



**ADDIS ABABA UNIVERSITY**

**Addis Ababa Institute of Technology (AAiT)**

School of Electrical and Computer Engineering

**Evaluation of Static Voltage Stability of Ethiopian Grid**

By: Mizan Welderufael Massa

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

**Advisor:**

**Dr.-Ing. Getachew Biru**

**Date: July 2017**



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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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# Acknowledgement

First of all, I would like to thank the Almighty God for giving me the strength and motivation to complete the entire work.

Secondly, I would like to express my sincere gratitude to my advisor Dr. -Ing. Getachew Biru, for understanding me, giving me continuous support, constructive comments, motivation, suggestions, and encouragements. His guidance helped me at all the thesis time and without him this work could have not been completed. I am grateful to his devotion and his dynamic suggestions for solutions to any challenges during the total work of this thesis.

I would like to extend my appreciation to Mr. Yesehak Kidane, Senior Power System Planning Engineer, for showing and letting me work with the PSS/E simulation software, Mr. Miraj Fereja, Mr. Gulilat Engida, Mr. Milkias Abayneh, Mr. Mikias Wondimu, and all Real Time Operation staff members from National Load Dispatch Center (NLDC) for their kind advice and help in providing necessary data.

I take this opportunity to extend my thanks to other EEP and EEU staffs that provided me with numerous valuable data. I received a very keen support from these offices during my data collection for the successful completion of this thesis.

I also highly appreciate the encouragements kindly provided by Mr. Kiros Tesfay, Mr. Amare Assefa, and Mrs. Kibework Alemayehu from Addis Ababa Institute of Technology, and my classmates from Electrical Power Engineering department for their useful idea and constructive comments on this thesis work.

Last but not least, I would like to thank my family, friends, and my Young African Leaders Initiative (YALI) family who always stood by my side.

# Abstract

A power system is set to operate within its maximum operating limits for better utilization of the existing network facilities. The main factor causing voltage instability is the inability of a power system to meet the demand for reactive power. A system enters a state of voltage instability due to loss of loaded generation unit or transmission line, or a change in loading conditions that causes progressive and uncontrollable decline or rise in voltage. This thesis attempts to evaluate voltage stability problems of Ethiopian high voltage transmission grid.

Load flow simulations using PSS/E software has been done for peak load (2,200MW) and light-load (900MW) conditions. After conducting load flow simulations, ‘Voltage limit checking’ results within tolerable range of  $\pm 0.05$ pu is applied to identify the buses/areas with unacceptable low and high voltage values. Low voltage profiles during peak hour are registered around Addis Ababa, and high voltage values are registered at North-western part of Ethiopia, i.e. around Bahirdar & Debre Markos.

Mitigation techniques applied to improve the low voltages for peak load conditions include; installation of 15MVAR shunt capacitors each at Weregenu and Mekanissa substations, upgrading of transmission lines; i.e. Legetafo–Cottobie line from 132kV into 230kV, Cottobie–Addis East-I line from 45kV into 132 kV double lines, and Sebeta1–Addis West line from 45kV into 132kV, and upgrading of transformers; two 25MVA into two 50MVA at Addis North, two 12.5MVA into two 50MVA each at Addis East-I and Addis West, and each of two 125MVA transformers are installed at Cottobie and Sebeta-1. Simulation results for peak load case after mitigation show that, voltage at Addis West substation 15kV bus improved from 0.7647 to 0.9674pu and at Addis North substation 15kV bus from 0.8187 to 0.99pu, which is 20.07% and 17.13% improvements respectively.

Mitigation techniques applied to improve the unacceptable voltages for light load conditions include; installation of shunt reactors with capacities of 45MVAR at Debre Markos, 30MVAR at Gashena, and 15MVAR at Nifas Mewcha substations. Simulation results under light-load condition after mitigation show that, voltage at Debre Markos 66 & 15kV buses are adjusted from 1.1428 to 0.962pu and 1.1407 to 0.964pu, which is -18.08% and -17.67% improvements respectively.

This thesis assesses the blackouts that have occurred in Ethiopian power system during 2015 and 2016. The observations from the blackouts show that, most of the faults are initiated by a sudden tripping of generating units and transmission lines. These faults resulted in the surrounding area to be exposed to a lack of reactive power and several generators to be field current limited.

This project recommends voltage stability assessment to be investigated during each and every change on the transmission grid by including the sub-transmission and distribution sides. In the future, dynamic voltage stability analysis should be investigated by including the common contingencies, the distribution side, and the load behaviours.

***Key words:*** *Static voltage stability, Ethiopian grid, reactive compensation, blackout, PSS/E*

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# List of Abbreviation

AGC: Automatic Generation Control  
AVR: Automatic Voltage Regulator  
CB: Circuit Breaker  
CBF: Circuit Breaker Failure  
CIGRE: International Council of Large Electric Systems  
DSWORK: Dynamic Simulation Working File  
EAAR: East Addis Ababa Region  
EEP: Ethiopian Electric Power  
EEPCO: Ethiopian Electric Power Corporation  
EEU: Ethiopian Electric Utility  
EHV: Extra High Voltage  
FACTS: Flexible Alternating Current Transmission System  
FMWORK: Factorized Matrix Working File  
GERD: Grand Ethiopian Renaissance Dam  
GIS: Gas Insulated Substation  
GoE: Government of Ethiopia  
GPS: Global Positioning System  
GTP: Growth and Transformation Plan  
HV: High Voltage  
HVDC: High Voltage Direct Current  
ICS: Interconnected System  
IPP: Independent Power Producers  
IEEE: International Electrical and Electronics Engineers  
IGBT: Insulated Gate Bipolar Transistor  
LFF: Load Flow Feasibility  
LG: Line to Ground Fault  
LFWORK: Load Flow Working File  
MCCB: Mechanically Controlled Circuit Breaker  
MVA: Mega Volt Ampere  
MVAr: Mega Volt Ampere Reactive

NLDC: National Load Dispatch Center  
NAAR: North Addis Ababa Region  
OPF: Optimum Power Flow  
OXL: Over Excitation Limiter  
OLTC: On Load Tap Changer  
PPA: Power Purchase Agreement  
PSS/E: Power System Simulator for Engineering  
PU: Per Unit  
SCADA: Supervisory Control And Data Acquisition  
SCS: Self Contained System  
SCWORK: Short Circuit Working File  
SIL: Surge Impedance Limit  
SSS: Steady State Stability  
STATCOM: Static Synchronous Compensator  
SVC: Static Var Compensator  
SAAR: South Addis Ababa Region  
TCR: Thyristor Controlled Reactor  
TSC: Thyristor Switched Capacitor  
WAAR: West Addis Ababa Region  
WT: Wind Turbines

# Chapter One

## 1 Introduction

### 1.1 Background

Ethiopian power system consists of generating stations mainly from hydro, transmission lines, substations, and distribution network. The interconnected system is monitored centrally from the National Load Dispatch Center (NLDC) located in Addis Ababa, Bole sub-city, Gerji Mebrat Hayl area. Currently Ethiopian transmission grid involves voltage levels of 400kV, 230kV and 132 kV as primary transmission systems and 66kV and 45kV as sub-transmission system. A 500 kV extra high voltage (EHV) transmission lines are also under construction that will connect the generation from Grand Ethiopian Renaissance Dam (GERD) with the grid through Dedessa and Holeta 500kV lines and Holeta – Sebeta-II 400kV line.

Power system stability, whether it is generator driven or load driven, is a characteristic of a power system to stay in state of equilibrium at normal operating conditions and after being exposed to a disturbance. Power system is voltage stable if voltages after a disturbance are close to voltages at normal operating conditions. Voltage stability problems typically occur on power systems which are heavily loaded, faulted, and/or has reactive power problems. Voltage stability problem involves many power system components and their variables at once and an entire power system, although it usually has a relatively larger involvement in one particular area of the network.

In recent years, an increase in peak load demand and power transfers between utilities has resulted in concerns about system voltage stability. One of the reasons for the concern is that, the significant number of blackouts which have occurred in different countries and involved voltage stability issues. This voltage stability problem deals with the ability to have the voltage level within a narrow band around normal operating voltage conditions.

In Ethiopia, electric power interruption is becoming a day to day phenomenon. When the incidence of power interruption is at the transmission level (can be due to the high voltage transmission line or generating unit outages), the consequence will cover larger area of the country. This can lead to partial or total black-outs and hence takes longer restoration time.

## 1.2 Problem Statement

The Government of Ethiopia (GoE), under its latest Growth and Transformation Plan (GTP), envisions transitioning from a developing country to a middle-income country by 2025 (GTP-2, World Bank). Ethiopia's ability to achieve this ambitious goal in key sectors such as agriculture and industry is significantly constrained by the current challenges in the power sector. Ethiopia is gifted with abundant renewable energy resources and currently EEP is constructing generating plants in different parts of the country.

The current Ethiopian transmission network involves transmission constraints and doesn't fulfil N-1 security and therefore is unable to withstand line or transformer outages without loss of supply to part of the network. Many of the substations are supplied over single radial 132 kV circuits and will of course lose supply completely on loss of that circuit. Recently the existing transmission network is getting upgraded; i.e. the newly constructed transmission lines are helping in improving the supply to these substations such that N-1 security is achieved.

At light-loading condition the system generates reactive power that must be absorbed, while at heavy loading the system consumes a large amount of reactive power that must be replaced. The capacity of the available shunt reactors and shunt capacitors connected at the bus-bars and lines in the grid is insufficient. During off-peak hours the MVar generated by the light-loaded & long transmission lines increases which is beyond the compensation capacity of the available shunt reactors, so that, voltage at most of the regions will be higher.

In some transmission lines there are un-switchable shunt reactors that are connected to a bus or a line with isolators only (without circuit breakers). These fixed shunt reactors are causing low voltages at many buses and limiting the power transfers especially at peak load conditions. Hence, the resulting low voltage profiles can be causes for voltage instability.

This thesis addresses the problem of voltage instability and voltage collapse in Ethiopian power transmission grid and investigates the mitigation techniques to solve the problem.

## 1.3 Objectives

### 1.3.1 General Objective

The general objective of this thesis is to investigate the causes for voltage instability and voltage collapse in power transmission network and investigate the mitigation techniques to improve the voltage stability of the power transmission networks.

### 1.3.2 Specific Objectives

The specific objectives of this thesis are:

- To assess the voltage profiles of the existing Ethiopian power system (by Dec, 2016) in terms of voltage stability.
- To gather blackout data of the power system and analyze the reasons of occurrences.
- To investigate the mitigation techniques for improving the static voltage stability.
- To model the existing transmission network using PSS/E power system simulation software and simulate the system to investigate voltage stability under peak load and light-load conditions.
- To identify the buses that can lead to voltage instability and/or voltage collapse during peak load and light-load conditions.
- To draw conclusions and recommend mitigation techniques for improving the static voltage stability of the Ethiopian National grid.

## 1.4 Methodology

The data of existing transmission network is collected from the respective departments of Ethiopian Electric Power (EEP) and Ethiopian Electric Utility (EEU). Most data are collected from the National Load Dispatch Center (NLDC) and Transmission Planning departments.

The next and major part of the thesis is literature review related to voltage stability of power systems. Particular focus is given to steady state voltage stability, voltage collapse, reactive compensation, real world blackouts, and the PSS/E program.

PSS/E, Power System Simulator for Engineering Software is used for load flow and optimum load flow analysis of the transmission network.

The following methodology has been followed in conducting the thesis:

- Literature Review: Literatures reviewed that includes articles, journals, books, and previous researches.
- Repeated visit to National Load Dispatch Center (NLDC), Real Time Operation office to observe the voltage behaviors at peak and light load conditions.
- Data collection: General transmission network diagram, list of available transmission lines, available generation stations, reactive compensation, transformers, load data of substations, two years black out data, and total Ethiopian demand in 2015 and 2016.
- The MVAR capacity of available shunt reactors and shunt capacitors in the grid, and active and reactive power capacity of the power plants in the grid. Moreover, Transmission line parameters such as conductor size, conductor type, configurations, distance of line in km etc.
- Collection and analysis of blackouts occurred in 2015 and 2016.
- Load flow simulation of Ethiopian power system using PSS/E under peak and light load conditions before and after applying the mitigation techniques, and observe the improved voltage profiles.

## 1.5 Literature Review

Voltage stability issues have gained significant attention over the past years, due to the occurrences of voltage collapses in many systems. In the liberalized electricity market, a power system is forced to operate at its maximum operating limits for better utilization of existing generation, transmission, and substation facilities [1]. The main factor causing voltage instability is the inability of a power system to meet the demand for reactive power. A system enters a state of voltage instability due to increase in demand, a sudden large disturbance, loss of heavily loaded transmission lines or generating units, and a change in system conditions that causes progressive and uncontrollable decline or rise in voltage [2].

Voltage stability analysis helps in designing and selecting countermeasures which will avoid voltage collapse and enhance stability. There are two different approaches of analyzing voltage stability problem, namely the static and dynamic approach. Static voltage stability investigates the capability of the network to withstand smaller system disturbances without leaving a stable equilibrium point and involves the static model of the power system components [3]. The dynamic methods analyze the effect of dynamic loads, such as generator over excitation limiters (OXL), Transformer on load tap changers (OLTC), etc. on the voltage collapse and use time domain simulations to reveal the voltage collapse mechanism [4].

It is tried to review research papers and journals to get acquainted with the research carried out related to the scope of this thesis. Some of the literatures reviewed are the following.

The paper by Maria Zerva [4] quantifies the voltage stability limits of the Swiss Power System and identifies the determining factors which may lead to voltage instability incidents. Two models are developed for the steady-state evaluation of the system and its post-disturbance behavior. The paper addresses on improving the voltage stability limit of power flow between two different regions in an electric power system in MATLAB/SIMULINK.

The paper by [5] by 'Pothula Uma Maheswara Rao' studies and models various power system components, such as OLTC, OXL, and AVR etc. in MATLAB/SIMULINK platform and then integrates to investigate the short-term and long-term voltage stability of a power system. The short-term stability is investigated by using the network PV curve. The phenomenon of long-term voltage stability is investigated by considering the dynamics of both fast and slow-acting devices.

The paper [6] by ‘Baheej Alghamdi and Mohammed Alamri’, investigates the voltage stability and post disturbance voltage recovery times for the Nordic 32 test system for different load combinations with and without large scale integration of solar PV power plants through PSS/E. In addition, the mitigation of the voltage stability and voltage recovery time phenomena through various dynamic Var Compensators such as SVC and STATCOM are investigated.

The Paper [7] by J. Hossain and H. R. Pota analyzes the driving force and main causes of voltage instability, the different methods and devices used to enhance voltage stability, and present the distinctions between voltage and angle instability. In addition, the steady-state and dynamic modelling of the power system devices including wind generators and photovoltaic units have been discussed.

The paper [8] by Abebe Kahsay studies the Steady-state Voltage Stability Analysis of the Ethiopian HV grid (during 2010) using Continuation Power Flow. The thesis deals on the integration of ACLK (Alamata– Combolcha– Legetafo– Kaliti-1) transmission line project that played significant role on the power transfers from Tekeze HEPP and in strengthening the Northern and North-eastern corridors.

In 2010, Ethiopian transmission grid was not complex and was composed of about 40 % sub-transmission 45kV and 66kV substations, which these buses were causes for voltage instability/collapse. 400kV transmission line was only limited to New Gibe (Sekoru) – Sebeta-II, and power plants like Beles, Gilgel Gibe-III and Gilgel Gibe-II were not synchronized to the system.

The paper [3] by Jan Veleba, deals with steady-state voltage stability problem in power system operation and control. It mainly focuses on analytical description of the problem and conventional solution of simple power systems using the theory of load flow analysis. It also introduces Continuation load flow analysis, which is currently used for evaluation voltage stability margins, volume of available reactive power reserves and location of weak buses/areas of the power system sensitive to load increase.

## **1.6 Organization of the Thesis**

The thesis is organized into five chapters which are briefly summarized below.

Chapter one presents the introduction, background, statement of the problem, objectives of the study and methodology followed in the thesis work. In addition, it provides the literature review and outline of the thesis.

The second chapter discusses about the theoretical background of the study topic, mainly on voltage stability analysis, power system stability, static and dynamic voltage stability, real world blackout experiences, PV and QV curves, voltage stability and FACTS devices, and the PSS/E simulation software.

Chapter three assesses the existing Ethiopian transmission system, which is the generation system, 400kV, 230kV, and 132 kV networks, 66 and 45kV networks, international interconnections, reactive compensation, available transformers, protection coordination and control, and the load demand in the grid.

Chapter four presents detailed static voltage stability analysis of the Ethiopian transmission system using PSS/E simulation software. In this chapter, load flow simulation by conducting “Voltage Limit Checking” results are described in network diagrams before and after applying the mitigation techniques for the evaluated regions/areas. Mitigation techniques are applied to improve the unacceptable low and high voltage profiles that can lead to voltage instability and collapse. Blackouts in 2015 and 2016 and the observations are presented in this chapter.

Conclusions, recommendations and future work are incorporated in chapter five.

## Chapter Two

### 2 Voltage Stability Analysis of a Power System

#### 2.1 Power System Stability Analysis

Power system stability is the ability of an electric power system, for a given initial operating condition, to recover a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains complete [1].

The classification of power system stability assists in identifying the main causes of each form of instability and develops the appropriate countermeasures. However, it should be made clear that when one type of instability occurs within the power system, the parallel occurrence of other forms of instability cannot be excluded. Figure 2.1 gives the overall picture of the power system stability problem, identifying its categories and subcategories.

The IEEE/CIGRE classification of power system stability introduces three main categories (Figure 2.1):

- *Rotor angle stability* is the ability of interconnected synchronous machines of a power system to remain in synchronism. Angle stability is associated with the balance between the mechanical torque of the generating unit's turbine and the electromagnetic torque of its generator [4].
- *Frequency stability* refers to the ability of the power system to maintain the system frequency within acceptable limits under normal operation or following a system disturbance. The condition to keep the nominal frequency is keeping the equilibrium between the active power generated, and the sum of the power (consumed) absorbed by the loads and the system's active power losses on the other hand [2].
- *Voltage stability* refers to the ability of the power system to maintain steady voltages within acceptable limits at all buses of the system under normal operating conditions or after being subjected to a disturbance. The robustness of a system to voltage instability derives from the capability of the system to meet the reactive power demands at all buses across the network [4].

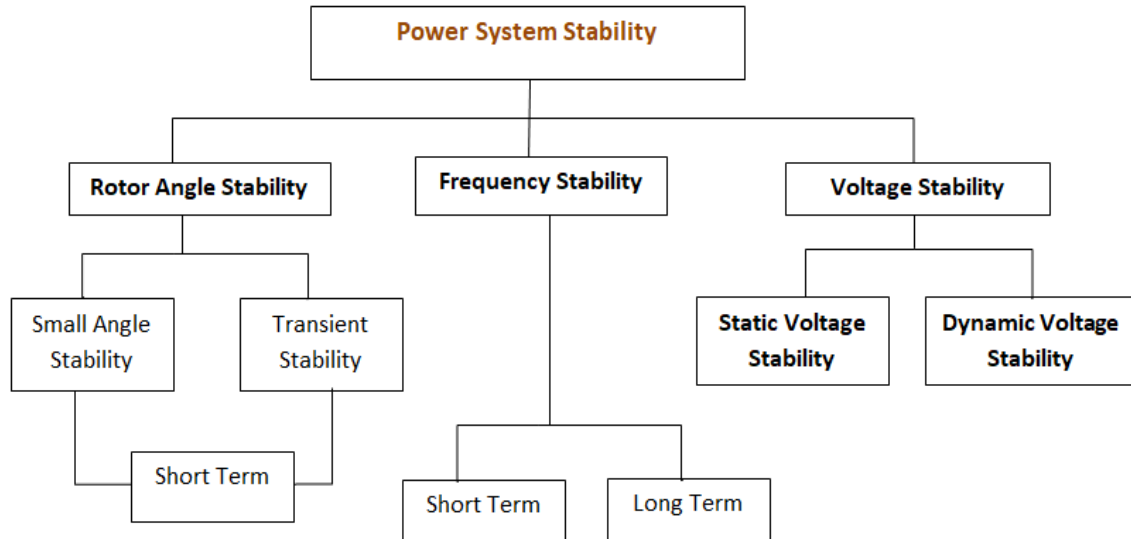


Figure 2-1: Power System Stability Classification [7]

Voltage stability issues have gained significant attention over the past years, due to the occurrences of voltage collapse or voltage instability. In the liberalized electricity market, a power system is forced to operate at its maximum operating limits for better utilization of existing generation, transmission, and substation facilities. A system enters a state of voltage instability due to increase in demand, a sudden large disturbance, loss of heavily loaded transmission lines or generating units, and a change in system conditions that causes progressive and uncontrollable decline or rise in voltage [1].

## 2.2 Voltage Stability Analysis

Voltage stability is the ability of a power system to maintain steady acceptable voltages at all buses in the system under normal operating conditions and after being exposed to a disturbance [1]. The main factor causing the voltage instability is the inability of a power system to meet the demand for reactive power [9]. A possible consequence of voltage instability is loss of load in an area, or tripping of transmission lines and other elements by their protections leading to cascading outages that in turn may lead to loss of synchronism of some generators [2].

The process by which voltage instability leads to loss of voltage in a significant part of a power system is called ‘*Voltage Collapse*’. The ability of a power system to operate not only in stable condition but also to remain stable following any reasonable contingency or adverse system

change is termed as '*Voltage Security*' [5]. The increase in power demand has forced the power system to operate closer to its stability limit.

According to the size of the disturbance that could lead to voltage instability, the voltage stability can be classified into two classes: Large-disturbance and small-disturbance voltage stability. Large disturbances such as loss of big generating unit or loss of heavily loaded transmission line require performing studies of sub-transient and transient nature. Voltage stability in this case tests the system ability to maintain bus voltages after such major disturbances. For an operator, it is required to perform nonlinear dynamic analysis with time frame ranging from few seconds to tens of minutes. In this time range, the operation of on-load tap-changers, generator field current limiters and transmission protection can be noticed. The type of analysis used here is dynamic analysis [1].

Small-disturbance voltage stability is the system's ability to maintain steady voltages when subjected to small variations such as small incremental changes in system load or losing small distributed generator. It is more related to static nature where the effect of the disturbance on voltage stability is not as big as the large disturbances. The type of analysis used here is steady state or static analysis where the change in voltage due to such small disturbances is examined at buses [1].

### **2.2.1 Main Causes of Voltage Instability**

The driving force for voltage instability is usually the loads; in response to a disturbance, power consumed by the loads tends to be restored by the action of distribution voltage regulators, tap-changing transformers and thermostats [7]. Restored loads increase the stress on a high-voltage network by increasing the reactive power consumption and causing further voltage reduction. A run-down situation causing voltage instability occurs when load dynamics attempt to restore power consumption beyond the capability of the transmission network and the connected generation [7].

A major factor contributing to voltage instability is the voltage drop that occurs when both active and reactive power flow through the inductive reactance of a transmission network. In almost all voltage instability incidents, one or several crucial generators were operating with a limited reactive capability. Voltage stability is threatened when a disturbance increases the

reactive power demand beyond the sustainable capacity of the available reactive power resources.

The risk of voltage instability due to progressive rises in bus voltages also exists, while the most common form of voltage instability is progressive drops in bus voltages. It is caused by the capacitive behavior of a network and by under-excitation limiters preventing generators and/or synchronous compensators from absorbing the excess reactive power [7]. In this case, instability is associated with the inability of the combined generation and transmission systems to operate below some load level. In their attempt to restore this load power, transformer tap changers may cause long-term voltage instability.

The self-excitation of synchronous machines that can arise if the capacitive load is too large is one form of over-voltage instability. Examples of excessive capacitive loads that can initiate self-excitation are open-ended high-voltage lines and shunt capacitors. The over-voltages that result when a generator load changes to a capacitive load are characterized by an instantaneous rise at the instant of change followed by a more gradual rise [7]. This later rise depends on the relationship between the capacitive load component and the machine reactance, together with the excitation system of the synchronous machine.

Voltage stability problems may also be experienced at the terminals of HVDC links used for long-distance applications [7]. They are usually associated with HVDC links connected to weak AC systems and may occur at rectifier or inverter stations, and are associated with the unfavorable reactive power load characteristics of converters.

### 2.2.2 Voltage Collapse

Several definitions of voltage stability can be found that consider time frames, system states, large or small disturbances etc. CIGRÉ and IEEE define Voltage collapse as:

CIGRÉ: Following voltage instability, a power system undergoes *Voltage Collapse* if the post-disturbance equilibrium voltages are below acceptable limits. Voltage collapse may be *total* or *partial* [10].

Voltage collapse can occur not only as the immediate consequence of a contingency, but can also be the result of changes in system conditions due to restoration of loads, limitation of generator currents, or capacitor and/or reactor switching etc. These varying conditions will increase the demands on the solution algorithms used in the program.

Voltage collapse is the process by which the sequence of events accompanying voltage instability leads to intolerable voltage profile in a major part of the power system. Typical scenarios of voltage collapse would be as follows:-

- i) Power system undergoing abnormal operating conditions with large generating units near the load areas being tripped. As a result some EHV lines are heavily loaded and reactive power resources are at a minimum [1].
- ii) Loss of heavily loaded line which would cause extra loading on the nearby lines. This would increase the reactive power losses in the line, thereby causing a heavy reactive power demand on the system (Q absorbed by a line increases rapidly for loads above surge impedance loading) [1].
- iii) Following the immediate loss of EHV line, there would be an extensive reduction in voltage at adjacent load centers due to extra reactive power demand. This would cause a reduction in power flow through the lines. The generator AVRs would, however restore terminal voltage by increasing excitation. The resulting additional reactive power flow associated with generator transformers and lines would cause increased voltage drop across each of these elements [1].
- iv) The transmission voltage level reduction at load centres would be reflected into the distribution system. In about 2 to 4 minutes, the ULTCs of substation transformers would restore distribution voltages and loads to pre fault levels. With each tap change operation, the resulting increment in load in EHV lines would increase the line  $XI^2$  and  $RI^2$  losses [1]. As a result, with each tap changing operation, the reactive output of generators throughout the system would increase. With fewer generators on automatic excitation control, the system would be much more likely to voltage instability. This would likely be compounded by the reduced effectiveness of shunt compensators at low voltages [1].

The process will eventually lead to voltage collapse, possibly leading to loss of synchronism of generating units and a major black out.

### 2.2.3 PV and QV Curves and Voltage Stability

Transmission systems have limited capability for power transfer. This limit (as affected by generation system as well) marks the onset of voltage instability. Voltage instability results from the attempt of loads to draw more power than can be delivered by the transmission and generation system. Many voltage instability problems can be demonstrated with the simple radial two bus system of Figure 2.2. Voltage instability problems are mostly locally met and originate from the inability of the system to meet the reactive power demand, which cannot be transported over long distances. Voltage instability phenomena which cover bigger parts of a power system are caused in a cascaded manner and the two bus system can easily be extended for studying larger grids. The system consists of a load fed from a voltage source E through a transmission line modeled as a series reactance, where the transmission line's resistance is neglected for simplicity reasons. The voltage at the load end is [9]:

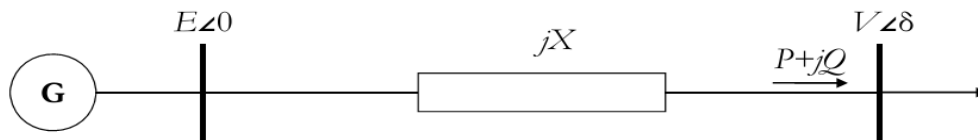


Figure 2-2: Single line diagram of a two bus system

$$\bar{V} = \bar{E} - jX\bar{I} \tag{2.1}$$

whereas, the complex power  $S$  transmitted over the line to the composite load is:

$$\begin{aligned} S = P + jQ &= \bar{V}\bar{I}^* = \bar{V} \frac{\bar{E}^* - \bar{V}^*}{-jX} \\ &= \frac{j}{X}(EV \cos \delta + jEV \sin \delta - V^2) \end{aligned} \tag{2.2}$$

Thus, the active (Equation 2.3) and reactive (Equation 2.4) power can be written as:

$$P = -\frac{EV}{X} \sin \delta \tag{2.3}$$

$$Q = \frac{EV}{X} \cos \delta - \frac{V^2}{X} \tag{2.4}$$

The relationship of active and reactive power transmitted over a line indicates the relationship between active power and transmission angle and reactive power and voltage. Since our main focus is the voltage on the system buses, we eliminate the transmission angle  $\delta$ .

### 2.2.3.1 The PV Curves

PV curves can be used to measure the system stability. At a load bus, PV curve can be achieved by increasing the active power absorbed by the load and monitor what happens to the voltage. Then the voltage is plotted versus power to obtain a shape which is sometimes called the “nose curve” [1].

The projection of the surface on the (P,V) plane generates the curves known as PV curves or ‘nose’ curves (Figure 2.4), which depict the relationship between the active power transmitted and the bus voltage. The edge of the curves is the maximum active power that can be transmitted over the line and is considered as the voltage collapse point. A first interpretation of the ‘nose’ curves is that for each load there are two operating conditions. However, normal operation is always on the upper part, since the lower solution yields voltages away from the nominal value and higher currents, which results in unacceptable high transmission losses [4]. Moreover, the operation at the lower part of the curves is unstable due to load demand restoration mechanisms. The multiple ‘nose’ curves represent the different types of load and/or the degree of load compensation which yield a different power factor. The problem that arises from load compensation is that curves are shifted upwards, thus implying that the voltage collapse point can be near the normal operational voltage, making it, subsequently, hard to detect the proximity to voltage instability. The shaded area illustrates operation within the normal voltage range and stresses out that the high compensation of load can cause the voltage collapse point to lie within the span of nominal voltage operation.

In order to understand the relation between voltage and power, the system Thevenin equivalent circuit is presented in Figure 2.1. It consists of the equivalent voltage source (E), equivalent reactance (X) and the load by considering a lossless network.

Voltage stability depends on the relationships between P, Q, and V. In complex practical power systems, many factors contribute to the process of system collapse because of voltage instability: strength of transmission system, load characteristics, power-transfer levels, generator reactive power capability limits, and characteristics of reactive power compensating devices. In many cases of poor transmission networks, the problem is compounded by uncoordinated action of various protective systems, controls and operation.

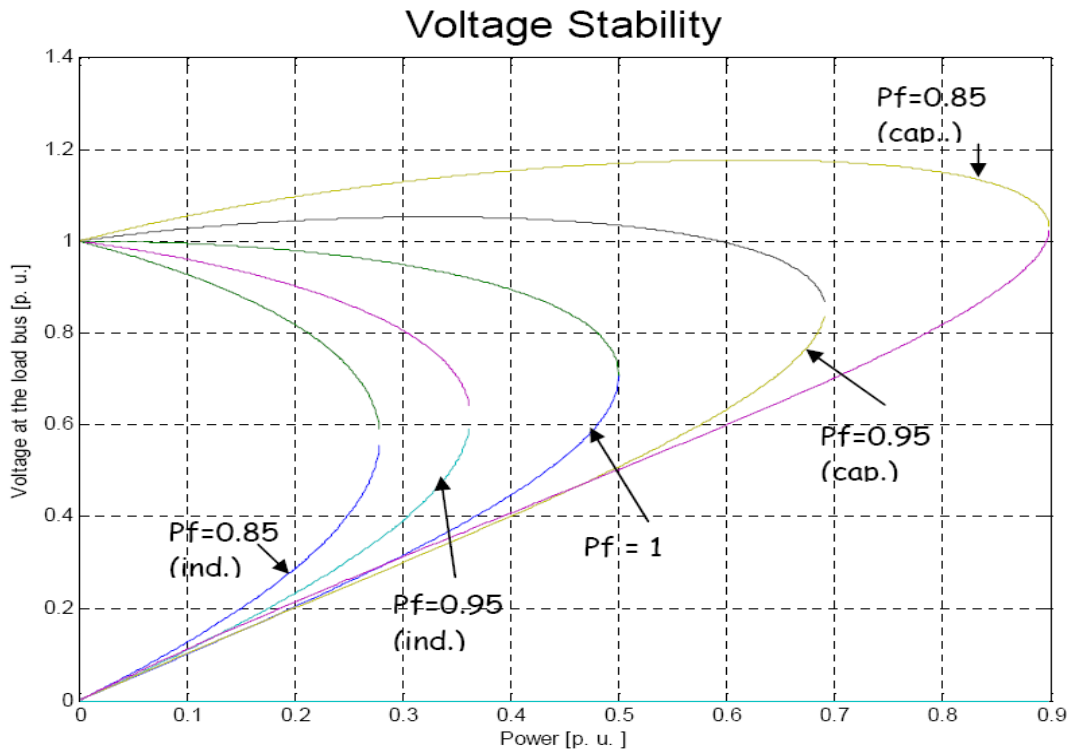


Figure 2-3: Voltage versus Power (Nose) curve for various load power factors [1]

### 2.2.3.2 The QV Curves

The QV curve expresses the relationship between the reactive support  $Q_c$  at a given bus and the voltage at that same bus. They are used to determine the MVar distance from the operating point to the critical voltage, and are more general method of assessing voltage stability. They are used by utilities as a pillar for voltage stability analysis to determine the proximity to voltage collapse and to establish system design criteria based on Q and V margins determined from the curves. QV curve can be determined by connecting a synchronous condenser (fictions generator) with zero active power and recording the reactive power  $Q_c$  produced at the terminal voltage V is being varied [1]. The voltage set-point of this generator is varied and its Var output is allowed to be any value needed to meet this voltage set-point. The vertical axis of figure 2.4-A of the QV curve below depicts the output of the fictitious generator in MVar. The horizontal axis represents the respective voltage under this condition.

QV curves can help determining the amount of reactive compensation needed to either restore the operating point or obtain a desired voltage. The QV curves have been produced by

successive power-flow calculations with a variable reactive power source at the selected bus and recording its values required to hold different scheduled bus voltages [11].

A typical QV curve is shown in Figure 2.4-B. It shows the sensitivity and variation of bus voltages with respect to reactive power injections or absorptions. Scheduling reactive loads rather than voltage produces QV curves. These curves are a more general method of assessing voltage stability. Operators may use the curves to check whether the voltage stability of the system can be maintained or not take suitable control actions [12].

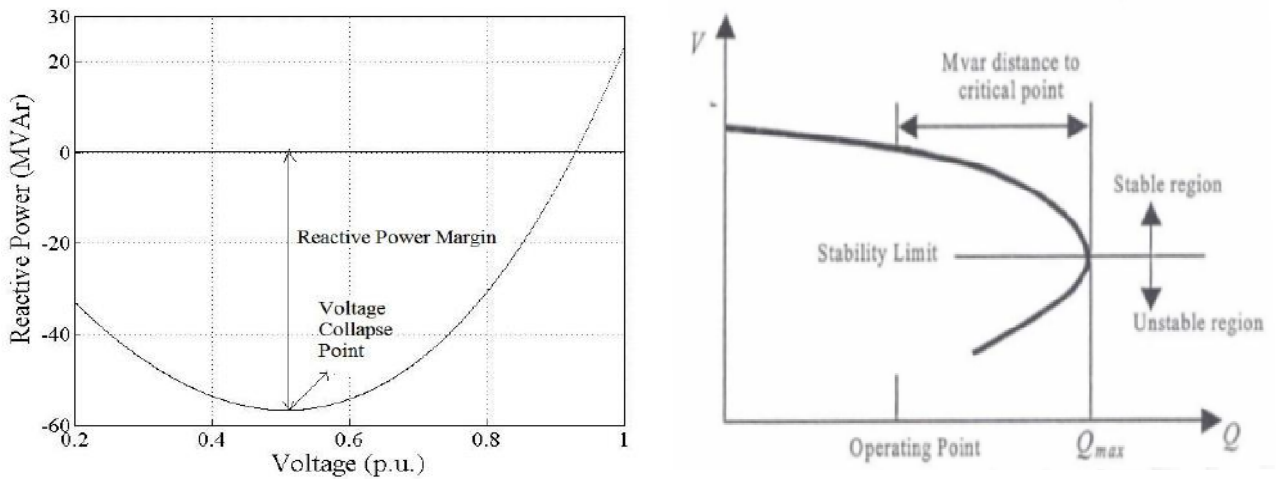


Figure 2-4: Voltage versus Reactive Power curves (A and B)

As a traditional solution in system planning and operation, the voltage level is used as an index of system voltage instability. If it exceeds the limit, reactive support is installed to improve voltage profiles. With such an action, voltage level can be maintained within acceptable limits under a wide range of MW loadings. In reality, voltage level may never decline below that limit as the system approaches its steady state stability limits. Consequently, voltage levels should not be used as a voltage collapse warning index.

In Figure 2.4-B, the Q axis shows the reactive power that needs to be added or removed from the bus to maintain a given voltage at a given load. The reactive power margin is the MVAR distance from the operating point to the bottom of the curve. The curve can be used as an index for voltage instability. Near the nose of a QV curve, sensitivities get very large and then reverse sign. Also, it can be seen that the curve shows two possible values of voltage for the same value of power [9]. The power system operated at lower voltage value would require very high current to produce the power.

That is why the bottom portion of the curve is classified as an unstable region; the system cannot be operated, in steady state, in this region. The top portion of the curve represents the stability region while the bottom portion from the stability limit indicates the unstable operating region. It is preferred to keep the operating point far from the stability limit.

A system is voltage stable if V-Q sensitivity is positive for every bus in the grid and voltage unstable if V-Q sensitivity is negative for at least one bus in the system [2]. The disturbance leading to voltage collapse may be initiated by variety of causes; the primary, problem is an essential weakness in the power system. Operation at or near the stability limit is impractical and a satisfactory operating condition is ensured by allowing sufficient 'power margin' [9]. Voltage stability depends on how variations in Q as well as p in the load area affect the voltages at the load buses. A more useful characteristic for certain aspects of voltage stability analysis is the Q-V relationship, which shows the sensitivity and variation of bus voltages with respect to reactive power injections or absorptions.

### **2.2.4 Voltage Stability Assessment**

There are two different approaches of analyzing voltage stability problem, namely the static approach and the dynamic approach. Static methods are especially important to analyze the power system planning and operation stages to make an adequate plan for meeting the power requirements during peak hours and different types of contingencies, and it involves the static model of the power system components. The dynamic methods analyze the effect of dynamic loads, such as generator over excitation limiters (OXL), Transformer on load tap changers (OLTC), etc. on the voltage collapse [5]. Dynamic methods use time domain simulations to reveal the voltage collapse mechanism, i.e. why and how the voltage collapse occurs.

The practical importance of voltage stability analysis is that it helps in designing and selecting countermeasures which will avoid voltage collapse and enhance stability. Voltage stability analysis has gained increasingly importance in recent years due to:

- Generation being centralized in fewer, larger power plants which means fewer voltage-controlled buses, and longer electrical distances between generation and load;
- Voltage instability caused by line and generator outages;

- Many blackout incidents throughout the world occurred due to voltage instability (e.g. France, Belgium, Sweden, Japan, USA, etc.) [13];
- The operation of a system being closer to its limits;
- The integration of large-scale induction generators; and
- The extensive use of shunt capacitor compensation.

#### 2.2.4.1 Static Analysis

Static analysis (also referred to as load-flow or steady-state analysis) reveals equilibrium points of a system under study. Steady-state stability is defined as the capability of the network to withstand a small disturbance (fault, small change of parameters, topology modification) in the system without leaving a stable equilibrium point [3]. The power flow equations employed in static analysis assume constant system frequency. Voltage stability studies are frequently undertaken through the use of static analysis. A common use of this is the development of PV curves as shown in figure 2.3 above.

The graph is obtained in power-flow simulation by monitoring a voltage at a bus of interest and varying the power in small increments until power-flow divergence is encountered. Each equilibrium point shown represents a steady-state operating condition. In other words, each point may be considered as representing a system that has been in a stable operating point for about half an hour. This means that the generation real-power dispatch and all voltage support equipment have been established such that the system meets criteria for each operating point on the graph up to and including the operating limit point indicated on the graph. Beyond the operating limit, further increase in power may result in an opening of one or more lines. A series of curves can be produced, each one as shown in figure 2.3, with each curve depicting one or more transmission outages.

Given that each operating point on the PV curve represents a unique steady-state operating condition, a pessimistic but realistic generation dispatch is normally employed as load is increased. A post-transient power flow method (also referred to as governor-based power flow method) is used in the case where contingency result in governor action but before system operators have an opportunity to intervene [12].

The loadability limit is defined as the maximum power that the system can transmit. Line capacities, generator capabilities and voltage-dependent load characteristics have to be considered, in order to compute the voltage stability limit [4]. For this purpose, the system is

appropriately modeled and sequential load flow computations are conducted. During each step, the loads are scaled and the procedure is repeated until the load flow algorithm diverges. It can be shown that the divergence of the load flow algorithm takes place, when the operation point is in the proximity of the voltage collapse point [5]. Thus, an estimation of the voltage stability limit is obtained.

Voltage stability static analysis can be achieved through two study methods: Load Flow Feasibility (LFF) and Steady-State Stability (SSS) [6]. The first method, LFF, examines if the voltage profile is acceptable or not after running power flow. It is more related to the transmission lines capacity to transfer the power within the network. On the other hand, SSS method examines if the system is operating at a stable point or not when that system is represented by algebraic and differential equations. These equations are linearized around the operating point in order to obtain the steady state [6].

The amount of corrective measures and application time to be applied for a specified system following a large disturbance cannot be obtained using static analysis.

The static approach using power-flow analysis and sensitivity studies has been extensively studied over the past two decades, whereas the dynamic approach where power system components are modelled by appropriate dynamic equations is still an active area of research. For a general power system, static voltage stability involves the determination of the system loadability limit under pre-disturbance conditions and post-disturbance conditions, the identification of weak buses from the PV curves, and the determination of the amount of corrective measures required at some of these weak buses for a specified system [10].

#### **2.2.4.2 Dynamic Analysis**

Dynamic analysis (also referred to as time-domain analysis) is commonly employed in the study of power system stability to reveal system course after a disturbance [6]. In contrast to static analysis in which equilibria points of a PV curve are not time-dependent, dynamic analysis method reveals the transient and/or the longer-term stability of a power system.

Voltage stability can be classified into short-term and long-term based on time scale of operation. In short-term, the dynamics of fast acting devices such as generators, induction motors, switched capacitors, etc. determines the system performance. However, in long-term

the dynamics of slow acting devices, such as over excitation limiters (OXL) of generators and on load tap changers (OLTC) on the transformers, etc., comes in to effect [12].

When a severe disturbance such as fault, line tripping, etc. occurs, the voltage of some buses reduces drastically. Reduction of system voltage may cause to stall the heavily loaded induction motors and that may ultimately lead to voltage instability.

The voltage instability initiated by an induction motor load belongs to the category of short-term stability. Analysis of such stability requires the results in time domain to understand the mechanism or reason of voltage collapse [4]. System states in time domain also provide the information on the timeline of voltage instability process following a large disturbance.

For the dynamic contingency analysis the system model is adjusted to include load, generators and compensation devices dynamics. The system is subjected to credible disturbances and the system's behavior is simulated by solving the respective differential equations. The ultimate goal is to detect the most critical disturbances, the determining dynamic factors which lead to voltage instability and the response of the system to them.

Dynamic operating modes in interconnected power systems are initiated whenever unexpected changes occur to otherwise steady operating conditions. They arise from momentary imbalances in system operation, which can project the system or individual items of a plant within the system into unplanned operating regions [5]. Continued and safe operation is then momentarily at risk. The nature of the risk is one of operating instability.

### **2.2.5 Real World Blackouts due to Voltage Instability**

Independent system operators (ISO) and power system planners can learn much from real world voltage collapses. Analyzing real blackouts such as the Ethiopian power system involves two problems; the lack of event recorders in the right places about the disturbance, and the difficulty to distinguish between voltage stability and transient stability. There might be other mutual actions which make the system more difficult to understand, such as human interaction, frequency deviation etc. The following experiences gained from real blackouts point out several important properties that are common in many different disturbances.

### 2.2.5.1 Transmission System Limitations

Belgian collapse in August 4, 1982 was initiated by a sudden tripping of one of the few generating units, which resulted in the surrounding area to be exposed to a lack of reactive power and several generators were field current limited. After a while the generators tripped one by one due to protection system operation. At that time, the transmission system was unable to transmit the necessary amount of reactive power to the voltage suppressed area and this caused a continuous voltage decline [10].

Tripping of small generators, which are placed near voltage weak positions, could cause a large increase of reactive power losses in the nearby transmission lines. This causes large voltage drops which can generate stability problems. The 1970 New York disturbance and the disturbance in Denmark 1979 can be examples [10]. In the New York disturbance, tripping of 35 MW generators and an increased loading on the transmission system resulted in a post-contingency voltage decline. At Denmark, a tripping of the only unit in the southern part producing 270 MW caused a slow voltage decline in that area, after 15 minutes the voltages had declined to 0.75pu. Both systems were saved by manual load shedding.

Canada collapse, July 1979: A loss of 100 MW load along a tie-line resulted in an increased active power transfer between the two systems. The generators close to the initial load loss area were on manual excitation control, which aggravated the situation. Due to the increased power transfer, voltages along the tie-line started to fall, hence the connected load decreased proportionally to the voltage squared. About one minute after the initial contingency, the tie-line voltage fell to approximately 0.5pu and the tie-line was tripped due to overcurrent at one end and due to a distance relay at the other.

### 2.2.5.2 Load Behavior Including On-load Tap Changers

On 23 July 1987, Tokyo suffered from very hot weather. Despite the fact that all the available shunt capacitors were put into the system, the voltages started to decay on the 500 kV-system. In 20 minutes the voltage had fallen to about 0.75pu and the protective relays disconnected parts of the transmission network and by that action shed about 8,000 MW of load. Unfavorable load characteristics of air conditioners were thought to be part of the problem.

Sweden, on 27 December 1983, the load behavior at low voltage levels was also a probable source leading to a collapse [10]. Transmission capacity from the northern part of Sweden was

lost due to an earth fault. Virtually nothing happened the first ~50 seconds after the initial disturbance when the remaining transmission lines from the northern part of Sweden were tripped. Since these lines carried over 5,500 MW, the power deficit in southern Sweden was too large for the system to survive. The cause of the cascaded line tripping's was a voltage decline and a current-increase in the central part of Sweden.

The on-load tap changer transformers contributed to the collapse when they restored the customer voltage level. Field measurements performed afterwards in the Swedish network have also shown the inherent load recovery after a voltage decrease [13]. This recovery aggravated the situation when voltages started to decline. The cause of this load recovery in the Swedish network is believed to be due to electrical heating appliances.

### **2.2.5.3 The Influence of Protection and Control Systems**

Almost all voltage instability courses are interrupted by protective relays which are disconnecting parts of the system causing a definite collapse. The Swedish and Tokyo network finally collapsed due to (proper) protective relay operations. The collapse in France in 1987 was aggravated by the fact that many generators were tripped by maximum field current protective relays instead of being field current limited [13]. These show that the importance of taking protection systems into account in the analysis. It also implies the necessity of having a well-tuned control and protection system.

In almost all known collapses there is one contingency (or a series of related contingencies) that triggers a sequence of events causing voltage collapse or an insecure operating situation.

## **2.3 Methods for Improving Voltage Stability**

The control of voltage levels is accomplished by controlling the production, absorption and flow of reactive power at all levels in a system [7]. Keeping the bus voltages close to their nominal value is necessary in order the entire power system to function properly. In transmission networks, a large-scale centralized power plant keeps the node voltages within tolerable voltage range and the number of dedicated voltage control devices is limited. Methods for improving voltage stability include reactive power compensation, Generators AVR, under load tap changer, and load shedding during contingencies [14]. In this section, the reactive compensation methods for improving voltage stability are discussed.

Distribution grids integrate dedicated equipment for voltage control and the distributed generations (DGs) are hardly involved in controlling the node voltages. Mostly tap-changer transformers, and switched capacitors and reactors are used for voltage control in distribution grids. The increased use of wind turbines (WTs) for generating electricity is a challenge for the traditional approach. When large-scale wind farms are connected to the grids, it will be difficult to maintain node voltages using the outdated reactive power control devices. In these cases, equipment such as flexible AC transmission system (FACTS) devices will have to be used as well. FACTS devices offer fast and reliable control over the three AC transmission system parameters, i.e., voltage, line impedance and phase angle, and make it possible to control voltage stability dynamically [7].

### **2.3.1 Determination of Critical Bus or Busses**

A key element of voltage stability studies is the determination of a critical bus or a group of critical busses. These buses can then be monitored as they will invariably form the electrical centroid of a voltage collapse.

In a radial transmission system consisting of a generator serving several loads along a transmission line, the critical or weak bus is generally located electrically and physically furthest away from the generator. In a networked or meshed transmission system, finding the weakest bus or a cluster of weak busses is not an intuitive. Industry experience has demonstrated that the weakest bus or set of busses are generally located in locations with reactive power deficiencies.

The critical bus exhibits one or more of the following characteristics under the worst single or multiple contingency:

- has the highest voltage collapse point on the V-Q curve,
- has the lowest reactive power margin
- has the greatest reactive power deficiency,
- has the highest percentage change in voltage

### **2.3.2 Reactive Compensation**

In order to achieve efficient and reliable operation of power system, the control of voltage and reactive power should satisfy the following objectives [9]:

- Voltages at all terminals of all equipment in the system are within acceptable limits,
- System stability is enhanced to maximize utilization of the transmission system,
- The reactive power flow is minimized so as to reduce  $RI^2$  and  $XI^2$  losses.

As load varies, the reactive power requirements of the transmission system vary. Since reactive power cannot be transported over long distances, voltage control has to be made by using reactive compensation devices located throughout the power system. The proper selection and coordination of equipment for controlling reactive power and voltage stability are among the major challenges of power system engineering [15].

Reactive compensation equipment is used as a voltage stability improvement and is to be differentiated from load compensation devices which are used for load power factor improvement [15]. If the reactive power of a power system is not enough to support the terminal voltage of the buses, it can be supported using reactive compensation equipment. The main purpose of the compensation devices within the transmission system is to provide the system with adequate reactive power in order for the voltages to remain within normal operation limits.

As side effect compensation devices reduce the line currents and thus, the transmission losses. The inherent nature of the transmission system is inductive (transmission lines, motor loads etc.) and, hence, capacitors are used as compensation devices [15]. However, in case of low load conditions, inductive compensation could be necessary. Mainly, there are two types of compensation methods:

1. Line series compensation is the arrangement where the compensation devices (capacitors) are placed in series, so as to reduce the impedance of the transmission line. The reactive power produced is  $Q = XI^2$ , and the direct effect is a net reduction of the transmission's line reactive power demand, and subsequently an increase in the active power that can be transmitted over the line [4]. Series capacitors are used in cases where power has to be transmitted over long distances, such as remote generation and load centers.
2. Shunt compensation is the disposition of reactor or capacitor banks with a reactive power absorption/injection of  $Q = BV^2$ . The drawback of shunt compensation is that in case the compensation device is saturated and the voltage can no longer be kept steady, the reactive power supply decreases with the square of the descending voltage [15]. Shunt

compensation can either be mechanically switched which has a relatively slow response time, or voltage controlled which acts in faster time scales. Shunt compensation is easier to install and is used in problematic, in terms of voltage and power factor, areas, such as load centers or near generating units [4].

In order to cover the additional demand for reactive power and maintain voltage stability within the target range, various sources of reactive power, such as SVC (Static Var Compensator) and STATCOM (Static Compensator) are used.

### **2.3.3 Voltage Stability and FACTS Devices**

Voltage instability is mainly associated with a reactive power imbalance. Improving a system's reactive power-handling capacity via FACTS devices is a solution for the prevention of voltage instability and voltage collapse [7]. FACTS are able to change the grid parameters; series and shunt impedances, and voltage and current values that control the transmission lines operation. FACTS offer operation flexibility such as increasing the maximum line transfer capacity, increasing the bus voltage profiles and reducing the transmission line losses [6].

FACTS devices have been installed in power systems and can be utilized to control power flow and improve system stability. For a better utilization of existing power systems, i.e. to increase their capacities and controllability, installing FACTS devices becomes vital.

In the present situation, there are two main aspects that should be considered when using FACTS devices: the flexible power system operation according to their power flow control capability; and improvements in the transient and steady-state stability of power systems [7]. FACTS devices are the right equipment to meet these challenges and different types are used in different power systems.

More smoothly controlled, and faster, reactive support than mechanically switched capacitors can be provided by true dynamic sources of reactive power such as static Var compensators (SVCs), static synchronous compensators (STATCOMs), synchronous condensers and generators [6]. There are two main types of parallel FACTS; Static Var Compensator (SVC) and Static Synchronous Compensation (STATCOM). Below sections explain these two types.

### 2.3.3.1 Static Var Compensator (SVC)

SVC is composed of parallel combinations of thyristor controlled reactors (TCRs) and thyristor switched capacitors (TSCs). TCR is composed of reactance in series with power electronics (thyristors) in order to do the required switching to adjust the value of the reactor. This device consumes the reactive power and hence, it is used to reduce the voltage in case of having overvoltage condition in the system [7]. On the other hand, TSC is composed of a capacitance that is connected in series with power electronics (thyristors) in order to do the required switching either to switch the capacitor on or off. TSC injects the reactive power to the system and hence, it is used to upgrade the voltage in case of having bus under-voltage [7].

Hence, SVC has the ability to operate based on a control algorithm to keep the voltage stable as shown in Figure 2.4. That means SVC can reduce the voltage at a bus by absorbing reactive power from the system through TCRs and it can upgrade the voltage by injecting reactive power to the system through TSCs [6].

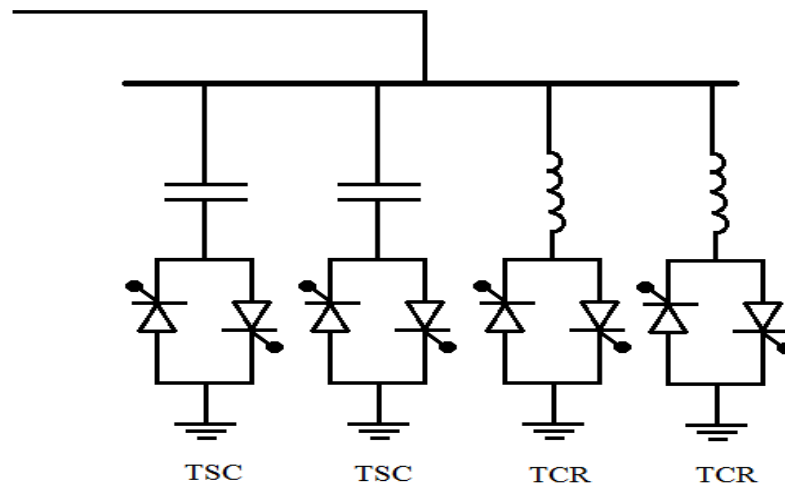


Figure 2-5: The layout of an SVC [6]

### 2.3.3.2 Static Synchronous Compensation (STATCOM)

STATCOM as shown in Figure 2.6 is composed of fixed capacitor and voltage source convertor (VSC) to convert the DC output of the capacitor to AC. The voltage source convertor is composed of power electronics (mainly thyristors) that will do the required switching according to the required pulse width modulation. STATCOM is connected in parallel to the bus where the compensation is required and it can provide active and reactive power to the network which makes it different from SVC [6, 7].

In addition, FACTS can improve the stability, loadability and reliability of the system since the area under the power angle curve will be increased by using FACTS. This can be done without performing any change in generation schedules or network topology [7].

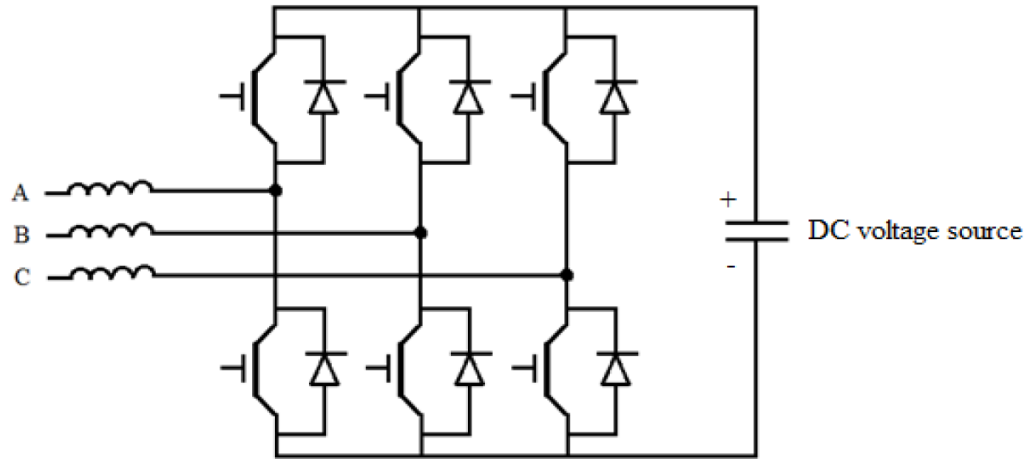


Figure 2-6: The layout of STATCOM [6]

## 2.4 The PSS/E Program

### 2.4.1 Introduction

Power System Simulator for Engineering (PSS/E) is an integrated, interactive program for simulating, analyzing, and optimizing power system performance and provides probabilistic and dynamic modeling features. The software provides for transmission planning and engineers a tool for use in the design and operation of reliable networks.

PSS/E is composed of a comprehensive set of computer programs and structured data files for studies of power system transmission network and generation performance in both steady-state and dynamic conditions [10]. PSS/E model is designed to handle the basic functions of power system performance simulation work, namely:

- Data handling, updating, and manipulation
- Power Flow and Optimal Power Flow
- Fault Analysis
- Dynamic Simulations
- Extended Term dynamic Simulations
- Open network Access and Price calculation

- Equivalent Construction

Since its introduction in 1976, the PSS/E tool has become the most comprehensive, technically advanced, and widely used commercial program of its type. It is widely recognized as the most fully featured, time-tested and best performing product [6]. The program employs the latest technology and numerical algorithms to efficiently solve small and large networks.

## 2.4.2 PSS/E Structure

The program contains a set of modules which handle different power system analysis and operate from the same set of data whose structure is divided into four different “working files”. These working files are set up in a way that optimizes the computational aspects of the key power system simulation functions: network solution and equipment dynamic modelling. Depending on the study type, the user has a variety of ways of operating PSS/E. The modules used for voltage collapse simulations are *Power flow*, *Dynamic simulation*, and *Extended Term Dynamic simulation* [10]. PSS/E integrates the modules into a single package centered on the power flow case. Furthermore, the modules operate on the same set of data through the working files.

The four working files have the following names and general functions [10]:

- LFWORK- Contains a complete set of power flow data (Load Flow Working file).
- FMWORK- Working file for all operations involving the factorized system admittance matrix (Factorized Matrix Working file).
- SCWORK- Working file for fault analysis (Short Circuit Working file).
- DSWORK- Scratch file for dynamic simulation activities (Dynamic Simulation Working file).

PSS/E is comprised of the following modules:

- PSS/E Power Flow:** This module is basic, powerful and easy-to-use for basic power flow network analysis. Besides analysis tool it is also used for Data handling, updating, and manipulation. To calculate a steady state solution in PSS/E, one can use either the Gauss-Seidel or the Newton-Raphson algorithm. PSS/E allows the user to choose from five different ac power flow iteration schemes. These are:
  - Gauss-Seidel iteration

- Modified Gauss-Seidel iteration suitable for series capacitors
- Fully coupled Newton-Raphson iteration
- Decoupled Newton-Raphson iteration
- Fixed slope Decoupled Newton-Raphson iteration

There are many problems which are difficult to solve with a single iterative method but which can readily be solved by successive application of more than one method. Therefore, it may be noted that: a) Gauss-Seidel methods are quite tolerant of poor starting voltage estimates but converge slowly as the voltage estimate gets close to the true solution. b) Newton-Raphson methods are prone to failure if given poor starting voltage estimate, but are usually superior to Gauss-Seidel methods once the voltage solution has been brought close to the true solution [10].

**ii) PSS/E Optimal Power Flow (PSS/E OPF):** It is a powerful analysis tool that goes beyond traditional load flow to fully optimize and improve a transmission system. PSS/E OPF improves the efficiency and throughput of power system performance studies by adding intelligence to the load flow solution process [10].

PSS/E OPF directly changes controls to quickly determine the best solution. From virtually any reasonable starting point, you are assured that a unique and globally optimal solution will be achieved; one that simultaneously satisfies system limits and minimizes costs or maximizes performance.

**iii) PSS/E Balanced or Unbalanced Fault Analysis:** The PSS/E Fault Analysis (short circuit) program is fully integrated with the power flow program. The system model includes exact treatment of transformer phase shift, and the actual voltage profile from the solved power flow case.

**iv) PSS/E Dynamic Simulation:** PSS/E offers users inflexible dynamic simulation capabilities. It models system disturbances such as faults, generator tripping, motor starting and loss of field. The program contains an extensive library of generator, exciter, governor, and stabilizer models as well as relay model including under-frequency, distance and overcurrent relays to accurately simulate disturbances [10]. To simulate voltage collapse, it is important to choose a numerical integration method which combines reasonable computational time with good precision.

## Chapter Three

### 3 Modeling of the Ethiopian Transmission Grid

#### 3.1 Existing Ethiopian Power System

The former Ethiopian Electric Power Corporation (EEPCO) is split in to two companies, i.e. the Ethiopian Electric Power (EEP) and the Ethiopian Electric Utility (EEU). EEP is responsible for the construction and operation of generation, transmission, and substations with the voltage levels of 132 kV, 230kV, 400kV, and 500kV. EEU mainly focuses in the distribution and retail of electricity supply to end consumers. The sub-transmission i.e. with voltage levels of 66kV and 45kV and the distribution system with 33kV, and 15kV are managed by EEU.

The Ethiopian transmission Interconnected System (ICS) which feeds the major cities, towns and industrial zones links the major generation to the load centers via transmission lines at 400kV, 230kV and 132kV and sub-transmission lines at 66kV and 45kV. The system frequency is 50 Hz. There are a total of 162 substations across the system; and generating plants of 12 hydro, 3 wind farms, 1 geothermal, and 3 diesel plants and 146 transmission substations, of which 8 are at 400 kV, 33 at 230 kV, 63 at 132 kV, 30 at 66 kV and 12 at 45 kV level. The total circuit lengths of transmission and sub-transmission lines on the existing system are shown in Table 3.1. EEP/EEU plans to phase out 45 kV in favor of 66 kV and/or 132kV and also to replace some 66 kV lines with 132 kV [16]. A map of the existing system and the planned transmission projects up to 2018 is shown in Figure 3.1.

*Table 3-1: Total circuit lengths (km) of existing transmission lines in Ethiopia*

<b>No.</b>	<b>Voltage Level (kV)</b>	<b>Total Circuit length (km)</b>
1	400kV Transmission Lines	1,311.3
2	230kV Transmission Lines	7,157.88
3	132kV Transmission Lines	4,449.34
4	66kV Transmission Lines	1,901.6
5	45kV Transmission Lines	376.4
	<b>Total</b>	<b>15,195.52</b>

There are a number of ‘off-grid’ areas which are supplied by small-scale diesel or hydro generation feeding isolated distribution networks. These supplies are collectively known as the Self Contained System (SCS). The total installed generation capacity of the SCS is 34 MW of which 6.2 MW represents the small hydro contribution. The ICS is being progressively extended to include these areas. The single line diagram of Ethiopian ICS Network is shown in Appendix A.

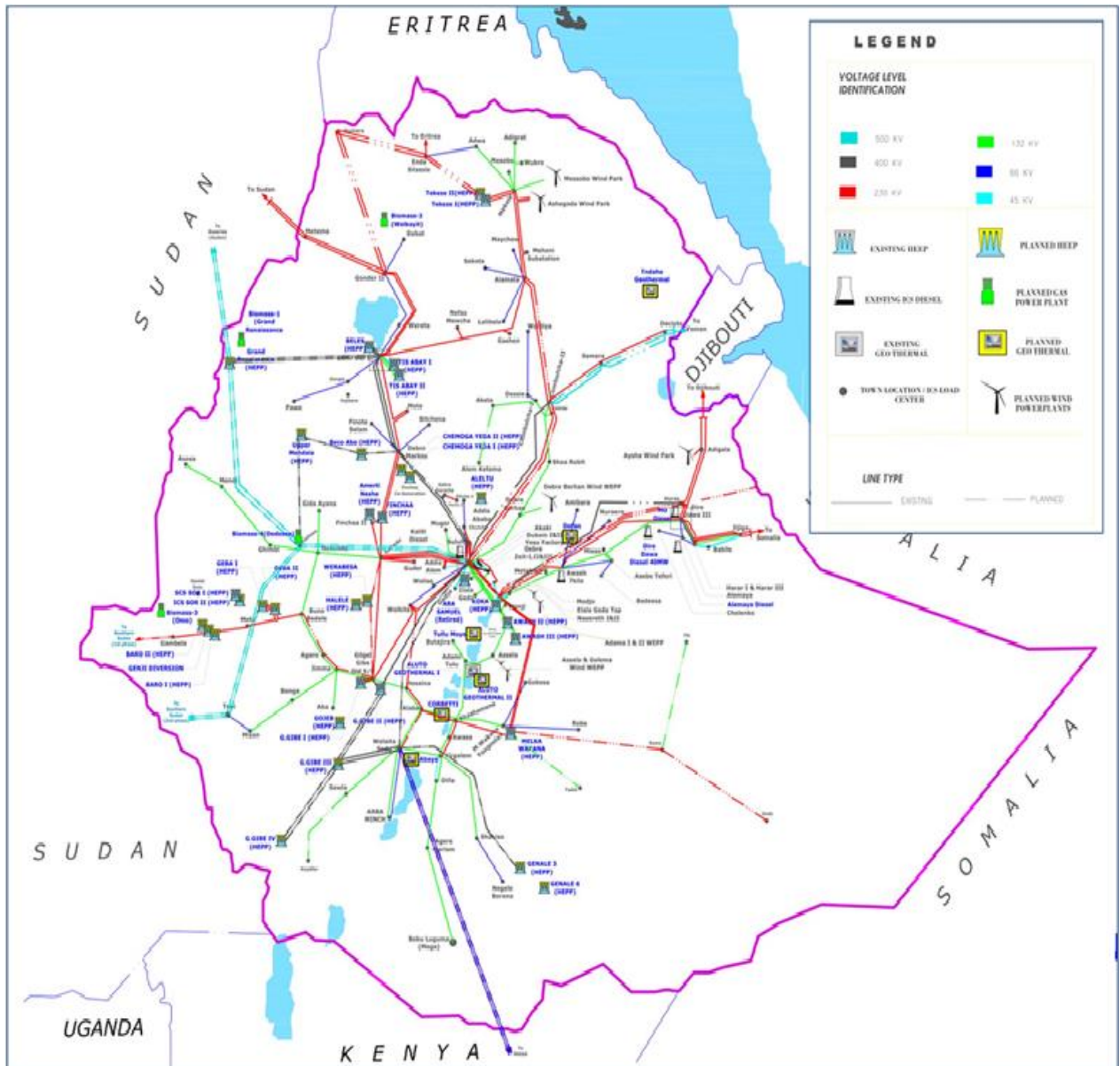


Figure 3-1: Map of Ethiopian power plants and transmission lines [16]

### 3.1.1 Generating Plants in Ethiopian Power System

Ethiopia is a country with a very high hydropower potential, with only a fraction of this potential having been harnessed. In 2009 and 2010 three hydro plants; Tekeze, Beles and Gilgel Gibe II, were commissioned that doubled the 2008 installed capacity of the country [17]. Since then the Government of Ethiopia (GoE) has created a Growth and Transformation Plan (GTP) to boost the country's economy and contracts for more large dams have been signed. Ethiopia is striving to be the power hub of Africa by exporting electricity to neighboring countries.

The generation plants connected to the ICS in 2016 had a total installed capacity of 4,111MW, and in 2012 it was 2124MW installed capacity (i.e. available capacity of 1871 MW) [17]. The available generating plants in 2016 are listed below:

- 12 hydro power plants (Koka, Awash II and III, Tis Abay II, Finchaa, Melka Wakena, Gilgel Gibe I and II, Tekeze, Amerti Neshe, Tana Beles, and the newly inaugurated Gilgel Gibe III).
- 3 medium sized diesel power plants (Kaliti, Awash and Dire Dawa)
- 3 wind farms (Adama I and II, and Ashegoda),
- 1 geothermal plant (Aluto Langano)

In 2016, the installed hydropower capacity is around 3.79GW with the above 12 existing hydro plants and the installed wind energy capacity is 324MW. When the committed GERD projects are commissioned, the installed capacity will exceed 10GW.

Gilgel Gibe III is finished and came in to operation in April 2016 with an installed capacity of 1870MW. It is connected to Gelan substation through Wolaita Sodo-II substation and also connected to Gilgel Gibe II PP. This power plant strengthens and used as a voltage sources for the weak part of the southern corridor. The construction of GERD project started in 2011 and currently about 60% of its construction work had been finished.

In 2012, the peak MW generation (including Ethiopian peak demand, losses and exports) was 1377MW, and in 2016 the peak MW demand load reaches 2200MW [16].

Table 3-2: List of generating plants in Ethiopian grid

No.	Power Plant Name	No. of Units	Capacity (MW)	$S_n$ (MVA)	Type	$U_n$ (kV)	$Q_{min}$ (MVar)	$Q_{max}$ (MVar)
1	Gilgel Gibe III	10	1870		Hydro	15		
2	Beles	4	460	532	Hydro	15		
3	Gilgel Gibe II	4	420	500	Hydro	15	-200	200
4	Tekeze	4	300	346.8	Hydro	13.8	-152	152
5	Gilgel Gibe I	3	184	219	Hydro	13.8	-63	63
6	Melka Wakena	4	153	180	Hydro	13.8	-136.5	125.45
7	Finchaa	4	128	140	Hydro	13.8	-82	65
8	Amerti Neshe	2	98	106	Hydro	13.8		
9	TIS ABAY II	2	68	80	Hydro	10.5	-16	13
10	Koka	3	42	54	Hydro	10.5	-42	36.7
11	Awash II	2	32	40	Hydro	10.5	-30	26
12	AWASH III	2	32	40	Hydro	10.5	-30	26
13	Adama Wind II		153	180	Wind	33	-75	75
14	Ashegoda		120		Wind	15	-30	30
15	Adama Wind I		51	60	Wind	33	-30	30
16	Awash 7Kilo		30	43.75	Diesel	11	-35	35
17	Dire Dawa		40	50	Diesel	15	-40	40
18	Kaliti I		14	17.5	Diesel	11	-14	14

### 3.1.2 Existing 400 kV Network

The 400 kV network is currently limited to few transmission lines and substations, and is adopted with the construction of Gilgel Gibe II and Beles power plants. These include;

- Interconnection between Gilgel Gibe II power plants and Sebeta II substation in the Southwest of Addis Ababa (i.e. Sekoru (New Gibe) - Gilgel Gibe II- Sebeta II), and in 2015 Sebeta II substation is linked with the new Gelan substation around Addis Ababa.
- Interconnection between Tana Beles power plant, Bahir Dar II, Debre Markos, and Sululta substations to the Northwest of Addis Ababa, and
- The newly finished double circuit line interconnecting Gilgel Gibe III power plant and Wolaita Sodo II substation then to Gelan substation around Addis Ababa. And another single circuit line from Wolaita Sodo to Gilgel Gibe II (Sekoru) substation that connects the two power plants i.e. Gilgel Gibe II & III.

### 3.1.3 Existing 230 kV Network

The 230 kV network is mainly used as the backbone of the transmission system that links the major power plants with the load centers. The 230 kV network includes;

- An incomplete ring around Addis Ababa, including; Sululta, Gefersa, Sebeta I & II, Kaliti I, Legetafo, and Gelan as shown in Figure 3.3.
- North-western corridor, including interconnection with Finchaa and Amerti Neshe power plants, via Gefersa and Ghedo substations; and with Beles power plant via Debre Markos, Mota, Bahir Dar II and interconnection to Sudan via Gondar and Shehedi (Metema).
- Northern corridor including Legetafo, Combolcha II, Alamata, Mekhoni, Ashegoda Wind, Mekelle and Tekeze power plant, and expands to Endasilassie and Humera.
- South-western corridor, including Sebeta, Wolkit, Gilgel Gibe I, and expands to Jimma, Agaro, Bedelle, and Metu substations.
- A link between Addis Ababa and power plants to the Southeast including Koka, Adama II Wind, and Melka Wakena, and expands to Ramo and Gode substations.
- Interconnection between Koka, Hurso and Dire Dawa III, in the Easter, with onward interconnection to Djibouti directly from Dire Dawa III and via Adigala substation.
- A 230 kV transmission line between Bahir Dar and Alamata interconnects the Northwestern and Northern corridors.
- A 230kV transmission line between Ghedo and Sekoru (New Gibe) interconnects the South Western and the north western corridors.
- A 230kV transmission line that interconnects Southern and South western corridors is constructed between Hossaina, Alaba, and Melka Wakena Yugoslav.
- Extension of the network to the southwest including; Melka Wakena-Alaba-Hossaina-Wolkite and Gilgel Gibe-Jimma-Agaro-Bedelle-Metu-Gambela

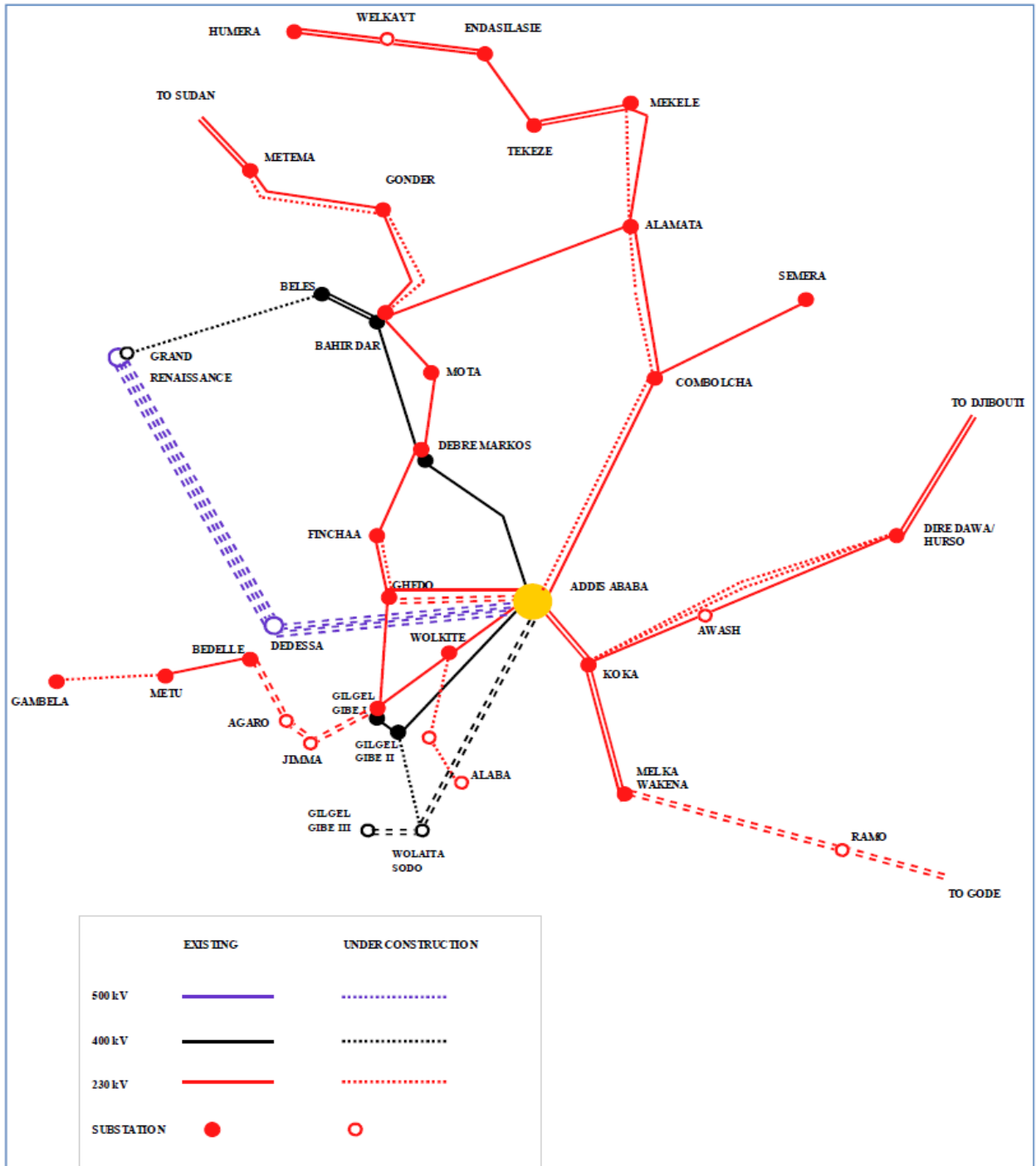


Figure 3-2: Existing 400 and 230kV transmission network [16]

The transmission line parameters for the 400kV and 230kV lines, their voltage levels, conductor size, length (km), and tower configuration in the grid is listed in table 3.2 below.

Table 3-3: List of 400kV and 230kV transmission lines in Ethiopian Grid

No.	Transmission Line Name	Voltage (kV)	Conductor Type	Tower Config.	Length (km)	Line Rating (MVA)
1	Gilgel Gibe2 PP- Sebeta II	400	Twin Aster 851	Single	183.5	1341
2	Gilgel Gibe2 PP- Sekoru (New Gibe)	400	Twin Aster 851	Single	27.9	1341
3	Sululta - Debre Markos	400	Twin Aster 851	Single	215.6	1341
4	Debre Markos - Bahir Dar II	400	Twin Aster 851	Single	193.7	1341
5	Beles PP - Bahir Dar2 Line 1	400	Twin Aster 851	Double	62.8	1341
6	Beles PP - Bahir Dar2 Line 2	400	Twin Aster 851	Double	62.8	1341
7	Sebeta II – Gelan	400	Twin Aster 851	Single	33	1341
8	Gilgel Gibe3- Wolaita Sodo2 L1	400	Quad Dove	Single	51	1341
9	Gilgel Gibe3- Wolaita Sodo2 L2	400	Twin Aster 851	Single	51	1341
10	Gilgel Gibe3- Wolaita Sodo2 L3	400	Twin Aster 851	Single	51	1341
11	Wolaita Sodo2 – Gelan	400	Twin Aster 851	Double	260	1341
12	Wolaita Sodo2 - Gilgel Gibe2	400	Quad Dove	Single	119	1341
					<b>1311.3</b>	
1	Kaliti I - Sebeta I	230	Mallard	Single	14.3	274
2	Kaliti I – Legetafo	230	Twin Ash	Double	34.9	318
3	Legetafo - Combolcha II	230	Twin Ash	Double	287	318
4	Combolcha II – Semera	230	Twin Ash	Double	170	318
5	Semera – Dichito	230	Twin Ash	Single	55	318
6	Combolcha II – Alamata	230	Twin Ash	Double	168.8	318
7	Alamata – Ashegoda	230	Twin Ash	Double	126	318
8	Alamata – Mekhoni	230	Twin Ash	Double	42.6	318
9	Mekhoni – Mekelle	230	Twin Ash	Double	98	318
10	Ashegoda - Mekelle	230	Twin Ash	Double	14.8	318
11	Mekelle - Tekeze PP L1	230	Twin Ash	Double	105	318
12	Mekelle - Tekeze PP L2	230	Twin Ash	Double	105	318
13	Tekeze PP - Enda Silassie	230	Twin Ash	Double	159.5	318
14	Enda Silassie - Humera	230	Twin Ash	Double	229.7	318
15	Alamata - Gashena Tap	230	Twin Ash	Single	102.3	318
16	Gashena Tap - Gashena	230	Twin Ash	Single	1	318
17	Gashena Tap - Nifas Mewcha Tap	230	Twin Ash	Single	102.3	318
18	Nifas Mewcha Tap - Nifas Mewcha	230	Twin Ash	Single	1	318
19	Nifas Mewcha - Bahir Dar II	230	Twin Ash	Single	136	318
20	Bahir Dar II - Gonder II L1	230	Twin Ash	Single	137	318
21	Bahir Dar II - Gonder II L2	230	Twin Ash	Single	137	318
22	Gonder II - Shehedi L1	230	Twin Ash	Double	165	318
23	Gonder II - Shehedi L2	230	Twin Ash	Double	165	318

24	Shehedi - Gadarif (Border) L1	230	Twin Ash	Double	37	318
25	Shehedi - Gadarif (Border) L2	230	Twin Ash	Double	37	318
26	Bahir Dar - Mota	230	Yew	Single	83	280
27	Mota - Debre Markos	230	Yew	Single	111.8	280
28	Debre Markos - Finchaa PP	230	Yew	Single	95.2	280
29	Finchaa PP - Finchaa II	230	Twin Ash	Single	8.3	318
30	Finchaa II - Amerti Neshe PP	230	Twin Ash	Single	29.2	318
31	Finchaa II - Ghedo	230	Twin Ash	Single	69.7	318
32	Finchaa PP - Ghedo	230	ACAR 241	Single	67.2	284
33	Finchaa PP - Ghedo (New Line)	230	Twin Ash	Single	69.7	284
34	Ghedo - Gefersa L1	230	Yew	Single	133.14	284
35	Ghedo - Gefersa L2	230	Twin Ash	Double	133	318
36	Ghedo - Gefersa L3	230	Twin Ash	Double	133	318
37	Ghedo - Sekoru (New Gibe)	230	Mallard	Single	130.8	274
38	Sekoru - Gilgel Gibe1 L1	230	Mallard	Double	5	274
39	Sekoru - Gilgel Gibe1 L2	230	Mallard	Double	5	274
40	Sekoru (New Gibe) - Wolkitie	230	Yew	Single	71	280
41	Wolkitie - Hossaina	230	Twin Ash	Single	89.3	318
42	Hossaina - Alaba	230	Twin Ash	Single	39.5	318
43	Wolkitie - Sebeta I	230	Yew	Single	136.2	280
44	Sebeta I - Sebeta II L1	230	Yew	Double	15	280
45	Sebeta I - Sebeta II L2	230	Yew	Double	15	280
46	Sebeta I - Gefersa	230	Mallard	Single	10.6	274
47	Gefersa - Sululta L1	230	Twin Ash	Double	16.7	318
48	Gefersa - Sululta L2	230	Twin Ash	Double	16.7	318
49	Bedelle - Metu L1	230	Twin Ash	Single	90.5	318
50	Bedelle - Metu L2	230	Twin Ash	Single	90.34	318
51	Kaliti I - Gelan L1	230	Redwing	Double	9.2	257
52	Kaliti I - Gelan L2	230	Redwing	Double	9.2	257
53	Gelan - Koka	230	Mallard	Double	56.8	274
54	Gelan - East Ind. Zone Tap	230	Redwing	Double	23.8	257
55	East Ind. Zone Tap- East Ind.Zone	230	Redwing	Double	1	257
56	East Ind. Zone - Koka	230	Mallard	Double	33	274
57	Koka - Melka Wakena PP L1	230	Redwing	Double	164	257
58	Koka - Melka Wakena PP L2	230	Redwing	Double	164	257
59	Koka - Adama Wind II	230	Twin Ash	Single	12.5	318
60	Koka - Dire Dawa III	230	Mallard	Double	335.1	274
61	Koka - Hurso	230	Twin Ash	Double	315	318
62	Koka - Hurso	230	Twin Ash	Double	315	318
63	Melka Wakena - Wakena Yugoslav	230	Twin Ash	Double	5	318
64	Dire Dawa III - Adigala	230	Twin Ash	Single	120	318

65	Adigala - PK-12	230	Twin Ash	Single	167	318
66	Dire Dawa III - PK-12	230	Twin Ash	Single	277	318
67	Wakena Yugoslav - Ramo (Raitu)	230	Twin Ash	Double	222.4	318
68	Ramo (Raitu) - Gode	230	Twin Ash	Double	296	318
69	Sekoru (New Gibe) - Jimma	230	Twin Ash	Double	65.6	318
70	Jimma - Agaro	230	Twin Ash	Double	38.7	318
71	Agaro - Bedelle	230	Twin Ash	Double	81.5	318
72	Metu - Gambella	230	Twin Ash	Single	150	318
	<b>230 kV Total Length (km)</b>				<b>7157.88</b>	

### **3.1.4 Existing 132 kV Network**

In the past 132 kV lines has been used extensively for transmission, however in many parts of the network, due to extension of the 230 kV systems, 132 kV is now effectively used more for sub-transmission along with 66 kV and 45 kV. But still the length of 132kV lines in the system is more than 230kV. The 132kV network includes:

- Transmission lines from Kaliti-I, Sebeta-I, Gefersa, and Legetafo to different substations around Addis Ababa as well as Muger and Derba cement factories mostly in radial fashion, and making partial ring network.
- Transmission lines around the southern parts of Ethiopia, i.e. Shashemene, Awassa, Arba Minch, Dilla, Yirgalem, Sawla, Qey Afer, Hagere Mariam, Shakisso, Bukuluguma etc.
- Transmission lines from Ghedo to Guder, and Nekemte, Gida Ayana, Ghimbi, Mendi, Assosa etc.
- Transmission lines from Koka, Awash, Debre Zeit, Wonji, Nazareth, Metehara, Assela, Adamitulu, Butajira, etc.
- Transmission lines from Mekelle, Messobo, Wukro, Adigrat, Adwa etc.
- Transmission lines from Dire Dawa III to Dire Dawa I & II, Harar, Jigjiga, Fiq etc.
- Transmission lines from Legetafo, Debre Birhan, Shoa Robit, Combolcha-I, Alem Ketema, Akista etc.

Transmission line data of Ethiopian high voltage grid has been collected for 149 line type branches and rearranged as follows.

Table 3-4: Existing 132 kV Transmission Network

No.	Transmission Line Name	Voltage (kV)	Conductor Type	Tower Config.	Length (km)	Line Rating (MVA)
1	Kaliti I - Addis Center	132	Tiger	Single	14.4	82
2	Kaliti I - Kaliti II	132	Tiger	Single	7	82
3	Kaliti I - Kaliti North Tap	132	Tiger	Single	1.5	82
4	Kaliti I - Mekanissa	132	Tiger	Single	16.2	82
5	Kaliti I - Weregenu Tap	132	Tiger	Single	17.5	82
6	Kaliti I - Yesu	132	Ash	Single	9	91
7	Kaliti I - Gelan L1	132	Tiger	Single	9.2	82
8	Kaliti I - Gelan L2	132	tiger	Single	9.2	82
9	Kaliti I - Gefersa	132	Tiger	Single	24.8	82
10	Kaliti2 - Nifas Silk Line 1	132	Ash	Double	3	91
11	Kaliti2 - Nifas Silk Line 2	132	Ash	Double	3	91
12	Kaliti North Tap - Kaliti North	132	Tiger	Single	0.44	82
13	Weregenu Tap - Weregenu	132	Tiger	Single	4.5	82
14	Kalti North Tap - Cottobie	132	Tiger	Single	18.7	82
15	Weregenu Tap - Cottobie	132	Tiger	Single	2.5	82
16	Cottobie - Bela ( Addis East II)	132	Ash	Single	5.5	91
17	Cottobie - Legetafo	132	Tiger	Single	8	82
18	Legetafo - Debre Birhan	132	Tiger	Single	100	82
19	Debre Birhan - Shoa Robit	132	Tiger	Single	57.5	82
20	Shoa Robit - Combolcha II	132	Tiger	Single	129.5	82
21	Combolcha II - Combolcha I	132	Ash	Single	7	91
22	Combolcha I - Akista	132	Ash	Single	106	91
23	Akista - Alem Ketema	132	Ash	Single	150.2	91
24	Bela (Addis East II) - Addis North	132	Ash	Single	9.9	91
25	Addis North - Gefersa	132	Tiger	Single	11.1	82
26	Gefersa - Derba Tap	132	Ash	Single	62	91
27	Derba Tap - Derba Cement	132	Ash	Single	49.5	91
28	Derba Tap - Muger	132	Ash	Single	18	91
29	Gefersa - Sebeta I Tap	132	Tiger	Single	10.8	82
30	Sebeta I Tap - Sebeta I	132	Tiger	Single	1	82
31	Sebeta I Tap - Mekanissa	132	Tiger	Single	7.8	82
32	Mekanissa - Gofa (Addis South2)	132	Ash	Single	2	91
33	Ghedo - Guder	132	Ostrich	Single	34	89
34	Ghedo - Nekemte	132	Ostrich	Single	116	89
35	Nekemte - Gida Ayana	132	Ash	Single	93.6	91
36	Nekemte - Bedelle	132	Ash	Single	116	91
37	Nekemte - Ghimbi	132	Ostrich	Single	84.3	89

38	Ghimbi - Mendi	132	Ash	Single	130	91
39	Mendi - Assosa	132	Ash	Single	80	91
40	Gilgel Gibe I-PP - Old Gibe	132	Ostrich	Single	2.6	89
41	Old Gibe - Sekoru ( New Gibe)	132	Ostrich	Single	0.12	89
42	Sekoru ( New Gibe) - Jimma	132	Ostrich	Single	71.3	89
43	Jimma - Abba	132	Ash	Single	47	91
44	Jimma - Agaro	132	Ostrich	Single	34.8	89
45	Jimma - Bonga	132	Ash	Double	102.3	91
46	Bonga - Mizan	132	Ash	Single	88.3	91
47	Old Gibe - Hossaina	132	Ostrich	Single	70.6	89
48	Hossaina - Alaba	132	Ostrich	Single	39.6	89
49	Alaba - Wolaita Sodo	132	Ostrich	Single	61.8	89
50	Alaba - Shashemene	132	Ostrich	Single	63.2	89
51	Wolaita Sodo - Sawla	132	Ash	Single	124	91
52	Sawla - Qey Afer	132	Ash	Single	111	91
53	Wolaita Sodo - Arba Minch	132	Ostrich	Single	109.1	89
54	Shashemene - Awassa	132	Tiger	Single	21.6	82
55	Shashemene - M/Wakena Yugo	132	Ostrich	Single	119.2	89
56	Shashemene - Adamitulu	132	Tiger	Single	76.8	82
57	Awassa - Yirga Alem	132	Tiger	Single	35.1	82
58	Yirga Alem - Dilla	132	Ash	Single	40	91
59	Dilla - Hagere Mariam	132	Ash	Single	90	91
60	Hagere Mariam - Bukuluguma	132	Ash	Single	170	91
61	Yirga Alem - Shakisso	132	Tiger	Single	133.2	82
62	Adamitulu - Butajira	132	Ash	Single	46.8	91
63	Adamitulu - Assela	132	Tiger	Single	51	82
64	Assela - Awash II PP	132	Tiger	Single	51.2	82
65	Awash II-PP - Awash III-PP	132	Tiger	Double	1.5	82
66	Awash II-PP - Koka PP	132	Tiger	Single	25.4	82
67	Awash II-PP - Wonji Tap	132	Tiger	Single	18	82
68	Wonji Tap - Wonji	132	Tiger	Single	0.6	82
69	Wonji Tap - Koka PP	132	Tiger	Single	7.4	82
70	Melka Wakena Yugo - Yadot	132	Ash	Single	100	91
71	Koka PP - Elala Geda Tap	132	Tiger	Single	23.8	82
72	Elala Geda Tap - Elala Geda	132	Tiger	Single	4.9	82
73	Elala Geda Tap - Gelan	132	Tiger	Single	34.3	82
74	Koka PP - Debre Zeit-II Tap	132	Tiger	Single	38.6	82
75	Debre Zeit-II Tap - Debre Zeit-II	132	Tiger	Single	0.2	82
76	Debre Zeit-II Tap - Gelan	132	Tiger	Single	29.38	82
77	Koka PP - Gelan	132	Tiger	Single	58.7	82
78	Gelan - Yesu	132	Ash	Single	1	91

79	Koka PP - Nazareth	132	Tiger	Single	11.5	82
80	Nazareth - Adama Wind I	132	Ash	Single	4.8	91
81	Nazareth - Metehara Tap	132	Tiger	Single	88.2	82
82	Metehara Tap - Metehara	132	Tiger	Single	0.1	82
83	Metehara Tap - Awash Town	132	Tiger	Single	29.6	82
84	Awash Town - Asebe Teferi I & II	132	Tiger	Single	99	91
85	Dire Dawa III - Dire Dawa I	132	Tiger	Single	3.7	82
86	Dire Dawa III - Dire Dawa II	132	Tiger	Single	12.4	82
87	Dire Dawa III - Dire Dawa Diesel	132	Tiger	Single	3.6	82
88	Dire Dawa II - Harar III	132	Ash	Single	43.8	91
89	Harar III - Jigjiga II	132	Ash	Single	95	91
90	Harar III - Fiq	132	Ash	Single	154	91
91	Mekelle - Messobo	132	Ostrich	Single	5.1	89
92	Mekelle - Wukro Tap	132	Ostrich	Single	31	89
93	Wukro Tap - Wukro	132	Ostrich	Single	1.2	89
94	Wukro Tap - Adigrat	132	Ostrich	Single	56.6	89
95	Mekelle - Adwa	132	Ostrich	Single	116.7	89
96	Bahir Dar II - Tis Abay II PP-L1	132	Ash	Double	29	91
97	Bahir Dar II - Tis Abay II PP-L2	132	Ash	Double	29	91
	132kV Total length (km)				<b>4,449.34</b>	

### 3.1.5 Existing 66 kV and 45 kV Networks

Sub-transmission provides the link between the main transmission system and the distribution systems. The ‘sub-transmission’ voltages on the EEP network are 45 kV and 66 kV. EEP/EEU has around 18 x 45 kV lines with associated substations. The lines range in length from 3 km to 93 km, with the majority less than 20 km long. Most of the 45 kV lines and substations are located in and around Addis Ababa, with a few to the east and north-west of the country.

Across EEP/EEU network there are approximately 34 x 66 kV lines with associated substations.

The lines range in length from 4 km to 146 km, with the majority more than 40 km long.

The 45 kV and 66 kV lines are almost exclusively single circuit construction and supply step-down substations to the 33 kV and 15 kV systems. The substations are equipped with one or two step-down transformers. It is understood that EEP is phasing out 45 kV in favor of 66 kV or 132 kV due to the limited transfer capability of 45 kV lines. In rural areas, 45 kV and 66 kV are being replaced by 132 kV for the same reason.

On relatively short lines, the transmission capability of the line is limited by the thermal rating, while on longer lines, the limitation is due to voltage drop across the line and for a particular conductor size and line length, the transmission capability is therefore proportional to voltage squared ( $V^2$ ). Table 3.5 shows the list of 66kV and 45kV transmission lines in the grid.

*Table 3-5: Existing 66kV and 45kV transmission lines in the grid*

<b>No.</b>	<b>Transmission Line Name</b>	<b>Voltage (kV)</b>	<b>Conductor Type</b>	<b>Tower Config.</b>	<b>Length (km)</b>	<b>Line Rating (MVA)</b>
1	Gefersa - Fiche	66	Merlo	Single	96	24
2	Wolkite - Wolisso	66	Quail	Single	39.2	27
3	Metu - Sor	66	Merlo	Single	24	24
4	Metu - Gambella1	66	Merlo	Single	146	24
5	Gambella1 - Denbidolo	66	Merlo	Single	64	24
6	Gambella2 - Gambella1	66	Merlo	Single	15	24
7	Mizan - Tepi	66	Quail	Single	30.2	27
8	Shakisso - Negele Borena	66	Quail	Single	113.9	27
9	Melka Wakena Yugo - Gobessa	66	Quail	Single	74.2	27
10	Melka Wakena Yugo - Robe	66	ACSR 70/12	Single	72.9	28
11	Alamata - Lalibela	66	Quail	Single	104.9	27
12	Alamata - Sekota	66	Quail	Single	80	27
13	Alamata - Maichew	66	Quail	Single	48	27
14	Adwa - Shire	66	Penguin	Single	66.4	36
15	Combolcha I - Dessie	66	Merlo	Single	12.7	24
16	Dessie - Woldia	66	Merlo	Single	88	24
17	Awash Town - Amibara	66	Merlo	Single	42.6	24
18	Awash Town - Nuraera	66	Merlo	Single	103	24
19	Asebe Teferi I - Bedessa	66	Merlo	Single	24	24
20	Harar III - Harar I	66	Merlo	Single	7	24
21	Harar III - Alemaya2	66	Quail	Single	19	27
22	Alemaya2 - Chelenko	66	Quail	Single	49.8	27
23	Dire Dawa1 - Alemaya2	66	Merlo	Single	25.3	24
24	Finchaa PP - Finchaa Sugar I	66	Racoon	Single	11	30
25	Finchaa Sugar I - Finchaa Sugar II	66	Racoon	Single	15.4	30
26	Debre Markos - Bichena	66	Merlo	Single	65.7	24
27	Debre Markos - Finote Selam	66	Merlo	Single	80	24
28	Bahir Dar II - Bahir Dar I	66	Merlo	Single	4.5	24
29	Bahir Dar II - Dangla	66	Merlo	Single	68.6	24
30	Dangla - Pawie	66	Merlo	Single	109	24
31	Bahir Dar I - Woreta	66	Merlo	Single	51.6	24
32	Gonder II - Gonder I	66	Merlo	Single	4.3	24
33	Gonder I - Woreta	66	Merlo	Single	87	24

34	Gonder I - Dabat	66	Merlo	Single	58.4	24
<b>66 kV Total Length (km)</b>					<b>1901.6</b>	
33	Kaliti I - Akaki I	45	Raven	Single	3	17
34	Kaliti I - Akaki II L1	45	Merlo	Double	6	17
35	Kaliti I - Akaki II L2	45	Merlo	Double	6	17
36	Akaki I - Dukem	45	Raven	Single	15	17
37	Dukem - Debre Zeit I	45	Raven	Single	8.4	17
38	Akaki I - Aba Samuel	45	Raven	Single	18.5	17
39	Cottobie - Addis East I	45	Raven	Single	6	17
40	Sebeta I - Addis West L1	45	Raven	Single	6.8	17
41	Sebeta I - Addis West L2	45	Raven	Single	6.2	17
42	Sebeta I - Gedja	45	Merlo	Single	23	17
43	Koka PP - Modjo	45	Raven	Single	17.4	17
44	Gefersa - Addis Alem	45	Raven	Single	29.6	17
45	Addis Alem - Ginchi	45	Raven	Single	35	17
46	Bahir Dar I - Tis Abay I	45	Pemice	Single	30	25
47	Harar I - Babile	45	Merlo	Single	24	17
48	Babile - Jigjiga	45	Merlo	Single	93	17
49	Kaliti I - Addis South I	45	Merlo	Single	8.8	17
50	Yirgalem - Dilla I	45	Merlo	Single	39.7	17
<b>45 kV Total Length (km)</b>					<b>376.4</b>	

During both normal and single contingency conditions, transmission lines should be operated within their normal thermal ratings. The normal thermal rating is the level of loading that may be sustained indefinitely.

The conditions under which transmission line ratings have been calculated are as follows: [15]

- Ambient temperature 25° C
- Wind speed 0.6 m/s
- Altitude 2000 m
- Intensity of solar radiation 1100 W/m<sup>2</sup>
- Emissivity of conductor 0.4
- Solar absorption coefficient 0.6

For existing transmission lines, the thermal rating is based on a maximum conductor temperature of 65°C. For new transmission lines, the thermal rating is based on a maximum conductor temperature of 85°C [16].

The existing system employs a large number of conductor sizes, particularly at the lower voltage levels. Table 3.6 shows the conductor types, tower configuration, thermal rating and SIL of those currently in use. The table shows thermal rating and surge impedance loading (SIL) for each of the line types.

Table 3-6: Calculated parameters for the overhead line conductor types

Voltage (kV)	Conductor Type	Tower Config.	No. of Conductor	Positive Sequence			Zero Sequence			Thermal Rating			SIL
				R	X	B	Ro	Xo	Bo	Conductor		Circuit	Circuit
				Ω/km	Ω/km	μS/km	Ω/km	Ω/km	μS/km	A	A	MVA	MW
45	Merlo	Single	1	0.617	0.412	2.760	0.808	1.468	1.633	214	214	17	5
45	Merlo	Double	1	0.617	0.419	2.719	0.761	1.474	1.485	214	214	17	5
45	Pemice	Single	1	0.311	0.394	2.904	0.502	1.450	1.682	320	320	25	5
45	Raven	Single	1	0.600	0.421	2.732	0.791	1.477	1.623	214	214	17	5
45	Raven	Double	1	0.600	0.421	2.732	0.791	1.477	1.623	214	214	17	5
66	Penguin	Single	1	0.317	0.404	2.847	0.507	1.445	1.658	316	316	36	12
66	Quail	Single	1	0.502	0.419	2.743	0.693	1.460	1.622	240	240	27	11
66	Racoon	Single	1	0.428	0.414	2.778	0.619	1.455	1.635	264	264	30	11
66	Merlo	Single	1	0.617	0.418	2.721	0.808	1.458	1.615	214	214	24	11
66	Merlo	Single	1	0.617	0.418	2.721	0.808	1.458	1.615	214	214	24	11
132	Ash	Single	1	0.213	0.427	2.702	0.478	1.196	1.662	399	399	91	44
132	Ash	Double	1	0.214	0.424	2.737	0.466	1.215	1.768	399	399	91	44
132	Ostrich	Single	1	0.225	0.423	2.699	0.489	1.192	1.660	388	388	89	44
132	Tiger	Single	1	0.261	0.424	2.680	0.526	1.194	1.653	357	357	82	44
132	Tiger	Double	1	0.261	0.422	2.731	0.513	1.212	1.740	357	357	82	44
230	ACAR 228.6/241	Single	1	0.079	0.424	2.730	0.319	1.136	1.829	713	713	284	134
230	Mallard	Single	1	0.086	0.418	2.742	0.326	1.130	1.835	687	687	274	136
230	Mallard	Double	1	0.086	0.409	2.812	0.316	1.159	1.850	687	687	274	139
230	Redwing	Single	1	0.096	0.421	2.719	0.336	1.133	1.824	646	646	257	134
230	Redwing	Double	1	0.096	0.413	2.788	0.326	1.162	1.838	646	646	257	138
230	Twin Ash	Single	2	0.107	0.326	3.522	0.347	1.038	2.153	399	798	318	174
230	Twin Ash	Double	2	0.107	0.317	3.643	0.337	1.067	2.208	399	798	318	179
230	Yew	Single	1	0.082	0.423	2.734	0.322	1.136	1.831	704	704	280	134
230	Yew	Double	1	0.082	0.415	2.804	0.312	1.165	1.846	704	704	280	138
400	Twin ASTER 851	Single	2	0.025	0.329	3.752	0.293	0.829	2.676	968	1936	1341	526
400	Twin ASTER 851	Double	2	0.024	0.310	3.751	0.263	0.912	2.368	968	1936	1342	560

### 3.1.6 International Interconnections

Ethiopia is currently interconnected with Djibouti and Sudan at 230 kV level, and the construction of future interconnection with Kenya is started by means of HVDC.

The Djibouti interconnector comprises a 283 km, 230 kV double circuit line; one is directly from Dire Dawa III to PK-12 Djibouti and the other from Dire Dawa III, Ethiopia via Adigala to PK-12 substation in Djibouti. Dire Dawa is in the Eastern region of Ethiopia and was connected to Koka substation to the southeast of Addis Ababa via a 335 km single circuit 230 kV line. In 2016 Koka - Hurso (near Dire Dawa) - Dire Dawa III double circuit transmission

project came to the grid, and strengthens the eastern corridor. The transmission system around eastern Ethiopia was particularly weak at Dire Dawa.

There is a diesel fired power plant at Dire Dawa, however this has limited capacity for providing voltage support. Hence, there are issues with energizing the tie-line to Djibouti at periods of low demand in Ethiopia, and there is limited power transfer capacity to Djibouti during peak hours. Power transfer to Djibouti is significantly improved by the new double circuit line of Koka – Hurso - Dire Dawa III.

Ethiopia is connected to Sudan via a 292 km, 230 kV double circuit line from Shehedi (Metema) in the north west of Ethiopia to Gedarif in Sudan. The agreed export from Ethiopia is 100 MW firm (continuous). This will however be limited to 30 MW or total disconnection during peak load periods in Ethiopia if there is power generation shortage in Ethiopia.

Construction of the Ethiopia to Kenya HVDC interconnection has been started in 2014 and assumed to be completed by 2019 [16]. The interconnection comprises:

- 1066 km, +/- 500 kV HVDC bipolar overhead line from Wolaita Sodo substation (Ethiopia) to Longonot substation (Kenya), with a 2000 MW capacity
- 1000 MW converter capacity at each substation in Phase 1, upgraded by an additional 1000MW converter capacity during Phase 2.
- One 200 MVA synchronous condenser at Longonot substation plus additional line connected reactors at same substation.

### **3.2 Existing Reactive Compensation of the Grid**

Reactive compensation is installed at various locations across the network on the system and includes shunt capacitors with a total capacity of approximately 225 MVAR and shunt reactors (both line and bus-bar connected), with a total capacity of approximately 840 MVAR. Some of the line and bus-bar connected shunt reactors are directly connected without a circuit breaker i.e. they are un-switchable, which are causing additional stress to the system during peak hours. Out of the above twenty seven shunt reactors nine of them are without breaker and normally closed.

Switched reactive compensation should be used to provide better voltage control and to reduce the amount of reactive power flowing in the transmission system. Mechanically switched

capacitor banks will generally be applied to provide voltage support as required. Line connected shunt reactors are required, particularly on longer lines of 230 kV and above, to prevent over-voltage during energization and light load conditions. These should be switched to provide operational flexibility and to reduce the need for shunt capacitor banks during peak load conditions. The existing bus-connected and line-connected reactive compensation in the grid are listed below in tables 3.7 and 3.8 respectively.

*Table 3-7: Bus-connected reactive compensation in Ethiopian grid*

No	Voltage (kV)	Compensation Type	Substation /Bus Name	Size (MVar)	Switchable /Fixed
1	15	Reactor	Dire Dawa3	10	Switchable
2	15	Reactor	Arba Minch	5	Switchable
3	15	Reactor	Agaro	5	Switchable
4	15	Reactor	Bedele	5	Switchable
5	15	Reactor	Mekelle	5	Switchable
6	15	Reactor	Alamata1	15	Switchable
7	132	Reactor	Dire Dawa3	8	Switchable
8	132	Reactor	Combolcha1	10	Switchable
9	132	Reactor	Shakisso	6	Switchable
10	132	Reactor	Mizan	5	Switchable
11	132	Capacitor	Muger	15	Switchable
12	132	Reactor	Mekelle	12	Switchable
13	132	Reactor	Mendi	15	Switchable
14	132	Reactor	Bukuluguma	10	Switchable
15	230	Reactor	Bahirdar2	15	Switchable
16	230	Reactor	Gondar2	15	Switchable
17	230	Reactor	Semera	15	Switchable
18	230	Reactor	Dicheto	15	Switchable
19	230	Reactor	Shehedi	15	Switchable
20	230	Reactor	Endasilassie	15	Switchable
21	230	Reactor	Humera	30	Switchable
22	230	<b>Capacitor</b>	Sebeta2	45	Switchable
23	400	<b>Capacitor</b>	Sebeta2	90	Switchable
24	400	<b>Capacitor</b>	Gelan	90	Switchable
25	400	Reactor	Sekoru (New Gibe)	45	Switchable
26	400	Reactor	Sululta	45	Switchable
27	400	Reactor	Debre Markos	45	Switchable
28	400	Reactor	Bahirdar2	45	Switchable

Table 3-8 Line-connected reactive compensation in Ethiopian grid

No	Voltage (kV)	Compensation Type	Substation Name	Line Name	Size (MVar)
1	230	Reactor	Alamata	Alamata- Bahirdar2	15
2	230	Reactor	Alamata	Alamata- Bahirdar2	15
3	230	Reactor	Bahirdar2	Bahirdar2- Alamata	15
4	230	Reactor	Bahirdar2	Bahirdar2- Gondar2	15
5	230	Reactor	Combolcha2	Combolcha2- Legetafo	15*2
6	230	Reactor	Dire Dawa3	Diredawa3- PK-12	15*2
7	230	Reactor	Dire Dawa4	Diredawa3- Adigala	10
8	230	Reactor	Debre Markos	D. Markos- Mota	15
9	230	Reactor	Adigala	Adigala- PK-12	10*2
10	230	Reactor	Gondar2	Gondar2- Shehedi	15
11	230	Reactor	Humera	Humera- Endasilassie	15
12	230	Reactor	Koka	Koka- Diredawa3	15*2
13	230	Reactor	Semera	Semera- Dicheto	15*2
14	230	Reactor	Tekeze	Endasilassie	15
15	400	Reactor	Gilgel Gibe2	Sekoru Line	45
16	230	Reactor	Diredawa3	Hurso	15
17	230	Reactor	Diredawa4	Hurso	15

### 3.3 Available Transformers of the Grid

There are different types of transformers in Ethiopian national grid, 3 winding, 2 winding, and autotransformers. The power transformers are with different voltage levels, such as 132/15, 230/33, 230/132/15, 132/66, 132/66/33, 132/66/15, 132/45/15, 132/45, etc. They are dispersed almost in all the available substations. The Auto Transformers available in the grid are with voltage levels of 400/230 and 230/132 and their MVA capacity ranges from 500MVA, 250MVA, 125 MVA, and seventeen 230/132.

Suitable transformer ratings have been selected from EEP's current list of standard sizes which are as follows: 12, 16, 20, 25, 31.5, 40, 50, 63, 125, 250 and 500 MVA.

Three-winding transformers would generally be used for substations with a requirement to supply both a local demand and transmit power to other transmission/sub-transmission substations.

Auto-transformers are used on the existing system for; 400/230 kV, 230/132 kV, 132/66 kV and 66/45 kV. Auto-transformers are generally employed for voltage ratios of 2:1 or less due to cost benefits.

### **3.4 Bus-Bar Arrangements of the Grid**

The 162 substations in Ethiopian grid have different types of bus-bar arrangements, even though it is advisable to have the same bus-bar arrangements throughout the transmission system for better operation and control, as well as protection settings. The bus-bar arrangement varies from one substation to another even in the same region.

Main criteria's to be taken during bus-bar selection of one particular bus-bar arrangement scheme among others is: Simplicity of system, Easy maintenance of different equipment, Minimizing the outage during maintenance, Future provision of extension with growth of demand, Optimizing the selection of bus bar arrangement scheme so that it gives maximum return from the system.

The types of bus-bar arrangement in Ethiopian grid includes; Single bus-bar system, Main & transfer bus-bar system, double bus-bar single breaker system, Double main bar and transfer bus-bar system, Double bus-bar with double breaker system, One and half breaker scheme, and single bus system with bus sectionalizer.

### **3.5 Protection and Control System of the Grid**

The objective of a protection scheme is to keep the power system stable by isolating the faulted components only, whereas leaving as much of the network as possible stay in operation. In Ethiopian transmission system there are about sixteen 132kV transmission lines, and about nine shunt reactors directly connected to the bus-bars without circuit breakers (with isolators only), and there are old breakers that do not act or act with some delay at 230kV and 132kV transmission lines. Any maintenance work or fault incidents on these lines demands for a power interruption of larger area coverages and protection is difficult within their zones.

In the power system many blackout incidents happened because of the poor protection coordination. Sometimes there are cases when a fault on 15kV or 45kV line leading to the opening of the incoming high voltage transmission lines with 132kV voltage level and above. Whereas the neighboring newer circuit breakers act quickly in zone 3 or 4 protection, which

leads to cascaded outage of transmission lines and hence drives to voltage instability or outages of generating units and larger parts of the transmission lines. As can be seen from the blackout data, some distance protection relays record wrong kilometers, and most of the time it is normal to find 'No Signal' on the relay readings when a fault occurred. Such protection coordination's are bottlenecks to analyze the system behavior, causes of faults, and sequence of events easily.

Protection coordination is handled through dividing the power system into protective zones. For the ease of future substation upgrading works by either, an additional line, additional transformer or both; it is recommended to construct a bus section bay fitted with a circuit breaker, two bus-bar disconnectors, and current transformers. This arrangement will enable operational flexibility, with uninterrupted running of the substation following either a line or transformer fault.

### **3.6 The Demand/Load Increase in Ethiopia**

Ethiopia envisions transitioning from a developing country to a middle-income country by 2025. Due to industrialization growth in Ethiopia, the increased dependency on electricity resulted into rapid growth of the power demand especially in the 4 regions of Addis Ababa. The distribution of peak demand in 2016 across the 15 EEU sales regions is with 59 % of the demand located in the four Addis Ababa distribution regions i.e. East, West, North, and South Addis Ababa regions that are located in and surrounding towns of Addis Ababa (Source EEU).

The Peak load in Dec 2015 was round 1700MW, when compared with this year's peak load which is 2,100MW, the growth each year is about 15%. Average demand in MW of 4 months i.e. from September up to December 2016 is shown in the graph below. According to the daily load sheet recorded in 15 minutes and 1 hour interval, the peak load recorded is 2,189.24 MW which is on Dec, 19, 2016 at 19:15 hours. Currently the peak load is about 2,200MW which is increasing from month to month. The peak recorded in November, 2016 is 2,119.71, which is recorded on Nov, 29<sup>th</sup>, 2016 at 18:45 hours. A 70 MW increase is recorded within less than one month, that is in the month of September the loading was 2,010.58MW on 29<sup>th</sup> Sep, 2016 at 19:15 hours and in October it was 2,011.2MW on 03<sup>rd</sup> Oct, 2016 at 19:00.

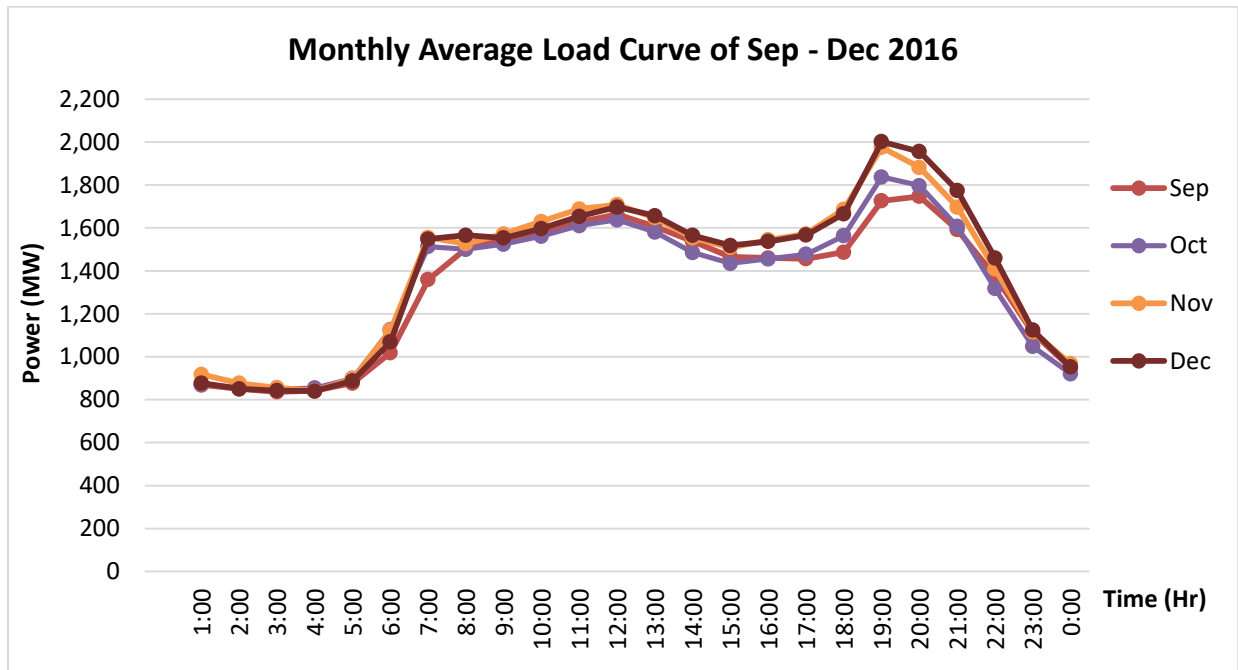


Figure 3-3: Load (MW) Curve of Sep – Dec 2016

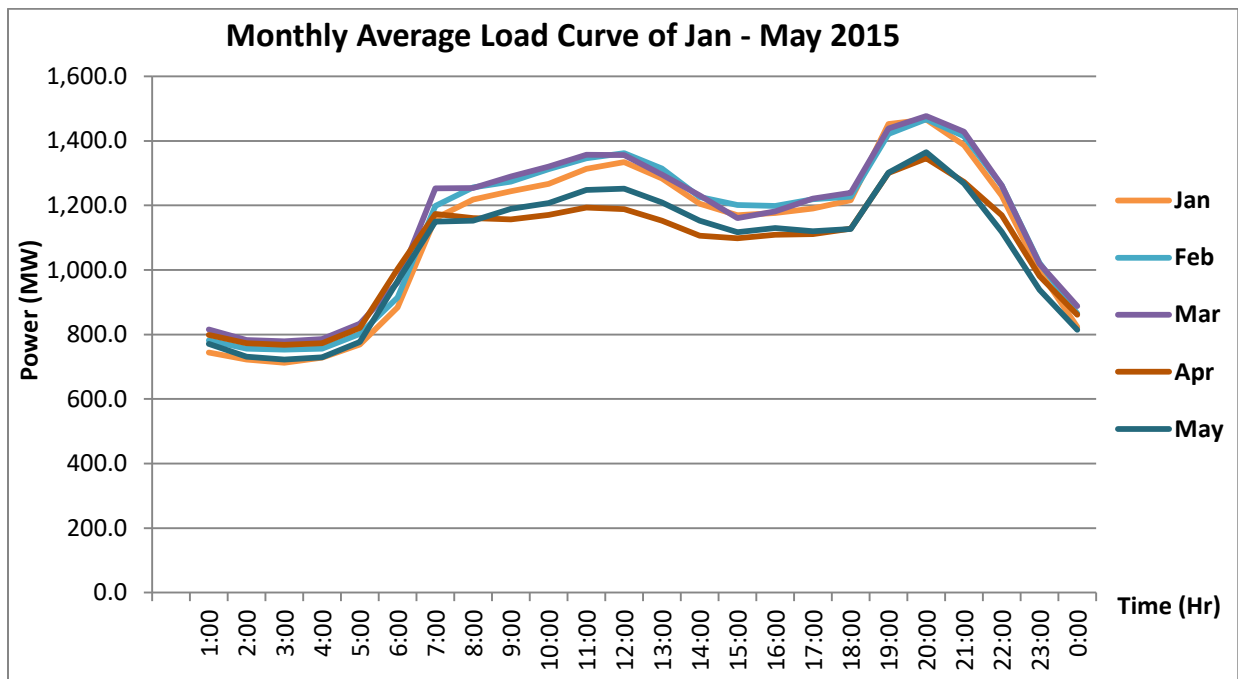


Figure 3-4: Load (MW) Curve of Jan – May 2015

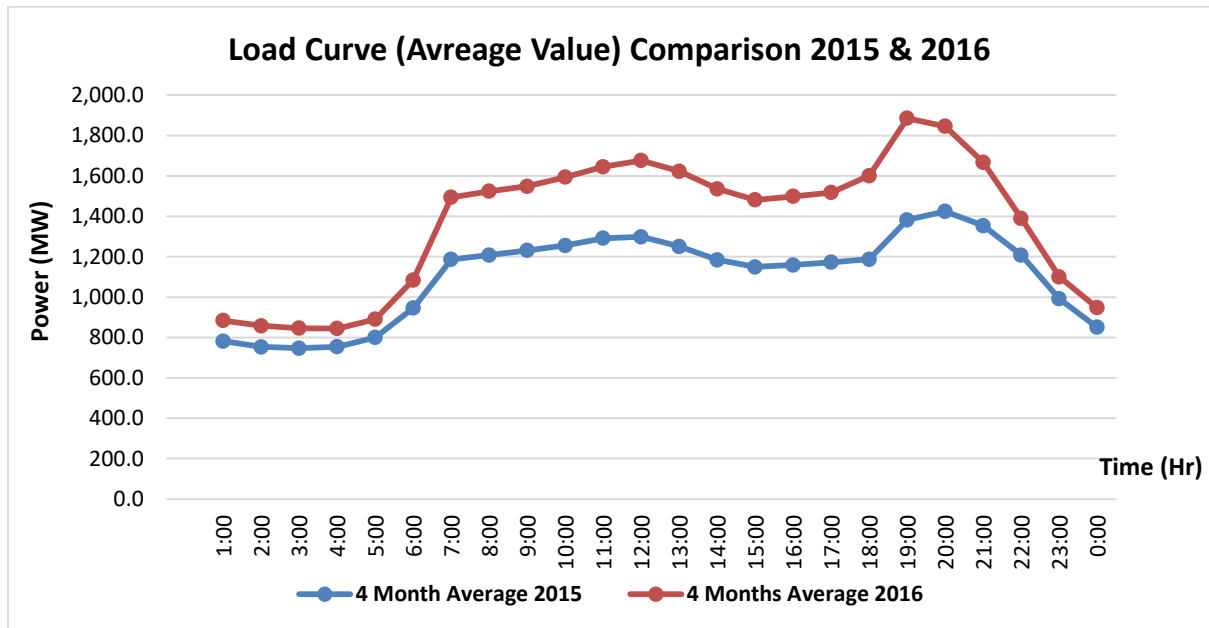


Figure 3-5: Load (MW) Curve Comparison of Average 2015 and 2016

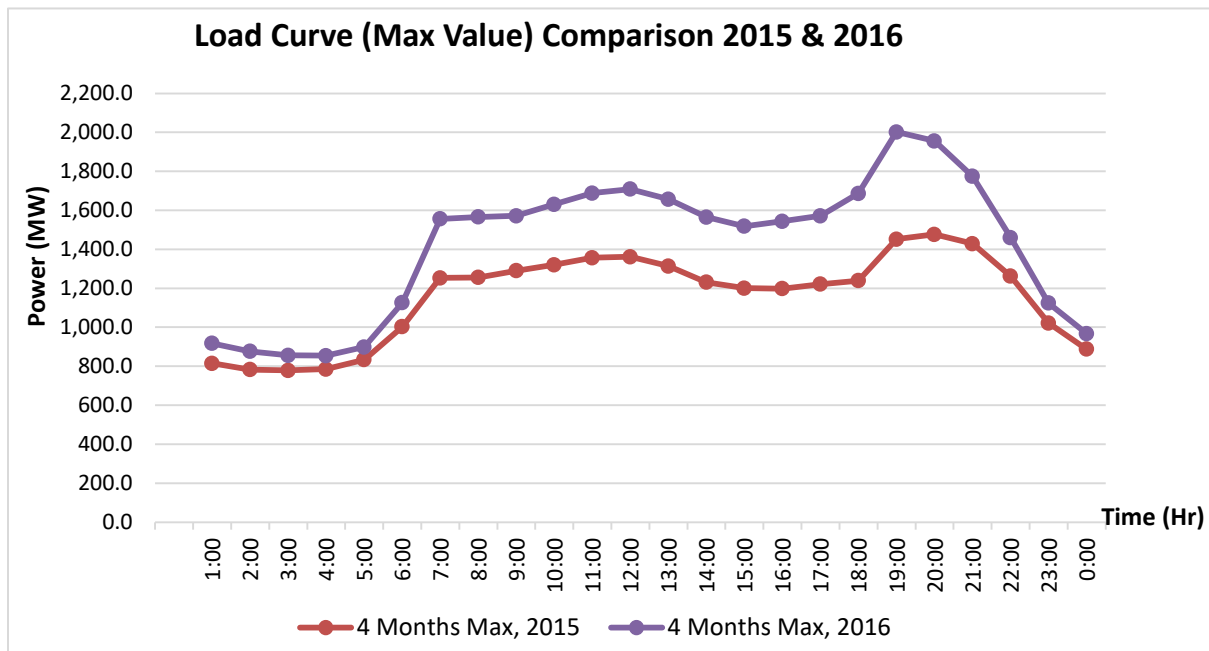


Figure 3-6: Load (MW) Curve Comparison of Maximum 2015 and 2016

Based on the study by Ethiopian Power System Expansion Master Plan, an increasing power deficit in Addis Ababa, North Eastern and Eastern regions and large amounts of surplus generation capacity in North Western and Western regions of the country is to be occurred.

## Chapter Four

### 4 Voltage Stability Analysis of Transmission Grid

#### 4.1 Introduction

A voltage collapse can be initiated by either a primary fault or a sudden load demand increase, in combination with insufficient reactive power reserves or transmission capacity. In order to avoid voltage collapse, a detailed knowledge of the reactive power capacity in stressful and light load situations of the available generators and load centers is necessary.

This chapter begins by conducting power flow simulations using PSS/E on the entire Ethiopian high voltage grid (by Dec, 2016) and the methodology at which the study will be carried out. Steady state voltage stability analysis is carried out by performing ‘Voltage Limit Checking’ simulation results to identify which scenario affects the voltage stability from which the buses with unacceptable voltage values of the system will be determined. The blackouts occurred in 2015 and 2016 are collected and the observations are presented by relating to voltage problems.

Currently, the existing Ethiopian power system doesn’t withstand the N-1 contingency and carries very little redundancy, i.e. it will not operate normally if one of the critical high voltage transmission lines or generating units tripped. Many of the substations are supplied over single radial 132 kV circuits and will of course lose supply completely on loss of that circuit. The transmission network around Addis Ababa can be a good example and is shown in figure 4.1 below. As the network is getting developed, it is assumed that supply to these substations will be improved such that N-1 security is achieved. To have an overview of Ethiopian power system, the single line diagram of the entire transmission network is shown in Appendix A.

There are fifteen regions/areas in Ethiopian power system that is grouped according to geographical location to allocate the existing transmission lines, generation stations, and distribution loads as much as possible. The PSS/E simulation software groups the regions according to the fifteen load/demand areas. List of the fifteen regions; their names and some substations within the region in Ethiopian power system is shown in table 4.1 below.

Table 4-1: List of 15 regions/areas in Ethiopian power system

Area	Region Name	Some Substations in the Area/Region
1	Assosa	Assosa, Ghimbi, Mendi,
2	East Addis Ababa	Cottobie, Addis East1, Legetafo, Weregenu,
3	Eastern	Dire Dawa 1, 2, &3, Harar 2&3, Alemaya, Gelemso, Chelenko...
4	Gambela	Gambela, Dembi Dolo, Metu, Sor
5	Jigjiga	Jigjiga, Adigala
6	North Eastern	Combolcha 1 &2, Dessie, Shoa Robit, Woldia, Akista, Alem Ketema
7	North Western	Bahirdar 1&2, Gondar 1&2, Debre Markos, Mota, Shehedi, Woreta
8	North Addis Ababa	Addis North, Gefersa, Sululta, Fiche,
9	Northern	Alamata, Mekelle, Adigrat, Adwa, Humera, Wukro, Messobo
10	Semera	Semera, Dicheto, Amibara
11	South Western	Jimma, Agaro, Mizan, Tepi, Sekoru (New Gibe), Old Gibe, Abba,
12	South Addis Ababa	Kaliti 1&2, Gelan, Debre Zeit 1&2, Akaki 1&2, Addis South2
13	Southern	Shashemene, Awassa, Wolaita Sodo 1&2, Alaba, Yirga Alem, Dilla, Arba Minch, Shakisso, Hagere Mariam,
14	West Addis Ababa	Addis West, Sebeta 1&2, Gedja, Wolisso,
15	Western	Nekemte, Ghedo, Finchaa 1&2, Gida Ayana, Guder,

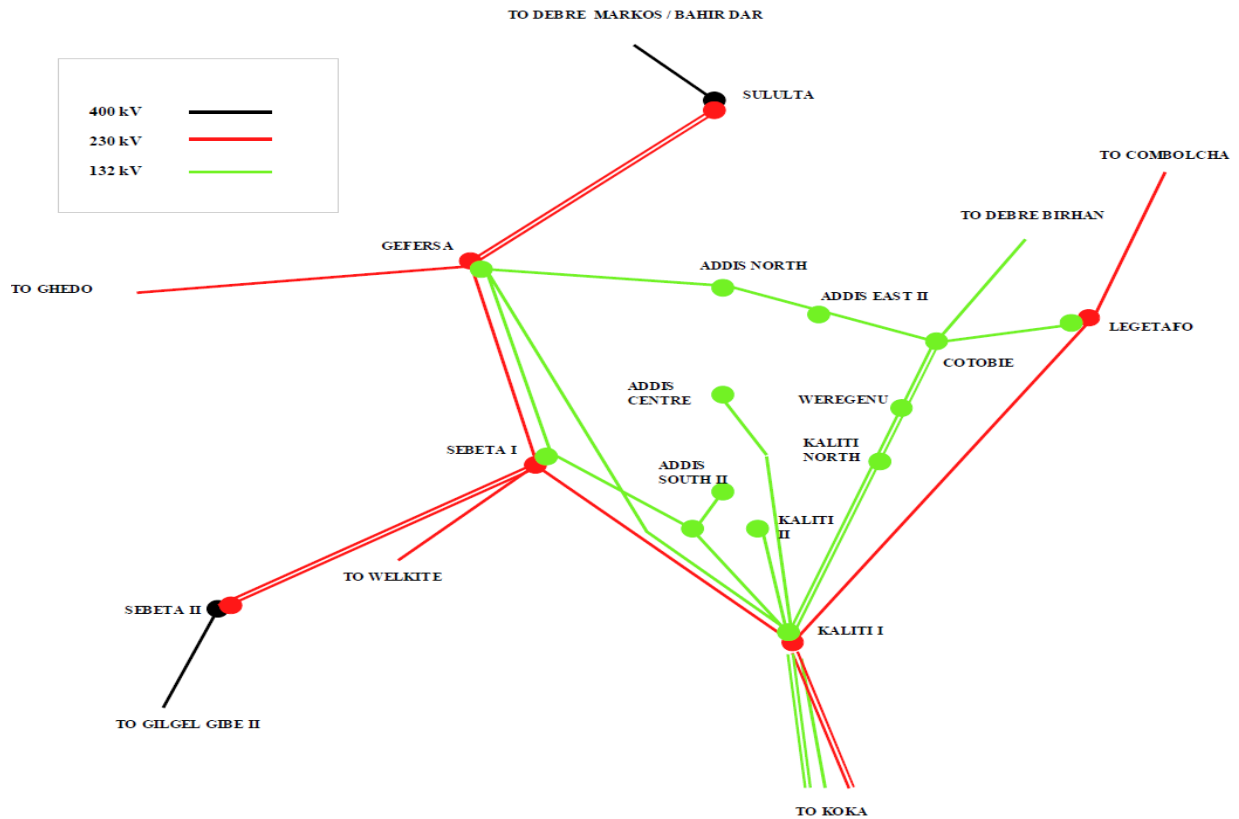


Figure 4-1: Existing Transmission Network of Addis Ababa [16]

## 4.2 Load Flow Analysis of Ethiopian Grid using PSS/E

Detailed network models were developed using PSS/E Version 32, to represent the existing Ethiopian network in 2016 including generating plants, transmission infrastructure, and substation loads. Load flow studies were conducted, with the objective of identifying the voltage weak buses/areas that can lead to voltage instability or voltage collapse. The load flow simulation is studied in terms of reactive compensation, essential transmission line upgrades and developments in order to meet the increasing demand.

PSS/E, Power System Simulator for Engineering is an integrated, interactive program for simulating, analyzing, and optimizing power system performance and provides probabilistic and dynamic modeling features. The software provides for transmission planning and engineers a tool for use in the design and operation of reliable networks.

In this chapter, load flow simulations have been made so as to study the voltage profiles in the existing power system conditions during peak and light-load conditions. The mitigation techniques applied to bring the unacceptable low and high voltage values in to tolerable range are discussed as ‘voltage limit checking’ simulation results and network diagram form.

The load flow under maximum loading conditions; a number of transmission line and transformer overloads, and unacceptable low voltages at some buses were found. Total generation is considered to be the peak generation value in December 2016, which is about 2,200MW. The low voltage profiles were registered mostly at the load center, Addis Ababa and its surrounding. For the load flow during light-load conditions, a number of generating units were operated out of service and unacceptable high voltage values were listed. The off-peak hour loading is considered about 900MW, which is close to the actual off-peak loading in December 2016. The network was assessed to confirm that the voltage and loading limits were not violated.

Beles power plant is set to be the slack bus which has a capacity of 460MW, responsible to monitor the frequency deviations in the grid, and set in automatic generation control (AGC) mode. The newly commissioned Gilgel Gibe-3 hydroelectric power plant is also included in the simulation, since it is synchronized to the grid in the actual case.

Actual MW loading of some of the high voltage transmission lines that connect the main generation to the load centers, during peak and off-peak hours is shown in table 4.2 below.

The actual loading shown in the table below is taken from the monthly average of peak and minimum loading of the lines in December, 2016. This thesis takes the MW and MVAR loading of the substations (load buses) from the actual loading in December, 2016. The MW and MVAR loading of the substations in the power system are listed in Appendix B.

*Table 4-2: Loading (MW) of some transmission lines in Ethiopian grid*

Serial No.	Name of Transmission Line	Voltage Level (kV)	Peak Loading (MW)	Off-Peak Loading (MW)
1	Sebeta-1 – Kaliti-1	230	76	0.8
2	Gefersa – Sebeta1	230	36	0.2
3	Alamata – Combolcha-2	230	75	3
4	Awash Town – Dire Dawa3	230	61	38
5	Bahirdar2 - Gondar2 Line-1	230	100	12
6	Bahirdar2 - Gondar2 Line-2	230	96	18
7	Sebeta-1 – Mekanissa	132	74	2.4
8	Wolaita Sodo – Alaba	132	78	49
9	Shashemene – Wakena Yugo	132	31	12

### 4.3 Identification of Unacceptable Voltages in the System

Voltage-weak buses have unacceptable low or high voltage profiles for their maximum or minimum power transfers. Voltage-weak buses identification is done by conducting load flow simulations and undertaking the ‘Voltage Limit Checking’ simulation results; with 0.95 and 1.05pu to be the limits ( $\pm 0.05$ pu from nominal voltage) for the entire transmission grid. Even though voltage stability problems often involve the entire power system, unacceptable voltage values usually have relatively larger impact locally.

During the simulation process this project has made an assessment on the overall system during peak and off-peak times and presents the existing condition of the transmission grid. Generally it has understood that, number of buses with unacceptable low voltages at peak hour is dominant around Addis Ababa (substations like Sebeta-1, Kaliti 1 & 2, Addis South2, Weregenu, Addis East 1 & 2, Cottobie, Addis West, Gedja, Legetafo, Mekanissa, Muger, etc.). The buses with unacceptable high voltage values at off-peak hour, are located around North-western (Bahirdar, Debre Markos, Gashena etc.), North-eastern (Combolcha, Dessie, Shoa Robit, Woldia etc.), and Northern (Alamata, Mekelle, Endasilassie, Humera), regions of the grid. The reason for the over-voltages in these regions is; the generation stations available in

those areas, the smaller amount of load consumed by the substations, and the reactive power generated by the long 400kV & 230kV transmission lines during light-load periods.

To do load flow simulation of Ethiopian power system in PSS/E, the following main power flow parameters have been considered as input:

- Transmission line parameters, generation stations, and transformer ratings,
- Four months average of peak and minimum values of the daily loading in 2016,
- Period of minimum loading is considered at 03:00,
- Period of peak loading is considered at 19:00, and
- Power factor of 0.8 is considered for the loads on the substations,

The basic input data required for the PSS/E software to carry out load flow simulation studies under different loading conditions include; bus data, branch (transmission lines) data, generator/machine data, load data, two and/or three winding transformer data, shunt reactor data, shunt capacitor data, etc. The substations which have power plants are considered as generation (PV) buses and the substations which feed the distribution load are considered as load buses. Some of the required basic input data records in PSS/E are shown in figures 4.2, 4.3 and 4.4 below.

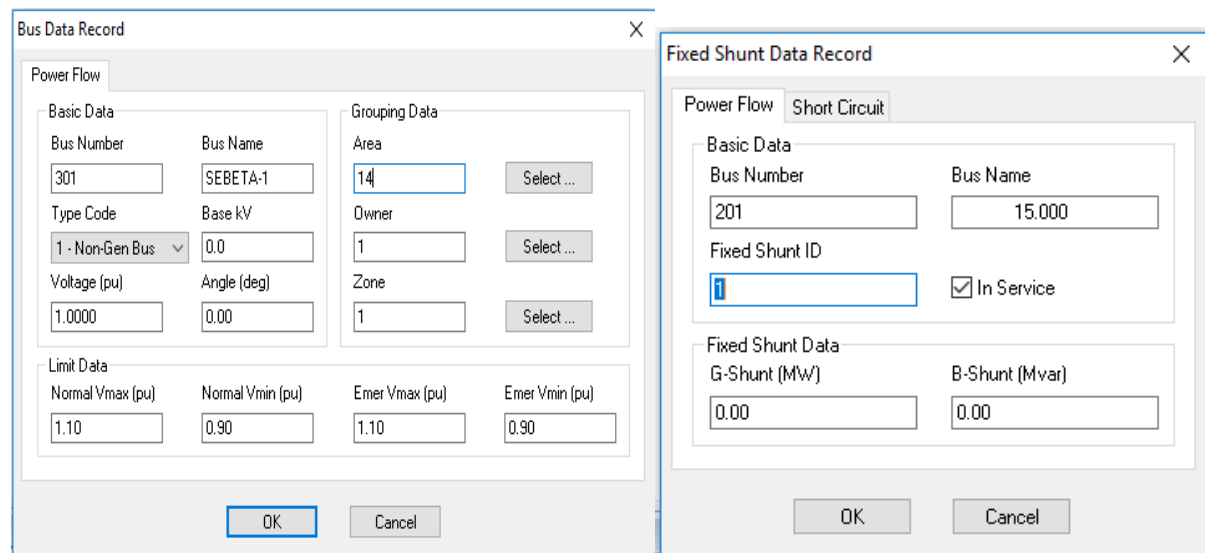


Figure 4-2: Input data for PSS/E: (A) Bus data record (B) Fixed Shunt data record

Machine Data Record ✕

Power Flow Short Circuit

**Basic Data**

Bus Number  Bus Name

Machine ID   In Service Bus Type Code

<b>Machine Data</b>			<b>Transformer Data</b>
Pgen (MW)	Pmax (MW)	Pmin (MW)	R Tran (pu)
<input type="text" value="380.0000"/>	<input type="text" value="420.0000"/>	<input type="text" value="0.0000"/>	<input type="text" value="0.00000"/>
Qgen (Mvar)	Qmax (Mvar)	Qmin (Mvar)	X Tran (pu)
<input type="text" value="20.0000"/>	<input type="text" value="200.0000"/>	<input type="text" value="-200.0000"/>	<input type="text" value="0.00000"/>
Mbase (MVA)	R Source (pu)	X Source (pu)	Gentap (pu)
<input type="text" value="100.00"/>	<input type="text" value="0.000000"/>	<input type="text" value="1.000000"/>	<input type="text" value="1.00000"/>

**Owner Data**

Owner	Fraction
<input type="text" value="1"/> <input type="button" value="Select ..."/>	<input type="text" value="1.000"/>
<input type="text" value="0"/> <input type="button" value="Select ..."/>	<input type="text" value="1.000"/>
<input type="text" value="0"/> <input type="button" value="Select ..."/>	<input type="text" value="1.000"/>
<input type="text" value="0"/> <input type="button" value="Select ..."/>	<input type="text" value="1.000"/>

**Wind Data**

Control Mode

Power Factor (WPF)

**Plant Data**

Sched Voltage  Remote Bus

Figure 4-3: Input data for PSS/E: Generator/Machine data record

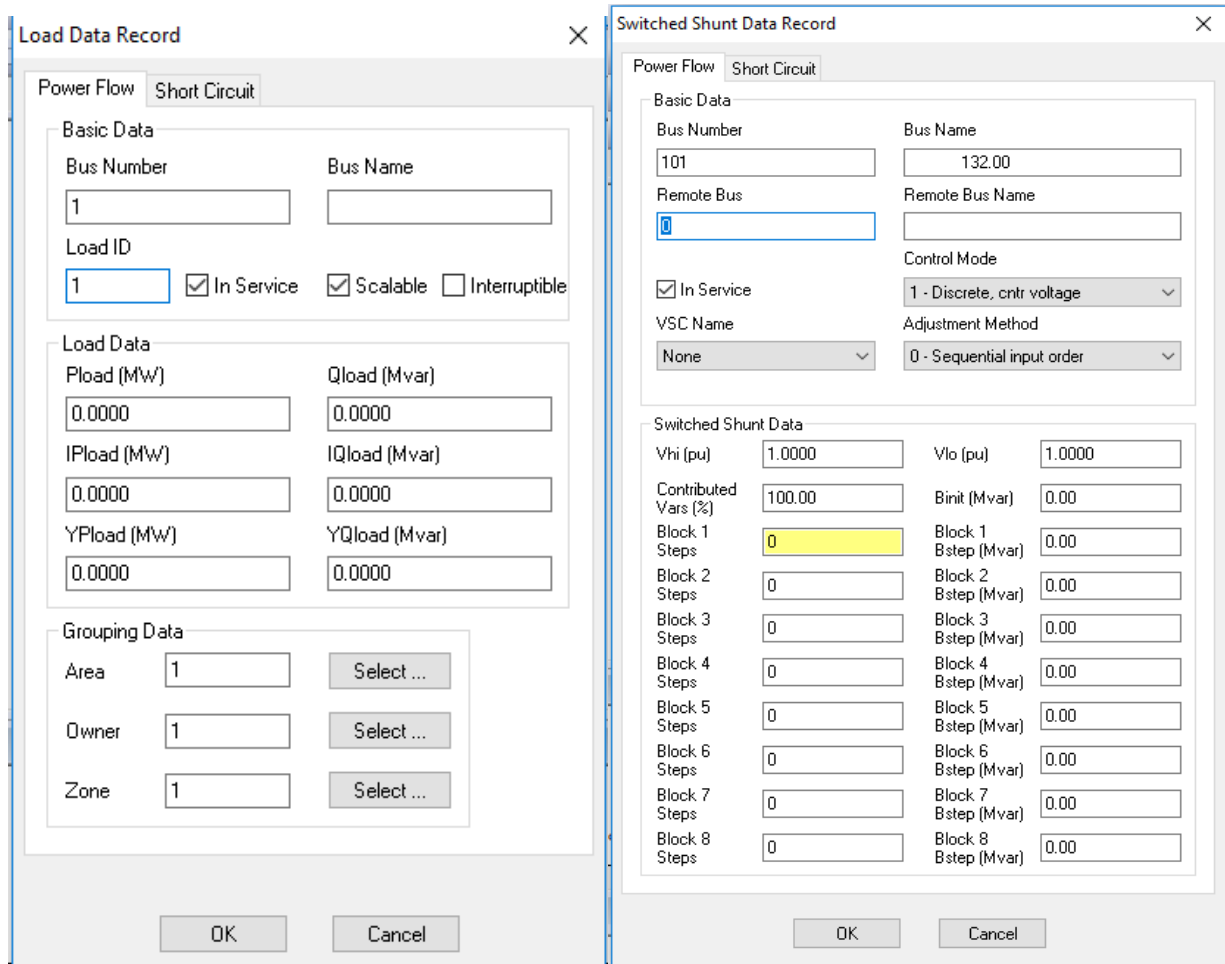


Figure 4-4: Input data for PSS/E: (A) Load data record (B) Switched Shunt data record

In order to analyze the problem of the existing Ethiopian power system and put the mitigation techniques, simulations have been made under the two scenarios i.e. Peak-hour loading and off-peak hour loading cases. These two cases are discussed in the following sub sections.

### 4.3.1 Case-1: Voltage Profile at Peak Load Conditions with and without Mitigation Techniques

Period of daily maximum MW loading in Ethiopian power system lies between 18:00 and 22:00 in the evening, and between 09:00 and 12:00 morning time. As can be seen from the load curves in figures 3.3 - 3.6 in chapter 3, the evening peak load is bigger than the morning one, and 19:00 is considered to be the period of maximum load in a day.

Repeated load flow simulations using PSS/E have been carried out until the simulation iteration met convergence. The simulations have been made for the existing power system at peak load time of 19:00 that is total generation of about 2,200MW, which is consumed by the available substations. The available substations' active and reactive power loading at peak hour by December 2016 is shown in Appendix B.

During peak hour, most of the generating units are forced to be operated close to their maximum capacity. At peak load condition, all the hydro, and wind power plants in the grid are modelled and put 'in service' as generation/PV buses. The three diesel generation plants (Kaliti1, Awash, and Diredawa) and Aluto geothermal plant are modelled but put 'out of service' while conducting load flow simulations using PSS/E.

During light-load condition, some generating units of the hydro plants, and some of the wind power plants in the grid are modelled and put 'in service' as a generation/PV buses. The three diesel generation plants (Kaliti1, Awash, and Diredawa) and Aluto geothermal plant are not modelled while conducting load flow simulations using PSS/E.

Network analysis was conducted on the existing Ethiopian transmission system, to identify buses with unacceptable voltage values that can lead to voltage instability and/or collapse and to develop a model which would provide the basis for improved operation of the power system. In this section of the thesis it is discussed the findings of the studies on the existing system and identify reactive compensation supports (mitigation techniques) required to support the power flow during peak-hours.

The buses with unacceptable low voltage profiles; i.e. less than 0.95pu have been shortlisted by conducting '*Voltage limit checking*' simulation results. The buses with low voltage profiles during peak load time in Ethiopian grid are listed in the PSS/E simulation result table 4.3 below. The '*voltage limit checking*' result during peak load condition shows, no buses that have registered unacceptable high voltage profiles (>1.05pu).

Table 4-3: Peak load flow 'Voltage Limit Checking' simulation result before mitigation

PTI INTERACTIVE POWER SYSTEM SIMULATOR-PSS/E  
 ETHIOPIAN POWER SYSTEM TRANSMISSION STUDY  
 YEAR 2016 - PEAK LOAD FLOW

BUSES WITH VOLTAGE GREATER THAN 1.0500: \* None \*

BUSES WITH VOLTAGE LESS THAN 0.9500:

BUS#	Substation-Name	BASKV	AREA	V (PU)	V (kV)
<b>102001</b>	<b>Addis East-2</b>	<b>132.00</b>	<b>2</b>	<b>0.8898</b>	<b>117.46</b>
102002	Weregenu-Tap	132.00	2	0.9327	123.12
102003	COTOBIE-I	132.00	2	0.9370	123.68
102005	SULULTA-132	132.00	2	0.9142	120.68
102006	WEREGENU	132.00	2	0.9239	121.96
<b>108001</b>	<b>Addis-North</b>	<b>132.00</b>	<b>8</b>	<b>0.9027</b>	<b>119.16</b>
108003	GEFERSA	132.00	8	0.9368	123.66
<b>108006</b>	<b>MUGER</b>	<b>132.00</b>	<b>8</b>	<b>0.8907</b>	<b>117.58</b>
<b>108011</b>	<b>Derba-Tap2</b>	<b>132.00</b>	<b>8</b>	<b>0.9010</b>	<b>118.93</b>
108015	MINILIK TS	132.00	8	0.9078	119.83
112001	A.CENTER	132.00	12	0.9064	119.65
112002	ADS-II	132.00	12	0.9131	120.52
112003	DB-ZEIT2	132.00	12	0.9107	120.22
112004	DBZT2-TP	132.00	12	0.9108	120.23
112005	KALITI1	132.00	12	0.9345	123.36
112006	KALTI-N	132.00	12	0.9340	123.29
112007	KALTWO	132.00	12	0.9300	122.77
112008	KaltiNorth-Tap	132.00	12	0.9342	123.32
112009	MEKANISA	132.00	12	0.9155	120.85
112010	YESU	132.00	12	0.9396	124.02
112011	AKAKI 2	132.00	12	0.9404	124.13
112014	NIFAS SILK	132.00	12	0.9295	122.69
112015	DANGOTE-CEM	132.00	12	0.9163	120.95
112016	KILINTO	132.00	12	0.9356	123.50
112017	KALITI TS	132.00	12	0.9317	122.98
<b>114002</b>	<b>SEBETA</b>	<b>132.00</b>	<b>14</b>	<b>0.9294</b>	<b>122.68</b>
402001	SULULTA	400.00	2	0.9285	371.41
814005	SABETA-B	15.000	14	0.9166	13.750
<b>702002</b>	<b>COTOBIE</b>	<b>45.000</b>	<b>2</b>	<b>0.8809</b>	<b>39.639</b>
<b>712002</b>	<b>AKAKI-I</b>	<b>45.000</b>	<b>12</b>	<b>0.8788</b>	<b>39.547</b>
<b>712003</b>	<b>AKAKI-SP2</b>	<b>45.000</b>	<b>12</b>	<b>0.8779</b>	<b>39.507</b>
<b>712007</b>	<b>KALITI-1</b>	<b>45.000</b>	<b>12</b>	<b>0.8909</b>	<b>40.090</b>
<b>714001</b>	<b>Addis-West1</b>	<b>45.000</b>	<b>14</b>	<b>0.8161</b>	<b>36.726</b>
<b>714002</b>	<b>Addis-West2</b>	<b>45.000</b>	<b>14</b>	<b>0.8280</b>	<b>37.262</b>
<b>714003</b>	<b>GEDJA</b>	<b>45.000</b>	<b>14</b>	<b>0.7932</b>	<b>35.692</b>
<b>714004</b>	<b>SEBETA1</b>	<b>45.000</b>	<b>14</b>	<b>0.8584</b>	<b>38.629</b>

<b>714005</b>	<b>SEBETA2</b>	<b>45.000</b>	<b>14</b>	<b>0.8505</b>	<b>38.275</b>
<b>802001</b>	<b>Addis-East1</b>	<b>15.000</b>	<b>2</b>	<b>0.8898</b>	<b>13.346</b>
802002	WEREGENU	15.000	2	0.9460	14.190
<b>802003</b>	<b>COTOBIE-15B1</b>	<b>15.000</b>	<b>2</b>	<b>0.8770</b>	<b>13.155</b>
802008	SULULTA-15	15.000	2	0.9318	13.976
802009	Addis-East2	15.000	2	0.9073	13.609
802010	COTOBIE-15B2	15.000	2	0.9185	13.778
<b>808002</b>	<b>Addis-North</b>	<b>15.000</b>	<b>8</b>	<b>0.8187</b>	<b>12.281</b>
808008	GEFERSA	15.000	8	0.9306	13.960
808012	MUGER	15.000	8	0.9370	14.055
<b>808016</b>	<b>MUGER2</b>	<b>15.000</b>	<b>8</b>	<b>0.9027</b>	<b>13.541</b>
812001	Addis Center	15.000	12	0.9268	13.901
<b>812003</b>	<b>Addis-South2</b>	<b>15.000</b>	<b>12</b>	<b>0.8458</b>	<b>12.686</b>
812004	AKAKI-1	15.000	12	0.9194	13.791
812005	AKAKI-SP2	15.000	12	0.9367	14.050
812008	Debre-Zeit2	15.000	12	0.9109	13.664
812010	KALITI-1	15.000	12	0.9365	14.047
812011	KALITI-2	15.000	12	0.9268	13.903
812012	Kaliti-North	15.000	12	0.9325	13.987
812013	MEKANISA	15.000	12	0.9181	13.771
812014	NIFAS SILK	15.000	12	0.9114	13.671
812015	YESU	15.000	12	0.9339	14.008
<b>814001</b>	<b>Addis West1</b>	<b>15.000</b>	<b>14</b>	<b>0.7647</b>	<b>11.470</b>
<b>814004</b>	<b>GEDJA</b>	<b>15.000</b>	<b>14</b>	<b>0.7452</b>	<b>11.178</b>
<b>814006</b>	<b>SEBETA-1</b>	<b>15.000</b>	<b>14</b>	<b>0.8531</b>	<b>12.796</b>

As can be seen from the simulation results above, the unacceptable low voltages registered are in the four regions located in Addis Ababa, i.e. East Addis Ababa region (Area-2), South Addis Ababa region (Area-12), West Addis Ababa region (Area-14), and North Addis Ababa region (Area-8). Unacceptable low voltages are not registered in other regions of the power system except the four regions of Addis Ababa.

While running the load flow simulations at peak loading condition, it's observed from the above simulation result table that, out of the entire transmission grid severely low voltage profiles at three areas around Addis Ababa (West, East, and South Addis Ababa regions), which those weak areas/buses could be the primary prone to the entire power system voltage collapse. Those three areas are presented as follows:

- Around East Addis Ababa Region (Cottobie, Legetafo, Addis East-2 (Bela), Weregenu, Bole Lemi, Addis North 132 kV, and Addis East-1 45 kV substations);

- Around West Addis Ababa region (Sebeta1, Sebeta2, Mekanissa, Addis Sourh-2 (Gofa), Addis West, Gedja, and Gefersa substations); and
- Around South Addis Ababa region (Kaliti1, Kaliti2, Kaliti North, Nifas Silk, Akaki1, Akaki2, Debre Zeit, Dukem, and Gelan 230kV and 132kV substations etc.);

The reason for the unacceptable low voltage profiles registered around Addis Ababa can be because there are no generating plants that can be voltage sources in the area and Addis Ababa being a load center. The closest power plants to Addis Ababa are, Koka, Awash 2 & 3, Adama Wind 1&2, and may be the Independent Power Producer (IPP) from Wonji Sugar factory. In the future Reppi Waste to Energy plant which is currently under construction might give a voltage support to the load center.

For further analysis two areas out of the three (East and West Addis Ababa regions) are selected in order to bring the bus voltages in to tolerable range within their areas, neighboring regions, and in Addis Ababa in general. The reason for selecting these two regions for further analysis; is because they have registered the lowest unacceptable bus voltages while running the load flow simulations and have substations with 45kV sub-transmission lines. The voltage problems in South Addis Ababa region can be improved by the mitigation techniques applied in the neighboring East & West Addis Ababa regions. The two regions with unacceptable low voltage profiles are discussed in details below.

#### **4.3.1.1 West Addis Ababa Region (Sebeta-1 Substation Area)**

West Addis Ababa region includes the substations such as; Sebeta 1 & 2, Addis West, Gedja, Holeta, Mekanissa, Addis Alem etc., and expands up to Wolisso. Sebeta1 is connected to other surrounding substations, and radially connected to Addis West and Gedja substations via 45kV sub-transmission lines, and feeds the industrial, commercial, and residential loads around its area. Sebeta1 is connected to Sebeta2, Gefersa, Kalitit1, Tor Hailoch GIS, and Wolkitie stations via 230kV lines, and with Gefersa, Mekanissa, and Addis South2 (Gofa) via 132kV lines. Habesha cement is located in this region, and Dangote, Derba, and Muger cement factories are supplied directly from Gefersa substation, which is directly interconnected with Sebeta1, and have big impact in this region in terms of voltage stability. Kaliti-I is further connected to about eight substations radially, which are Addis Center, Kalili-2, Nifas Silk, Weregenu, Kaliti North, and Bole Lemi substations with 132kV lines, and Akaki 1 & 2 sub-

transmission substations with 45kV lines. West Addis Ababa region is the main gate to Addis Ababa from Gilgel Gibe 1 and 2, and an interconnection to the South-Western and Western corridors. This area is grouped as one of the regions with upcoming and existing industrial zones at Sebeta and Holeta areas.

As the two 45kV transmission lines go far from Sebeta-I 45kV bus-bars towards Addis West and Gedja substation; the voltage values are getting lower and lower up to 0.7452pu at Gedja 15kV bus. These two substations have registered the lowest voltage values; the load connected to Addis West substation is approaching the transformers' capacity, and Gedja is further connected to one of Addis West's 45kV bus. These low voltage profiles can be the reason to system voltage collapse especially during peak hours of the system.

The single line diagram of the load flow simulation results of the existing system around West Addis Ababa region is shown in figure 4.5 below. Since the single line diagram of the load flow simulations' of the entire transmission grid is congested and not suitable to display here, this thesis prefers to draw only the regions with unacceptable voltage profiles. The single line diagram at figure 4.5 is drawn by selecting one substation (Sebeta-1) and applying 'Grow N+1 network' to show the surrounding substations by focusing at West Addis Ababa region from the entire network diagram.

Most bus voltages in this area are below the acceptable voltage limit i.e.  $<0.95pu$ . The yellow color in most of the buses shows the unacceptable low voltage profiles. The coloring to identify unacceptable low voltage profiles is applied only at the buses, whereas the branch/transmission lines before and after the mitigation techniques represent the same colors. On the network model single diagram below, the color codes that are representing different voltage levels and unacceptable voltage profiles are as follows;

- Yellow- Buses with unacceptable low voltage profiles for all voltage levels;
- Green- 132kV lines, Red- 230kV lines, Gray- 33kV & 15kV lines, and Dark Brown- 45kV transmission lines before and after mitigation;
- Buses with acceptable voltage values have the same colors as the transmission lines;
- Light brown- Branch/transmission line overloads

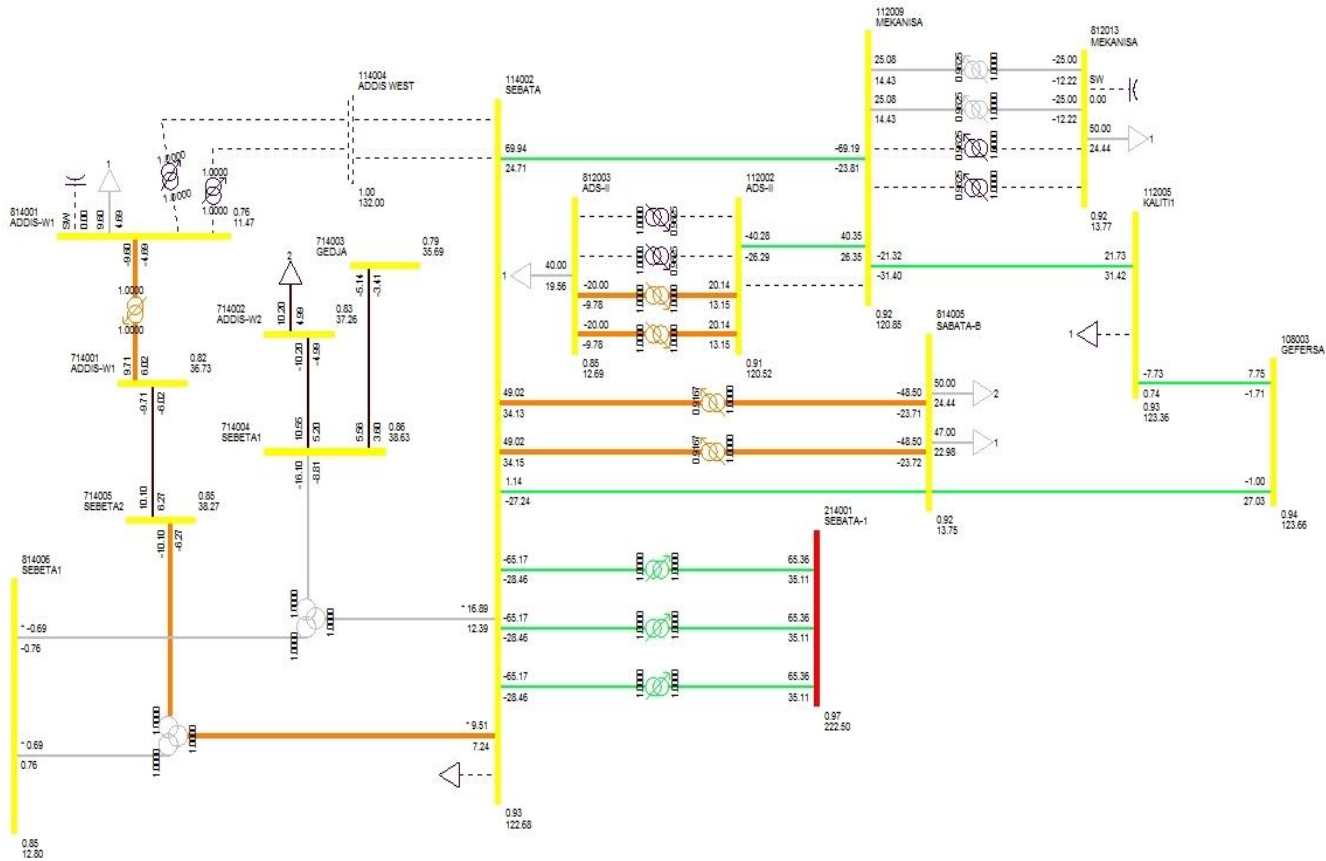


Figure 4-5: Single line diagram around West Addis Ababa region

To improve the unacceptable low voltage profiles in this area, different mitigation techniques are used; such as installing 15MVAR shunt capacitor at Mekanissa substation 15kV bus side. The basis for selecting the MVAR rating of capacitor bank at Mekanissa substation is made by taking the 25-30% of the 50MVA transformers at the substation and taking the closest standard MVAR rating of capacitor banks. The reactive power consumed by the substation is also taken into consideration so as to compensate the MVAR amount for voltage value improvement. This capacitor bank has slightly improved the voltage values at Mekanissa, Addis South2, and Sebета1, but was not helpful to other surrounding substations. Addis North substation is connected to EAAR via Bela (Addis East2) and Cottobie lines/substations and to WAAR via Gefersa and Sebета1 lines/substations. Upgrading the transformers at Addis North substitution is also applied as mitigation technique in this region; i.e. upgrading the existing 2\*25MVA transformers into 2\*50MVA, and this has relieved the transformer overloads in the substation and so the weak voltage profiles on the buses.

This thesis work has obtained a solution to this problem by a project called ‘Sebeta1 – Addis West’ i.e. upgrading the two 45kV Sebeta1 – Addis West sub-transmission lines into 132kV, so that one 45kV bus at Sebeta-1 to supply Gedja substation only. The construction of this project for transmission line and substation upgrade is already started. Upgrading the transmission lines is found to be viable solution not only to voltage stability but also to increased reliability.

With the industrial expansion around Sebeta, Holeta, Gefersa areas, this transmission project enables to transfer power from Western & South-western regions to the load center, Addis Ababa. Sebeta1 – Addis West transmission/substation upgrading project will help in increasing power transfer to the most populated commercial place, Merkato, Sebategna, Kolfe, and Autobus Tera area in Addis Ababa, and improve the voltage profiles in the region. It may further be used in creating another route for strengthening the incomplete ring network around Addis Ababa as well, i.e. via Sebeta1, Addis West, and future transmission route to Gefersa, Addis North, or Addis Center.

Having this in mind, steady state voltage stability assessment has been made by including the upgrading project of Sebeta1 – Addis West 45kV into 132kV double lines in the existing high voltage grid and the results are discussed as follows.

This under construction project includes the following network parameters:

- a) Transmission line upgrades: Sebeta1 – Addis West upgrading of the double 45 kV transmission lines into 132kV.
- b) Two 132/15, two winding transformers at Addis West substation with a capacity of 50MVA each, and two 230/132 kV, two winding transformers at Sebeta1 substation with a capacity of 125MVA.

After applying the mitigation techniques, the voltage profiles of the buses in this region are improved within the acceptable limits. The single line diagram of the load flow simulations showing the voltage values at the buses by displaying ‘voltage limit checking’ results of West Addis Ababa area network model, the different techniques applied to mitigate the low voltage profiles in this region, and the resulting improved voltage profiles after mitigation is shown in figure 4.6 below.

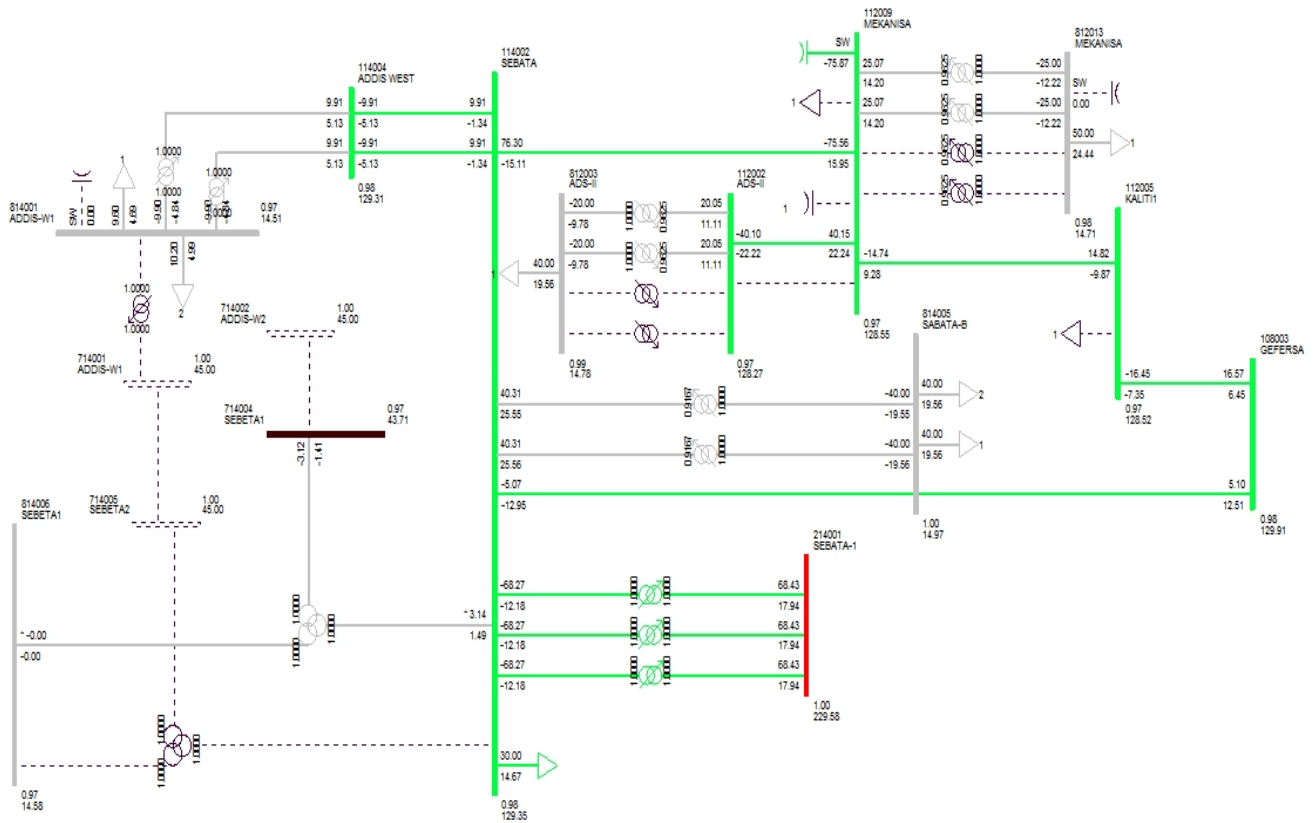


Figure 4-6: Single line diagram of West Addis Ababa region voltage profiles with mitigation techniques

After applying the mitigation techniques, all the previous yellow colored buses are improved and changed their colors in to the normal voltage level colors, i.e. green for 132kV, red for 230kV, and gray for 33 & 15kV, and dark brown for 45kV. The different mitigation techniques applied in WAAR to improve the low voltage profiles into the tolerable range are the following;

- Reactive compensation: 15MVAR shunt capacitor at Mekanissa substation
- Transmission line upgrade: Sebeta1- Addis West double 45kV lines into 132kV
- Transformer upgrade: 2\*25 MVA transformers (132/15kV) into 2\*50MVA at Addis North, 2\*12.5 MVA transformers into 2\*50MVA (four times) at Addis West, and two 230/132 kV 125MVA transformers added at Sebeta1 substation.

For further comparison, per unit voltages before and after the mitigation techniques, and the percentage voltage value improvements of most buses in WAAR are presented in table 4.4.

The per unit voltage values before and after mitigation techniques are also presented graphically in figure 4.7 below.

Table 4-4: Voltage value comparison before and after mitigation (West Addis Ababa area)

S. No.	Substation Bus –bar Name	Voltage Level (kV)	Voltage before Mitigation (pu)	Voltage after Mitigation (pu)	Improved Voltage in %
1	Sebeta-1	230	0.9673	1.00	3.27
2	Sebeta-1	132	0.9294	0.98	5.06
3	Sebeta-1 45 A1	45	0.8584	0.9713	11.29
4	Sebeta-1 45 A2	45	0.8505	Upgraded	
5	Sebeta-1 A	15	0.8531	0.972	11.89
6	Sebeta-1 B	15	0.9167	0.998	8.13
7	Addis West1	45	0.8161	Upgraded	
8	Addis West2	45	0.8280	Upgraded	
9	Addis West1	15	0.7647	0.9674	20.27
10	Addis West	132	New line	0.98	
11	Gedja	45	0.7932	0.983	18.98
12	Gedja	15	0.7852	0.9782	19.28
13	Mekanissa	132	0.9155	0.9739	5.84
14	Mekanissa	15	0.918	0.981	6.3
15	Addis South2 (Gofa)	132	0.913	0.9717	5.87
16	Addis South2 (Gofa)	15	0.846	0.9853	13.93
17	Gefersa	132	0.9368	0.9842	4.74
18	Kaliti-1	132	0.9345	0.9736	3.91

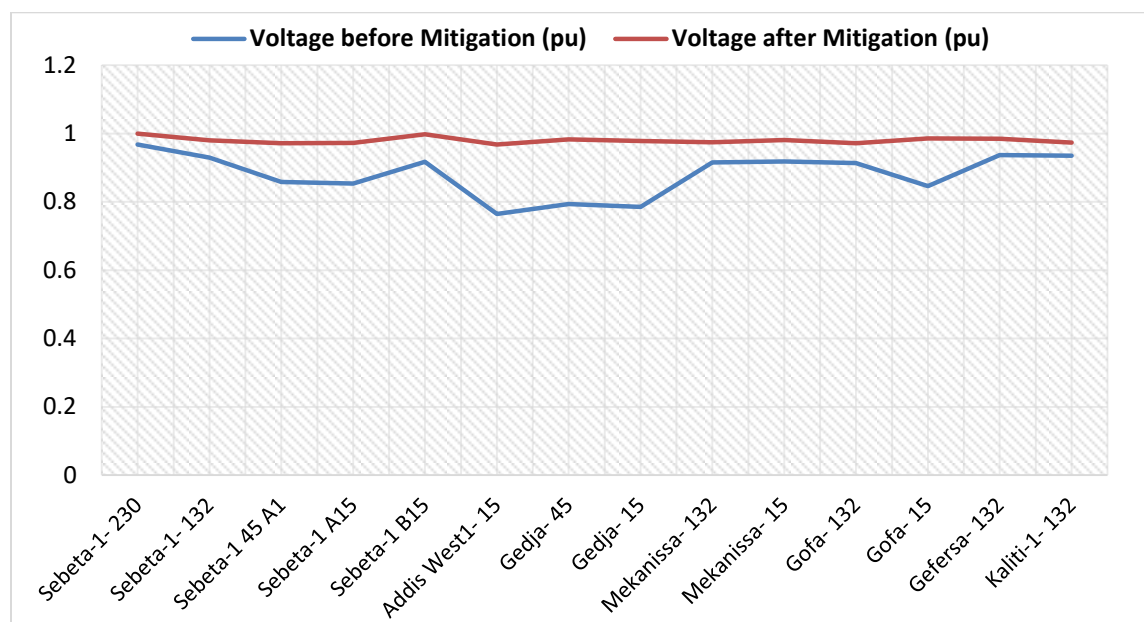


Figure 4-7: Per unit voltage values before & after mitigation techniques (WAAR)

As can be seen in table 4.4, the percentage improvement varies from 3.27% at Sebeta1 substation 230kV bus (which was already within limits) and 3.91% at Kaliti1 132kV bus to 20.27% at Addis West 15kV bus and to 19.28% at Gedja substation 15kV bus. The big percentage improvement at Addis West and Gedja substations is due to the substation and transmission upgrade at Addis West and this helped Gedja substation to be supplied alone from Sebeta1 45kV line (no sharing of 45kV bus with Addis West).

#### **4.3.1.2 East Addis Ababa Region (Cottobie Substation Area)**

This region includes substations such as Legetafo, Cottobie, Addis East I, Weregenu, Bela (Addis East-2), Bole Lemi, etc. Cottobie substation is connected to Legetafo, Ayat GIS, Debre Birhan, Addis East2 (Bela), Kaliti1, Weregenu, Kaliti North, Bole Lemi and radially to Addis East1 via 45kV line. This area is one of the regions with upcoming and existing industrial zones at Sendafa, Bole Lemi, and Legetafo, and residential condominium apartments at Ayat, and Yeka Abado. This thesis tried to optimally locate the reactive compensation, i.e. in Eastern and Western side of the city; so that the Southern Addis Ababa region's weak voltage profiles can also be improved.

Since Kaliti1 substation is located in between EAAR and WAAR, locating the reactive compensation around Sebeta1 and Cottobie is found to be reasonable. The same as West Addis Ababa region, this region suffers from having low voltages at peak time. The network model of load flow simulation of the existing system around East Addis Ababa region that indicates voltage profiles of the buses is shown in figure 4.8. Since the single line diagram of the load flow simulations' of the entire transmission grid is congested and not suitable to present here, this thesis prefers to draw only the regions with unacceptable voltage profiles.

The single line diagram of figure 4.8 is drawn by selecting one substation (Cottobie) and applying 'Grow N+1 network' to show the surrounding substations by focusing at East Addis Ababa region from the entire network diagram. Most bus voltages in this area are below the acceptable voltage limit i.e.  $<0.95pu$ . Coloring 'yellow' to identify unacceptable low voltage profiles is applied only at the buses, whereas the branch/transmission lines represent the same colors before and after the mitigation techniques. The single line diagram of figure 4.8 below and the 'voltage limit checking' simulation results at table 4.3 indicate that, this region faces under-voltages in many of its buses.



the simulation results obtained from the ‘voltage limit checking’ above, this problem needs some kind of complete and reliable mitigation approach.

By integrating the mitigation solutions in this area, the voltage profiles at all the buses is improved and almost all the bus terminal voltages become within the tolerable range of above 0.95 pu and less than 1.05pu. The simulation results for peak loading condition of bus voltages after applying the mitigation approach is shown in table 4.5 below.

As can be seen in the table below, buses at East and West Addis Ababa regions are improved into acceptable ranges, the remaining buses that are still below 0.95pu even if their voltage values are improved; are from South Addis Ababa region. Further analysis can be done considering the industrial load behavior at South Addis Ababa region, so that the voltage values can be improved.

*Table 4-5: Peak load flow ‘Voltage Limit Checking’ simulation result after mitigation*

```

PTI INTERACTIVE POWER SYSTEM SIMULATOR--PSS (R) E
ETHIOPIAN POWER SYSTEM TRANSMISSION STUDY
YEAR 2016 - PEAK LOAD FLOW
BUSES WITH VOLTAGE GREATER THAN 1.0500:
BUS No. Substation-Name BASKV AREA V (PU) V (KV)
814009 BUTAJIRA33 33.000 14 1.0531 34.754
BUSES WITH VOLTAGE LESS THAN 0.9500:
BUS# Substation-Name BASKV AREA V (PU) V (kV)
112003 DB-ZEIT2 132.00 12 0.9464 124.93
112015 DANGOTECEM 132.00 12 0.9362 123.58
802018 FITCHE 2 15.000 2 0.9472 14.208
712002 AKAKI 45.000 12 0.9234 41.551
712007 KALITI1 45.000 12 0.9348 42.066
112001 A.CENTER 132.00 12 0.9470 125.00
112004 DBZT2-TP 132.00 12 0.9466 124.95
712003 AKAKI-SP 45.000 12 0.9225 41.513
    
```

To improve the low voltage profiles in this area, different mitigation approaches are used first, such as installing 15MVar shunt capacitor at Weregenu substation 15kV bus side. The basis for selecting the shunt capacitor’s MVar rating at Weregenu substation is made by considering the reactive power consumed by the substation and the reactive power flow around the

substation while conducting load flow analysis using PSS/E so as to compensate the MVAR amount for voltage value improvement. The shunt capacitor bank at Gelan substation is also taken into consideration. This capacitor bank only helped in improving the bus voltages at Weregenu, but was not helpful to other surrounding substations. Even the voltage profile improvement at Weregenu was not satisfactory, since the reactive power consumed by the substation is comparable to the shunt capacitor MVAR value. The transformers upgrade work at Addis North substation (2\*25MVA into 2\*50MVA) implemented as mitigation method for West Addis Ababa area has an impact in this region as well, and this relieved the previous transformer overloads and so the weak voltage profiles mainly on the buses at Addis North substation and neighboring substations.

Considering the above reason, this thesis work has obtained a remarkable solution to this problem by a project called “Legetafo – Cottobie – Addis East-1’ i.e. upgrading the existing 132kV Legetafo – Cottobie line into 230kV and upgrading the 45kV Cottobie – Addis East1 sub-transmission line in to 132kV double transmission lines. The construction of this project, for transmission lines and substation upgrade is already started.

With the 100MW Debre Birhan wind farm under construction and the newly industrial expansion (like textile) around Legetafo, Sendafa, and Ayat; this transmission project enables to transfer power from the Northern and North-eastern corridors to Addis Ababa. The Legetafo – Cottobie transmission upgrade will help in strengthening the incomplete ring network around Addis Ababa, and increase power transfers to the load center i.e. via Cottobie, Addis East-2 (Bela), Addis North, to Gefersa and then to Sebeta1 and Mekanissa. Cottobie-Addis East1 upgrade solution can also serve additional customers around Hayahulet (22) Mazoria, Kazanchis, Adwa-Dildiy, Balderas, and Megenagna areas of Addis Ababa

Load flow simulation has been made on the existing transmission grid with and without including this upgrading project, and the voltage profile improvements are achieved to bring the low voltages within tolerable limits. Steady state voltage stability assessment has been made by including the upgrade project of Cottobie – Legetafo line and Cottobie – Addis East-1 double lines in the existing power system.

This under construction project includes the following additional network parameters:

- a) Transmission line upgrades, Legetafo – Cottobie upgrade from 132kV to 230kV and Cottobie –Addis East I upgrade from 45kV into 132 kV double lines.
- b) Two, 132/15kV two winding transformers at Addis East-1 substation with a capacity of 50MVA each, and two 230/132 kV two winding transformers at Cottobie substation with a capacity of 125MVA each.

After applying all the mitigation techniques, which are the Legetafo – Cottobie – Addis East-1 upgrade project, the transformers upgrade at Cottobie and Addis East1, and installing 15MVA shunt capacitor at Weregenu, the voltage profiles across the buses in the area are improved and become within the acceptable limit. The single line diagram of East Addis Ababa area network model, the different techniques applied to mitigate the low voltage profiles in this area, and the resulting voltage profiles at the buses is shown in figure 4.9 below.

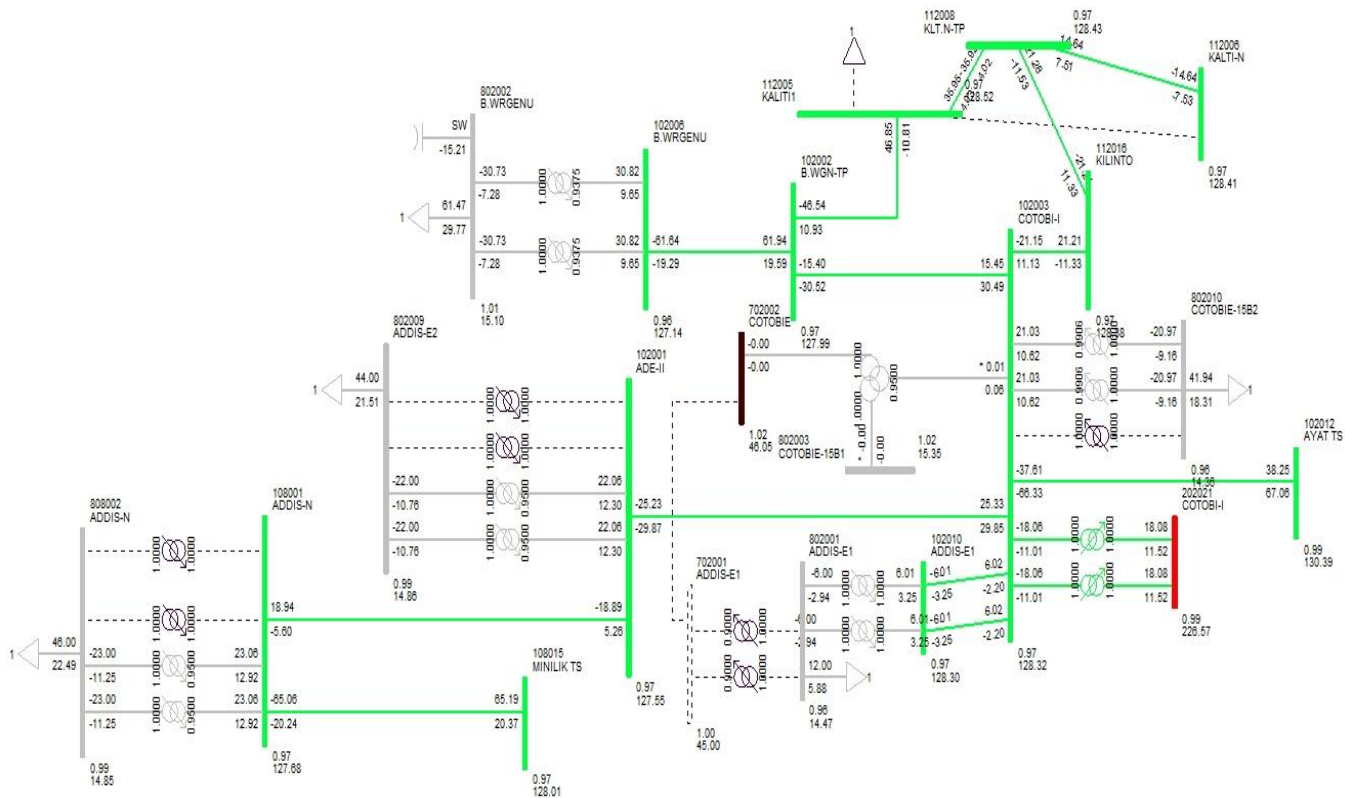


Figure 4-9: Single line diagram of East Addis Ababa region voltage profiles with mitigation techniques

We can see that, after applying the mitigation techniques, all the yellow colored buses are changed in to the normal voltage level colors, i.e. green for 132kV, red for 230kV, and gray for 33 & 15kV, and brown for 45kV. For further comparison, per unit voltages before and after

applying the mitigation techniques, and the percentage voltage improvements at buses in East Addis Ababa region are presented in table 4.6 below. The per unit voltage values before and after mitigation techniques are presented graphically in figure 4.10 below.

Table 4-6: Voltage comparison before and after mitigation (East Addis Ababa area)

S. No.	Substation Bus –bar Name	Voltage Level (kV)	Voltage before Mitigation (pu)	Voltage after Mitigation (pu)	Improved Voltage in %
1	Legetafo	230	0.9535	0.9937	4.02
2	Cottobie	132	0.937	0.9721	3.51
3	Cottobie	45	0.881	1.0233	14.23
4	Cottobie 15 Bus 1	15	0.877	1.0233	14.63
5	Cottobie 15 Bus 2	15	0.9185	0.964	4.55
6	Weregenu	132	0.9239	0.9632	3.93
7	Weregenu Tap	132	0.9327	0.971	3.83
8	Weregenu	15	0.946	1.006	6.0
9	Addis East2 (Bela)	132	0.8898	0.972	8.22
10	Addis East2 (Bela)	15	0.9073	0.992	8.47
11	Addis East1	132	New line	0.972	
12	Addis East1	45	0.845	Upgraded to 132	
13	Addis East1	15	0.8898	0.965	7.52
14	Addis North	132	0.903	0.969	6.6
15	Addis North	15	0.8187	0.99	<b>17.13</b>
16	Kaliti-1	132	0.9345	0.9736	3.95
17	Kaliti North Tap	132	0.9342	0.973	3.88
18	Kaliti North	132	0.934	0.9728	3.88

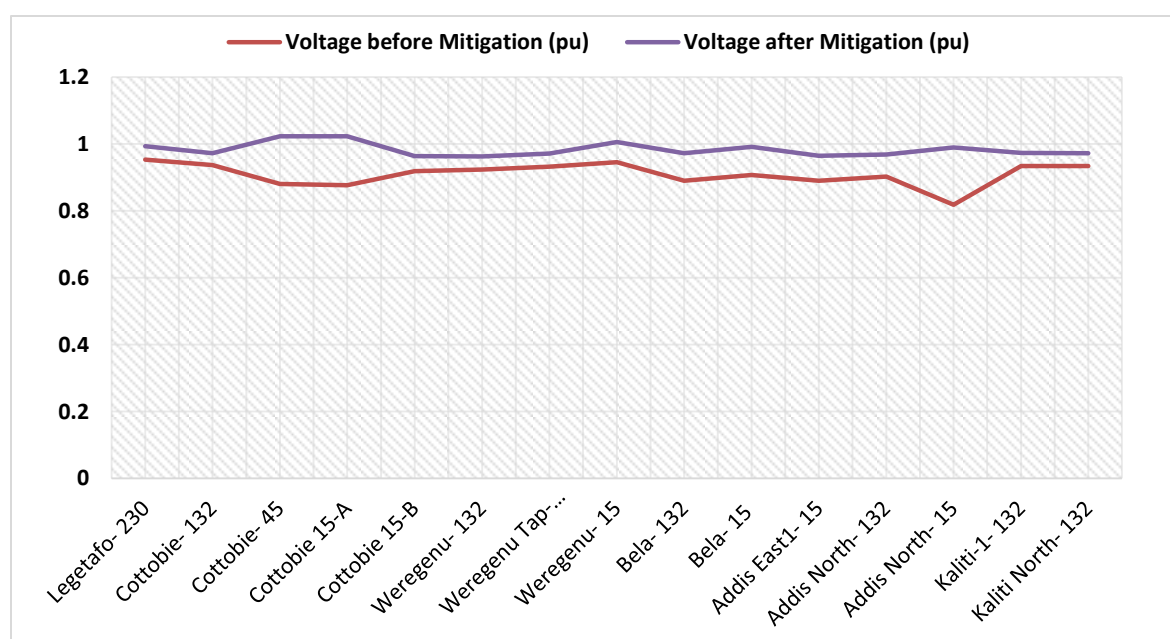


Figure 4-10: Per unit voltage values before & after mitigation techniques (EAAR)

Generally, the different mitigation techniques applied in East Addis Ababa region to improve the low voltage profiles into the tolerable range are the following;

- Reactive compensation: 15MVAR shunt capacitor at Weregenu substation;
- Transmission line upgrade: Legetafo – Cottobie 132kV lines into 230kV and Cottobie – Addis East1 single 45kV line into double 132kV lines;
- Transformer upgrade: 2\*12.5 MVA transformers into 2\*50MVA (four times) at Addis East1, and two 230/132 kV 125MVA transformers added at Cottobie substation.

As can be seen on table 4.6, the percentage improvement varies from 3.51% at Cottobie substation 132kV bus, up to 17.13% at Addis North 15kV bus. The big percentage improvement at Addis North substation is due to the transformers upgrade within the substation and, Addis North is benefiting from the mitigation techniques from East Addis Ababa and West Addis Ababa regions.

### **4.3.2 Case-2: Voltage Profile at Light Load Conditions with and without Mitigation Techniques**

According to Ethiopian power system's load curve, it is observed that daily minimum load is registered between 23:00 and 05:00 that is at 03:00, where the load drops down to almost one third of the peak load. Currently a system peak load of about 2,200 MW is reached at 19:00, whereas at 03:00 the system load is about 900MW [NLDC loading in Dec, 2016], hence many generating units are forced to be operated out of service.

During light-load condition, some of the modelled units of the hydro generation plants (PV buses) in the grid are put 'out of service' while conducting load flow simulations using PSS/E. At off-peak period, some power flow directions during peak hour might be changed, i.e. flows will only be towards industrial load area. The problem during light loading hours is that, an over voltage is observed in many areas/buses, that can be due to the long transmission lines, the remoteness of the generation stations, and the light loaded overall system.

The overall 'Voltage Limit checking' simulation result of Ethiopian power system at light-loading case is indicated in Appendix C. Region wise, the voltage profiles that passed 1.05pu during off-peak hour are listed here. The 'Voltage Limit checking' simulation result before applying the mitigation techniques in North-western region is listed in table 4.7 below. The

over voltages registered before mitigation in North-eastern, and Northern regions during light-load condition are listed in tables 4.8, and 4.9 respectively.

Table 4-7: North West Region Voltage Profile results for Light Load Case

BUS#	Substation-Name	BASKV	AREA	V (PU)	V (kV)
107003	PAWIE	132.00	7	1.0631	140.33
107004	BELESSUGRFAC	132.00	7	1.0658	140.68
107006	DANGLA-132	132.00	7	1.0512	138.76
<b>207002</b>	<b>DB-MRKOS</b>	<b>230.00</b>	<b>7</b>	<b>1.1181</b>	<b>257.15</b>
207003	GASHENA	230.00	7	1.0834	249.19
207004	GASHE-TA	230.00	7	1.0834	249.19
207007	MOTA	230.00	7	1.0802	248.44
207008	N.MEW TP	230.00	7	1.0685	245.75
207009	N.MEWCHA	230.00	7	1.0684	245.73
207011	WORETA	230.00	7	1.0557	242.81
607001	B.DAR1	66.000	7	1.0569	69.754
607002	B.DAR2	66.000	7	1.0603	69.980
<b>607003</b>	<b>BITCHENA</b>	<b>66.000</b>	<b>7</b>	<b>1.1336</b>	<b>74.818</b>
607004	DABAT	66.000	7	1.0524	69.456
<b>607006</b>	<b>DB.MARKS</b>	<b>66.000</b>	<b>7</b>	<b>1.1500</b>	<b>75.899</b>
<b>607007</b>	<b>FNOT-SLM</b>	<b>66.000</b>	<b>7</b>	<b>1.1194</b>	<b>73.882</b>
607008	GONDAR2	66.000	7	1.0667	70.402
607009	GONDER1	66.000	7	1.0649	70.281
607011	WORETA	66.000	7	1.0597	69.943
807002	B.DAR2-1	15.000	7	1.0568	15.852
<b>807003</b>	<b>BITCHENA</b>	<b>15.000</b>	<b>7</b>	<b>1.1260</b>	<b>16.890</b>
807004	DABAT	15.000	7	1.0609	15.914
<b>807006</b>	<b>DB-MRKOS</b>	<b>15.000</b>	<b>7</b>	<b>1.1479</b>	<b>17.219</b>
<b>807007</b>	<b>FNOT-SLM</b>	<b>15.000</b>	<b>7</b>	<b>1.1241</b>	<b>16.861</b>
807008	GASHENA	33.000	7	1.0576	34.900
807009	GONDAR2	33.000	7	1.0997	36.290
<b>807010</b>	<b>GONDER1</b>	<b>15.000</b>	<b>7</b>	<b>1.1091</b>	<b>16.636</b>
807011	METEMA	33.000	7	1.0846	35.791
<b>807012</b>	<b>MOTA</b>	<b>33.000</b>	<b>7</b>	<b>1.1056</b>	<b>36.485</b>
807013	NEFASMEWCHA	15.000	7	1.0659	15.989
807014	N-MEWCHA	33.000	7	1.0653	35.156
807015	PAWIE	15.000	7	1.0591	15.887
807018	GASHENA-15	15.000	7	1.0586	15.879
807019	GONDAR2	15.000	7	1.0552	15.827
807020	PAWIE	33.000	7	1.0612	35.018
807021	WORETA	15.000	7	1.0562	15.843
<b>807022</b>	<b>GONDER</b>	<b>15.000</b>	<b>7</b>	<b>1.1141</b>	<b>16.711</b>

Table 4-8: North-Eastern Region Voltage profile results for Light-load case

BUS#	Substation-Name	BASKV	AREA	V (PU)	V (kV)
106001	A-KETEMA	132.00	6	1.1033	145.64
106002	AKSTA	132.00	6	1.1126	146.86
106003	COMBOL-I	132.00	6	1.1028	145.57
106004	SHWA-RBT	132.00	6	1.0920	144.15
<b>106005</b>	<b>COMBOL-II</b>	<b>132.00</b>	<b>6</b>	<b>1.1072</b>	<b>146.15</b>
<b>206001</b>	<b>COMBOL-II</b>	<b>230.00</b>	<b>6</b>	<b>1.1040</b>	<b>253.92</b>
606001	AKSTA	66.000	6	1.1019	72.725
<b>606002</b>	<b>COMBO-1</b>	<b>66.000</b>	<b>6</b>	<b>1.1030</b>	<b>72.801</b>
606003	DESIE	66.000	6	1.0944	72.231
606004	LALIBELA	66.000	6	1.0626	70.134
606005	SEKOTA	66.000	6	1.0660	70.358
606006	WOLDIA	66.000	6	1.0982	72.482
<b>806001</b>	<b>A-KETEMA</b>	<b>33.000</b>	<b>6</b>	<b>1.1148</b>	<b>36.788</b>
806003	COMBOL-1	15.000	6	1.0928	16.392
806005	LALIBELA	15.000	6	1.0588	15.883
806006	SEKOTA	15.000	6	1.0737	16.105
806007	SHWA-RBT	15.000	6	1.1327	16.990
806009	KEMISS33	33.000	6	1.1151	36.800
806010	KEMISS15	15.000	6	1.1151	16.727

Table 4-9: Northern Region voltage profile results for Light-load case

BUS#	Substation-Name	BASKV	AREA	V (PU)	V (kV)
109001	ADIGRAT	132.00	9	1.0563	139.44
109002	ADWA	132.00	9	1.0535	139.06
109003	ALAMATA	132.00	9	1.0739	141.76
109004	MEKELE	132.00	9	1.0578	139.63
109005	MESOBO	132.00	9	1.0560	139.39
109007	WUKRO	132.00	9	1.0575	139.60
209001	ALAMATA	230.00	9	1.0864	249.88
209004	MEKELE	230.00	9	1.0657	245.12
209007	MEHONI	230.00	9	1.0828	249.04
209013	ASHEGODA WF	230.00	9	1.0683	245.71
<b>609001</b>	<b>ADIGRAT</b>	<b>66.000</b>	<b>9</b>	<b>1.1059</b>	<b>72.988</b>
609003	ALAMATA	66.000	9	1.0761	71.021
609004	MAYCHEW	66.000	9	1.0709	70.677
809002	ADWA	15.000	9	1.0980	16.470
809005	MYCHEW	15.000	9	1.0678	16.016
809006	MEKELE	15.000	9	1.0518	15.777
809008	ENDASILASIE	15.000	9	1.0603	15.905
809012	ALAMATA2	15.000	9	1.0750	16.124
809015	MEKHONI33	33.000	9	1.0811	35.675

During load flow simulations using PSS/E on the entire system for light load condition, unacceptable high voltages have been registered mainly at North-western (Bahirdar & Debre Markos area), North-eastern (Combolcha area), and Northern (Alamata area). Out of the three regions with unacceptable high voltages at off-peak time, this thesis selects North-western region where majority of the over voltages are registered. This region owns the longest 400kV transmission lines in the existing grid, which transmit power from Beles via Bahirdar, Debre Markos, and Sululta to Addis Ababa. Another 400kV transmission line that interconnects GERD with Beles power plant to be commissioned in near future is also located in this region.

As can be seen in the simulation result from PSS/E above, most buses in North-western region have registered over-voltages. In actual case, the system operators at NLDC are doing de-energizing of some high voltage lines at off-peak hours for voltage control in this region. The lines that are forced to be de-energized during light load conditions include; either of Sebeta2 – Gibe2, or Bahirdar2 – Debre Markos 400kV lines, and sometimes either of 230 kV lines of Combolcha – Legetafo, Ramo – Gode, Koka – Melka Wakena one line etc,

The single line diagram of the load flow simulation results of North-western region before applying mitigation that displays the voltage values at the buses is shown in figure 4.11 below. Since the single line diagram of the load flow simulations' of the entire transmission grid is jammed and not suitable to display here, this thesis prefers to draw only the regions with unacceptable voltage profiles. The single line diagram at figure 4.11 is drawn by selecting one substation (Debre Markos) and applying 'Grow N+1 network' to show the surrounding substations by focusing at North-western region from the entire network diagram.

Lots of over-voltages are registered in this area especially at Debre Markos substation. Debre Markos substation is connected to Bahirdar and Sululta stations with long 400kV lines, and also there is another 230kV route from Bahirdar2 via Mota to Debre Markos and from Debre Markos via Finchaa, Ghedo then to Gefersa. The unacceptable high voltage profiles occurred in this region is mainly in the 230kV, 132kV, & 66kV buses.

In the single line diagram of simulation results below, the '**light blue**' colors at the buses indicate that, unacceptable high voltages during light load condition. Substations such as, Debre Markos, Mota, Bahirdar-2, Nifas Mewcha, Gashena, Alamata have registered unacceptable high voltage profiles. The red colors represent 230kV, green for 132kV, dark

blue for 66kV, and gray color represent 33kV or 15kV lines and also buses which are within acceptable voltage limits. The blue coloring to identify unacceptable low voltage profiles is applied automatically only at the buses, whereas the branch/transmission lines represent the same colors before and after the mitigation techniques.

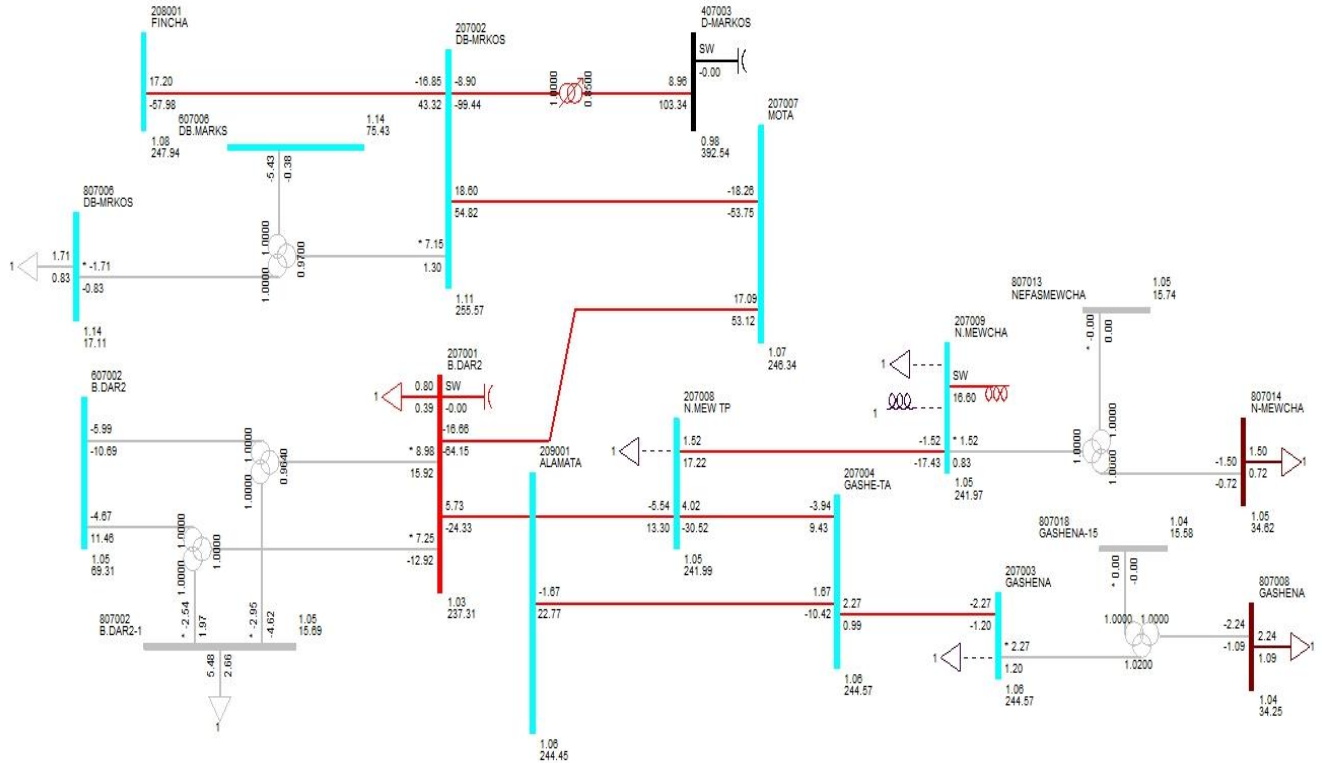


Figure 4-11: Over voltages during light load condition of North-western region

Since North-western region is interconnected with Northern and North-eastern regions, the voltage compensation method applied in it also helps in improving the voltage profile in these two neighboring regions. Similar mitigation techniques can be applied to these two regions, i.e. North-eastern & Northern regions. Whereas these regions do not contain 400kV transmission lines, so that suitable mitigation method shall be implemented.

After doing repeated load flow simulations with PSS/E to mitigate the over-voltages in Bahirdar area, shunt reactors are modelled with a capacity of 45MVAR at Debre Markos substation 230kV bus, 30MVAR at Gashena substations 230 kV bus side, and 15MVAR at Nifas Mewcha 230kV bus side. Adjusting the transformer tap changing ratio at the three winding 230/66/15kV transformer and the 400/230kV auto-transformer is done and brought some substations that are radially connected to Debre Markos substation in to acceptable limits.

The criteria for selecting the shunt reactor’s MVAR rating at these substations is made by considering the 70% of the no-load (energization) condition of the reactive power that can be generated by the lines and SIL of Bahirdar-II - Debre Markos - Sululta 400kV line. While conducting load flow simulations using PSS/E, the existing shunt reactors’ MVAR capacity at Debre Markos, Bahirdar-II, and other substations is also considered so as to compensate the excess MVAR amount.

Debre Markos and Gashena substations are selected for shunt reactor installations, because they have registered the biggest unacceptable high voltage values in the region and due to their suitable locations. Debre Markos’s voltage values are 1.1181pu at 230kV, 1.150pu at 66kV bus, and 1.1479pu at 15kV bus. Gashena and Nifas Mewcha substations are selected because they serve as interconnection of North-western region with North-eastern and Northern regions and registered high unacceptable voltage profile when compared to the other surrounding stations. Since the load around Nifas Mewcha and Gashena is so small (<3MW), it’s likely to happen over voltages on the lines around this area

After applying the voltage mitigation techniques, the voltage profiles (voltage limit checking results) of the buses at North-western region is listed in table 4.10 below.

*Table 4-10: Light load voltage profiles of North-Western Region after mitigation*

**PTI INTERACTIVE POWER SYSTEM SIMULATOR--PSS (R) E**  
**ETHIOPIAN POWER SYSTEM TRANSMISSION STUDY**  
 YEAR 2016 - LIGHT LOAD FLOW  
**BUSES WITH VOLTAGE GREATER THAN 1.0500:**

<b>BUS#</b>	<b>Substation-Name</b>	<b>BASKV</b>	<b>AREA</b>	<b>V (PU)</b>	<b>V (KV)</b>
807009	GONDAR2	33.000	7	1.0722	35.383
807010	GONDER1	15.000	7	1.0798	16.197
807011	METEMA	33.000	7	1.0709	35.338
807022	GONDER	15.000	7	1.0845	16.267

**BUSES WITH VOLTAGE LESS THAN 0.9500:**

<b>BUS#</b>	<b>Substation Name</b>	<b>BASKV</b>	<b>AREA</b>	<b>V (PU)</b>	<b>V (KV)</b>
607007	Finote-Selam	66.000	7	0.9480	62.568

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The mitigation techniques for correcting the voltage profiles at North-western region is helping in improving the profiles of neighboring North-eastern and Northern regions, mainly the shunt

reactors placed at Gashena and Nifas Mewcha substations contributes to these two regions. After applying the mitigation techniques at North-western region, the voltage profiles (‘voltage limit checking’ result) of the buses at both North-eastern and Northern regions is listed in table 4.11 below. After applying the mitigation approaches the bus voltage levels that were above the tolerable limit become within the limits of less than 1.05pu.

In actual case, during light load periods there might be only reactive power flows with almost zero MW active power flow at transmission lines such as Bahir Dar- Gashena- Alamata 230kV, and Bahir Dar-II – Mota – Debre Markos 230kV routes.

*Table 4-11: Light load voltage profiles of the Ethiopian grid after mitigation*

<b>BUS#</b>	<b>Substation-Name</b>	<b>BASKV</b>	<b>AREA</b>	<b>V (PU)</b>	<b>V (KV)</b>
106001	A-KETEMA	132.00	6	1.0782	142.29
106002	AKSTA	132.00	6	1.0909	143.99
106003	COMBOL-I	132.00	6	1.0762	142.06
106004	SHWA-RBT	132.00	6	1.0676	140.92
106005	COMBOL-II	132.00	6	1.0764	142.08
106006	KEMISSIE	132.00	6	1.0753	141.94
206001	COMBOL-II	230.00	6	1.0726	246.69
606001	AKSTA	66.000	6	1.1675	77.057
606002	COMBO-1	66.000	6	1.0720	70.749
606003	DESIE	66.000	6	1.0630	70.158
606006	WOLDIA	66.000	6	1.0667	70.401
609001	ADIGRAT	66.000	9	1.0800	71.278
806001	A-KETEMA	33.000	6	1.1410	37.652
806002	AKSTA	33.000	6	1.1590	38.246
806003	COMBOL-1	15.000	6	1.0618	15.927
806004	DESIE	15.000	6	1.1594	17.391
806007	SHWA-RBT	15.000	6	1.1069	16.604
806008	WOLDIA	15.000	6	1.1427	17.141
806009	KEMISS33	33.000	6	1.0862	35.844
806010	KEMISS15	15.000	6	1.0862	16.293
807009	GONDAR2	33.000	7	1.0722	35.383
807010	GONDER1	15.000	7	1.0798	16.197
807011	METEMA	33.000	7	1.0709	35.338
807022	GONDER	15.000	7	1.0845	16.267
809001	ADIGRAT	15.000	9	1.0779	16.168
809002	ADWA	15.000	9	1.0716	16.073
809008	ENDASILASSIE	15.000	9	1.0603	15.905
809011	WUKRO	15.000	9	1.0763	16.145

As can be seen in the load flow simulation results of table 4.11, some of the bus voltage profiles are still above the acceptable range, so that optimum shunt compensation system shall be provided. To provide shunt compensation, identifying the optimum placement and magnitude of the compensator is very essential and the optimization shall be done in these two regions as well. The single line diagram (network diagram) of North-western region (Debre Markos area) with ‘Voltage limit checking’ simulation results after applying mitigation techniques is shown in figure 4.12 below.

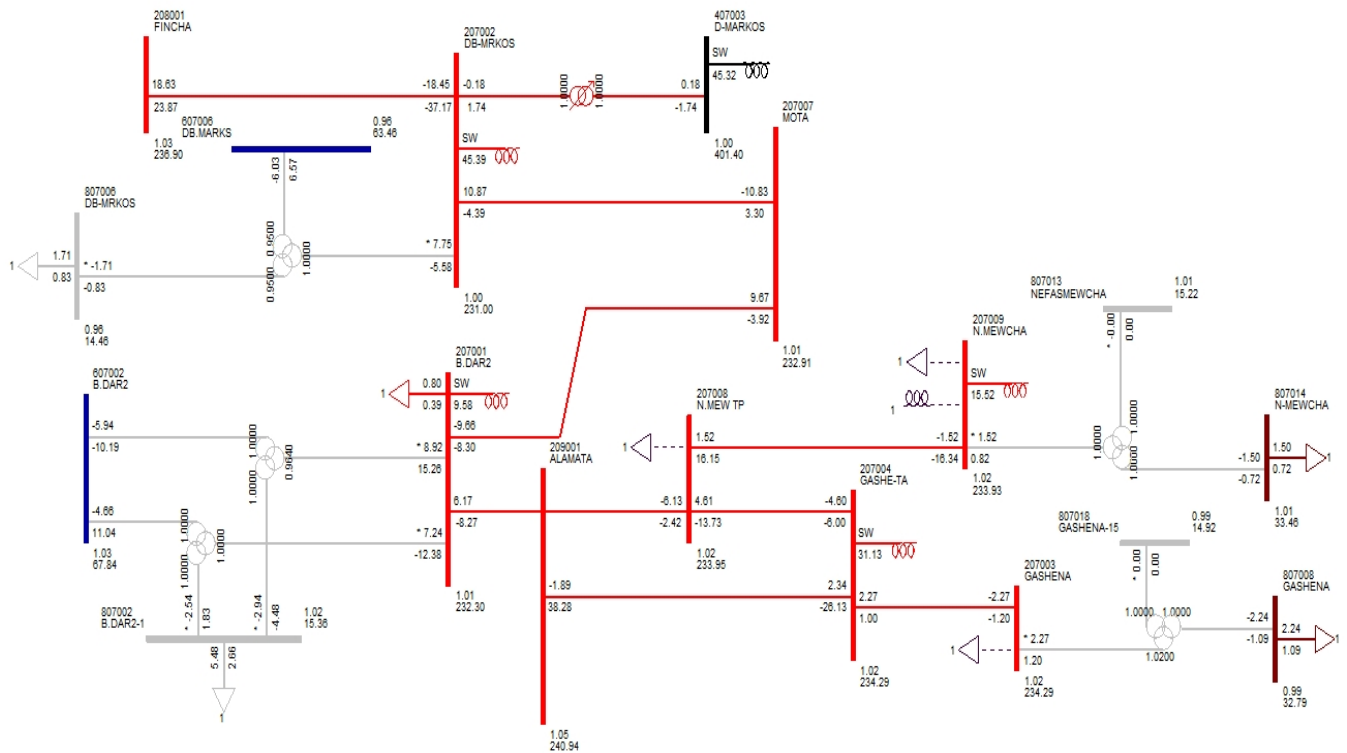


Figure 4-12: North-western region voltage profiles after applying mitigation techniques.

Here all the previous ‘light blue’ colored buses that have registered unacceptable low voltage values are changed in to the normal voltage level colors, i.e. green for 132kV bus, red for 230kV bus, dark blue for 66kV bus, and gray for 33 & 15kV buses. For further comparison, the voltage profiles before and after applying the reactive compensation in per unit, and the percentage voltage value improvement is listed in the table 4.12, and the graphical per unit voltage comparison is shown in figure 4.13 below.

As can be seen in table 4.12 below, the percentage voltage value improvements vary from (-) 1.53% at Alamata substation 230kV bus (which is far from Debre Markos substation and located in Northern region), to -18.08% at Debre Markos substation 66kV bus, where the shunt

reactive compensation is installed. The negative percentage values indicate that, the unacceptable high voltage values are reduced and brought to less than 1.05pu tolerable range. The big percentage improvement at Debre Markos substations is due to the installation of 50MVA additional shunt reactor at the station.

Table 4-12: Voltage profile comparison before and after mitigation (North-Western region)

S. No.	Substation/Bus-bar Name	Voltage Level (kV)	Voltage before Mitigation (pu)	Voltage after Mitigation (pu)	Improved Voltage in %
1	Bahir Dar-2	230	1.0318	1.01	-2.18
2	Bahir Dar-2	66	1.0502	1.0279	-2.23
3	Bahir Dar-2	15	1.046	1.024	-2.2
4	Debre Markos	230	1.1181	1.0043	-11.38
5	Debre Markos	66	1.1428	0.962	<b>-18.08</b>
6	Debre Markos	15	1.1407	0.964	<b>-17.67</b>
7	Mota	230	1.0710	1.0126	-5.84
8	Nifas Mewcha Tap	230	1.0685	1.0172	-5.13
9	Nifas Mewcha	230	1.0684	1.0171	-5.13
10	Nifas Mewcha	33	1.0491	1.0139	-3.52
11	Nifas Mewcha	15	1.0493	1.0147	-3.46
12	Gashena Tap	230	1.0633	1.0186	-4.47
13	Gashena	230	1.0834	1.0186	-6.48
14	Gashena	33	1.0834	0.9936	-8.98
15	Gashena	15	1.0387	0.9947	-4.4
16	Finchaa	230	1.0825	1.0387	-4.38
17	Alamata	230	1.0628	1.0475	-1.53

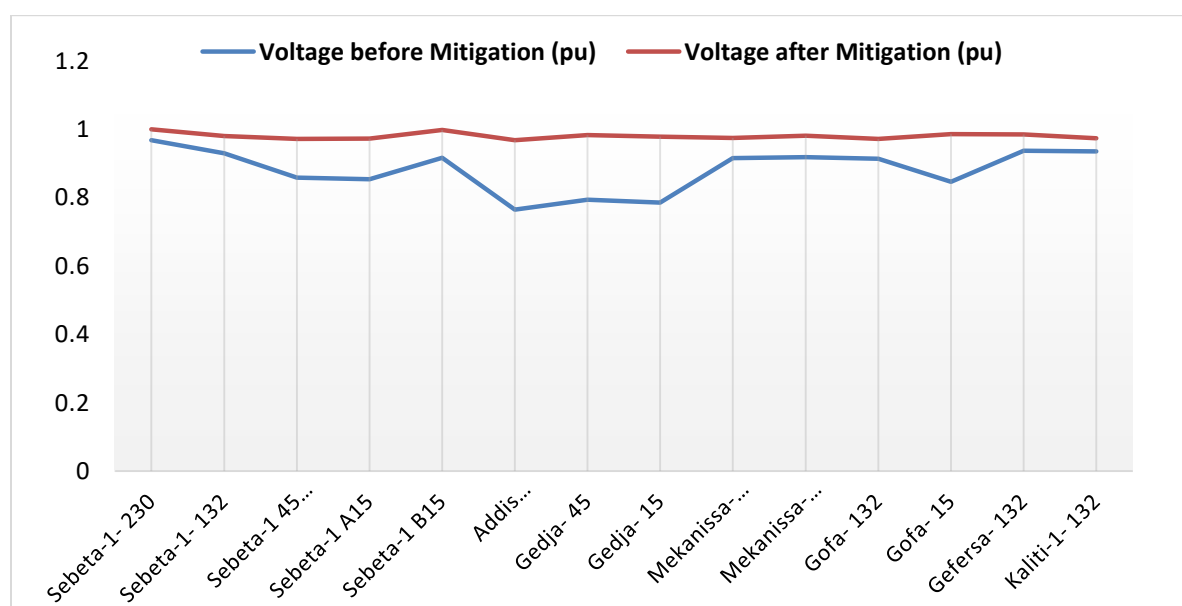


Figure 4-13: Per unit voltage values before & after mitigation techniques North-Western region

## 4.4 Blackout Occurrences in Ethiopian Power System

Power outages are categorized into three different phenomena, relating to the duration and effect of the outage:

- A blackout is the total loss of power to a geographic area and is the most severe form of power outage that occurs. Depending on the root cause of the blackout, restoring power is often a complex task that utilities and power stations must undertake and repair timeframes vary greatly depending on the configuration of the affected electrical network. Outages may last from a few minutes to a few weeks depending on the nature of the blackout and the configuration of the electrical network.
- A permanent fault is a massive loss of power typically caused by a fault on a power line. Power is automatically restored once the fault is cleared.
- A brownout (the term comes from the dimming experienced by lighting when the voltage sags) is a drop in voltage in an electrical power supply. Brownouts can cause poor performance of equipment or even incorrect operation.

In Ethiopian power system total and partial blackout is occurring repeatedly. Sometimes, total shutdown of the network may happen twice a day. Currently the frequency of blackout occurrence is decreasing from year to year. The reason can be the newly energized transmission lines that contribute in improving the N-1 security criterion. The newly energized Gilgel Gibe 3 power plant is another means of strengthening the system mainly from the southern side of the grid. The blackout data of Ethiopian grid in 2015 and 2016 is presented in this thesis. As can be seen in the table below, the black out in 2015 is more frequent than that of 2016, and in 2015 the blackout incidents are mostly total shutdown. System collapse/blackouts in Ethiopian power system occurred in 2015 and 2016 are briefly presented in below tables 4.13 and 4.14 respectively.

Table 4-13: Blackout data of Ethiopian power system in 2015

S. No.	Date	Time of Event	Affected Regions/Areas	Plant &/or Element Directly Involved	Event Triggering Element/Branch	Pre-Fault Conditions	Restorstion Time (Minutes)
1	15-Jan-15	16:11	Western region, 1st & 2nd stage under freq	Fincha, Neshe & Gibe1, Ghedo 230/132 Trafo	Earth fault on D/markos Fincha 230kV line	Generation 1176.3 MW, Export 37 MW, 50Hz,	Under freq shedded loads in 20mins & Western loads in 125 mins
2	15-Mar-15	14:30	All region/areas except Bahirdar & Gondar	All power plants except Beles U4	Overcurrent at Bahirdar-Markos 400kV line with 318 MW loading	Generation 983 MW, Export 42.9MW, 50Hz,	60 mins to restore >80% of the system load
3	22-Apr-15	20:20	All regions/areas (Total Blackout)	All power plants & Ss	Earth fault on Finchaa-Markos 230kV line	Generation 1306.3 MW, Export - 14.4MW, 50Hz,	83 mins to restore first loads in Addis,
4	8-May-15	1:54	All regions/areas (Total Blackout)	All plants & Ss except 1 unit at Beles	Transient earth fault at Bahirdar-Markos 400kV line	Generation 746.4MW, Export 35.36 MW, 50Hz,	111 mins to restore important loads in Addis
5	26-May-15	6:43	All regions except West & Northwest	All plants except Beles & Finchaa	Earth fault on Sebeta2-Gibe2 400kV line	Generation 1,077.1 MW, Export 51.6MW, 50Hz,	29 mins to connect 1st loads in Addis & 2 hours to restore the sys
6	23-Jul-15	0:20	All regions except the Isolated North region	Beles, Neshe, Koka, Awash 2&3, & Adama 1&2	Beles trips by Busbar transfer & Leads to over V at Bahirdar lines	Generation 878 MW, Export 18.46 MW, 50Hz,	36mins to connect 1st loads in Addis & 80% load is restored after 2 hrs
7	27-Jul-15	14:34	All regions except Northwest & Ghedo SS	All plants except 2 units of Beles	Earth fault on Sebeta2-Gibe2 400kV & Kaiti1-Sebeta1 230kV lines	Generation 1261.2MW, Export 8.46MW, 50Hz,	31mins to connect 1st loads in Addis & 80% load is restored after 2 hrs
8	14-Aug-15	10:00	All regions except Northwest & Ghedo SS	All plants except Beles & Ss except Ghedo & Nwest	Flame on Gefersa- Addis Alem 45kV line that burns T phase	Generation 1420MW, Export 31.55 MW, 50Hz,	40 mins to connect first loads in Addis & 80% load is restored within 2 hours
S. No.	Date	Time of Event	Affected Regions/Areas	Plant &/or Element Directly Involved	Event Triggering Element/Branch	Pre-Fault Conditions	Restorstion Time (Minutes)
9	16-Aug-15	23:16	East, Northeast, North, Central & partial Addis	Tekeze, Koka, Wakena, Gibe2 (2 units), all Wind	A flame on 230/132kV Transformer1 at Sebeta1 SS	Generation 938.72 MW, Export 19 MW, 50Hz,	16 mins to connect first loads & most Ss connected in 75 mins
10	28-Nov-15	12:31	All regions/areas (Total Blackout)	All power plants & Ss tripped	Earthfault on GERD-Beles 400kV line & Teleprotection signal at Beles- Bahirdar2 400kV 2 lines	Generation 1,318.04 MW, Export 24.74MW, 50Hz,	219 mins to connect first loads & most Ss connected within 4 hours
11	29-Nov-15	15:43	All regions/areas (Total Blackout)	All power plants & Ss tripped	Teleprotection signal at Beles- Bahirdar2 400kV line 1	Generation 1081.32 MW, Export 26.96 MW, 50Hz,	55 mins to connect first loads & most Ss connected within 2 hours
12	29-Nov-15	19:27	All regions/areas (Total Blackout)	All power plants & Ss tripped	Earth fault (LL) at Ghedo-Sekoru 230kV line	Generation 1145.2 MW, Export 0 MW, 50Hz,	System was recovering from previous blackout. It took >2hours to restore most Ss.
13	11-Dec-15	5:53	All regions/areas (Total Blackout)	All power plants & Ss Except Unit 2 of Beles	Earth fault on Kaliti1-Mekanisa 132kV line	Generation 880.6 MW, Export 0 MW, 50Hz, Some lines were out for work	35 mins to connect important loads & most Ss connected within 2 & half hours
14	22-Dec-15	15:07	All regions except Northwest region	All power plants & Ss Except Beles	Earth fault at Gefersa-Sululta & Ghedo-Gefersa 230kV lines	Generation 1239.8 MW, Export 19.56 MW, 50Hz,	35 mins to connect important loads & most Ss connected in 2 hrs
15	25-Dec-15	4:34	All regions/areas (Total Blackout)	All power plants & Ss tripped	Over-voltage during Bahirdar2-D.markos 400kV line energization	Generation 838.96 MW, Export 38.5 MW, 50Hz,	42 mins to connect important loads & most Ss connected in 2 hrs

Table 4-14: Blackout data of Ethiopian power system in 2016

S. No.	Date	Time of Event	Affected Area/ Loads	Plant &/or Equipment Involved	Event Triggering Line	Pre-Fault Conditions	Restorstion Time (Minutes)
1	6-Jan-16	15:16	South, West, Addis, East, Central Regions	All Power plants except Beles	Earth fault on Sekoru-Gibe2-Sebeta2 400kV line	Generation 1300MW, Exoort 16MW, 50Hz,	Most SSs in 95min & First Loads in 20min
2	17-Jan-16	7:59	All regions affected (Total Blackout)	All power plants	All units of Beles tripped when the DC supply is transferred from bank A to bank B	Generation 1322.61MW, Export 37.5MW, 50Hz	Most SSs after 120mins & First Loads in Addis in 1 hour
3	22-Feb-16	9:09	All regions affected (Total Blackout)	All power plants & SSs	When W.Sodo2-Gibe3 400kV Line 2 is connected- Distance protection	Generation 1300MW, Export 39MW, 50Hz,	Most SSs in 120 min & First Loads in 20min
4	2-Mar-16	20:41	Feeders set with 1st &2nd stage Under-frequency load shedding	Isolation of Beles and Fincha from the grid	Short Circuit on Ghedo-Gefersa 230kV line & Ghedo-Fincha line tripped	Generation 1,575.6MW, 50Hz	Under-freq shedded loads connected in 30 mins, survived total blackout
5	6-Mar-16	16:03	1st & 2nd stage under frequency & other load shedding action	Gibe3, Gibe2, Fincha, Tekeze, Adama2	Earth fault on Gelan-W.Sodo2 400kV line, Sebeta2- Gelan 400kV line by Over-voltage	Generation 1319MW, Export 39MW, 50Hz,	Under-freq shedded loads connected in 40 mins, survived total blackout
6	6-Mar-16	19:19	1st & 2nd stage under frequency & other load shedding action	Gibe3 tripped again at 19:19 & 21:54 & system survived.	Tripping of all units at Gibe3 with a loading of 300MW	Generation 1,534.6MW, Export 22MW, 50Hz	System survived from blackout by the updated under-Frequency relays

S. No.	Date	Time of Event	Affected Area/ Loads	Plant &/or Equipment Involved	Event Triggering Line	Pre-Fault Conditions	Restorstion Time (Minutes)
7	13-Apr-16	19:14	Feeders set with Under frequency load shedding	Isolation of Beles from the Grid	Earth fault at Ghedo-Gefersa, & Fincha-Ghedo 230kV lines	Generation 1,573MW, Export 21MW, 50Hz	Most SSs after 120mins & First Loads in Addis in 36 mins, Isolation occurred
8	16-May-16	2:00	Load rejection of 41% & over voltage occurs	Gibe3, Wakena, Koka, Awash 2&3, Adama 1&2	Earth fault at Kaliti1-Kaliti-North tap & Cascade tripping of Kaliti1-Sebeta1 230kV line	Generation 813.3MW, Export 136.88MW, 50Hz,	Most SSs after 3 hrs & First Loads in Addis in 90 mins
9	25-Jun-16	11:19	44% of the demand affected	Gibe3, Tekeze, Adama1,	Earth fault at Gelan-W.Sodo2 400kV line	Generation 1691.8MW, Export 201MW, 50Hz,	System survived by 3rd under-frequency shedding stage
10	18-Jul-16	15:38	26% of the demand (East Addis Ababa & Eastern Region)	Gibe2 (U1,3&4), Adama2, Gibe1 (U1&2), tekeze (U1)	Earth fault at egetafo-Combolcha2 & Legetafo-Kalit1 230kV lines	Generation 1800.92MW, Export 333MW, 50Hz,	System survived with the 26% load interrupted
11	31-Jul-16	3:54	All regions except North West (Bahirdar area)	All power plants & SSs except 2 units of Beles	Tripping of all units at Gibe3	Generation 792.22MW, Export 98MW, 50Hz,	Most SSs restored within 2 hours & First Loads in Addis in 58 mins
12	7-Nov-16	3:00	All regions affected	All power plants & SSs	Tripping of Unit 8 of Gibe3	Generation 782 MW, Export 50 MW, 50Hz,	Most SSs restored in 2 hours & First Loads in Addis in 30mins
13	30-Dec-16	8:42	All power plants & SSs	All power plants & SSs	Tripping of both 400kV Gibe3-W.Sodo lines by human mistake	Generation 1517.96 MW, Export 29 MW, 49.5Hz,	Most SSs restored in 80 mins & First Loads in Addis in 45mins

In 2015 fifteen blackouts occurred excluding the tripping of radially connected transmission lines and substations that did not lead into cascaded tripping.

The incidents that lead the power system to collapse and the area affected, or the system isolations leading to some generating stations to supply in island mode is presented.

#### 4.4.1 Blackout Incidents on Ethiopian Power System in 2015

- 1- The earth fault at Finchaa - Ghedo line leads to the opening of Ghedo - Sekoru 230kV line with a Zone 3 protection. The one & half bus-bar arrangement and the circuit breakers at Ghedo substation made the system to continue in to a cascaded tripping. Since the circuit breakers at Ghedo substation were not acting and one was out of service and the fault was not cleared at Zone 1 protection; a cascaded tripping of these lines forced the power plants in Western region (i.e. Finchaa, Amerti Neshe, & Gibe1) to trip. The first and second stage under-frequency load shedding cannot compensate the generation lost, and hence leads to about 80 % of the system to blackout.
- 2- Tripping of Bahir Dar2 – Debre Markos 400kV transmission line with a loading of 318MW by earth fault, resulted in to cascaded tripping of the neighboring 230kV transmission lines which are Bahirdar2 – Alamata and Bahirdar2 – Mota – Debre Markos (alternate path for the power flow, if in case this 400kV line trips) by overload (over current). The grid lost 57% of its generation which is unlikely to survive with the existing system defense mechanism (under frequency relays action) that has to be updated.
- 3- Earth fault occurred on phase B of Finchaa – Debre Markos 230kV line at 20:20 and the fault is cleared from Debre Markos end but not from Finchaa end, which resulted in tripping of Finchaa generating units by under frequency. Following the above event Amerti Neshe and Tis Abay2 power plants tripped by *loss of voltage* and under frequency consecutively. Sudan was supplying 33MW to Ethiopia and the interconnection power flow increased from 33 to 138MW (there was a time Sudan supplying to Ethiopia during evening peak hours and importing the rest of the day). The interconnector trips by under frequency at Shehedi (Metema) end at 20:20. Following the above event the system lost 18% of the generation and the frequency regulating plant i.e. Beles’s generation increased from 410MW to 461MW. However, the units of Beles tripped by bus bar circuit breaker failure (CBF) protection and the whole system collapsed at 20:21. Following the outage of

Beles, the system lost 49.7% of its generation which is unlikely to survive with the existing under frequency load shedding.

- 4- Bahirdar2 – Debre Markos 400kV line tripped by transient earth fault on phase B at 01:51, which resulted in cascaded outage of Bahirdar2 – Mota – Debre Markos and Bahirdar2 – Alamata 230kV lines by overload. Following this, Beles and Tekeze power plants became isolated from the grid with a total generation of 472MW (63% share), and led all power plants except one unit at Beles to trip by under frequency, which resulted in a total blackout. Delay of planned interruptions on transmission lines or power plants for protection purpose is also making the incidence worse. The planned outage (for maintenance) of a line or units may stay for more than 10 days; and at such scenario when a fault occurs the system is unlikely to survive since the alternate path may already be open.
- 5- The initiating event is the tripping of Sebeta2 – Gibe2 400kV line by earth fault. This resulted in all units of Gibe-2 and one unit of Amerti Neshe to trip by over frequency, and Sebeta I – Kaliti1 230kV line by over current. The outage of Sebeta-1 – Kaliti-1 230kV line triggered Gefersa – Kaliti-1 132kV line to trip with over current, hence Awash 2 & 3 and Koka plants tripped with under frequency. Dire Dawa-3 – Koka 230kV line tripped due to over current and forced units of Melka Wakena to trip. Alamata – Bahirdar2 230kV line tripped due to main protection trip, which caused all units of Tekeze to trip. Finally Gefersa –Mekenissa 132kV line tripped by over-load which caused the partial blackout.
- 6- Tripping of Gilgel Gibe2 – Sebeta2 400kV transmission line by earth fault with a loading of 318MW, resulted in to cascaded tripping of the neighboring Sekoru – Wolkite – Sebeta1 and Sekoru – Ghedo 230kV transmission lines (which are alternate route for the power flow if in case this 400kV line trips) by overload. The grid lost 57% of its generation which is unlikely to survive with the existing system defense mechanism (under frequency load shedding relays' action), which has to be updated.
- 7- The initiating event is the outage of generating units of Beles when bus-bar transfer is made at the time of light-load condition, and system *voltage* was high in many buses. Bahirdar2 – Beles 400kV lines 1 & 2 and Bahirdar2- Debre Markos 400kV line tripped due to *over voltage* at 00:19. Most of the neighboring high voltage lines tripped due to *over voltage*, and NLDC operators also disconnected some lines to monitor system voltage. After the outage of lines by over voltage, some lines were over loaded and tripped with over current.

- 8- Spark detected at Gefersa - Addis Alem 45kV outgoing line, phase-C fallen to ground and burnt. Since the fault was not cleared by opening the breaker at Gefersa on Addis Alem line; this 45kV line fault leads to tripping of three 230/132 kV transforms, incoming 230kV lines of Gefersa and also all outgoing 132kV lines from Gefersa tripped. This further forced the generating units of Finchaa, Melka Wakena, Amerti Neshe, Koka, Awash 2 & 3, Gilgel Gibe 1 & 2, and Tekeze to trip. The poor protection coordination on Gefersa – Addis Alem 45kV line resulted in to tripping of other transmission lines and HV transformers.
- 9- Flame was seen on 132kV side of 230/132kV transformer-1 at Sebeta1. When Sebeta1 230/132kV transformer-1 was closed. During this time the transformer tripped and all the incoming 230kV lines of Sebeta 1 – Gefersa , Sebeta 1 – Welkite , Sebeta1 – Sebeta2 line 1 & 2, and Sebeta1 – Kaliti1 and the 132 kV outgoing line of Sebeta1 – Mekenissa tap tripped. Following this all the generating units of Tekeze, Melka Wakena, Koka, Awash 2 & 3, two units of Gibe-2, and one unit of Gibe-1 were tripped because of the load rejection.
- 10- Earth fault on Beles – GERD 400kV line at 700km distance from GERD triggered the event, whereas the distance between these two substations is 240kms (the distance relay showed wrong signal). The relay also sent a tele-protection signal to Beles and leads to the opening of the circuit breaker from Beles side, and Beles - Bahirdar 400kV lines 1 & 2 tripped with tele-protection command. Before the fault, Beles’s loading was about 410MW (30%-37% of the total), and during the fault other power plants couldn’t share the lost MWs of Beles; and resulted in to the occurrence of blackout.
- 11- Planned maintenance activities were going on the system in different regions such as, replacement of 230kV circuit breaker at Ghedo substation. Due to this the 230kV Finchaa – Ghedo – Gefersa line, one 230 kV Gefersa – Sululta lines were out of service for the upgrading work at Gefersa substation, and only one line was connecting Gefersa & Sululta, and the 400kV & 230kV bus bars at Gelan substation were under planned maintenance. In addition Bahirdar – Alamata 230kV line was out for maintenance. With all these planned outages when an earth fault on Kaliti1 – Mekanissa 132 kV line occurred a cascaded tripping on the neighboring 132 kV lines in Addis Ababa made the event to be worse.
- 12- The tripping of Sululta – Gefersa, Sokoru – Ghedo, and both Ghedo – Gefersa 230kV lines with earth fault, made the system to be divided into two parts. Beles, Finchaa, Amerti Neshe as one (but Finchaa and Amerti Neshe tripped with over frequency and Beles remained supplying Northwest region). On the other hand Gibe1 & 2, Gibe3 (only 2 units

were synchronized for test), Melka Wakena, Koka, Awash 2 & 3, Tekeze, and the wind power plants were not capable of supplying majority of the system load. Due to this, all the isolated units in the second part tripped with under frequency and over current.

- 13- For the purpose of **voltage regulation** and water management of the available dams; at off-peak time Bahirdar2 – Debre Markos and Sebeta2 – Gibe2 400kV lines were de-energized in normal operation. At the same time all units of Gibe2 were out of service for the Gibe3 bus bar extension from the old bus-bar. Then, system load started to increase and the operators wanted to connect Bahirdar2 – Debre Markos 400kV line, when it is energized an **over voltage occurred** at Bahirdar substation, and the two 400/230 kV transformers and Bahirdar2 – Gondar2 230kV line tripped and the supply from Beles became disconnected, due to this system tends to collapse. (*The over-voltage setting, the voltage value that made the transformers and lines at Bahirdar substation to open at night time shall be identified.*)
- 14- The triggering event is the outage of Sekoru – Ghedo 230kV line by two phase (LL) fault, i.e. phase B was cut and fallen on phase C. The system was recovering from previous blackout (some lines like Sebeta2 – Gibe2 and Sokoru – Wolkite 230kV were not connected, Gibe 1 was not synchronized, and also Tekeze was in isolated mode). Following the above event, the units of Gibe2 became isolated from the grid with a loading of 200MW (17%), as the system was restoring from previous blackout, which aggravate the situation and it's unlikely the system to survive from collapsing.

#### 4.4.2 Blackout Incidents on Ethiopian Power System in 2016

- 1- The triggering event is the tripping of Gibe2 – Sokoru 400kV line with earth fault. Gibe2 – Sebeta2 400kV line also tripped without any recorded signal, which resulted in Gilgel Gibe2 to trip with over frequency with 27% loading of the total generation. All of the power plants in the grid were forced to trip with under-frequency except the units of Beles. Outage of these power plants led to the long 400kV and 230kV transmission lines to trip with **over voltage** and over current and hence partial blackout was occurred.
- 2- The initiating event is the tripping of Beles power plant (all units), when the maintenance team transferred the DC supply from Bank A to Bank B. Following the outage of Beles power plant, all other generating stations in the system tripped by under frequency, **under voltage** and over load. The system defense mechanism (under-frequency load shedding) at that time

cannot contribute in saving the system from blackout, because it cannot compensate the 30% generation that Beles was supplying.

- 3- The initiating event is earth fault (distance protection at 47km from Wolaita Sodo) on Wolaita Sodo2 – Gibe3 400kV line 2 during energization for the first time. This resulted in tripping of Gilgel Gibe3 units with zone 3 protection (poor protection coordination) with a loading of 500MW which is 36% of the system load at the time of outage. Since the distance protection of Gibe3 – Wolaita Sodo2 400kV line-2 did not isolate the fault and units of Gibe-3 tripped by zone-3 protection, the system is unlikely to survive from blackout. This is an indication of poor coordination of the protection relays and need to be corrected urgently.
- 4- Flame detection at Ghedo substation on the line disconnectors of Ghedo – Finchaa-II 230kV line and short circuit fault on phase B of Ghedo – Gefersa 230kV line triggers the event. Following the outage of Ghedo – Gefersa and Ghedo – Finchaa 230kV lines; 400/230kV power transformers at Sululta, Ghedo – Sekoru 230kV line, Gefersa – Kaliti1 and Gefersa – Sebeta1 132kV lines tripped due to earth fault and over-current. This leads to cascaded outage of Bahirdar2 – Alamata 230kV line, as a result Beles and Finchaa plants were isolated from the grid with a total generation of 425MW (27%). The system lost 425MW and survived from total blackout by the action of the updated system defense mechanism.
- 5- Tripping of Gelan – Wolaita Sodo2 400kV line by earth fault at 16:03, leads to the outage of Gibe 2 & 3, Finchaa, Tekeze, and Adama2 power plants with a total loading of 768MW (64% of total generation), and Gelan – Sebeta2, Koka – Hurso – Diredawa3 lines tripped by **over voltage**. The system frequency dropped (the updated under frequency load shedding scheme is designed for a loading of 430MW), and it gave time to the operators to take further corrective actions and system survived from total black out. After the restoration of the above event Gibe3 tripped again at 19:29 and 21:54 with a loading of 300MW, and the system survived by the action of the updated under frequency load shedding relays.
- 6- Tripping of Ghedo – Gefersa 230kV lines 1 & 2, and Ghedo – Finchaa2 by earth fault, leads to tripping of Sululta – Debre Markos 400kV lines and Bahirdar2 - Alamata 230kV by **over voltage**. Other transmission lines were also tripped by earth fault and over voltage, and forced Beles power plant to be isolated from the system. One unit of Tekeze and two

units of Finchaa tripped with load of 123 MW and Beles decreases its loading from 414 MW to 72 MW. The power deficiency was about 465 MW and most of this was covered with the first and second stage under frequency load shedding.

- 7- Earth fault on Kaliti I – Cottobie 132kV line leads to the resulting cascaded tripping of Kaliti 1 – Sebeta1 230kV line, Kaliti 1 – Gelan 132 kV line 1 & 2, Kaliti 1 – Weregenu Tap 132kV line, and Kalti1– Mekenissa 132kV lines with over current. Following the above event, the system rejects 41% of the load and system over voltage occurred. Sebeta2- Gelan and Wolaita Sodo2 – Gelan 400 kV lines tripped with over voltage, due to this Gibe3, Melka Wakena, Koka, Awash 2 & 3, and Adama Wind 1 & 2 tripped with over voltage, over frequency and under frequency. The system lost 60% of the generation; however other power plants remained in the grid and the system survived from total blackout.
- 8- Earth fault on Gelan – Wolaita Sodo2 400kV line initiated the tripping of all units of Gibe3 due to over frequency with a loading of 700MW (44% of total generation). At the same time Tekeze and Adama wind I also tripped with no signal recorded. The system survived from total blackout, because the system defense mechanism was updated to have third stage under- frequency load shedding (considering the synchronization of additional units of Gibe3 with a loading of up to 700MW).
- 9- Capacitor Voltage Transformer (CVT) fault on phase-A bus-bar, at Legetafo substation during extension work is the triggering event. This leads to tripping of Legetafo – Combolcha2 and Legetafo – Kaliti1 230kV lines by earth fault, and the 230/132 kV & 132/15 kV power transformers at the substation by over current and earth fault. This fault caused to the tripping of three units of Gibe2 due to over frequency, two units of Gibe1 with reverse power, one unit of Tekeze with no signal, and Adama wind-2 due to loss of voltage; which is with total loading of 478MW.
- 10- Bahirdar – Debre Markos and Sebeta2- Gibe2 400kV lines were de-energized for voltage monitoring purpose, as it's common during off-peak/light load periods. The triggering event is manual switching of Gibe3 – Wolaita Sodo2 400kV lines 1 & 3 which were transmitting 379MW generation to the grid. Following this event the 1<sup>st</sup>, 2<sup>nd</sup>, & 3<sup>rd</sup> stage under frequency load shedding acted to recover system frequency. Since there was only one path connecting Beles to Debre Markos via Bahirdar – Mota – Debre Markos 230kV line, the loading of this line increased suddenly from 44MW to 320MW and the line

tripped by overload. Following this event, all power plants except two units of Beles, forced to trip by overload and under frequency.

- 11- Before the occurrence of the fault, four lines were switched off, i.e. Gibe2 – Sebeta2, Bahirdar2 – Debre Markos 400kV lines, and Combolcha2 – Alamata, Hurso – Adigala 230kV lines. The absence of shunt reactors, 15MVAR at Bahirdar2 (230kV bus), 15MVAR at Alamata (230kV bus), 10MVAR (at 132kV bus) & 5MVAR (at 15kV bus) at Diredawa3 substations due to different reasons aggravates the system over voltage during evening time. Having the above situation, the triggering event is outage of unit 8 of Gibe3 by ‘oil sump level too low’ signal and following this the frequency drops below 49Hz (Gibe3’s generating units will go to isolated mode when the frequency reaches 49Hz). This makes the system voltage to increase above acceptable limits, and Gelan – Wolaita Sodo2, Gelan – Sebeta2, and Gibe3 – Wolaita Sodo 400kV lines tripped by over voltage. The under frequency load shedding relays acted but the system cannot survive because the above mentioned important lines were out for voltage monitoring.
- 12- The triggering event is the outage of Gibe3 – Wolaita Sodo2 400kV lines 1 & 2 (the contractor was doing interlock test without notifying NLDC), which were transmitting the generated power of 704MW (46%) from Gibe3 to the grid. Two units at Gibe1 and one unit of Gibe2 were out of service, and AGC was not working due to the telecom work to connect the fibers of Gebre Guracha substation with the existing Sululta – Debre Markos fiber optic cable. The shunt reactors of 15MVAR at Alamata (230kV bus), and 10MVAR (at 132kV bus) & 5MVAR (at 15kV bus) at Diredawa3 substations were out of service. Due to the pre-fault scenario, there were variations on the system frequency control and export power to Sudan; hence the system is unlikely to survive from blackout because it was already weak.

### 4.4.3 Observations from the 2015 and 2016 Blackouts

The observations from the blackouts occurred in 2015 and 2016 are presented here in order to investigate the power interruptions occurred due to voltage problems during peak-load and light-load conditions in Ethiopian power system. The following observations are presented while analyzing the blackout incidents.

- No time Synchronization: The GPS time at NLDC and different locations (substations and power plants) of the power system may vary with seconds and minutes. It makes difficult to put the exact chronological order of the outage incidents and to specify the triggering event correctly.
- Pre-fault system frequency is assumed to be 50Hz.
- Circuit breakers at some substations are out of service for longer time.
- Before the updated system defense mechanism (under-frequency load shedding) applied, if a system disturbance occurs during the peak hours, it's unlikely the system to survive from blackout. This time a total shutdown will happen.
- At peak hour most of the elements in the power system operate close to their operating limits.
- System defense mechanisms, such as under frequency load shedding, *under voltage load shedding* and over voltage protection coordination shall be conducted. (Total system study is necessary)
- Poor protection coordination, circuit breakers out of use, some lines which do not have circuit breakers and connected with isolator/disconnector only, false signals, abnormal bus-bar protection etc. are causing the system not to sustain stability.
- Communication problem is another bottleneck for the restoration time to be late. There is no smooth communication like Fiber Optics and mostly the operators are dispatching by using phone calls (this leads to longer restoration time & may affect the security of the system operation).
- Most of the time planned maintenance is done on Sundays. And at the same time different transmission lines and power plants can be out for maintenance. When some fault occurs while planned maintenance is going on, the system is unlikely to survive the incident.

- During any disturbance in the system, the 3 wind power plants trip due to *loss of voltage*.
- The capacitor banks *will not isolate* themselves when *over voltage* occurs in the system, which will aggravate the *system over voltage* during disturbances, particularly following the action of *under frequency relays*.
- For any fault in the high voltage transmission line, only the faulty line shall be isolated without creating outages of other lines. However, for a fault on one line, other nearby lines detected the fault signal and they'll be forced to trip by zone 3 or 4 protections. So, the protection coordination of the 230kV and 132kV lines in some substations shall be checked again.
- Care must be taken during construction around &/or on the existing substations and transmission lines. Substation expansion works may lead to system disturbance.
- System security; the operators at the power plants and substations can get a phone call from someone else not from NLDC.
- Under frequency tripping of 230kV line from Shehedi to Gadarif (Sudan) has to be checked (the under frequency protection is not required on HV [11] transmission lines)
- When a fault occurs on a transmission line near a power plant and the fault is cleared from one end whereas not cleared from the other end near the power plant, it results in tripping of generating units.
- The pre-fault loading of the power plants should be equally shared among the regions, mostly the dams with higher water level cover majority of the generation. Most of the time Beles, Finchaa, & Amerti Neshe in the West and Northwest part of the grid are loaded and when any fault occurred on the transmission lines that connect to these power plants, the system is unlikely to survive the disturbance.

As we can see from the 2015 and 2016 blackout records of Ethiopian grid, the power system faces blackouts at least once in a month and sometimes twice. Other countries' blackout experience is different from Ethiopian scenario; even the neighboring Sudan which is interconnected with Ethiopia has a zero total blackout record in 2012. Unlike Ethiopian power system, it's very rare for the modern power systems such as in Europe and the US to register total blackouts, i.e. most of them faced total blackouts almost a decade ago.

In conclusion, the blackouts that are initiated by a sudden tripping of generating units or transmission lines resulted in the surrounding area to be exposed to a lack of reactive power and several generators to be field current limited. These may lead to a cascaded tripping of transmission lines and/or generating stations, so that, the transmission system will be unable to transmit the necessary amount of reactive power to the voltage suppressed area and a continuous voltage decline will happen. Following the voltage decline at many buses/areas, voltage stability problems can be generated.

All the above presented Ethiopian blackouts in 2015 and 2016, whether they are caused by tripping of a generating station or transmission lines, keeping the voltage profiles at all the buses in the grid as close to the nominal voltage value as possible will help in minimizing the occurrence of blackouts. Voltage stability problem deals with the ability to have the voltage level within a narrow band around normal operating voltage conditions. Even if most of the above blackouts are initiated by tripping of transmission lines by earth fault, especially at peak load condition, most of the buses and lines in the system were operating at voltages lower than the nominal value. So that, in order to have the bus voltages close to their nominal value, conducting Load Flow Feasibility (LFF) method of static voltage stability can minimize the occurrence of cascaded tripping and so the occurrence of blackouts.

## Chapter Five

### 5 Conclusions, Recommendations and Future Work

#### 5.1 Conclusions

This thesis tries to evaluate the static voltage stability of the existing Ethiopian power system, and found three regions/areas with unacceptable low voltage profiles at peak load conditions and other three regions with high voltage profiles at light-load conditions that can be the causes for voltage instability.

Voltage-weak areas with unacceptable low voltage profile during peak-hour and unacceptable high voltage profiles during light-load periods have been identified. Out of the identified three areas with unacceptable low voltage profiles, two areas in Addis Ababa are further analyzed and mitigation techniques have been proposed. Out of the three areas with unacceptable high voltages, North-western region around Bahir Dar is selected for further analysis and simulations. The mitigation techniques applied include; installing shunt reactors or capacitors, upgrading transmission lines and substations, and tap changer actions.

The simulation results demonstrate that such voltage weak areas with unacceptable low &/or high voltage profiles can be causes for voltage instability and voltage collapse of the power system. The bus voltage profile improvements registered reach up to 20.07% at Addis West substation 15kV bus, and 17.13% at Addis North substation 15kV bus. For the light-load condition, bus voltage profile improvements of -18.08% and -17.67% at Debre Markos 66kV & 15kV buses are achieved respectively.

#### 5.2 Recommendations

Blackout occurs repeatedly in Ethiopian power system, in order to reduce the frequency of blackout occurrence, system study is necessary all the time when an upgrade, expansion, or new commissioning of power system element in the grid happens. Voltage stability assessment should not only be done on the high voltage transmission level, rather it should be done during each and every change of the power system network including the sub-transmission and distribution sides. As a result of voltage improvement at different areas and bus terminals of

the power system, power transfer capability of the system will be increased and so fewer blackouts will be registered.

This project recommends upgrading of substations and their incoming transmission lines to give trustworthy solution for the voltage stability problems and reduces overloads and interruptions of customers in that area. The substation and transmission lines upgrade projects called Legetafo – Cottobie – Addis East1 and Sebeta1 – Addis West helped not only to relieve the overloads in those substations, but also contributed to the voltages in their areas to be improved with in the tolerable limits of 0.95pu – 1.05pu. Finally this project recommends to EEP concerned offices to do further study to the indicated regions with unacceptable low and high voltage profiles to minimize the blackout occurrences. Doing this, we can generally say that the general and specific objectives of this thesis work have achieved.

### **5.3 Suggestion for Future Work**

In this thesis, static voltage stability assessment of the existing Ethiopian power system is investigated. In the future, dynamic voltage stability analysis should be investigated by including contingencies, the low voltage distribution side, and the load behaviours. Assessment of voltage stability under dynamic conditions will help to implement power system restoration procedures in the cases of disturbances and blackouts.

HVDC transmission for the energy export to Kenya is under construction and is going to synchronize with the system soon. The integration of wind farms such as Aysha, Debre Birhan, and Assela which are going to be operated in two years period is also increasing. The integration impacts of HVDC and wind farms on dynamic voltage stability of Ethiopian grid should be investigated in the future.

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# Appendices

## Appendix A: Single Line Diagram of Ethiopian Transmission Network

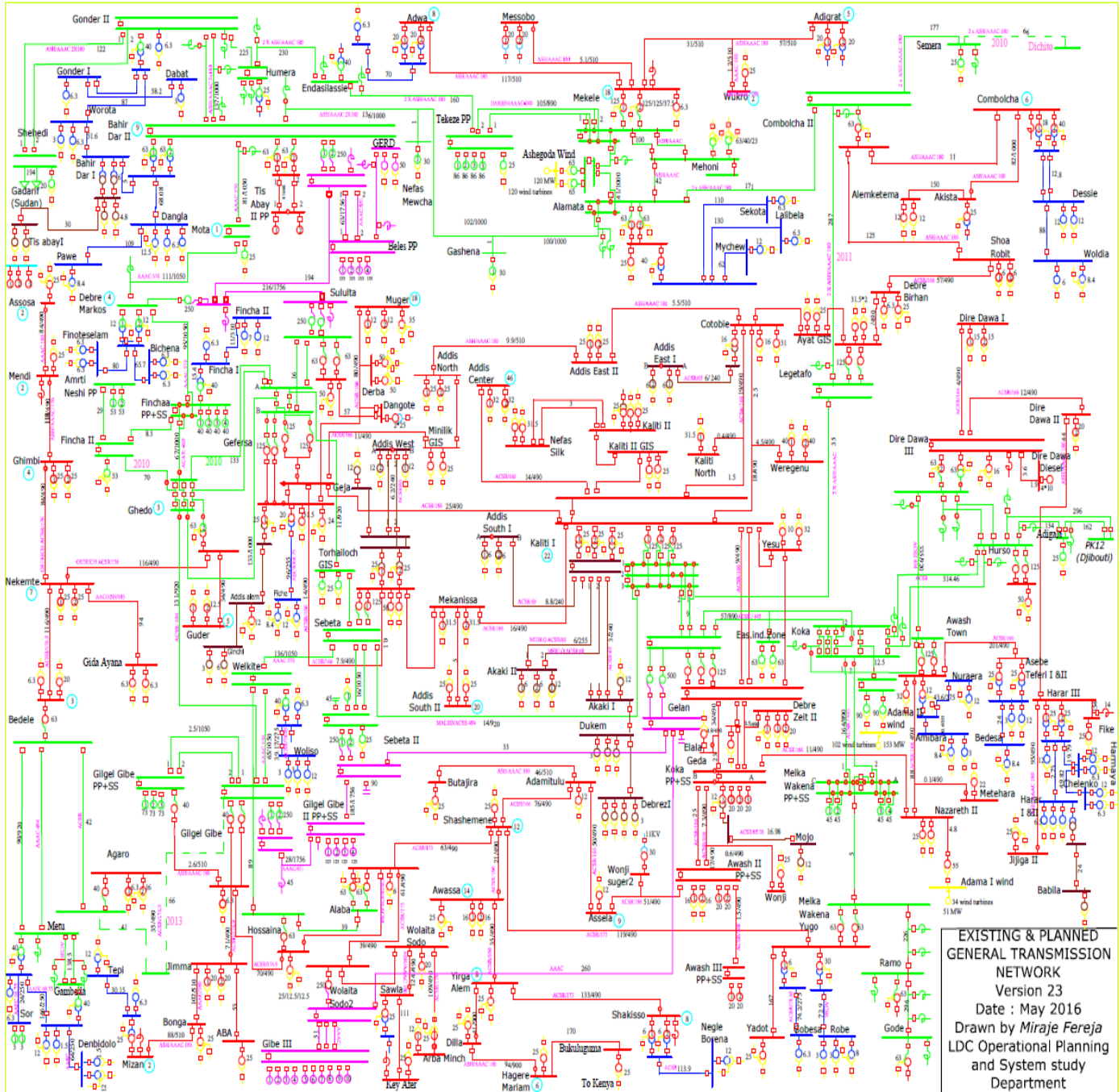


Figure: Single Line Diagram of Existing Transmission Network of Ethiopian grid

## Appendix B: Load Data of Substations in Ethiopian Grid

Serial No.	Name of Substation /Bus	HV Bus Voltage (kV)	P (MW)	Q (MVAR)
1	Aba Samuel	45	1.849	0.896
2	Abba	132	3.910	1.894
3	Adami Tulu	132	6.680	3.235
4	Addis Alem	45	4.710	2.281
5	Addis Center	132	80.778	39.123
6	Addis East I	45	17.277	8.368
7	Addis East II	132	35.826	17.351
8	Addis North	132	43.900	21.262
9	Addis South-I	45	13.823	6.695
10	Addis South-II	132	42.639	20.651
11	Addis West-I	45	12.820	6.209
12	Addis West-II	45	11.723	5.678
13	Adigala	230	0.899	0.435
14	Adigrat	132	13.900	6.732
15	Adwa	132	9.710	4.703
16	Agaro	132	4.821	2.335
17	Akaki-I	45	12.600	6.102
18	Akaki SP	45	9.482	4.592
19	Akista	132	6.619	3.206
20	Alaba	132	3.382	1.638
21	Alamata 33	230	4.872	2.360
22	Alamata	230	2.206	1.068
23	Alem Ketema	132	4.510	2.184
24	Alemaya	45	4.413	2.137
25	Alemaya 33	33	2.206	1.068
26	Amibara	45	3.591	1.739
27	Arba Minch	132	9.269	4.489
28	Asebe Teferi	132	3.211	1.555
29	Asebe Teferi 33	132/33	1.026	0.497
30	Assela	132	9.815	4.754
31	Assosa	132	5.516	2.672
32	Awash II	132	3.699	1.792
33	Awash 7	132	5.842	2.829
34	Awash III	132	2.489	1.205
35	Awassa	132	37.584	18.203
36	Bahir Dar-I	66	7.482	3.624
37	Bahir Dar-II 1	230	10.086	4.885
38	Bahir Dar-II 2	230	7.517	3.641
39	Babile	45	2.236	1.083
40	Bale robe	66	6.652	3.222
41	Bedele	230	7.654	3.707
42	Bedessa	66	2.964	1.436

43	Bichena	66	2.569	1.244
44	Bukuluguma	132	5.413	2.622
45	Bole Lemi	132	11.870	5.749
46	Bonga	132	4.601	2.228
47	Bonga	132	1.739	0.842
48	Butajira	132	5.423	2.626
49	Butajira 33	33	2.021	0.979
50	Chelenko	45	2.889	1.399
51	Combolcha-I	132	17.325	8.391
52	Combolcha-II	230	7.430	3.599
53	Cottobie 15	132/15	39.830	19.291
54	Debre Birhan	132	7.911	3.831
55	Dire Dawa-I	132	14.808	7.172
56	Dire Dawa-II	132	4.352	2.108
57	Dire Dawa-III	230	3.303	1.600
58	Debre Markos	230	4.529	2.193
59	Debre Zeit I	45	2.566	1.243
60	Debre Zeit II	132	59.499	28.817
61	Dangote	132	29.749	14.408
62	Dabat	45	2.042	0.989
63	Dangla	66	5.552	2.689
64	Dembi Dolo	66	3.970	1.923
65	Derba 33	132	36.820	17.833
66	Dessie	66	10.429	5.051
67	Dicheto	230	1.873	0.907
68	Dilla 1	45	2.206	1.068
69	Dilla 2	132	7.723	3.740
70	Dukem	45	3.267	1.582
71	Elala Geda	132	6.890	3.337
72	East Industry Zone	230	38.470	18.632
73	Finchaa SG 1	66	4.292	2.079
74	Finchaa SG 2	66	3.324	1.610
75	Finchaa	230	3.391	1.642
76	Finote Selam	66	4.987	2.415
77	Fiq	132	2.430	1.177
78	Fiche	66	10.590	5.129
79	Fiche 15	66/15	8.274	4.007
80	Gambela I	66	3.640	1.763
81	Gashena	230	3.310	1.603
82	Gedja	45	2.662	1.289
83	Gefersa	230	17.500	8.476
84	Gefersa	230	48.500	23.490
85	Gelan	400	44.400	21.504
86	Ghedo	230	2.840	1.375
87	Ghimbi	132	2.597	1.258
88	Gibe Old	132	2.514	1.218

89	Gida Ayana	132	6.941	3.362
90	Ginchi 15	45	4.413	2.137
91	Gode	230	1.892	0.916
92	Gobessa	66	1.725	0.835
93	Gonder 2	230	1.835	0.889
94	Gonder I	66	5.280	2.557
95	Gonder II	230	14.495	7.020
96	Guder	132	7.479	3.622
97	Hagere Mariam	132	3.825	1.853
98	Harar 1	45	4.263	2.065
99	Harar 2	132	5.254	2.545
100	Harar 3	132	4.798	2.324
101	Hossaina	230	7.064	3.421
102	Humera	230	4.383	2.123
103	Jigjiga II	132	6.376	3.088
104	Jigjiga II	132	5.046	2.444
105	Jimma	230	11.271	5.459
106	Kaliti North	132	38.600	18.695
107	Kaliti I	230	18.064	8.749
108	Kaliti II	132	36.900	17.871
109	Koka	132	2.903	1.406
110	Lalibela	66	2.101	1.018
111	Legetafo	230	64.900	31.432
112	Maichew	66	2.593	1.256
113	Mekanissa	230	38.600	18.695
114	Mekelle	230	23.894	11.572
115	Mekhoni	230	2.149	1.041
116	Mendi	132	3.206	1.553
117	Messobo	132	37.966	18.388
118	Metehara	132	8.175	3.959
119	Metema /Shehedi	230	60.240	29.176
120	Metu	132	2.811	1.361
121	Mizan	132	2.319	1.123
122	Modjo	45	4.179	2.024
123	Mota	230	2.683	1.299
124	Muger	132	31.218	15.120
125	M-Wakena Yugo	230	4.812	2.331
126	Nazareth II	132	34.733	16.822
127	Negele Borena	66	1.906	0.923
128	Negele Borena	66	1.027	0.497
129	Nekemte	132	9.638	4.668
130	Nifas silk	132	36.100	17.484
131	Nifas Mewcha	230	2.871	1.390
132	Nuraera	45	3.124	1.513
133	Pawie	66	2.324	1.126
134	PK-12 (To Djibouti)	230	39.868	19.309

135	Qey Afer	132	3.174	1.537
136	Ramo/Raitu	230	2.723	1.319
137	Sebeta-I A	230	49.600	24.022
138	Sebeta-I B	230	47.400	22.957
139	Sebeta-II	230	15.400	7.459
140	Sekoru/ New Gibe	230	1.947	0.943
141	Sekota	66	2.423	1.174
142	Semera	230	6.619	3.206
143	Shakisso	132	7.047	3.413
144	Shashemene	132	24.612	11.920
145	Shoa Robit	132	4.252	2.059
146	Shire /Endasilassie	230	5.297	2.565
147	Sululta 15	230	36.260	17.562
148	Sululta 33	230	9.495	4.599
149	Tepi	66	2.629	1.273
150	Tepi	66	1.801	0.872
151	Weregenu	132	64.650	31.311
152	Wolaita Sodo	132	9.868	4.779
153	Woldia	66	8.340	4.039
154	Wolisso	66	7.723	3.740
155	Wolisso 33	33	1.623	0.786
156	Wolkitie	132	2.659	1.288
157	Wolkitie	132	3.548	1.718
158	Wonji Pulp	132	14.989	7.260
159	Woreta	66	5.044	2.443
160	Wukro	132	5.353	2.593
161	Yadot	132	2.980	1.443
162	Yesu	132	13.800	6.684
163	Yirgalem	132	8.826	4.275
164	Yirgalem	132	2.206	1.068

## Appendix C: 'Voltage Limit Checking' Simulation Result at Light-Load Condition

PTI INTERACTIVE POWER SYSTEM SIMULATOR--PSS (R) E

### ETHIOPIAN POWER SYSTEM TRANSMISSION STUDY

#### YEAR 2016 - LIGHT LOAD FLOW

BUSES WITH VOLTAGE GREATER THAN 1.0500:

BUS#	NAME	BASKV	AREA	V (PU)	V (KV)	BUS#	NAME	BASKV	AREA	V (PU)	V (KV)
102007	COTOBI-II	132.00	2	1.0541	139.15	102012	AYAT TS	132.00	2	1.0529	138.98
103002	D.DAWA-1	132.00	3	1.0610	140.05	102004	D.BERHAN	132.00	2	1.0802	142.59
103003	D.DAWA-3	132.00	3	1.0615	140.12	103006	HARAR-3	132.00	3	1.0640	140.45
103008	D.DAWA-2	132.00	3	1.0618	140.16	103009	D.DAW-DS	132.00	3	1.0615	140.12
103011	ALEMAYA	132.00	3	1.0633	140.36	103012	BABILE	132.00	3	1.0639	140.44
106001	A-KETEMA	132.00	6	1.1330	149.55	814003	BUTAJIRA	15.000	14	1.0956	16.434
106002	AKSTA	132.00	6	1.1226	148.19	106003	COMBOL-I	132.00	6	1.1068	146.10
106004	SHWA-RBT	132.00	6	1.0920	144.15	106005	COMBOL-II	132.00	6	1.1072	146.15
106006	KEMISSIE	132.00	6	1.1040	145.73	107003	PAWIE	132.00	7	1.0631	140.33
107004	BELESSUGRFAC1	132.00	7	1.0658	140.68	107006	DANGLA-132	132.00	7	1.0512	138.76
108004	GHEDO	132.00	8	1.0677	140.93	108005	GUDER	132.00	8	1.0658	140.68
109001	ADIGRAT	132.00	9	1.0563	139.44	109002	ADWA	132.00	9	1.0535	139.06
109003	ALAMATA	132.00	9	1.0739	141.76	109004	MEKELE	132.00	9	1.0578	139.63
109005	MESOBO	132.00	9	1.0560	139.39	109007	WUKRO	132.00	9	1.0575	139.60
109008	WUKRO-TP	132.00	9	1.0576	139.60	115001	ABA	132.00	15	1.0533	139.03
115003	B.BEDELE	132.00	15	1.1715	154.63	115004	BONGA	132.00	15	1.0678	140.95
115005	G.G OLD	132.00	15	1.0576	139.60	115006	G-GIBE-1	132.00	15	1.0575	139.59
115007	GIDA-AYANA	132.00	15	1.1215	148.04	115008	JIMMA	132.00	15	1.0536	139.07
115009	MIZAN	132.00	15	1.0760	142.03	115010	NEKEMPTE	132.00	15	1.1224	148.16
115011	GIDAMI	132.00	15	1.0992	145.10	115014	TUM	132.00	15	1.0902	143.91
202001	COTOBI-II	230.00	2	1.0782	247.99	204001	GAMBELA2	230.00	4	1.1955	274.97
204002	METU	230.00	4	1.0958	252.03	206001	COMBOL-II	230.00	6	1.1040	253.92
<b>207002</b>	<b>DB-MRKOS</b>	<b>230.00</b>	<b>7</b>	<b>1.1181</b>	<b>257.15</b>	207003	GASHENA	230.00	7	1.0834	249.19
207004	GASHE-TA	230.00	7	1.0834	249.19	207007	MOTA	230.00	7	1.0802	248.44
207008	N.MEW TP	230.00	7	1.0685	245.75	207009	N.MEWCHA	230.00	7	1.0684	245.73
207011	WORETA	230.00	7	1.0557	242.81	208001	FINCHA	230.00	8	1.0825	248.97
208002	FINCHA-II	230.00	8	1.0828	249.05	208004	GHEDO	230.00	8	1.0705	246.22
208005	NESHE	230.00	8	1.0833	249.17	208007	GINCHI	230.00	8	1.0538	242.37
209001	ALAMATA	230.00	9	1.0864	249.88	209004	MEKELE	230.00	9	1.0657	245.12
209007	MEHONI	230.00	9	1.0828	249.04	209013	ASHEGODA WF	230.00	9	1.0683	245.71
210002	DITCHETO	230.00	10	1.0665	245.30	210003	SEMERA	230.00	10	1.0701	246.12
210004	TENDAHO	230.00	10	1.0703	246.18	215001	BEDELLE	230.00	15	1.1918	274.12
603002	ASB-TFR	66.000	3	1.0569	69.755	603003	BEDDESA	66.000	3	1.0502	69.315
603008	BABILE66	66.000	3	1.0631	70.164	604001	DEMBI DO	66.000	4	1.1563	76.319
606001	AKSTA	66.000	6	1.2019	79.322	606002	COMBO-1	66.000	6	1.1030	72.801
606003	DESIE	66.000	6	1.0944	72.231	606004	LALIBELA	66.000	6	1.0626	70.134

606005	SEKOTA	66.000	6	1.0660	70.358	606006	WOLDIA	66.000	6	1.0982	72.482
607001	B.DAR1	66.000	7	1.0569	69.754	607002	B.DAR2	66.000	7	1.0603	69.980
607003	BITCHENA	66.000	7	1.1336	74.818	607004	DABAT	66.000	7	1.0524	69.456
607006	DB.MARKS	66.000	7	1.1500	75.899	607007	FNOT-SLM	66.000	7	1.1194	73.882
607008	GONDAR2	66.000	7	1.0667	70.402	607009	GONDER1	66.000	7	1.0649	70.281
607011	WORETA	66.000	7	1.0597	69.943	608001	FINCHAA	66.000	8	1.0781	71.153
608002	FNCH-SG1	66.000	8	1.0733	70.836	608003	FNCH-SG2	66.000	8	1.0703	70.640
609001	ADIGRAT	66.000	9	1.1059	72.988	609003	ALAMATA	66.000	9	1.0761	71.021
609004	MAYCHEW	66.000	9	1.0709	70.677	610001	AMIBARA	66.000	10	1.0833	71.497
610002	AWSH-7KL	66.000	10	1.0941	72.213	611004	NURAEERA	66.000	11	1.1002	72.611
613002	SAWLA	66.000	13	1.1115	73.360	613003	SHAKISO	66.000	13	1.0544	69.594
615001	MIZAN	66.000	15	1.0749	70.946	615002	TEPI	66.000	15	1.0728	70.807
702001	ADDIS-E1	45.000	2	1.0637	47.865	702002	COTOBIE	45.000	2	1.0737	48.315
806002	AKSTA	33.000	6	1.1935	39.387	806003	COMBOL-1	15.000	6	1.0928	16.392
806004	DESIE	15.000	6	1.1941	17.911	806005	LALIBELA	15.000	6	1.0588	15.883
806006	SEKOTA	15.000	6	1.0737	16.105	806007	SHWA-RBT	15.000	6	1.1327	16.990
806008	WOLDIA	15.000	6	1.1765	17.647	806009	KEMISS33	33.000	6	1.1151	36.800
806010	KEMISS15	15.000	6	1.1151	16.727	807002	B.DAR2-1	15.000	7	1.0568	15.852
807003	BITCHENA	15.000	7	1.1260	16.890	807004	DABAT	15.000	7	1.0609	15.914
807006	DB-MRKOS	15.000	7	1.1479	17.219	807007	FNOT-SLM	15.000	7	1.2131	18.197
807008	GASHENA	33.000	7	1.0576	34.900	807009	GONDAR2	33.000	7	1.0997	36.290
807010	GONDER1	15.000	7	1.1091	16.636	807011	METEMA	33.000	7	1.0846	35.791
807012	MOTA	33.000	7	1.1056	36.485	807013	NEFASMEWCHA	15.000	7	1.0659	15.989
807014	N-MEWCHA	33.000	7	1.0653	35.156	807015	PAWIE	15.000	7	1.0591	15.887
807018	GASHENA-15	15.000	7	1.0586	15.879	807019	GONDAR2	15.000	7	1.0552	15.827
807020	PAWIE	33.000	7	1.0612	35.018	807021	WORETA	15.000	7	1.0562	15.843
807022	GONDER	15.000	7	1.1141	16.711	814005	SABATA-B	15.000	14	1.0976	16.463
809001	ADIGRAT	15.000	9	1.1038	16.557	809002	ADWA	15.000	9	1.0980	16.470
809005	MAYCHEW	15.000	9	1.0678	16.016	809006	MEKELE	15.000	9	1.0518	15.777
809007	MESOBO	6.3000	9	1.1401	7.183	809008	SHIRE ENDASI	15.000	9	1.0603	15.905
809011	WUKRO	15.000	9	1.1019	16.529	809012	ALAMATA2	15.000	9	1.0750	16.124
809015	MEHONI33	33.000	9	1.0811	35.675	810001	AMIBARA	15.000	10	1.1305	16.957
810002	AWASH-7D	15.000	10	1.0789	16.184	810003	AWSH-7KL	15.000	10	1.0782	16.172
810004	DITCHETO	33.000	10	1.0665	35.195	811004	ASSELA	15.000	11	1.1076	16.614
811006	AWASH-2	15.000	11	1.0524	15.785	811009	ELALA-GD	15.000	11	1.0893	16.339
811014	METAHARA	15.000	11	1.1107	16.661	811016	NAZ-II	15.000	11	1.0700	16.050
811018	NURAEERA	15.000	11	1.0579	15.868	811019	WONJIPUL	15.000	11	1.0635	15.952
811020	NURAEERA-33	33.000	11	1.0579	34.909						