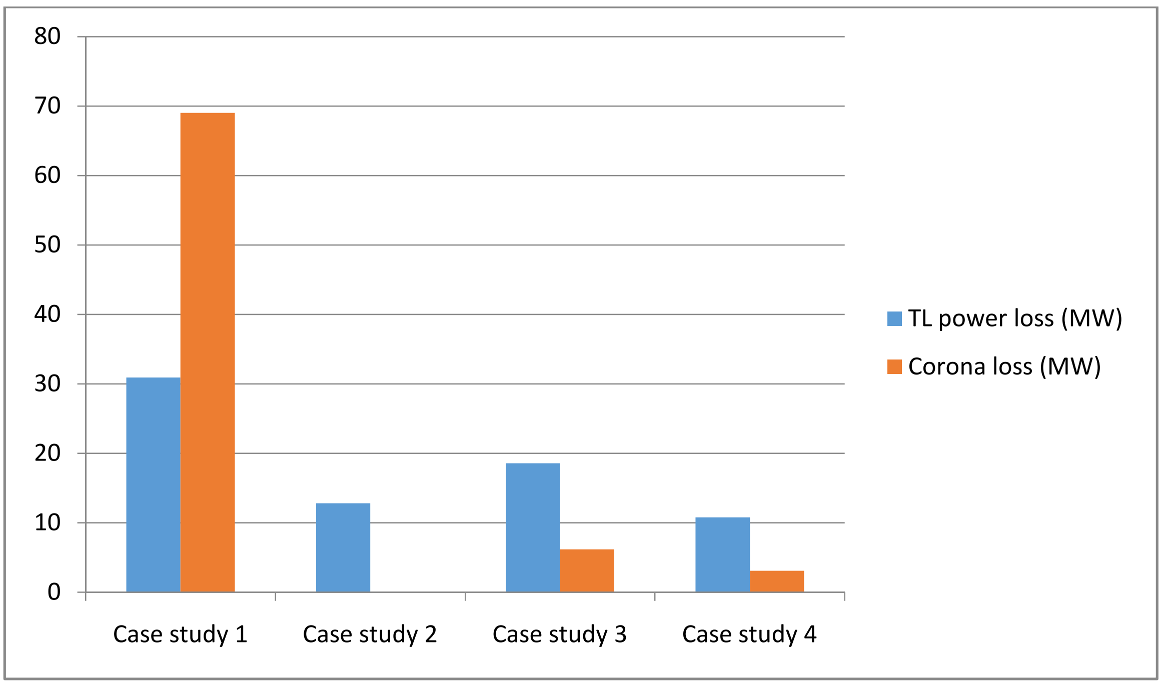


Figure 5.4: Transmission line loss and Corona loss

In Case study 1 the existing overhead line has a transmission line loss of 30.92 MW, which accounts for 16.76% it the total power transferred by the line. In Case study 2 the transmission line loss of the parallel OH line is 12.8 MW, which accounts for 2.41% of the total power transmitted by the line. In case study 3 the transmission line loss of the converted bipolar line is 18.56 MW. The large amount of loss is due to the impedance exerted by the second pole. The loss accounts for 2.06% of the total power transmitted by the line. Furthermore, in case study 3 the monopolar HVDC line only has a transmission line loss of 10.79 MW, which is the lowest loss from all the four case studies. The loss accounts for 2.1% of the total power transferred by the line.

From Figure 4.4 it can be seen that the corona loss in case study 1 for the existing HVAC transmission line is very high, which is 69.02 MW. In case study 3, the corona loss is 6.194 MW for the bipolar HVDC transmission line. Case study 4 has the lowest corona loss of 3.094 MW. Figure 4.4 shows that the monopolar HVDC line has the lowest both transmission line and corona loss.

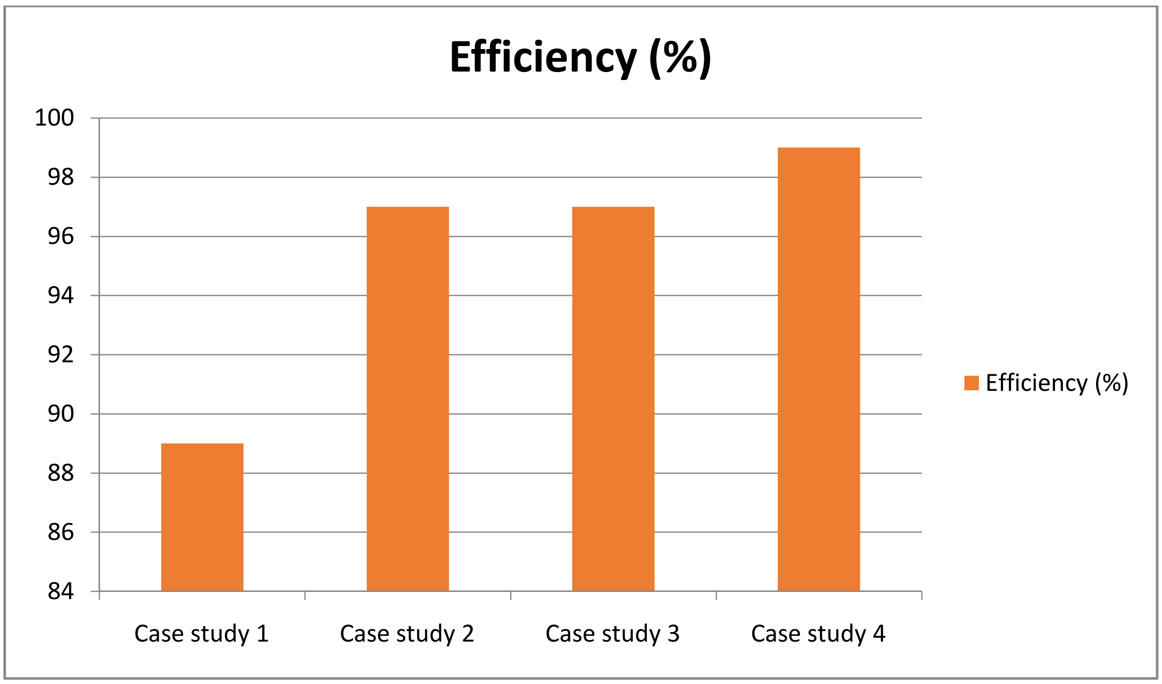


Figure 5.5: Efficiency of the Lines

Figure 4.5 shows that case study 4 is the most efficient of all the four case studies and case study 1 is the least efficient one. On the other hand case study 2 and case study 3 has similar efficiency.

5.2 Economical Aspect

In the previous section HVDC and HVAC transmission systems was compared based on the transmission line efficiency and corona loss comparison and seen that HVDC has better performance with respect to efficiency. In addition to this evaluation made above, the two systems have been evaluated in terms of the investment cost and energy cost as follows.

5.2.1 Cost of Conversion Versus Cost of a New Line

The basic cost of converting a line from AC to DC stems from the following:

a) Dismantling and mounting the conductors

- Replacement of the insulator assemblies
- Tower and foundation reinforcements, possibly required due to higher cantilever forces, overhead lines being hung higher, or additional sub-conductors

Additional costs can be incurred as a result of:

b) Older conductors having to be replaced as they cannot be re-used.

- Extra cost of conductor material as a result of the bundle conductors having more sub-conductors

c) Overhead lines having to be raised to comply with the latest regulations applying to electric field intensity

Any comparison of the cost of converting from AC to DC with the cost of erecting conventional AC lines should only take account of the expenditures incurred as a direct result of the line being used to transmit DC. Conversion costs resulting from the higher demands made on mechanical strength – both for AC and DC lines – should not be attributed to the conversion as such. The extra cost of raising the overhead lines in order to comply with lower field value requirements will have to be borne whether replacing

AC lines by new AC lines or converting from AC to DC. They can therefore be neglected when comparing the costs.

A rough estimate of the costs as fractions of the total is given below [3]:

Conversion according to a)

- ✓ approximately 1⁄3 of the cost of erecting a new DC line

in addition, according to b)

- ✓ approximately 1⁄7 to 1⁄10 of the cost of erecting a new DC line, depending on the configuration of the conductor bundle (quadruple or triple bundles)

Conversion according to c)

- ✓ approximately 1⁄2 of the cost of building a new line

In view of the possible extra costs, it should be considered from case to case whether a new line would make more sense than a conversion.

The absolute cost of erecting a new line varies strongly from country to country, since it depends mainly on labor costs and on the type of terrain crossed by the line. In mostcases, the cost of building a single bipole HVDC line is about US$ 210,000 per kilometer. For a double bipoleHVDC line , the figure is about US$ 325,000 to 360,000 per kilometer [3].

HVDC has a higher installation cost due to the converter stations and filtering requirement. Nevertheless; according to ABB (one of the leader supplier in HVDC transmission system equipments all over the world) Power Technologies posted in 2012 [34], the trend of power electronic components, for use in the main circuit of an HVDC transmission, being developed means that the relative cost of HVDC transmissions is reduced as the components become cheaper as a result of continuing innovative technological developments. Thus a large converter station costs about 50 kUS$/MW which is cheaper in current dollars compared with the situation 20 years ago.

In principle, existing overhead AC lines can be converted to overhead HVDC lines. For transmission voltages of ± 500kV, such a conversion can increase the AC power level by a factor of more than 2.5 for the same current density. This presumes re-use of the existing conductors and an unchanged tower design. The specific transmission losses are reduced by more than half.

The roughly estimated cost of conversion would in the best case be equal to only something more than one third of the cost of building a new DC line in compliance with the regulations in force today. The cost will be higher when the existing conductors are so old that they cannot be re-used. A completely new line is also an attractive proposition in such cases because of the gain in transmission power it brings with it.

The regulations governing the mechanical loading of overhead lines and the requirements in terms of electric and magnetic fields were recently revised. More strict requirements result in additional costs whether modifying existing AC lines or converting from AC to DC. For this reason, any comparison of the resultant cost of converting a line or of building a new one with the cost of previously built lines should be looked at more closely and not just be taken at its face value[3].

5.2.2 HVDC Investment Cost

The cost of a HVDC transmission system depends on many factors, such as power capacity to be transmitted, type of transmission medium, environmental conditions and other safety, regulatory requirements etc [16]. Even when these are available, the options available for optimal design(different commutation techniques, variety of filters, transformers etc.) render it is difficult to give a cost figure for a HVDC system. Nevertheless, a typical cost structure for the converter stations can be as shown in Fig5.6.

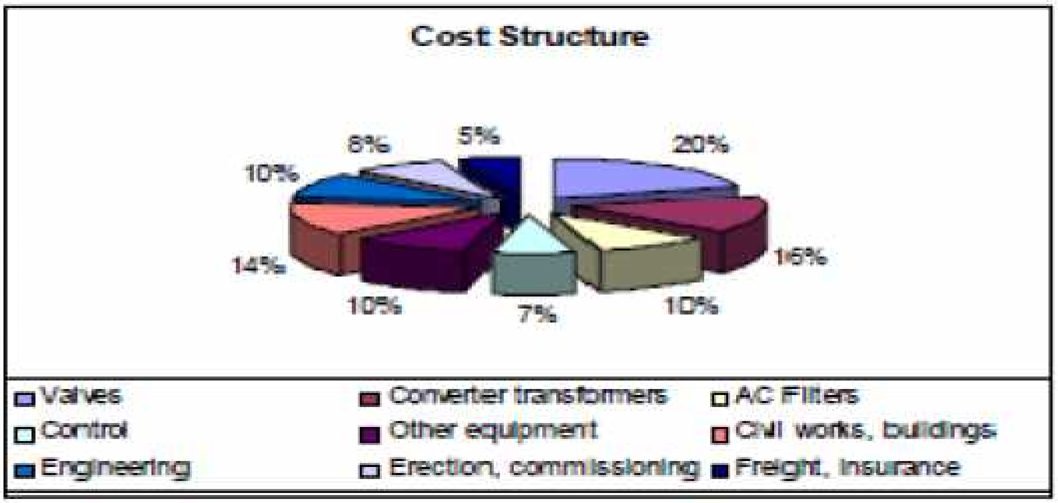


Figure 5.6: Cost structure for converter stations

The price per km for the bipolar OH line is 210,000 US$/km and for the converter station the average unit cost assumed is 50 kUS$/MW [23]. Single bipolar line have been assumed with a capacity of 1000 MW. The average investment cost of HVDC overhead transmission system is done based on Environmental and Social Impact Assessment (ESIA) & Resettlement Action Plan (RAP) cost for an HVDC Transmission system (4.0%), Physical Contingencies (5.0%), Price Contingencies (4.0%) and Engineering (4.5%) [25].

Physical Contingencies vs. Price Contingencies

It is common to encounter the term contingencies in project cost estimation and is an important concept in economic analysis of projects. Contingencies come in two categories:

- **Physical contingencies :**represent the estimated costs of the additional real resources expected to be required and therefore are always included in the economic analysis.
- **Price contingencies :**can arise either from expected changes in relative prices of project inputs or from expected general inflation and changes in the value of the monetary unit in which costs are measured.

Table 5.3: Average investment cost of HVDC bipolar transmission system.

Cost item	±500kV, 1000MW bipolar transmission line cost estimation	
Line length	km	352
Line Costs	US$/km	210,000.00
Total line costs	US$	73,920,000.00
EIA & RAP of line costs (4%)	US$	2,956,800.00
Power of one converter unit	MVA	250
Unit cost	kUS$/MVA	50.00
Converter cost	kUS$	12,500.00
Number of converters	-	8
Total converter cost	kUS$	100,000.00
Subtotal cost	US$	176,876,800.00
Engineering (4.5%)	US$	7,959,456.00
Total project cost	US$	184,836,256.00
Physical contingencies (5%)	US$	9,241,812.80
Price contingencies (5%)	US$	9,241,812.80
Grand Total cost	US$	203,319,881.60
Grand Total cost @ US$=20.22birr	Birr	4,111,128,006.00

The cost of erecting a new single bipolar HVDC transmission system costs about 203.32 Million US$. However, in this thesis the existing HVAC transmission line is converted to HVDC based on dismantling and mounting the conductors , which include replacement of the insulator assemblies, and tower and foundation reinforcements required due to higher ground clearance and overhead lines being hung higher. According to [3] the rough estimate of the costs as fractions of the total according to the above method is approximately 1⁄3 of the cost of erecting a new DC line. Therefore, the cost of conversion of Koka-Hurso transmission line is about 67.77 Million US$(1,370 Million Birr).

5.2.3 Parallel HVAC Investment Cost

The parallel HVAC transmission line will be constructed from Debrezeit III-Hurso as double circuit 400kV OH line .The rough cost estimation of the parallel HVAC OH line based on similar line cost in the grid is summarized on Table 4.5[34].

Table 5.4: Transmission line cost

Description	Unit	Qty.	Unit cost (US$)	Total Cos (US$)
400kV double circuit OH line	km	387	349,200.00	135,140,400.00

Table 5.5: Substation costs

Substation costs at Debrezeit III substation

Description	Unit	Qty.	Unit cost (US$)	Total cos (US$)
400kV out going line bay, double bus	Each	2	1,200,000.00	2,400,000.00

Substation costs at Hurso substation

Description	Unit	Qty.	Unit cost (US$)	Total cost (US$)
400kV incoming line bay, double bus	Each	2	1,200,000.00	2,400,000.00
400kV transformer bay, double bus	"	2	730,000.00	1,460,000.00
400kV bus-coupler bay	"	1	790,000.00	790,000.00
230kV transformer bay, double bus	"	2	447,492.13	894,984.26
230kV bus-coupler bay	"	1	449,945.68	449,945.68
230kV, shunt capacitor bay	"	1	453,600.00	453,600.00
400/230kV, 250 MVA transformer	"	2	5,447,836.77	10,895,673.54
230kV, 9×10MVar shunt capacitor	Mvar	90	22,000.00	1,980,000.00
Substation basics 400/230	LS	1	1,350,524.90	1,350,524.90
General civil work	LS	1	533,912.03	533,912.03
Total Substation Cost				23,608,640.41

Table 5.6: Cost estimation of Debrezeit III-Hurso HVAC transmission line

Item	Total price (US$)
Transmission cost	135,140,400.00
Substation cost	23,608,640.41
Total cost	158,749,040.40
Engineering and administration (5%)	7,937,452.02
Total project cost	166,686,492.40
Physical contingency (5%)	8,334,324.62
Price contingency (10%)	16,668,649.24
Grand Total project cost US$	191,689,466.30
Grand Total project cost(Birr) @ 1US$=20.22birr	3,875,961,009.00

From the Investment cost comparison, it is seen that, the parallel double circuit HVAC transmission system costs about 191.68 Million US$ and erecting a new bipolar HVDC transmission system costs about 203.32 Million US$. However the cost of converting the existing line to HVDC will only cost about 67.77 Million US$.

From the investment cost analysis it is obvious to see that 123.91 Million US$ investment cost can be saved by converting the existing line in to bipolar HVDC transmission system instead of constructing a new double circuit HVAC transmission line in parallel with the existing line as proposed by EEP.

5.2.4 Economic and Financial Analysis of Conversion

The analysis aims at evaluating the financial and economic viability of converting the existing Koka-Hurso 230kV double circuit line in to HVDC bipole transmission line. The main purpose of this transmission line conversion is to increases delivery of power to Eastern region of the national grid as well as improving the technical performance of the transmission line.

Methodology

The basic methodology applied is the discounted cash flow analysis with a feature of treating the annual capital charges associated with the conversion.

Valuation of Costs and Benefits

Financial Benefits are calculated based on the electricity tariff during operation period of the conversion. Not all economic benefits can be quantified properly and expressed in monetary terms. Economic benefits of HVDC conversion of the existing transmission line has been calculated by multiplying standard conversion factor in order to account those benefits, which are difficult to capture in this analysis.

Period of Analysis

The period of analysis of the present study is 35 years with the assumption that equipment which is amortized before the analysis period is to be replaced.

Discount Rate and Exchange Rate

Ethiopian Ministry of Finance and Economic Development recommends a discount rate of 10% for public sector projects [34].Hence in this thesis a base case discount rate of 10 % utilized for the financial and economic analysis, which is a current borrowing rate and opportunity cost of capital. The exchange rate is 1 US Dollar with 20.22 ETB (National Bank of Ethiopia, April, 2015).

Insurance and Interim Replacement

An insurance and interim replacement factor of 0.5% of the capital cost per year is applied, taken from recent studies for substation and transmission line by EEP.

Financial and Economic Analysis

The financial and economic analysis serves to assess the financial viability of converting the existing Koka-Hurso 230kV double circuit line in to HVDC bipole transmission line. The financial analysis is calculated by weighted average tariff of 0.06 US$/kWh which determines the revenues of EEP [34]. The cash flows associated with the Project are set-up over the lifetime of the project. The evaluation covers construction and 35 years of operation up to 2051. All costs and benefits are to be considered in the Financial Analysis.

The key assumptions for the Financial Analysis are summarized in the table below.

Table 5.7: Key assumptions for analysis

Item	Value
discount rate - Base	10%
discount rate - Low, High	8%, 12%
Exchange rate Birr/USD	20.22
Economic lifetime	35 year
O&M cost	2% of investment cost
Insurance & interim replacement	0.5% of investment cost
Demand growth from 2017 up to 2030	14%
Demand growth from 2031 up to 2039	7%

Analysis of Results (Quantifiable Benefits)

Cost-benefit analysis is conducted to evaluate the financial and economic viability of converting the existing Koka-Hurso 230kV double circuit line in to HVDC bipole transmission line. The tests applied in this analysis are; net present value (NPV), benefit cost ratio (B/C ratio) and internal rate of return (IRR).

The financial and economic analysis indicated in Appendix-5 shows that converting the existing Koka-Hurso 230kV double circuit line in to HVDC bipole transmission line for the three cases of discount rate leads to the following results. Considering all three cases have a financial Internal Rate of Return (FIRR) of 24.82%, a Net Present Value a profit of 5,304 million birr and a Benefit/Cost Ratio of 1.64 at a discount rate of 8% which is far above the minimum criteria and at a discount rate of 10% a Net Present Value a profit of 3,632 million birr and a Benefit Cost Ratio of 1.56 which is also far above the minimum criteria. At the higher discount rate of 12% the Project is still above the minimum criteria with a Net present value a profit of 2,502 million birr and a benefit cost ratio of 1.48.

In the same manner the economic analysis presented in Appendix-5 shows that, Considering all three cases have economical Internal Rate of Return (EIRR) of 30.23%, a Net Present Value a profit of 6,258 million birr and a Benefit/Cost Ratio of 1.85 at a discount rate of 8% which is far above the minimum criteria and at a discount rate of 10% a Net Present Value a profit of 4,399 million birr and a Benefit Cost Ratio of 1.77 which is also far above the minimum criteria. At the higher discount rate of 12% the conversion is still above the minimum criteria with a Net present value a profit of 3,138 million birr and a benefit cost ratio of 1.69. The Detail financial and economic analysis results are depicted in the attached Appendix-5. The summary result for the analysis is presented in Table 5.8 below.

Table 5.7: Summary of Financial & Economic Analysis

Financial & Economic Analysis result at 0.06US$/Kwh sales	Net Present Value (NPV)		Benefit Cost Ratio (B/C)		Internal Rate of Return (IRR)	
	Financial	Economic	Financial	Economic	Financial	Economic
At 8% Discount rate	5,304	6,258	1.64	1.85	**24.82%**	**30.23%**
At 10% Discount rate	3,632	4,399	1.56	1.77		
At 12% Discount rate	2,502	3,138	1.48	1.69		

Figure 5.7 and Figure 5.8 below shows the financial net present value and benefit cost ratio of converting the existing Koka-Hurso 230kV double circuit line in to HVDC bipole transmission line respectively. Also Figure 5.9 and 5.10 below shows economic net present value and benefit cost ratio respectively.

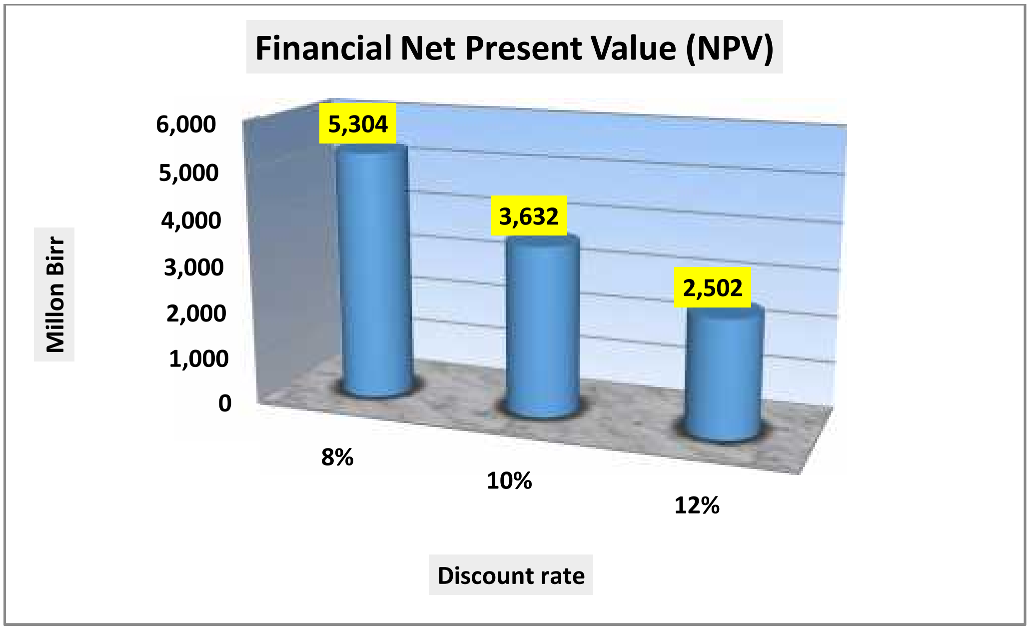


Figure 5.7: Financial Net Present Value of Conversion for Different Discount Rate

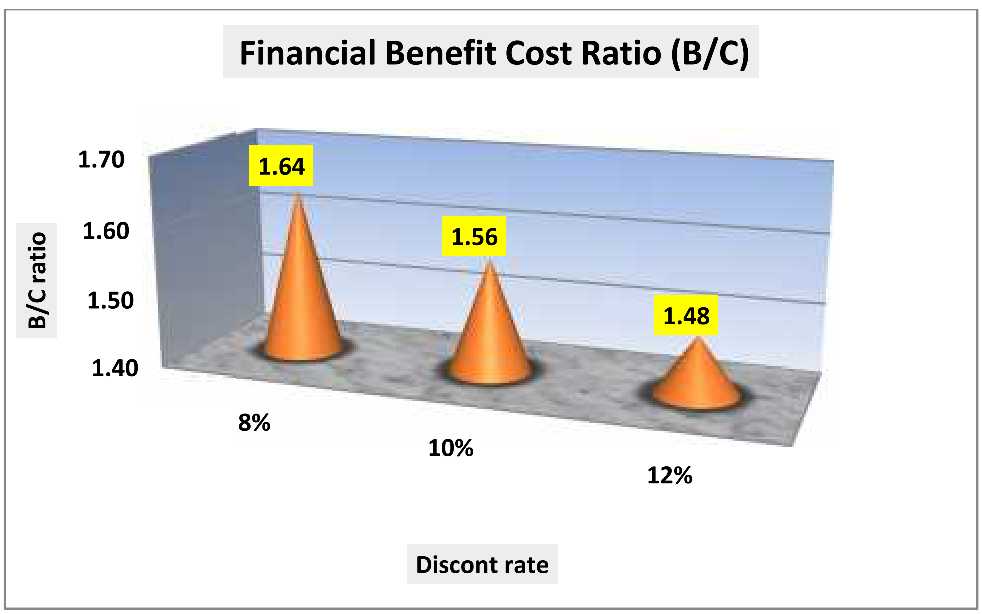


Figure 5.8: Financial Benefit Cost Ratio of Conversion for Different Discount Rate

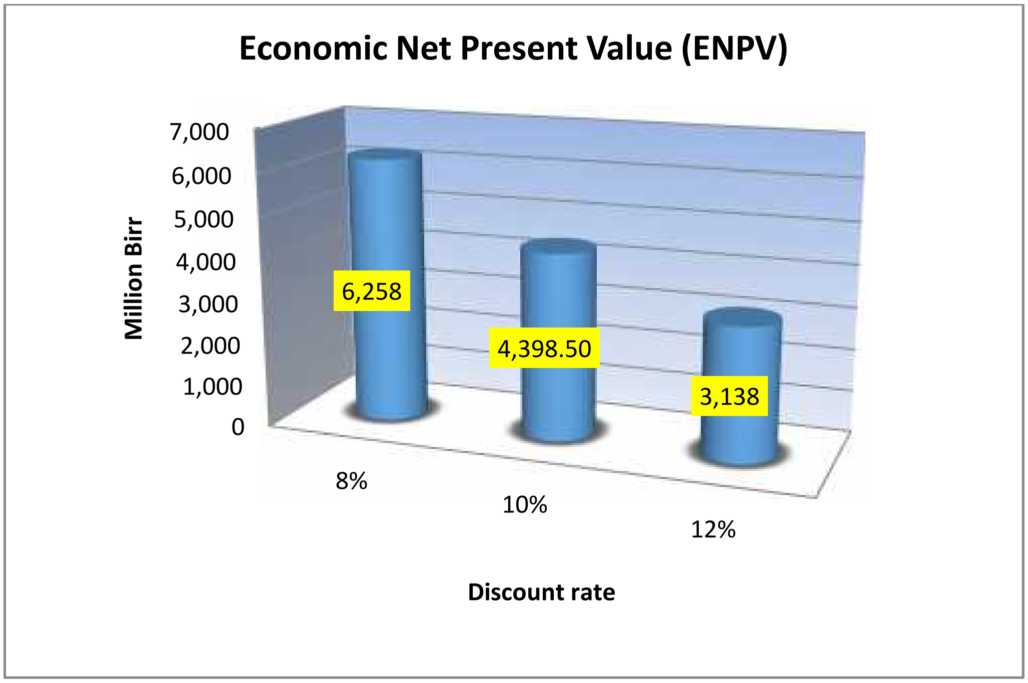


Figure 5.9: Economic Net Present Value of Conversion for Different Discount Rate

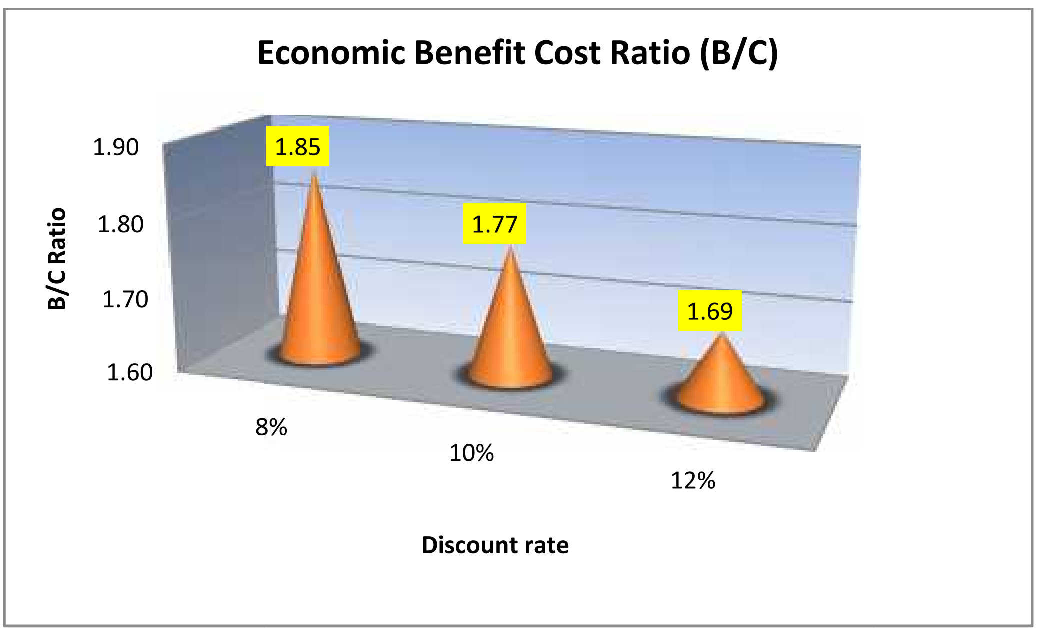


Figure 5.10: Economic Benefit Cost Ratio of Conversion for Different Discount Rate

CHAPTER SIX

CONCLUSION, RECOMMENDATIONS & FUTURE WORKS

6.1 Conclusion

In this thesis it is shown that existing overhead AC lines can be converted to overhead HVDC lines for transmission voltages of ± 500 kV, such a conversion can increase the AC power level by a factor of more than 2 for the same current density. This presumes re-use of the existing conductors and an unchanged tower design, but with changes in insulation assemblies. The specific transmission losses are reduced by more than half and the efficiency was improved by 16.18%.

From the technical comparison based on the transmission losses and transmission power for AC and DC lines assuming the same cross sectional area for the lines (DC lines with triple bundles), the bipolar HVDC lines has a loss as much as 69.75% lower compared to the existing transmission lines and the monopolar HVDC line has a loss as much as 83.02% lower compared to the existing transmission lines. On the other hand, the transmission powers of the bipolar HVDC line at ± 500 kV increase by 217% and the monopolar HVDC line at ± 500 kV increase by 75.8% from the power transfer capacity of the existing HVAC line.

Due to the technology advance made in the last century, the investment cost of conversion of HVDC transmission line is lower than an HVAC transmission line. From the Investment cost comparison, it is seen that, the parallel double circuit HVAC transmission system costs about 191.68 Million US$ and whereas erecting a new bipolar HVDC transmission system costs about 203.32 Million US$. However the cost of converting the existing line to HVDC will only cost about 67.77 Million US$. Cost of conversion is approximately 33% of cost of a new HVDC line and approximately 36% of cost of new HVAC line.

The financial and economic analysis indicated that the conversion of the existing transmission line to DC line is both financially and economically feasible for the three cases of discount rates of 8%, 10% and 12%. Considering all three cases have a financial Internal Rate of Return (FIRR) of 24.82%, a Net Present Value a profit of 3,632 million birr and a Benefit/Cost Ratio of 1.56 at the base discount rate of 10% which is far above the minimum criteria. In the same manner considering all three cases have economical Internal Rate of Return (EIRR) of 30.23%, a Net Present Value a profit of 4,399 million birr and a Benefit/Cost Ratio of 1.77 at the base discount rate of 10% which is far above the minimum criteria.

The construction of new overhead electric lines has various difficulties; thus, there is a need to look at alternatives options that increases the power transfer capability of the existing right of ways. It is technically feasible to achieve a substantial power upgrading of existing AC lines through their conversion for use with DC**,** by using the same conductors, tower bodies and foundations, but with changes in tower head and insulation assemblies.

An advantage of converting long AC lines into DC lines is that the thermal limit rating can be fully exploited. This particularly increases the availability of HVDC bipole systems. In the event of a DC line failing, the remaining pole can easily transmit double the power. Long AC lines, on the other hand, often cannot be loaded to their thermal limit rating as this would make them unstable.

In a general comparison of HVDC versus HVAC power transmission, the design of the transmission lines and the related investment costs are of great importance. The objective of this thesis is to evaluate the performance and efficiency of the transmission line by upgrading the existing HVAC transmission line to HVDC for increased power transfer capacity.

For the line insulation, air clearance requirements are more critical with HVAC due to the nonlinear behavior of the switching overvoltage withstand. The corona effects are more pronounced at AC voltage, therefore, larger conductor bundles are needed at higher system voltages.

The high transmission capacity of the HVDC lines, combined with lower requirements on conductor bundles and air clearances at the higher voltage levels, makes the HVDC lines very cost efficient compared to EHVAC lines. The cost advantage is even more pronounced at the highest voltage levels.

The roughly estimated cost of conversion would in the best case be equal to only something more than one third of the cost of building a new line incompliance with the regulations in force today. The cost will be higher when the existing conductors are so old that they cannot be re-used. A completely new line is also an attractive proposition in such cases because of the gain in transmission power it brings with it.

6.2 Recommendations

Based on the result of this thesis work, it is strongly recommended that EEP has to convert the existing HVAC transmission line in to an HVDC transmission line to solve the power delivery problem in the Eastern region of the national grid.

In this era of smart grids and smart technologies, it will be smart for the power company EEP to go back and investigate how existing lines can be re-employed for higher power transfer application.

6.3 Future Works

In this paper, it is shown that by converting the existing HVAC line into bipolar HVDC , we can improve the transmission capacity of the line by the factor of 2 or more the loss decreases considerably without altering the physical equipment. This work can be extended for research into integrated HVAC/HVDC transmission systems. As software tools are now available there is also a great need to evaluate them for their capability to conduct integrated studies. The in-depth stability analysis of both dynamic and transient stability requires also some study.

REFERENCES

[1] P. KUNDUR, “Power System Stability and Control”, MCGRAWHILL, 1994.

[2] OlofHeymn, Lars Weimers, and Mie-LotteBohl, “HVDC a Key Solution in Future Transmission Systems”, ABB, 2009.

[3] Dr. Michal Hausler, GrenotSchlayer, and GerdFitterer, “Converting AC Power Lines to DC for Higher Transmission Ratings”, ABB, 1997.

[4] IEEE Power & Energy Society, “IEEE Standard General Requirements and Test Code for Dry-Type and Oil-Immersed Smoothing Reactors for DC Power Transmission”, 14 February 2009.

[5] IEEE Power Engineering Society, “IEEE Standard for Calculating the Current-Temperature of Bare Overhead Conductors”, 30 January 2007.

[6] http://en.wikipedia.org/wiki/IEEE

[7] PARSON BRINCKERHOFF, “Ethiopian Power System Expansion Master Plan Study”, Volume 4, February 2014.

[8] A. Clerici, L. Paris, P. Danfors, “HVDC conversion of HVAC lines to provide substantial power upgrading”, IEEE Transactions on Power Delivery, Vol. 6, No.1 January 1991.

[9] EPRI. “Transmission Line Reference Book, HVDC to ± 600 kV”, Based on HVDC Transmission Research Project RP104, Palo Alto, USA, 1976.

[10] Siemens AG, “High Voltage Direct Current Transmission-Proven Technology for Power Exchange”, Germany, 2011.

[11] C.I.S.P.R. Radio, “Interference Characteristic of Overhead Power Lines and High-Voltage Equipment.”,Publicaton 18-1 First Edition 1982, Geneva.

[12] DIN VDE 0848-4/A3, “Sicherheit in elektromagnetischenFeldern. Vornorm”, July 1995

[13] ClaudloFacchinanddHanspeterFassler, “Special Report 60 Years of HVDC”, The Corporate Technical Journal, ABB.

[14] Lazaros P. Lazaridis," Economic Comparison of HVAC and HVDC Solutions for Large Offshore Wind Farms under Special Consideration of Reliability" Master’s Thesis, Royal Institute of Technology, Stockholm 2005.

[15] Joe Mooney, "Electrical Consideration for HVDC Transmission Lines", Power Engineers, March, 2010.

[16] D.M. Larruskain, I. Zamora, A.J. Mazón, O. Abarrategui, J. Monasterio, “Transmission and Distribution Networks: AC versus DC”, 9CHLIE Marbella 2005.

[17] Bahrman M.P., Johanson B.K., “The ABCs of HVDC transmission technologies.”, Power and energy maga-zine, IEEE Volume: , Issue: 2,2007.

[18] A. K. Pawani, B. SachidanandOjha, C. Rama Mishra, "Challanges of HVDC and Prospects ", IJATER Volume 2 , Issue 2, March 2012.

[19] Baljit Singh, Gagandeep Sharma, " Power upgrading of Transmission Line by converting EHVAC into EHVDC", IJSETT, 2012

[20] J R Lucas, “High Voltage Engineering”, 2001

[21] Crystal Eppinger, Andrew Gao, Brandon Valentine, and Nicole Zimmerman, “HVDC Transmission Senior Capstone Project,” PSU-ECE POWER Engineers, June 2003.

[22] ABB, “Reactive Power Compensation and Harmonic Filters for HVDC Classic,” ABB, Zurich, Switzerland

[23] Alstom, “HVDC: Connecting to the Future,” Alstom, France, 2010

[24] FITCHTNER, “Eastern Electricity Highway Project ”,Network Study Report Final , June 2012.

[25] FICHTNER, “Ethiopia-Kenya Power Systems Interconnection Project”, Basic Design of Transmission Lines Report, Volume 2, February 2009

[26] A. Singh, A.C. Britten, R. Stephen, D. Muftic, “Optimised Conductor and Conductor Bundle Solutions for Long Distance HVDC Transmission”, Inaugural IEEE PES 2005 Conference and Exposition in Africa Durban, South Africa, 11-15 July 2005

[27] IEE Power Series 17, “High Voltage Engineering and Testing”, ANNEXURE – B Calculation of Conductor Surface Voltage Gradient, Appendix 3.4.

[28] HATCH, “DC1010-Voltage and Conductor Optimization”, The Lower Churchill Project, April 2008.

[29] MelakuDesta, “Design and Evaluation of High Voltage Transmission Line for Grand Renaissance Hydro Electric Power Plant”, Master of Science Thesis, Addis Ababa Institute of Technology, October 20012.

[30] SIEMENS, “PSS/E™ 31.0 Program Application Guide”, Volume I, December, 2007.

[31] EEPCo, “Construction of 230kV Koka-Hurso Transmission line”, Section VI.

[32] http://www.pdu.edu.eg. (Book Material corona discharge.pdf) Downloaded June 06 2012

[33] Lars Weimers, “Bulk power transmission at extra high voltages, a comparison between transmission lines for HVDC at voltages above 600 kV DC and 800 kV AC.”, ABB Power Technologies ,Sweden, 2012.

[34] EEPCo, “Cost of Akaki II -Debrezeit III Poer Transmission Project”, June 27, 2011.

[35] Ludvica , “Feasibility of HVDC for City Infeed”, Master of Science Thesis, Royal Institute of Technology, Stockholm, 2003.

[36] J.Arrillaga, N.R.Watson, “Power System Harmonics”, John Wiley & Sons, Ltd, 2nd Edition, 2003.

[37] Chan-Ki Kim, Vijay K. Sood, Gil-Soo Jang, Seong-Joo Lim, and Seok-Jin Lee, “HVDC Transmission”, John Wiley & Sons (Asia) Pte Ltd ,2009

[38] Shu Zhou, “Modeling and Control of Multi-Terminal HVDC Networks for Offshore Wind Power Generation”, Master of Science Thesis, Cardiff University, October 20011.

[39] AB, G.S.-H., “It's time to connect - Technical description of HVDC Light technology. ”, ABB Power Technologies, 2006.

[40] Chan-Ki Kim, Vijay K. Sood, Gil-Soo Jang, Seong-Joo Lim and Seok-Jin Lee, “HVDC TRANMISSION-Power Conversion Applications in Power Systems.” , : IEEE Press, 2009.

[41] N. Flourentzou, V. G. Agelidis and G. D. Demetriades, “VSC-Based HVDC Power Transmission Systems: An Overview,” IEEE Trans. On Power Electronics, vol. 24, no. 3, pp. 592-602, Mar. 2009.

[42] M. Ragheb, “High Voltage Direct Current Power Transmission,” USA, May 2012.

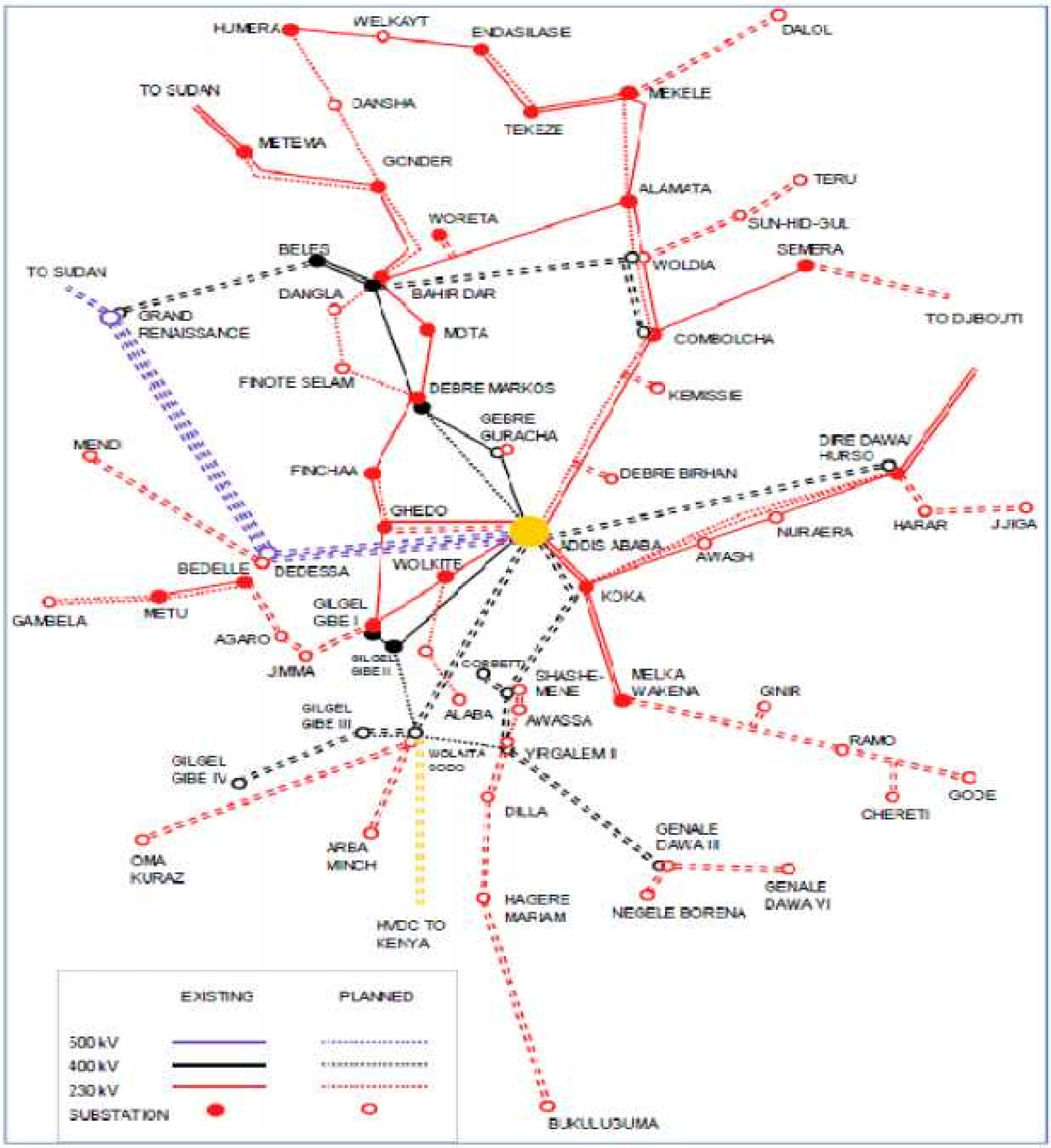
[43] Baljit Singh and Gagnadeep Sharma, “Power Upgrading of Transmission Line by Converting EHVAC into EHVDC,” IJSETT, 2012.

[44] K. Halsan and D. Loudon, “Feasibility of upgrading 300kV AC line to DC for Increase Power Transmission Capability,” CIGRE, 2008.

[45] K. Pawani, B. Sachidanand, and C. Rama Mishra, “Challenges of HVDC and its Prospect,” IJATER,Volume 2,Issue 2, March 2012.

Annex 1 : Main developments at 500/400/230 kV

Annex 1-1 - 2017: Main developments at 500/400/230 kV [7]



Annex 2: Metrological data for design [31]

(a) Rainfall

The amount of rainfall varies in different part of the country. The heaviest average annual precipitation is in the extreme south. The average annual rainfall for Koka is over 800 mm and Dire Dawa is 350mm.The highest rainfall is usually between July and September. The rest of the year is generally dry with occasional light rains.

(b) Temperatures

Temperatures are relatively high at all times of the year along the whole route of the transmission line. Average annual temperature is 20ºC - 26ºC absolute minimum temperature is 0ºC and absolute maximum temperature is 40ºC. The highest temperatures along the transmission line route generally occur between December and February. The lowest Temperature is registered between June and August.

Minimum temperature	$0^{o}C$
Average temperature	$25^{o}C$
Maximum temperature	$40^{0}C$
Loading temperature	75ºC

(c) Humidity

Mean relative humidity 50 to 70 %

(d) Isokeraunic Level

Although an isokeraunic level (storm) of 130 days/year can occur in the highlands of Ethiopia, the isokeraunic level in the lowlands is much less and a level of 70 days/year may be considered for design purposes.

(e) Maximum Solar Radiation

For design purposes a solar radiation value of 1100 W/m² may be considered.

(f) Earth quake loading

For design purposes an earthquake loading of 0.15 g may be assumed.

(g) Seismology

According to ESCP1: 1983 the route cross seismic zones I, II, III, however no special measure are required for the designs of transmission lines.

(h) Topography

The transmission line passes through the South Eastern high lands and their associated low lands and North Western highlands and their associated lowlands. These two geographical regions in which the transmission line passes are separated by Ethiopian rift Valley. These regions are made up of plateaus and mainly lowlands. The transmission line crosses the Awash River and the crossing is within the design span.

(i) Wind Speeds

Maximum recorded wind speed in the areas is 34m/s.

Annex 3 :ACSR conductor details [7]

Annex 3-1 – ACSR conductor details [7]

Code Name	Nominal Al Area	Equivalent Cu Area	Aluminium		Steel		Overall Dia.	Max. dc resistance at 20 °C	Stranding Factor[1]
	mm²	mm²	No.	mm	No.	mm	mm	Ohm/km	
Ostrich	152.2	95.48	26	2.73	7	2.12	17.23	0.1897	0.8086
Penguin	107.2	65.4	6	4.77	1	4.77	14.31	0.2676	0.768
Merlo	55.74	34	30	1.54	7	1.54	10.73	0.522	0.0264
Pernice	110.9	70	26	2.33	7	1.81	14.75	0.263	0.8086
Redwing	362.1	221	30	3.92	19	2.35	27.43	0.08	0.0220
Mallard	403.8	246	30	4.14	19	2.48	28.96	0.0717	0.8228
Raven	62.38	33.61	6	3.37	1	3.37	10.11	0.5078	0.768
Tiger	125	80.7	30	2.36	7	2.36	16.52	0.22020	0.8264
Quail	67.33	42.39	6	3.78	1	3.78	11.34	0.42470	0.768
Racoon	75	48.4	6	4.10	1	4.10	12.30	0.36220	0.768
70/12	70	42.6	26	1.85	7	1.44	11.7	0.413	0.8086

Annex 3-2 – Performance of the transmission line [7]

Voltage (kV)	Type	Conductor name	No of Cond. in bundle	Tower Config	Rac @ 85 °C	Thermal rating @ 85 °C per conductor	Thermal rating @ 85 °C per circuit		SIL Per circuit
					Ω/km	A	A	MVA	MW
66	ACSR	Penguin	1	Single	0.3379	395	395	45	12
66	ACSR	Penguin	1	Double	0.3379	395	395	45	12
66	ACSR	Raven	1	Single	0.6409	266	266	30	11
66	ACSR	Raven	1	Double	0.6409	266	266	30	11
132	AAAC	Ash	1	Single	0.2262	504	504	115	44
132	AAAC	Ash	1	Double	0.2262	504	504	115	44
132	ACSR	Tiger	1	Single	0.2782	450	450	103	44
132	ACSR	Tiger	1	Double	0.2782	450	450	103	44
230	AAAC	Ash	2	Single	0.2262	504	1008	402	174
230	AAAC	Ash	2	Double	0.2262	504	1008	402	174
230	ACSR	Mallard	1	Single	0.0914	887	887	353	136
230	ACSR	Mallard	1	Double	0.0914	887	887	353	139
230	ACSR	Redwing	1	Single	0.1018	831	831	331	134
230	ACSR	Redwing	1	Double	0.1018	831	831	331	138
230	AAAC	Yew	1	Single	0.0862	910	910	363	134
230	AAAC	Yew	1	Double	0.0862	910	910	363	138
400	AAAC	Aster	2	Single	0.0499	1273	2546	1764	526
400	AAAC	Aster	2	Double	0.0499	1273	2546	1764	557
400	ACSR	Condor	3	Single	0.0915	878	2634	1825	575
400	ACSR	Condor	3	Double	0.0915	878	2634	1825	612
400	ACSR	Dove	4	Single	0.1296	712	2848	1973	620
400	ACSR	Dove	4	Double	0.1296	712	2848	1973	664
500	ACSR	Condor	4	Single	0.0915	878	3512	3041	1003
500	ACSR	Condor	4	Double	0.0915	878	3512	3041	1048

Annex 4 : Standard insulation levels for range II. Extract from IEC 60071-1 [25]

Standard insulation levels for range II
(U_m > 245 kV)

Highest voltage for equipment U_m kV (r.m.s. value)	Standard switching impulse withstand voltage			Standard lightning impulse withstand voltage kV (peak value)
	Longitudinal insulation (note 1) kV (peak value)	Phase-to-earth kV (peak value)	Phase-to-phase (ratio to the phase-to-earth peak value)	
300	750	750	1,50	850 950
	750	850	1,50	950 1 050
362	850	850	1,50	950 1 050
	850	950	1,50	1 050 1 175
420	850	850	1,60	1 050 1 175
	950	950	1,50	1 175 1 300
	950	1 050	1,50	1 300 1 425
525	950	950	1,70	1 175 1 300
	950	1 050	1,60	1 300 1 425
	950	1 175	1,50	1 425 1 550
765	1 175	1 300	1,70	1 675 1 800
	1 175	1 425	1,70	1 800 1 950
	1 175	1 550	1,60	1 950 2 100

NOTES

1 Value of the impulse component of the relevant combined test.

2 The introduction of U_m = 550 kV (instead of 525 kV), 800 kV (instead of 765 kV), 1 200 kV, of a value between 765 kV and 1 200 kV, and of the associated standard withstand voltages, is under consideration.

Annex 5 : Financial and Economic analysis

Annex 5-2 : Financial analysis

Financial analysis

Discount rate	FNPV million birr	B/C ratio	FIRR
8%	5304	1.64	25%
10%	3632	1.56	
12%	2502	1.48	

Capital Investement in Million Birr	
Total cost	1,392.60
C/S Cost	800.71
T/L cost	591.89

	Capital Cost		Annual Costs						Benefit	
			0per. & Maint.		Grid	Insurance	Total			Net
Year	C/S	T/L	C/S	T/L	Energy	cost	Cost	demand		Benefit
	(M. Birr)	(M. Birr)	(M. Birr)	(M. Birr)	(M. Birr)	(M. Birr)	(M. Birr)	(MWh)	(M. Birr)	(M. Birr)
215	400	296	8.01	5.92	0.00	6.96	717.19		0.00	-717.19
216	400	296	8.01	5.92	0.00	6.96	717.19		0.00	-717.19
217			8.01	5.92	251.40	6.96	272.29	414,436	502.79	230.51
218			8.01	5.92	270.65	6.96	291.53	446,167	541.29	249.76
219			8.01	5.92	287.85	6.96	308.74	474,531	575.70	266.96
220			8.01	5.92	288.91	6.96	309.80	476,272	577.81	268.02
221			8.01	5.92	352.87	6.96	373.76	581,726	705.75	331.99
222			8.01	5.92	431.01	6.96	451.89	710,527	862.01	410.12
223			8.01	5.92	526.43	6.96	547.32	867,845	1,052.87	505.55
224			8.01	5.92	642.99	6.96	663.88	1,059,993	1,285.98	622.10
225			8.01	5.92	644.81	6.96	665.70	1,062,994	1,289.62	623.92
226			8.01	5.92	723.02	6.96	743.91	1,191,925	1,446.04	702.13
227			8.01	5.92	810.72	6.96	831.61	1,336,493	1,621.43	789.83
228			8.01	5.92	908.00	6.96	928.89	1,496,872	1,816.00	887.11

229			8.01	5.92	1,016.96	6.96	1,037.85	1,676,496	2,033.93	996.07
230			8.01	5.92	1,095.66	6.96	1,116.54	1,806,224	2,191.31	1,074.77
231			8.01	5.92	1,095.66	6.96	1,116.54	1,806,224	2,191.31	1,074.77
232			8.01	5.92	1,095.66	6.96	1,116.54	1,806,224	2,191.31	1,074.77
233			8.01	5.92	1,095.66	6.96	1,116.54	1,806,224	2,191.31	1,074.77
234			8.01	5.92	1,095.66	6.96	1,116.54	1,806,224	2,191.31	1,074.77
235			8.01	5.92	1,095.66	6.96	1,116.54	1,806,224	2,191.31	1,074.77
236			8.01	5.92	1,095.66	6.96	1,116.54	1,806,224	2,191.31	1,074.77
237			8.01	5.92	1,095.66	6.96	1,116.54	1,806,224	2,191.31	1,074.77
238			8.01	5.92	1,095.66	6.96	1,116.54	1,806,224	2,191.31	1,074.77
239			8.01	5.92	1,095.66	6.96	1,116.54	1,806,224	2,191.31	1,074.77
240			8.01	5.92	1,095.66	6.96	1,116.54	1,806,224	2,191.31	1,074.77
241			8.01	5.92	1,095.66	6.96	1,116.54	1,806,224	2,191.31	1,074.77
242			8.01	5.92	1,095.66	6.96	1,116.54	1,806,224	2,191.31	1,074.77
243			8.01	5.92	1,095.66	6.96	1,116.54	1,806,224	2,191.31	1,074.77
244			8.01	5.92	1,095.66	6.96	1,116.54	1,806,224	2,191.31	1,074.77
245			8.01	5.92	1,095.66	6.96	1,116.54	1,806,224	2,191.31	1,074.77
246			8.01	5.92	1,095.66	6.96	1,116.54	1,806,224	2,191.31	1,074.77
247			8.01	5.92	1,095.66	6.96	1,116.54	1,806,224	2,191.31	1,074.77
248			8.01	5.92	1,095.66	6.96	1,116.54	1,806,224	2,191.31	1,074.77
249			8.01	5.92	1,095.66	6.96	1,116.54	1,806,224	2,191.31	1,074.77

Annex 5-2 : Economical analysis

Economical analysis

Discount rate	ENPV million birr	B/C	EIRR
8%	6258	1.85	30%
10%	4399	1.77	
12%	3138	1.69	

Capital Investement in Million Birr	
Total cost	1,253.34
C/S Cost	720.64
T/L cost	532.70

	Capital Cost		Annual Costs						Benefit	
			0per. & Maint.		Grid	Insurance	Total			Net
Year	C/S	T/L	S/S	T/L	Energy	cost	Cost	demand		Benefit
	(M. Birr)	(M. Birr)	(M. Birr)	(M. Birr)	(M. Birr)	(M. Birr)	(M. Birr)	(MWh)	(M. Birr)	(M. Birr)
2015	360	266	7.21	5.33	0.00	6.96	581.55		0.00	-581.55
2016	360	266	7.21	5.33	0.00	6.96	581.55		0.00	-581.55
2017			7.21	5.33	251.40	6.96	243.80	414,436	502.79	258.99
2018			7.21	5.33	270.65	6.96	261.13	446,167	541.29	280.16
2019			7.21	5.33	287.85	6.96	276.61	474,531	575.70	299.09
2020			7.21	5.33	288.91	6.96	277.56	476,272	577.81	300.25
2021			7.21	5.33	352.87	6.96	335.13	581,726	705.75	370.62
2022			7.21	5.33	431.01	6.96	405.45	710,527	862.01	456.56
2023			7.21	5.33	526.43	6.96	491.34	867,845	1,052.87	561.53
2024			7.21	5.33	642.99	6.96	596.24	1,059,993	1,285.98	689.74
2025			7.21	5.33	644.81	6.96	597.88	1,062,994	1,289.62	691.75
2026			7.21	5.33	723.02	6.96	668.27	1,191,925	1,446.04	777.78
2027			7.21	5.33	810.72	6.96	747.19	1,336,493	1,621.43	874.24
2028			7.21	5.33	908.00	6.96	834.75	1,496,872	1,816.00	981.26
2029			7.21	5.33	1,016.96	6.96	932.81	1,676,496	2,033.93	1,101.11
2030			7.21	5.33	1,095.66	6.96	1,003.64	1,806,224	2,191.31	1,187.67
2031			7.21	5.33	1,095.66	6.96	1,003.64	1,806,224	2,191.31	1,187.67
2032			7.21	5.33	1,095.66	6.96	1,003.64	1,806,224	2,191.31	1,187.67
2033			7.21	5.33	1,095.66	6.96	1,003.64	1,806,224	2,191.31	1,187.67
2034			7.21	5.33	1,095.66	6.96	1,003.64	1,806,224	2,191.31	1,187.67
2035			7.21	5.33	1,095.66	6.96	1,003.64	1,806,224	2,191.31	1,187.67

2036			7.21	5.33	1,095.66	6.96	1,003.64	1,806,224	2,191.31	1,187.67
2037			7.21	5.33	1,095.66	6.96	1,003.64	1,806,224	2,191.31	1,187.67
2038			7.21	5.33	1,095.66	6.96	1,003.64	1,806,224	2,191.31	1,187.67
2039			7.21	5.33	1,095.66	6.96	1,003.64	1,806,224	2,191.31	1,187.67
2040			7.21	5.33	1,095.66	6.96	1,003.64	1,806,224	2,191.31	1,187.67
2041			7.21	5.33	1,095.66	6.96	1,003.64	1,806,224	2,191.31	1,187.67
2042			7.21	5.33	1,095.66	6.96	1,003.64	1,806,224	2,191.31	1,187.67
2043			7.21	5.33	1,095.66	6.96	1,003.64	1,806,224	2,191.31	1,187.67
2044			7.21	5.33	1,095.66	6.96	1,003.64	1,806,224	2,191.31	1,187.67
2045			7.21	5.33	1,095.66	6.96	1,003.64	1,806,224	2,191.31	1,187.67
2046			7.21	5.33	1,095.66	6.96	1,003.64	1,806,224	2,191.31	1,187.67
2047			7.21	5.33	1,095.66	6.96	1,003.64	1,806,224	2,191.31	1,187.67
2048			7.21	5.33	1,095.66	6.96	1,003.64	1,806,224	2,191.31	1,187.67
2049			7.21	5.33	1,095.66	6.96	1,003.64	1,806,224	2,191.31	1,187.67

Annex 6 : PSS/E Load Flow Simulation Results

Annex 6-1: Case-1

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PTI INTERACTIVE POWER SYSTEM SIMULATOR--PSS(tm)E    FRI, DEC 19 2014  19:19

 ETHIOPIAN POWER SYSTEM TRANSMISSION UPGRADING STUDY                          RATING
%MVA FOR TRANSFORMERS

 YEAR 2017  - PEAK LOAD FLOW                                                 SET A   %
I  FOR NON-TRANSFORMER BRANCHES



 BUS 203004 HURSO       230.00 CKT     MW     MVAR     MVA   % 0.9571PU  -65.87  X--
- LOSSES ---X X---- AREA -----X X---- ZONE -----X 203004

                                                               220.13KV
MW     MVAR    3 EASTERN         4 OROMIA

  TO  103007  HURSO          132.00   1       12.1       0.3      12.1   10  1.0000LK
0.00    0.17    3 EASTERN         4 OROMIA

  TO  103007  HURSO          132.00   2       12.1       0.3      12.1   10  1.0000LK
0.00    0.17    3 EASTERN         4 OROMIA

  TO  203001  ADIGALA         230.00    1       -16.8      -12.6       21.0      5
0.12    0.35    3 EASTERN        15 EXPORT

  TO  203002  D.DAWA3         230.00    1       -23.6         8.9       25.2      7
0.05    0.13    3 EASTERN        10 DIRE DAWA

  TO  203002  D.DAWA3         230.00    2       -23.6         8.9       25.2      7
0.05    0.13    3 EASTERN        10 DIRE DAWA

  TO  203003  DJIB-PK12      230.00    1       -27.5      -15.6       31.6      8
0.54    1.55    3 EASTERN        15 EXPORT

  TO  203005  HARAR  IV       230.00    1         46.2      -30.6        55.5    14
0.33    0.94    3 EASTERN         9 HARARI

  TO  203005  HARAR  IV       230.00    2         46.2      -30.6        55.5    14
0.33    0.94    3 EASTERN         9 HARARI
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  TO  203006  DIRE-IND-230230.00    1          99.4        23.7      102.2    27
0.27   0.76   3 EASTERN       10 DIRE DAWA

  TO  203006  DIRE-IND-230230.00    2          99.4        23.7      102.2    27
0.27   0.76   3 EASTERN       10 DIRE DAWA

  TO  203021  HURSO  TS       230.00    1          5.2        -9.1       10.5     3
0.00   0.00   3 EASTERN        5 SOMALE

  TO  211001  KOKA              230.00    1      -126.8        20.7      128.4    33
15.46   43.22   11 SOUTH EASTER    4 OROMIA

  TO  211001  KOKA              230.00    2      -126.8        20.7      128.4    33
15.46   43.22   11 SOUTH EASTER    4 OROMIA

   M I S M A T C H                   24.4    -8.6    25.8



 BUS 211001 KOKA        230.00 CKT     MW     MVAR     MVA   % 0.9960PU  -47.09  X--
- LOSSES ---X X---- AREA -----X X---- ZONE -----X 211001

                                                                229.08KV
MW     MVAR   11 SOUTH EASTER    4 OROMIA

  TO  203004  HURSO             230.00    1       142.2      -42.2      148.3    37
15.46   43.22    3 EASTERN         4 OROMIA

  TO  203004  HURSO             230.00    2       142.2      -42.2      148.3    37
15.46   43.22    3 EASTERN         4 OROMIA

  TO  210001  AWSH-7KL        230.00    1       215.2      -14.7      215.7    61
10.49   46.73   10 SEMERA          4 OROMIA

  TO  211002  M-WAKNA         230.00    1       -22.0         1.3       22.0     9
0.20   0.85   11 SOUTH EASTER    4 OROMIA

  TO  211002  M-WAKNA         230.00    2       -22.0         1.3       22.0     9
0.20   0.85   11 SOUTH EASTER    4 OROMIA

  TO  211006  ADAMA    WF      230.00    1       -27.4      -53.2       59.8    15
0.08   0.23   11 SOUTH EASTER    4 OROMIA

  TO  211006  ADAMA    WF      230.00    2       -27.4      -53.2       59.8    15
0.08   0.23   11 SOUTH EASTER    4 OROMIA
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TO 211011 ASSELA WF 230.00 1 -52.9 54.6 76.0 19
0.92 2.56 11 SOUTH EASTER 4 OROMIA

TO 211011 ASSELA WF 230.00 2 -52.9 54.6 76.0 19
0.92 2.56 11 SOUTH EASTER 4 OROMIA

TO 213001 DUKEM TAP 2 230.00 2 -155.6 48.1 162.8 60
1.45 6.88 13 SOUTHERN 4 OROMIA

TO 215002 DUKEM TAP 1 230.00 1 -155.6 48.1 162.8 60
1.45 6.88 15 WESTERN 4 OROMIA

M I S M A T C H 16.2 -2.6 16.4

BUS 412001 DB-ZEIT2400 400.00 CKT MW MVAR MVA % 1.0058PU -36.75 X--
- LOSSES ---X X---- AREA -----X X---- ZONE -----X 412001

402.30KV
MW MVAR 12 SOUTHERN A.A 4 OROMIA

TO 212003 DB-ZEIT3230 230.00 1 193.9 -15.0 194.5 39 1.0000LK
0.22 10.10 12 SOUTHERN A.A 4 OROMIA

TO 212003 DB-ZEIT3230 230.00 2 193.9 -15.0 194.5 39 1.0000LK
0.22 10.10 12 SOUTHERN A.A 4 OROMIA

TO 402002 AKAKI2400 400.00 1 -193.9 15.0 194.5 10
0.23 1.85 12 SOUTHERN A.A 14 ADDIS ABABA

TO 402002 AKAKI2400 400.00 2 -193.9 15.0 194.5 10
0.23 1.85 12 SOUTHERN A.A 14 ADDIS ABABA

Annex 6-2: Case-2

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     PTI INTERACTIVE POWER SYSTEM SIMULATOR--PSS(tm)E    FRI, DEC 19 2014  19:23

 ETHIOPIAN POWER SYSTEM TRANSMISSION UPGRADING STUDY                          RATING
%MVA FOR TRANSFORMERS

 YEAR 2017  - PEAK LOAD FLOW                                                 SET A   %
I  FOR NON-TRANSFORMER BRANCHES

 BUS 203004 HURSO       230.00 CKT     MW     MVAR     MVA   % 1.0212PU  -48.08  X--
- LOSSES ---X X---- AREA -----X X---- ZONE -----X 203004

                                                                    234.88KV
MW     MVAR    3 EASTERN         4 OROMIA

  TO  103007  HURSO          132.00   1       23.7       5.8      24.4   20  1.0000LK
0.02    0.62    3 EASTERN         4 OROMIA

  TO  103007  HURSO          132.00   2       23.7       5.8      24.4   20  1.0000LK
0.02    0.62    3 EASTERN         4 OROMIA

  TO  203001  ADIGALA         230.00    1         11.5       -9.8       15.1      4
0.05    0.15    3 EASTERN       15 EXPORT

  TO  203002  D.DAWA3         230.00    1         22.1       11.3       24.8      6
0.04    0.11    3 EASTERN       10 DIRE DAWA

  TO  203002  D.DAWA3         230.00    2         22.1       11.3       24.8      6
0.04    0.11    3 EASTERN       10 DIRE DAWA

  TO  203003  DJIB-PK12      230.00    1         -0.5      -12.9       12.9      3
0.00    0.00    3 EASTERN       15 EXPORT

  TO  203005  HARAR  IV       230.00    1          56.7      -17.1       59.2    14
0.34    0.97    3 EASTERN         9 HARARI

  TO  203005  HARAR  IV       230.00    2          56.7      -17.1       59.2    14
0.34    0.97    3 EASTERN         9 HARARI
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  TO  203006  DIRE-IND-230230.00     1        117.9         29.7       121.6    30
0.33    0.94    3 EASTERN       10 DIRE DAWA

  TO  203006  DIRE-IND-230230.00     2        117.9         29.7       121.6    30
0.33    0.94    3 EASTERN       10 DIRE DAWA

  TO  203021  HURSO  TS        230.00    1         38.9        -7.5        39.6    10
0.00    0.01    3 EASTERN        5 SOMALE

  TO  211001  KOKA              230.00    1       -64.2       -7.3        64.6    16
3.56    9.95   11 SOUTH EASTER    4 OROMIA

  TO  211001  KOKA              230.00    2       -64.2       -7.3        64.6    16
3.56    9.95   11 SOUTH EASTER    4 OROMIA

  TO  403001  HURSO400       400.00   1     -181.1      -7.3     181.2   72  1.0000UN
0.37   17.01    3 EASTERN        4 OROMIA

  TO  403001  HURSO400       400.00   2     -181.1      -7.3     181.2   72  1.0000UN
0.37   17.01    3 EASTERN        4 OROMIA


 BUS 211001 KOKA        230.00 CKT     MW     MVAR     MVA   % 1.0224PU  -39.44  X--
- LOSSES ---X X---- AREA -----X X---- ZONE -----X 211001

                                                               235.15KV
MW     MVAR   11 SOUTH EASTER    4 OROMIA

  TO  203004  HURSO             230.00    1         67.8      -53.5        86.4    21
3.56    9.95    3 EASTERN        4 OROMIA

  TO  203004  HURSO             230.00    2         67.8      -53.5        86.4    21
3.56    9.95    3 EASTERN        4 OROMIA

  TO  210001  AWSH-7KL        230.00    1        124.5       -23.5      126.7    35
3.37   15.01   10 SEMERA         4 OROMIA

  TO  211002  M-WAKNA         230.00    1       -14.7        -7.2        16.4     6
0.07    0.30   11 SOUTH EASTER    4 OROMIA

  TO  211002  M-WAKNA         230.00    2       -14.7        -7.2        16.4     6
0.07    0.30   11 SOUTH EASTER    4 OROMIA

  TO  211006  ADAMA    WF      230.00    1       -27.7        29.2        40.2    10
0.04    0.10   11 SOUTH EASTER    4 OROMIA
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  TO  211006  ADAMA    WF      230.00    2        -27.7        29.2        40.2    10
0.04    0.10   11 SOUTH EASTER    4 OROMIA

  TO  211011  ASSELA  WF      230.00    1        -53.9        19.2        57.2    14
0.48    1.33   11 SOUTH EASTER    4 OROMIA

  TO  211011  ASSELA  WF      230.00    2        -53.9        19.2        57.2    14
0.48    1.33   11 SOUTH EASTER    4 OROMIA

  TO  213001  DUKEM  TAP  2  230.00    2        -33.7        24.1        41.4    15
0.09    0.45   13 SOUTHERN        4 OROMIA

  TO  215002  DUKEM  TAP  1  230.00    1        -33.7        24.1        41.4    15
0.09    0.45   15 WESTERN         4 OROMIA


 BUS 403001 HURSO400    400.00 CKT     MW     MVAR     MVA   % 1.0316PU  -42.76  X--
- LOSSES ---X X---- AREA -----X X---- ZONE -----X 403001

                                                               412.64KV
MW     MVAR    3 EASTERN         4 OROMIA

  TO  203004  HURSO          230.00   1      181.5      24.3     183.1   73  1.0000LK
0.37   17.01    3 EASTERN         4 OROMIA

  TO  203004  HURSO          230.00   2      181.5      24.3     183.1   73  1.0000LK
0.37   17.01    3 EASTERN         4 OROMIA

  TO  412001  DB-ZEIT2400  400.00    1      -181.5      -24.3      183.1       9
2.44   18.84   12 SOUTHERN A.A    4 OROMIA

  TO  412001  DB-ZEIT2400  400.00    2      -181.5      -24.3      183.1       9
2.44   18.84   12 SOUTHERN A.A    4 OROMIA


 BUS 412001 DB-ZEIT2400 400.00 CKT     MW     MVAR     MVA   % 1.0245PU  -36.93  X--
- LOSSES ---X X---- AREA -----X X---- ZONE -----X 412001

                                                               409.81KV
MW     MVAR   12 SOUTHERN A.A    4 OROMIA

  TO  212003  DB-ZEIT3230  230.00   1      194.0      55.8     201.9   40  1.0000LK
0.23   10.48   12 SOUTHERN A.A    4 OROMIA
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  TO  212003  DB-ZEIT3230  230.00    2       194.0       55.8      201.9   40  1.0000LK
0.23   10.48   12 SOUTHERN A.A    4 OROMIA

  TO  402002  AKAKI2400       400.00     1       -377.9       103.3       391.8     19
0.89    7.28   12 SOUTHERN A.A   14 ADDIS ABABA

  TO  402002  AKAKI2400       400.00     2       -377.9       103.3       391.8     19
0.89    7.28   12 SOUTHERN A.A   14 ADDIS ABABA

  TO  403001  HURSO400         400.00     1         183.9    -159.1       243.2     12
2.44   18.84    3 EASTERN         4 OROMIA

  TO  403001  HURSO400         400.00     2         183.9    -159.1       243.2     12
2.44   18.84    3 EASTERN         4 OROMIA
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Annex 6-3: Case-3

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     PTI INTERACTIVE POWER SYSTEM SIMULATOR--PSS(tm)E    FRI, DEC 19 2014  19:27

 ETHIOPIAN POWER SYSTEM TRANSMISSION UPGRADING STUDY                          RATING
%MVA FOR TRANSFORMERS

 YEAR 2017  - PEAK LOAD FLOW                                                 SET A   %
I  FOR NON-TRANSFORMER BRANCHES



 BUS 203004 HURSO       230.00 CKT     MW     MVAR     MVA   % 1.0000PU  -35.21  X--
- LOSSES ---X X---- AREA -----X X---- ZONE -----X 203004

                                                               230.00KV
MW     MVAR    3 EASTERN         4 OROMIA

  TO SWITCHED SHUNT                    0.0  -346.4   346.4

  TO 211001 KOKA         230.00 2DI  -440.7   185.9   478.3      0.9000LO   21.83HI
9.28  252.34   11 SOUTH EASTER    4 OROMIA       "1"

  TO 211001 KOKA         230.00 2DI  -440.7   185.9   478.3      0.9000LO   21.83HI
9.28  252.34   11 SOUTH EASTER    4 OROMIA       "2"

  TO  103007  HURSO          132.00   1       41.8       5.5      42.2   34  1.0000LK
0.05    1.92    3 EASTERN         4 OROMIA

  TO  103007  HURSO          132.00   2       41.8       5.5      42.2   34  1.0000LK
0.05    1.92    3 EASTERN         4 OROMIA

  TO  203001  ADIGALA          230.00    1          39.8      -20.9        45.0    11
0.54    1.56    3 EASTERN        15 EXPORT

  TO  203002  D.DAWA3          230.00    1       151.3         8.5      151.6    38
1.41    3.94    3 EASTERN        10 DIRE DAWA

  TO  203002  D.DAWA3          230.00    2       151.3         8.5      151.6    38
1.41    3.94    3 EASTERN        10 DIRE DAWA

  TO  203003  DJIB-PK12      230.00    1         28.3      -24.7        37.5      9
0.60    1.73    3 EASTERN        15 EXPORT
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  TO  203005  HARAR  IV        230.00    1          61.4      -18.5        64.1    16
0.42    1.20    3 EASTERN        9 HARARI

  TO  203005  HARAR  IV        230.00    2          61.4      -18.5        64.1    16
0.42    1.20    3 EASTERN        9 HARARI

  TO  203006  DIRE-IND-230230.00    1        117.9        23.8      120.3    30
0.34    0.96    3 EASTERN       10 DIRE DAWA

  TO  203006  DIRE-IND-230230.00    2        117.9        23.8      120.3    30
0.34    0.96    3 EASTERN       10 DIRE DAWA

  TO  203021  HURSO  TS        230.00    1          68.3      -18.5        70.7    18
0.01    0.04    3 EASTERN        5 SOMALE



 BUS 211001 KOKA        230.00 CKT     MW     MVAR     MVA   % 0.9513PU  -55.97  X--
- LOSSES ---X X---- AREA -----X X---- ZONE -----X 211001

                                                               218.81KV
MW     MVAR   11 SOUTH EASTER    4 OROMIA

  TO 203004 HURSO       230.00 2DR   450.0    66.4   454.9     0.9000LO    5.00LO
9.28  252.34    3 EASTERN        4 OROMIA       "1"

  TO 203004 HURSO       230.00 2DR   450.0    66.4   454.9     0.9000LO    5.00LO
9.28  252.34    3 EASTERN        4 OROMIA       "2"

  TO  210001  AWSH-7KL        230.00    1      -143.2        32.6      146.8    44
5.51   24.54   10 SEMERA         4 OROMIA

  TO  211002  M-WAKNA         230.00    1       -28.6      -55.2        62.2    25
0.91    3.92   11 SOUTH EASTER    4 OROMIA

  TO  211002  M-WAKNA         230.00    2       -28.6      -55.2        62.2    25
0.91    3.92   11 SOUTH EASTER    4 OROMIA

  TO  211006  ADAMA    WF      230.00    1       -27.6      -49.4        56.6    15
0.08    0.22   11 SOUTH EASTER    4 OROMIA

  TO  211006  ADAMA    WF      230.00    2       -27.6      -49.4        56.6    15
0.08    0.22   11 SOUTH EASTER    4 OROMIA

  TO  211011  ASSELA  WF      230.00    1       -53.7      -42.2        68.3    18
0.65    1.82   11 SOUTH EASTER    4 OROMIA
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TO 211011 ASSELA WF 230.00 2 -53.7 -42.2 68.3 18
0.65 1.82 11 SOUTH EASTER 4 OROMIA

TO 213001 DUKEM TAP 2 230.00 2 -268.4 64.1 276.0 106
4.54 21.56 13 SOUTHERN 4 OROMIA

TO 215002 DUKEM TAP 1 230.00 1 -268.4 64.1 276.0 106
4.54 21.56 15 WESTERN 4 OROMIA

BUS 412001 DB-ZEIT2400 400.00 CKT MW MVAR MVA % 0.9899PU -39.08 X--
- LOSSES ---X X---- AREA -----X X---- ZONE -----X 412001

395.97KV
MW MVAR 12 SOUTHERN A.A 4 OROMIA

TO 212003 DB-ZEIT3230 230.00 1 194.0 4.2 194.1 39 1.0000LK
0.23 10.38 12 SOUTHERN A.A 4 OROMIA

TO 212003 DB-ZEIT3230 230.00 2 194.0 4.2 194.1 39 1.0000LK
0.23 10.38 12 SOUTHERN A.A 4 OROMIA

TO 402002 AKAKI2400 400.00 1 -194.0 -4.2 194.1 10
0.23 1.88 12 SOUTHERN A.A 14 ADDIS ABABA

TO 402002 AKAKI2400 400.00 2 -194.0 -4.2 194.1 10
0.23 1.88 12 SOUTHERN A.A 14 ADDIS ABABA

Annex 6-4: Case-4

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     PTI INTERACTIVE POWER SYSTEM SIMULATOR--PSS(tm)E    FRI, DEC 19 2014  19:30

 ETHIOPIAN POWER SYSTEM TRANSMISSION UPGRADING STUDY                          RATING
%MVA FOR TRANSFORMERS

 YEAR 2017  - PEAK LOAD FLOW                                                 SET A   %
I  FOR NON-TRANSFORMER BRANCHES



 BUS 203004 HURSO       230.00 CKT     MW     MVAR     MVA   % 1.0000PU  -54.31  X--
- LOSSES ---X X---- AREA -----X X---- ZONE -----X 203004

                                                               230.00KV
MW     MVAR    3 EASTERN         4 OROMIA

  TO SWITCHED SHUNT                   0.0  -194.3   194.3

  TO 211001 KOKA         230.00 2DI  -489.2   162.8   515.6      0.9000LO   17.00LO
10.79  263.10   11 SOUTH EASTER    4 OROMIA       "1"

  TO  103007  HURSO          132.00   1       24.2       6.7      25.1   20  1.0000LK
0.02    0.68    3 EASTERN         4 OROMIA

  TO  103007  HURSO          132.00   2       24.2       6.7      25.1   20  1.0000LK
0.02    0.68    3 EASTERN         4 OROMIA

  TO  203001  ADIGALA         230.00    1           3.2       -4.5         5.5      1
0.00    0.01    3 EASTERN        15 EXPORT

  TO  203002  D.DAWA3         230.00    1         32.9       10.8        34.6      9
0.08    0.22    3 EASTERN        10 DIRE DAWA

  TO  203002  D.DAWA3         230.00    2         32.9       10.8        34.6      9
0.08    0.22    3 EASTERN        10 DIRE DAWA

  TO  203003  DJIB-PK12      230.00    1         -9.0       -7.5        11.7      3
0.07    0.20    3 EASTERN        15 EXPORT

  TO  203005  HARAR  IV       230.00    1          57.3     -18.7        60.3    15
0.37    1.05    3 EASTERN         9 HARARI
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  TO  203005  HARAR  IV        230.00    2          57.3      -18.7        60.3    15
0.37    1.05    3 EASTERN         9 HARARI

  TO  203006  DIRE-IND-230230.00     1         117.9         23.8       120.3    30
0.34    0.96    3 EASTERN        10 DIRE DAWA

  TO  203006  DIRE-IND-230230.00     2         117.9         23.8       120.3    30
0.34    0.96    3 EASTERN        10 DIRE DAWA

  TO  203021  HURSO  TS        230.00    1         30.2        -1.7        30.3     8
0.00    0.01    3 EASTERN         5 SOMALE



 BUS 211001 KOKA        230.00 CKT     MW     MVAR     MVA   % 0.9893PU  -48.47  X--
- LOSSES ---X X---- AREA -----X X---- ZONE -----X 211001

                                                                  227.53KV
MW     MVAR   11 SOUTH EASTER    4 OROMIA

  TO 203004 HURSO        230.00 2DR   500.0   100.3   510.0      0.9000LO    8.95RG
10.79  263.10    3 EASTERN         4 OROMIA       "1"

  TO  210001  AWSH-7KL        230.00    1          85.6      -25.4        89.3    26
1.74    7.75   10 SEMERA          4 OROMIA

  TO  211002  M-WAKNA          230.00    1       -23.5      -29.9        38.0    15
0.27    1.15   11 SOUTH EASTER    4 OROMIA

  TO  211002  M-WAKNA          230.00    2       -23.5      -29.9        38.0    15
0.27    1.15   11 SOUTH EASTER    4 OROMIA

  TO  211006  ADAMA    WF      230.00    1       -27.6      -49.7        56.9    14
0.07    0.21   11 SOUTH EASTER    4 OROMIA

  TO  211006  ADAMA    WF      230.00    2       -27.6      -49.7        56.9    14
0.07    0.21   11 SOUTH EASTER    4 OROMIA

  TO  211011  ASSELA  WF      230.00    1       -54.0      -10.5        55.0    14
0.42    1.17   11 SOUTH EASTER    4 OROMIA

  TO  211011  ASSELA  WF      230.00    2       -54.0      -10.5        55.0    14
0.42    1.17   11 SOUTH EASTER    4 OROMIA

  TO  213001  DUKEM  TAP  2  230.00    2      -187.7        52.7      195.0    72
2.10    9.98   13 SOUTHERN        4 OROMIA
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TO 215002 DUKEM TAP 1 230.00 1 -187.7 52.7 195.0 72
2.10 9.98 15 WESTERN 4 OROMIA

BUS 412001 DB-ZEIT2400 400.00 CKT MW MVAR MVA % 1.0021PU -36.50 X--
- LOSSES ---X X---- AREA -----X X---- ZONE -----X 412001

400.83KV
MW MVAR 12 SOUTHERN A.A 4 OROMIA

TO 212003 DB-ZEIT3230 230.00 1 194.0 1.2 194.0 39 1.0000LK
0.22 10.12 12 SOUTHERN A.A 4 OROMIA

TO 212003 DB-ZEIT3230 230.00 2 194.0 1.2 194.0 39 1.0000LK
0.22 10.12 12 SOUTHERN A.A 4 OROMIA

TO 402002 AKAKI2400 400.00 1 -194.0 -1.2 194.0 10
0.23 1.84 12 SOUTHERN A.A 14 ADDIS ABABA

TO 402002 AKAKI2400 400.00 2 -194.0 -1.2 194.0 10
0.23 1.84 12 SOUTHERN A.A 14 ADDIS ABABA