



Addis Ababa University

Addis Ababa Institute of Technology

Department of Electrical and Computer Engineering

**ASSESSING TRANSMISSION LINE LOSS IN ETHIOPIAN ELECTRIC POWER
SYSTEM UNDER CONTINGENCY CONDITIONS**

**A thesis Submitted to Addis Ababa Institute of Technology, School of Graduate Studies,
Addis Ababa University in Partial Fulfillment of the Requirement for the Degree of Master
of Science in Electrical Engineering (Electrical Power Engineering)**

By

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March, 2018, Addis Ababa



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DECLARATION

I, the undersigned, declare that this MSc 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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ACKNOWLEDGMENT

First of all, I would like to thank the Almighty God for his provision of Grace to complete the entire work. Secondly, I wish to express my deepest gratitude to my advisor, Dr. Getachew Bekele for his patience, guidance, encouragement and support in shaping the outlook of this thesis. He provided invaluable insights that have guided my thinking and understanding. And also, I would like to thank Ethiopia Electric Power, especially to Load Dispatch Center and Engineering offices for their sincere cooperation in providing me the necessary data and information. Finally to those who encouraged me and showed me great affection throughout this thesis work, my sincere thank is here, Thank you all.

Natnael Muluneh

ABSTRACT

Ethiopian Electric Power (EEP) is comprised of large interconnected power systems with far apart and geographically remote generators and loads connected by long transmission lines. This results high transmission line loss and transmission line contingencies frequently. Contingency of any one of transmission line increases the losses in the remaining transmission lines and lead to overloading. This overload triggers their corresponding protection system and thereby result in cascaded tripping lines, transformers and generating units. This in turn leads to total or partial blackout.

In this thesis work, transmission line loss of EEP high voltage 400 kV and 230 kV grid network have been analyzed, under base case condition and each N-1 transmission line contingency condition, using power world simulator software.

From load flow simulation result the base case total transmission loss during peak load is found to be 66.53 MW and the corresponding power loss share obtained for transmission line and transformers are 91.7 % and 8.3% respectively. The annual energy loss due to transmission line power loss is found to be 184.026 Giga Watt hour, amounting to 3.735 million US Dollar financial losses. During N-1 transmission line contingency condition total peak capacity transmission line loss varies with maximum loss of 188.4 MW and minimum loss of 59.37 MW with 10 unsolved simulations. To reduce these; addition of transmission lines and capacitor compensation measures both individually and two methods at a time have been presented. The corresponding transmission line capacity gain obtained form addition of transmission lines, shunt compensation and integrated loss mitigation were 12.86 MW, 4.09 MW and 13.15 MW respectively.

N-1 transmission line contingency analysis before loss mitigation techniques and after integrating loss mitigation techniques of the system network recorded a total of 151 and 52 bus voltage limit violations respectively. Accordingly, the result recorded an appreciable loss reduction and the problem of transmission lines overloading, bus bar voltage limit deviation from the normal limits have been partially solved in normal as well as N-1 transmission line contingency conditions.

Key words: Base case, Contingency, Energy loss, Loss mitigation, Peak load, Power loss

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LIST OF ABBREVIATIONS

AC	Alternating Current	P_L	Total active transmission loss
DC	Direct Current	I_{ij}	Current through branch ij
DSSC	Distributed Static Series Compensator	r_{ij}	Series resistance of the branch ij
EEP	Ethiopian Electric Power	L_f	Loss factor
EEU	Ethiopian Electric Utility	L_F	Load factor
FACTS	Flexible AC Transmission Systems	U_k	Reactance of transformer
GERD	Grand Ethiopian Renaissance Dam	U_r	Resistance of the transformer
GG	Gilgel Gibe	R	Resistance of the transmission line
HV	High Voltage	X	Reactance of the transmission line.
HVAC	High Voltage Alternating Current	B	Susceptance of transmission line.
HVDC	High Voltage Direct Current	L	Length of the transmission line.
ICS	Inter Connected System	I_{th}	Thermal current of the line.
KVA	Kilo Volt Ampere	U_n	Voltage of the transmission line.
LV	Low Voltage	S_n	Thermal limit of transmission line.
MW	Mega Watt		
MWh	Mega-Watt hour		
MV	Medium Voltage		
MVA	Mega Volt Ampere		
NLDC	National Load Dispatch Center		
N-1	From number of N minus one		
SA	Security Assessment		
USD	United State Dollar		

CHAPTER 1: INTRODUCTION

1.1. Background

The history of modern civilization begun more than one century ago when electricity generators and infrastructure for electricity transmission were invented. As the demand for electrical power has increased, the electrical power systems have been expanded over large distances and become more complex. There has been, thus, a continuous need for innovation to create more efficient and reliable components [1].

In a modern Interconnected System (ICS) of power grids, the key components are the generating plants, High Voltage (HV) transmission lines, Medium Voltage (MV) and Low Voltage (LV) distribution sub-networks. The generation system is mainly responsible for the conversion of energy resources into electrical power by alternators or generators. After electrical power is generated, the transmission systems transmit the bulk power to various load centers through transmission lines and the distribution system, then conveys the electrical power to the consumers [2]. In general, the generation and transmission systems are referred to as bulk power supply, and the sub-transmission system and distribution systems are considered to be the final means to transfer the electric power to the ultimate customer. The primary task of an electric power system is to deliver the power requested by the customers, without exceeding acceptable voltage limits and transmission overloading. Thus, the security of the system must be explored and strengthened in order that the reliable energy supply can be maintained [3].

Ethiopia's ICS grid comprises mainly of hydro power generating plants operated at a frequency of 50 Hz, all enclosed within the ICS with relatively long HV transmission lines of 400-kV, 230-kV and 132-kV, and with supports from 66-kV and 45 kV sub-transmission links. A new HV line of 500-kV will also be added soon into the Ethiopian ICS after the completion of the new Grand Ethiopian Renaissance Dam (GERD) with more than 6,000 MW power generation capacity [4]. Mainly hydropower based, the country's power generation capacity was expanding very slowly to reach only up to 400-MW capacity in the early 1990s. Then the Ethiopian power system started to grow at a faster pace in the late 20th century and in the early next century had been raised to a total capacity of over 2200 MW by 2012. The generating capacity has been increased by the interconnection of the new Gilgel Gibe (GG) III 1870-MW power plant [4, 5].

Though EEP has put tremendous efforts to boost the generation capacities, transmission line expansion and line loss reduction were not considered in pace with power generations. As a result, losses occur during the process of transmitting electrical power from generating stations to various load centers. The total losses encountered in transmitting electrical power through a system are basically termed as transmission losses. Mathematically, transmission losses can be defined as the difference between the amount of electricity entering the grid network from the generation section or import from neighboring transmission grids and the export to the transmission grids or the electricity leaving the grid for consumption [6, 7, 8].

Generally, the losses occurring in transmission systems are classified as in two, non-technical and technical losses [7]. Further classified as non-technical losses as: unauthorized line tapping and meter tampering, unauthorized line diversions and illegal connections, inadequacies and inaccuracies in meter reading, inaccurate customer electricity billing, non-payment of electricity bills, inaccurate estimation of non-metered supplies such as public lighting, agricultural consumption and rail traction. Technical losses are losses due to energy dissipation in the conductors and equipment used for transmission, transformation, sub-transmission and distribution of electrical power [7, 9].

The present situation of losses in the power sectors on the average figures for declaration range between 25% and 40% of the load from generation to billing, in some developed and developing countries [10], these are really high. This indicates, saving electrical power has become a major challenge worldwide. However, due to the increase in environmental concerns the expansion of power stations that use traditional energy resources, such as coal and oil are being considered to be put on hold, forcing the existing transmission and/or distribution networks to be used more efficiently [7]. Researchers have shown that a reduction of power loss in the network is much more beneficial than the increase in generation capacity [9]. Traditionally, a well-designed network serves its purpose best when it is working under normal operating conditions and power loss are kept at a minimum. Failure of a major component in a ring main network, such as a substation in feed or main distribution line can cause a network to go into an unacceptable state of operation requiring contingency analysis [11].

Contingency is a failure of any power system equipment from the network due to some emergency situations and transmission line congestion is any one of the failures that leads the overall transmission network to be either overloaded, normal or under load condition. Loading effects of the entire network may lead the system to cascaded outage or total blackout. And therefore, to increase the efficiency of any system, there are several techniques, one of the feasible method is loss mitigation. [12, 13]. The implementation of technology-based solutions to improve transmission efficiency requires utilities to study and assess not only the technologies, but also their transmission systems. A clear understanding of the magnitude of technical and non-technical losses is the first step in the direction of reducing transmission and distribution losses. The correct evaluation of technical losses on the power line is an important quality measure and a pathway to reduce energy losses in order to increase the efficiency [14].

1.2. Statement of the Problem

Reliable power delivery plays a key role to profitability and customer satisfaction. But, electric power interruption in Ethiopia is becoming a day to day phenomenon. Even there are times when electric power interruption occurs several times a day, not only at the low voltage but also at the medium voltage distribution systems, one of the reasons is that, Ethiopian electric power transmission network is more complicated due to the large interconnected power systems with distributed and geographically isolated generators and loads connected by long transmission lines. This poses high chances of disturbances more and more frequently which affected the customers. A loss of one transmission line from the network will gradually disturb the rest of the system. Following the occurrence of these disturbances, the power system transmissions are loaded beyond their limits and the substations voltage deviate from the normal limit range, thus making it subject to partial or total blackout under minor or major disturbances.

It should not be forget that the result of any increase in the power losses in a network is further loading of the system elements which intends to shorten their life as the losses are dissipated in the form of heat. Higher losses also require a higher rate of the generation sources commitment, which in other words means a higher installed power. The computational procedure aiming at having the energy losses determined with a sufficient accuracy is a greater problem. To make accurate loss estimations, hourly measurements at locations where energy is fed into the system and at locations where energy is consumed would be necessary.

As the electric power consumption of Ethiopia is increasing rapidly, EEP is working hard to generate more and more power than before. But, even though the transmission network planned for the expansion purpose is expected to be employing modern equipment's and technologies for loss reduction, most of the lines serving self-consumption of the country are old and are not designed to handle the increasing demand of power efficiently. The aim of this thesis is to analyze state of transmission losses in the existing and contingency conditions of the grid network of EEP and testing loss reduction methods for the existing network and contingency conditions.

1.3. Significance of the Study

- ✍ The result of the study will be useful for power system planners and decision makers since it presents on how much primary energy is lost to supply for the transmission loss.
- ✍ As EEP is on the way of building GERD to overcome the scarcity of electric power, an additional energy from loss reduction will benefit the corporation to earn extra profit.
- ✍ Since this thesis assesses the contingency of the existing network it will boost those researchers to study further for security enhancement measures.
- ✍ The total electrical system technical loss of EEP technical losses should have to be investigated so that appropriate loss mitigation measures will be taken.
- ✍ Thus the result of this thesis work will be best input for those study groups and researchers who are working on the analysis and mitigation of bulk power transmission system losses in EEP.
- ✍ The ultimate achievements are to transfer energy over power lines with maximum efficiency and reliability, to deliver to consumers at nearly fixed voltage and frequency.

1.4. Objective

The general objective of this work is analyzing the contingency of EEP 400 kV and 230 kV high voltage transmission line and assessing transmission line loss to propose some loss mitigation techniques.

The specific objectives includes;

- ✍ Analyze the grid network under N-1 transmission line contingency condition.
- ✍ Analyze transmission line loss as a base case condition and under N-1 transmission line contingency condition.
- ✍ Determine loss, shares between transmission line and transformers for the existing transmission network and under N-1 transmission line contingency condition.
- ✍ Determine the annual capacity and energy losses in the existing transmission network and under N-1 transmission line contingency condition.
- ✍ Recommend and test some loss mitigation techniques in the high voltage transmission network.

1.5. Scopes and Limitations

- ✍ As EEP grid interconnected network is bulk this study is limited to 230 and 400 kV transmission line at peak load condition.
- ✍ The contingency analysis of the EEP interconnected high voltage transmission system is limited to determine transmission line loss based on N-1 criteria.
- ✍ It deals with analysis of power loss, but it is limited to, transmission line loss under base case condition and transmission line contingency condition.
- ✍ Propose some loss reduction methods employ for high voltage grid networks only for more sensitive network areas.

1.6. Methodology

To scaffold this study and therefore, to make a meaning for the subsequent findings, the conceptual framework is designed as follows in Figure 1.1.

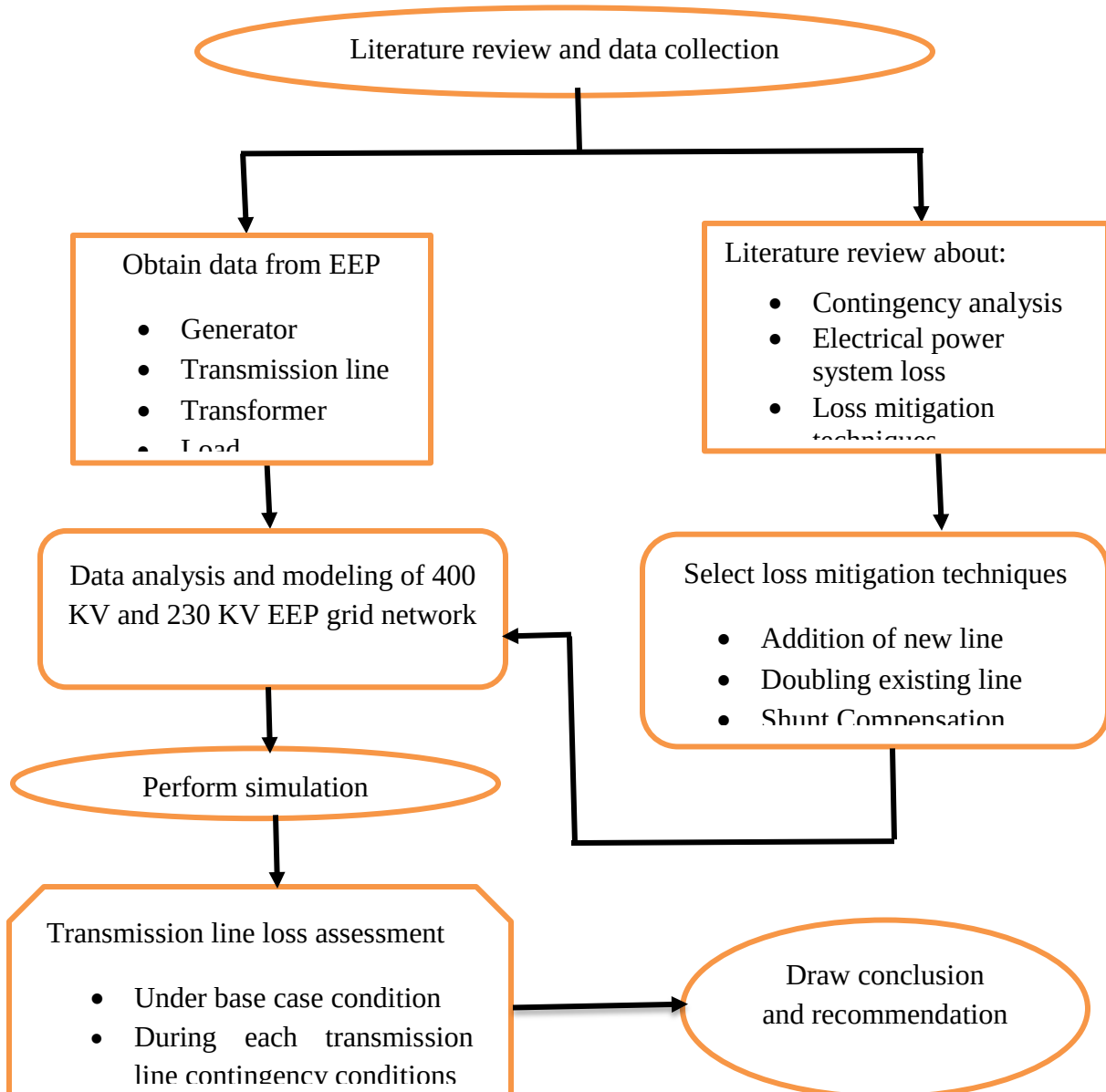


Figure 1.1 Flow chart of the conceptual framework

1.7. Thesis Outline

This thesis is organized into five chapters. Chapter one is an introductory part giving the background of the study. The basic problem to be investigated is described. The objectives of the thesis work are stated finally the scopes and limitations have presented. Chapter two review literatures of previous works which are related to contingency analysis, loss analysis and mitigation techniques. Chapter three describes about the analysis of the EEP high voltage grid data, introduction for power world simulator and network modeling of EEP 400 kV and 230 kV grid network. Chapter four presents simulation results and analysis of transmission line loss under base case condition and when single transmission lines are under contingency conditions. This chapter deals annual energy loss for both conditions and test some loss mitigation techniques. Chapter five describes conclusion, recommendation and suggestion for future work.

CHAPTER 2: THEORETICAL BACKGROUND AND LITERATURE REVIEW

2.1. Introduction

Traditionally, a well-designed network serves its purpose best when it is working under normal operating conditions and power loss are kept at a minimum. Failure of a major component in a ring main network, such as a transmission line, transformer or generator can cause a network to go into an unacceptable state of operation requiring contingency analysis. Contingency analysis helps us look at the systems vulnerable points and helps in possibly building a solution offline. In this contingency state, the network operators must attempt to control the network defensively, that is, to make the input power to the ring main network as small as possible, by using techniques to decrease losses.

2.2. Contingency Analysis

In an interconnected network, when transmission lines are lost, some of the transmission lines get overloaded. Thus a loss of one transmission line from the network will gradually disturb the rest of the system [2, 15]. The network needs latest autonomous control and protective mechanisms on the selected transmission line to keep the system secure [16]. Now a days, because of the modernization of the power system with the help of computers, it is possible to identify the most critical transmission lines that causes the system to be operates in an uncontrolled manner and leads to failures and cascading outages. Therefore, it is necessary to perform a contingency analysis to predetermine the system unstable operating state before and keep the system under normal operating state [11].

Contingency analysis can be defined as the evaluation of the security degree of a power system. It is related to the analysis of abnormal system conditions [16]. In common practice, contingency analysis is performed on a given system with single outage events (one transmission line outage or one generator outage) or multiple outage events (two/more transmission lines outage or two/more generators outage or combinations of there) are analyzed. For each of the events, the limit violations of power flow in transmission lines and voltage magnitude deviations at buses are identified [11, 12, 17]. Finally, the event which has highest severity is identified and the respective precautions are suggested to improve the system security for safer operation.

Generally, once the current working state of a system is known, contingency analysis can be broken down into the following steps:

- a) Contingency definition involves preparing a list of probable contingencies. This typically includes line outages and generator outages.
- b) Contingency selection process consists of selecting the set of most probable contingencies; they need to be evaluated in terms of potential risk to the system
- c) Contingency evaluation the selected contingencies are ranked in order of their security, till no violation of operating limits is observed [18, 19]

The algorithm for a typical contingency analysis is shown in Figure 2.1.

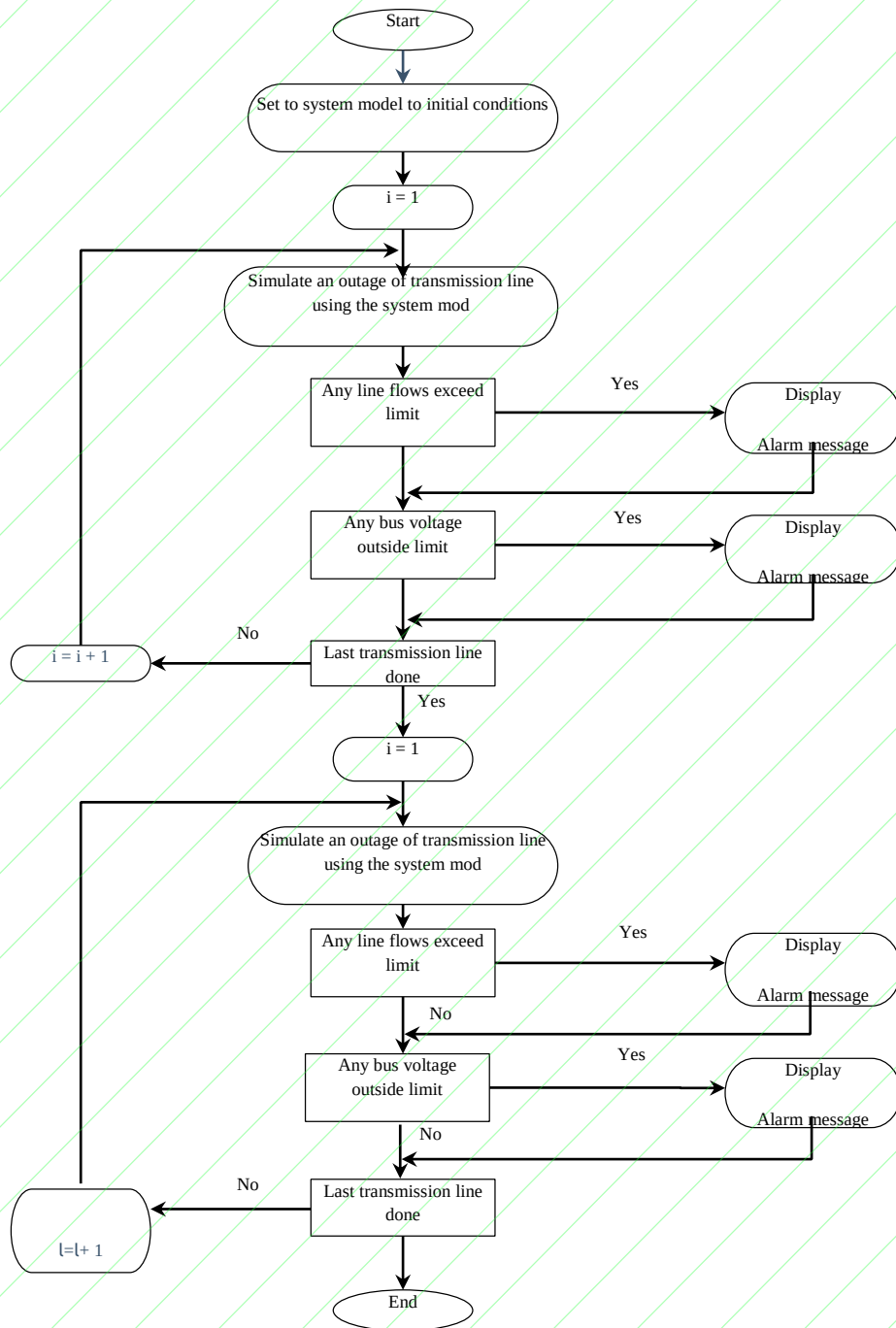


Figure 2.1 Contingency analysis procedure [2]

Necessity of Contingency Analysis

For improving system reliability: In a developing country they are already facing a huge amount of load shedding. There have been a number of reforms in the power sector. But government reforms failed to bring desired improvements in the power sector. On the other hand, they are losing transformers and generators for security violation or for any overload problem, or a bus voltage outside the limit. It means that if they aren't able to maintain their existing generator or network properly, it might be a great loss of their valuable property. With the help of contingency analysis, it will be able to know the ranking of which helps to know the amount of losses for any fault in bus, generator, transformer and transmission line. So it must have to be aware to solve the problem before they arise.

For secured operation: As it can determine early by using this method that which components are risky and have a probability to fail in the near future so it can be more aware about these components and can take additional steps of maintenance to protect it. That means, it can operate components of the power system more safely and effectively utilizing this analysis.

For future planning and expansion: If a fault occurs in any transmission line, then the load flows through the rest of the lines in the system and this process will increase pressure on those lines. To avoid such a problem, it is a better run contingency analysis and designs a parallel line and avoids this kind of problem. Thus contingency analysis helps to expand transmission line and improve future power system [2, 19].

2.3. Power System Reliability and Security

The fundamental objective of an electric power system is to supply its customers with electrical energy as economically as possible and with a reasonable assurance of continuity and quality. To maintain such security standards the power systems are required to be reliable. Reliability may be measured by the frequency, duration, and magnitude of adverse effects on electricity supply. Electric system reliability can be addressed by considering two basic functional aspects of the electric system, which are adequacy and security [20]. System security is a subset of power system reliability, which comprises of two components which are related to the time-frame of power system dynamics:

Adequacy is the ability of the power system to supply the aggregate electric power and energy requirements of the customers within component ratings & voltage limits, taking into account planned and unplanned component outages. Security is the ability of the system to withstand specific sudden disturbance such as unanticipated loss of system components. And power system security is the ability of a system to withstand without serious consequences any one of pre-selected list of credible disturbances contingencies [21].

Security Assessment (SA) is the analysis performed to determine whether, and to what extent, a power system is reasonably safe from serious interference to its operation. In other words power system security assessment is the process of determining if the power system is in a secure or alert (insecure) state, the secure state implies the load is satisfied and no limit violation will occur under present operating conditions and in the presence of unforeseen contingencies (i.e., outages of one or several lines, transformers or generators). The alert state implies that some limits are violated or the load demand cannot be met and corrective actions must be taken in order to bring the power system back to the secure state [2, 13].

The three states are defined as follows:

- ✍ Preventive state: The preventive state is actually the normal state. The term preventive was used to stress the Security aspect of the normal operation. Normal operating conditions usually means that all the apparatus are running within their prescribed limits, and all the system variables are within acceptable ranges. The system should also continue to operate normally even in the case of credible contingencies. The operator should foresee such contingencies (disturbances) and take preventive control actions (as economically as possible) such that the system integrity and quality of power supply is maintained.
- ✍ Emergency state: The power system enters an emergency state when some of the components operating limits are violated; some of the states wander outside the acceptable ranges, or when the system frequency starts to decrease. The control objective in the emergency state is to relieve system stress by appropriate actions.

- ✍ Restorative state: Restorative state is the condition when any parts or whole of the system has lost power. The control objective in this state is to steer the system to a normal state again by taking appropriate actions. An important part of a security study, therefore, moves around the power system's ability to withstand the effects of contingencies.

A particular system state is said to be secure only with reference to one or more specific contingency cases and a gives set of quantities monitored for violation. Most power systems are operated in such a way that any single contingency will not leave other components heavily overloaded. So that cascading failure are avoided [22].

2.4. Electrical Power System Loss

Power generated in power stations pass through large and complex networks like transformers, overhead lines, cables and other equipment and reaches at the end users. It is fact that the unit of electric energy generated by Power Station does not match with the units distributed to the consumers, some percentage of the units is lost [14]. Utility companies are constantly installing and upgrading their transmission lines, transformers and capacitors in order to reduce the losses [6, 23]. Basically, there are two types of losses, technical losses and non-technical losses.

Technical losses in power system are caused by the physical properties of the components of the power system. The most obvious example is the power dissipated in transmission lines and transformers due to internal electrical resistance. Technical losses are naturally occurring losses (caused by action internal to the power system) and consist mainly of power dissipation in electrical system component such as transmission lines, power transformers, measurement system [24]. These losses are possible to compute and control, provided the power system in question consists of known quantities of loads. Technical losses occur during transmission and distribution and involve substation, transformer, and line related losses [25]. The following are some of the causes of technical losses:

- ✍ Long transmission line
- ✍ Unbalanced load
- ✍ Losses due to overloading and low voltage
- ✍ Losses due to poor standard of equipment's [8, 14].

On the other hand, non-technical losses occurs as a result of theft, metering inaccuracies and unmetered energy. Theft of power is the energy delivered to customers that is not measured by the energy meter for the customer. This can happen as a result of meter tampering or by bypassing the meter. Losses due to metering inaccuracies are defined as the difference between the amounts of energy actually delivered through the meters and the amount registered by the meters [9, 26].

In general power losses in electric power grids represent one of the main parameters of electric power system performance. Especially transmission losses become a major factor to be considered when electric energy is transmitted over long distances or in the case of relatively low load density, over a vast area [10]. Thus, line loss minimization is a topical issue when designing, operating and upgrading power grids. The investigation of issues pertaining to power loss minimization in electric grids as a mean of optimized electric power system operation is one of the current trends of scientific efforts. Therefore, this thesis concentrates in technical loss analysis, especially on high voltage transmission line and its mitigation techniques.

Transmission Line Loss

Line loss refers to electrical energy loss in the process of the transmission, substation and distribution when the power is transmitted from the power plant to the customer. Transmission losses in this paper refer to active (MW) losses and reactive (Mvar) losses. Active losses in power transmission systems are generally expressed in terms of two components, a capacity (MW) component, and an energy (MWh) component [26].

Capacity losses effectively increase the total load that the power system generation has to supply. Consequently, MW losses are generally evaluated at the system peak-load in order to determine the maximum load to be supplied. This evaluation is useful for sizing system generation facilities. Capacity losses (and especially changes in capacity losses) are also very useful when evaluating alternative system operating strategies, such as different energy transactions between interconnected utilities, and when evaluating alternative transmission plans [23, 26].

The total active transmission loss can be given by [6, 10];

$$P_L = \sum_{i=1}^n \sum_{j=1}^n [I_{ij}]^2 r_{ij} \quad (2.1)$$

Where;

P_L The total active transmission loss

I_{ij} The current through branch ij

r_{ij} The series resistance of the branch ij and n is the number of buses.

Estimation of Energy Loss Using Loss - Load Factor Method

Traditionally, total energy losses have been estimated by means of energy balances that consist of subtracting the total energy consumed (metered and billed) by customers from the total energy generated or delivered to distribution substations and feeders [29]. Since total energy losses account for technical and non-technical losses, then further analysis is required to estimate them individually. Usually, technical losses are estimated by using approximate methods and assumptions. Specifically, by calculating active power losses at peak load conditions (through computational models and recorded load data), then applying a loss factor to estimate average power losses and finally multiplying average losses by time (hours), to obtain monthly or annual energy losses [6, 25].

Typically, for economic reason, load losses of feeders are calculated under peak demand condition using load-flow simulation software and the associated power losses, P_{Loss} are then calculated using loss factor. This method of energy loss calculation is the simplest and relatively required low data. The maximum current carrying capacity of the feeder may be less than the maximum current load demand and therefore it is necessary to use factors.

$$\text{Energy loss (T)} = (\text{Average power loss for period T}) \times (T) \quad (2.2)$$

For annual energy loss calculation, the period T is equal to 8760, then

$$\text{Annual energy loss} = (\text{annual average power loss}) \times (8760) \quad (2.3)$$

$$\text{Average power loss in period T} = (\text{loss factor}) \times (\text{peak loss in period T}) \quad (2.4)$$

Loss factor refers to a factor used to scale enduses demand or retail sales to produce net energy for loads. A loss factor is used to calculate how much more energy needs to be produced to account for losses and meet load. Multiplying the loss factor by the amount of energy actually delivered (usually retail sales) produces an estimate of how much energy must be produced by the generator.

An approximate value of loss factor can be found from the following equation [6, 10];

$$L_f = (0.92)(L_F)^2 + (0.08)(L_F) \quad (2.5)$$

Where;

L_f – Loss factor

L_F – Load factor

Load factor of a system is the ratio of the average load over a given period of time to the maximum demand or peak load occurring in that period [29]. Multiplying the numerator and denominator by time T; this relation shows that the load factor can also be defined as the ratio of the actual energy consumed during a given period to the energy which would have been used if the maximum demand or peak load had been continuously maintained throughout the period. Depend upon the number of hours in a day, weeks, months, or years we define different load factors. For daily load factor the period of time T is taken as 24 hours and for annual load factor $T = 8760$ hours [24].

For this study the load factor was obtained from the EEP historical and forecast data showing its value to be 57% [27].

Loss Mitigation Techniques

Nowadays, the electrical energy demand has increased continuously from time to time. To meet this situation, either construction of new generation facilities and transmission networks is required or the existing infrastructure of power system has to be improved. The construction of new generation systems and installing of new transmission lines involve huge installation cost, environmental impact, politics, large displacement of population and land acquisition. One of the simplest ways is to minimize the transmission loss rather than constructing new generation systems because loss analysis and reduction are important and well-known areas of power system engineering and key elements for efficient system operation [11, 14, 28].

There are many of loss reduction strategies within the electric power transmission industry. In the majority of cases, these modifications have been implemented for reducing transmission losses, to increase transmission capacity, keep the stability of the system or improve the power quality. Some transmission loss reduction techniques described below.

A) Addition of New Transmission Lines

Adding new transmission line can reduce loading losses in two ways. First, the current in the existing transmission line could effectively be cut in half, resulting in a reduction in I^2R losses, net of the losses in the new line. Second, there could be a net loss reduction in the substation transformers if the new feeder is fed from another substation transformer and the transformer losses serving the new feeder do not increase more than the loss reduction in the original transformer [3]. This procedure has the advantage of reducing the electrical characteristics of the transmission line, and thereby reducing losses.

Doubling the existing conductor with a second conductor of the same diameter reduces line resistance by 50%, allowing a reduction in losses by half. Doubling can save money over removing and replacing the existing conductor with the installation of a single conductor [6]. But, adding new transmission line and doubling of the existing line cannot be cost-justified by loss reductions alone. Many factors need to be considered when adding transmission line, including cost analysis, reliability issues, and growth estimations.

B) Capacitance Compensation

Capacitor placement at the transmission line is a beneficial loss-reduction technique. Some end-use loads and the distribution system equipment are inductive by nature, causing a lagging power factor and requiring the electric grid to supply reactive power to the distribution circuits. Capacitor placement at or near the var load to eliminate or reduce the lagging power factor will reduce system losses and increase capacity in the primary lines and substation transformers by reducing the line current. The reduction in losses is proportional to the square of the reduction in line current [9]. The capacitance shunt compensation is injected into the identified low voltage violated buses in order to ensure that they are within acceptable limits. The capacitance shunt compensation method is applied on these buses because of its merits such as higher speed of response and absence of fault to the test system, and the results recorded appreciable voltage profile improvement and a reasonable reduction in the power loss [9, 11].

Not only the above mentioned minimization techniques, various researchers testes different loss mitigations techniques, some of them are;

- ✍ Using Flexible AC Transmission (FACT) Device [7, 8, 29, 30].
- ✍ Using Distributed Flexible AC Transmission System (D-FACTS) devices [12].
- ✍ Using High Voltage DC (HVDC) Transmission [6, 31, 32].
- ✍ Voltage Uprating [6, 14].

2.5. Literature Review

There have been different approaches of determining technical loss and contingency analysis of power system. The methodologies applied by various researches have been summarized below:

Woldemariam Wolde-Ghiorgis et al [4], presented research findings from a simulation study on technical power loss reductions in selected outgoing feeders of 15-kV to distribution transformers in Sebeta Substation using DigSILENT software. Along the selected routes, with all transformers loaded to their 60% capacity, the total nominal power losses in the feeders and the transformers were also appraised. Alternative technical power loss reduction techniques have been studied with different loading considerations.

Wubante Getachew et al [6], in their research work focused on the minimization of bulk power transmission loss in high voltage transmission grid networks of EEP using ETAP-PowerStation environment. This study focused on methods to improve the efficiency of the grid. Transmission line upgrading were undertaken to minimize the power loss of EEP's transmission grid from the existing state. The author chose lines to be upgraded for loss reduction. For double circuit loss reduction method of the study, 55% of 45 kV lines, 40% of 66 kV lines and 30% of 132 kV lines were proposed to be upgraded resulted reduce loss from 42.67 to 33.18 MW. For voltage uprating technique of loss reduction, 45 and 132 kV voltage levels were chosen to be uprated. All 45 kV lines were decided to be upgraded to 66 kV whereas 132 kV lines which lie in the main loops of the grid network were selected to be uprated to 230 kV which reduce the active power loss to 35.42 MW. For reactive power compensation method of loss reduction, candidate buses were selected for compensation and which have a total loss reduction of 10.33 MW.

S. Musa and A. G. Ellams et al [8], highlighted various ways in which energy was lost between the point of generation and consumption and how these losses can be minimized. MATLAB was used for the simulation. The result showed that there were losses some of these losses were technical while others are non-technical. The authors suggested that it was important to have a power factor as close to unity as possible. These losses can be reduced to an optimum level with use of devices like FACTS and switched capacitor banks.

Kingsley Bediako Owusu et al [9], investigated the causes of these high transmission technical losses being experienced on the interconnected network of Ghana. The authors were used literature survey and field interactions to validate their conclusions. The power system simulation for engineering software package was used to simulate the entire grid to identify areas of the grid violating system pre-set parameters. Results from the simulations conducted showed that, most areas in the northern network section of the grid were experiencing low voltages, which were in violation of system parameters. Subsequently, an optimal capacitor allocation technique was implemented for critical buses in that area to determine the ideal amount of compensation needed to be installed on these buses. Voltage profiles in the critical areas improved immensely, after the needed compensation was injected. The authors finally recommended the use of distributed generation and smart grid technologies should be adopted to improve the grid system voltage profile in the future.

Admola Abdulkareem et al [11], in their paper were focused on compressive study and analysis of line loss associated with Nigeria 330 kV power transmission line. The methodology was based on power flow analysis on the existing network using both Newton Raphson has written in code based MATLAB and the model based Newton Raphson in the power world simulator, the power flow analysis was further subjected to contingency analysis and simulation. Two load flows was performed to expose voltage violated. The result showed that the bus voltages outside the saturation limits occurred at the buses under normal uncompensated condition. Capacitive shunt compensation was applied on these buses and the result recorded an appreciable loss reduction.

Mohammed Ahmed et al [12], Presented contingency analysis of Ethiopia's 230 kV transmission network a case of Sebeta to Kaliti transmission line. The result shows that the outage of this line causes overloading on Gefersa to Kaliti transmission line and makes the system not to be secure and reliable; further cascaded outage lead the system to the total blackout. The analysis has been conducted by considering four scenarios such as a normal state, single line outage, cascaded line outage and inserting Distributed Static Series Compensator (DSSC) into the overloaded line. The authors achieved that the system became reliable and secure by inserting the device (DSSC) in the most sensitive line of the network.

Chibuzo Nnonyelu et al [13], in their paper did contingency analysis and reliability evaluation of the Nigeria power system were performed using the load flow method. The result of this analysis used to determine the security level of the Nigeria power system and suggestions also made on the level of protection to be applied to the Nigeria power system with the aim of improving system security the writer suggests that the transmission company of Nigeria should adopt the FACT devices as they can improve the lines active power capability in any contingency event as have faster switching than the traditional compensation devices.

O. J. Onojo et al [33], studied single line contingency analysis of Nigeria 330kV post reform grid to determine violations in the network due to the individual contingencies were considered. The power world simulation software was used to perform a set of single line contingencies. The simulation result indicates that with generator contingency at different buses several violations were happening. The author recommended; the existing transmission lines and substations

should be upgraded to improve the voltage profile of vulnerable buses, provision of double circuit and Nigeria should adopt the use of FACT devices.

Abdelaziz Yousif Mohamed¹ et al [18], in their work outlined mathematical models for the simulation of generator outages and transmission line and transformer outages so as to carry out a full AC load flow based contingency analysis and ranking. The method has been applied to Sudan national grid and gives good results in determining the network weaknesses and suggesting the new transmission lines and transformer capacities which ensures better power system security. Forty four contingencies have been done for Sudan national grid and the results of contingency ranking and the weaknesses of the transmission system have been detected and the new capacities have been suggested. The new capacities ensure better power system security should any single contingency or any of the sets of multiple contingencies occurs.

Generally, most of the above studies focus on different countries regarding contingency analysis, electric power system loss and loss mitigation techniques. At this point, it is important to restate that this study focuses on Ethiopia, whose grid is significantly different from other countries in its size, major concerns, and application. On the other hand, some of the research and concepts are based on Ethiopia's electric power network with separately, contingency analysis or electrical power loss assessment, techniques. But, this study focused on both contingency analysis and line loss assessment for EEP 400 kV and 230 kV grid network. However, important lessons can be drawn from these various works, and as will be described, can be applied to the specific case of Ethiopia.

CHAPTER 3: ETHIOPIAN ELECTRIC POWER NETWORK MODELING AND DATA COLLECTION

3.1. Introduction

The Ethiopian high voltage grid data of transmission lines, transformers, generators and loads have been collected from EEP concerned offices such as Ethiopia Electric Power National Load Dispatch Center (EEP NLDC) and analysis of this data has been made to make it ready for simulation. The collected data and the data prepared for simulation have been presented in sections 3.2. The existing EEP grid network one line diagram looks like [27].

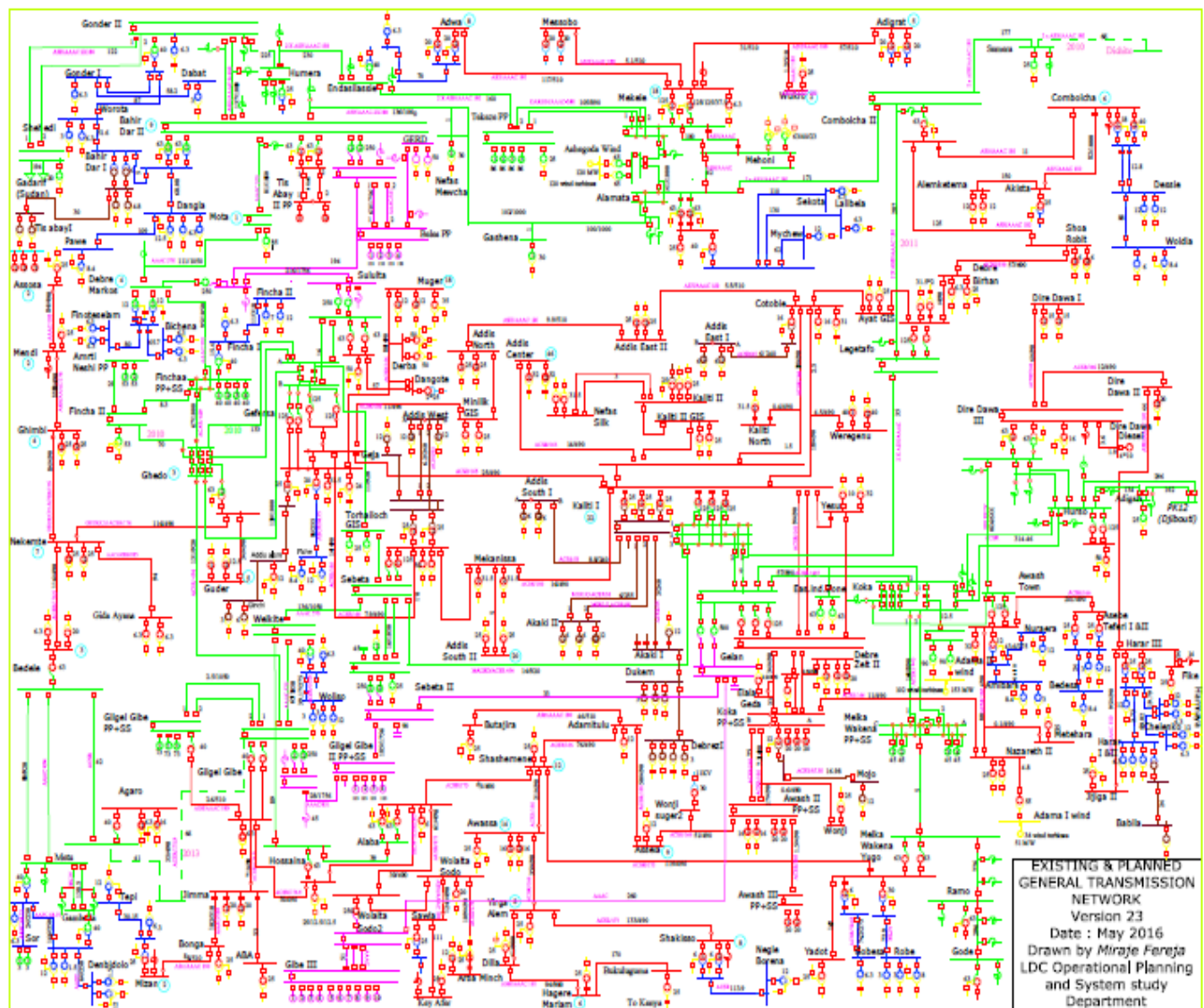


Figure 3.1 the existing EEP grid network one line diagram [27]

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3.2.Ethiopian Electric Power Grid Data

In this section the grid data collected from different source is presented.

Generator Data

The Ethiopian ICS, high voltage grid generators (units) data have been collected from NLDC (27), as shown in, Table A.1 of Appendix A: and for simulation purpose it has been made ready in the following final form. Diesel and wind generators were not included in this study as they become into service only during power shortages and this will not be the case in EEP's future, as its expansion is even to export power from hydroelectricity.

Table 3.1 The Ethiopian ICS high voltage grid hydro power plant generators units

No	Power station	Unit	Sn (MVA)	Un (kV)	P (MW)	Pmin (MW)	Pmax (MW)	Qmin (MVar)	Qmax (MVA)
1	Awash II	2	40	10.5	12	6	30	-30	26
2	Awash III	2	40	10.5	18	6	30	-30	26
3	Beles	4	520	15	291	0	460	-230	230
4	Fincha	4	145	13.8	112	0	128	-82	65
5	Amertinesshe	2	106	10.5	70	0	82	-45	40
6	Gilgel Gibe I	3	228	13.5	180	0	210	-63	63
7	Gilgel Gibe II	4	500	15	380	0	420	-200	200
8	Gilgel Gibe III	10	2200	15	1000	0	1870	-1000	1000
9	Koka	3	54	10.5	30	0	39	-38	36.5
10	Melka Wekana	4	180	13.8	135	0	153	-135	130
11	Tekeze	4	346	13.8	186	0	312	-152	152
12	Tisabay II	2	80	10.5	54		72	-56	40

Transformer Data

Ethiopian interconnected power system grid has three winding and two winding transformers. For this study the only required transformers are two-winding transformers. Hence, the two-winding transformers short circuit data of the high voltage grid has been collected from NLDC as shown in Table A.2 of Appendix A: [27].

The collected transformers short circuit test data should be converted into Per Unit (PU) system to use in the power world simulator using 100 MVA as base value which is taken as the base

value for the entire system. To convert the given percentage impedance (reactance and resistance) to the per-unit system by using equations (3.1) and (3.2) [3, 34];

$$UK_{new}^{PU} = \frac{UK_{given} \%}{100} \times \left(\frac{baseKV_{given}}{baseKV_{new}} \right)^2 \times \left(\frac{baseMVA_{new}}{baseMVA_{given}} \right) \quad (3.1)$$

$$Ur_{new}^{PU} = \frac{Ur_{given} \%}{100} \times \left(\frac{baseKV_{given}}{baseKV_{new}} \right)^2 \times \left(\frac{baseMVA_{new}}{baseMVA_{given}} \right) \quad (3.2)$$

Where; $UK_{given} \%$ - is the given percentage reactance of the transformer

$Ur_{given} \%$ - the given percentage resistance of the transformer

Base kV_{given} - the old base voltage of the transformer winding

Base kV_{new} - the new base voltage of the transformer winding

Base MVA_{given} - old base power for transformers winding

Base MVA_{new} - the new MVA base of the transformer winding, 100 MVA

The short circuit test values of the two-winding transformer data are converted to PU values using the equations (3.1) and (3.2). Then the result is arranged in Table 3.2.

Table 3.2 Per Unit (PU) values of two winding transformer

Node 1	Node 2	Un1 [kV]	Un2 [kV]	Sn [MVA]	uk [pu]	ur [pu]
GG2 400 kV	GG1 230 kV	400	230	250	0.041	0.002
GG2 400 kV	GG1 230 kV	400	230	250	0.041	0.002
Sebeta 2 400 kV	Sebeta 2 230 kV	400	230	250	0.039	0.002
Sebeta 2 400 kV	Sebeta 2 230 kV	400	230	250	0.039	0.002
Bahir Dar 400 kV	Bahir Dar 230 kV	400	230	250	0.047	0.002
Bahir Dar 400 kV	Bahir Dar 230 kV	400	230	250	0.047	0.002
D/Markos 400 kV	D/Markos 230 kV	400	230	250	0.047	0.002
Geln 400 kV	Geln 230 kV	400	230	250	0.047	0.002
Geln 400 kV	Geln 230 kV	400	230	250	0.047	0.002
Akaki 400 kV	Akaki 230 kV	400	230	500	0.049	0.002
Akaki 400 kV	Akaki 230 kV	400	230	500	0.049	0.002
Geln 230 KV	Geln 132 kV	230	138	24.2	0.162	0.013
Geln 230 KV	Geln 132 kV	230	138	24.2	0.162	0.013
Geln 230 KV	Geln 132 kV	230	138	24.2	0.162	0.013

Transmission Line Data

Ethiopian electric power, high voltage interconnected system transmission line data has been collected from NLDC. From the collected data which have been compiled in Table A.3 of Appendix A: 400 kV and 230 kV transmission lines have been filtered and converted into per unit values considering 100 MVA and network level voltage as a base value of power and voltage respectively [3, 34, 35];

$$r(pu) = \frac{r\left(\frac{\Omega}{Km}\right) * L(Km) * MVA_{base}}{(\text{network level voltage in kV})^2} \quad (3.3)$$

$$x(pu) = \frac{x\left(\frac{\Omega}{Km}\right) * L(Km) * MVA_{base}}{(\text{network level voltage in kV})^2} \quad (3.4)$$

$$B[pu] = \frac{B\left[\frac{U}{km}\right] * l[km] * (\text{network level voltage in kV})^2}{MVA \text{ base}} \quad (3.5)$$

$$Sn(MVA) = \sqrt{3} * I_{th}(KA) * U_n(KV) \quad (3.6)$$

Where;

- r**, resistance of the transmission line
- x**, reactance of the transmission line.
- B**, is susceptance of the transmission line.
- L**, is length of the transmission line.
- I_{th}**, is thermal current of the line.
- U_n**, the voltage of the transmission line.
- Sn**, thermal limit of the transmission line.

Then transmission line resistance, reactance and susceptance are converted into PU values and the result is compiled as follows.

Table 3.3 The PU value existing 400 kV of EEP's ICS grid transmission line

No	Type	L [Km]	R [PU]	X [PU]	B [PU]	Sn [MVA]
1	Gibe II –gibe I	28	0.000656	0.0074533	0.12238	1732
2	Gibe II –Sebeta II 400	185	0.004336	0.0492455	0.90861	1732
3	Beles- BahirDar 400 kV	62.8	0.0008203	0.012093	0.3786	1732
4	Beles- BahirDar 400 kV	62.8	0.0008203	0.012093	0.3786	1732
5	BahirDar-markos400 kV	193.77	0.0025311	0.0374945	1.1876	1732
6	Markos-Sululta 400 kV	215.89	0.00282	0.041775	1.2900	1732
7	Gelan - Sebeta II 400 kV	33	0.0003918	0.006787	0.184029	1732
8	Gelan-Welytasodo	267	0.0034376	0.05143	1.6767	1732
9	Gibe III -Welytasodo	51	0.000606	0.0099297	0.32029	1732
10	Gibe III -Welytasodo	51	0.000606	0.0099297	0.32029	1732
11	Gibe III - Welytasodo	51	0.000606	0.0099297	0.32029	1732

Table 3.4 The PU value existing 230 kV of EEP's ICS grid transmission line

No	Type	L [Km]	R [PU]	X [PU]	B [PU]	SN [MVA]
1	Gilgel Gibe - Wolkite T 143	65.3	0.007367	0.05076	0.09658	418.3
2	Wolkite - Sebeta SC	132.523	0.014953	0.1031	0.196	418.3
3	Bahir Dar II - Gonder II	136.97	0.023764	0.08284	0.2595	398.4
4	Bahir Dar II - Gonder II	136.97	0.023764	0.08284	0.2595	398.4
5	Debre markos- fincha	136.97	0.023764	0.08284	0.2595	398.4
6	Bahir Dar II Mota	81.11	0.009152	0.06305	0.11996	418.3
7	Debre markos - Mota	111.76	0.01261	0.08687	0.1623	418.4
8	Sebeta I - Kaliti I	14.26	0.0020	0.0110	0.0211	418.3
9	Fincha - Ghedo	71.3625	0.009152	0.06305	0.11996	418.3
10	Fincha - Ghedo	71.3625	0.009152	0.06305	0.11996	418.3
11	Ghedo - Gilgel Gibe	130.82	0.01792	0.1011	0.1935	418.3
12	Sebeta II - Sebeta I 230 L1	16	0.00189	0.01243	0.02366	418.3
13	Sebeta II - Sebeta I 230 L2	16	0.00189	0.01243	0.02366	418.3
14	Sebeta i -Gefersa	10.7	0.0015	0.0082	0.0157	398.4
15	Koka – Awash	128.84	0.01765	0.09957	0.1935	366.5
16	Koka - Kaliti I	66.4	0.00927	0.05198	0.0982	354.5
17	Koka - Kaliti I	66.4	0.00927	0.05198	0.0982	354.5
18	Koka -Melka Wakena	163.86	0.02288	0.12827	0.2423	354.5
19	Koka -Melka Wakena	163.86	0.02288	0.12827	0.2423	354.5
20	Bahir Dar II - Alamata	348	0.06037	0.21	0.6593	398.3
21	Tekeze - Mekele L1	105	0.0144	0.0806	0.1523	204.7

22	Tekeze - Mekele L2	105	0.0144	0.0806	0.1523	204.7
23	Tekeze-Endeselase-Humera	229.8	0.03987	0.1405	0.4315	354.5
24	Tekeze-Endeselase	177.07	0.03077	0.1073	0.3355	366.5
25	Ghedo-Gefersa	133.5	0.01688	0.1035	0.1975	366.5
26	Ghedo-Gefersa	133.5	0.01688	0.1035	0.1975	366.5
27	Ghedo-Gefersa	133.5	0.01688	0.1035	0.1975	366.5
28	Alamata-Combolcha	170.6	0.02963	0.1021	0.3289	354.5
29	Gefersa – Sululta	17	0.0029	0.0101	0.0317	354.5
30	Gefersa - Sululta	17	0.0029	0.0101	0.0317	354.5
31	Combolcha-Semera	177.07	0.03077	0.1073	0.3355	366.5
32	Semera-Decheto	63.93	0.01108	0.03874	0.1211	354.5
33	Alameta - Mekele	141	0.0244	0.0849	0.2664	354.5
34	Sheh-Ghadarif	292	0.3825	0.1769	0.5532	366.5
35	Sheh-Ghadarif	292	0.3825	0.1769	0.5532	366.5
36	Gonder II-Shehadi	121	0.021	0.0733	0.2292	354.5
37	Gonder II-Shehadi	121	0.021	0.0733	0.2292	354.5
38	Mekele -Mehoni	100	0.01736	0.05987	0.19113	366.5
39	Koka-Hurso 230	313	0.05436	0.1874	0.6034	366.5
40	Koka-Hurso 230	313	0.05436	0.1874	0.6034	366.5
41	Awash - Dire Dawa III	208.99	0.02863	0.1615	0.309	366.5
42	Wolkite-Hosana	89.3	0.01713	0.07348	0.1276	354.5
43	Hosana-Alaba 230	39.3	0.00754	0.03234	0.0545	354.5
44	Agaro-Bedele	67.21	0.0074	0.04	0.1295	354.5
45	Agaro-Bedele	67.21	0.0074	0.04	0.1295	354.5
46	Jimma-Agaro	38.602	0.00431	0.023	0.0774	354.5
47	Gilgel gibe old(i)- Jimma	81.558	0.0092	0.04863	0.15722	354.5
48	Metu-Gambela 230 kV	140	0.01561	0.08197	0.2745	354.5
49	Metu-Gambela	140	0.01561	0.08197	0.2745	354.5
50	Melkawakena Yougo-Ramo	267	0.07882	0.2083	0.395	398.4
51	Ramo-Ghode	252	0.07439	0.1966	0.3727	398.4
52	Gonder - humera	225	0.03987	0.1405	0.4315	354.5
53	Kaltiy- Legetafo	35	0.0381	0.0874	0.0160	354.5
54	MelkWakena – MW yugo	5	0.0053	0.0124	0.0024	204.7
55	Gelan- kaliti	9	0.0015	0.0082	0.0157	354.5
56	Gelan- kaliti	9	0.0015	0.0082	0.0157	354.5
57	Hurso- Diredawa	210.5	0.00365	0.01256	0.04042	204.7
58	Hurso- Diredawa	210.5	0.00365	0.01256	0.04042	204.7
59	Hurso - Adigala	134	0.01688	0.1035	0.1975	366.5
60	Hurso - Djibuti	296	0.3825	0.1769	0.5532	366.5
61	Adigala-Djibuti	162	0.02288	0.12827	0.2423	354.5

The Ethiopian high voltage grid has also shunt capacitors and reactors. The operational capacitor and reactors are shown in, Table A.5.1 and Table A.5.2 of Appendix A [27].

Load Data

Active and reactive power load data for each bus of the entire grid have been collected from each 230 kV and 400 kV substation and rearranged for the entire EEP ICS grid system. It is compiled in Table A.4 of Appendix A: Then these load data have been analyzed and compiled to make suitable to the focus of the thesis and software fed. That means the substations' loads of radial structures, which are not connected to another substation, are summed to the load of "upstream" substations buses. Accordingly, the existing 400 kV and 230 kV EEP's ICS power system has been modified as shown in Figure 3.3. The load data for this network is arranged in Table 3.5.

Table 3.5 Organize load data of EEP 230 kV and 400 Substations

Sl No.	Station Name	Region	Base kV	Peak Load (MW)	Q Load [Mvar]
1	Sebeta-II	Addis Ababa	230	12.5	3
2	Sululta	Addis Ababa	230	74	25.5
3	Geferssa	Addis Ababa	230	238	126.5
4	Legetafo	Addis Ababa	230	120	62.5
5	Kaliti -I	Addis Ababa	230	235	109.43
6	Sebeta I	Addis Ababa	230	233	102.2
7	Gelan	Addis Ababa	230	295	95.56
8	welkite	Central	230	15.5	6.2
9	Dire Dawa III	Eastern	230	100	44
10	MW Yugo	Eastern	230	75	33.2
11	Hurso	Eastern	230	53.3	21.32
12	Awash town	Eastern	230	45	17.6
13	Combolcha-II	North East	230	43.5	21.8
14	Bahir DarII	North West	230	55.85	25.54
15	D/markos	North West	230	38.21	16
16	Gonder	North West	230	127.5	30
17	Indaselassie	North	230	17.5	8.2
18	Mekelle	North	230	79.8	35.88
19	Alamata	North	230	21	8.39
20	Alamata	North	230	2.8	1.3
21	GG I and II	South West	230	54.8	23.12
22	Welayitasodo	South West	400	79	35.6
23	Hossaina	South West	230	56.75	26.7
24	Gedo	West	230	49	22
25	Fincha II	West	230	6	2.2
26	Bedle	West	230	50	20.35
27	Agaro	West	230	7.5	3.37
28	Beless	North West	400	20	6.3

3.3. Simulation Software

In this thesis Power World Simulator software is used to carry out simulation study. This power system simulation software package that can be used to give an analyst a comprehensive look at electrical power flows in a transmission grid. In addition, it can be used to examine the benefits of power transactions between different areas as well as the consequences of those transactions. This Simulator allows the user to visualize the system through the use of full-color animated one line diagrams complete with zooming and panning capability. System models can be either modified on the fly or built from scratch using Simulator's full featured graphical case editor. Transmission lines can be switched in (or out) of service, new transmission or generation can be added, and new transactions can be established, all with a few mouse clicks.

Key features of power world simulator includes:

- ✍ **Power Flow Option** Basic power flow for voltage drop, loss, component loading or reactive power support analysis.
- ✍ **Contingency Analysis Option** Contingency Analysis is to analyze the system that results from any statistically likely contingency condition. Industry planning and operating criteria often refer to the N-1 rule, which holds that the system must operate in a stable and secure manner for the outage of any single transmission or generation outage
- ✍ **Fault Analysis Option** Solution of a faulted network and determination of all post-fault node voltages and branch flows. Fault type includes three-phase balanced, single line to ground, line to line and double line to ground fault [3, 17, 36].

3.4. Network Modeling of EEP 400 kV and 230 kV grid System

The starting point of any power-flow problem is the development of a single-line diagram of the power system, from which computer solutions can be obtained. The input parameters of the power world simulator are:

- ✍ Branch data
- ✍ Generator data
- ✍ Transformer data
- ✍ Load data

Assessment of transmission line loss of EEP's interconnected grid system, both in pre-contingency and post-contingency operating states using the power world simulator. The first function in this process is assessing in the pre-contingency state that is a base-case simulation, whereas the second is contingency analysis, which identifies potential emergency. The analysis of them will be presented in the next sections. The one-line diagram of existing 38 buses EEP 400 kV and 230 kV transmission system was redrawn for the purpose of load flow study performed under power world environment.

The single line diagram of the existing 400 kV and 230 kV EEP transmission network used as the case study is as shown in Figure 3.3. Which have 38 buses and Gilgel Gibe III bus was chosen as the slack bus among other power generating stations because, Gilgel-Gibe III (GGIII) bus as a slack bus brought about the lowest power mismatch in the network, hence, the generator with the largest power should be used as slack bus [11].

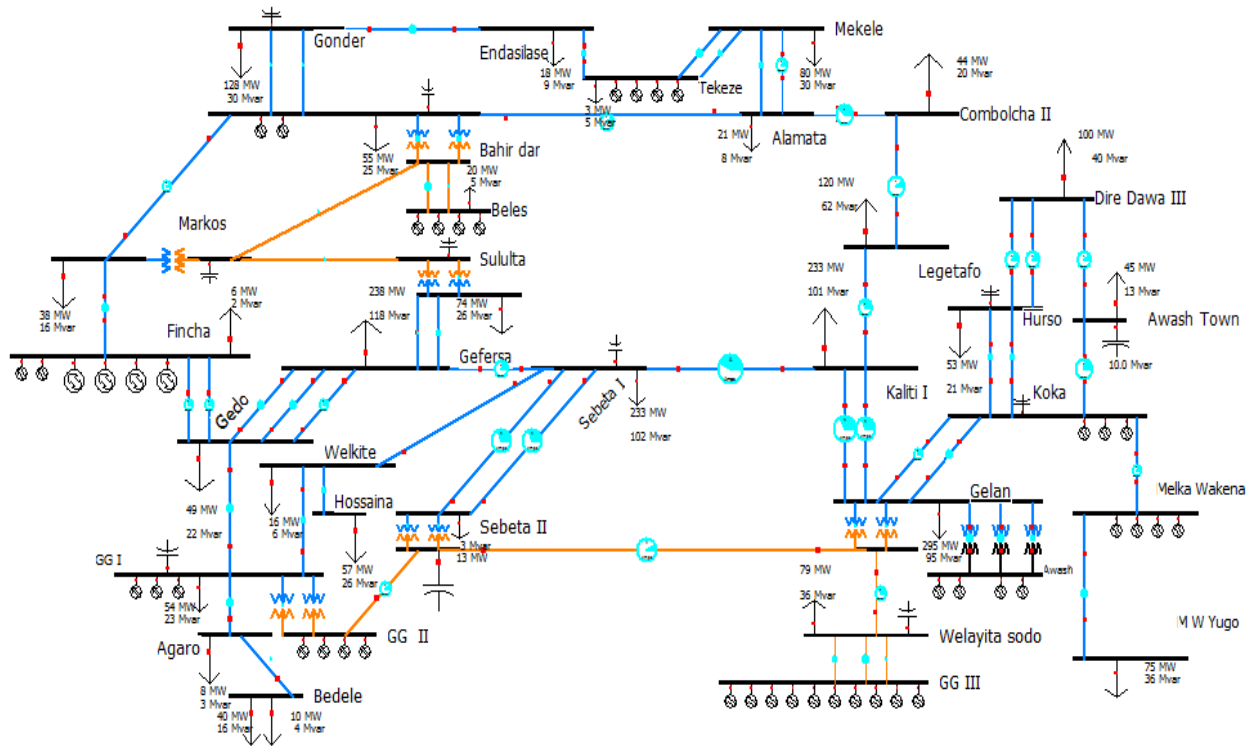


Figure 3.3 Single line diagrams of EEP Existing 400 kV and 230 kV grid network

The summary of the input data which has been fed to the software is shown in Figure 3.4.

Case Summary for Current Case

Number of Devices in Case		Case Totals (for in-service devices only)	
		MW	Mvar
Buses	38	Load	2202.6
Generators	44	Generation	2269.1
Loads	29	Shunts	0.0
Switched Shunts	11	Losses	66.5
Trans. Lines (AC)	67	Generator Spinning Reserves	
LTCs (Control Volt)	0	Positive [MW]	1536.7
Phase Shifters	0	Negative [MW]	2269.1
Mvar Controlling	0	Slack Buses:	
Series Capacitors	0	GG III (1); in Area 1 (1)	
2 Term. DC Lines	0		
N-Term. DC Lines	0		
Areas	1		
Zones	1		
Islands	1		
Interfaces	0		
Injection Groups	0		

Case pathname: C:\Users\user\Desktop\NATNAEL\SIMULATION base case.F

OK Print ? Help

Figure 3.4 Summary of input data to the power world simulator

CHAPTER 4: SIMULATION STUDIES AND RESULT ANALYSIS

4.1. Introduction

This chapter presents simulation studies and result analysis which includes: transmission line loss assessment under base case condition and when single transmission lines are under contingency conditions, loss mitigation techniques and estimation of loss mitigation techniques.

4.2. Base Case Simulation

The base case is where the power system in its normal steady-state operation, with all elements in the service that are expected to be in service. All substation loads are supplied power and all elements of the power system (transmission line, transformers and generators) are in service.

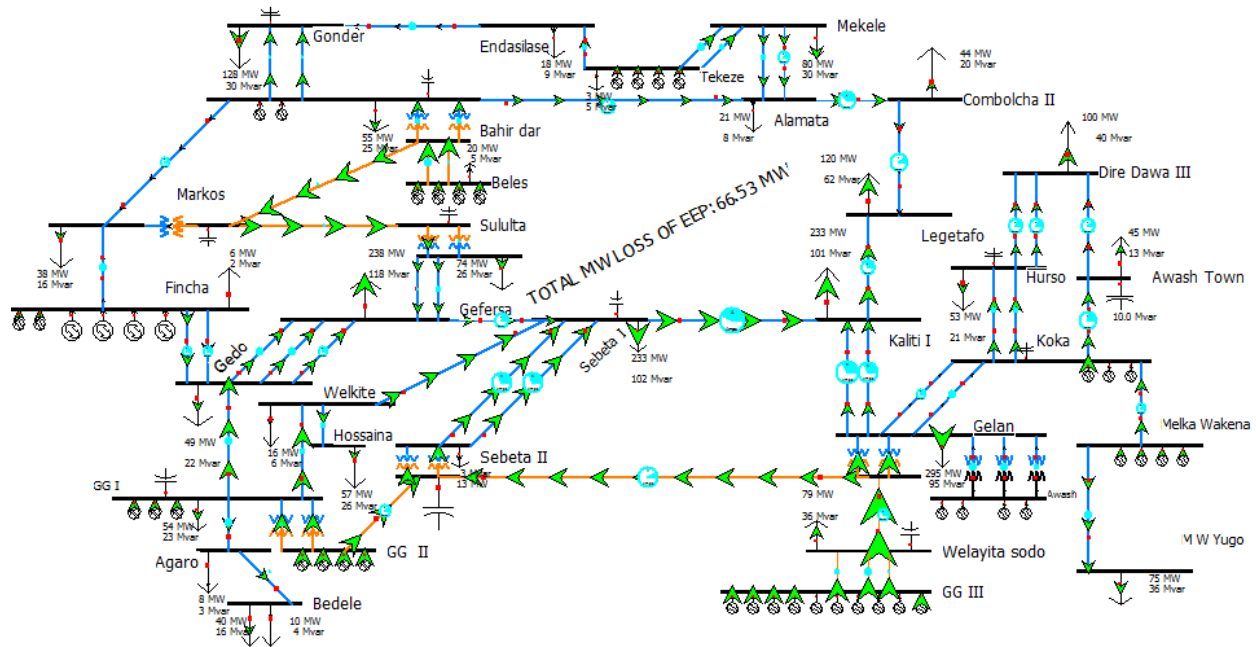


Figure 4.1 Base case simulations of EEP 400 and 230 Existing Grid network

Here, for the base case the real power load for the system is 2202.6 MW and the generators in the system supply 2273.1 MW active a power. The base case simulation has been made and the result of simulation is presented in Figure 4.1. The load flow analysis is carried out to determine the bus voltage, real and reactive power flow and line losses using the run mode of power world simulator. Under normal operation condition the existing EEP 400 kV and 230 kV grid network bus voltage and its PU value presented in Table 4.1. The result obtained from Power World

Simulation showed low voltage values at the following buses; Bus 25- Legetafo (0.86682 PU), Bus 34- Melkawekana Yugo (0.85882 PU) and Bus 26- Kaliti (0.88729 PU).

Table 4.1 Bus voltage record of the network under base case simulation

Bus Number	Name	Nom KV	PU Volt	Volt (KV)
1	GG III	400	1	400
2	Gelan	400	0.97693	390.771
3	Sebeta II	400	0.98004	392.014
4	GG II	400	1	400
5	Beles	400	1.04026	416.105
6	Bahir dar	400	1.0503	420.118
7	Sululta	400	1.04163	416.651
8	Markos	400	1.06554	426.217
9	Gelan	230	0.9507	218.661
10	Sebeta II	230	0.95506	219.664
11	GG I	230	1	230
12	Sululta	230	0.97416	224.058
13	Markos 230	230	1.04622	240.63
14	Bahir dar 230	230	1.06107	244.045
15	Gonder	230	1.06582	245.139
16	Agaro	230	0.99019	227.744
17	Bedele	230	0.98042	225.495
19	Welkite	230	0.97201	223.563
20	Endasilase	230	1.04562	240.493
21	Tekeze	230	0.99032	227.773
22	Alamata	230	1.02737	236.295
23	Mekele	230	1.00835	231.92
24	Combolcha II	230	0.97953	225.292
25	Legetafo	230	0.86682	199.369
26	Kaliti I	230	0.88729	217.048
27	Sebeta I	230	0.95027	218.562
28	Gefersa	230	0.96671	222.343
29	Koka	230	1	230
30	Hurso	230	0.99109	227.951
31	Awash Town	230	1.00202	230.465
32	Dire Dawa III	230	0.9886	227.379
33	Melka Wakena	230	1	230
34	M W Yugo	230	0.85882	197.529
35	Hossaina	230	0.94534	217.428
36	Gedo	230	0.98681	226.967
37	Fincha	230	1	230
38	Awash	132	0.99757	131.679
39	Welayita sodo	400	1.00055	400.219

Transmission Line Loss Assessment under Base Case Condition

In this section, the active power losses for each voltage level line of EEP's transmission network were analyzed. After filling all the necessary data into the on-line diagram of the existing EEP's grid network Power world software, the load flow simulation was run for the peak load condition.

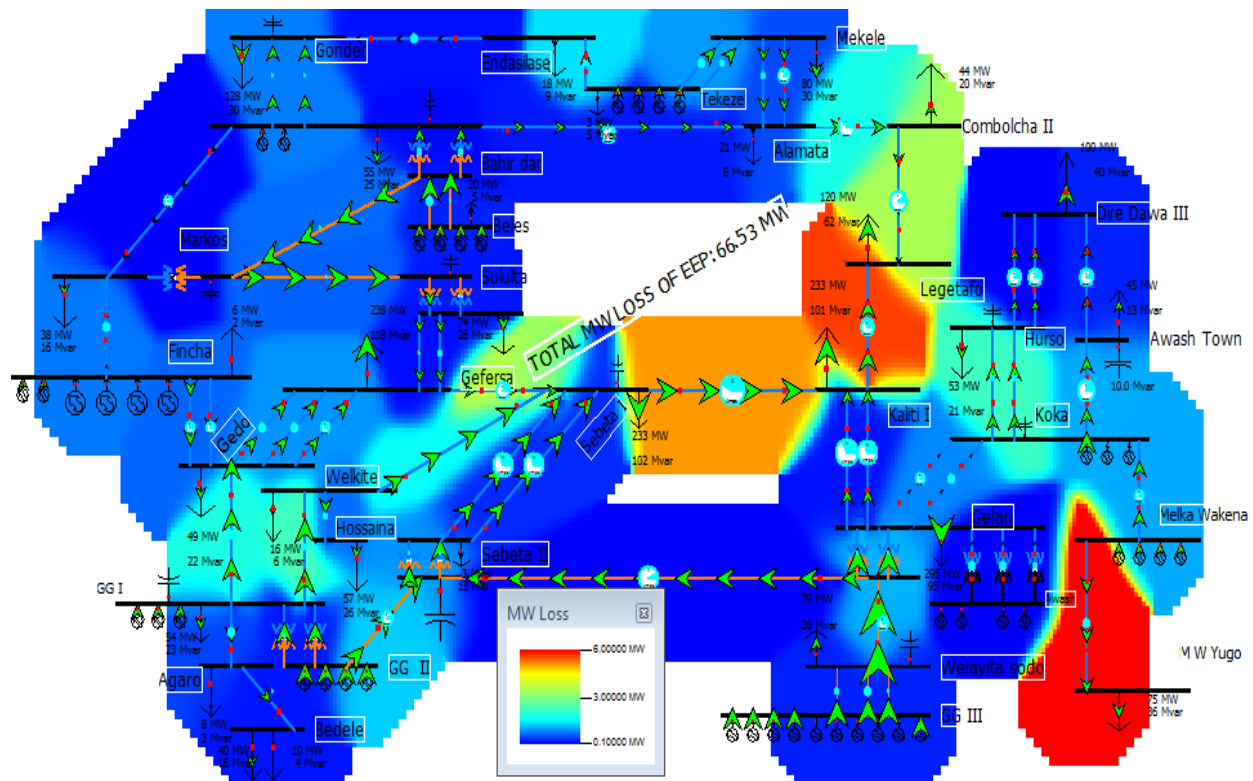


Figure 4.2 Base case simulation showing the MW loss levels of each transmission lines

From the load flow result, total transmission loss as well as loss, shares at each 230kV and 400 kV voltage level transmission lines were identified. The result of the load flow simulation quantifies the total transmission loss during peak load to be 66.53 MW active power losses. This value accounts 3.02% of the EEP's total peak load of 2202.6 MW and MW loss level of each transmission line shows in Figure 4.2.

The simulation results of the models were then recorded in subsequent tables which were then exported to Microsoft Office Excel to further demonstrate the transmission line and transformer

loss proportionality. Hear this thesis is focused only transmission line loss and the transmission line loss between each bus as follow.

Table 4.2 Transmission line loss of base case simulation

From Name	To Name	MW From	Mvar From	MVA From	MW Loss	Mvar Loss
GG III	Welayita sodo	211.1	-32.1	213.5	0.27	-27.57
GG III	Welayita sodo	211.1	-32.2	213.5	0.27	-27.57
GG III	Welayita sodo	211.1	-32.2	213.5	0.27	-27.57
Sebeta II	Gelan	-98.7	42.1	107.3	0.05	-16.75
Welayita sodo	Gelan	553.5	40.4	555	1.11	1.38
Sebeta II	GG II	-166.9	-61.8	177.9	1.27	-74.62
Beles	Bahir dar	167.9	-116.5	204.3	0.28	-37.19
Beles	Bahir dar	167.9	-116.5	204.4	0.28	-37.19
Markos	Bahir dar	-168	-7.8	168.1	0.71	-122.43
Markos	Sululta	151.2	-18.3	152.3	0.64	-133.7
Kaliti I	Gelan	-83.3	-66	106.2	0.19	-0.38
Kaliti I	Gelan	-83.3	-66	106.2	0.19	-0.38
Gelan	Koka	9.6	-96.1	96.6	0.87	-4.46
Gelan	Koka	9.6	-96.1	96.6	0.87	-4.46
Sebeta II	Sebeta I	125.6	11.1	126.1	0.33	1.56
Sebeta II	Sebeta I	125.6	11.1	126.1	0.33	1.56
GG I	Agaro	58.9	-7.4	59.3	0.47	-19.79
GG I	Welkite	176.3	32.4	179.3	2.39	7.09
GG I	Gedo	102.2	-9.4	102.6	1.87	-8.54
Sululta	Gefersa	38	59.5	70.6	0.16	-2.44
Sululta	Gefersa	38	59.5	70.6	0.16	-2.44
Bahir dar 230	Markos 230	16.5	-4.3	17.1	0.06	-23.83
Fincha	Markos 230	5.8	-70.2	70.5	0.79	-24.43
Bahir dar 230	Gonder	58.4	-35.9	68.6	0.82	-26.5
Bahir dar 230	Gonder	58.4	-35.9	68.6	0.82	-26.5
Bahir dar 230	Alamata	31.9	-22.4	39	0.23	-69.6
Gonder	Endasilase	-12.3	-35.2	37.3	0.18	-89.78
Agaro	Bedele	50.4	9	51.2	0.21	-11.44
Welkite	Sebeta I	101	2.1	101	1.63	-6.84
Welkite	Hossaina	57.4	16.9	59.9	0.69	-8.75
Tekeze	Endasilase	31.3	-75.3	81.5	1.39	-29.93
Tekeze	Mekele	74.9	-40.4	85.1	0.98	-9.71
Tekeze	Mekele	74.9	-41.4	85.6	0.98	-11.7
Mekele	Alamata	34.1	-45.2	56.6	0.52	-25.8
Mekele	Alamata	34.1	-45.2	56.6	0.52	-25.8

Alamata	Combolcha II	77.8	0.1	77.8	1.79	-13.87
Combolcha II	Legetafo	32.5	-6	33	3.51	-44.6
Legetafo	Kaliti I	-91	-23.4	94	5.64	8.94
Kaliti I	Sebeta I	-163.1	-1.4	163.1	5.1	11.03
Gefersa	Sebeta I	55.1	45.5	71.5	3.78	-0.45
Gedo	Gefersa	73.4	0.4	73.4	0.95	-13.01
Gedo	Gefersa	73.4	0.4	73.4	0.95	-13.01
Gedo	Gefersa	73.4	0.4	73.4	0.95	-13.01
Koka	Hurso	63.4	-39.7	74.8	2.23	-52.11
Koka	Hurso	63.4	-39.7	74.8	2.23	-52.11
Koka	Awash Town	77.5	-22.3	80.6	1.09	-13.26
Koka	Melka Wakena	-66.8	2.9	66.8	1.07	-18.22
Hurso	Dire Dawa III	34.5	7.7	35.3	0.05	-3.8
Hurso	Dire Dawa III	34.5	7.7	35.3	0.05	-3.79
Awash Town	Dire Dawa III	31.4	-12	33.6	0.28	-29.01
Melka Wakena	M W Yugo	82.2	19.1	84.4	7.17	-17.11
Fincha	Gedo	85.1	4.8	85.2	0.67	-7.2
Gedo	Fincha	-84.4	-12	85.3	0.67	-7.2
Total transmission line loss					60.98	

The result of Table 4.2 obtained from power world simulator showed that active and reactive power flow reactive power loss and active power loss at each transmission line. Numerically maximum active power transmission loss observed at the following transmission lines. Melka wekana to Melka wekana yougo, Kaliti I to Sebeta I, Kaliti I to Legetafo and Combolcha to Legetafo.

Subtract transformer losses the considered transmission network of EEP (starting from generating to the load) consist 14 transformers all of them are two winding transformers; The load flow simulation result provided transformer losses account 5.55 MW of the total 66.53 MW loss which means it takes a share of 8.3% of the total loss. Hence the total transmission line (i.e. 400 kV and 230 kV) accounts 60.98 MW.

Annual Energy Estimation under Base Case Simulation

Once the annual peak load loss is determined from the load flow simulation, then it is possible to estimate the annual energy loss, using empirical “Loss factor, Load factor” method. Thus the

annual energy loss for the existing condition can be estimated with the following steps. From equation (2.2), energy loss for period T can be determined as;

$$\text{Energy loss (T)} = (\text{Average power loss for period T}) \times (T)$$

For annual energy loss calculation, the period T is equal to 8760 which is the number of hours in a year since energy is measured in watt-hours. So, the annual energy loss due to load losses on transmission lines for the existing condition of EEP was determined as:

$$\text{Annual energy loss} = (\text{annual average power loss}) \times (8760)$$

Here the difficulty comes in determining the annual average power loss. This task requires two important quantities to be determined before. The average power loss for period T was given by equation (2.4) as:

$$\text{Average power loss in period T} = (\text{loss factor}) \times (\text{peak loss in period T})$$

Thus, these two quantities, namely, loss factor and transmission line peak loss for the given period were given by equation (2.5) as;

$L_f = (0.92) (L_F)^2 + (0.08) (L_F)$ Where the load factor was obtained from the EEP historical and forecast data showing its value to be 57%. Thus, the annual loss factor was determined as:

$$L_f = (0.92) (0.57)^2 + (0.08) (0.57) = 0.3445$$

Which means the annual loss factor of the EEP grid network is $34.45\% = 0.3445$. The average hourly annual power loss for the existing condition of EEP can then be calculated from the loss factor and annual peak loss- determined from the load flow simulation at peak load as:

$$\begin{aligned} \text{Annual average power loss} &= (\text{loss factor}) \times (\text{annual peak loss}) \\ &= (0.3445) \times (60.98 \text{ MW}) \\ &= 21.01 \text{ MW} \end{aligned}$$

Now, the last step to determine the annual energy loss would be, multiplying the average power loss with the number of hours of a year, 8760 hours. This thesis did not consider no-load losses.

$$\begin{aligned}
\text{Annual energy loss} &= (\text{annual average power loss}) \times (8760\text{hrs}) \\
&= (21.01 \text{ MW}) \times (8760\text{hrs}) \\
&= 184.026 \text{ GWh}
\end{aligned}$$

Actual annual energy consumed by all substation loads can be determined from total annual substation peak load and annual load factor as follows:

$$\begin{aligned}
\text{Total substation energy consumed} &= \text{Peak load} \times \text{load factor} \times 8760\text{hrs} \\
&= 2202.6\text{MW} \times 0.57 \times 8760 \\
&= 10998.022\text{GWh}
\end{aligned}$$

Thus, to transmit 10998 GWh of energy, EEP's grid consumes 184.026 GWh of energy on transmission lines. This shows the loss constitutes 1.67% of the actual energy consumed. With the present EEU's bill tariff for the industrial customers is 0.4736 birr/kWh [27] as shown in, Table A.6 of Appendix A: and it is equal to 0.0203 USD/KWh, @1USD=23.31Birr [38].

$$\begin{aligned}
\text{Annual financial loss} &= \text{bill tariff} * \text{annual energy loss} \\
&= 0.0203 \text{ USD/KWh} * 184.026 \text{ GWh} \\
&= 3.735 \text{ million USD.}
\end{aligned}$$

4.3. Transmission Line Loos Assessment under Contingency Conditions

In this section, efforts have been made to see the effect of a single transmission line outage on loss of transmission lines and transformers. But this thesis focused only on transmission line loss. Since the system has 66.53 MW loss under normal operating condition as it has been seen in base case simulation, the transmission line loss has fluctuated for a single transmission line outage. Because, when there is single transmission line outage the remaining transmission lines should have the responsibility to feed the substation peak load, at this time those transmission lines becomes overloaded. Hence, the transmission line loss increases. The outage of different transmission lines either 400 kV or 230 kV from the system has their own effect on transmission line loss. A comprehensive 53 contingency analysis for each transmission line (ten 400 kV and forty three 230 kV) has been done and the result has been summarized in Table 4.3. Which shows the result of transmission line contingency analysis indicating the number of constraint

violation, the lowest and highest voltage deviations from the normal limits for each single transmission line outage.

Table 4.3 Simulation result of a single transmission line contingency

Line contingency	Solved	No of bus voltage limit Violation	Min Volt	Max Volt
GGIII-WelayitasodoC1	YES	0		
GGIII-WelayitasodoC2	YES	0		
GGIII-WelayitasodoC3	YES	0		
SebetaII-GelanC1	YES	0		
Welayitasodo-GelanC1	NO	Unsolved		
SebetaII-GGIIC1	YES	0		
Beles-BahirdarC1	YES	4		1.135
Beles-BahirdarC2	YES	4		1.135
Markos-BahirdarC1	YES	10		1.333
Markos-SulultaC1	YES	0		
KalitiI-GelanC1	YES	0		
KalitiI-GelanC2	YES	0		
Gelan-KokaC1	YES	0		
Gelan-KokaC2	YES	0		
Sebetaii-SebetaIC1	YES	0		
Sebetaii-SebetaIC2	YES	0		
GGI-AgaroC1	YES	0		
GGI-WelkiteC1	YES	1	0.877	
GGI-GedoC1	YES	1	0.899	
Sululta-LegetafoC1	YES	0		
Sululta-GefersaC1	YES	1	0.894	
Sululta-GefersaC2	YES	1	0.894	
Bahirdar230 kV-Markos230C1	YES	0		
Fincha-Markos230C1	YES	1	0.879	
Bahirdar230 kV-GonderC1	YES	0		
Bahirdar230 kV-GonderC2	YES	0		
Bahirdar230 kV-AlamataC1	NO	Unsolved		
Gonder-EndasilaseC1	NO	Unsolved		
Agaro-BedeleC1	YES	0		
Welkite-SebetaIC1	YES	0		
Welkite-HossainaC1	YES	1	0.898	
Tekeze-EndasilaseC1	NO	Unsolved		
Tekeze-MekeleC1	YES	1		1.103
Tekeze-MekeleC2	YES	3		1.109

Mekele-AlamataC1	YES	4		1.118
Mekele-AlamataC2	YES	4		1.118
Alamata-CombolchaIIC1	YES	2	0.604	
CombolchaII-LegetafoC1	YES	1	0.858	
Legetafo-KalitiIC1	YES	18	0.366	1.491
KalitiI-SebetaIC1	YES	2		
Gefersa-SebetaIC1	YES	2	0.877	
Gedo-GefersaC1	YES	0		
Gedo-GefersaC2	YES	0		
Gedo-GefersaC3	YES	0		
Koka-HursoC1	YES	0		
Koka-HursoC2	YES	0		
Koka-AwashTownC1	YES	0		
Koka-MelkaWakenaC1	YES	0		
Hurso-DireDawaIIIC1	YES	0		
Hurso-DireDawaIIIC2	YES	0		
AwashTown-DireDawaIIIC1	YES	0		
MelkaWakena-MWYugoC2	YES	0		
MelkaWakena-MWYugoC1	YES	1	0.893	
Fincha-GedoC1	YES	0		
Gedo-FinchaC2	YES	0		

The outage of some transmission lines made the interconnected system of EEP 400 kV and 230 kV to be unstable. That means the system was subjected to total blackout. As it has been obtained from simulation output, the outage of ten transmission lines could make the system to be unstable. These credible transmission lines which made the system to be unstable include three 400 kV transmission lines and seven 230 kV transmission lines. The outages of many transmission lines made transmission lines and transformers carry beyond their ratings, and the substation bus voltage to be out of acceptable range. Accordingly; a single line contingency could result in a minimum of a number of violations.

As it can be seen from Table 4.3, The transmission lines that have resulted in maximum number of constraint violation, maximum overloading of the branch limit and highest voltage deviations from the normal limits for each single transmission line outage was observed when Kaliti to Legetafo 230 kV transmission line outage: for investigation hear it is sample transmission line contingency analysis (Kaliti to Legetafo 230 kV). The rest of transmission lines contingency analysis detail descriptions have been attached in Table B.1 of Appendix B.

4.4. Losses Analysis for Kaliti to Legetafo line under Contingency Condition

In the same run mode, the power world simulation software was used to perform single line contingencies of Kaliti to Legetafo 230 kV transmission line.

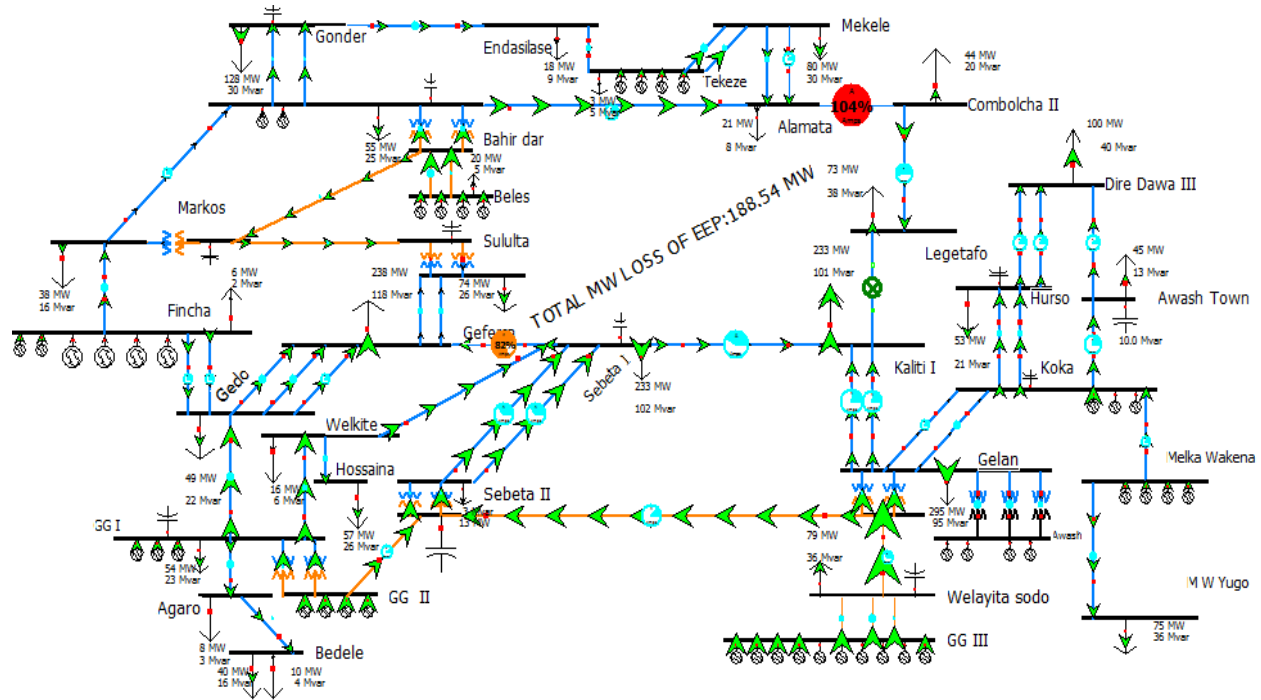


Figure 4.3 Simulation result for outage of Kaliti to Legetafo line

The outage of Kaliti to Legetafo 230 kV transmission line from the grid system causes for a loading effect over others that lead the network to have 188.54 MW active power losses. The line was 5.64 MW losses of total transmission line losses under normal condition as shown in the Table 4.1.

When Kaliti to Legetafo 230 kV transmission line is out of the system, it causes high overloading of Gefersa to Sebeta transmission line which has a line loading of 82% and Alamata to Combolcha transmission line which has a line loading of 104% as shown in the Figure 4.3. It indicates that the lines will go to emergency and alert states because of their loading beyond their rated capacity. The load flow analysis is carried out to determine the bus voltage, real and reactive power flow and line losses using the run mode of power world simulator and the bus voltage and its PU value is presented in Table 4.4.

Table 4.4 Bus voltage record of the network under line contingency case simulation

Bus Number	Name	Nom kV	PU Volt	Volt (kV)
1	GG III	400	1	400
2	Gelan	400	1.00984	403.936
3	Sebeta II	400	1.01639	406.556
4	GG II	400	1.00498	401.992
5	Beles	400	1.49306	597.225
6	Bahir dar	400	1.49822	599.29
7	Sululta	400	1.34206	536.824
8	Markos	400	1.44306	577.224
9	Gelan	230	0.98938	227.558
10	Sebeta II	230	1.0466	240.718
11	GG I	230	1.03319	237.634
12	Sululta	230	1.17525	270.308
13	Markos 230	230	1.39351	320.508
14	Bahir dar 230 kV	230	1.52478	350.699
15	Gonder	230	1.56074	358.971
16	Agaro	230	1.02501	235.753
17	Bedele	230	1.01577	233.627
19	Welkite	230	1.03071	237.064
20	Endasilase	230	1.59149	366.042
21	Tekeze	230	1.51448	348.33
22	Alamata	230	1.46722	337.46
23	Mekele	230	1.4998	344.953
24	Combolcha II	230	0.97223	223.613
25	Legetafo	230	0.39748	91.421
26	Kaliti I	230	0.99016	227.737
27	Sebeta I	230	1.05398	242.415
28	Gefersa	230	1.15707	266.126
29	Koka	230	1.00001	230.003
30	Hurso	230	0.9911	227.954
31	Awash Town	230	1.00203	230.468
32	Dire Dawa III	230	0.98862	227.382
33	Melka Wakena	230	1.00001	230.003
34	M W Yugo	230	0.85883	197.532
35	Hossaina	230	1.0063	231.449
36	Gedo	230	1.17537	270.336
37	Fincha	230	1.23073	283.069
38	Awash	132	1.00001	132.001
39	Welayita sodo	400	1.00174	400.696

The result of Table 4.4 obtained from Power World Simulation under Kaliti to Legetafo 230 kV transmission line contingency condition shows that high voltage and low voltage values at several buses.

The active power losses for each voltage level line of EEP's transmission network under KalitiC1 to LegetafoC11 230 kV transmission line contingency conditions were analyzed. The result of the load flow simulation quantifies the total transmission loss during peak load under contingency condition to be 188.4 MW active power losses. This value accounts 8.53 % of the EEP's total peak load of 2202.6 MW. This result shows that an increasing of transmission line loss under transmission line contingency condition.

The MW loss levels of each transmission lines have been popup from Power World Simulation under Kaliti to Legetafo 230 kV transmission line contingency condition with color full display as shown in the Figure 4.4.

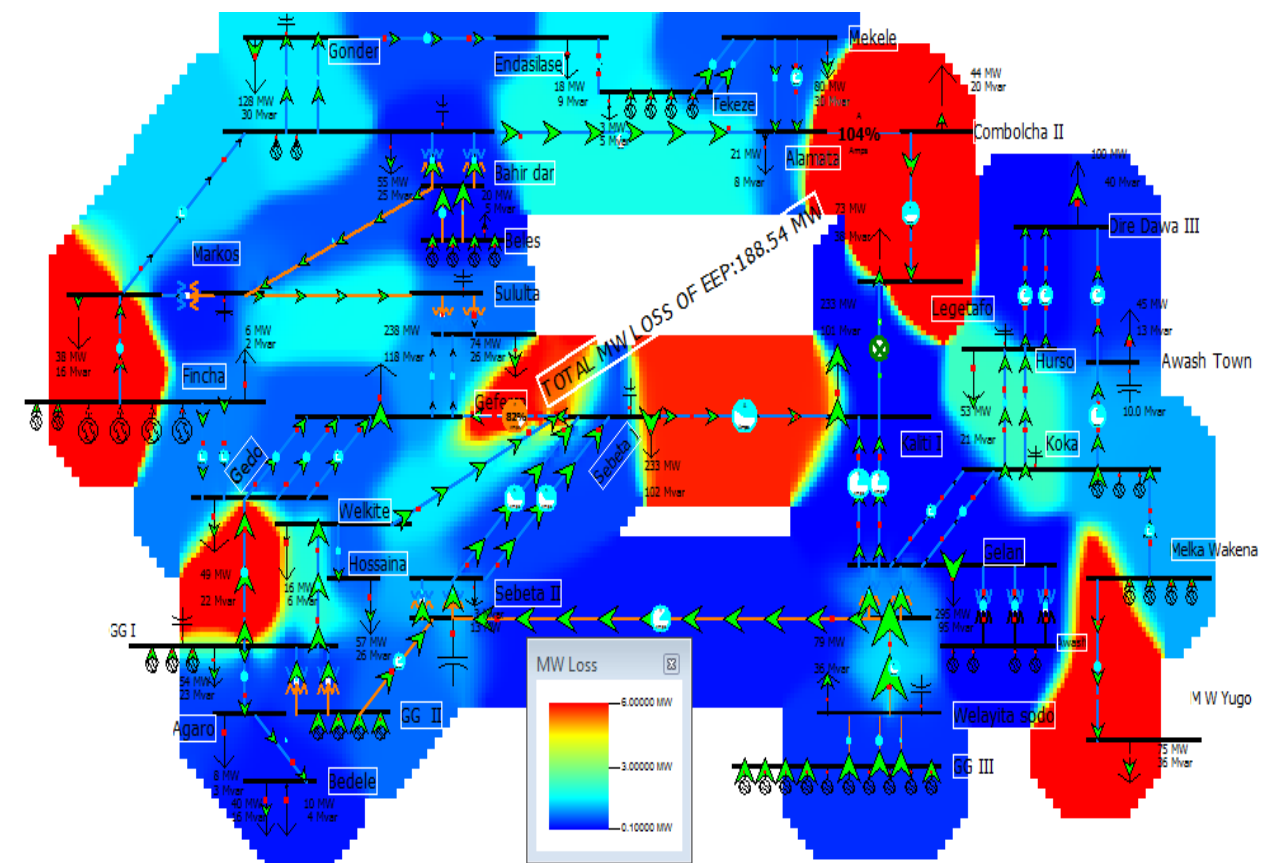


Figure 4.4 MW loss levels of lines under Kaliti to Legetafo line contingency condition

The effect of KalitiC1 to LegetafoC1 230 kV transmission line outage on carrying capacities of transmission system components (transmission lines and transformers) and substation bus bars voltage has been visualized. As a result of this transmission line outage, some of the 230 kV transmission lines of the grid faced maximum amount of MW loss as it is indicated by red color in Figure 4.4. Due to this line outage, more power flow from Beles and Tekeze power Plants through Bahir Dar – Alamata and Mekele – Alamata lines towards Combolcha which would flow through Combolcha- Legetafo 230 kV line to feed Legetafo load. That is why the transmission lines of Alamata-Combolcha and Combolcha-Legetafo 230 kV overloaded and have the maximum amount of MW loss. In addition to Beles and Tekeze power plants, most of the other power plants have also supplied more power than before. Hence; at GilgelGibe- Gedo, Fincha-Markos, Gefersa-Sebeta and Sebeta-Kaliti has observed more than 6 MW losses at each transmission line

The result of MW loss levels of each transmission line under KalitiC1 to LegetafoC1 230 kV transmission line contingency condition shows that the maximum amount of active power losses observed in red and yellow color, then Simulation results of the models were recorded in subsequent tables which were then exported to Microsoft Office Excel to further demonstrate the transmission line and transformer loss proportionality.

Table 4.5 MW line losses under Kaliti to Legetafo line contingency condition

From Name	To Name	Status	MW From	Mvar From	MVA From	MW Loss	Mvar Loss
GG III	Welayita sodo	Closed	236	-44.9	240.2	0.34	-26.44
GG III	Welayita sodo	Closed	236	-45	240.3	0.34	-26.44
GG III	Welayita sodo	Closed	236	-45	240.3	0.34	-26.44
Sebeta II	Gelan	Closed	-195.2	101.2	219.9	0.19	-15.58
Sebeta II	GG II	Closed	-122.9	-8.7	123.2	0.69	-84.92
Beles	Bahir dar	Closed	167.9	-116.5	204.3	0.12	-82.86
Beles	Bahir dar	Closed	167.9	-116.5	204.4	0.12	-82.86
Markos	Sululta	Closed	44.9	211.6	216.3	1.65	-226.0
Markos	Bahir dar	Closed	-55.3	-332.1	336.7	0.57	-248.5
Gelan	Koka	Closed	8.8	-26.6	28	0.05	-9.42
Gelan	Koka	Closed	8.8	-26.6	28	0.05	-9.42
Sebeta II	Sebeta I	Closed	151.7	-48.8	159.3	0.44	2.28
Sebeta II	Sebeta I	Closed	151.7	-48.8	159.3	0.44	2.28
GG I	Welkite	Closed	171	-17.8	172	2.03	3.7

GG I	Agaro	Closed	58.8	-10.1	59.7	0.44	-21.5
GG I	Gedo	Closed	151.8	-169	227.1	8.09	21.96
Sululta	Gefersa	Closed	-16.1	214.2	214.8	0.99	-0.87
Sululta	Gefersa	Closed	-16.1	214.2	214.8	0.99	-0.87
Bahir dar 230 kV	Alamata	Closed	135.7	-40.2	141.5	1.79	-129.7
Bahir dar 230 kV	Gonder	Closed	81.1	-117.7	142.9	1.46	-56.7
Bahir dar 230 kV	Gonder	Closed	81.1	-117.7	142.9	1.46	-56.7
Bahir dar 230 kV	Markos 230	Closed	-19.7	101.2	103.1	1.32	-35.31
Gonder	Endasilase	Closed	31.9	-122.7	126.8	0.49	-199.7
Agaro	Bedele	Closed	50.4	8	51	0.19	-12.43
Welkite	Hossaina	Closed	57.4	15.1	59.3	0.61	-10.63
Welkite	Sebeta I	Closed	96.2	-42.8	105.2	1.45	-11.31
Tekeze	Mekele	Closed	96.8	-7.9	97.1	0.6	-35.8
Tekeze	Mekele	Closed	96.8	-5.6	97	0.6	-31.25
Tekeze	Endasilase	Closed	-12.4	-143.6	144.1	1.5	-75.73
Alamata	Combolcha II	Closed	224.4	218.3	313.1	15.9	119.72
Mekele	Alamata	Closed	56.3	11.8	57.5	0.53	-56.78
Mekele	Alamata	Closed	56.3	11.8	57.5	0.53	-56.78
Combolcha II	Legetafo	Closed	165	78.6	182.8	92.36	40.99
Legetafo	Kaliti I	Open	0	0	0	0	0
Kaliti I	Sebeta I	Closed	-86.5	-145.5	169.3	5.82	10.16
Kaliti I	Gelan	Closed	-73.3	22.3	76.6	0.09	-1.04
Kaliti I	Gelan	Closed	-73.3	22.3	76.6	0.09	-1.04
Gefersa	Sebeta I	Closed	-64.9	373.6	379.2	6.95	32.08
Koka	Awash Town	Closed	77.5	-22.3	80.6	1.09	-13.26
Koka	Hurso	Closed	63.4	-39.7	74.8	2.23	-52.11
Koka	Hurso	Closed	63.4	-39.7	74.8	2.23	-52.11
Koka	Melka Wakena	Closed	-66.8	2.9	66.8	1.07	-18.23
Hurso	Dire Dawa III	Closed	34.5	7.7	35.3	0.05	-3.79
Hurso	Dire Dawa III	Closed	34.5	7.7	35.3	0.05	-3.8
Awash Town	Dire Dawa III	Closed	31.4	-12	33.6	0.28	-29.01
Melka Wakena	M W Yugo	Closed	82.2	19.1	84.4	7.17	-17.11
Gedo	Gefersa	Closed	69.7	-2.5	69.8	0.61	-23.13
Gedo	Gefersa	Closed	69.7	-2.5	69.8	0.61	-23.13
Gedo	Gefersa	Closed	69.7	-2.5	69.8	0.61	-23.13
Gedo	Fincha	Closed	-57.3	-102.8	117.6	0.81	-11.81
Fincha	Markos 230	Closed	59.8	-274.4	280.8	10.74	-7.4
Fincha	Gedo	Closed	58.1	91	107.9	0.81	-11.8
Welayita sodo	Gelan	Closed	628	-1.4	628	1.37	36
Total transmission line loss						181.35	

The result of Table 4.5 obtained from power world simulator showed that active and reactive power flow reactive power loss and active power loss at each transmission line and also status of each transmission line. Subtract transformer losses the considered transmission network of EEP. From the load flow simulation result transformer losses is 7.20 MW of the total 188.54 MW loss. Hence the total transmission line (i.e. 400 kV and 230 kV) accounts 181.35 MW.

4.5.Summary of Contingency Analysis and Transmission Line Loss

In the same run mode, the power world simulation software was used to perform a set of single line contingencies. Load flow analysis is applied during simulation of lines outages. Some violations were noticed when the actual power flow simulation was conducted on the thirty eight bus interconnected networks. The summary of various transmission line contingencies is shown in Table 4.6 by ignoring unsolved transmission line contingency conditions.

Table 4.6 Summary of contingency analysis and transmission line loss

Name of line outage	Voltage (kV)	Solve	Total line loss (MW)
GGIII-Welayitasodo	400	YES	66.98
GGIII-Welayitasodo	400	YES	66.98
GGIII-Welayitasodo	400	YES	66.98
SebetaII-Gelan	400	YES	66.79
SebetaII-GGII	400	YES	81.17
Markos 400 kV-BahirdarkV	400	YES	83.05
Markos-SulultaC1	400	YES	81.01
Gelan-KokaC1	230	YES	68.91
Gelan-KokaC2	230	YES	68.91
SebetaII-SebetaIC1	230	YES	67.51
SebetaII-SebetaIC2	230	YES	67.51
GGI-AgaroC1	230	YES	67.01
GGI-WelkiteC1	230	YES	75.29
GGI-GedoC1	230	YES	67.60
Sululta-GefersaC1	230	YES	67.02
Sululta-GefersaC2	230	YES	67.02
Bahirdar230 kV-MarkosC1	230	YES	66.39
Agaro-Bedele	230	YES	66.85
Welkite-SebetaI	230	YES	68.33
Welkite-Hossaina	230	YES	65.68
Alamata-Combolch	230	YES	107.85
Combolc-Legetafo	230	YES	72.91
KalitiI – LegetafoC1	230	YES	188.4
KalitiI-GelanC1	230	YES	67.17
KalitiI-GelanC2	230	YES	67.17
KalitiI-SebetaIC1	230	YES	67.34
Gefersa-SebetaIC1	230	YES	66.78
Koka-HursoC1	230	YES	70.27
Koka-HursoC2	230	YES	70.27
Koka-AwashTown	230	YES	74.33
Koka-MelkaWakena	230	YES	68.57
Hurso-DireDawaC1	230	YES	68.53
Hurso-DireDawaC2	230	YES	68.53
Awash-DireDawa	230	YES	70.35
MelkaWak-MWYugo	230	YES	59.37
Gedo-GefersaC1	230	YES	69.90
Gedo-GefersaC2	230	YES	69.90
Gedo-GefersaC3	230	YES	69.90
Gedo-FinchaC2	230	YES	69.84
Fincha-Markos230C1	230	YES	69.37
Fincha-GedoC1	230	YES	69.84

4.6. Testing of Transmission Line Loss Mitigation Techniques

Since electrical power generation and distribution is the most critical of any country; reliability, loss, security and other related issues have to be taken into account both in planning and operation stages. In this thesis, 400 kV and 230 kV transmission line loss of the EEP interconnected grid system have been investigated both in the case of normal operation and contingencies. Therefore; transmission line loss mitigation measures have to be taken for the EEP interconnected system. In this study, two methods of transmission line loss mitigation methods were applied in the existing 400 kV and 230 kV transmission network of EEP. These include reactive power compensation and addition of transmission lines.

4.6.1. Loss Mitigation by Addition of Transmission Lines

Improvement of the existing transmission capacities and recommendation of additional transmission lines have been done to sufficiently transmit and distribute the existing and expected power. Therefore, these lines should be included in the existing transmission network to mitigate the loss of the system. Doubling circuiting was implemented in the load flow simulation program for selected lines of 230 kV transmission networks. In addition to the transmission lines, doubling new transmission lines have also been proposed to mitigate the system loss. The 400 kV transmission line was not included in the double as well new transmission circuit upgrading technique of this study because most of its branches are comparatively less loss than 230 kV and also its complexity (to have additional 400 kV transmission line the 230 kV side substations should undertake bulk expansion). The following two transmission lines are sample lines of the proposed additional lines. Melkawakena to Melkawakena Youg and Sululta to Legetafo.

Melkawakena to Melkawakena Youg; this transmission line is the highest power loss line which consumes above 11.2 % of the total transmission line active power loss. The outage of this transmission resulted in islanding of the Melkawakena Youg, Ramo and Gode 230 KV substations loads. To make the system more secure and to mitigate transmission line loss this line has been recommended to make add the transmission line. As the length of Melkawakena to Melkawakena Youg is covers relatively short which is 5Km it is economically feasible.

Sululta to Legetafo The transmission line from Gefersa to Sebeta, Sebeta to Kaliti, Kaliti to Legetafo and Combolcha to Legetafo substation has been investigated in overloading problem since the load demand in Kaliti, Sebets and Legetafo substations are so much. And the outage of Kaliti to Legetafo transmission line leads unexpected transmission loss to have 188 MW active power losses. That is the reason why from Sululta substation to Legetafo substation a new 230 kV line has been recommended. The air distance from the Sululta substation to Legetafo substation is 19.08 Km but the real transmission line distance depends on geographical situations between the two substations. Let assume that by considering the geographical situation, the real transmission line distance to be 22 Km. The other parameters of Sululta to Legetafo transmission line has been estimated from the data of EEP for the previous lines which are used for the 230 kV transmission line. Therefor relatively the same data is used on the basis of similar voltage ratings of Gefersa to Sululta.

Then the transmission lines resistance, reactance and suceptance are converted into PU values to make them possible for the software fed using equations (3.3-3.6) and the data of Melkawakena to Melkawakena Youg was similar to the previous line as it is double circuit.

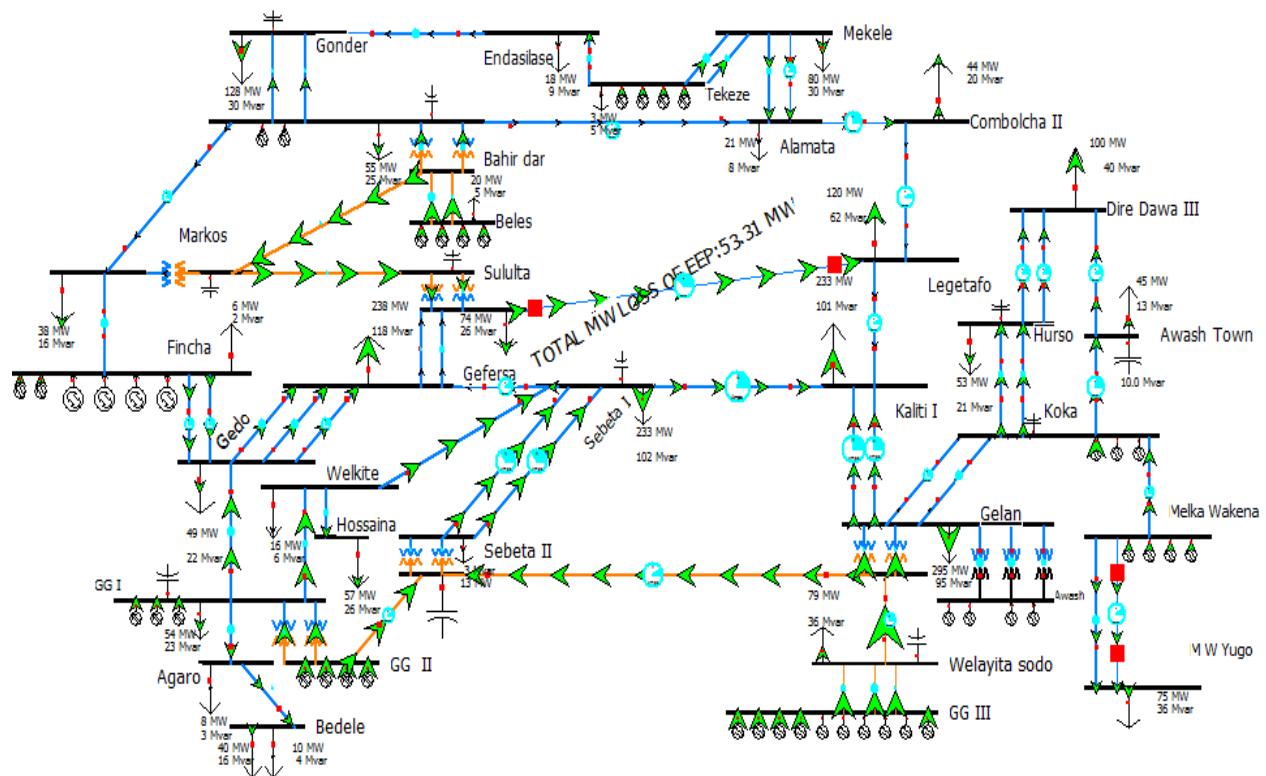


Figure 4.5 Simulations of Existing Grid network after addition and doubling of line.

Loss Assessment and Annual Energy Estimation after Addition of Lines

After selecting candidate lines, the proposed Melkawakena to Melkawakena Young circuiting and addition of Sululta to Legetafo transmission line was implemented in the one line diagram of the Power world software and the load flow simulation was run to determine the peak transmission loss as shown in Figure 4.5.

The result of the load flow returned a total transmission peak active power loss of 53.31 MW, which is a reduction of 13.22 MW of the unmodified existing EEP peak loss of 66.53 MW and the transformer losses account 5.19 MW of the total 53.31 MW loss. Hence the total transmission line losses become 48.12 MW. Therefore, the annual energy loss for the determined peak capacity loss of 48.12 MW can be determined in a similar manner as the unmodified base case loss was calculated.

$$\begin{aligned}\text{Annual energy loss} &= (\text{average power loss}) \times (8760 \text{ hrs}) \\ &= (\text{Loss Factor} \times \text{peak loss}) \times (8760 \text{ hrs}) \\ &= 0.3445 \times 48.12 \text{ MW} \times (8760 \text{ hrs}) \\ &= 145.45 \text{ GWh}\end{aligned}$$

This energy loss constitutes 1.32 % of the total actual annual energy consumed by all the substations which was determined previously to be 10998.022GWh. As compared to the loss percentage of the existing unmodified network of 1.67%, there is a net energy saving of 0.35% which is 38.57 GWh. When this energy gain is converted into financial profit, according to the existing bill tariff of EEP for industrial customers (0.0203 USD/KWh), it amounts around 0.78 million USD annually.

Contingency Analysis and Loss Assessment with Addition of Lines

Based on the N-1 contingency of transmission line the contingency analysis of EEP interconnected 400 kV and 230 kV power system after addition and doubling of transmission lines has been made. The effect of the transmission line outage on bus bar voltage limit has been summarized in Table 4.7.

Table 4.7 Simulation output of a single line contingency after addition and doubling lines

Line contingency	Level (kV)	Solved	Violations	Min Volt	Max Volt
GGIII-WelayitasodoC1	400	YES	0		
GGIII-WelayitasodoC2	400	YES	0		
GGIII-WelayitasodoC3	400	YES	0		
SebetaII-GelanC1	400	YES	0		
Welayitasodo-GelanC1	400	NO	Unsolved		
SebetaII-GGIIC1	400	YES	0		
Beles-BahirdarC1	400	NO	7		1.189
Beles-BahirdarC2	400	NO	7		1.189
Markos-BahirdarC1	400	YES	9		1.367
Markos-SulultaC1	400	YES	0		
KalitiI-GelanC1	230	YES	0		
KalitiI-GelanC2	230	YES	0		
Gelan-KokaC1	230	YES	0		
Gelan-KokaC2	230	YES	0		
Sebetaii-SebetaIC1	230	YES	0		
Sebetaii-SebetaIC2	230	YES	0		
GGI-AgaroC1	230	YES	0		
GGI-WelkiteC1	230	YES	2	0.862	
GGI-GedoC1	230	YES	0		
Sululta- Legetafo	230	YES	1	0.867	
Sululta-GefersaC1	230	YES	0	0.897	
Sululta-GefersaC2	230	YES	0	0.897	
Bahirdar-Markos230C1	230	YES	0		
Fincha-Markos230C1	230	YES	0		
Bahirdar230 kV-GonderC1	230	YES	2		1.196
Bahirdar230 kV-GonderC2	230	YES	2		1.196
Bahirdar230 kV-AlamataC1	230	NO	Unsolved		
Gonder-EndasilaseC1	230	NO	Unsolved		
Agaro-BedeleC1	230	YES	0		
Welkite-SebetaIC1	230	YES	0		
Welkite-HossainaC1	230	YES	0		
Tekeze-EndasilaseC1	230	NO	Unsolved		
Tekeze-MekeleC1	230	YES	6		1.135
Tekeze-MekeleC2	230	YES	7		1.135
Mekele-AlamataC1	230	NO	Unsolved		
Mekele-AlamataC2	230	NO	Unsolved		
Alamata-CombolchaIC1	230	YES	1	0.815	

CombolchaI-LegetafoC1	230	YES	0		
Legetafo-KalitiIC1	230	YES	0		
KalitiI-SebetaIC1	230	YES	0		
Gefersa-SebetaIC1	230	YES	0		
Gedo-GefersaC1	230	YES	0		
Gedo-GefersaC2	230	YES	0		
Gedo-GefersaC3	230	YES	0		
Koka-HursoC1	230	YES	0		
Koka-HursoC2	230	YES	0		
Koka-AwashTownC1	230	YES	0		
Koka-MelkaWakenaC1	230	YES	0		
Hurso-DireDawaIIC1	230	YES	0		
Hurso-DireDawaIIC2	230	YES	0		
Awash-DireDawaIIC1	230	YES	0		
MelkaWaken-MWYugoC1	230	YES	1	0.868	
MelkaWaken-MWYugoC2	230	YES	1	0.868	
Fincha-GedoC1	230	YES	0		
Gedo-FinchaC2	230	YES	0		

As it can be seen from the result, there is a remarkable decrease of the effect of transmission line outage as compared with the previous base case system, without including the recommended loss mitigation enhancements, as it has been obtained from simulation output, the outage of six transmission lines could make the system to be unstable. Comparatively it reduces four of them.

Generally addition of Melkawakena to Melkawakena Young and additional transmission line from Sululta to Legetafo to the existing 400 and 230 kV grid network have appreciable line loss mitigation and security enhancement as it finished with 46 Violations and 6 Unsolvability single transmission line Contingencies.

4.6.2. Loss Mitigation by Reactive Power Compensation

The profile of bus voltages strongly affects the reactive power flow throughout the power network, which in turn substantially impacts transmission losses. Hence, by adjusting bus voltages to minimize the transfer of reactive power over the grid, a significant reduction in transmission losses can be accomplished together with improving the voltage regulation. The load flow simulation was run for the existing unmodified EEP grid network and buses with under voltage conditions were identified. Shunt reactors used to the buses with highest over voltages and shunt capacitors used to the buses with lowest under voltages. As it has been seen from Table 4.1 bus voltage record of the network under base case simulation condition, low voltage profile values at the following buses; Bus 25- Legetafo (0.86682 PU), Bus 34- Melkawekana Yugo (0.85884 PU) and Bus 26- Kaliti (0.88729 PU). Therefor; Shunt capacitors were added to each weak voltage profile buses to minimize the reactive power flow and hence reducing losses.

Placing and Sizing of Shunt Capacitors

Shunt capacitors were added to the weak voltage profile buses to minimize the reactive power flow and hence reducing losses. Accordingly, 3 buses with the worst voltage profile (Bus 25- Legetafo (0.86682 PU), Bus 34- Melkawekana Yugo (0.85884 PU) and Bus 26- Kaliti (0.88729 PU)) were selected to place the compensators and functioning dual purposes of voltage regulation and loss minimization. Size of Mvar requirement was obtained from simulation by trial and error, which gave minimum losses at an acceptable voltage level.

The Mvar values were improved through iterations; each iteration giving a specific value of Mvar at each placement. It has been shown that the real power losses vary whether the Mvar value increases or decreases from a specific value. Hence, there is a point where minimum real power losses occur. This is an optimum point in the operation of an electrical power system as long as the voltage is within allowable range.

Table 4.8 Determination of capacitor sizes at Legetafo, Melkawekana Yugo and Kaliti

Bus	Shunt capacitor (Mvar)	Bus voltage (PU)	Total active loss (MW)
Legetafo	0	0.86682	66.52
	30	0.87645	65.06
	35	0.89892	64.93
	40	0.90341	64.80
	45	0.90732	64.72
	50	0.90755	64.81
Melkawekana Yugo	0	0.85884	64.72
	25	0.90432	63.34
	30	0.91658	63.23
	35	0.92905	63.18
	40	0.93176	63.20
Kaliti	0	0.88729	63.18
	110	0.94874	62.24
	115	0.95045	62.22
	120	0.96620	62.20
	125	0.97021	63.23

As is observed in the Table 4.8, a sensitivity check of 5 Mvar per step for each Mvar requirements were considered. In this study, determining the optimum size of the Mvar requirement for minimum loss was begun at bus Legetafo as the Mvar value was increased starting from 30, the total active power loss shows reduction as the Mvar value reaches 45 Mvar and then increases as the Mvar is increased. The same thing is observed at Melkawekana Yugo and optimum sizes of shunt capacitor for this iteration, as indicated in Table 4.8 is 35 Mvar, Similarly optimal Mvar sizes were determined for Bus Kaliti which was 120Mvar. From EEP engineering office data the available capacitor banks are 90Mvar and 45Mvar. Therefore, it requires 45 Mvar at Legetafo, 45 Mvar at Melkawekana Yugo and one 90Mvar and additional 45Mvar at Kaliti.

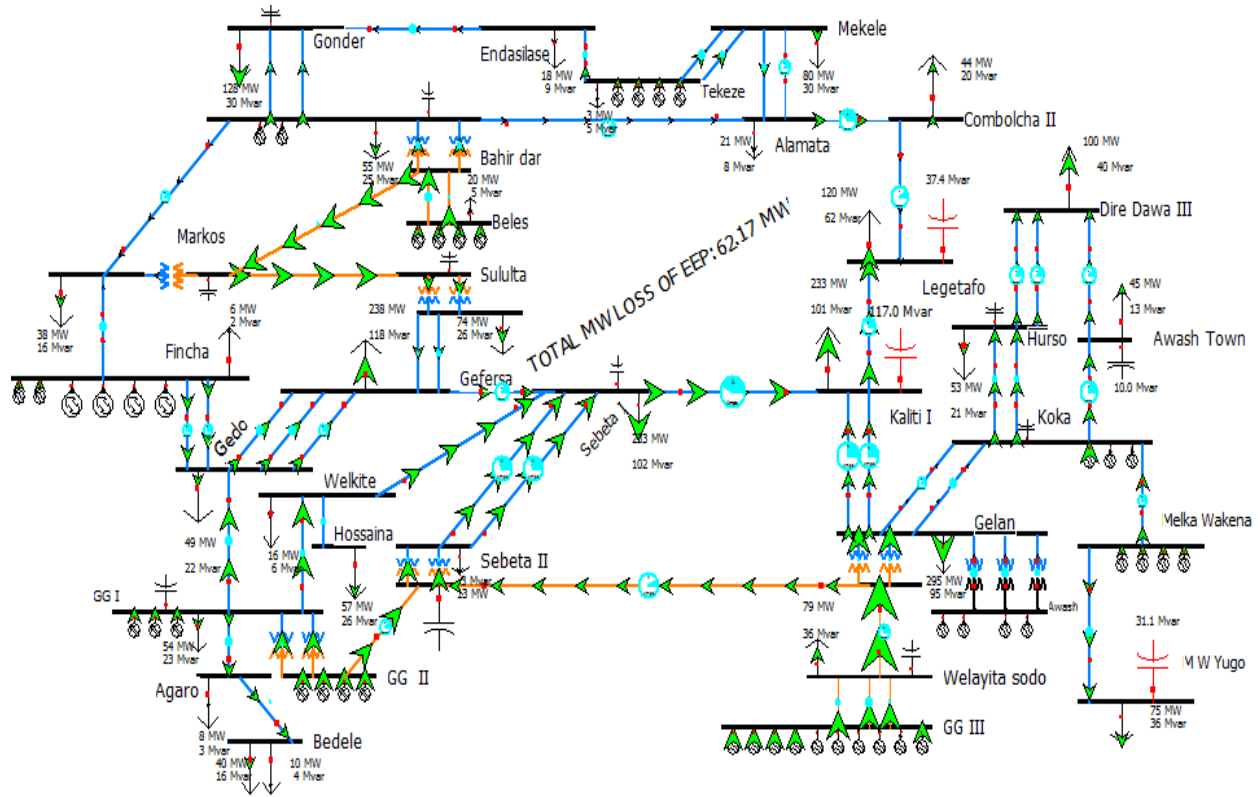


Figure 4.6 Simulations of EEP 400 and 230 Existing Grid network after reactive compensation

As it is shown in Figure 4.6 the new shunt capacitors are indicated in red color to differentiate from the previous base case shunts.

Loss Assessment with Reactive Power Compensation

After determining the sizes of compensators, the final load flow runs yielded the total active power loss of 62.17 MW, which has a capacity gain of 4.36 MW from the existing unmodified network of EEP and the transformer loss accounts 5.28 MW. Hence, the transmission line loss after reactive power compensation becomes 56.89 MW. The annual energy loss after implementing reactive power compensation of this study is thus determined as usual

$$\begin{aligned}
 \text{Annual energy loss} &= (\text{Average power loss}) \times (8760 \text{ hrs}) \\
 &= (\text{Loss Factor} \times \text{peak loss}) \times (8760 \text{ hrs}) \\
 &= 0.3445 \times 56.89 \text{ MW} \times (8760 \text{ hrs}) \\
 &= 171.683 \text{ GWh.}
 \end{aligned}$$

Thus, the reduction of annual energy loss of total transmission line loss before reactive power compensation which was determined previously to be 184.026 GWh to 171.683 GWh effected by reactive power compensation method of loss reduction provided a net energy gain of 12.343 GWh. which is a yearly profit of 0.25 million USD, as per the described tariff of EEU.

Contingency Analysis and Loss Assessment with Reactive Power Compensation

After modifying the base case simulation by appropriate reactive power compensation contingency analysis of the power line 400 kV and 230 kV network is evaluated in the give bus system by subjecting the various lines to a single contingency analysis to examine the effect of loss of any single line on the network. The effect of the transmission line outage has been summarized

Table 4.9 Simulation output of a single transmission line contingency after compensation

Transmission line contingency	Solved	Violations	Min Volt	Max Volt
GGIII-WelayitasodoC1	YES	0		
GGIII-WelayitasodoC2	YES	0		
GGIII-WelayitasodoC3	YES	0		
SebetaII-GelanC1	YES	0		
Welayitasodo-GelanC1	NO	Unsolved		
SebetaII-GGIIC1	YES	0		
Beles-BahirdarC1	YES	4		1.135
Beles-BahirdarC2	YES	4		1.135
Markos-BahirdarC1	YES	10		1.333
Markos-SulultaC1	YES	0		
KalitiI-GelanC1	YES	0		
KalitiI-GelanC2	YES	0		
Gelan-KokaC1	YES	0		
Gelan-KokaC2	YES	0		
Sebetaii-SebetaIC1	YES	0		
Sebetaii-SebetaIC2	YES	0		
GGI-AgaroC1	YES	0		
GGI-WelkiteC1	YES	1	0.877	
GGI-GedoC1	YES	1	0.899	
Sululta-LegetafoC1	YES	0		
Sululta-GefersaC1	YES	1	0.894	
Sululta-GefersaC2	YES	1	0.894	
Bahirdar230 kV-Markos230C1	YES	0		

Fincha-Markos230C1	YES	1	0.879	
Bahirdar230 kV-GonderC1	YES	0		
Bahirdar230 kV-GonderC2	YES	0		
Bahirdar230 kV-AlamataC1	NO	Unsolved		
Gonder-EndasilaseC1	NO	Unsolved		
Agaro-BedekeC1	YES	0		
Welkite-SebetaIC1	YES	0		
Welkite-HossainaC1	YES	1	0.898	
Tekeze-EndasilaseC1	NO	Unsolved		
Tekeze-MekeleC1	YES	1		1.103
Tekeze-MekeleC2	YES	3		1.109
Mekele-AlamataC1	YES	4		1.118
Mekele-AlamataC2	YES	4		1.118
Alamata-CombolchaIIC1	YES	2	0.604	
CombolchaII-LegetafoC1	YES	1	0.858	
Legetafo-KalitiIC1	YES	18	0.366	1.491
KalitiI-SebetaIC1	YES	2		
Gefersa-SebetaIC1	YES	2	0.877	
Gedo-GefersaC1	YES	0		
Gedo-GefersaC2	YES	0		
Gedo-GefersaC3	YES	0		
Koka-HursoC1	YES	0		
Koka-HursoC2	YES	0		
Koka-AwashTownC1	YES	0		
Koka-MelkaWakenaC1	YES	0		
Hurso-DireDawaIIIC1	YES	0		
Hurso-DireDawaIIIC2	YES	0		
AwashTown-DireDawaIIIC1	YES	0		
MelkaWakena-MWYugoC2	YES	0		
MelkaWakena-MWYugoC1	YES	1	0.893	
Fincha-GedoC1	YES	0		
Gedo-FinchaC2	YES	0		

The result of the single line contingency analysis for the compensated constraints violation has been reduced as compared with the previous uncompensated system which indicates a total of 151 and 62 violation as shown in table 4.3 and 4.9 respectively. Hence, numbers of blackout under transmission line contingency condition reduce from ten to four.

4.6.3. Loss Mitigation by Addition of Lines and Compensation

In the previous sections it has seen the reduction of power loss due to application of each method, namely the addition of new transmission line and reactive compensation individually. In this and the upcoming section, the effect of implementing collective of the above techniques will be discussed. Now selecting candidate lines adding the proposed Melkawakena to Melkawakena Youg circuiting and Sululta to Legetafo transmission line was implemented in the one line diagram of the Power world software with the previous specification and similarly the only reactive compensation shunt capacitor have been shunted with optimal size at bus Legetafo 45 Mvar, at bus Melkawekana Yugo 35 Mvar and Similarly optimal Mvar sizes were determined for Bus Kaliti which was 120Mvar.

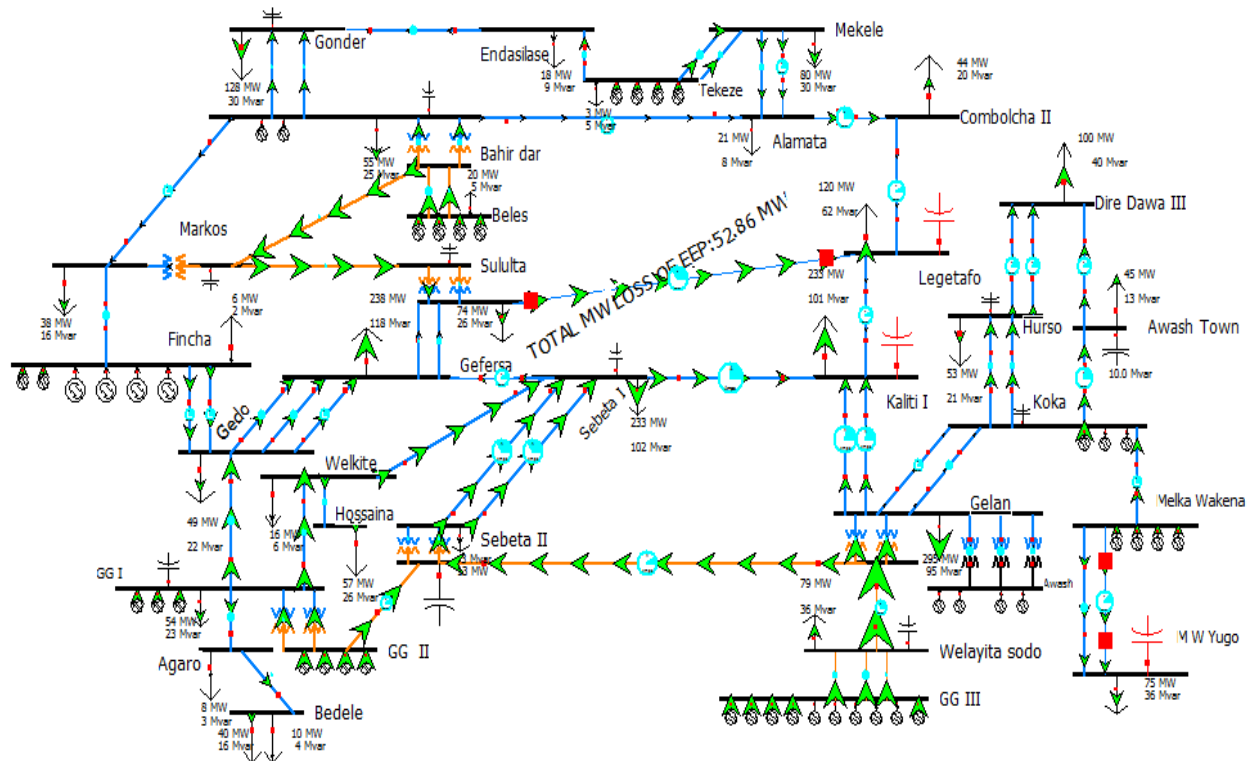


Figure 4.7 Simulations of EEP 400 kV and 230 kV networks after integrated loss mitigation

As can be seen from Figure 4.7, the base case simulation the new additional transmission line, doubled circuit and switched shunts compensations are indicated in red color. From the load flow simulation result total transmission active power loss reduced to 52.86 MW.

Loss Assessment and Annual Energy Estimation with Integrated Loss Mitigation

In this case, the active power losses for each voltage level line of EEP's transmission network were analyzed by applying integrated loss mitigation techniques. After filling all the necessary data into the one-line diagram of the modified EEP's grid network Power world software, the load flow simulation was run for the peak load condition. From the load flow result, total transmission loss as well as loss, shares at each 230 and 400 kV voltage level transmission lines were identified.

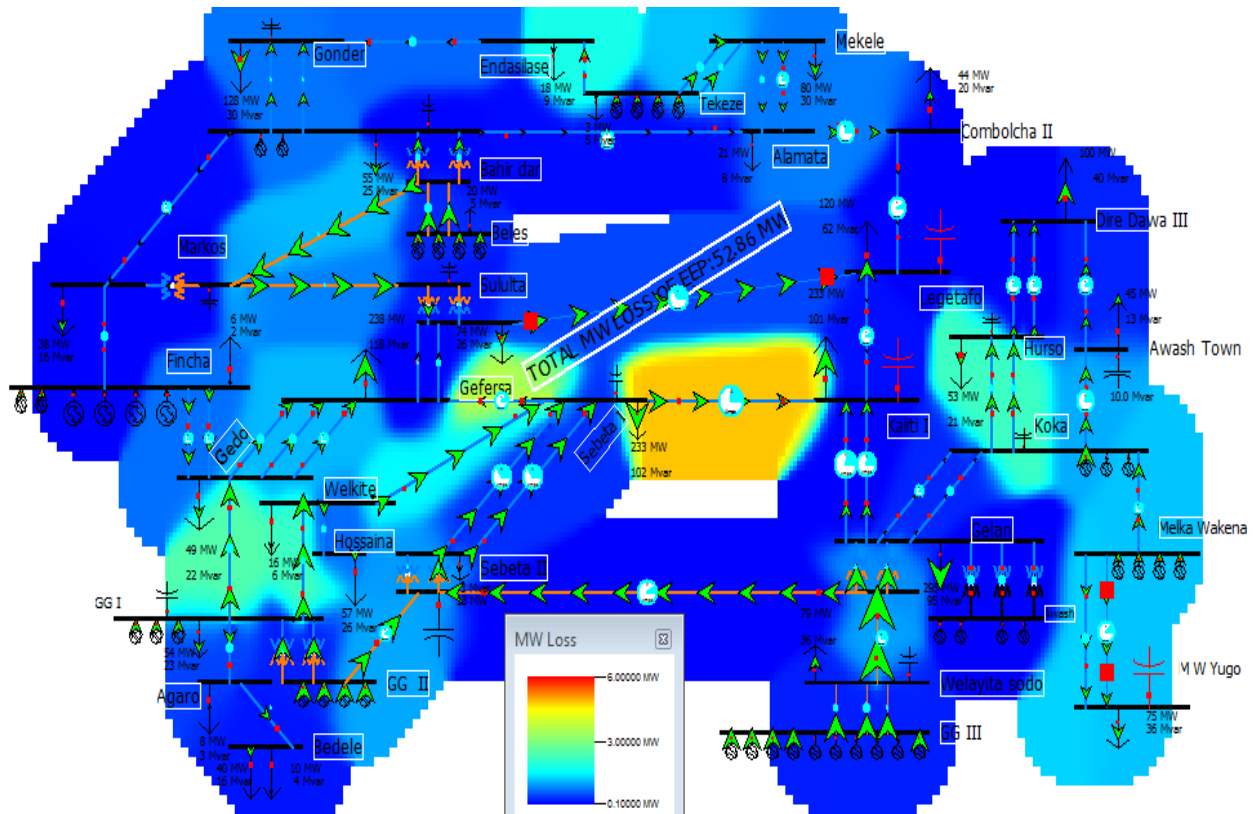


Figure 4.8 MW loss levels of each transmission lines after integrated loss mitigation

As is observed in Figure 4.8, transmission lines active power loss status of the system are represented by a colored background. In the simulation, the red color indicates highest active power loss around 6 MW whereas blue is lowest active power loss below a MW.

When we have seen transmission loss statues of the existing transmission line before application of loss mitigation techniques Figure 4.2 Melka wekana to Melka wekana yougo, Kaliti to Sebete,

Kaliti to Legetafo Gefersa to Sebea, Gilgel Gibe to Welkite, Gilgel Gibe to Gedo and Koka to Hurso have been almost red colored. But, as can be seen easily from Figure 4.8, after application of integrated loss mitigation techniques the only Kaliti to Sebeta transmission line indicated near to red color which have maximum active power loss relative to others transmission lines. On the other hand almost all transmission lines indicated in near to blue colors. The transmission line loss proportionality have been summarized in Table 4.10.

Table 4.10 Transmission line loss of base case simulation after integrated loss mitigation techniques

From Name	To Name	Status	MW From	Mvar From	MVA From	MW Loss	Mvar Loss
GG III	Welayita sodo	Closed	206.6	-40.1	210.4	0.26	-27.75
GG III	Welayita sodo	Closed	206.6	-40.1	210.4	0.26	-27.75
GG III	Welayita sodo	Closed	206.5	-40	210.3	0.26	-27.75
Sebeta II	Gelan	Closed	-123.2	23.7	125.5	0.07	-16.83
Sebeta II	GG II	Closed	-154.3	-47.5	161.4	1.06	-77.85
Beles	Bahir dar	Closed	167.9	-116.5	204.3	0.33	-31.55
Beles	Bahir dar	Closed	167.9	-116.5	204.4	0.33	-31.55
Markos	Sululta	Closed	174.1	-51	181.4	0.83	-120.36
Markos	Bahir dar	Closed	-189.2	47.8	195.1	1.16	-102.03
Gelan	Koka	Closed	6.8	-60.2	60.6	0.31	-7.81
Gelan	Koka	Closed	6.8	-60.2	60.6	0.31	-7.81
Sebeta II	Sebeta I	Closed	131.5	12.1	132.1	0.36	1.83
Sebeta II	Sebeta I	Closed	131.5	12.1	132.1	0.36	1.83
GG I	Agaro	Closed	58.9	-7.4	59.3	0.47	-19.79
GG I	Gedo	Closed	117.6	-6.3	117.8	2.48	-5.01
GG I	Welkite	Closed	173.6	27.6	175.8	2.3	6.42
Sululta	Gefersa	Closed	-13	34.9	37.3	0.05	-2.76
Sululta	Gefersa	Closed	-13	34.9	37.3	0.05	-2.76
Sululta	Legetafo	Closed	124.9	1.6	125	0.49	-1.23
Bahir dar 230 kV	Alamata	Closed	11	-9.3	14.4	0.14	-60.04
Bahir dar 230 kV	Gonder	Closed	55	-21.9	59.2	0.75	-22.73
Bahir dar 230 kV	Gonder	Closed	55	-21.9	59.2	0.75	-22.73
Bahir dar 230 kV	Markos 230	Closed	22.7	-24.6	33.4	0.13	-20.75
Gonder	Endasilase	Closed	-19.1	-16.7	25.4	0.68	-72.44
Agaro	Bedeke	Closed	50.4	9	51.2	0.21	-11.44
Welkite	Hossaina	Closed	57.4	16.9	59.9	0.69	-8.83
Welkite	Sebeta I	Closed	98.4	-1.9	98.4	1.53	-7.71
Tekeze	Mekele	Closed	71.1	-44.9	84.1	1.21	-7.01

Tekeze	Mekele	Closed	71.1	-44.1	83.7	1.21	-5.41
Tekeze	Endasilase	Closed	39.1	-68	78.4	1.8	-21.45
Alamata	Combolcha II	Closed	48.2	-24.3	54	0.82	-21.29
Mekele	Alamata	Closed	30	-53.3	61.1	0.8	-19.94
Mekele	Alamata	Closed	30	-53.3	61.1	0.8	-19.94
Combolcha II	Legetafo	Closed	3.9	-23.1	23.4	0.06	-51.46
Legetafo	Kaliti I	Closed	8.2	-17	18.9	0.17	-1.17
Kaliti I	Sebeta I	Closed	-90.1	31.3	95.4	4.84	2.35
Kaliti I	Gelan	Closed	-67.4	-17.8	69.7	0.08	-1.05
Kaliti I	Gelan	Closed	-67.4	-17.8	69.7	0.08	-1.05
Gefersa	Sebeta I	Closed	-27.6	3.8	27.8	3.69	-1.86
Koka	Melka Wakena	Closed	-71.2	4.1	71.4	1.22	-17.38
Koka	Awash Town	Closed	77.5	-22.3	80.6	1.09	-13.26
Koka	Hurso	Closed	63.4	-39.7	74.8	2.23	-52.11
Koka	Hurso	Closed	63.4	-39.7	74.8	2.23	-52.11
Hurso	Dire Dawa III	Closed	34.5	7.7	35.3	0.05	-3.8
Hurso	Dire Dawa III	Closed	34.5	7.7	35.3	0.05	-3.79
Awash Town	Dire Dawa III	Closed	31.4	-12	33.6	0.28	-29.01
Melka Wakena	M W Yugo	Closed	39.1	-24.1	46	1.22	-35.57
Melka Wakena	M W Yugo	Closed	38.4	-25.4	46	1.31	-35.65
Gedo	Gefersa	Closed	80	4.1	80.1	1.15	-11.54
Gedo	Gefersa	Closed	80	4.1	80.1	1.15	-11.54
Gedo	Gefersa	Closed	80	4.1	80.1	1.15	-11.54
Gedo	Fincha	Closed	-86.9	-17.8	88.8	0.73	-6.76
Fincha	Markos 230	Closed	0.6	-24.8	24.8	0.03	-26.09
Fincha	Gedo	Closed	87.7	11	88.4	0.73	-6.76
Welayita sodo	Gelan	Closed	539.8	17.4	540.1	1.03	-10.99
Total transmission line loss						47.83	

In the previous sections it has seen that the total active power loss was reduced from 66.53 MW to 53.31 MW through addition and doubling circuit and to 62.17 MW by reactive power compensation. The result of the load flow simulation quantifies the total transmission loss during peak load after integrated loss mitigation to be 52.86 MW active power losses. Subtract transformer loss, then transmission line loss accounts 47.83 MW. This has a capacity loss reduction of around 13.67 MW after reactive compensation, additional transmission line and doubling circuit. Thus, the annual energy loss after implementing integrated loss mitigation techniques of this study would be:

Annual energy loss = (Average power loss) X (8760 hrs)
= (Loss Factor X peak loss) X (8760 hrs)
= 0.3445 X 47.83 MW X (8760 hrs)
= 144.34 GWh. Which have an energy gain of 39.67 GWh from the unmodified network loss 184.02 GWh .Thus, to transmit 10,998GWh of total energy; EEP's grid consumes 144.34 GWh of energy on transmission lines. Therefore, it is a significant gain of energy as compared to employing individual techniques. In financial terms, the energy gain due to such collective loss reduction technique profits is 0.805 million USD annually with the given tariff of EEP, 0.0203 USD/KWh.

Contingency Analysis and Loss Assessment after Integrated Mitigation Techniques

Contingency analysis is achieved by running power flow cases by removing transmission line Based on N-1 contingency of transmission line. The contingency analysis of the EEP interconnected power system after integrating loss mitigation techniques has been made. The result of the contingency analysis can be organized to determine the effect of each contingency on transmission line loss. The outage of different transmission lines either 400 kV or 230 kV from the system has their own effect on transmission line loss. A comprehensive 55 contingency analysis for each transmission line has been made and the result has been summarized.

Table 4.11 Results with integrated mitigation under single line contingency condition

Transmission line contingency	Solved	Violations	Min Volt	Max Volt
GGIII-WelayitasodoC1	YES	1	0.881	
GGIII-WelayitasodoC2	YES	1	0.881	
GGIII-WelayitasodoC3	YES	1	0.881	
SebetaII-GelanC1	YES	1	0.884	
Welayitasodo-GelanC1	NO	Unsolved		
SebetaII-GGIIC1	YES	0		
Beles-BahirdarC1	YES	2		1.123
Beles-BahirdarC2	YES	2		1.123
Markos-BahirdarC1	YES	10		1.338
Markos-SulultaC1	YES	0		
KalitiII-GelanC1	YES	1	0.884	
KalitiII-GelanC2	YES	1	0.884	
Gelan-KokaC1	YES	1	0.896	
Gelan-KokaC2	YES	1	0.896	

Sebetaii-SebetaIC1	YES	1	0.886	
Sebetaii-SebetaIC2	YES	1	0.886	
GGI-AgaroC1	YES	1	0.881	
GGI-WelkiteC1	YES	1	0.875	
GGI-GedoC1	YES	1	0.885	
Sululta-LegetafoC1	YES	1	0.889	
Sululta-GefersaC1	YES	1	0.878	
Sululta-GefersaC2	YES	1	0.878	
Bahirdar230-Markos230C1	YES	0		
Fincha-Markos230C1	YES	1	0.883	
Bahirdar230-GonderC1	YES	0		
Bahirdar230-GonderC2	YES	0		
Bahirdar230-AlamataC1	NO	Unsolved		
Gonder-EndasilaseC1	NO	Unsolved		
Agaro-BedeleC1	YES	1	0.881	
Welkite-SebetaIC1	YES	0		
Welkite-HossainaC1	YES	1	0.877	
Tekeze-EndasilaseC1	NO	Unsolved		
Tekeze-MekeleC1	YES	0		
Tekeze-MekeleC2	YES	1		1.103
Mekele-AlamataC1	YES	2		1.113
Mekele-AlamataC2	YES	2		1.113
Alamata-CombolchaIIC1	YES	1	0.833	
CombolchaII-LegetafoC1	YES	0		
Legetafo-KalitiIC1	YES	1	0.893	
KalitiI-SebetaIC1	YES	1	0.879	
Gefersa-SebetaIC1	YES	1	0.888	
Gedo-GefersaC1	YES	0		
Gedo-GefersaC2	YES	0		
Gedo-GefersaC3	YES	0		
Koka-HursoC1	YES	1	0.881	
Koka-HursoC2	YES	1	0.881	
Koka-AwashTownC1	YES	1	0.882	
Koka-MelkaWakenaC1	YES	1	0.889	
Hurso-DireDawaIIIC1	YES	1	0.881	
Hurso-DireDawaIIIC2	YES	1	0.881	
AwashTown-DireDawaIIIC1	YES	1	0.881	
MelkaWakena-MWYugoC2	YES	2	0.881	
MelkaWakena-MWYugoC1	YES	1	0.881	
Fincha-GedoC1	YES	0		
Gedo-FinchaC2	YES	0		

The effect of the transmission line outage on bus bar voltage limit has been summarized in Table 4.11. As it can be seen from the result, there is a remarkable decrease of the effect of the transmission line outage on different constraints (i.e. Number of violation and the lowest and highest voltage deviations). When we comparing this result from the base case contingency analysis (Table 4.3) before this mitigation techniques at the base case simulation the outage of ten transmission lines could make the system to be unstable or unsolved. But after recommendation the unsolved transmission lines reduced to four.

4.7.Summary of Contingency Analysis and Transmission Line Loss after Integrated Loss Mitigation Techniques

In the previous sections it have seen the reduction of power transmission line loss due to application of different methods. To finalize the summary of various transmission line contingencies are shown in Table 4.12 by ignoring unsolved transmission line contingency conditions, determine total transmission loss during each contingency conditions.

Table 4.12 Summary of contingency analysis and transmission line loss after integrated loss mitigation techniques

Name of transmission line contingency	Voltage level(kV)	Solved	Total loss (MW)
GGIII-WelayitasodoC1	400	YES	53.25
GGIII-WelayitasodoC2	400	YES	53.25
GGIII-WelayitasodoC3	400	YES	53.25
SebetaII-GelanC1	400	YES	51.85
Welayitasodo-GelanC1	400	NO	Unsolved
SebetaII-GGIIC1	400	YES	64.79
Beles-BahirdarC1	400	YES	53.70
Beles-BahirdarC2	400	YES	53.70
Markos-BahirdarC1	400	YES	69.40
Markos-SulultaC1	400	YES	68.51
KalitiI-GelanC1	230	YES	53.01
KalitiI-GelanC2	230	YES	53.01
Gelan-KokaC1	230	YES	52.65
Gelan-KokaC2	230	YES	52.65
SebetaII-SebetaIC1	230	YES	53.66
SebetaII-SebetaIC2	230	YES	53.66

GGI-AgaroC1	230	YES	53.52
GGI-WelkiteC1	230	YES	58.70
GGI-GedoC1	230	YES	53.39
Sululta-LegetafoC1	230	YES	59.54
Sululta-GefersaC1	230	YES	52.95
Sululta-GefersaC2	230	YES	52.95
Bahirdar-Markos230C1	230	YES	52.70
Fincha-Markos230C1	230	YES	52.78
Bahirdar230 kV-GonderC1	230	YES	52.89
Bahirdar230 kV-GonderC2	230	YES	52.89
Bahirdar230 kV-AlamataC1	230	NO	Unsolved
Gonder-EndasilaseC1	230	NO	Unsolved
Agaro-BedeleC1	230	YES	53.34
Welkite-SebetaIC1	230	YES	53.67
Welkite-HossainaC1	230	YES	52.36
Tekeze-EndasilaseC1	230	NO	Unsolved
Tekeze-MekeleC1	230	YES	55.06
Tekeze-MekeleC2	230	YES	55.06
Mekele-AlamataC1	230	YES	53.99
Mekele-AlamataC2	230	YES	53.99
Alamata-CombolchaIIC1	230	YES	58.68
CombolchaII-LegetafoC1	230	YES	52.22
Legetafo-KalitiIC1	230	YES	53.19
KalitiI-SebetaIC1	230	YES	52.90
Gefersa-SebetaIC1	230	YES	52.89
Gedo-GefersaC1	230	YES	52.94
Gedo-GefersaC2	230	YES	52.94
Gedo-GefersaC3	230	YES	52.94
Koka-HursoC1	230	YES	55.88
Koka-HursoC2	230	YES	55.88
Koka-AwashTownC1	230	YES	60.47
Koka-MelkaWakenaC1	230	YES	54.11
Hurso-DireDawaIIIC1	230	YES	52.91
Hurso-DireDawaIIIC2	230	YES	52.91
Awash-DireDawaIIIC1	230	YES	54.63
M Wakena-MWYugoC1	230	YES	55.88
MWakena-MWYugoC2	230	YES	55.88
Fincha-GedoC1	230	YES	53.23
Gedo-FinchaC2	230	YES	53.23

According to load flow simulation output Table 4.13 summarizes the active power loss, energy loss, capacity gain, energy gain, financial gain, bus bar voltage limit violation and numbers of blackout compared for base case simulation and for each loss mitigation techniques.

Table 4.13, Summary of quantification of loss reductions

conditions	Normal					Line Contingency	
	Capacity loss (MW)	Energy loss (GWh)	Capacity gain (MW)	Energy gain (GWh)	Profit (million USD)	Black out	Bus bar voltage violation
Unmodified	60.98	184.02	-----	-----	-----	10	151
Addition of transmission lines	48.12	145.45	12.86	38.57	0.78	6	46
Capacitor compensation	56.89	171.68	4.09	12.34	0.25	4	62
Integrated loss mitigation	47.83	144.30	13.15	39.67	0.805	4	52

A comparison can be made observing Table 4.13 for different loss mitigation techniques. Taking the capacity gain, energy gain and profit gain in normal condition, integrated loss mitigation technique accounts the maximum value. Similarly under transmission line contingency condition, numbers of unsolved lines have been registered with minimum numbers for integrated loss mitigation techniques. Therefore it is better to use integrated loss mitigation techniques than each methods separately.

4.8. Estimation of Investment cost of Loss Mitigation Techniques

The main objective of this study is to investigate the contingency of EEP 400 kV and 230 kV high voltage transmission line and assessing loss to propose some loss mitigation techniques, and it is important to study economic feasibility. Hence, this section deals with cost estimation of the integrated loss mitigation techniques and to observe, share of cost from final profit from annual energy loss mitigation. For addition and doubling of transmission line it is not required to construct a new substation because both transmission lines are 230 kV with the same voltage level substations (Melkawakena, Melkawakena Young, Sululta and Legetafo). Hence there is consideration of four substation expansion cost.

Table 4.14 Average substation expansion cost estimation for single substation [41].

No.	Description	Unit	Qty.	Unit Cost (USD)	Total Cost (USD)
1	Circuit Breakers	Each	3	1,600	4,800
2	230 kV Disconnecter	Each	3	13,000	39,000
3	230 kV Insulator	Each	3	1,000	3,000
4	230 kV Current Transformer	Each	12	11,000	132,000
5	230 kV Voltage Transformer	Each	6	11,200	67,200
6	Lightning Arresters	Each	3	8,000	24,000
7	230 kV bus bar Disconnecter	Each	1	10,000	10,000
8	Post Insulator	Each	3	2,300	6,900
9	Modification of existing control and signal panel	Each	1	34,623	34,623
10	Total cost				321,523
11	Engineering cost (10 % of the total costs)				32,152.3
12	Total substation expansion costs				353,675.3

According to [36], engineering cost accounts 10% of total costs.

It is common to encounter the term contingencies in project cost estimation and is an important concept in economic analysis of projects. Physical contingencies which represent the estimated costs of the additional real resources expected to be required and therefore are always included in the economic analysis. And 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. Physical contingencies accounts 5% of the total cost and price contingencies accounts 10% of the total cost [40]. Cost estimation of 230 kV single circuit transmission line, the double circuit Steel Tower and reactive compensation has been collected from the EEP Engineering office [27]. Hence, the average investment cost of loss mitigation techniques becomes.

Table 4.15 Average investment cost of loss mitigation techniques

No.	Description	Unit	Qty.	Unit Cost (USD)	Total Cost (USD)
1	Sululta to Legetafo 230 kV single circuit transmission line	Km	22	178,757.59	3,932,666.98
2	Melkawakena to Melkawakena Youg 230 kV single circuit transmission line	Km	5	178,757.59	893,787.95
3	Double circuit 230 kV Steel Tower from Sululta to Legetafo	Km	22	1,117,000.00	24,574,000
4	90 MVAR shunt capacitor	each	1	347,498.30	347,498.30
5	45 MVAR shunt capacitor	each	3	193,814.00	581,442.00
6	Substation expansion	each	4	353,675.3	1,414,701.2
7	Total Cost				31,744,096.43
8	Commissioning Costs (1% of total cost)				317,440.96
9	Physical Contingency (5% of total cost)				1,587,204.82
10	Price contingency (10% of total cost)				3,174,409.64
11	Total loss mitigation cost				36,823,151.85

According to [40, 41], commissioning cost accounts 1% of total costs.

Determination of payback period of a given investment or project is an important determinant of feasibility. Here to determine the length of time required to recover the cost of an investment it requires cost analysis of power interruption and each blackout event which includes;

- ✍ Cost of profits from whole customer during the interruption and blackout period.
- ✍ Costs of households
- ✍ Costs of Industries and commercial services: There are primarily four sources of indirect costs of power outages in industries and commercial services. First, their output will be affected leading to a loss of profits. Second, power outages can result in a loss of productivity during the outage and when restarting production/operations after an interruption (e.g., recovering unsaved computer files). Third, materials and/or equipment can be damaged by an electricity outage. Fourth, there may be costs of labor required after a power outage. For instance, additional labor is sometimes required to restart production for which overtime, bonuses may have to be paid.
- ✍ Environmental and social cost because of power interruption diesel generators may come into service.

The mission of EEU is to be a world-class utility and contribute towards nation building by ensuring delivery of cost- effective, safe, reliable and high quality power and to enable interconnections across the African Continent for exporting surplus power [42]. Beside enhancement of reliability and security of the EEP interconnected grid system those loss mitigation profits have supportive value for the investment cost of loss minimization techniques.

CHAPTER 5: CONCLUSIONS RECOMMENDATIONS AND SUGGESTING FUTURE WORKS

5.1. Conclusions

The aim of this thesis is assessing transmission line loss in EEP 400 kV and 230 kV high voltage interconnected grid system under contingency condition and propose loss mitigation techniques at most critical lines. Furthermore, in this thesis work, annual capacity and energy losses in the existing transmission network under the transmission line contingency is conducted and economic feasibility of mitigation techniques is presented. Data analysis, modeling of the network, simulation result analysis is carried out. The collected data from the EEPNLDC was analyzed using power world simulator software. Transmission line loss of the system is determined under normal operating and N-1 Contingency conditions.

The result of the load flow simulation of the existing EEP 400 kV and 230 kV grid network at the peak load delivered a total annual peak capacity transmission line loss of 66.53 MW. The loss factor-load factor method was employed to determine the annual energy loss in the load flow derived annual peak transmission line loss gives 184.02 GWh energy loss under base case condition. The contingency occurs due to the outage of a single line in the network, and it causes overloading on the other line and leads the system increase transmission line loss. Hence, under N-1 transmission line contingency condition total peak capacity transmission line loss varies with maximum loss of 188.4 MW and minimum loss of 59.37 MW with 10 unsolved simulations and different security problems.

In this study necessary methodologies have been proposed for mitigation of transmission loss and improvement of the security of the system, including additional transmission line expansion, doubling of the existing line and reactive power compensation has been made and those techniques were tested for loss reduction both individually and collectively. The corresponding transmission line capacity gain obtained from addition and doubling of transmission lines, shunt compensation and integrated loss mitigation were 12.86 MW, 4.09 MW and 13.15 MW respectively. After integrating loss mitigation techniques total peak capacity transmission line loss under N-1 transmission line contingency condition, vary with maximum loss of 69.43 MW and minimum loss of 52.22 MW with 4 unsolved simulations and minimize security problems.

The annual energy gain with additions of transmission lines, shunt compensation and integrated loss mitigation were respectively found to be 38.57 GWh, 12.34 GWh and 39.67 GWh, as per the EEP bill tariff of 0.0203 USD/KWh, which is a charge to industrial customers, amounting to 0.78 million USD, 0.25 million USD and 0.805 million USD saving respectively.

5.2. Recommendations

The electrical energy consumption of Ethiopia is expected to increase rapidly in the coming years being the country is on the way of transformation and development and when the grand renaissance dam starts to generate power most of existing transmission lines and transformers in the system will highly loaded and it is obvious that loss of any transmission line result in overloading, cascade outage and blackout. Thus, EEP, the sole utility company of the country, should have to implement technology based loss reduction techniques to keep the promising wealth of the country.

5.3. Suggestions for Future works

- ✍ This thesis covers only 400 kV and 230 kV high voltage transmission line network of EEP. Thus, future work should include total grid high voltage system, including 132 kV, 66 kV and 45 kV transmission line to analyze transmission line loss and transformer loss.
- ✍ This thesis work gives extensive analysis the contingency analysis for assessing transmission technical line loss. It has not assessed those non-technical transmission losses during base case and contingency conditions. Thus, the future work should include non-technical transmission loss assessment as well as the simulation of N-2 contingencies to assess the transmission line loss.
- ✍ As we know EEP is under construction of the grand Renaissance dam and other power plants. If there is no equivalent expansion of high voltage transmission network and substations most of transmission lines and transformers in the system will be highly loaded, it is obvious that loss of any transmission line will result in overloading, voltage dip and even partial or total blackouts during contingencies. Thus, the future work should include security assessment of EEP interconnected grid system.

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APPENDIX

Appendix A: EEP Grid Data

A.1 Generator Data

Table A.1: Existing Generator data of the Ethiopian High Voltage Grid

No	Name	Sn [MVA]	Type	Un [kV]	P [MW]	Pmin [MW]	Pmax [MW]	Qmin [MVA _r]	Qmax [MVA _r]
1	Gibe III G1	441	Hydro	15	100	0	220	-100	100
2	Gibe III G2	441	Hydro	15	100	0	220	-100	100
3	Gibe III G3	441	Hydro	15	100	0	220	-100	100
4	Gibe III G4	441	Hydro	15	100	0	220	-100	100
5	Gibe III G5	441	Hydro	15	100	0	220	-100	100
6	Gibe III G6	441	Hydro	15	100	0	220	-100	100
7	Gibe III G7	441	Hydro	15	100	0	220	-100	100
8	Gibe III G8	441	Hydro	15	100	0	220	-100	100
9	Gibe III G9	441	Hydro	15	100	0	220	-100	100
10	Gibe III G10	441	Hydro	15	100	0	220	-100	100
11	Beles G1	133	Hydro	15	80	0	115	-130	130
12	Beles G2	133	Hydro	15	100	0	115	-130	130
13	Beles G3	133	Hydro	15	90	0	115	-130	130
14	Beles G4	133	Hydro	15	100	0	115	-130	130
15	Gibe II G1	125	Hydro	15	95	0	105	-50	50
16	Gibe II G2	125	Hydro	15	95	0	105	-50	50
17	Gibe II G3	125	Hydro	15	95	0	105	-50	50
18	Gibe II G4	125	Hydro	15	95	0	105	-50	50
19	Tekeze G1	90	Hydro	13.8	66	0	78	-38	38
20	Tekeze G2	90	Hydro	13.8	40	0	78	-38	38
21	Tekeze G3	90	Hydro	13.8	40	0	78	-38	38
22	Tekeze G4	90	Hydro	13.8	40	0	78	-38	38
23	Ashegoda	150	Wind	230	31.4	0	120	-150	150
24	Tis Abay I G1	4.8	Hydro	6	4	0	4	-2.9	2.9
25	Tis Abay I G2	4.8	Hydro	6	4	0	4	-3.84	3.84
26	Tis Abay I G3	4.8	Hydro	6	4	0	4	-2.9	2.9
27	Tisabay II G1	40	Hydro	10.5	27	0	36	-40	40
28	Tisabay II G1	40	Hydro	10.5	27	0	36	-40	40
29	Fincha G1	35	Hydro	13.8	29	0	33.33	-16	14
30	Fincha G2	35	Hydro	13.8	29	0	33.33	-16	14
31	Fincha G3	35	Hydro	13.8	29	0	33.33	-16	14
32	Fincha G4	35	Hydro	13.8	29	0	33.33	-16	14
33	Gibe I G1	73	Hydro	13.8	60	0	70	-21	21
34	Gibe I G2	73	Hydro	13.8	60	0	70	-21	21

35	Gibe I G3	73	Hydro	13.8	60	0	70	-21	21
36	Neshe G1	53	Hydro	13.8	15	0	50	-25	19
37	Neshe G2	53	Hydro	13.8	15	0	50	-25	19
38	Kality G1	4.375	Diesel	11	3.5	0	3.5	-3.5	3.5
39	Kality G2	4.375	Diesel	11	3.5	0	3.5	-3.5	3.5
40	Kality G3	4.375	Diesel	11	3.5	0	3.5	-3.5	3.5
41	Kality G4	4.375	Diesel	11	3.5	0	3.5	-3.5	3.5
42	Kality G5	4.375	Diesel	11	3.5	0	3.5	-3.5	3.5
43	Kality G6	4.375	Diesel	11	3.5	0	3.5	-3.5	3.5
44	Kality G7	4.375	Diesel	11	3.5	0	3.5	-3.5	3.5
45	Dire Dawa G1	12.5	Diesel	15	10	0	10	-10	10
46	Dire Dawa G2	12.5	Diesel	15	10	0	10	-10	10
47	Dire Dawa G3	12.5	Diesel	15	10	0	10	-10	10
48	Dire Dawa G4	12.5	Diesel	15	10	0	10	-10	10
49	Adama II	190	Wind	230	73.67	0	150	-190	190
50	Adama I	60	Wind	132	26.82	0	48	-60	60
51	MWakena G1	45	Hydro	13.8	35	0	38.25	-42	35
52	MWakena G2	45	Hydro	13.8	35	0	38.25	-31.5	30.15
53	MWakena G3	45	Hydro	13.8	30	0	38.25	-31.5	30.15
54	MWakena G4	45	Hydro	13.8	30	0	38.25	-31.5	30.15
55	Koka G 1	18	Hydro	10.5	10	0	13	-12	11.6
56	Koka G 2	18	Hydro	10.5	10	0	13	-12	11.6
57	Koka G 3	18	Hydro	10.5	10	0	13	-12	11.6
58	Awash II G1	20	Hydro	10.5	6	3	15	-15	13
59	Awash II G2	20	Hydro	10.5	6	3	15	-15	13
60	Awash III G1	20	Hydro	10.5	9	3	15	-15	13
61	Awash III G2	20	Hydro	10.5	9	3	15	-15	13
62	MU G1	1.875	Diesel	4.16	1.68	0	1.7	-1.5	1.5
63	MU G2	1.875	Diesel	4.16	1.68	0	1.7	-1.5	1.5
64	MU G1	1.875	Diesel	4.16	1.68	0	1.7	-1.5	1.5
65	MU G1	1.875	Diesel	4.16	1.68	0	1.7	-1.5	1.5
66	Awash 7 A	4.375	Diesel	11	3	0	4.375	-3.5	3.5
67	Awash 7 B	4.375	Diesel	11	3	0	4.375	-3.5	3.5

A.2 Transformer Data

Table A. 2: Two winding transformer data of the Ethiopian High Voltage Grid

Node 1	Node 2	Un1 [kV]	Un2 [kV]	Sn [MVA]	uk [%]	ur [%]
GG2 400 kV	GG1 230 kV	400	230	250	10.3	0.41
GG2 400 kV	GG1 230 kV	400	230	250	10.3	0.41
Sebeta 2 400 kV	Sebeta 2 230 kV	400	230	250	9.85	0.41
Sebeta 2 400 kV	Sebeta 2 230 kV	400	230	250	9.85	0.41
Bahir Dar 400 kV	Bahir Dar 230 kV	400	230	250	11.87	0.41
Bahir Dar 400 kV	Bahir Dar 230 kV	400	230	250	11.87	0.41
D/Markos 400 kV	D/Markos 230 kV	400	230	250	11.87	0.41
Geln 400 kV	Geln 230 kV	400	230	250	11.87	0.41
Geln 400 kV	Geln 230 kV	400	230	250	11.87	0.41
Akaki 400 kV	Akaki 230 kV	400	230	500	12.5	0.41
Akaki 400 kV	Akaki 230 kV	400	230	500	12.5	0.41
Geln 230 KV	Geln 132 kV	230	138	24.2	3.92	0.306
Geln 230 KV	Geln 132 kV	230	138	24.2	3.92	0.306
Geln 230 KV	Geln 132 kV	230	138	24.2	3.92	0.306

A.3 Transmission line Data

Table A. 3: 400 kV and 230 kV Existing Overhead Transmission line data

No	Level [KV]	Type	q [mm ²]	l [km]	r [Ω/km]	x [Ω/km]
1	230	Gilgel Gibe - Wolkite T 143	570.2	65.3	0.0597	0.4113
2	230	Wolkite - Sebeta SC	570.2	132.523	0.0597	0.4113
3	230	Bahir Dar II - Gonder II	180.7	0.01	0.0918	0.3205
4	230	Bahir Dar II - Gonder II	180.7	136.97	0.0918	0.3205
5	230	Bahir Dar II - Alamata	180.7	0.01	0.0918	0.3193
6	230	Fincha - Mota	570.2	81.11	0.0597	0.4113
7	230	Mota - Bahir Dar II	570.2	111.76	0.0597	0.4113
8	230	Fincha - Bahir Dar II	570.2	71.3625	0.0597	0.4113
9	230	Finchaa - Ghedo	469.8	67.19	0.0671	0.4272
10	230	Ghedo - Gilgel Gibe	402.8	130.82	0.0725	0.4089
11	230	Ghedo - Gefersa	469.8	99.78	0.0671	0.4272
12	230	Bahir Dar II - Alamata	180.7	0.005	0.0918	0.3193
13	230	Bahir Dar II - Alamata	180.7	0.005	0.0918	0.3193
14	230	Koka - Dire Dawa III	402.8	128.4	0.0725	0.4089
15	230	Koka - Dire Dawa III	402.8	128.84	0.0725	0.4089
16	230	Koka - Dire Dawa III	402.8	128.4	0.0725	0.4089

17	230	Koka - Kaliti I	394	66.4	0.0739	0.4142
18	230	Koka - Kaliti I	394	163.86	0.0739	0.4142
19	230	Koka - Kaliti I	394	163.86	0.0739	0.4142
20	230	Kaliti I - Gefersa	402.8	10.695	0.0725	0.408
21	230	Bahir Dar II - Mekele	180.7	0.01	0.0918	0.3193
22	230	Bahir Dar II - Mekele	180.7	129.69	0.0918	0.3193
23	230	Kaliti I - Gefersa	402.8	10.64	0.0725	0.408
24	230	Bahir Dar II - Mekele	180.7	348	0.0918	0.3193
25	230	Tower No. 143 upto Wolkite	570.2	3.812	0.0597	0.4113
26	230	Wolkite	570.2	3.657	0.0598	0.4063
27	230	Wolkite	570.2	3.657	0.0598	0.4063
28	230	Fincha - Bahir Dar II	570.2	23.7875	0.0597	0.4113
29	230	Kaliti I - Sabata	402.8	3.565	0.0725	0.408
30	230	Finchaa - Ghedo	469.8	33.26	0.0671	0.4272
31	230	Tekeze – Humera 230 kV	180.7	103	0.0918	0.3234
32	230	Tekeze – Humera 230 kV	180.7	103	0.0918	0.3234
33	400	Gibe -Sebeta 400	850	28	0.0375	0.4259
34	230	Finchaa - Ghedo - Gefersa	469.8	100.5	0.0671	0.4272
35	230	Gilgel Gibe - Wolkite T 143	570.2	2.5	0.0597	0.4113
36	400	Gibe -Sebeta 400	850	185	0.0375	0.4259
37	230	Wolkite - Sebeta SC	570.2	16	0.0597	0.4113
38	400	Gibe -Sebeta 400	850	185	0.0375	0.4259
39	230	Gilgel Gibe - Wolkite T 143	570.2	180	0.0597	0.4113
40	400	Beles B/Dar400 kV	850.7	62.8	0.0209	0.3096
41	400	Beles B/Dar400 kV	850.7	62.8	0.0209	0.3096
42	400	B/Dar – D/Markos 400 kV	850.7	193.77	0.0209	0.3034
43	400	D/Markos - Sululta 400 kV	850.7	215.89	0.0209	0.3096
44	230	Sululta - Geferssa 230 kV	570.2	16.86	0.0599	0.4081
45	230	Sululta - Geferssa 230 kV	570.2	16.86	0.0599	0.4081
46	230	Tekeze-Endeselase	180.7	229.8	0.0918	0.3234
47	230	FinchaI-Fincha II	469.8	19.44	0.0668	0.4211
48	230	Fincha II -Ghedo 230 kV	469.8	69.73	0.0668	0.4211
49	230	Ghedo-Geferssa	469.8	133.5	0.0669	0.4144
50	230	Ghedo-Geferssa	469.8	133.5	0.0669	0.4144
51	230	Alamata-Combolcha230 kV	180.7	400.6	0.0919	0.3167
52	230	CotobieII-KaltiII 230 kV	180.7	34.5	0.0918	0.3225
53	230	Combolch-Semera 230 kV	180.7	263.07	0.0918	0.3206
54	230	Combolch-Semera 230 kV	180.7	263.07	0.0918	0.3206
55	230	Combolch-Semera 230 kV	180.7	263.07	0.0918	0.3206
56	230	Combolch-Semera 230 kV	180.7	263.07	0.0918	0.3206
57	230	Metu-Bedele 230 kV	180.7	90.4	0.0919	0.3166
58	230	Metu-Bedele 230 kV	180.7	90.4	0.0919	0.3166
59	230	Sheh-Ghadarif	240	292	0.0693	0.3206
60	230	Sheh-Ghadarif	240	292	0.0693	0.3206
61	230	Gonder II-Shehadi	180.7	121	0.0918	0.3206

62	230	Gonder II-Shehadi	180.7	121	0.0918	0.3206
63	230	Alamata Mehoni - Mekele 230	180.7	42	0.1835	0.4313
64	230	Alamata Mehoni - Mekele 230	180.7	100	0.0919	0.3168
65	230	Koka-Hurso 230 double mir	180.7	313	0.0919	0.3168
66	230	Alamata-Combolch 230 kV	180.7	170.6	0.0919	0.3167
67	230	Koka - Dire Dawa III	402.8	208.99	0.0725	0.4089
68	230	Koka-Hurso 230	180.7	313	0.0919	0.3168
69	400	D/Markos - Sululta 400 kV	850.7	215.89	0.0209	0.3096
70	400	D/Markos - Sululta 400 kV	850.7	215.89	0.0209	0.3096
71	400	Akaki II- Sebeta II 400 kV	850.7	33	0.019	0.3291
72	400	Akaki II- Sebeta II 400 kV	850.7	119	0.019	0.3291
73	400	Akaki-Welytasodo 400 kV	850.7	51	0.0206	0.3082
74	400	Akaki - Welytasodo 400 kV	850.7	51.3	0.0189	0.3097
75	230	Hosana-Alaba 230	282.5	89.3	0.1015	0.4354
76	230	Hosana-Alaba 230	282.5	89.3	0.1015	0.4354
77	230	Agaro-Bedele-GG1 230 kV	282.5	81.558	0.0591	0.3155
78	230	Agaro-Bedele-GG1 230 kV	282.5	81.558	0.0591	0.3155
79	230	Metu-Gambela 230 kV	282.5	140	0.059	0.3098
80	230	Metu-Gambela 230 kV	282.5	140	0.059	0.3098
81	230	Melkawekana - Ramo	180.7	267	0.1562	0.4129
82	230	Ramo-Ghedo	180.7	252	0.1562	0.4129

A.4 Load Data

Table A. 4: Existing 230 and 400 kVsubstations load data of the Ethiopian High Voltage Grid

No	Station Name	Region	Voltage Ratio (kV)	Equipment	Rating (MVA)	Peak Load (MW)	Reactive Load [Mvar]
1	Sebeta-II	A/Ababa	230/33	TR 1	25	12.5	3
2	Sululta	A/Ababa	230/132	TR 1	63	37	12.75
3	Sululta	A/Ababa	230/132	TR 2	63	37	12.75
4	Gararssa	A/Ababa	230/132	TR 1	125	60	32
5	Gararssa	A/Ababa	230/132	TR 2	125	60	32
6	Gararssa	A/Ababa	230/132	TR 3	125	59	31
7	Gararssa	A/Ababa	230/132	TR 4	125	59	31
8	Legatafo	A/Ababa	230/132	TR 1	125	63	32.5
9	Legatafo	A/Ababa	230/132	TR 2	125	57	30
10	Kaliti -I	A/Ababa	230/132	TR 1	125	58.75	37.5
11	Kaliti -I	A/Ababa	230/132	TR 2	125	58	36
12	Kaliti -I	A/Ababa	230/132	TR 3	125	58	36
13	Sebeta I	A/Ababa	230/132	TR 1	125	74	34
14	Sebeta I	A/Ababa	230/132	TR 2	125	74	34
15	Sebeta I	A/Ababa	230/132	TR 3	125	75	34.2
16	Eiz(Dukem)	A/Ababa	230/33	TR 1	63	6.5	2.5

17	Eiz(Dukem)	A/Ababa	230/33	TR 2	63	10.6	4
18	Gelan	A/Ababa	230/132	TR 1	125	92	29
19	Gelan	A/Ababa	230/132	TR 2	125	93	30
20	Gelan		230/132	TR 3	125	93	30
21	Welkite	Central	230/66/33	TR 1 and 2	40/20/20	15.5	6.2
22	Dire Dawa	Eastern	230/132/15	TR 1 and 2	63/63/18.9	100	44
23	Adigala	Eastern	230/33	TR 1	25	1.5	0.81
24	Gode	Eastern	230/33	TR 1	63	1.5	0.9
25	Hurso	Eastern	230/33	TR 1	125	2.5	1.6
26	Djibuti					50	17.5
27	Combolcha-	NER	230/132/33	TR 1 and 2	63/63/23	36	17.7
28	Semera	NER	230/33	TR 1	25/25	7.5	3.375
29	B/Dar II	NW	230/132/1	TR 1	66/63/21	15	7
30	B/Dar II	NW	230/132/15	TR 2	66/63/21	15.5	7.5
31	B/Dar II	NW	230/66/15	TR 3	63/40/23	19.5	8.54
32	N/mewucha	NW	230/33	TR 1	30	5.8	2.5
33	D/markos	NW	230/66/15	TR 1 and 2	63/40/23	32	13.3
34	Gonder	NW	230/66/15	TR 1 and 2	40/20/20	27.5	7.9
35	Sudan					100	22
36	Mota	NW	230/33	TR 1	25	6.21	2.7
37	Metema	NW	230/33	TR 1	25	2.5	1.1
38	Humera	North	230/33/15	TR 1 and 2	25/12.5/12.5	3.5	1.5
39	Indaselassie	North	230/66/15	TR 1 and 2	40/20/20	12	5.8
40	Mekelle	North	230/132/15	TR 1	125/125/37	19.6	7.88
41	Mekelle	North	230/132/15	TR 2	125/125/37	25	11.2
42	Mekelle	North	230/132	TR 3	63/63	28	14.5
43	Mekhoni	North	230/33/15	TR 1	63/40/23	3.6	1.44
44	Mekhoni	North	230/33/15	TR 2	63/40/23	3.6	1.44
45	Alamata	North	230/132/15	TR 1	63/40/23	18	5.25
46	Alamata	North	230/132/15	TR 2	63/40/23	4	2.12
47	Gahena	NER	230/33	TR 1	30/30/10	3	1.25
48	Gilgel Gibe I	SWR	132/15	TR 1	6	3.8	1.71
49	Gibe II	SWR	230/132	TR 1	63	30	11.25
50	Gibe II	SWR	230/132/33	TR 2	40/40/12	21	10.12
51	Beadle	SWR	230/132	TR 1	63	36.9	15.35
52	Metu	SWR	66/15	TR 1	1.5	3	0.8
53	Metu	SWR	66/33	TR 2	6.3	1.8	0.73
54	Metu	SWR	230/66/15	TR 3	40/20/20	6.52	2.61
55	Gambela II	SWR	230/66/33	TR 1	40/40/20	1.8	0.72
56	Alaba	SR	132/15	TR 1	12	6.5	3.2
57	Alaba	SR	230/132/15	TR 2	60/40/23	13	7
58	Alaba	SR	230/132/15	TR 3	60/40/23	13.75	7.5
59	Hossaina	SR	132/33/15	TR 1	25/12.5/12.5	15	6
60	Hossaina	SR	230/132	TR 2	63	7.5	3
61	Gedo ss	West	230/132/15	TR 1	63/63/21	30	15

62	Gedo ss	West	230/132/15	TR 2	63/63/21	19	7.5
63	Fincha II ss	West	230/33/15	TR 1	20/10/10	6	2.2
64	Torhailoch		230/33/15	TR 1	125	1	0.4
65	MW Yugo		230/132	TR 1	63	37	16
66	MW Yugo		230/132	TR 2	63	35.3	15
67	Gode		230/132/33	TR 1		1.2	0.8
68	Ramo		230/132/33	TR 1		1	0.45
69	Awash town		230/132	TR 1	125	22.5	8.8
70	Awash town		230/132	TR 1	125	22	8.8
71	Agaro		230/132	TR 1	63	7.5	3.37
72	Gerd		400/33	TR 1	50	10	3.15
73	Gerd		400/33	TR 2	50	10	3.15
74	Welayitasodo		400/132	TR 1	250	79	35.6

A. 5: Shunt reactors and capacitors

Table A.5.1 Shunt Reactors

Node 1	Element Name	Network Level	Sn [MVA]	Vcu [kW]	Vfe [kW]
Sululta 400 kV	SHR1305	400	45	118.2	0
Humera 230 kV	SHR1324	230	15	60.3	0
Semera 230 kV	SHR1349	230	15	65	0
Detecho 230 kV	SHR1357	230	15	65	0
GG old 400 kV	SHR1370	400	45	55.27	38.05
PK 12	SHR1400	230	15	65	0
Adigala	SHR1402	230	10	50	0
Shehedi	SHR1456	230	15	70	0
Gonder II 230	SHR1457	230	15	70	0
Koka 230	SHR1515	230	15	28.51	23.24
Metu230 kV	Metu 230	230	15	39.296	18.414
D/Markos 400 kV	SHR1674	400	15	118.2	0
Ramo	SHR1720	230	15	118.2	0
Gode	SHR1721	230	15	118.2	0

Table A.5.2: Shunt Capacitors

Node 1	Element Name	Network Level	Sn [MVA]	Vdi [kW]	Un [kV]
SEBETA 2 400 kV	SHC1282	400	90	0	400
SEBETA 2 33	SHC1284	230	45	10	230
Gelan	SHC1283	400	90	0	400
Bahirdar		230	45	0	230

A.6 Existing EEU electric energy sales price

Table A.5: electric energy sales price (tariff)

No	Tariff category	Monthly consumption (KWh)	Tariff rate (Birr/KWh)
1	Domestic	0-50	0.2730
		51-100	0.3564
		101-200	0.4993
		201-300	0.5500
		301-400	0.5666
		Above 500	0.6943
2	commercial	0-50	0.6088
		Above 50	0.6943
3	Industrial (low voltage Industry)	Peak	0.7423
		Off-peak	0.5435
4	High voltage Industry @15 KV	Peak	0.5085
		Off-peak	0.3933
5	High voltage Industry @132KV	Peak	0.4736
		Off-peak	0.3664
6	Street light	Equivalent flat rate	0.4843
7	Office (EEU)	-	-
8	Staff	0-440	Free
		Above 440	Domestic tariff

Appendix B: Simulation Result of EEP 230 kV and 400 kV network

Table B.1: Simulation result of transmission line contingency before loss mitigation techniques

Contingency Name	Category	Element	Value	Nom KV
GGIII-Welayita SodoC1	Bus Low Volts	Legetafo (25)	0.87	230
GGIII-Welayita SodoC1	Bus Low Volts	M W Yugo (34)	0.86	230
GGIII-Welayita SodoC2	Bus Low Volts	Legetafo (25)	0.87	230
GGIII-Welayita SodoC2	Bus Low Volts	M W Yugo (34)	0.86	230
GGIII-Welayita SodoC3	Bus Low Volts	Legetafo (25)	0.87	230
GGIII-Welayita SodoC3	Bus Low Volts	M W Yugo (34)	0.86	230
SebetaII-GelanC1	Bus Low Volts	Legetafo (25)	0.86	230
SebetaII-GelanC1	Bus Low Volts	M W Yugo (34)	0.86	230
SebetaII-GGIIC1	Bus High Volts	Bahir dar 230 kV(14)	1.1	230
SebetaII-GGIIC1	Bus High Volts	Gonder (15)	1.12	230
SebetaII-GGIIC1	Bus High Volts	Endasilase (20)	1.13	230
SebetaII-GGIIC1	Bus High Volts	Alamata (22)	1.1	230
SebetaII-GGIIC1	Bus Low Volts	Legetafo (25)	0.88	230
SebetaII-GGIIC1	Bus Low Volts	M W Yugo (34)	0.86	230
Markos-BahirdarrC1	Bus High Volts	Beles (5)	1.22	400
Markos-BahirdarrC1	Bus High Volts	Bahir dar (6)	1.22	400
Markos-BahirdarrC1	Bus High Volts	Markos (8)	1.11	400
Markos-BahirdarrC1	Bus High Volts	Markos 230 (13)	1.1	230
Markos-BahirdarrC1	Bus High Volts	Bahir dar 230 kV(14)	1.25	230
Markos-BahirdarrC1	Bus High Volts	Gonder (15)	1.28	230
Markos-BahirdarrC1	Bus High Volts	Endasilase (20)	1.37	230
Markos-BahirdarrC1	Bus High Volts	Tekeze (21)	1.33	230
Markos-BahirdarrC1	Bus High Volts	Alamata (22)	1.33	230
Markos-BahirdarrC1	Bus High Volts	Mekele (23)	1.34	230
Markos-BahirdarrC1	Bus High Volts	Combolcha II (24)	1.2	230
Markos-BahirdarrC1	Bus Low Volts	M W Yugo (34)	0.86	230
Markos-SulultaC1	Bus Low Volts	Legetafo (25)	0.85	230
Markos-SulultaC1	Bus Low Volts	M W Yugo (34)	0.86	230
KalitiI-GelanC1	Bus Low Volts	Legetafo (25)	0.86	230
KalitiI-GelanC1	Bus Low Volts	M W Yugo (34)	0.86	230
KalitiI-GelanC2	Bus Low Volts	Legetafo (25)	0.86	230
KalitiI-GelanC2	Bus Low Volts	M W Yugo (34)	0.86	230
Gelan-KokaC1	Bus High Volts	Gonder (15)	1.11	230
Gelan-KokaC1	Bus High Volts	Endasilase (20)	1.11	230
Gelan-KokaC1	Bus Low Volts	Legetafo (25)	0.86	230
Gelan-KokaC1	Bus Low Volts	M W Yugo (34)	0.86	230
Gelan-KokaC2	Bus High Volts	Gonder (15)	1.11	230
Gelan-KokaC2	Bus High Volts	Endasilase (20)	1.11	230
Gelan-KokaC2	Bus Low Volts	Legetafo (25)	0.86	230
Gelan-KokaC2	Bus Low Volts	M W Yugo (34)	0.86	230

Sebetaii-SebetaIC1	Bus Low Volts	Legetafo (25)	0.87	230
Sebetaii-SebetaIC1	Bus Low Volts	M W Yugo (34)	0.86	230
Sebetaii-SebetaIC2	Bus Low Volts	Legetafo (25)	0.87	230
Sebetaii-SebetaIC2	Bus Low Volts	M W Yugo (34)	0.86	230
GGI-AgaroC1	Bus Low Volts	Legetafo (25)	0.87	230
GGI-AgaroC1	Bus Low Volts	M W Yugo (34)	0.86	230
GGI-WelkiteC1	Bus High Volts	Bahir dar 230 kV(14)	1.11	230
GGI-WelkiteC1	Bus High Volts	Gonder (15)	1.12	230
GGI-WelkiteC1	Bus Low Volts	Welkite (19)	0.9	230
GGI-WelkiteC1	Bus High Volts	Endasilase (20)	1.14	230
GGI-WelkiteC1	Bus High Volts	Alamata (22)	1.11	230
GGI-WelkiteC1	Bus Low Volts	Legetafo (25)	0.88	230
GGI-WelkiteC1	Bus Low Volts	M W Yugo (34)	0.86	230
GGI-WelkiteC1	Bus Low Volts	Hossaina (35)	0.87	230
GGI-GedoC1	Bus Low Volts	Legetafo (25)	0.86	230
GGI-GedoC1	Bus Low Volts	M W Yugo (34)	0.86	230
Sululta-LegetafoC1	Bus Low Volts	Legetafo (25)	0.87	230
Sululta-LegetafoC1	Bus Low Volts	M W Yugo (34)	0.86	230
Sululta-GefersaC1	Bus Low Volts	Legetafo (25)	0.86	230
Sululta-GefersaC1	Bus Low Volts	M W Yugo (34)	0.86	230
Sululta-GefersaC2	Bus Low Volts	Legetafo (25)	0.86	230
Sululta-GefersaC2	Bus Low Volts	M W Yugo (34)	0.86	230
Bahirdar-Markos230C1	Bus Low Volts	Legetafo (25)	0.88	230
Bahirdar-Markos230C1	Bus Low Volts	M W Yugo (34)	0.86	230
Fincha-Markos230C1	Bus Low Volts	Legetafo (25)	0.85	230
Fincha-Markos230C1	Bus Low Volts	M W Yugo (34)	0.86	230
Bahirdar-GonderC1	Bus High Volts	Bahir dar (6)	1.11	400
Bahirdar-GonderC1	Bus High Volts	Markos (8)	1.11	400
Bahirdar-GonderC1	Bus High Volts	Bahir dar 230 kV(14)	1.12	230
Bahirdar-GonderC1	Bus High Volts	Gonder (15)	1.14	230
Bahirdar-GonderC1	Bus High Volts	Endasilase (20)	1.16	230
Bahirdar-GonderC1	Bus High Volts	Tekeze (21)	1.12	230
Bahirdar-GonderC1	Bus High Volts	Alamata (22)	1.14	230
Bahirdar-GonderC1	Bus High Volts	Mekele (23)	1.13	230
Bahirdar-GonderC1	Bus Low Volts	Legetafo (25)	0.9	230
Bahirdar-GonderC1	Bus Low Volts	M W Yugo (34)	0.86	230
Bahirdar-GonderC2	Bus High Volts	Bahir dar (6)	1.11	400
Bahirdar-GonderC2	Bus High Volts	Markos (8)	1.11	400
Bahirdar-GonderC2	Bus High Volts	Bahir dar 230 kV(14)	1.12	230
Bahirdar-GonderC2	Bus High Volts	Gonder (15)	1.14	230
Bahirdar-GonderC2	Bus High Volts	Endasilase (20)	1.16	230
Bahirdar-GonderC2	Bus High Volts	Tekeze (21)	1.12	230
Bahirdar-GonderC2	Bus High Volts	Alamata (22)	1.14	230
Bahirdar-GonderC2	Bus High Volts	Mekele (23)	1.13	230
Bahirdar-GonderC2	Bus Low Volts	Legetafo (25)	0.9	230

Bahirdar-GonderC2	Bus Low Volts	M W Yugo (34)	0.86	230
Agaro-BedeleC1	Bus Low Volts	Legetafo (25)	0.87	230
Agaro-BedeleC1	Bus Low Volts	M W Yugo (34)	0.86	230
Welkite-SebetaIC1	Bus Low Volts	Legetafo (25)	0.87	230
Welkite-SebetaIC1	Bus Low Volts	M W Yugo (34)	0.86	230
Welkite-HossainaC1	Bus Low Volts	Legetafo (25)	0.87	230
Welkite-HossainaC1	Bus Low Volts	M W Yugo (34)	0.86	230
Alamata-CombolchaC1	Bus Low Volts	Combolcha II (24)	0.47	230
Alamata-CombolchaC1	Bus Low Volts	Legetafo (25)	0.67	230
Alamata-CombolchaC1	Bus Low Volts	Kaliti I (26)	0.89	230
Alamata-CombolchaC1	Bus Low Volts	M W Yugo (34)	0.86	230
Combolcha-LegetafoC1	Bus Low Volts	Legetafo (25)	0.78	230
Combolcha-LegetafoC1	Bus Low Volts	M W Yugo (34)	0.86	230
Legetafo-KalitiIC1	Bus High Volts	Beles (5)	1.49	400
Legetafo-KalitiIC1	Bus High Volts	Bahir dar (6)	1.5	400
Legetafo-KalitiIC1	Bus High Volts	Sululta (7)	1.34	400
Legetafo-KalitiIC1	Bus High Volts	Markos (8)	1.44	400
Legetafo-KalitiIC1	Bus High Volts	Sululta (12)	1.18	230
Legetafo-KalitiIC1	Bus High Volts	Markos 230 (13)	1.39	230
Legetafo-KalitiIC1	Bus High Volts	Bahir dar 230 kV(14)	1.52	230
Legetafo-KalitiIC1	Bus High Volts	Gonder (15)	1.56	230
Legetafo-KalitiIC1	Bus High Volts	Endasilase (20)	1.59	230
Legetafo-KalitiIC1	Bus High Volts	Tekeze (21)	1.51	230
Legetafo-KalitiIC1	Bus High Volts	Alamata (22)	1.47	230
Legetafo-KalitiIC1	Bus High Volts	Mekele (23)	1.5	230
Legetafo-KalitiIC1	Bus Low Volts	Legetafo (25)	0.4	230
Legetafo-KalitiIC1	Bus High Volts	Gefersa (28)	1.16	230
Legetafo-KalitiIC1	Bus Low Volts	M W Yugo (34)	0.86	230
Legetafo-KalitiIC1	Bus High Volts	Gedo (36)	1.18	230
Legetafo-KalitiIC1	Bus High Volts	Fincha (37)	1.23	230
KalitiI-SebetaIC1	Bus Low Volts	Legetafo (25)	0.84	230
KalitiI-SebetaIC1	Bus Low Volts	M W Yugo (34)	0.86	230
Gefersa-SebetaIC1	Bus Low Volts	Legetafo (25)	0.84	230
Gefersa-SebetaIC1	Bus Low Volts	M W Yugo (34)	0.86	230
Gedo-GefersaC1	Bus Low Volts	Legetafo (25)	0.87	230
Gedo-GefersaC1	Bus Low Volts	M W Yugo (34)	0.86	230
Gedo-GefersaC2	Bus Low Volts	Legetafo (25)	0.87	230
Gedo-GefersaC2	Bus Low Volts	M W Yugo (34)	0.86	230
Gedo-GefersaC3	Bus Low Volts	Legetafo (25)	0.87	230
Gedo-GefersaC3	Bus Low Volts	M W Yugo (34)	0.86	230
Koka-HursoC1	Bus Low Volts	Legetafo (25)	0.86	230
Koka-HursoC1	Bus Low Volts	M W Yugo (34)	0.86	230
Koka-HursoC2	Bus Low Volts	Legetafo (25)	0.86	230
Koka-HursoC2	Bus Low Volts	M W Yugo (34)	0.86	230
Koka-AwashTownC1	Bus Low Volts	Legetafo (25)	0.87	230

Koka-AwashTownC1	Bus Low Volts	M W Yugo (34)	0.86	230
Koka-MelkaWakenaC1	Bus Low Volts	Legetafo (25)	0.87	230
Koka-MelkaWakenaC1	Bus Low Volts	M W Yugo (34)	0.86	230
Hurso-DireDawaIIIC1	Bus Low Volts	Legetafo (25)	0.87	230
Hurso-DireDawaIIIC1	Bus Low Volts	M W Yugo (34)	0.86	230
Hurso-DireDawaIIIC2	Bus Low Volts	Legetafo (25)	0.87	230
Hurso-DireDawaIIIC2	Bus Low Volts	M W Yugo (34)	0.86	230
Awash-DireDawaIIIC1	Bus Low Volts	Legetafo (25)	0.87	230
Awash-DireDawaIIIC1	Bus Low Volts	M W Yugo (34)	0.86	230
MelkaWakena-MWYugoC1	Bus Low Volts	Legetafo (25)	0.87	230
Fincha-GedoC1	Bus Low Volts	Legetafo (25)	0.87	230
Fincha-GedoC1	Bus Low Volts	M W Yugo (34)	0.86	230
Gedo-FinchaC2	Bus Low Volts	Legetafo (25)	0.87	230
Gedo-FinchaC2	Bus Low Volts	M W Yugo (34)	0.86	230

Table B. 2: Simulation result of transmission line contingency after integrated loss mitigation techniques

Contingency Name	Category	Element	Val	Limit	Nom KV
GGIII-Welayita SodoC1	Bus Low Volts	Tekeze (21)	0.88	0.9	230
GGIII-Welayita SodoC2	Bus Low Volts	Tekeze (21)	0.88	0.9	230
GGIII-Welayita SodoC3	Bus Low Volts	Tekeze (21)	0.88	0.9	230
SebetaII-GelanC1	Bus Low Volts	Tekeze (21)	0.88	0.9	230
Beles-BahirdarC1	Bus High Volts	Endasilase (20)	1.12	1.1	230
Beles-BahirdarC1	Bus High Volts	Alamata (22)	1.11	1.1	230
Beles-BahirdarC2	Bus High Volts	Endasilase (20)	1.12	1.1	230
Beles-BahirdarC2	Bus High Volts	Alamata (22)	1.11	1.1	230
Markos-BahirdarC1	Bus High Volts	Beles (5)	1.18	1.1	400
Markos-BahirdarC1	Bus High Volts	Bahir dar (6)	1.18	1.1	400
Markos-BahirdarC1	Bus High Volts	Markos (8)	1.11	1.1	400
Markos-BahirdarC1	Bus High Volts	Bahir dar (14)	1.21	1.1	230
Markos-BahirdarC1	Bus High Volts	Gonder (15)	1.25	1.1	230
Markos-BahirdarC1	Bus High Volts	Endasilase (20)	1.34	1.1	230
Markos-BahirdarC1	Bus High Volts	Tekeze (21)	1.3	1.1	230
Markos-BahirdarC1	Bus High Volts	Alamata (22)	1.31	1.1	230
Markos-BahirdarC1	Bus High Volts	Mekele (23)	1.31	1.1	230
Markos-BahirdarC1	Bus High Volts	Combolcha (24)	1.21	1.1	230
KalitiI-GelanC1	Bus Low Volts	Tekeze (21)	0.88	0.9	230
KalitiI-GelanC2	Bus Low Volts	Tekeze (21)	0.88	0.9	230
Gelan-KokaC1	Bus Low Volts	Tekeze (21)	0.9	0.9	230
Gelan-KokaC2	Bus Low Volts	Tekeze (21)	0.9	0.9	230

Sebetaii-SebetaIC1	Bus Low Volts	Tekeze (21)	0.89	0.9	230
Sebetaii-SebetaIC2	Bus Low Volts	Tekeze (21)	0.89	0.9	230
GGI-AgaroC1	Bus Low Volts	Tekeze (21)	0.88	0.9	230
GGI-WelkiteC1	Bus Low Volts	Hossaina (35)	0.88	0.9	230
GGI-GedoC1	Bus Low Volts	Tekeze (21)	0.88	0.9	230
Sululta-LegetafoC1	Bus Low Volts	Legetafo (25)	0.89	0.9	230
Sululta-GefersaC1	Bus Low Volts	Tekeze (21)	0.88	0.9	230
Sululta-GefersaC2	Bus Low Volts	Tekeze (21)	0.88	0.9	230
Fincha-Markos230C1	Bus Low Volts	Tekeze (21)	0.88	0.9	230
Agaro-BedeleC1	Bus Low Volts	Tekeze (21)	0.88	0.9	230
Welkite-HossainaC1	Bus Low Volts	Tekeze (21)	0.88	0.9	230
Tekeze-MekeleC2	Bus High Volts	Gonder (15)	1.1	1.1	230
Mekele-AlamataC1	Bus High Volts	Bahir dar (14)	1.11	1.1	230
Mekele-AlamataC1	Bus High Volts	Gonder (15)	1.11	1.1	230
Mekele-AlamataC2	Bus High Volts	Bahir dar (14)	1.11	1.1	230
Mekele-AlamataC2	Bus High Volts	Gonder (15)	1.11	1.1	230
Alamata-CombolchaIIC1	Bus Low Volts	Combolcha (24)	0.83	0.9	230
Legetafo-KalitiIC1	Bus Low Volts	Tekeze (21)	0.89	0.9	230
KalitiI-SebetaIC1	Bus Low Volts	Tekeze (21)	0.88	0.9	230
Gefersa-SebetaIC1	Bus Low Volts	Tekeze (21)	0.89	0.9	230
Koka-HursoC1	Bus Low Volts	Tekeze (21)	0.88	0.9	230
Koka-HursoC2	Bus Low Volts	Tekeze (21)	0.88	0.9	230
Koka-AwashTownC1	Bus Low Volts	Tekeze (21)	0.88	0.9	230
Koka-MelkaWakenaC1	Bus Low Volts	Tekeze (21)	0.89	0.9	230
Hurso-DireDawaIIC1	Bus Low Volts	Tekeze (21)	0.88	0.9	230
Hurso-DireDawaIIC2	Bus Low Volts	Tekeze (21)	0.88	0.9	230
AwashTown-DireDawaIIC1	Bus Low Volts	Tekeze (21)	0.88	0.9	230
MelkaWakena-MWYugoC2	Bus Low Volts	Tekeze (21)	0.88	0.9	230
MelkaWakena-MWYugoC2	Bus Low Volts	M W Yugo (34)	0.89	0.9	230
MelkaWakena-MWYugoC1	Bus Low Volts	Tekeze (21)	0.88	0.9	230