



**ADDIS ABABA UNIVERSITY**

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

School of Electrical and Computer Engineering

**Shunt Compensation for Sululta- Addis South-II**

**Transmission-Substation System**

By: Maaregu Berhe

A Thesis Submitted to Addis Ababa Institute of Technology  
In Partial Fulfillment of the Requirement for the Degree of Master of  
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In

Electrical Power Engineering

Advisor: Mengesha Mamo (PhD)

Jan, 2017



Addis Ababa University  
Addis Ababa Institute of Technology  
School of Electrical and Computer Engineering

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## **Declaration**

I hereby declare that the work which is being presented in this thesis entitled “Shunt Compensation for Sululta- Addis south –II Transmission-Substation system” is original work of my own, has not been presented for a degree in this or other universities and all sources of materials used for this thesis work have been fully acknowledged.

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Place: Addis Ababa

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

Dr. Mengesha Mamo

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Advisor’s Name

Signature

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Maaregu Berhe

*Table of Contents*

Acknowledgment ..... V

Abstract ..... VIII

List of Figures ..... IX

List of Tables ..... X

**Chapter One** ..... 14

1. Introduction..... 14

1.1 Background ..... 14

1.2 Statement of Problem and Motivation ..... 15

1.3 Research Objective ..... 16

1.3.1 General Objective ..... 16

1.3.2 Specific Objectives ..... 16

1.4 Methodology and Scopes ..... 17

1.5 Organization of the Thesis ..... 17

**Chapter Two** ..... 18

Theoretical Back Ground and Review of Literature..... 18

2.1 Importance of Reactive Power in Power System..... 18

2.1.1 Thyristor Switched Capacitor (TSC) ..... 20

2.1.1.1 Reactive Power Control ..... 23

2.1.1.2 Terminal Voltage Regulation..... 24

2.1.1.3 Harmonic Filtration..... 24

2.1.1.4 Transient Free Switching ..... 24

2.1.1.5 Operating principles of TSC ..... 25

2.2 Thermal Rating of Transmission Lines and Power Transfer Capability ..... 27

2.2.1 Thermal Rating of Transmission Lines: ..... 27

2.2.2 Power Transfer Capability: ..... 27

2.3 Related Works..... 28

**Chapter Three** ..... 30

Data Collection and Analysis..... 30

3.1 Data Collection ..... 30

3.1.1 Load Forecast of 2017-2021 ..... 39

3.2 Data Analysis .....	40
3.2.1. Load Flow Analysis .....	41
<b>Chapter Four</b> .....	43
4. Simulation Results and Discussions .....	43
<b>Chapter Five</b> .....	64
5. Economic Analysis.....	64
5.1 Investment Costs.....	64
5.2 Saving due to Installation of Thyristor Switched Capacitor .....	65
5.3. Evaluating the Voltage Violation Cost .....	71
<b>Chapter Six</b> .....	72
6. Conclusion and Recommendation .....	72
6.1 Conclusion .....	72
6.2 Recommendation .....	73
7. References.....	74
8. Appendices.....	76

## **Abstract**

In an electrical power system, if there is not enough reactive power, the voltage decreases. Thus, it is not possible to push the power demand to loads through the lines and has a strong effect on system stability. To overcome such kind of problems, shunt compensation near or at the load area is one solution. Thus, the power system networks under this case study i.e.

Sululta-Addis south-II transmission-substation which routes North West to South East of Addis Ababa uses TSC to the compensation task. The power supply during the peak hour time comes from Debre Markos to Sululta via 1x400kV transmission line, from Ghedo to Geffersa through 2x230kV transmission line and from Sebeta-II to Sebeta-I through 2x230kV transmission lines. To evaluate the voltage profile of this region, investigations has been conducted and under voltage problem at bus terminals of the substation has been found, this leads to reduction of power transfer capability of the network to the load side and to mitigate the problem, shunt compensation using FACTS device family called Thyristor Switched Capacitor (TSC) is used. To complete the entire study, necessary system parameters and data have been collected, analyzed and simulation task using DIG SILENT Power Factory software has been done for a time of peak hour of the day which is found to be at 19:00. Result of the study shows, an improvement of voltage profile at bus terminal of the substations. For example, voltage at Derba-132kV bus bar is corrected from 0.91 to 1.00 per unit (pu) which is 9.9% improvement, at Mekanissa substation 15kV bus bar from 0.93pu to 0.99 pu which is 6.5%, at Addis South-II 132kV and 15kV bus bars from 0.88 to 0.96 pu and 0.89 to 0.95 pu which is an improvement of 9.09% and 6.7% respectively. Thus, the power transfer capability increases by 27.07MW.

In terms of cost benefit analysis, cost of compensation system is estimated to be 9,372,085.13 USD and a new 66kV transmission/substation which has a rating of 27MW costs 9,578,000.00USD. Thus, the compensation system can omit the constructing of new 66kV transmission/substation system and definitely cost of land compensation, project completion time and environmental crises will be reduced. So, these shall be considered for economic viability.

**Keywords:** *Shunt compensation, thyristor switched capacitor, power transfer capability, DIG SILENT Power Factory, voltage violation*

## **List of Figures**

Fig1.1. substations surrounding the study area .....	[14]
Fig 2.1 Power triangle.....	[20]
Fig 2.2 thyristor switched reactor and capacitor .....	[21]
Fig 2.3. Thyristor switched capacitor (TSC) .....	[22]
Fig 2.4 Thyristor Valve with damping circuit .....	[22]
Fig 2.5 Configuration of Thyristor Switched Capacitor .....	[23]
Fig 2.6 Wiring diagram of TSC.....	[23]
Fig 2.7 Capacitor Bank in Thyristor Switched Capacitor .....	[24]
Fig 2.8 Circuit diagram of Thyristor .....	[25]
Fig 2.9 Power System Diagram .....	[27]
Fig 2.10 Power transfer capability curve .....	[28]
Fig 3.1 Hourly load profile of Mekanisa substation .....	[34]
Fig 3.2 Daily load profile of Mekanisa Substation .....	[35]
Fig 3.3 Hourly Load profile of Addis South-II Sub-Station .....	[36]
Fig 3.4 Daily Load profile of Addis South-II Sub-Station .....	[38]
Fig 4.1 Lay Out Diagram of Sululta-Addis South-II Transmission/Substation System.....	[43]
Fig 4.2 simulation result of Light Load Condition before shunt compensation for 2016 GC. ..	[45]
Fig 4.3 simulation result of Peak Load Condition before shunt compensation for 2016 GC....	[46]
Fig 4.4 simulation result of Peak Load Forecast of 2021GC before shunt compensation .....	[49]
Fig 4.5 simulation result of Peak Load Forecast of 2021GC After shunt compensation .....	[52]
Fig 4.6 Comparison between transmission Line Losses of EEP target with this study .....	[62]
Fig 4.7 Total Power Transferred To the Load Before and After Compensation .....	[62]
Fig5.1. 66KVsingle circuit tower .....	[67]
Fig 5.2 132KVsingle circuit tower .....	[68]

## **List of Tables**

Table 3.1: Transmission line Parameters-I.....	[31]
Table 3.2 Transmission Line Parameters-II.....	[31]
Table 3.3 Two winding transformer Parameters.....	[32]
Table 3.4 Three Winding Transformers Parameter.....	[32]
Table 3.5 Hourly load profile of Mekanisa Sub - Station.....	[33]
Table 3.6 Daily Load profile of Mekanisa Sub-Station.....	[34]
Table 3.7 Hourly Load Profile of Addis South-II Sub-Station.....	[36]
Table 3.8 Addis South-II 15KVFeeders Peak load.....	[37]
Table 3.9 Peak Daily Load profile of Addis South-II Sub-Station .....	[37]
Table 3.10 Peak & Light Load of Sululta-Addis South-II Transmission Substation in 2016...	[38]
Table 3.11 Gross Domestic Product growth rates .....	[39]
Table 3.12 In feed Power to Sululta-Addis South-II Transmission-Sub-Station .....	[39]
Table 3.13 Load Profile of Sululta-Addis South-II Transmission-Substation in 2016 &2021..	[40]
Table 4.1 Simulation result of un-compensated transmission lines in 2016 .....	[47]
Table 4.2 Simulation result of un-compensated two winding transformers in 2016 .....	[47]
Table 4.3 simulation result of un-compensated three winding transformers in 2016 .....	[49]
Table 4.4 Poor Voltage Profile of Bus terminals before Compensation in 2016.....	[48]
Table 4.5 Summarized load flow analysis of 2021(before compensation).....	[50]
Table 4.6 Candidate Buses For Shunt Compensation.....	[50]
Table 4.7 Summarized load flow analysis of 2021(after compensation).....	[53]
Table 4.8 Design parameters of main TSC components .....	[56]
Table 4.9 Sample data sheet of Thyristor parameters .....	[56]
Table 4.10 power transfer capability of transmission lines before and after compensation.....	[58]
Table 4.11 power transfer capability of two winding transformers before and after compensation.....	[58]

Table 4.12 power transfer capability of three winding transformers before & after compensation.....	[58]
Table 4.13 Voltage Profile of Substation before and After Compensation .....	[59]
Table 4.14 existing and planned transmission Line Losses of EEP .....	[60]
Table 4.15 comparison of transmission Line Losses between EEP target and this case study.....	[61]
Table 4.16 Total Power Transferred To the Load Before and After Compensation.....	[62]
Table 5.1 Investment Cost of TSCs and its bay equipment .....	[63]
Table 5.2. Existing 66kVtransmission lines Rating in EEP power system network .....	[66]
Table 5.3 Costs of 132 and 66kV capable transmission lines (<100 km).....	[66]
Table 5.4 Cost Comparison of Constructing new Transformers and related Switch Gear.....	[69]
Table 5.5 Total investment cost of constructing new 66kVtransmission-substation system.....	[69]
Table.5.6 Investment Analysis .....	[71]

## **List of Abbreviations**

AA	Addis Ababa
C	Capacitance
EEP	Ethiopian Electric Power
EEU	Ethiopian Electric Utility
F	Farad
FOB	Free On Board
GDP	Gross Domestic Product
I	Current
ICS	Inter connected System
kVar	kilovolt Ampere Reactive
kV	kilo Volt
kA	kilo Ampere
MVA	Mega Volt Ampere
Mvar	Mega Var
MW	Mega Watt
Nom	Nominal
P	Real Power
P/s	Process
PU	per Unit
Q	Reactive power
R	Resistance
SCS	Self-contained system
SS	Sub-Station
SVC	Static Var Compensation
SVS	Static Var System
T	Temperature
t	Time
TCR	Thyristor Controlled Reactor
TSC	Thyristor Switched Capacitor
USD	United states dollar
V	Voltage

$V_r$	Terminal Voltage
$V_s$	Supply Voltage
$X$	Reactance
$\mu s$	Micro susceptance
$\Omega$	Ohm

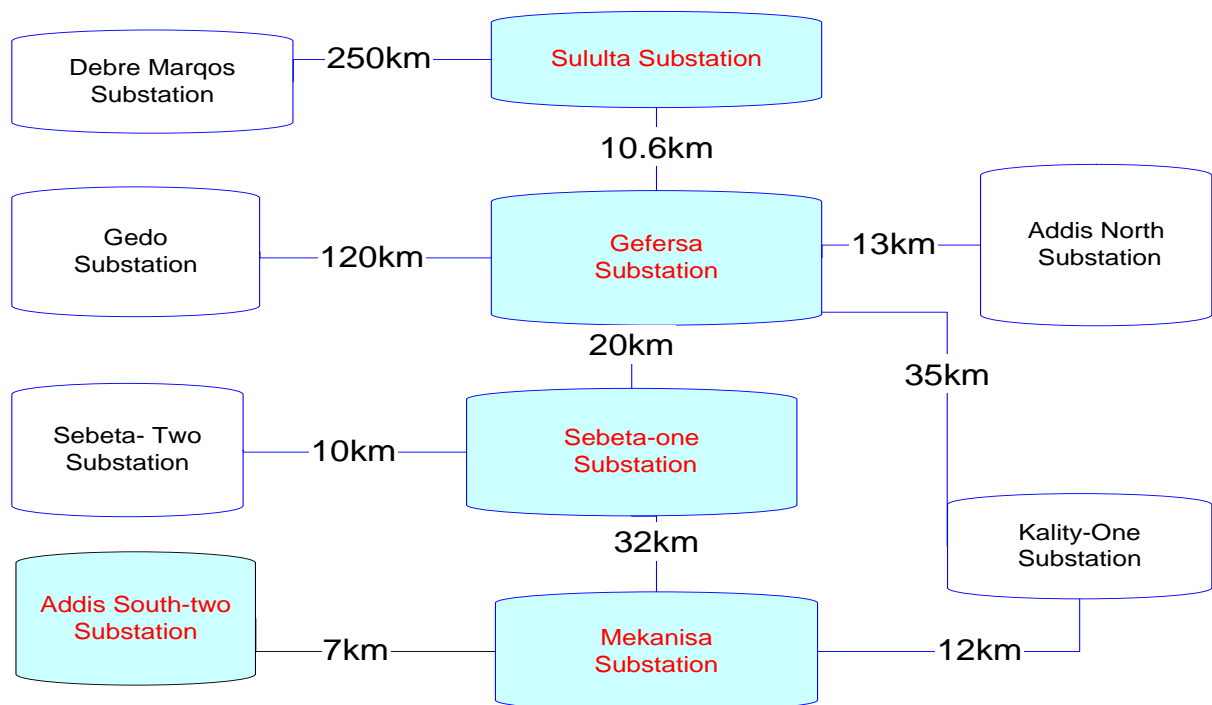
## Chapter One

### 1. Introduction

#### 1.1 Background

Sululta- Addis south-II transmission/substation is one of the existing transmission/substation in the EEP power system network which spans northwest to Southeast of Addis Ababa and the power supply for this region comes from different part of the interconnected power system network.

During peak hour time, the power supply for this region comes from Debre-Markos substation through 1x400kV transmission line which is connected to Sululta 400kVsubstation, from Ghedo to Geffersa substation via 2x230kV transmission line and from Sebeta-II to Sebeta-I substation Via 2x230kV transmission line. Moreover, the power supply flows from Gefersa to Addis North and Kaliti-I substations. This can be seen in fig1.1 below



**Fig1.1. Substations surrounding the study area**

As shown in Fig 1.1 above, the power system network of Sululta - Addis South-II transmission-substation consists of five main substations i.e. Sululta-230kV, Gefersa 230kV, Sebeta-I 230kV,

Mekanisa- 132kV and Addis South-II-132kV substations. And lower outgoing transmission/sub-transmission voltage levels and branch loads through step-down transformers which are not clearly shown in the above figure. It also shows the interconnection between Mekanisa and Kaliti-I substation, this happens only during the light load condition and some other special conditions like line outage either due to fault or operators choice for system stability.

Moreover, the transmission and substation system consists of different switches, transformers and other protecting and controlling electrical equipment, which are not seen in detail in this thesis. It is from these substations that power flows to industries, commercial buildings and households through reduction of voltage levels using step-down transformers and feeder conductors.

Due to the growth of industrialization and urbanization of the region, dependency on the electrical energy has been increased and resulted into rapid growth of the power system of the region. In addition to this, poor maintenance of power system equipment and the problems of replacement of old equipment on time led to over loading of power system equipment. Thus, the utility couldn't establish the match between supply and demand without violating power system parameters rated value.

## **1.2 Statement of Problem and Motivation**

Prior to discussing, the power system network of this case study, let's talk a few about a recent study done by the utility's consulting firm in 2015 on the General Ethiopian Power System Network. Based on the study made, an increasing power deficit in Addis Ababa, North Eastern and Southern regions and large amounts of surplus generation capacity in North Western and Western regions of the country is to be occurred. The power deficit in Addis Ababa is expected to grow from approximately 950 MW in 2015 to 5700 MW by 2037 and shall be met primarily from the Western, North Western regions by constructing new major transmission lines from these regions into Addis Ababa [1]. The detail of these figures is shown in appendix I and II.

Sululta- Addis south-II transmission/substation system provides electrical power supply to large cement factories like Dangote, Derba, and Muger. It also supply to small and micro industries, commercial buildings and households.

Generally, to narrow the gap between the electrical supply and demand, the power system of this region is growing very fast. However, frequent power interruptions are common and many customers have been throwing lots of complains timely for the government. Some of the causes of power interruptions are operating power system equipment beyond their capacity, violating their

name plate ratings, lack of redundancy power supply network during abnormalities, and improper and out dated maintenances of power system equipment. However, except temporary solutions as a relief, nothing is almost done on longer time solutions and power interruption is continuing almost two to three days per week.

To accommodate, the timely growing energy demand, either new transmission-substation has to be constructed and upgrade the old ones or shall utilize the existing system effectively through different mechanisms.

So, this thesis work focuses in optimum utilization of the existing transmission/substation system of Sululta - Addis South-II. Which is normally composed of different voltage levels i.e. 230/132kV, 132/66kV, 132/45kV, 132/33kV, and 132/15kV and is characterized with weak voltage profile i.e. under voltage. However, this can be solved using the shunt compensation method and therefore, the power transfer capability will increase.

All in all, the main reason for reactive power compensation of Sululta- Addis South-II transmission /substation line is to improve the weak voltage profile of the region. Therefore, the power needed to be transferred through the transmission line to the load side will be increased and the inadequacy of power will be minimized.

## **1.3 Research Objective**

### **1.3.1 General Objective**

The general objective of this thesis is to improve the weak voltage profile of the transmission/substation system and to increase power transfer capability of the region to the load side; therefore, energy deficiency of the specified region can be minimized.

### **1.3.2 Specific Objectives**

- Study Sululta - Addis South-II transmission line route problems
- Introducing Thyristor Switched Capacitor (TSC) to the selected transmission/substation system
- Model and analysis of Sululta- Addis South-II transmission/substation system using TSC
- Cost benefits analysis of the mitigation techniques.

## **1.4 Methodology and Scopes**

To mitigate the existing problem of the region, an overall transmission- substation of Addis Ababa region has been assessed and specific study of the power transmission and substation of Sululta - Addis south II has been done and provide shunt compensation system using thyristor switched capacitor (TSC). Specifically, the following methodologies have been followed in this thesis work:

- Literature Review: Literatures are reviewed, including articles, journals, books, thesis done in similar topics and others.
- Data collection: Real data has been collected from EEP and EEU which includes the ratings of transmission lines and power transformers and their impedances
- After necessary data has been collected, the data is organized using EXCEL sheet and the single lay out diagram and analysis using DIG SILENT Power Factory Soft Ware.
- Data analysis: Analysis has been done using power factory software in different load scenarios i.e. under peak and light power demand and five years load forecast, After analysis, an optimum shunt compensator has been designed for the proposed transmission/substation system using thyristor switched capacitor(TSC)
- Comparison has been done between the system with no compensation, with the proposed shunt compensator and its Cost benefit analysis.

## **1.5 Organization of the Thesis**

The thesis is organized into six chapters. Chapter one presents the introduction, background, motivation and statement of the problem, objectives of the study, methodology followed in the thesis work and the outline of the thesis.

Chapter two deals the theoretical background and literature review of the study topic, mainly on shunt compensation for a transmission/substation system, application of TSC and power transfer capability of a system.

Chapter three discusses the data collection and analysis of the transmission/substation system of the selected area. In this chapter all main data's that are needed for power flow analysis are provided and analyzed using DIG SILENT Power Factory software under different scenarios.

Chapter four discusses about simulation results and detailed discussion of the gain in forms of calculations, tables and column charts for comparison of the system before and after compensation.

Chapter five discusses about economic analysis. In this chapter, an investment costs and the savings due to the installation of shunt compensation is presented and an explanation for the evaluation of the investment.

## **Chapter Two**

### **Theoretical Back Ground and Review of Literature**

#### **2.1 Importance of Reactive Power in Power System**

The expansion in power transmission/substation system has taken place not only due to the increase in generation and loads but also due to the extensive interconnection among different power utilities. The major factor for system interconnections is to economize the generation reserves, to minimize generation costs and also to achieve the reliability of supplies [10].

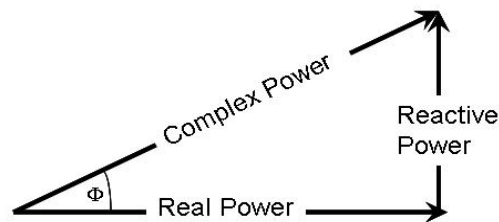
In order to narrow the gap between the ever growing electricity demand and the available generation capacity, setting up of a new generation station is not feasible because of economic and environmental considerations. So, it shall be achieved by improving the performance of the existing power system network through effective reactive power control mechanisms, providing and enhancing the existing power system using distributed generation resources and by implementation of energy management system. As far as, effective power system control is made, it is possible to run power system parameters with in their normal operating ranges. However, the consistency of these parameters is dependent on the type of load the system provides. For example, a load characterized with inductive load and other with resistive load consumes different amount of reactive power. The characteristic of inductive loads reflects with under voltage, reduction in operating power factor which further results in increased power losses. This in turn results in degradation in the power system performance and also the consumer getting frequent electrical power interruption.

Specially, industrial zone areas which are characterized with high demand of reactive power for their operation of induction machines, they shall be connected to a power system of strong reactive power profile or be connected to shunt reactive power compensator with faster switching controls.

In electrical power system, the reactive power is the power that supplies the stored energy in reactive elements mainly inductors and capacitors and is temporarily stored in the form of magnetic or electric fields and flows back and forth in the transmission line due to inductive and capacitive network elements.

Before discussing a lot about reactive power and the compensation system, let's first see the relation between the power components i.e. active power which is measured in watt and reactive

power measured in Var and the combination (vector product) of these components called complex Power. See the following power triangle [24].



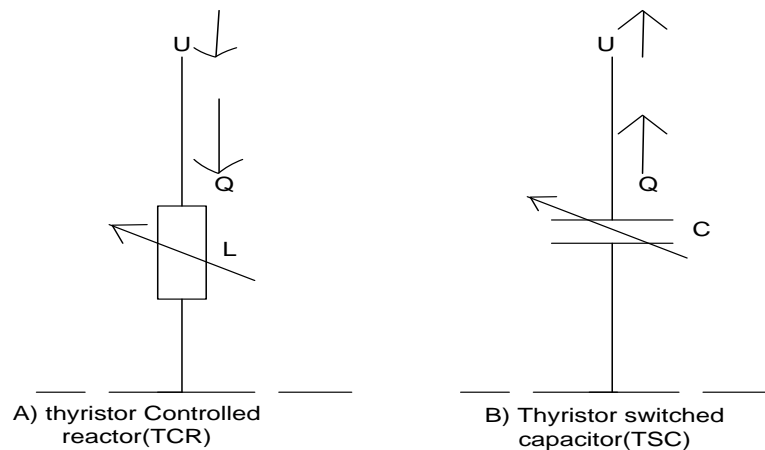
**Fig 2.1 Power triangle**

Reactive power can also be defined as, the unused power in which the system has to incur in order to transmit power. so, it is the by-product of alternative current (AC) and created when the voltage and current are not in phase i.e. one waveform leads the other or Phase angle not equal to  $0^\circ$  which results Power factor to be less than unity[24].

In an electrical power system, a balanced reactive power is the carrier of the true power. If it is consumed, the voltage decreases, and hence its ability to transport the true power decreases. So, reactive power in power system is required to deliver the active power (watts) through transmission lines, and to produce magnetic fields in Electric motors and transformers for their operation. If the reactive power of the system is not sufficient to support the terminal voltage of bus terminals, it can be supported using shunt reactive compensation system, so that, the reactive power which has to come from the system is to be provided by the compensation system and therefore the main equipment of the power system which were forced to deliver the reactive power to the load are getting relaxed and utilized the reactivity for their own operation.

The Shunt reactive compensation can modify the parameters of the system to give enhanced VAR compensation. It can do quite satisfactorily job of generating reactive power with a faster time response and come under Flexible AC Transmission Systems (FACTS). This allows an increase in transfer of apparent power through a transmission line, and much better stability by the adjustment of parameters that govern the power system i.e. current, voltage, phase angle, frequency and impedance. Unnecessary voltage drops lead to increased losses which needs to be supplied by the source and in turn leading to outages in the line due to increased stress on the system to carry this imaginary power. Thus we can infer that the compensation of reactive power not only mitigates all these effects but also helps in better transient response to faults and disturbances. In recent times there has been an increased focus on the techniques used for the compensation and with better devices included in the technology, the compensation is made more effective.

The terminal voltages at bus bar of the substations is influenced by loading i.e. heavy or light, active/passive load, power factor and voltage dependency, so shall be controlled and regulated via voltage controlling devices, one out of many is Static Var Compensator. Normally there are many voltage regulating devices of static Var Compensators such as, Thyristor- controlled reactor(TCR), Thyristor switched capacitor(TSC), thyristor-switch reactor(TSR) and voltage or current source convertors( VSC, CSC), let's see thyristor switched reactor and capacitors in figure2.2 below.

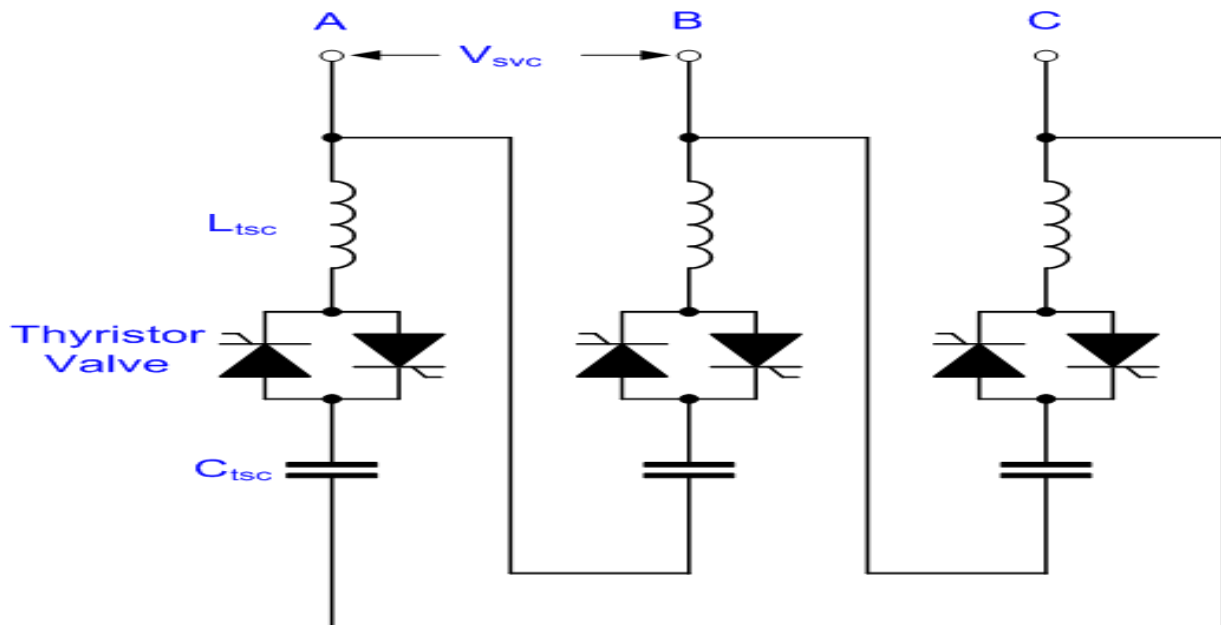


**Fig2.2 Thyristor Switched Reactor and Capacitor**

Fig 2.2 above shows the basic diagrams of static Var compensation with thyristor controlled reactor (TCR) and thyristor switched capacitor (TSC). Fig2.2-A shows the thyristor controlled reactor consumes reactive power from a system where as fig 2.2-B shows thyristor switched capacitor (TSC) contributes reactive power to the system, in this case study, since the area needs reactive power and voltage source, thyristor switched capacitor (TSC) is the right shunt compensator and main focus is on it.

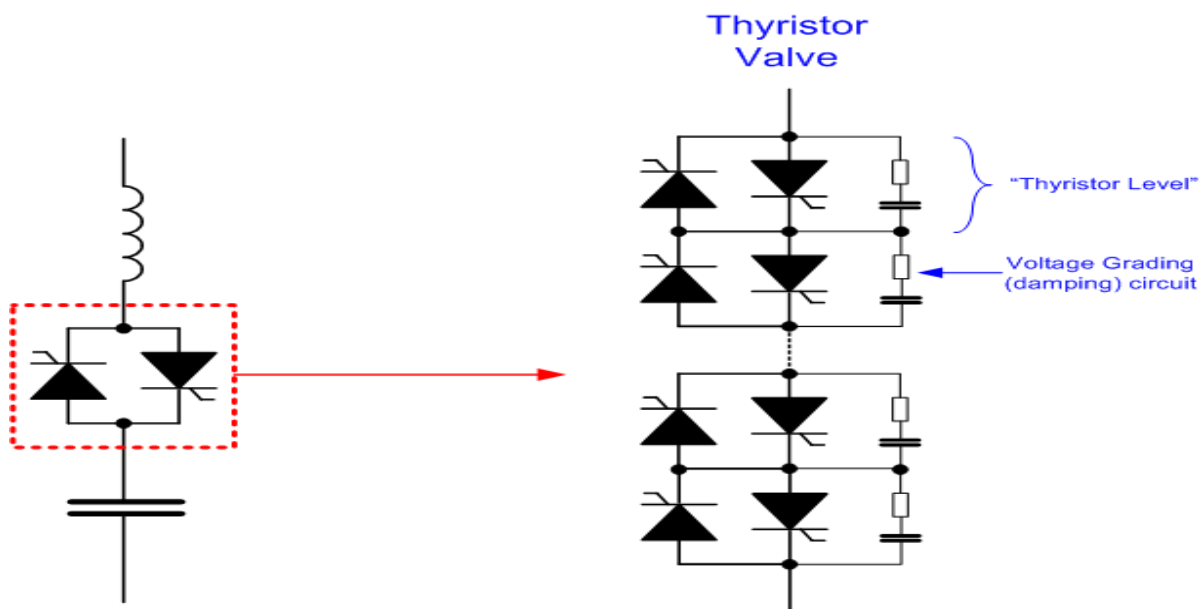
### **2.1.1 Thyristor Switched Capacitor (TSC)**

A thyristor switched capacitor (TSC) is a type of equipment which consists of a power capacitor connected in series with a bidirectional thyristor valve and, usually, a current limiting reactor (inductor). As can be seen in fig2.3 below:



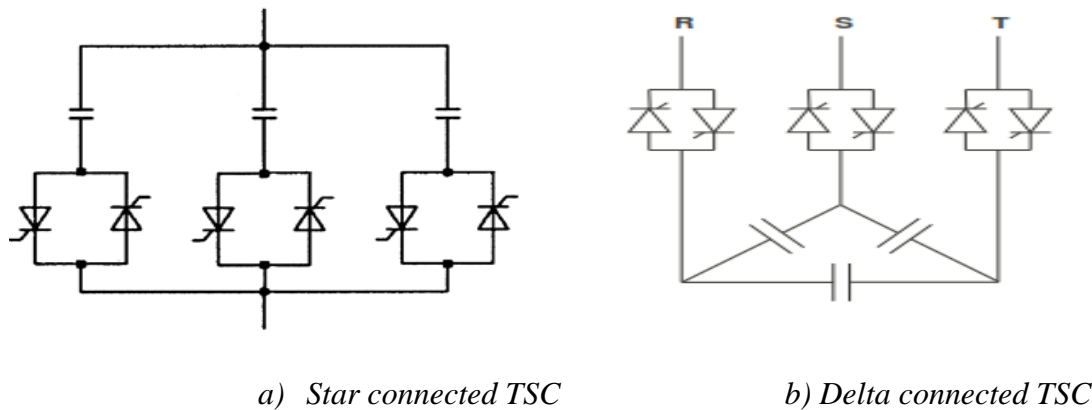
**Fig2.3. Thyristor switched capacitor (TSC)**

In fig 2.3 above, the single phase consists of a number of back-to-back connected thyristor pair in series to a capacitor and a reactor. The number of branches in one phase depends on the required precision of the reactive power. Moreover the structure usually consists of voltage grading (damping) circuit. This can be seen in fig2.4 below



**Fig2.4 Thyristor Valve with damping circuit**

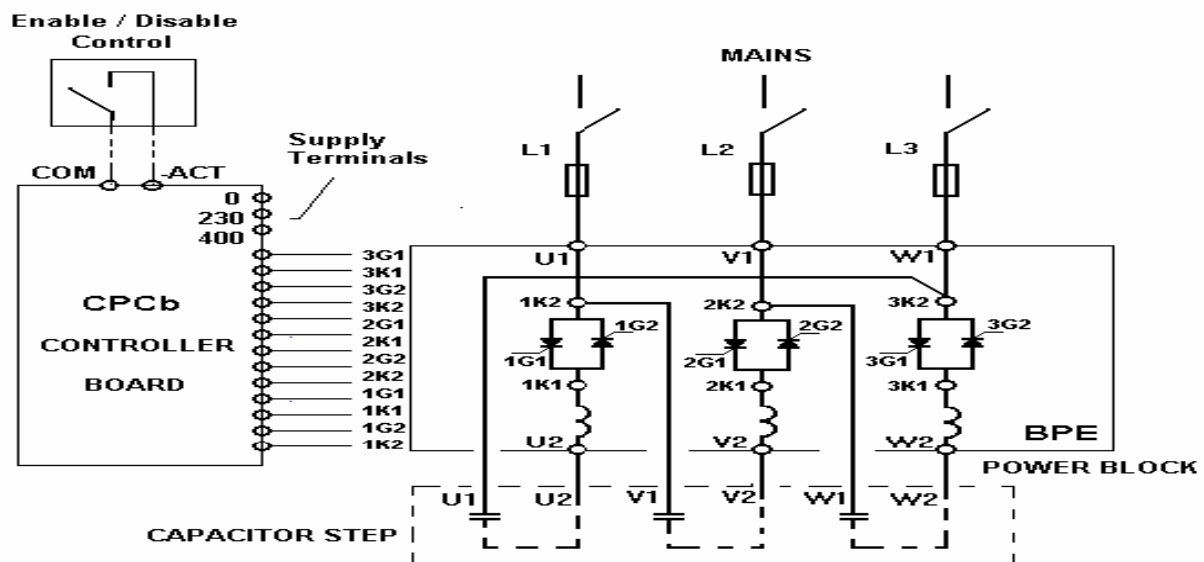
TSC can be configured in star connected TSC or delta connected capacitors topology. These topologies are used according to the voltage and current ratings of the components as can be shown in fig 2.5 below.



**Fig 2.5 Configuration of Thyristor Switched Capacitor**

The three thyristor valves are connected in delta in order to eliminate zero sequence and triplen harmonics (3<sup>rd</sup>, 9<sup>th</sup>...). So that, the harmonics remain trapped inside the delta and thus reduce harmonic injection into the power system. Reactor L is used to limit the surge current when thyristor is on under abnormal operating condition.

Regarding to the configuration of each components of TSC with the power supply block and the controller the wiring system is shown in fig2.6 below.



(Source: Electrical Engineering Portal)

**Fig 2.6 Wiring diagram of TSC**

The controller part in fig 2.6 above controls the power system parameters, mainly the magnitude of the reference voltage with the measured one. And, therefore, to switch the thyristor valves on and off according the required magnitude of reactive power of the system so, that the power supply to TSC will either be connected or interrupted



**Fig2.7 Capacitor Bank in Thyristor Switched Capacitor**

The main application areas of thyristor switched capacitor are: Terminal voltage regulation, reactive power control, harmonic filtration and transient free switching. And the general operating principle of TSC for all these application areas will be discuss in this portion.

### **2.1.1.1 Reactive Power Control**

Loads which need to have reactive power for their operation such as inductive loads shall be provided shunt reactive compensation using TSC. But, the total reactive power that the system needs should be carefully determined so that there is no excess or less capacitive reactive power produced by TSC. In order to avoid this, the system design should be handled delicately so that the reactive power contribution is optimum. After the decision of reactive power demand, the necessary capacitance needs to be calculated according to the amount of reactive power.

$$B_{cap} = \frac{Q_{cap}}{U_{nom}^2} \times 10^6 \text{ In } \mu\text{S} \quad (2.1)$$

Where 'B' is a susceptance 'Q' is the required reactive power, 'V' is the rms of the line voltage. Since the admittance is constant through an operation, the current varies linearly with the applied voltage. Therefore, the current ratings of the remaining components must be considered accordingly.

### **2.1.1.2 Terminal Voltage Regulation**

Many electronic devices are exposed to voltage variations due to the change in load type or load number connected to the electricity network. So TSC avoids the existence of under voltage and also the voltage variation.

### **2.1.1.3 Harmonic Filtration**

At the beginning of the turn-on process, a discharged capacitor behaves as a short circuit which leads to flow inrush current component through the thyristors which is too high such that  $di/dt$  is higher than its rating and can cause a failure in these switches. To overcome this problem, a series inductor is usually connected to each branch. This inductor works for a current limiting and filtering purpose [9].

### **2.1.1.4 Transient Free Switching**

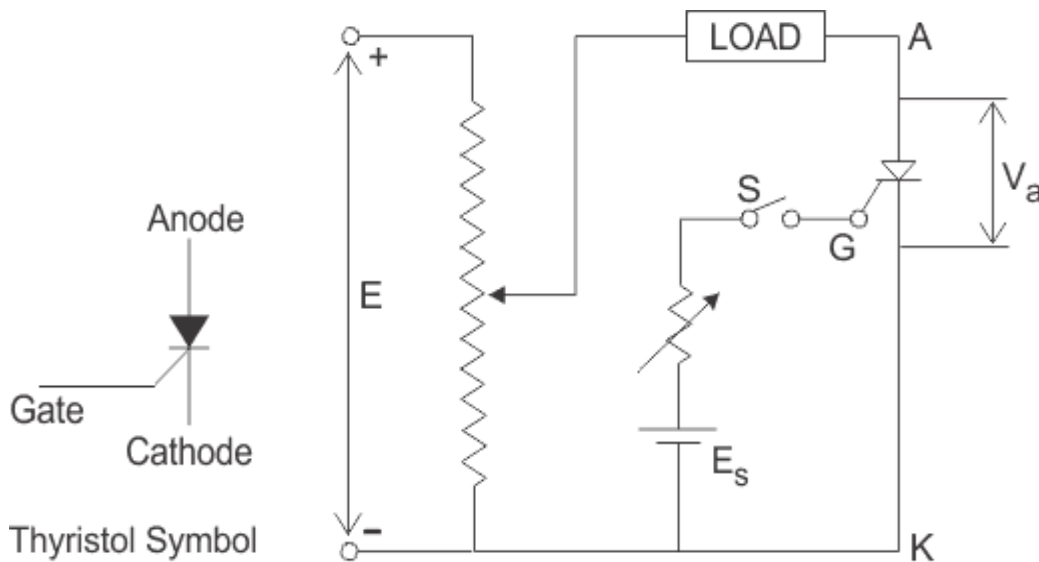
During switching of transmission lines and circuit breakers large amount of current flows towards the power system equipment. The transient value comes to its steady state value after a moment through exponential decay of sinusoidal wave. But the oscillating current pollutes the electrical system and causes the voltage supply to be distorted and the power quality to decrease. Moreover this transient value is much greater than power system equipment's rated value which could damage the equipment. Hence a great care must be given to switching performance.

Similarly in TSC, the capability of thyristor and capacitor for the inrush current that can occur during switching should be taken into account. Since, the rate of increase in current through the thyristor cannot be more than its  $di/dt$  ratings and capacitors cannot withstand a peak of the inrush current higher than 100 times its rated current [9], both of them can get damaged. However, in the TSC design scope, current limiting reactor is usually connected to create transient-free switching environment. It means that switching occurs with lesser distortion or oscillation in current and voltage waveforms.

There are also two conditions to examine here. The First one is when the capacitors are discharged or have not been energized yet and the second one is during energization of capacitors.

### 2.1.1.5 Operating principles of Thyristor switched capacitor

Thyristor is a four layer with three junction (p-n-p-n) and three basic terminals namely anode, cathode and gate. Both the cathode and anode are connected to the supply voltage through the load and a secondary supply between the gate and the cathode terminals which supplies for the positive gate current when the switch S is closed [7]. This is shown in fig 2.8 below



**Fig 2.8 circuit diagram of thyristor**

According to fig 2.8 above, the thyristor has three basic modes of operation, namely the reverse blocking mode i.e. when the cathode is made positive with respect to anode by supplying voltage E and the gate to cathode supply voltage E<sub>s</sub>, Forward blocking (off-state) mode when the anode is positive with respect to the cathode with gate kept in open condition and forward conduction (on-state) mode when the anode to cathode forward voltage is increased, with gate circuit open [7]. With the above thyristor mode of operation let's see the operation principle of TSC as follows:

**Steady state current:** When the TSC is on, the current leads the voltage 90° (as with any capacitor). The rms current is given by:

$$I_{tsc} = \frac{V_{tsc}}{X_{tsc}} \quad (2.2)$$

Where:

$$X_{tsc} = \frac{1}{2\pi f C_{tsc}} - 2\pi f L_{tsc} \quad (2.3)$$

C<sub>tsc</sub> is the total TSC capacitance per phase

$L_{tsc}$  is the total TSC inductance per phase

$f$  is the frequency of the AC system

The TSC forms an inductor-capacitor (LC) resonant circuit with a characteristic frequency of:

$$f = \frac{1}{2\pi f C t_{sc} L_{tsc}} \quad (2.4)$$

The TSC is usually adjusted to a non-integer harmonic of the mains frequency. The purposes of the adjustment is in order to overcome the over loading that can be happened due to the harmonic current coming from the AC system.

**Off-state Voltage:** When the TSC is switched off, no current flows via the device and the voltage is supported by the thyristor valve. If the TSC is switched off for a long time (hours), the capacitor in the TSC will slowly discharged. Thus, the capacitor voltage reaches its peak value and the voltage experienced by the thyristor valve will reach a peak of more than twice the peak AC voltage, which is about half a cycle after blocking.

The thyristor valve needs to contain enough thyristor in series to withstand the voltage of the power system to which it is connected, otherwise, the valves are to be over loaded and burn.

**De-blocking - normal conditions:** In order not to create a very large oscillatory current, care must be taken in choosing the correct instant of switching of TSC. Because, the TSC is a resonant circuit which could produce a high swinging frequency effect which could be a sudden shock excitation and damage the thyristor valve.

Thus, the optimum time to turn on a TSC is when the capacitor is still charged to its normal peak value and the turn-on command is sent at the minimum of valve voltage. If the TSC is de-blocked at this point, the transition back into the conducting state will be smooth.

**De-blocking – abnormal conditions:** Sometimes TSC can be turn on at an incorrect instant due of measurements or control faults, or the capacitor may be charged above its normal value. As a result, a large transient current results even at the minimum of valve voltage,

So, the voltage waveform across the thyristor, capacitor and the current waveforms through the reactor determine the design direction and each phases (turn-on with capacitors are discharged, turn-on with capacitors are charged and self-turn) are examined carefully.

## 2.2 Thermal Rating of Transmission Lines and Power Transfer Capability

### 2.2.1 Thermal Rating of Transmission Lines:

During normal operating 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. Sometimes, due to poor power system parameters, the system Loadability will be less than the thermal rating value. This however can be improved through different boost mechanisms

### 2.2.2 Power Transfer Capability:

To examine the power transfer capability of a system, a simple diagram is shown in Fig2.8 below. In this system, to simplify the calculation, the voltage phase angle at the receiving end is seen as reference, and the voltage magnitude of the sending end,  $V_S$  is constant [12].

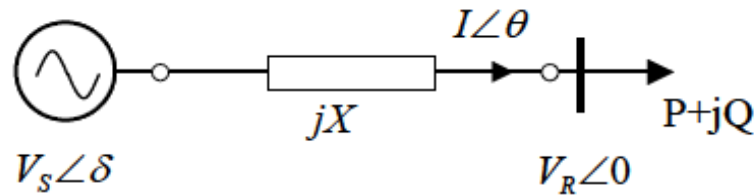


Fig 2.9 Power System Diagram

At the Receiving end,

$$V_r I^* = P + jQ \quad (2.5)$$

So

$$I = \frac{P - jQ}{V_r}$$

The Sending end Voltage is:

$$V_S = V_r + \frac{P - jQ}{V_r} jX = V_r + \frac{QX}{V_r} + j\left(\frac{PX}{V_r}\right)$$

The Corresponding magnitude equation is

$$V_S^2 = V_r^2 + \left(\frac{QX}{V_r}\right)^2 + \left(\frac{PX}{V_r}\right)^2$$

The power delivered to the load as a function of receiving end voltage when  $Q = 0$  can be solved as

$$P = \frac{\sqrt{V_s^2 + V_r^2}}{X} V_r \quad (2.6)$$

Since  $V_s$  is constant and close to 1 per-unit, and  $X$  cannot change,  $V_r$  is the only variable that can vary. So the power will vary with  $V_R$ .

The maximum power that can be transmitted to the load is reached when  $\frac{dp}{dv_r} = 0$  [12]. which can be determined as

$$P_{\max} = (V_s)^2 / 2X \quad (2.7)$$

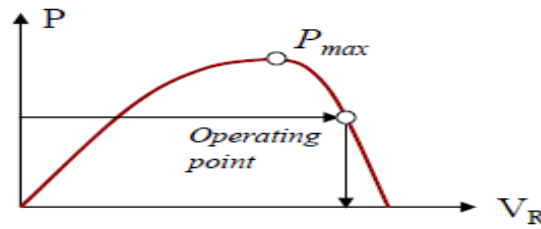


Fig 2.10 Power transfer capability curve

Figure 2.9 above shows, the maximum power transfer capability curve without violating the voltage stability limit.

If the terminal voltage at or near load bus decrease, the power to be transferred to the load side will decrease, this however can minimized by providing an appropriate shunt compensation at a bus terminals which are characterized with weak voltage profile .

### 2.3 Related Works

It is tried to compare the work of this thesis with researches done in similar areas in recent time, and is discussed as follow:

Research work done by “Ghanshyam Vishwakarma and Nitin Saxena” a study made on Enhancement of Voltage Profile using Fixed Capacitor- Thyristor Controlled Reactor (FC-TCR) [18]. This study focuses on improving the voltage stability limit of power flow between two different regions. It also discusses about the increasing in utilization of transmission lines because of the increasing demand of power owing to industrialization, this causes power supply degradation. As a result of the above consequence, the study tries to brief a ways of maximizing power transfer mechanism using FACTS devices and the modeling has been carried out in MATLAB/SIMULINK environment.

Another related study done by “Dr. B.V Sumangala on” implementation of Thyristor Switched Capacitor For reactive Power Compensation at secondary of distribution level feeders for voltage stability improvement” [10]. Its main focus is in regulation and enhancement of the power flows by reducing transmission losses, improve voltage stability through fast acting of voltage regulation and secure loading of lines nearer to their thermal limits. In order to carry out the above tasks, the simulation work is done using Simulink in MAT LAB.

But, this case study mainly focuses on improvement of voltage profile to the acceptable limit in order to increase the power transfer capability of the system and minimize the energy deficiency of the region using shunt compensator device called thyristor switch capacitor (TSC) and simulation work is done in power factory software environment.

## **Chapter Three**

### **Data Collection and Analysis**

#### **3.1 Data Collection**

While doing the research work of Sululta- Addis South- II transmission line route, different data have been collected from different sources and for ease of this study; it is divided in to two major types: one is the primary data and the other is secondary data.

The Primary data is the result of own studies of the Problem. It includes the collection of information through direct observation of the substations with in the transmission line route such as major equipment rating, loading of transformers and feeders and through conducting personal conversations and interviews.

The secondary data, on the other hand, is the result of other people's research in the same problem area, or from other related problem areas. It includes the study of documents and archival records obtained from the transmission line route, web-sites and other historical and documentary records relevant for the research.

The necessary data's for this thesis work are collected from different sources through,

- Conducting interviews with the respective personnel of the substations.
- Physical observation in the substations.
- And from Ethiopian electric power (EEP) and Ethiopian electric utility (EEU) engineering offices, Addis Ababa substation and transmission office
- From Ethiopian Electric Utility(EEU) Load Dispatch Center(LDC)

The data's include:

- Transmission line parameters.
- Transformers (Substation) main parameters
- Active and reactive power demand of the selected substations at their bus bar terminals.

Incoming power from the interconnected power system to the substations under study.

**Table 3.1 Transmission line parameters-I**

Transmission Line						
Voltage (kV)	From	To	Conductor Type	Tower Configuration	Line Rating (MVA)	Length (km)
230	Sululta	Geffersa	Twin Ash	Double	318	16.70
230	Geffersa	Sebeta-1	Mallard	Single	274	10.60
132	Geffersa	Sebeta-1	Tiger	Single	82	10.80
132	Sebeta-1	Mekanisa	Tiger	Single	82	7.80
132	Mekanisa	Addis South-II	Ash	Single	91	2.00
132	Gefersa	Muger	Ash	Single	91	80
132	Muger	Derba-tap	Ash	Single	91	19
66	Geffersa	Fitche	Merlo	Single	24	96

**Table 3.2 Transmission Line Parameter-I**

V(kV)	From	To	No	Positive Sequence			Zero Sequence			Thermal rating			SIL Circuit (MW)
				R ( $\Omega$ /km)	X ( $\Omega$ /km)	B ( $\mu$ S/km)	R0 ( $\Omega$ /km)	X0( $\Omega$ /km)	B( $\mu$ S/km)	Con(A)	Ckt (A)	MVA	
230	Sululta	Gefersa	2	0.11	0.32	3.64	0.34	1.07	2.21	399	798	318	179
230	Gefersa	sebeta-1	1	0.09	0.42	2.74	0.33	1.13	1.83	687	687	274	136
132	Gefersa	sebeta-1	1	0.26	0.42	2.68	0.53	1.12	1.65	357	357	82	44
132	Sebeta-1 tap	sebeta-1	1	0.26	0.42	2.68	0.53	1.19	1.65	357	357	82	44
132	Sebeta-1	Mekanisa	1	0.26	0.42	2.68	0.53	1.19	1.65	357	357	82	44
132	Mekanisa	Addis South – II	1	1.00	0.21	0.43	2.7	0.48	1.66	357	399	399	91

**Table 3.3 Two winding Transformers' Parameters**

V(kV)	Location	From Bus	To Bus	No	Rating (MVA)	Vector group	R (%)	X (%)	X/R Ratio
230/132	Sululta-132	1417	2379	2	65	YNa0+d	0.21	7.60	36.19
132/15	Gefersa	201	1361	1	25	YND11	0.36	9.70	26.94
230/132	Gefersa	1361	2303	4	125	YNa0d1	0.33	20.60	62.42
132/15	Sebeta-I	280	1364	1	40	YND11	0.58	12.00	20.69
230/33	Sebeta-I	383	2361	1	20	YND11	0.75	9.90	13.20
230/132	Sebeta-I	1364	2304	2	125	YNa0d1	0.33	20.60	62.42
132/15	Mekanisa	222	1365	2	20	YND11	0.35	8.10	23.14
132/15	Addis South-II	247	1385	2	20	YND11	0.36	9.70	26.94

**Table 3.4 Three Winding Transformers' Parameter**

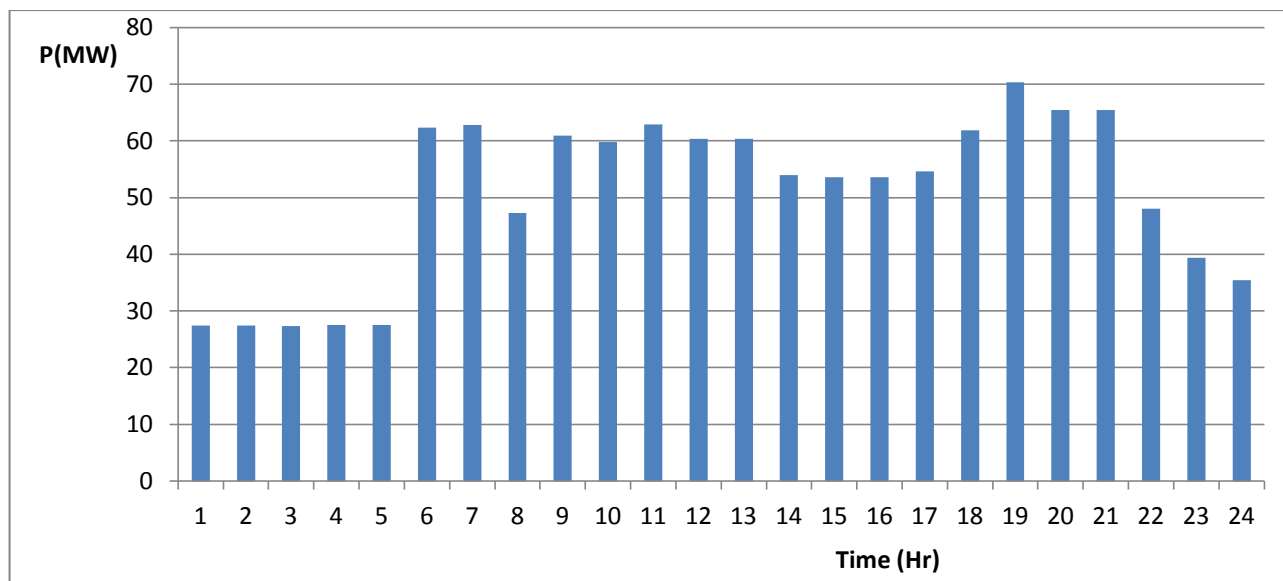
V(kV)	Bus name	From bus	To bus	Rating (MVA)	W1-2 R (%)	W1-2 X (%)	W2-3 R (%)	W2-3 X (%)	W3-1R(%)	W3-1 X (%)	W1-2 (MVA)	W2-3 (MVA)	W3-1 (MVA)
132/33/15	Geffersa	1361	304	281	0.40	6.70	0.40	4.00	0.40	11.00	24	12	12
132/45/15	Geffersa	1361	426	278	0.48	11.40	0.22	1.50	0.23	5.70	18	6	6
132/66/15	Geffersa	1361	654	278	0.45	7.90	0.36	5.70	0.46	14.80	20	20	20
132/45/15	Sebeta-I	1364	420	123	0.33	11.00	0.16	1.80	0.22	6.80	20	8	8
132/45/15	Sebeta-I	1364	420	123	0.56	12.50	0.80	4.70	0.97	18.40	12	4	4
132/33/15	Sululta	1417	388	282	0.34	10.30	0.59	17.7	0.23	7.00	50	25	25

To show the detail loading of substations a sample hourly and daily load profile of Mekanisa and Addis South-II substations are taken and shown on table (3.5 -3.10) and fig (3.5-3.10 ) below.

**Table 3.5 Hourly load profile of Mekanisa Substation**

Hour	132kV Addis South-II Line	15kV Outgoing Lines						
		H/Mariam	Lafto	Lebu	Mekanisa	Sebeta	C.G.C	Total
	MW	MW	MW	MW	MW	MW	MW	MW
1:00	11	5.83	1.14	2.89	1.87	1.35	3.32	27.40
2:00	11	5.83	1.14	2.89	1.87	1.35	3.32	27.40
3:00	11	5.83	1.14	2.89	1.87	1.35	3.30	27.38
4:00	11	5.83	1.14	2.89	1.87	1.49	3.30	27.52
5:00	11	5.83	1.14	2.89	1.87	1.56	3.28	27.57
6:00	31	9.65	3.76	7.99	4.38	2.20	3.38	62.37
7:00	32	9.84	3.53	7.31	4.73	2.14	3.30	62.85
8:00	23	10.48	2.99	4.44	4.38	1.97	0.00	47.27
9:00	31	11.96	3.22	4.38	4.75	1.99	3.65	60.96
10:00	31	10.75	3.11	4.28	4.96	1.97	3.76	59.84
11:00	32	12.04	3.40	4.42	4.82	2.03	4.19	62.91
12:00	31	11.00	3.24	4.42	4.71	2.20	3.80	60.38
13:00	31	11.00	3.24	4.42	4.71	2.20	3.80	60.38
14:00	26	11.02	2.99	3.80	4.19	1.74	4.24	53.98
15:00	26	11.21	2.93	3.59	4.11	1.74	3.97	53.55
16:00	26	11.21	2.93	3.59	4.11	1.74	3.97	53.55
17:00	28	9.63	3.03	4.21	4.11	1.68	3.94	54.61
18:00	32	10.01	3.53	5.15	4.92	2.35	3.94	61.89
19:00	37	10.92	4.03	6.08	5.67	2.55	4.09	70.34
20:00	34	10.63	3.78	5.46	5.31	2.47	3.78	65.43
21:00	34	10.63	3.78	5.46	5.31	2.47	3.78	65.43
22:00	23	9.32	2.60	3.84	3.65	1.62	4.01	48.04
23:00	19	8.14	1.87	2.51	2.97	1.25	3.67	39.41
0:00	16	7.91	1.74	2.43	2.72	1.14	3.47	35.41

(Source: Substation Registered data taken on 01/09/2008 EC)



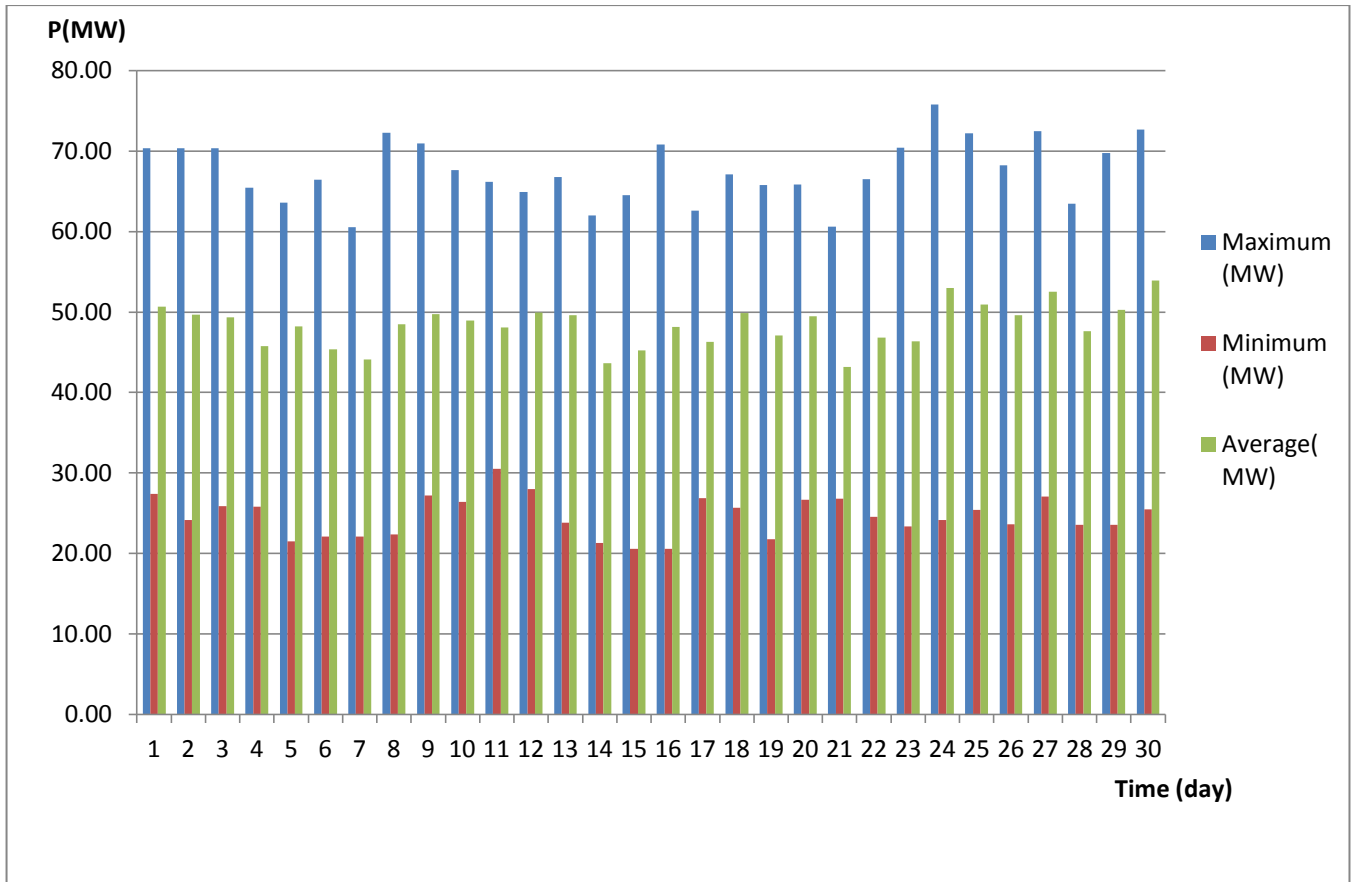
**Fig 3.1 Hourly load profile of Mekanisa Substation**

(Source: substation registered data taken on 01/09/2008EC)

**Table3.6 daily load profile of mekanisa substation taken from 01/09/2008 -30/09/2008 EC**

No	Time (days)	P(MW)			No	Time (days)	P(MW)		
	May	Max Load	Min Load	Average Load		May	Max Load	Min Load	Average Load
1	1/9/2008	70.34	27.38	50.66	16	16/09/2008	70.82	20.55	48.17
2	2/9/2008	70.34	24.13	49.64	17	17/09/2008	62.62	26.86	46.32
3	3/9/2008	70.34	25.88	49.31	18	18/09/2008	67.08	25.68	49.85
4	4/9/2008	65.44	25.78	45.76	19	19/09/2008	65.79	21.75	47.09
5	5/9/2008	63.56	21.52	48.2	20	20/09/2008	65.81	26.69	49.5
6	6/9/2008	66.41	22.12	45.38	21	21/09/2008	60.62	26.81	43.18
7	7/9/2008	60.57	22.13	44.07	22	22/09/2008	66.52	24.52	46.83
8	8/9/2008	72.3	22.36	48.45	23	23/09/2008	70.4	23.35	46.36
9	9/9/2008	70.95	27.23	49.77	24	24/09/2008	75.77	24.18	52.96
10	10/9/2008	67.62	26.42	48.96	25	25/09/2008	72.21	25.43	50.9
11	11/9/2008	66.18	30.49	48.09	26	26/09/2008	68.23	23.62	49.63
12	12/9/2008	64.94	28.01	49.92	27	27/09/2008	72.44	27.09	52.55
13	13/9/2008	66.79	23.81	49.62	28	28/09/2008	63.44	23.54	47.59
14	14/9/2008	62.01	21.3	43.66	29	29/09/2008	69.76	23.54	50.29
15	15/09/2008	64.53	20.55	45.25	30	30/09/2008	72.69	25.46	53.89

(Source: Sub Station Registered data taken from 01/09/2008 -30/09/2008 EC)



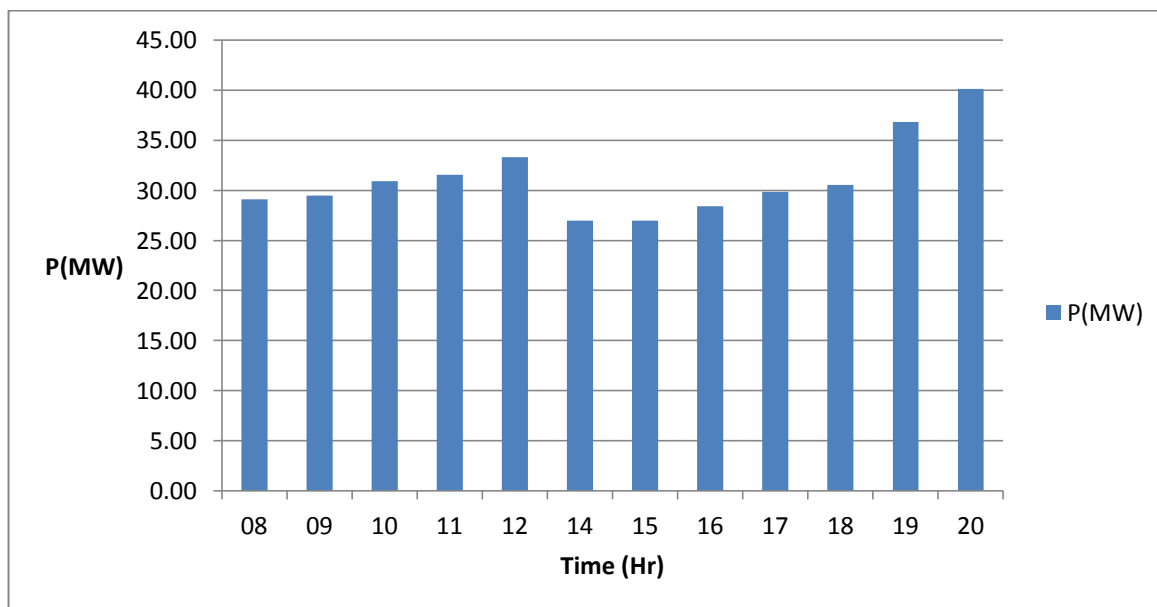
**Fig 3.2 Daily Load Profile of Mekanisa Substation**

(Source: Substation Registered data taken from 01/09/2008 -30/09/2008 EC)

**Table 3.7 Hourly load profile of Addis South-II Sub-Station**

Time (Hour)	15 kV Outgoing Lines of Addis South-II					Total (MW)
	L2	L3	L4	L5	L6	
	Power	Power	Power	Power	Power	
	MW	MW	MW	MW	MW	
08	4.55	5.40	7.20	5.43	6.55	29.13
09	4.85	5.60	7.08	5.75	6.20	29.48
10	4.98	5.88	7.43	6.05	6.60	30.93
11	5.15	6.03	7.58	6.03	6.80	31.58
12	5.45	6.38	7.90	6.15	7.45	33.33
14	4.23	5.03	6.25	5.10	6.40	27.00
15	4.23	4.93	6.30	5.28	6.23	26.95
16	4.65	5.18	6.43	5.48	6.70	28.43
17	4.75	5.63	6.65	5.75	7.05	29.83
18	4.70	5.80	7.15	5.80	7.08	30.53
19	5.40	6.85	8.98	6.80	8.78	36.80
20	6.93	7.38	9.13	7.15	9.55	40.13

(Source: Sub Station Registered data taken on 16/05/2016 )



**Fig3.3. Hourly Load Profile of Addis South-II Sub-Station**

(Source: SS Registered data taken on 16//09/2016)

According to the operators of the substation saying, “hourly load profile in the substation is recorded only between 08:00 and 20:00.it is because of the load profile on the rest hours of the day

is found to be normal and control mechanism is sometimes made from both the incoming and outgoing side of the substation”.

**Table 3.8** Daily Peak Load profile of Addis South-II Substation 15kV feeders for the month of May, 2016

Time (day)	15kV Out Going Lines					Time (day)	15kV Out Going Lines				
	L2	L3	L4	L5	L6		L2	L3	L4	L5	L6
	MW	MW	MW	MW	MW		MW	MW	MW	MW	MW
1	3.73	6.10	6.10	5.50	7.53	17	5.60	9.30	9.00	7.80	9.10
2	4.75	6.33	8.23	6.15	8.03	18	5.65	6.33	8.85	7.40	9.23
3	5.20	6.75	7.73	6.78	8.68	19	5.63	7.63	7.95	7.38	8.58
4	5.40	6.60	7.10	6.70	9.10	20	5.70	6.60	7.50	6.90	8.70
5	5.75	6.93	7.68	6.68	8.73	21	6.30	9.30	9.80	6.83	9.25
6	5.63	6.60	6.93	6.75	8.40	22	5.28	6.68	9.15	6.50	8.40
7	6.10	6.90	8.65	7.38	9.20	23	6.43	6.28	8.35	6.95	9.40
8	5.65	6.98	8.53	7.30	9.23	24	5.55	7.18	8.78	6.65	8.78
9	5.55	6.45	7.15	6.45	8.25	25	5.55	6.33	8.60	6.45	7.98
10	5.70	7.00	7.60	7.20	9.30	26	5.50	7.50	8.70	6.90	8.90
11	5.55	7.10	9.13	9.13	7.45	27	5.85	7.08	9.48	6.75	8.85
12	5.50	6.93	7.55	7.00	9.63	28	5.80	7.70	8.70	6.70	9.10
13	5.60	6.00	7.50	7.00	8.40	29	4.88	6.78	8.15	6.03	9.20
14	6.08	6.95	7.78	7.33	8.90	30	5.53	7.83	9.48	7.18	9.48
15	5.35	6.60	7.20	6.85	8.98	31	5.70	7.80	9.20	6.95	9.00
16	6.93	7.38	9.13	7.15	9.55						

**Table 3.9** Daily Peak Load Profile of Addis South-II Substation for the Month of May, 2016

Time (day)	Peak (MW)	Minimum (MW)	Average (MW)	Time (day)	Peak (MW)	Minimum (MW)	Average (MW)
1	28.95	19.28	24.11	17	40.80	27.13	33.96
2	33.48	21.20	27.34	18	37.45	25.85	31.65
3	35.13	26.40	30.76	19	37.15	25.05	31.10
4	34.90	24.60	29.75	20	35.40	22.90	29.15
5	35.75	23.13	29.44	21	41.48	26.10	33.79
6	34.30	25.48	29.89	22	36.00	23.63	29.81
7	38.23	26.90	32.56	23	37.40	25.68	31.54
8	37.68	21.23	29.45	24	36.93	26.08	31.50
9	33.85	26.95	30.40	25	34.90	26.78	30.84
10	36.80	20.60	28.70	26	37.50	28.20	32.85
11	38.35	26.88	32.61	27	38.00	23.63	30.81
12	36.60	24.85	30.73	28	38.00	25.90	31.95
13	34.50	26.25	30.38	29	35.03	20.60	27.81
14	37.03	26.25	31.64	30	39.48	26.10	32.79
15	34.98	24.53	29.75	31	38.65	24.60	31.63
16	40.13	26.70	33.41				

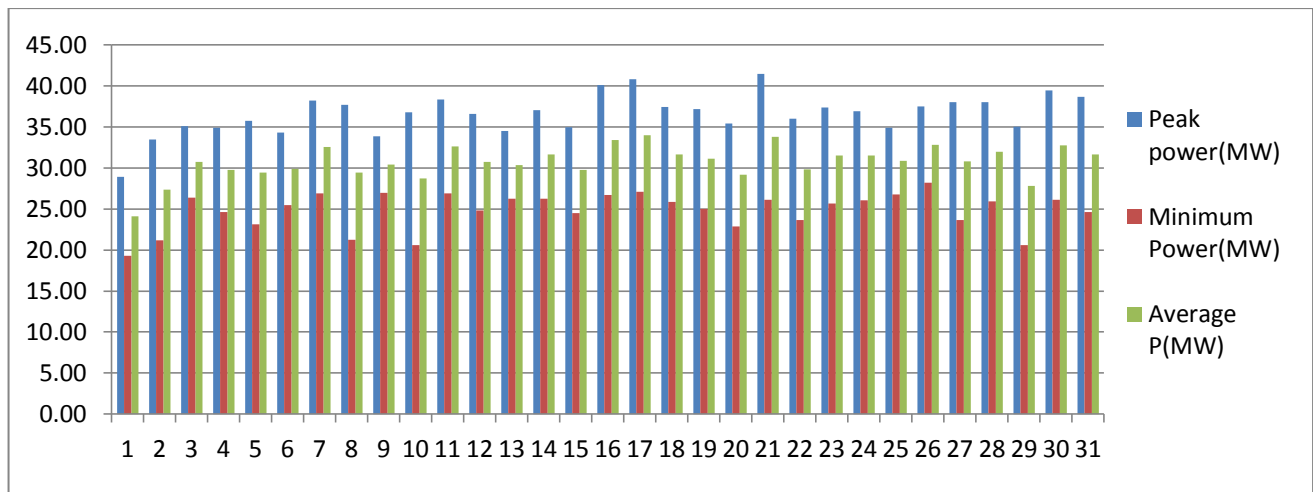


Fig 3.4 Load profile of Addis South-II Sub-Station for the month of May, 2016

**Table3.10 2016 Peak and light Load of Sululta-Addis South-II**

**Transmission-Substation**

Substation	Voltage (kV)	Peak load		Light load	
		P	Q	P	Q
Sululta	132	24.50	24.50	24.50	12.25
	33	3.24	3.24	2.43	1.22
	15	20.78	20.78	14.96	6.73
Geferssa	132 (Derba)	20.00	20.00	21.20	7.35
	132 (Muger)	16.00	16.00	16.00	7.53
	132 (Kality)	12.00	12.00	15.00	3.75
	66 (Fiche)	1.02	1.02	2.55	0.51
	45	4.20	4.20	4.20	2.10
	45	8.20	8.20	8.20	3.47
	33	0.19	0.19	0.19	0.08
	15	5.50	5.50	4.60	2.17
	15(3-winding)	1.11	1.11	0.79	0.40
	Addis north	22.00	22.00	18.26	8.43
Sebeta-I	230	22.60	22.60	15.28	7.06
	132	24.00	24.00	17.76	8.23
	45(Geja)	3.20	3.20	2.75	1.38
	45(AW-I)	3.20	3.20	2.62	1.31
	45(AW-II)	4.00	4.00	9.00	3.75
	15(1)	2.50	2.50	2.12	1.25
	15 (terminal)	9.00	9.00	9.00	4.24
	15 (Sebeta)	26.37	26.37	26.37	12.24
Mekanisa	15	12.19	12.19	12.19	6.25
Addis South-II	15	18.05	18.05	18.05	9.40

### 3.1.1 Load Forecast of 2017-2021

To implement the study of this work, it is vital to show its importance for the future time, thus, a short period of load forecast has been made for the incoming five years and out of many load forecast methodology, gross domestic product (GDP) growth rates of countries is one of the familiar one and normally EEP uses this to forecast electrical load in substation/ distribution levels. Let's see the following load forecast made by EEP for its power system master plan study for the next 21 years of the main developmental sectors in Table 3.11 below.

**Table 3.11 Gross Domestic Product Growth Rates**

Sector	2012-2015(%)	2016-2020(%)	2021-2025(%)	2026-2037(%)
Agriculture	8.1	6.3	5.4	3.9
Industrial	20	15.6	13.9	10.7
Commercial	10.9	9.3	8.4	6.9
Services	10.9	9.3	8.4	6.9
Total	11.2	9.6	9.0	7.6

(Source: EEP/EEU master plan study)

As can be seen from table 3.11 above, the average GDP growth in 2016-2020 GC is 9.6% and according independent study of World Bank on the GDP growth of Ethiopia 7% of growth (press released) is expected and the electrical power demand at substation/distribution level is expected to grow with the same. Moreover, some of the substations under this case study are old substations in which load demand is expected to grow (3-4) % yearly. Therefore, the average load growth at transmission/substation level for this case study is considered to be 5%

**Table 3.12:** In -feed Power for Sululta- Addis South-II Transmission-Substation System in 2016 and 2021

No	Substation		2016		2021	
	From – Bus	To –Bus	P (MW)	Q (Mvar)	P (MW)	Q (Mvar)
1	Debre Markos	Sululta	256	76	326.73	96.99
2	Ghedo	Gefersa	40	14	51.05	17.87
3	Sebeta-II	Sebeta-I	36	8	45.95	10.21

**Table 3.13 Load Profile of Sululta-Addis South –II Transmission-Substation system in 2016 and 2021**

No	Substation	Voltage level	2016		2021	
			P(MW)	Q(Mvar)	P(MW)	Q(Mvar)
1	Sululta	132	24.50	4.70	30.63	5.88
2	Sululta	33	3.24	1.70	4.05	2.13
3	Sululta	15	30.78	16.24	38.48	20.30
4	Gefersa	Kaliy-132	12.00	3.00	15.00	3.75
5	Gefersa	Addis North-132	22.00	10.00	27.50	12.50
6	Gefersa	45	4.40	1.80	5.50	2.25
7	Gefersa	Fit-66	2.00	0.98	2.50	1.23
8	Gefersa	15	5.50	4.60	6.88	5.75
9	Gefersa	15	1.11	0.64	1.39	0.80
10	Gefersa	33	0.20	0.10	0.25	0.13
11	Mekanisa	15	60.00	29.10	75.00	36.38
12	Addis South-II	15	38.60	16.23	48.25	20.29
13	Muger	132	16.00	7.00	20.00	8.75
14	Derba	132	20.00	9.00	25.00	11.25
15	Sebeta	230	22.60	11.10	28.25	13.88
16	Sebeta	15	48.90	20.00	61.13	25.00
17	Sebeta	132	24.00	13.07	30.00	16.34
18	Sebeta	15-ter	10.00	5.40	12.50	6.75
19	Sebeta	15	2.50	1.00	3.13	1.25
20	Add west	45	15.00	5.38	18.75	6.73
21	Geja	45	3.20	1.60	4.00	2.00
22	Addis West-I	45	3.20	2.00	4.00	2.50

### 3.2 Data Analysis

The above collected data is analyzed quantitatively and qualitatively using **Dig SILENT** power factory software. This program is a computer aided engineering tool which is designed as an advanced integrated and interactive software package dedicated to electrical power system and control analysis in order to achieve the main objectives of planning and operation optimization. The name **Dig SILENT** stands for "**D**igital **S**imulation and **E**lectrical **N**etwork calculation program".

The **Power Factory** package was designed and developed by qualified engineers and programmers with many years of experience in both electrical power system analysis and programming fields. The accuracy and validity of the results obtained with this package has been confirmed in a large number of implementations, by organizations involved in planning and operation of power systems.

In order to meet today's power system analysis requirements, the **Dig SILENT** power system calculation package was designed as an integrated engineering tool which provides a complete

'walk-around' technique through all available functions, rather than a collection of different software modules. The following key-features are provided within one single executable program:

- Integrated interactive single line graphic and data case handling
- Integrated calculation functions (e.g. line and machine parameter calculation based on geometrical or nameplate information)
- Power system network configuration with interactive or on-line access to the SCADA system
- Generic interface for computer-based mapping systems

By using just a single database, containing all the required data for all equipment within a power system (e.g. data for line, generator, protection, harmonic and controller), Power Factory can easily execute any or all available functions, all within the same program environment. Some of these functions are load-flow; short-circuit calculation, harmonic analysis, protection coordination, stability calculation and modal analysis [16]. But in this paper the software package is used only for load flow analysis.

### **3.2.1. Load Flow Analysis**

In this part, Load flow analysis is used to analyze the selected power systems under steady-state using power factory software. The load flow calculates the active and reactive power flows for all branches, loading of transmission lines and power transformers, the voltage magnitude at each bus bar of the substations in terms of kilo Volt (kV) and per unit (pu).

The main areas for the application of load flow calculations are: Calculation of branch loadings, voltage profiles for system planning and operation at normal conditions and compares with a system after introducing TSC.

Under normal operating conditions the in feed power as well as the loads is known, and it is therefore sufficient for the load flow calculation to represent these in feed power and to provide the active and reactive power of all loads. The results of the load flow calculation should represent a system condition in which none of the branch or generator limits are exceeded. The calculation methods and the options provided by *Power Factory*'s load flow analysis function allow the accurate representation of any 3-phase AC systems. For very fast and reliable analysis of complex transmission networks, only the flow of active and reactive power through the branches and voltage profile at bus bar of substations is considered.

*As a general concept, DIG SILENT Power Factory* software is implemented as a single executable program, and is fully compatible with Windows 2000/XP/Vista and Windows 7. The programming method employed allows for a fast 'walk around' the execution environment, and eliminates the need to reload modules and update or transfer results between different program applications. As an example, the power flow, fault analysis, and harmonic load flow analysis tools can be executed sequentially without resetting the program, enabling additional software modules and engines or reading external data files. A special feature of the *Dig SILENT Power Factory* software is the unique vertically integrated model concept. This allows models to be shared for all analysis functions and more importantly, for categories of analysis, such as "Generation", "Transmission", "Distribution" and "Industrial". No longer are separate software engines required to analyze separate aspects of the power system, as *Dig SILENT Power Factory* can accommodate everything within one integrated frame and one integrated database.

To determine the placement of TSC and the capacity, optimum capacitor placement (OCP) is used. Optimal Capacitor Placement (OCP) is an automatic algorithm that minimizes the cost of losses and voltage constraints in a power system network by proposing the installation of new capacitors at terminals along the selected feeder/s. The optimal size and type of capacitor is selected from a list of available capacitors entered. The algorithm in the software considers the annual cost of such capacitors and only proposes new capacitors for installation when the reduction of energy loss and voltage constraint costs exceeds the annual cost of the capacitor (investment, maintenance, insurance). This can be seen in the following output page of the power factory software to do OCP for this case study.

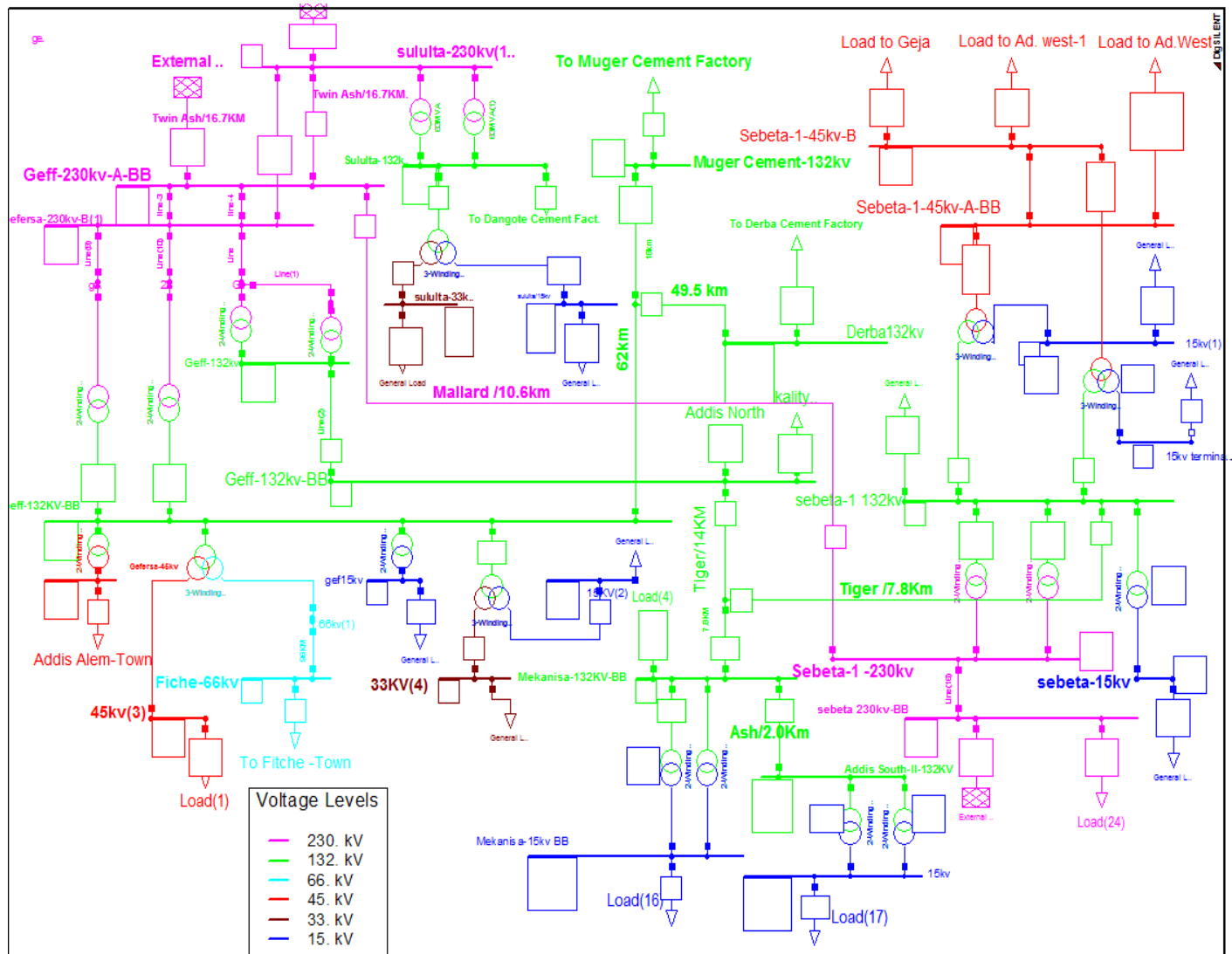
## **Chapter Four**

### **4. Simulation Results and Discussions**

In order to analysis the problem of the existing Sululta-Addis South-II Transmission- substation system and put the mitigation technique, simulations have been made under different scenarios.

- To simulate the transmission substation system, the following points has been considered as input:
- Transmission line parameters and transformer ratings
- Period of maximum loading of each substations in EEP load curve has been registered on Eve of public holidays i.e., Eve of Ethiopian New year on 09/09/15 at 19:00PM and Eve of charismas on 6/01/16 at 19:00 PM. then comparison has been done and selected the one with maximum demand which was found to be the Ethiopian new year.
- Period of minimum loading of each substation in EEP load curve of substation has been registered at 3:00pm night at normal days.
- Five years load forecast has been considered and so, load of 2021 is used for design of shunt compensation in this study.

The entire lay out diagram is shown in figure 4.1 below



**Fig 4.1 Lay Out Diagram of Sululta-Addis South-II Transmission/Substation Route**

Figure 4.1 above shows, the single line diagram of Sululta-Addis south-II transmission/substation system which is composed of external grids, transmission lines with different voltage levels, bus terminals of substations and general loads. The power supply to this system comes from Debre-Markos, Ghedo and Sebeta-II substations and these are represented by external grids.

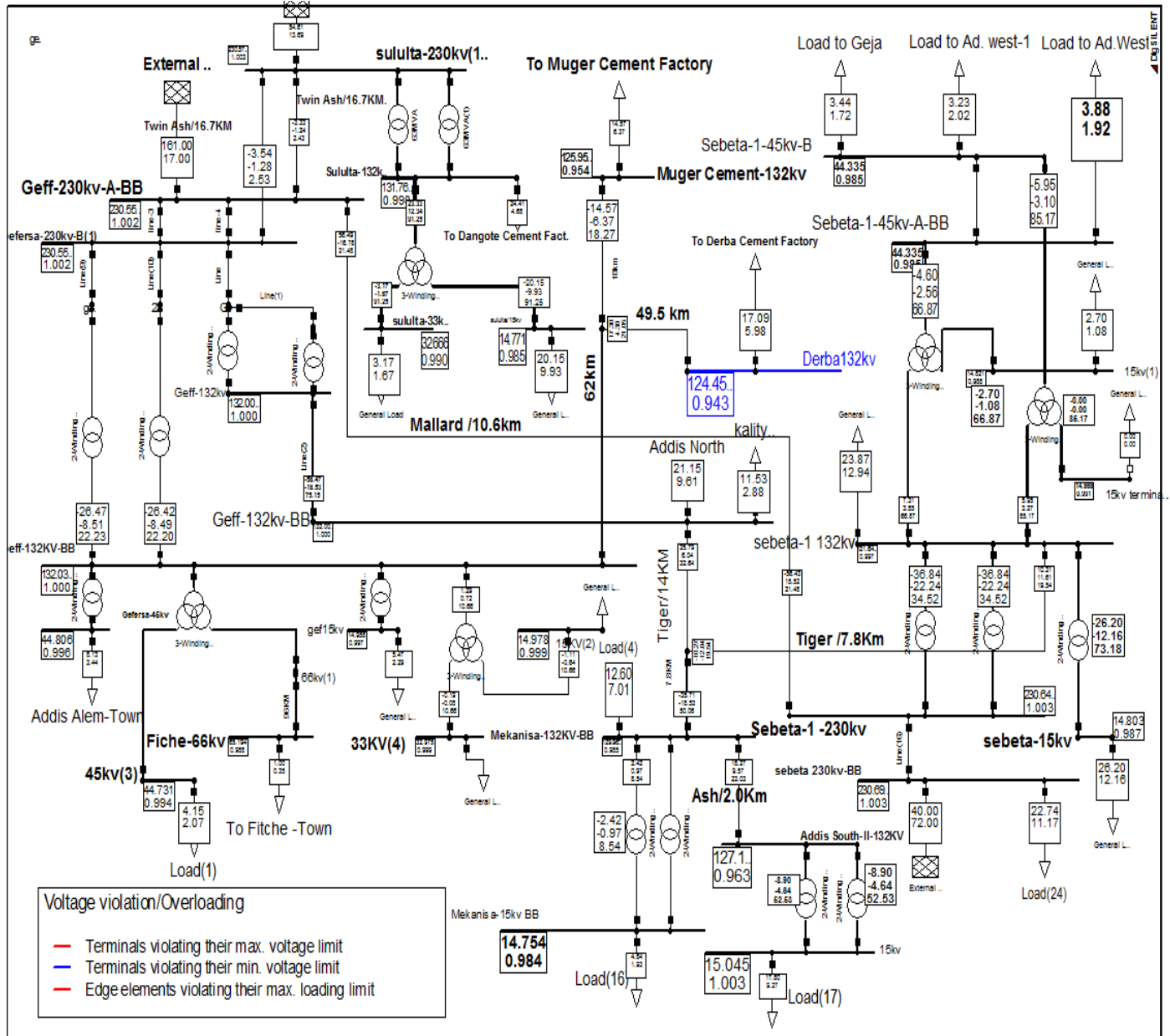
All branch loads at the outgoing line of the substation’s bus terminal are represented by general load which are composed of inductive behavior load types like in Dangote, Derba and Muger cement factories, a number of households (resistive type of loads) and different commercial buildings (various load type).

According, the above lay out diagram, the software uses the following assumptions for the power flow simulation i.e. AC load flow, positive sequence power flow, automatic tap adjust of

transformers, thermal loading limit of edge elements to be 100%, Automatic model adaptation for convergence, lower and upper voltage limits to be 0.95pu and 1.05p.u respectively.

Normally the operating principle of EEP substations main equipment i.e. transformer is 100% loading when the cooling system of transformers is set to be ONAF (Oil Natural and Air Forced) [1] and 80% when the cooling system of transformers is set to be, ONAN (Oil Natural and Air Natural) [1]. This can also be seen in appendix-III and IV.

The simulation has been done for the light, peak and five years load forecast .The light load condition of EEP transmission line is recorded to be at 3:00 pm in the morning. During this time, some of the power flow direction in the peak hour time is changed towards an area of rich factories and industries of the power system network. The single lay out diagram during the light load condition is shown in fig 4.2 below



**Fig 4.2 simulation result of Light Load Condition before shunt compensation for 2016**

As can be seen in fig4.2 above, the voltage profile of the region is within the normal limit i.e. between 0.95pu and 1.05pu value, except the 33kV voltage profile at Derba cement factory’s substation bus terminal which is below the normal operating level which is 0.943pu. So, in the early morning at 3:00pm, there is almost no issue of under voltage and no need of compensation.

Whereas, the loading of the transmission/substation system during the peak hour time which is at 19:00 pm in the evening is different and is as shown in fig 4.3 below

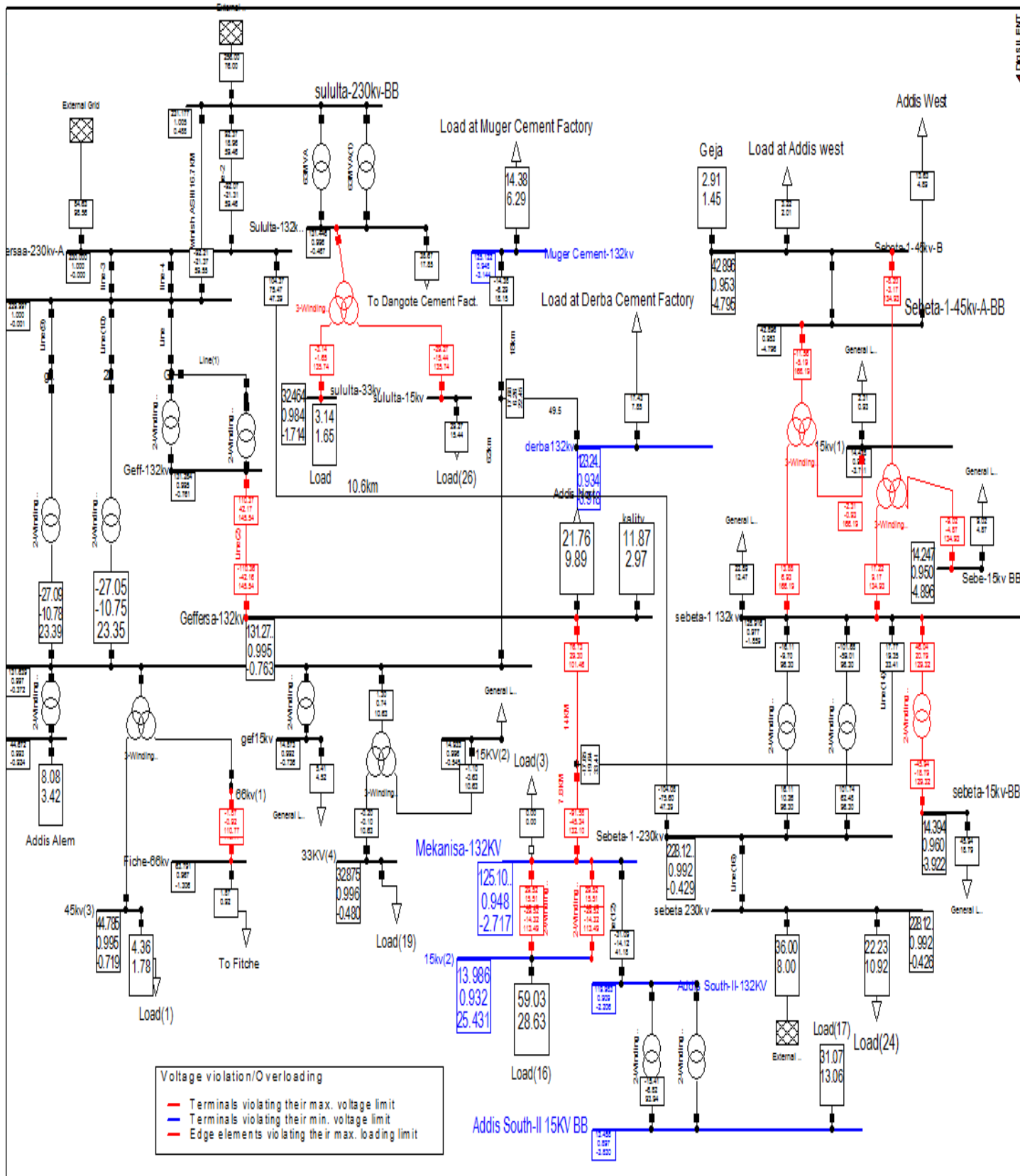


Fig 4.3 Simulation Result of Peak Load Condition before shunt compensation for 2016

The simulation result of fig 4.3 above shows that under voltage problems at bus terminals, over loading of transmission lines and power transformers. To solve this under voltage problem, first, a five years load forecast has been done to make the shunt compensation system of this study a problem solver of the coming five years. Thus, TSC is connected and comparison for system before compensation and after compensation has been made. The result of the software after compensation shows an improvement of voltage profile at bus terminals of the substations and an incremental of power transfer capability of the system. The outcome of the simulation and the analysis made is shown below

**Table 4.1 Simulation Result of Un-compensated transmission lines in 2016**

R/no	Transmission Line		Before Shunt Compensation
	From	To	Power transfer Capability (MW)
1	Geffersa-132kV	Geffersa-132kV	95.44
2	Geffersa-66kV	Fitche-66kV	2.41
3	Geffersa-132kV	Sebeta-I-132kVtap	29.19
4	Sebeta-I-132kV Tap	Mekanisa-132kV	106.02
5	Mekanisa-132kV	Addis South-II-132kV	38.13

**Table 4.2 Simulation Result of Un-compensated Two Winding Transformers in 2016**

No	Substation	Number	Before Compensation
			Power Transfer Capability (MW)
1	Sebeta-I-132/15kV	1	45.94
2	Mekanisa-132/15kV	2	59.04

**Table 4.3 Simulation result of un-compensated three winding transformers in 2016**

R/No	Substation	Before Compensation
		Power Transfer Capability (MW)
1	Sebeta-I-132/45-A/15kV	20.65
2	Sebeta-I-132/45-B/15kV	19.60
3	Sululta-132/33/15kV	32.41

**Table 4.4 Poor Voltage Profile of Bus terminals before Compensation in 2016**

R/no	Bus-terminal	Voltage Profile before Compensation (PU)
1	Muger-33kV BB	0.948
2	Derba-33kV BB	0.934
3	Mekanisa-132kV BB	0.948
4	Mekanisa-15kV BB	0.932
5	Addis South-II 132kV BB	0.909
6	Addis South- 15kV BB	0.897

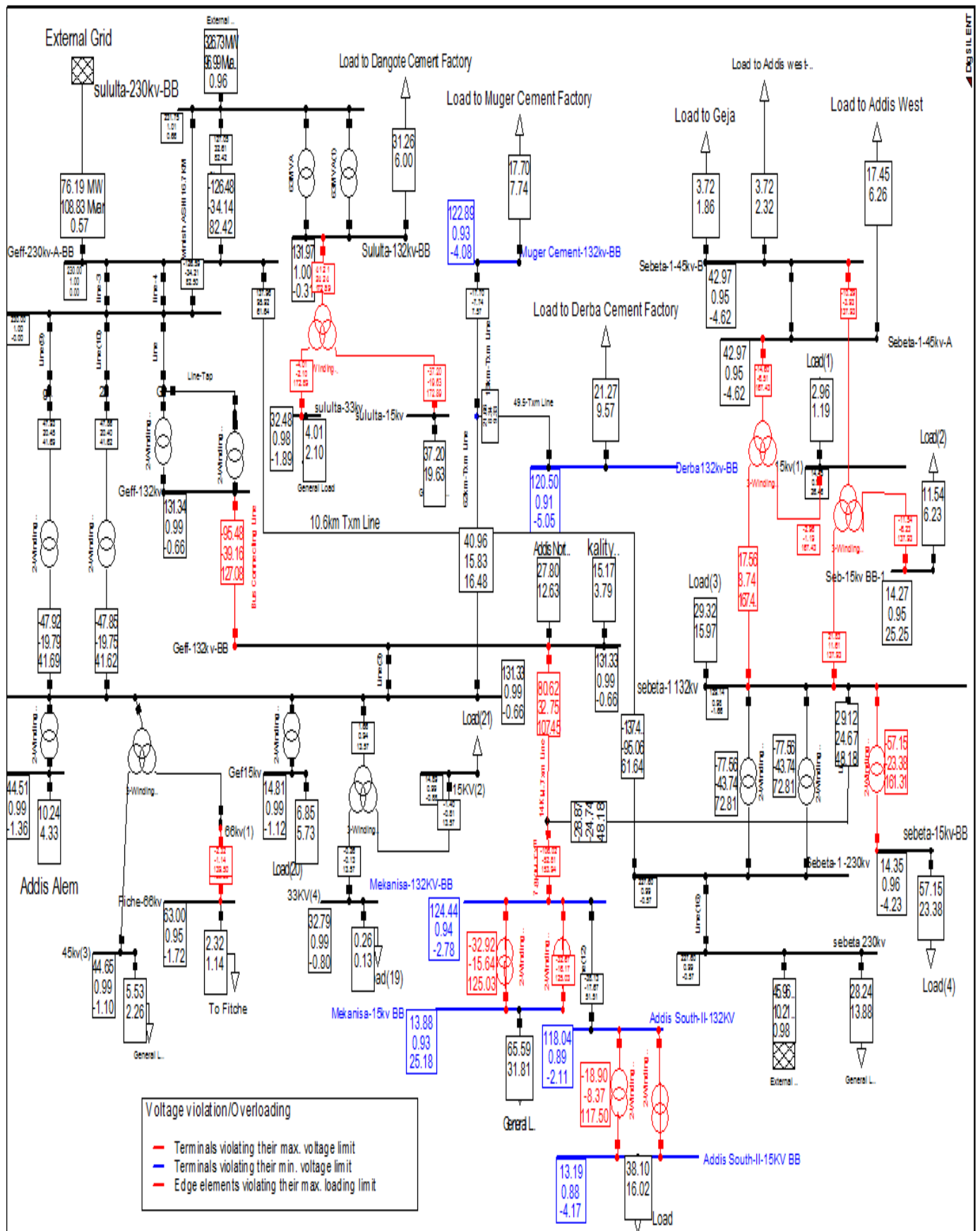


Fig 4.4 Simulation Result of Peak Load Forecast of 2021 before Shunt Compensation

**Table 4.5 Summarized Load Flow Analysis of 2021 [Before Compensation]**

[2016/08/17 12:31:16] DIgSI/info - Load flow calculation successful.

		DIgSILENT PowerFactory 14.0.524	Project:				
			Date: 8/17/2016				
Load Flow Calculation			Grid Summary				
AC Load Flow, balanced, positive sequence		Automatic Model Adaptation for Convergency		Yes			
Automatic Tap Adjust of Transformers	Yes	Max. Acceptable Load Flow Error for					
Consider Reactive Power Limits	No	Nodes	0.05 kVA				
		Model Equations	0.10 %				
Grid: PF-peak-after.	System Stage: PF-peak-after.	Study Case: Study Case	Annex:	/ 1			
Grid: PF-peak-after.	Summary						
No. of Substations	0	No. of Busbars	34	No. of Terminals	2	No. of Lines	21
No. of 2-w Trfs.	15	No. of 3-w Trfs.	7	No. of syn. Machines	0	No. of asyn.Machines	0
No. of Loads	24	No. of Shunts	0	No. of SVS	0		
Generation	=	0.00 MW	0.00 Mvar	0.00 MVA			
External Infeed	=	448.35 MW	216.35 Mvar	497.82 MVA			
Inter Grid Flow	=	0.00 MW	0.00 Mvar				
Load P(U)	=	438.27 MW	194.55 Mvar	479.51 MVA			
Load P(Un)	=	482.35 MW	214.57 Mvar	527.92 MVA			
Load P(Un-U)	=	44.08 MW	20.02 Mvar				
Motor Load	=	0.00 MW	0.00 Mvar	0.00 MVA			
Grid Losses	=	10.08 MW	21.80 Mvar				
Line Charging	=		-16.22 Mvar				
Compensation ind.	=		0.00 Mvar				
Compensation cap.	=		0.00 Mvar				
Installed Capacity	=	0.00 MW					
Spinning Reserve	=	0.00 MW					
Total Power Factor:							
Generation	=	0.00 [-]					
Load/Motor	=	0.91 / 0.00 [-]					

As can be seen in the load flow simulation results of fig 4.4above and its detail in appendix VI, some of the bus bar's voltage profiles are below acceptable range and so some 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 has been done in DIG Silent Power Factory simulator. First of all the simulator software do the sensitivity which needs compensation as can be seen in table 4.6 below:

**Table 4.6 candidate buses for shunt compensation**

```
[2016/08/17 10:10:17] DIgSI/info - Costs Evaluation <Power Losses + Voltage Violation Penalties> for Candidate Buses:
[2016/08/17 10:10:17] DIgSI/info - 1: Candidate bus: ➔Derbal32kv-BB Cost: 894028.72 $
[2016/08/17 10:10:17] DIgSI/info - 2: Candidate bus: ➔Muger Cement-132kv-BB Cost: 936351.45 $
[2016/08/17 10:10:17] DIgSI/info - 3: Candidate bus: ➔Terminal132kv Cost: 946285.10 $
[2016/08/17 10:10:17] DIgSI/info - 4: Candidate bus: ➔Addis South-II-15KV BB Cost: 1054900.29 $
[2016/08/17 10:10:17] DIgSI/info - 5: Candidate bus: ➔Mekanisa-15kv BB Cost: 1077867.41 $
[2016/08/17 10:10:17] DIgSI/info - 6: Candidate bus: ➔Addis South-II-132KV Cost: 1081969.78 $
[2016/08/17 10:10:17] DIgSI/info - 7: Candidate bus: ➔Mekanisa-132KV-BB Cost: 1099027.30 $
[2016/08/17 10:10:17] DIgSI/info - 8: Candidate bus: ➔mekl32kv Cost: 1126890.31 $
[2016/08/17 10:10:17] DIgSI/info - 9: Candidate bus: ➔33KV(4) Cost: 1142545.86 $
[2016/08/17 10:10:17] DIgSI/info - 10: Candidate bus: ➔15KV(2) Cost: 1142625.94 $
[2016/08/17 10:10:17] DIgSI/info - 11: Candidate bus: ➔66kv(1) Cost: 1143133.46 $
[2016/08/17 10:10:17] DIgSI/info - 12: Candidate bus: ➔45kv(3) Cost: 1143192.86 $
[2016/08/17 10:10:17] DIgSI/info - 13: Candidate bus: ➔Gefersa-132KV Cost: 1143322.61 $
[2016/08/17 10:10:17] DIgSI/info - 14: Candidate bus: ➔Geff-132kv-BB Cost: 1143325.08 $
[2016/08/17 10:10:17] DIgSI/info - 15: Candidate bus: ➔Geff-132kv Cost: 1143380.01 $
[2016/08/17 10:10:17] DIgSI/info - 16: Candidate bus: ➔Gefersa-45kv Cost: 1143459.02 $
[2016/08/17 10:10:17] DIgSI/info - 17: Candidate bus: ➔Gef15kv Cost: 1143512.11 $
[2016/08/17 10:10:17] DIgSI/info - 18: Candidate bus: ➔Fiche-66kv Cost: 1147159.65 $
[2016/08/17 10:10:17] DIgSI/info - 19: Candidate bus: ➔230kv Cost: 1157438.19 $
[2016/08/17 10:10:17] DIgSI/info - 20: Candidate bus: ➔geff 230kv Cost: 1157442.96 $
[2016/08/17 10:10:17] DIgSI/info - 21: Candidate bus: ➔sululta-230kv-BB Cost: 1157455.95 $
[2016/08/17 10:10:17] DIgSI/info - 22: Candidate bus: ➔Geff230kv Cost: 1157456.91 $
[2016/08/17 10:10:17] DIgSI/info - 23: Candidate bus: ➔geff230kv Cost: 1157461.37 $
[2016/08/17 10:10:17] DIgSI/info - 24: Candidate bus: ➔Gefersa-230kv-B(1) Cost: 1157483.31 $
[2016/08/17 10:10:17] DIgSI/info - 25: Candidate bus: ➔Geff-230kv-A-BB Cost: 1157531.01 $
[2016/08/17 10:10:17] DIgSI/info - 26: Candidate bus: ➔Sululta-132kv-BB Cost: 1157858.88 $
[2016/08/17 10:10:17] DIgSI/info - 27: Candidate bus: ➔sululta-33kv Cost: 1158519.69 $
[2016/08/17 10:10:17] DIgSI/info - 28: Candidate bus: ➔sululta-15kv Cost: 1159208.09 $
```

After sensitivity analysis, the algorithm does the optimization (need of compensation versus associated costs for the optimization) and places the TSC accordingly. This can be shown as in fig 4.5 below

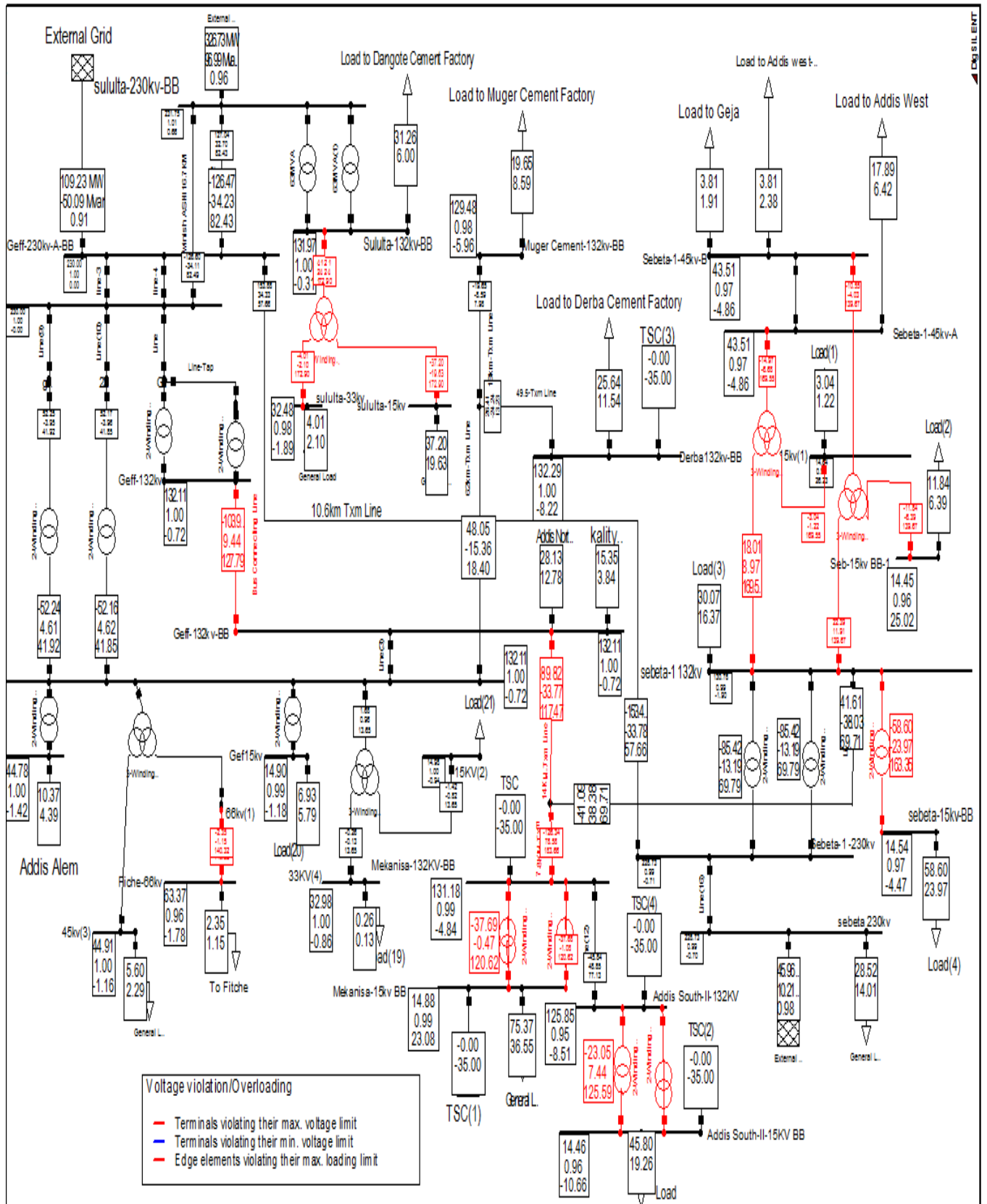


Fig 4.5 Simulation result of Peak Load Forecast of 2021 after Shunt Compensation

And the detail result is shown in Appendix VII

**4.7. summarized load flow analysis of 2021 [After compensation]**

AC Load Flow, balanced, positive sequence		Automatic Model Adaptation for Convergency	Yes
Automatic Tap Adjust of Transformers	Yes	Max. Acceptable Load Flow Error for	
Consider Reactive Power Limits	No	Nodes	0.05 kVA
		Model Equations	0.10 %

Grid: PF-peak-after.	System Stage: PF-peak-after.	Study Case: Study Case	Annex:	/ 1			
Grid: PF-peak-after.	Summary						
No. of Substations	0	No. of Busbars	34	No. of Terminals	2	No. of Lines	21
No. of 2-w Trfs.	15	No. of 3-w Trfs.	7	No. of syn. Machines	0	No. of asyn.Machines	0
No. of Loads	24	No. of Shunts	5	No. of SVS	0		
Generation	=	0.00 MW	0.00 Mvar	0.00 MVA			
External Infeed	=	479.42 MW	63.57 Mvar	483.62 MVA			
Inter Grid Flow	=	0.00 MW	0.00 Mvar				
Load P(U)	=	465.34 MW	206.83 Mvar	509.24 MVA			
Load P(Un)	=	482.35 MW	214.57 Mvar	527.92 MVA			
Load P(Un-U)	=	17.01 MW	7.74 Mvar				
Motor Load	=	0.00 MW	0.00 Mvar	0.00 MVA			
Grid Losses	=	14.08 MW	24.40 Mvar				
Line Charging	=		-16.87 Mvar				
Compensation ind.	=		0.00 Mvar				
Compensation cap.	=		-167.66 Mvar				
Installed Capacity	=	0.00 MW					
Spinning Reserve	=	0.00 MW					
Total Power Factor:							
Generation	=	0.00 [-]					
Load/Motor	=	0.91 / 0.00 [-]					

Now let's determine the magnitude of basic components of thyristor switched capacitor at each compensated bus terminals of the substations, it is known that the main equipment of TSC which

do the compensation task is the capacitor and the thyristor valve do the switching task. So it is vital to know the main design parameters which characterize a capacitor. That is

$$B_{cap} = \frac{Q_{cap}}{U_{nom}^2} \times 10^6 \text{ In } \mu S$$

Where

$Q_{cap}$       Rated Capacitive power in Mvar

$U_{nom}$       Line Voltage in kV

$B_{cap}$       Susceptance in  $\mu S$

$$C_{cap} = \frac{B_{cap}}{2\pi f_{nom}} \text{ in } \mu F$$

Where

$B_{cap}$       Susceptance in  $\mu S$

$f_{nom}$       Nominal Frequency in Hz of the grid

$$I_{cap} = \frac{Q_{cap}}{\sqrt{3}U_{nom}}$$

Where

$Q_{cap}$  is in MVar

$U_{nom}$  Nominal Line-Line Voltage in kV

$I_{cap}$  Rated Current, C in A [16]

Using the above formulas, it is possible to determine the basic design parameters as follow:

At Mekanisa substation of the 15kV bus terminal, the proposed reactive power magnitude is:

$$Q_{Cap} = 35 \text{ Mvar}$$

$$U_{nom} = 15 \text{ kV}$$

So to calculate the susceptance in  $\mu s$

$$B_{cap} = \frac{Q_{cap}}{U_{nom}^2} * 10^6$$

$$B_{cap} = \frac{35\text{Mvar}}{(15\text{kV})^2} * 10^6$$

$$B_{cap} = 155,555.56\mu\text{s}$$

To calculate the capacitive reactance

$$X_{cap} = \frac{1}{B_{cap}} \quad \text{which is } X_{cap} = \frac{1}{155,555.56\mu\text{s}}$$

$$X_{cap} = 6.43\Omega$$

$$C_{cap} = \frac{B_{cap}}{2\pi f}$$

$$C_{cap} = \frac{155,555.56\mu\text{s}}{2 * 3.14 * 50\text{Hz}}$$

$$C_{cap} = 495.40 \mu\text{F}$$

$$I_{cap} = \frac{Q_{cap}}{\sqrt{3} U_{nom}}$$

$$Q_{cap} = 35\text{Mvar}$$

$$I_{cap} = \frac{35\text{MVar}}{\sqrt{3} (15\text{kV})}$$

$$I_{cap} = 1348.75\text{A}$$

Rating of fuse current ( $I_{fuse}$ ) to protect the capacitor is equal to 2times the charging current of the capacitor ( $I_c$ ) and the rating of circuit breaker to protect the Capacitor is 1.5 times  $I_c$  (Source : WASVAR capacitor manufacturer)

Therefore

$$I_{fuse} = 2 * 1348.75\text{A}$$

$$= 2697.5\text{A}$$

$$I_{CB} = 1.5 * 1348.75\text{A}$$

$$= 2023.13\text{A}$$

**Sizing of cables for capacitor Connection:** Capacitors can withstand a permanent over current of 30% +tolerance of 10% on capacitor Current.

$$\begin{aligned}
 \text{So the Cables size for Capacitor Connection} &= 1.3 \times 1.1 \times \text{nominal capacitor Current} \\
 &= 1.43 \times \text{nominal capacitor Current} \\
 &= 1.43 \times 1348.75\text{A} \\
 &= 1928.71\text{A}
 \end{aligned}$$



The design parameters of the shunt capacitor for the other bus terminals of sub stations can be calculated in the same fashion and summarized in table 4.8

**Table 4.8 Design parameters of Main TSC Components**

No	Substation	V (kV)	Q (Mvar)	F (Hz)	B (μS)	C (μF)	Capacitor Charging current I <sub>c</sub> (A)	I <sub>fuse</sub> (A)	I <sub>CB</sub> (A)	Cable size of Capacitor connector (A)
1	Derba	132	35	50	2008.72	6.4	153.27	306.53	229.90	219.17
2	Mekanisa	132	35	50	2008.72	6.4	153.27	306.53	229.90	219.17
3	Mekanisa	15	35	50	155555.6	495.4	1348.75	2697.50	2023.12	1928.71
4	Addis South-II	132	35	50	2008.72	6.4	153.27	306.53	229.90	219.17
5	Addis South-II	15	35	50	155555.6	495.4	1348.75	2697.50	2023.12	1928.71

The detail parameter of the back to back thyristor for the high voltage switching application is determined according the specific application and detail design shall be conducted, it is because switching of thyristor is very sensitive and very important part of the TSC shunt compensation. Let's see sample data sheet of a high voltage AC thyristor manufacture as follow.

Table 4.9 Sample data sheet of Thyristor parameters

	<b>Naina Semiconductor Ltd.</b>	<b>160NTT</b>																																												
<b>Thyristor – Thyristor Module</b>																																														
<b>Features</b> <ul style="list-style-type: none"> <li>• Improved glass passivation for high reliability</li> <li>• Exceptional stability at high temperatures</li> <li>• High di/dt and dv/dt capabilities</li> <li>• Low thermal resistance</li> </ul>																																														
<table border="1" style="width: 100%;"> <thead> <tr> <th colspan="4" style="text-align: left;">Maximum Ratings (<math>T_A = 25^\circ\text{C}</math> unless otherwise noted)</th> </tr> <tr> <th>Parameter</th> <th>Symbol</th> <th>Values</th> <th>Units</th> </tr> </thead> <tbody> <tr> <td>Maximum average forward current @ <math>T_J = 85^\circ\text{C}</math></td> <td><math>I_{F(AV)}</math></td> <td>160</td> <td>A</td> </tr> <tr> <td>Maximum average RMS forward current</td> <td><math>I_{F(RMS)}</math></td> <td>350</td> <td>A</td> </tr> <tr> <td>Maximum non-repetitive surge current @ <math>t = 10\text{ms}</math></td> <td><math>I_{FSM}</math></td> <td>5100</td> <td>A</td> </tr> <tr> <td>Maximum <math>I^2t</math> for fusing @ <math>t = 10\text{ms}</math></td> <td><math>I^2t</math></td> <td>120</td> <td><math>\text{kA}^2\text{s}</math></td> </tr> </tbody> </table>			Maximum Ratings ( $T_A = 25^\circ\text{C}$ unless otherwise noted)				Parameter	Symbol	Values	Units	Maximum average forward current @ $T_J = 85^\circ\text{C}$	$I_{F(AV)}$	160	A	Maximum average RMS forward current	$I_{F(RMS)}$	350	A	Maximum non-repetitive surge current @ $t = 10\text{ms}$	$I_{FSM}$	5100	A	Maximum $I^2t$ for fusing @ $t = 10\text{ms}$	$I^2t$	120	$\text{kA}^2\text{s}$																				
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<b>1</b>	D-95, Sector 63, Noida – 201301, India • Tel: 0120-4205450 • Fax: 0120-4273653 sales@nainasemi.com • www.nainasemi.com																																													

Since, the value of current limiting inductor and other snub circuit are the sensitive part of TSC it is better to calculate after detail analysis of short circuit values, harmonic orders and transient switching parameters.

Now let's see some of the output of the simulation result and its analysis in a table format.

**Table 4.10** Power transfer capability of transmission lines before and after compensation in 2021

R/no	Transmission Line		Before Shunt Compensation	After Compensation	Increment in power transfer capability due to TSC (%)
	From	To	Power transfer Capability (MW)	Power Transfer Capability (MW)	
1	Geffersa-132kV	Geffersa-132kV	95.44	103.52	8.47
2	Geffersa-66 kV	Fitche 66 kV S/S	2.41	2.44	1.24
3	Geffersa-132kV	Sebeta-I-132kV Tap	29.19	40.72	39.50
4	Sebeta-I-132kV Tap	Mekanisa-132kV	106.02	124.84	17.75
5	Mekanisa-132kV	Addis South-II - 132kV	38.13	45.37	18.99

**Table 4.11** Power Transfer Capability of two winding transformers before and after Compensation in 2021

R/No	Two winding Transformers	Quantity	Before Compensation	After Compensation	Incremental of Power transfer due to TSC (%)
			Power Transfer Capability(MW)	Power Transfer Capability(MW)	
1	Sebeta-I-230/132kV	2	154.88	169.66	9.54
2	Sebeta-I-132/15kV	1	57.14	58.53	2.43
3	Mekanisa-132/15kV	2	65.84	75.00	13.91
4	Addis-South-II 132/15kV	2	37.80	45.58	20.58

**Table 4.12** Power Transfer Capability of Three winding transformers before and after Compensation in 2021

R/No	Three Winding Transformers	Before Compensation	After Compensation	Increment of power transfer capability due to TSC (%)
		Power Transfer Capability(MW)	Power Transfer Capability(MW)	
1	Sebeta-I-132/45-A/15kV	17.34	17.76	2.42
2	Sebeta-I-132/45-B/15kV	21.54	22.06	2.41
3	Sululta-132/33/15kV	41.3	41.3	0.00

**Table 4.13 Poor Voltage Profile of bus terminals in 2021**

R/no	Bus Terminal	Voltage Profile Before Compensation	Voltage Profile After Compensation	Voltage profile Improvement due to TSC (%)
1	Muger-132kV	0.93	0.98	5.38
2	Derba-132kV	0.91	1.00	9.89
3	Mekanisa-132kV	0.94	0.99	5.32
4	Mekanisa-15kV	0.93	0.99	6.45
5	Addis South-II 132kV	0.89	0.95	6.74
6	Addis South- 15kV	0.88	0.96	9.09
7	Sebeta-I 45kV	0.95	0.96	1.05
8	Sebeta-I 15kV	0.94	0.96	2.13

Moreover let's compare the entire grid losses represented in this work before and after compensation with the EEP and EEU loss targets put in 2015-2020

Before shunt compensation of the network in this work:

Total external supply to the grid is  $P = 448.35$  MW and  $Q = 216.35$

$$S = p+jq$$

$$= 448.35\text{MW}+j216.35\text{Mvar}$$

$$= \sqrt{448.35^2+216.35^2}$$

$$= 497.82\text{MVA}$$

And the grid loss is  $P = 10.08$  MW,  $Q = 21.80$  Mvar and here the total losses in percentage (%) is  $(10.08\text{Mw}/448.35\text{Mw}) * 100 = 2.25\%$

After shunt compensation of the network in this work:

Total external supply to the grid is  $P = 479.42\text{MW}$  and  $Q = 63.57$

$$S = p+jq$$

$$= 479.42\text{MW}+j63.57\text{Mvar}$$

$$= 483.62 \text{ MVA and the total grid loss is } P = 14.08 \text{ MW, } Q = 24.40 \text{ Mvar and } S = 26.10\text{MVA}$$

Here the losses in percentage (%) is  $(14.08\text{Mw}/483.62) * 100 = 2.91\%$ . the power losses is increased after compensation because the Loadability of the network is increased.

And according EEP and EEU losses minimization targets, the transmission and distribution network losses are quantified and forecasted as in the following table 4.12 below

**Table 4.14 Existing and planned transmission Line Losses of EEP**

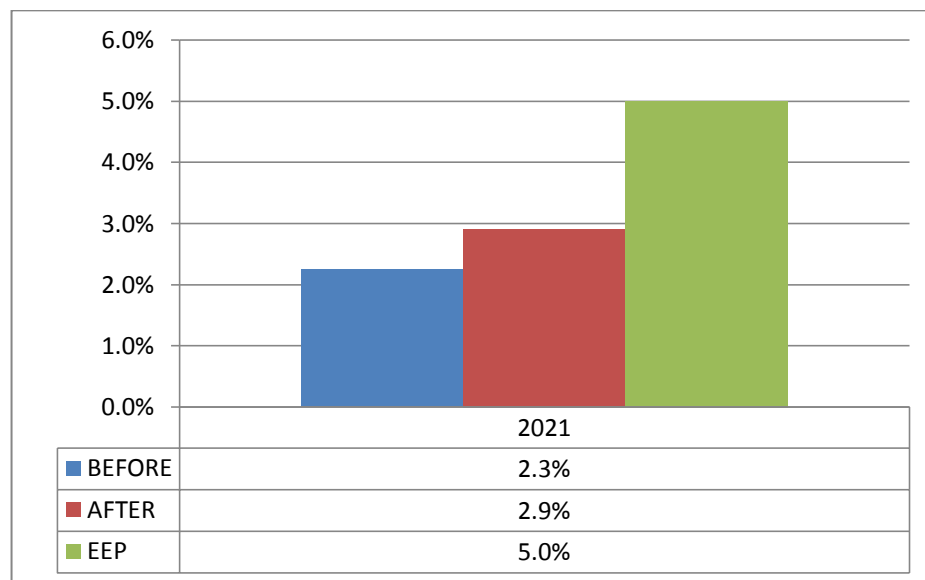
Years	Energy losses (percent of Generation sent out)			Peak power losses (Generation sent out)		
	Technical Losses	Non-Technical Losses	Total Losses	Transmission and distribution	Transmission	Distribution
	(%)	(%)	(%)	(%)	(%)	(%)
2012	14.0	9.4	23.4	28.6	5.0	23.6
2013	13.8	9.4	23.2	28.3	5.0	23.3
2014	13.6	9.4	23.0	27.9	5.0	22.9
2015	13.4	8.0	21.4	26.1	5.0	21.1
2016	13.2	6.0	19.2	23.8	5.0	18.8
2017	13.0	4.0	17.0	21.4	5.0	16.4
2018	12.9	2.0	14.9	19.2	5.0	14.2
2019	12.8	1.0	13.8	18.1	5.0	13.1
2020	12.7	1.0	13.7	18.1	5.0	13.1
2021	12.6	1.0	13.6	18.1	5.0	13.1
2022	12.5	1.0	13.5	18.0	5.0	13.0
2023	12.4	1.0	13.4	18.0	5.0	13.0
2024	12.3	1.0	13.3	18.0	5.0	13.0
2025	12.2	1.0	13.2	17.9	5.0	12.9
2026	12.1	1.0	13.1	17.9	5.0	12.9
2027	12.0	1.0	13.0	17.9	5.0	12.9
2028	12.0	1.0	13.0	17.9	5.0	12.9
2029	12.0	1.0	13.0	18.0	5.0	13.0
2030	12.0	1.0	13.0	18.1	5.0	13.1
2031	12.0	1.0	13.0	18.1	5.0	13.1
2032	12.0	1.0	13.0	18.1	5.0	13.1
2033	12.0	1.0	13.0	18.2	5.0	13.2
2034	12.0	1.0	13.0	18.2	5.0	13.2
2035	12.0	1.0	13.0	18.2	5.0	13.2
2036	12.0	1.0	13.0	18.2	5.0	13.2
2037	12.0	1.0	13.0	18.2	5.0	13.2

(Source: EEP /EEU planning office and consultant study final report, 2015)

As can be seen in table above the goal of EEP transmission line power losses in 2016 up to 2021 is to be 5% and the distribution losses of EEU to be lie between 18.80% and 13.10% respectively. And the above grid loss of the network for this work which is 2.70% is within the range of the utility’s target for the prescribed range of years. Here as a matter of fact, the distances of the transmission line route in this thesis work is very short which is less than 50km, so the losses are expected to be lower than longer transmission lines. See the comparison in table 4.13 and column chart form.

**Table 4.15** Comparison of transmission Line Losses between EEP target and this case study

R/No	Description	Transmission Lines	Remark
		Power Losses (%)	
1	Losses before shunt compensation	2.25	Most of the transmission lines of this case study spans for less than 50KM
2	Losses After shunt compensation	2.91	
3	Losses target of EEP/EEU in 2021	5	Composed of long, medium and short transmission lines



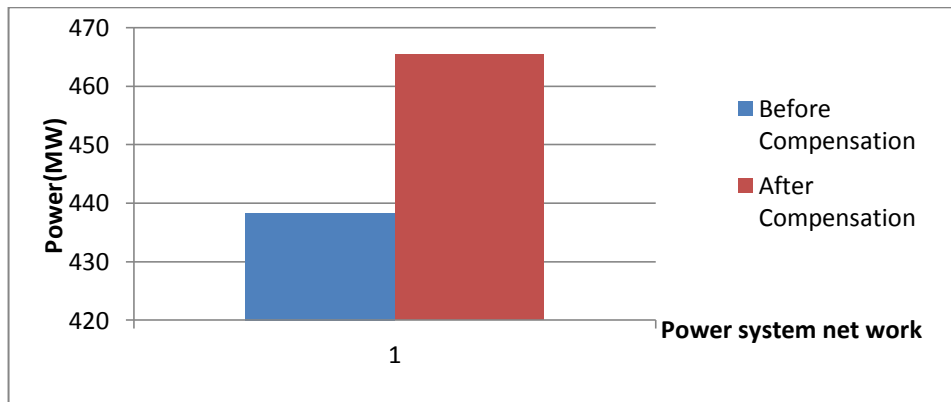
**Fig 4.6** Comparison between Transmission Line Losses of EEP Target with This Study

Comparison of power transfer capability of the power system network of this work towards the load center before and after shunt compensation is done. That is the nominal load demand of the entire power system network of this work is normally 482.35MW which is the constant value whether the system is compensated or not, but the power flow towards the load areas I.e. the rated value is different for a compensated and un- compensated systems.

**Table4.16 Total Power Transferred of the entire system to the Load side before and After Compensation**

No	Power demand of the region (MW)	Before Compensation		After Compensation		Improvement (MW)
		Power transferred to load (MW)	Un-served power (MW)	Power transferred to load (MW)	Un-served power (MW)	
1	482.35	438.27	44.08	465.34	17.01	27.07

This can be also shown in column chart form as:



**Fig 4.7 Total Power Transferred To the Load Before and After Compensation**

## Chapter Five

### 5. Economic Analysis

In order to analyze the economic viability of the thyristor switched capacitor (TSC), the following simplified assumptions have been considered i.e.:-

- The Proposed Thyristor switched capacitor (TSC) system is sized to deliver its full compensation task in need of any shunt compensation.
- The proposed equipment will operate at or near full output capacity in need of it.
- The number of hours per year plan to operate the system will meet.
- The information of the equipment data is obtained from the manufacturer and Ethiopian Electric Power/the power utility.

By considering the above assumptions, the cost benefit analysis is done as follow:-

#### 5.1 Investment Costs

The initial and possible running costs because of Shunt compensation installation:-

- Cost of equipment's to be installed i.e. Thyristor switched capacitor(TSC) and its bay equipment including Civil works
- Cost of operational and maintenance of TSC and bay equipment

**Table 5.1 Investment Cost of TSCs and its bay equipment**

No	Substation	Capacity of TSC(kVar)	Qty	Cost of TSC Per KVar(USD)	FOB Cost(USD)	References
1	Derba-132kV	35000	1 set	30	1,050,000	www.energy collection. US and ABB
2	Mekanisa-132kV	35000	1 set	30	1,050,000	
3	Mekanisa-15kV	35000	1 set	30	1,050,000	
4	Addis South-II-132kV	35000	1 set	30	1,050,000	
5	Addis South-II-15kV	35000	1 set	30	1,050,000	
6	Total FOB Cost				5,250,000	
7	Cost of sea, inland transport and insurance (9%)				472,500	EEP recent Sub-Station projects Cost Summary
8	Cost of Civil Works (7%)				367,500	
9	Cost of Installation, testing and commissioning (10%)				525,000	
10	Cost of Operation and Maintenance (20%)				1,050,000	
11	Total cost of TSCs Bay Equipment				1,707,085.13	
	Total Cost				9,372,085.13	

The Detail cost break down of bay equipment of Table 5.1 above is shown in Appendix V

## **5.2 Saving due to Installation of Thyristor Switched Capacitor**

To make the cost benefit analysis of this case study, there are a number of possible considerations such as, incremental of power transfer capability due to voltage at bus terminals correction and avoiding of penalty for the un acceptable voltage levels due to shunt compensation, the profit losses of heavy and small level factory and other customers due to insufficient power supply from the power utility which is normally estimated five to six times the profit loss by the utility. But, due to the limitation of some commercial standard resources, insufficient and inconsistent interruption data of power system equipment from the utility, limitation of time to collect the profit losses from the power customers which also needs permissions to access the raw data, this paper tries to made analysis based on power transfer capability to the load side versus the investment cost of constructing new transmission line routes to be incurred by the utility.

Static Var Compensating devices are cost effective alternatives comparing to new transmission line construction. One practical example can be seen i.e. an ABB SVC (TSC and TCR) installed in Australia at the Southern terminal Station has optimized the capacity of the existing Western Power infrastructure and deferred the need to build a new 330 kV transmission line from the South West of Western Australia to the Metro area of Perth. The SVC solution was less than 20% of the cost of an alternative new 330 kV transmission line and saved approximately four and a half years of project time and avoids in land clearing for hundreds of kilometers for the line easement and other compensation for land owners (Source: [www.abb.Com](http://www.abb.Com)).

So, to solve and reinforcing the existing power system network of the region on time, this thesis work is proposing a shunt compensation to one of the existing weak voltage profile transmission line which routes from Sululta to Addis South II. Using thyristor switched capacitor (TSC).

Following power system expansion of the country, energy mix such as Solar, winds and geothermal energies which are relativity with higher investment costs than hydro powers and significant growth in export of power anticipated over the period of the expansion plan, securing higher tariffs will be critical to ongoing financial viability. So, the tariff level diminished to date has been insufficient to generate profitability for Ethiopian Electric Power (EEP) and Ethiopian Electric Utility (EEU), particularly for years with poor hydrology.

So, to incorporate new technologies such as FACTS devices which have a significant importance in controllability for a fast growing power system network, reasonable tariff increase is necessary for economical validity for such immerging technologies.

As stated above, due to inadequate power supply of EEP and poor power services of EEU currently, The utility and its customers losses huge amount of money until implementation of planned solutions, think of the number of factories, commercial buildings and manufacturing sectors waiting for power supply from the power utility and loss of huge profit of their company which is estimated to be more than four or five times the money loss by the power utility/EEP/ and EEU. Due to the installation of TSC which has a relatively short life of project implementation, the following some benefits can be achieved.

In terms of power delivery from the transmission/substation level to the load side, TSC do a significant task for the region under this study. After shunt compensation, the power transfer capability of the region increases due to terminal voltages improvement at bus terminals which has a direct influence on the value of real power. So, the system delivers Additional 27.07MW power to the load side with the same and existing power system network. This in fact means, the compensation system can minimize constructing of some new transmission/sub-transmission lines to deliver electrical power to the load side. if it is to be seen in terms of constructing some new infrastructure in the power system, the additional 27.07MW means, it can omit the construction of new 66kVsub-transmission lines which can spans about100km with a power carry capacity of around 27MW. In EEP practice to deliver 24-32MW of electrical power to the load side, it invests huge amount of money and other considerable environmental and social disturbances, especially land compensation along the transmission line routes and resettling of people around Addis Ababa and other big cities which is expected with fast urbanization growth is very difficult. Let's see the existing 66kV transmission lines in different places of Ethiopian electric power system network as follow:

**Table5.2. Existing 66kV Transmission Lines in EEP Power System Network**

No.	Voltage (kV)	From Bus Num.	From Bus Name	To Bus Num.	To Bus Name	Id	Assumed Conductor Type	Tower Config.	Line Rating (MVA)	Length (km)
36	66	626	GAMBELA1	627	DEMBI DO	1	Merlo	Single	24	64.0
37	66	628	MIZAN	629	TEPI	1	Quail	Single	27	30.2
38	66	630	B.DAR2	631	B.DAR1	1	Merlo	Single	24	4.5
39	66	630	B.DAR2	635	DANGLA	1	Merlo	Single	24	68.6
40	66	631	B.DAR1	632	WORETA	1	Merlo	Single	24	51.6
41	66	632	WORETA	633	GONDER1	1	Merlo	Single	24	87.0
42	66	633	GONDER1	634	DABAT	1	Merlo	Single	24	58.4
43	66	633	GONDER1	680	GONDAR2	1	Merlo	Single	24	4.3
44	66	635	DANGLA	638	PAWIE	1	Merlo	Single	24	109.0
45	66	641	DB.MARKS	642	BITCHENA	1	Merlo	Single	24	65.7
46	66	641	DB.MARKS	643	FNOT-SLM	1	Merlo	Single	24	80.0
47	66	644	FINCHAA	645	FNCH-SG1	1	Racoon	Single	30	11.0
48	66	645	FNCH-SG1	646	FNCH-SG2	1	Racoon	Single	30	15.4
49	66	654	GEFERSA	655	FITCHE	1	Merlo	Single	24	96.0
50	66	656	COMB0-1	657	DESIE	1	Merlo	Single	24	12.7
51	66	657	DESIE	658	WOLDIA	1	Merlo	Single	24	88.0
52	66	664	ALAMATA	666	LALIBELA	1	Quail	Single	27	104.9
53	66	664	ALAMATA	665	MAYCHEW	1	Quail	Single	27	48.0
54	66	664	ALAMATA	667	SEKOTA	1	Quail	Single	27	80.0
55	66	668	ADWA	669	SHIRE	1	Penguin	Single	36	66.4
56	66	685	ALEMAYA2	686	CHELENKO	1	Quail	Single	27	49.8
57	66	685	ALEMAYA2	687	HARAR3	1	Quail	Single	27	19.0

(Source: EEP investment and strategy department of substation/transmission office)

And of-course, Ethiopian Electric Power/EEP/has been replacing the 66kV transmission line by 132kV and the 45kV sub-transmission lines by 66kV. Now let's see the typical cost for new 66kV and 132kV transmission lines for comparison

**Table 5.3 the costs of 132 kV and 66 kV capable transmission lines (<100 km)**

Pole Type	Cost USD X \$1000 per Km		Additional Cost for 132kV
	132kV	66kV	
Wood	57.2	46.6	+22.6
Concrete	61.6	51.0	+20.7
<b>Steel</b>	<b>81.8</b>	<b>71.2</b>	<b>+14.8</b>

The detail cost break down for 66kV transmission line steel structure can be seen in table5.5

The transmission tower type (steel) used for cost comparison is shown as below.

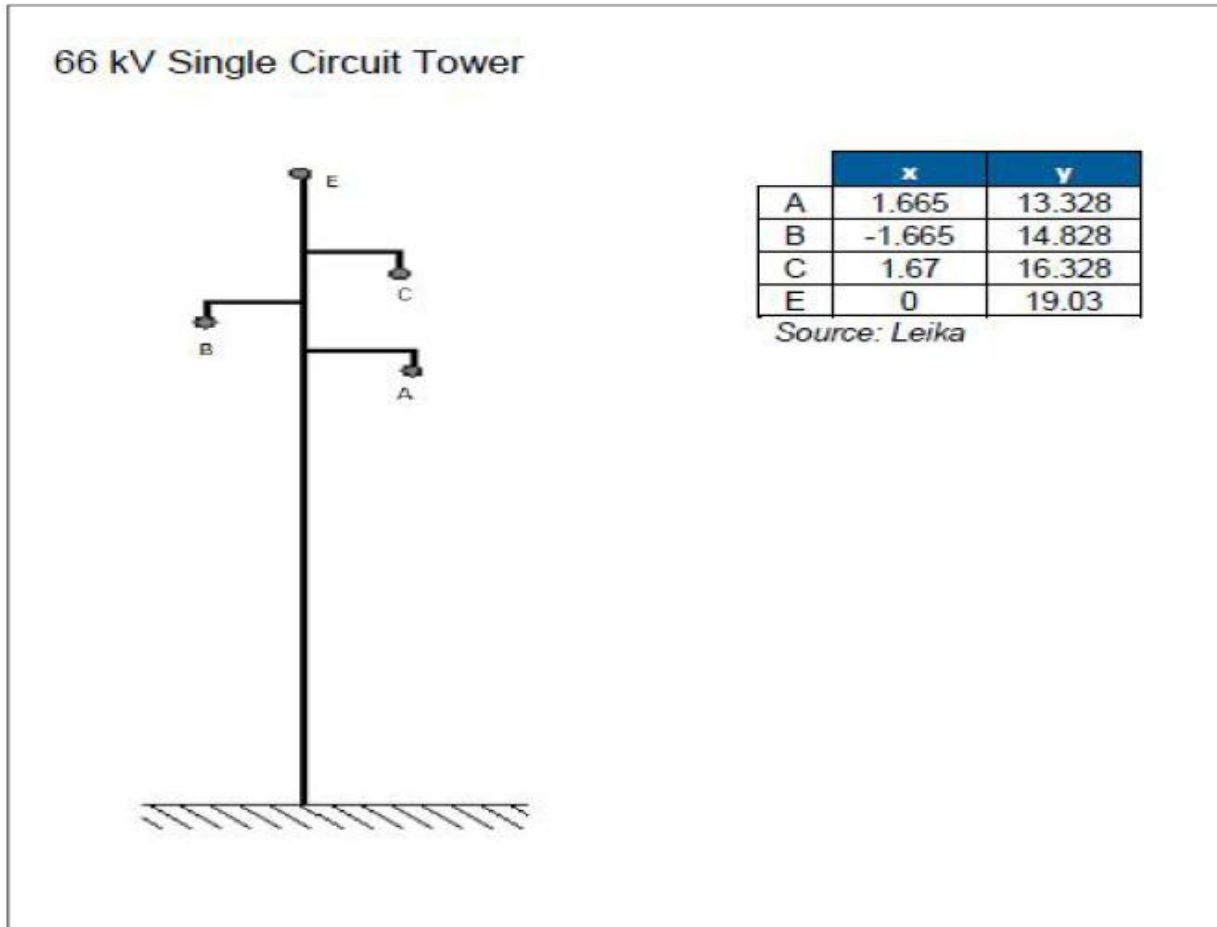


Fig 5.1. 66kV Single Circuit Tower

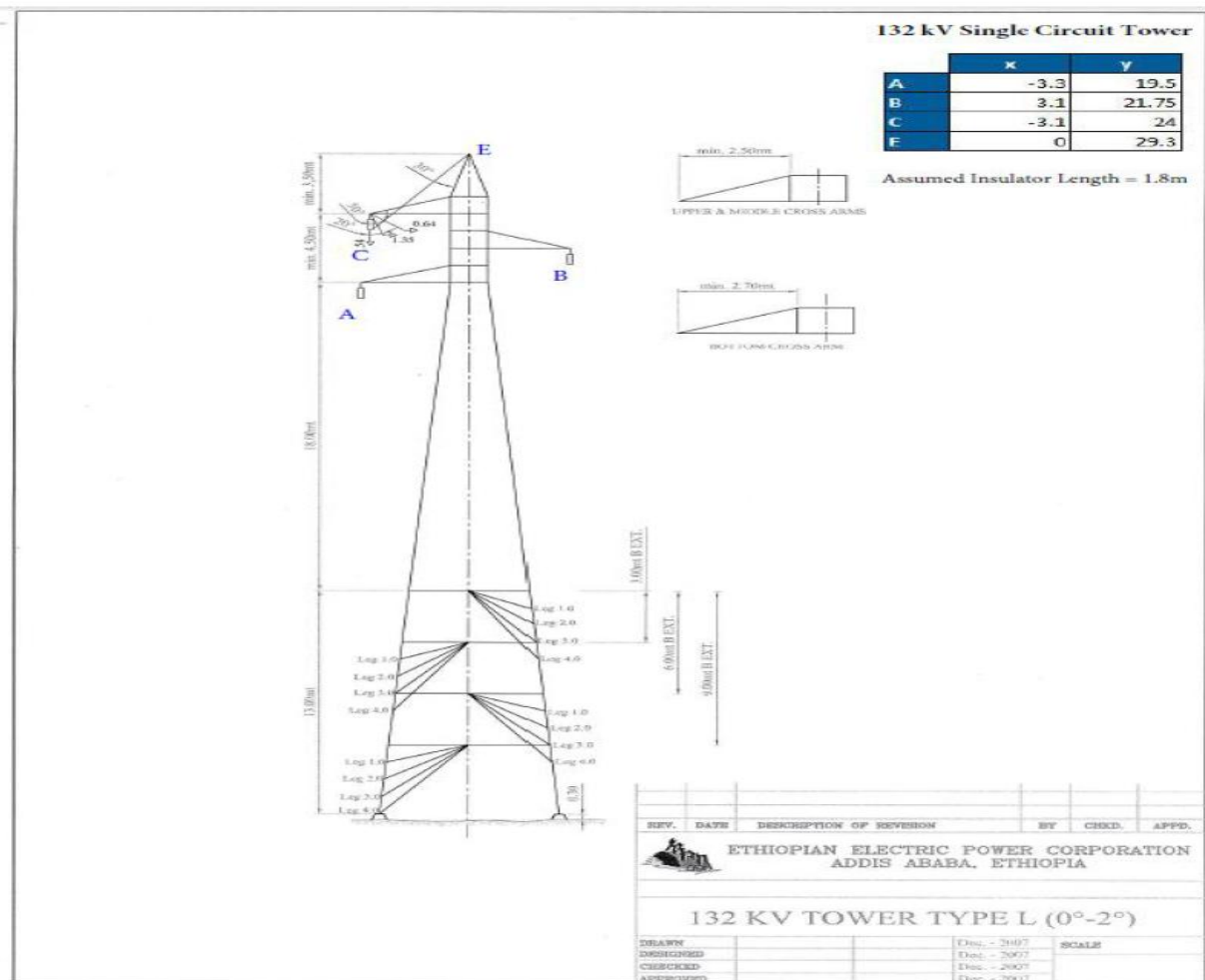


FIG5.2. 132kV Single circuit tower

Here detail cost break down of necessary equipment has been done and compared with typical unit cost per kilo meter. The cost per km stated in table5.3 above includes cost of: tower, tower foundation, overhead conductor (aluminum), insulators, and access road, labour and engineering costs. Other many costs such as cost of switched gears, step-down transformer and land compensations for land owners are not considered. however to validate the initial investment cost of TSC and its bay equipment, cost of associated switch gears and transformers shall be considered and presented as follow:

**Table 5.4 Cost Comparison of Constructing new Transformers and related Switch Gear**

Equipment	Unit	Cost of Foreign Portion (USD)	Cost of Local Portion (USD)	Quantity	Total installed cost (USD)
<b>Switchgear</b>					
66 kV switch gear	Circuit	366,000	92,000	1	458,000
33 kV switch gear	Circuit	120,000	30,000	1	150,000
15 kV switch gear	Circuit	56,000	14,000	1	70,000
<b>Transformer</b>					
132/15 kV, 20/25 MVA	Transformer	1,530,000	170,000	1	1,700,000
132/15 kV, 40 MVA	Transformer	1,800,000	200,000	1	2,000,000
132/33 kV, 31.5 MVA	Transformer	1,800,000	200,000	1	2,000,000
132/33 kV, 50 MVA	Transformer	1,980,000	220,000	1	2,200,000
132/33/15 kV, 63/40/23 MVA	Transformer	2,250,000	250,000	1	2,500,000
132/66/15 kV, 25/12/12 MVA	Transformer	1,800,000	200,000	1	2,000,000

Now let's consider constructing of new 66kV transmission line with a 100km long, 66kV switch gear and 66/15kV transformer and its total investment cost in table 5.5 below [1].

**Table 5.5. Total investment cost of constructing new 66kV transmission-substation system**

Item	Unit	Qty	Unit price	Amount
66kV transmission line	km	100	71200	7,120,000.00
66kV switch Gear	No	1	458,000	458,000.00
66/15kV transformer	No	1	2,000,000	2,000,000.00
Total price				9,578,000.00

The above investment cost is to deliver 27-30MW to an electrical power consumer, but as can be seen in this study, this cost can be omitted using the installation of TSC. This is because of the incremental of power transfer capability of the power system network. For project validity purpose, the other associated costs which are not quantified in this analysis shall also be taken in to account.

### 5.3. Evaluating the Voltage Violation Cost

In EEP and EEU power supply system, there is no cost penalty for poor power quality parameters such as, penalty for poor voltage quality which deviates or violates from the tolerable limits. It is because the attention of the power providers has been on expansion of the power system without giving an attention to the power quality and reliability. As a result of the above and associated problems, power interruption has been becoming a great issue, which also led to the customer to throw a lot of complains to the utility. In this regard, the utility has been trying its best to solve, but small part of it is solved to date. It seems, the scope is becoming beyond the power utility capability and by now the power provider is forced to introduce privatization in the power sector, as a first phase power purchase agreements (PPAs) with independent power producers (IPPs).the procurement process for some of the new projects has been finalized and engaged in pre-construction site investigation. So, power interruption and power quality issues will be more critical than before.

One of the existing poor power quality parameter which shall be kept within its acceptable range is voltage magnitude at all bus terminals of the power system. With the involvement of IPP in our power system, power interruption and power qualities will be a critical issue, because, after the type and cause of the interruption is identified, either the IPPs or the power utility will compensate the cost for power interruption. In this study due to unavailable penalty cost in the power providers, economical loss due to voltage deviation from the normal range is not calculated. So, future works shall consider this part.

**Table.5.6 Investment Analysis**

No	Item	Estimated Investment Cost	Achievement		Remarks
1	Constructing of new shunt compensator (TSC)	9,372,085.13	Make all bus terminals >0.95pu and omits the cost for voltage violation penalty	Power transfer capability increased by 27.07MW	Installation can be optimize with in spare spaces of existing substations and the construction time can be completed within 3 to 4 months
2	cost of constructing new 66kV transmission Line (<100km)	9,578,000.00	power can be transferred to the targeted consumer	Carry and transfer 27-35MVA power to consumer side	Cost of land compensation , environmental disturbances and other management costs that can be exist during the project life time(Average 2 years)are not considered

## **Chapter Six**

### **6. Conclusion and Recommendation**

#### **6.1 Conclusion**

This thesis tries to study the existing power system of an area in Addis Ababa region i.e. Sululta-Addis South-II Transmission/Sub-Station system and found a voltage profile of bus terminals of Mekanisa, Addis south-II and Muger substations which is less than that of IEC and EEP /EEU (the power companies) standards. This in turn causes the power system of the region to carry and transfer less real power than its capability.

To mitigation the under voltage problem, a shunt compensation method using TSC has been made, transmission line and power transformer parameters have been collected and simulation has been developed in power factory software environment.

The results demonstrate that, this kind of shunt compensation improves voltage profile at different bus terminals of substations to their normal operating range which lies between 0.95pu and 1.05pu. As a result of voltage improvement at different bus terminals of the substations power transfer capability of the system is increased.

In terms of economical aspect, since the compensation system is made in the existing transmission/substation system, it omits the investment cost of new 66kV transmission/substation system that could be constructed to carry and deliver of 27MW power to the load side with an estimated cost of 9.5MUSD, which is also found with higher investment cost than that of TSC which is estimated to be 9.3MUSD. Moreover, the compensation system omits the cost of land compensation that could be paid during construction of new transmission/substations, social and environmental crisis and fast track of project completion usually 4-5 months; this is less by 1.5 years from constructing of new transmission/substation system (EEP practices) and voltage violation penalties in applicable areas. These all make it feasible and attractive.

## **6.2 Recommendation**

Every countries economic development is dependent directly or indirectly on its energy generation and usage; hence, in addition to constructing new generation plants and transmission/substation systems, EEP/EEU shall utilize the existing power system effectively using modern FACTS device. So, the following recommendation shall be adopted in the future

- When TSC is used for terminal voltage improvement to deliver more power to the load side, the loading of the existing power system equipment increases and therefore over loading can be occurred, so, equipment shall be upgraded.
- The static Var System using Thyristor switched capacitor is used only in need of capacitive reactive energy but the full application of SVC which is composed of TSC and TCR shall be introduce to our power system for better voltage stability.
- The study focuses only in improving weak voltage profile and power transfer capability of the region, the impact of shunt compensation to the rest system shall be examined.
- Detail economical and technical comparison shall be done for the aforementioned options and suggestions.

## **7. References**

- [1] Ethiopian power system expansion master plan 2012-2037 GC report
- [2] Ethiopian electric power transmission and substation network design and construction office
- [3] Hadi Saadat, Power System Analysis, WCB McGraw Hill, 1999.
- [4] Narain Hingorani & L. Gyugi understanding FACTS, Concepts and Technology of Flexible AC Transmission System, IEEE Press, 2000.
- [5] Juan Dixon, Luis Moran, Jose Rodriguez, Ricardo Domke, Reactive Power compensation Technologies, State-of-the-Art Review, Pontificia Universidad Catolica de Chile, Universidad de Concepcion, Universidad Federico Sta. Maria.
- [6] Alper Cetin, Design and Implementation of VSC based STATCOM for Reactive power Compensation and Harmonic Filtering, Middle East Technical University, 2007.
- [7] On line Electrical Engineering Study
- [8] L. Dong, M.L. Crow, Z. Yang, C.Shen, L.Zhang, a Reconfigurable FACTS System For University Laboratories.
- [9] EDA UZ, Design and implementation of Thyristor switched shunt compensation, thesis submitted to Middle East Technical University, 2010
- [10]. Dr. B.V. Sumangala and Preethi B “ implementation of TSC for reactive power compensation at secondary of distribution level feeders for voltage stability improvement” department of E. Eng, Bangalore, 2013
- [11]. T.J.E.Miller, Reactive power control in electric systems, John Wiley, 1982),
- [12] Jin Hao, Member IEEE, and Wilsun Xu, Fellow IEEE “Extended Transmission Line Loadability Curve by Including Voltage Stability Constrains”
- [13] The J & P Transformer Book Twelfth edition a practical technology of the power transformer Martin J. Heath-cote, CEng, FIRE Newness
- [14] North Central REC Engineering Conference Duluth, Minnesota March 8, 2006
- [15] Md. Nazmus Sahadat , Nahid-Al-Masood , Md. Shakhawat Hossain , Gilmanur Rashi , A. Hasib Chowdhury “Real Power Transfer Capability Enhancement of Transmission Lines Using SVC” Department of Electrical and Electronic Engineering ,Bangladesh University of Engineering and Technology
- [16] DIG SILENT Power Factory-14 Software” Manual for Technical parameter
- [17] MACIEJ PIKULSKI, “Controlled Sources of Reactive Power Used for Improving Voltage Stability” Paper done in Erasmus University, June, 2008

- [18] Ghanshyam Vishwakarma and Nitin Saxena” Enhancement of Voltage profile using Fixed Capacitor- Thyristor Controlled Reactor (FC-TCR)” International Journal of Electrical, Electronics and Computer Engineering 2(2): 18-22, 2013
- [19] Dr. Pramod Deo, Shri S Jayaraman, Shri V.S.Verma “Central Electricity Regulatory Commission” New Delhi Sep.2010
- [20] Ahmed Elsheikh, Yahya Helmy, Yasmine Abouelseoud, Ahmed Elsherif “ Optimal capacitor placement and sizing in radial electric power systems” Sep, 2014
- [21] Yirgalem-II Substation, Genale Dawa-Three switch Yard, Wolayta-Sodo Sub-Stations “ Cost break down of power system equipment” 2014-2016GC
- [22].Houari Boudjella, Fatiha Lakdja ‘ Modelling and Simulation of Static Var Compensator in power system studies by using Mat lab”
- [23] Prof.C.Radhakrishna “Static Var Compensators” Oct, 2010
- [24] Oak Ridge National Laboratory Engineering Science and Technology Division Study “Reactive Power and Importance to Bulk Power System”

## 8. Appendices

### Appendix I: Regional distribution of peak demand at transmission substation level (MW)

EEP Zone	Sum 2012	Sum 2013	Sum 2015	Sum 2017	Sum 2020	Sum 2025	Sum 2030	Sum 2037
Eastern A.A	172.20	196.45	340.59	549.93	796.78	1,037.94	1,399.46	2,065.96
Northern AA	177.61	179.17	211.88	278.92	326.68	474.70	729.79	1,206.74
Southern AA	319.94	346.66	512.83	743.93	845.97	973.32	1,322.94	1,956.25
Western AA	81.42	92.42	145.94	189.04	251.71	364.52	543.34	880.48
South Eastern	96.34	108.80	165.03	221.33	260.28	444.24	757.18	1,349.84
Southern	95.21	138.16	246.06	374.08	615.11	1,054.78	1,653.99	2,646.99
Eastern	46.92	98.23	271.32	426.75	734.85	1,244.99	1,846.42	2,814.93
Jigijiga	11.42	11.80	30.12	59.55	63.58	81.88	113.00	164.49
Semera	14.05	16.44	61.98	132.15	310.18	676.75	1,063.48	1,638.33
North Eastern	38.55	84.34	205.43	401.13	644.61	764.41	959.06	1,280.61
Northern	87.02	87.28	129.48	265.44	460.55	699.72	849.12	1,128.22
North Western	65.94	73.56	122.29	177.85	391.40	907.33	1,262.28	1,888.60
Western	51.24	52.24	58.43	79.62	158.51	381.36	503.88	727.83
Assosa	7.80	7.82	14.29	25.34	32.99	60.17	88.26	140.17
Gambela	6.82	6.77	8.04	9.93	24.98	65.99	115.35	187.89
Grand total	1,272.48	1,500.14	2,523.70	3,935.00	5,918.17	9,232.11	13,209.54	20,077.35

(Source: Ethiopian power system expansion master plan 2012-2037 GC report)

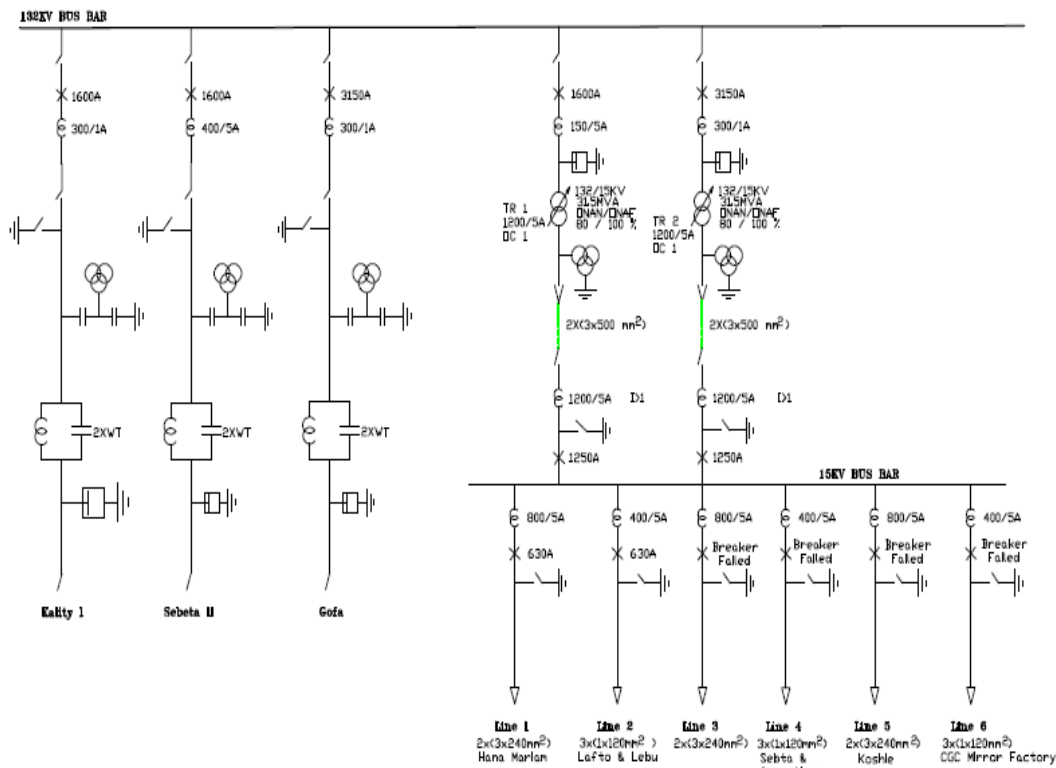
**Appendix II:** 2015-2037GC surplus/deficit of generation capacity (MW)

Year	A/A	Assosa	Eastern	Gambela	Jigjiga	N.eastern	N.western	Northern	Semera	S.Eastern	Southern	Western
2015	-948	-14	-298	-8	-30	-205	664	281	114	176	24	1605
2017	-1499	-25	-325	-10	-60	-401	4873	145	84	229	-284	1589
2020	-1968	293	-213	-25	-64	-645	4509	-50	-15	265	102	3263
2025	-2597	266	-201	-66	-82	-764	7498	-289	-182	281	-838	5364
2030	-3744	238	-243	-115	-113	-959	6693	-470	1071	402	-1587	5241
2037	-5747	736	-122	-188	-164	-1281	5692	-99	2717	365	-1980	5017

(Source: Ethiopian power system expansion master plan 2012-2037 GC report)

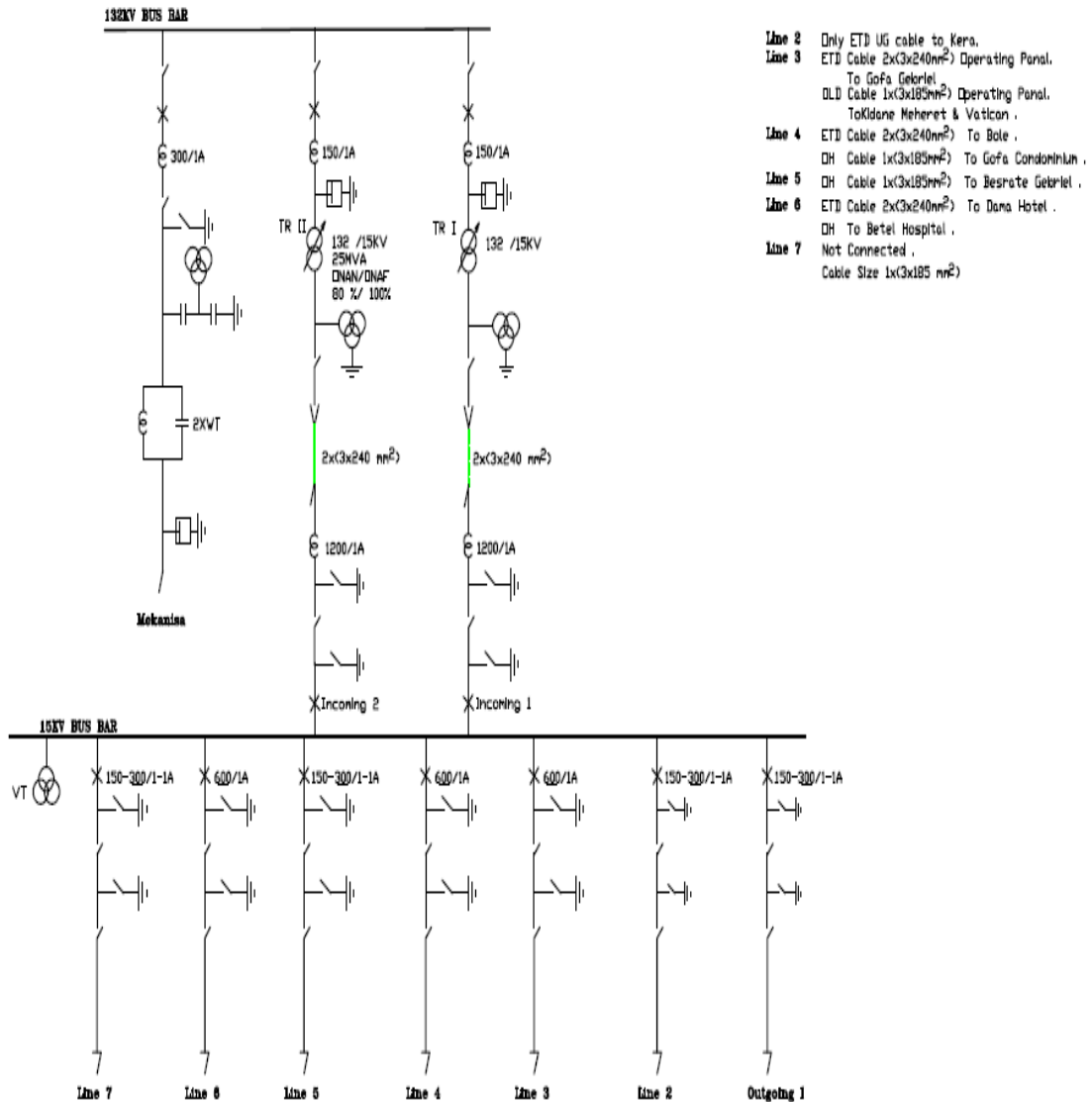
**Appendix III:** Lay out diagram of Mekanisa substation

**MEKANISA SUBSTATION**



Appendix IV: Lay out diagram of Addis south-II (Goffa) Substation

## GOFFA SUBSTATION



**Appendix V: Cost Break down TSC Bay Equipment**

Description	Supply (FOB)	Inland transport	Sea transport	Insurance	Civil Works		Erection, Test & Commissioning		TOTAL	
	Amount (USD)	Amount (BIRR)	Amount (BIRR)	Amount (BIRR)	Amount (BIRR)	Amount (USD)	Amount (BIRR)	Amount (USD)	Amount (BIRR)	Amount (USD)
132kV Line Bay	478,007.17	379,489.89	521,792.63	47,418.31	118,593.58	28,011.22	0.00	44,837.07	1,067,294.41	550,855.46
Terminal Cabinets	27,963.00	22,199.83	30,524.41	2,773.93	0.00	0.00	0.00	2,622.93	55,498.17	30,585.93
Control and Signaling Panels	120,814.50	95,914.63	131,881.11	11,984.80	0.00	0.00	0.00	11,332.40	239,780.54	132,146.90
Protection Panels	145,790.00	115,742.68	159,144.36	14,462.37	0.00	0.00	0.00	13,675.10	289,349.41	159,465.10
15kV equipment	229,713.42	182,369.48	250,755.16	22,787.57	10,139.60	2,394.92	0.00	21,547.12	466,051.82	253,655.46
Auxiliary Service Supply (AC&DC)	23,900.00	18,974.21	26,089.24	2,370.88	0.00	0.00	0.00	2,241.82	47,434.33	26,141.82
Galvanized Steel Structure	253,340.00	201,126.63	276,545.94	25,131.33	62,853.65	14,845.72	0.00	23,763.29	565,657.55	291,949.02
Grounding System	55,448.00	44,020.17	60,527.04	5,500.44	13,756.65	3,249.25	0.00	5,201.02	123,804.29	63,898.28
Shielding Wire System	5,000.00	3,969.50	5,458.00	496.00	0.00	0.00	0.00	469.00	9,923.50	5,469.00
Miscellaneous	47,500.00	37,710.25	51,851.00	4,712.00	11,784.75	2,783.50	0.00	4,455.50	106,058.00	54,739.00
	1,387,476.09	1,101,517.26	1,514,568.90	137,637.63	217,128.23	51,284.62	0.00	130,145.26	2,970,852.02	1,568,905.96
									<b>Total Cost</b>	<b>1,707,085.13</b>

(Reference: *Wolayta Sodo-II and Yirgalem-II 400/230/132/15 kV substation*)

**Appendix VI: Load flow analysis result of Sululta- Addis South-II Transmission/Substation before compensation in 2021**

Load Flow Calculation				Edge Elements				
AC Load Flow, balanced, positive sequence				Automatic Model Adaptation for Convergency		Yes		
Automatic Tap Adjust of Transformers		Yes		Max. Acceptable Load Flow Error for		0.05 kVA		
Consider Reactive Power Limits		No		Nodes		0.10 %		
				Model Equations				
				DIgSILENT PowerFactory 14.0.524		Project: Date: 8/30/2016		
Grid: PF-peak-after.		System Stage: PF-peak-after.		Study Case: Study Case		Annex: / 1		
Name	Type	Loading [%]	Busbar	Active Power [MW]	Reactive Power [Mvar]	Power-factor [-]	Current [kA]	[p.u.]
Addis Alem	Lod		Gefersa-45kv	10.244	4.334	0.92	0.144	0.989
Addis North	Lod		Geff-132kv-BB	27.797	12.631	0.91	0.134	0.995
General Load	Lod		sululta-33kv	4.011	2.102	0.89	0.080	0.984
General Load(1)	Lod		45kv(3)	5.533	2.264	0.93	0.077	0.992
General Load(16)	Lod		Mekanisa-15kv BB	65.592	31.811	0.90	3.032	0.925
General Load(2)	Lod		sebeta 230kv	28.242	13.876	0.90	0.080	0.990
General Load(26)	Lod		sululta-15kv	37.201	19.633	0.88	1.664	0.973
Load	Lod		Addis South-II-15KV..	38.097	16.017	0.92	1.809	0.879
Load to Addis West	Lod		Sebeta-1-45kv-A	17.450	6.263	0.94	0.249	0.955
Load to Addis west-1	Lod		Sebeta-1-45kv-B	3.720	2.325	0.85	0.059	0.955
Load to Dangote Cement Factory			Sululta-132kv-BB	31.257	5.997	0.98	0.139	1.000
Load to Derba Cement Factory			Derba132kv-BB	21.274	9.575	0.91	0.112	0.913
Load to Geja	Lod		Sebeta-1-45kv-B	3.720	1.860	0.89	0.056	0.955
Load to Muger Cement Factory			Muger Cement-132kv-BB	17.698	7.740	0.92	0.091	0.931
Load(1)	Lod		15kv(1)	2.961	1.188	0.93	0.127	0.963
Load(19)	Lod		33KV(4)	0.257	0.128	0.89	0.005	0.994
Load(2)	Lod		Seb-15kv BB-1	11.544	6.233	0.88	0.531	0.951
Load(20)	Lod		Gef15kv	6.848	5.726	0.77	0.348	0.988
Load(21)	Lod		15KV(2)	1.399	0.808	0.87	0.063	0.993
Load(3)	Lod		sebeta-1 132kv	29.319	15.966	0.88	0.149	0.978
Load(4)	Lod		sebeta-15kv-BB	57.146	23.377	0.93	2.484	0.957
To Fitcha	Lod		Fiche-66kv	2.324	1.139	0.90	0.024	0.955
kality-1	Lod		Geff-132kv-BB	15.166	3.791	0.97	0.069	0.995
External Grid	Xnet		Geff-230kv-A-BB	76.189	108.829	0.57	0.333	0.073
External Grid(1)	Xnet		sululta-230kv-BB	326.730	96.990	0.96	0.849	0.185
External Grid(2)	Xnet		sebeta 230kv	45.960	10.210	0.98	0.119	0.026
10.6km Txm Line	Lne	61.64	Geff-230kv-A-BB	137.962	95.915	0.82	0.422	0.614
			Sebeta-1 -230kv	-137.473	-95.060	-0.82	0.424	0.617
14KM-Txm Line	Lne	107.45	Geff-132kv-BB	80.624	32.754	0.93	0.383	1.072
			mek132kv	-79.018	-30.767	-0.93	0.384	1.075
18km-Txm Line	Lne	7.57	Terminal132kv	17.791	7.186	0.93	0.089	0.224
			Muger Cement-132kv-BB	-17.698	-7.740	-0.92	0.091	0.227
49.5-Txm Line	Lne	9.33	Terminal132kv	21.657	8.343	0.93	0.108	0.271

Grid: PF-peak-after.		System Stage: PF-peak-after.		Study Case: Study Case			Annex: / 2	
Name	Type	Loading [%]	Busbar	Active Power [MW]	Reactive Power [Mvar]	Power-factor [-]	Current [kA]	[p.u.]
62km-Txm Line	Lne	16.48	Derbal32kv-BB	-21.274	-9.575	-0.91	0.112	0.280
			Gefersa-132KV	40.963	15.829	0.93	0.193	0.484
7.8KM-Txm	Lne	153.94	Terminal132kv	-39.449	-15.529	-0.93	0.198	0.495
			mek132kv	107.885	55.508	0.89	0.549	1.537
96KM	Lne	139.50	Mekanisa-132KV-BB	-106.022	-52.811	-0.90	0.550	1.539
			66kv(1)	2.410	0.117	1.00	0.021	1.249
Bus Connecting Line	Lne	127.08	Fiche-66kv	-2.324	-1.139	-0.90	0.024	1.395
			Geff-132kv	95.485	39.165	0.93	0.454	1.271
Line	Lne	37.90	Geff-132kv-BB	-95.482	-39.161	-0.93	0.454	1.271
			Geff230kv	-95.506	-40.452	-0.92	0.260	0.379
Line(10)	Lne	19.01	Gefersa-230kv-B(1)	95.506	40.450	0.92	0.260	0.379
			Gefersa-230kv-B(1)	47.859	20.384	0.92	0.131	0.190
Line(12)	Lne	51.51	230kv	-47.858	-20.397	-0.92	0.131	0.190
			Mekanisa-132KV-BB	40.407	18.046	0.91	0.205	0.515
Line(14)	Lne	48.18	Addis South-II-132KV	-38.128	-17.673	-0.91	0.206	0.515
			mek132kv	-28.868	-24.741	-0.76	0.172	0.482
Line(16)	Lne	6.68	sebeta-1 132kv	29.115	24.667	0.76	0.171	0.478
			Sebeta-1 -230kv	-17.718	3.603	-0.98	0.046	0.067
Line(17)	Lne	5.60	sebeta 230kv	17.718	-3.666	0.98	0.046	0.067
			Sebeta-1-45kv-B	2.850	-0.251	1.00	0.038	0.056
Line(3)	Lne	10.94	Sebeta-1-45kv-A	-2.850	0.251	-1.00	0.038	0.056
			Geff-132kv-BB	-28.105	-10.016	-0.94	0.131	0.329
Line(9)	Lne	13.08	Gefersa-132KV	28.105	10.016	0.94	0.131	0.329
			Gefersa-230kv-B(1)	47.931	20.440	0.92	0.131	0.131
Line-Tap	Lne	18.94	geff230kv	-47.931	-20.446	-0.92	0.131	0.131
			Geff230kv	47.731	20.209	0.92	0.130	0.189
Twinish ASH/16.7KM	Lne	82.50	geff 230kv	-47.731	-20.213	-0.92	0.130	0.189
			sululta-230kv-BB	127.170	32.677	0.97	0.327	0.820
line-2	Lne	82.42	Gefersa-230kv-B(1)	-126.593	-34.208	-0.97	0.329	0.825
			sululta-230kv-BB	127.052	32.606	0.97	0.327	0.819
line-3	Lne	14.62	Geff-230kv-A-BB	-126.476	-34.139	-0.97	0.329	0.824
			Geff-230kv-A-BB	32.351	23.527	0.81	0.100	0.146
line-4	Lne	14.62	Gefersa-230kv-B(1)	-32.351	-23.533	-0.81	0.100	0.146
			Geff-230kv-A-BB	32.351	23.527	0.81	0.100	0.146
2-Winding Transformer	Tr2	161.31	Gefersa-230kv-B(1)	-32.351	-23.533	-0.81	0.100	0.146
			sebeta-1 132kv	57.298	26.496	0.91	0.282	1.613
2-Winding Transformer(1)	Tr2	117.50	sebeta-15kv-BB	-57.146	-23.377	-0.93	2.484	1.613
			Addis South-II-132KV	18.898	9.194	0.90	0.103	1.175
2-Winding Transformer(11)	r2	36.15	Addis South-II-15KV..	-18.898	-8.365	-0.91	0.905	1.175
			Gefersa-132KV	6.851	5.824	0.76	0.040	0.362
2-Winding Transformer(12)	r2	41.62	Gef15kv	-6.848	-5.726	-0.77	0.348	0.362
			230kv	47.858	20.397	0.92	0.131	0.416
2-Winding Transformer(13)	r2	41.69	Gefersa-132KV	-47.848	-19.747	-0.92	0.228	0.416
			geff230kv	47.931	20.446	0.92	0.131	0.417
2-Winding Transformer(16)	r2	44.98	Gefersa-132KV	-47.920	-19.794	-0.92	0.228	0.417
			Gefersa-132KV	10.250	4.486	0.92	0.049	0.450

Grid: PF-peak-after.		System Stage: PF-peak-after.		Study Case: Study Case			Annex: / 3	
Name	Type	Loading [%]	Busbar	Active Power [MW]	Reactive Power [Mvar]	Power-factor [-]	Current [kA]	[p.u.]
2-Winding Transformer (12) r2		41.85	230kv	52.167	-3.960	1.00	0.131	0.419
			Gefersa-132KV	-52.156	4.617	-1.00	0.229	0.419
2-Winding Transformer (13) r2		41.92	geff230kv	52.254	-3.949	1.00	0.132	0.419
			Gefersa-132KV	-52.243	4.608	-1.00	0.229	0.419
2-Winding Transformer (16) r2		45.25	Gefersa-132KV	10.371	4.539	0.92	0.049	0.452
			Gefersa-45kv	-10.366	-4.386	-0.92	0.145	0.452
2-Winding Transformer (2) Tr2		120.62	Mekanisa-132KV-BB	37.715	1.848	1.00	0.166	1.206
			Mekanisa-15kv BB	-37.693	-0.473	-1.00	1.462	1.206
2-Winding Transformer (24) r2		120.62	Mekanisa-132KV-BB	37.681	2.457	1.00	0.166	1.206
			Mekanisa-15kv BB	-37.681	-1.082	-1.00	1.462	1.206
2-Winding Transformer (26) r2		125.59	Addis South-II-132KV	22.790	-7.355	0.95	0.110	1.256
			Addis South-II-15KV..	-22.754	8.301	-0.94	0.967	1.256
2-Winding Transformer (3) Tr2		41.74	Geff230kv	52.021	-4.059	1.00	0.131	0.417
			Geff-132kv	-52.010	4.713	-1.00	0.228	0.417
2-Winding Transformer (4) Tr2		41.70	geff 230kv	51.968	-4.066	1.00	0.131	0.417
			Geff-132kv	-51.958	4.718	-1.00	0.228	0.417
2-Winding Transformer (5) Tr2		69.79	Sebeta-1 -230kv	85.445	15.018	0.98	0.219	0.698
			sebeta-1 132kv	-85.416	-13.192	-0.99	0.382	0.698
2-Winding Transformer (6) Tr2		69.79	Sebeta-1 -230kv	85.445	15.018	0.98	0.219	0.698
			sebeta-1 132kv	-85.416	-13.192	-0.99	0.382	0.698
63MVA	Tr2	62.33	sululta-230kv-BB	36.255	15.854	0.92	0.099	0.623
			Sululta-132kv-BB	-36.235	-15.120	-0.92	0.172	0.623
63MVA (1)	Tr2	62.33	sululta-230kv-BB	36.255	15.854	0.92	0.099	0.623
			Sululta-132kv-BB	-36.235	-15.120	-0.92	0.172	0.623
3-Winding Transformer Tr3		169.55	sebeta-1 132kv	18.008	8.965	0.90	0.089	0.812
			Sebeta-1-45kv-A	-14.971	-6.680	-0.91	0.218	1.696
			15kv (1)	-3.037	-1.218	-0.93	0.129	0.335
3-Winding Transformer (1) Tr3		172.90	Sululta-132kv-BB	41.213	24.242	0.86	0.209	0.956
			sululta-33kv	-4.011	-2.102	-0.89	0.080	0.184
			sululta-15kv	-37.202	-19.633	-0.88	1.664	1.729
3-Winding Transformer (10) r3		139.67	sebeta-1 132kv	22.390	11.906	0.88	0.112	1.024
			Sebeta-1-45kv-B	-10.552	-4.034	-0.93	0.150	1.168
			Seb-15kv BB-1	-11.838	-6.392	-0.88	0.538	1.397
3-Winding Transformer (2) Tr3		13.65	Gefersa-132KV	1.676	0.956	0.87	0.008	0.080
			33KV (4)	-0.260	-0.130	-0.89	0.005	0.024
			15KV (2)	-1.416	-0.818	-0.87	0.063	0.136
3-Winding Transformer (3) Tr3		25.25	Gefersa-132KV	4.485	1.431	0.95	0.021	0.118
			66kv (1)	-0.753	0.133	-0.98	0.007	0.048
			45kv (3)	-3.732	-1.527	-0.93	0.052	0.253
3-Winding Transformer (6) Tr3		16.85	Gefersa-132KV	1.310	0.325	0.97	0.006	0.067
			66kv (1)	-1.310	-0.318	-0.97	0.012	0.169
				-0.000	0.000	-1.00	0.000	0.000
3-Winding Transformer (7) Tr3		25.25	Gefersa-132KV	2.242	0.715	0.95	0.010	0.118
			66kv (1)	-0.376	0.067	-0.98	0.003	0.048
			45kv (3)	-1.866	-0.764	-0.93	0.026	0.253

**AppendixVII: Load flow analysis result of Sululta- Addis South-II Transmission/Substation After compensation in 2021**

Load Flow Calculation		Edge Elements	
AC Load Flow, balanced, positive sequence		Automatic Model Adaptation for Convergency	Yes
Automatic Tap Adjust of Transformers	Yes	Max. Acceptable Load Flow Error for	
Consider Reactive Power Limits	No	Nodes	0.05 kVA
		Model Equations	0.10 %

		DIGSILENT PowerFactory	Project:
		14.0.524	Date: 8/30/2016

Grid: PF-peak-after.	System Stage: PF-peak-after.	Study Case: Study Case	Annex: / 1
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Name	Type	Loading [%]	Busbar	Active Power [MW]	Reactive Power [Mvar]	Power-factor [-]	Current [kA]	[p.u.]
Addis Alem	Lod		Gefersa-45kv	10.366	4.386	0.92	0.145	0.995
Addis North	Lod		Geff-132kv-BB	28.126	12.781	0.91	0.135	1.001
General Load	Lod		sululta-33kv	4.011	2.102	0.89	0.080	0.984
General Load(1)	Lod		45kv(3)	5.598	2.291	0.93	0.078	0.998
General Load(16)	Lod		Mekanisa-15kv BB	75.374	36.555	0.90	3.250	0.992
General Load(2)	Lod		sebeta 230kv	28.523	14.014	0.90	0.080	0.994
General Load(26)	Lod		sululta-15kv	37.202	19.633	0.88	1.664	0.973
Load	Lod		Addis South-II-15KV..	45.804	19.257	0.92	1.983	0.964
Load to Addis West	Lod		Sebeta-1-45kv-A	17.894	6.423	0.94	0.252	0.967
Load to Addis west-1	Lod		Sebeta-1-45kv-B	3.814	2.384	0.85	0.060	0.967
Load to Dangote Cement Factory			Sululta-132kv-BB	31.258	5.998	0.98	0.139	1.000
Load to Derba Cement Factory			Derbal32kv-BB	25.644	11.541	0.91	0.123	1.002
Load to Geja	Lod		Sebeta-1-45kv-B	3.814	1.907	0.89	0.057	0.967
Load to Muger Cement Factory			Muger Cement-132kv-BB	19.647	8.592	0.92	0.096	0.981
Load(1)	Lod		15kv(1)	3.037	1.218	0.93	0.129	0.976
Load(19)	Lod		33KV(4)	0.260	0.130	0.89	0.005	0.999
Load(2)	Lod		Seb-15kv BB-1	11.838	6.392	0.88	0.538	0.963
Load(20)	Lod		Gef15kv	6.929	5.794	0.77	0.350	0.993
Load(21)	Lod		15KV(2)	1.416	0.818	0.87	0.063	0.999
Load(3)	Lod		sebeta-1 132kv	30.066	16.373	0.88	0.151	0.991
Load(4)	Lod		sebeta-15kv-BB	58.602	23.972	0.93	2.515	0.969
To Fitch	Lod		Fiche-66kv	2.351	1.153	0.90	0.024	0.960
kalidity-1	Lod		Geff-132kv-BB	15.345	3.836	0.97	0.069	1.001
TSC	Svs		Mekanisa-132KV-BB	-0.000	-35.000	-0.00	0.154	35.219
TSC(1)	Svs		Mekanisa-15kv BB	-0.000	-35.000	-0.00	1.358	35.279
TSC(2)	Svs		Addis South-II-15KV..	-0.000	-35.000	-0.00	1.397	36.296
TSC(3)	Svs		Derbal32kv-BB	-0.000	-35.000	-0.00	0.153	34.922
TSC(4)	Svs		Addis South-II-132KV	-0.000	-35.000	-0.00	0.161	36.711
External Grid	Xnet		Geff-230kv-A-BB	109.226	-50.086	0.91	0.302	0.066
External Grid(1)	Xnet		sululta-230kv-BB	326.730	96.990	0.96	0.849	0.185
External Grid(2)	Xnet		sebeta 230kv	45.960	10.210	0.98	0.119	0.026
10.6km Txm Line	Lne	57.66	Geff-230kv-A-BB	153.883	34.333	0.98	0.396	0.576
			Sebeta-1 -230kv	-153.454	-33.776	-0.98	0.397	0.577

*Shunt Compensation for Sululta- Addis South-II Transmission/Substation System*

Grid: PF-peak-after.		System Stage: PF-peak-after.		Study Case: Study Case			Annex: / 2	
Name	Type	Loading [%]	Busbar	Active Power [MW]	Reactive Power [Mvar]	Power.- factor [-]	Current [kA]	[p.u.]
14KM-Txm Line	Lne	117.47	Geff-132kv-BB	89.824	-33.773	0.94	0.419	1.175
			mek132kv	-87.904	36.250	-0.92	0.418	1.172
18km-Txm Line	Lne	7.98	Terminal132kv	19.751	7.978	0.93	0.094	0.236
			Muger Cement-132kv-BB	-19.647	-8.592	-0.92	0.096	0.240
49.5-Txm Line	Lne	13.23	Terminal132kv	26.406	-24.244	0.74	0.159	0.397
			Derbal132kv-BB	-25.644	23.459	-0.74	0.152	0.380
62km-Txm Line	Lne	18.40	Gefersa-132KV	48.052	-15.364	0.95	0.220	0.553
			Terminal132kv	-46.157	16.266	-0.94	0.216	0.542
7.8KM-Txm	Lne	183.66	mek132kv	128.995	-74.631	0.87	0.656	1.837
			Mekanisa-132KV-BB	-126.343	78.584	-0.85	0.655	1.834
96KM	Lne	140.32	66kv(1)	2.438	0.119	1.00	0.021	1.257
			Fiche-66kv	-2.351	-1.153	-0.90	0.024	1.403
Bus Connecting Line	Lne	127.79	Geff-132kv	103.968	-9.431	1.00	0.456	1.278
			Geff-132kv-BB	-103.965	9.435	-1.00	0.456	1.278
Line	Lne	38.11	Geff230kv	-103.989	8.129	-1.00	0.262	0.381
			Gefersa-230kv-B(1)	103.990	-8.131	1.00	0.262	0.381
Line(10)	Lne	19.12	Gefersa-230kv-B(1)	52.167	-3.973	1.00	0.131	0.191
			230kv	-52.167	3.960	-1.00	0.131	0.191
Line(12)	Lne	77.13	Mekanisa-132KV-BB	50.947	-47.889	0.73	0.308	0.771
			Addis South-II-132KV	-45.840	48.851	-0.68	0.307	0.770
Line(14)	Lne	69.71	mek132kv	-41.091	38.381	-0.73	0.247	0.693
			sebeta-1 132kv	41.611	-38.031	0.74	0.249	0.697
Line(16)	Lne	6.56	Sebeta-1 -230kv	-17.437	3.740	-0.98	0.045	0.066
			sebeta 230kv	17.437	-3.804	0.98	0.045	0.066
Line(17)	Lne	5.67	Sebeta-1-45kv-B	2.923	-0.257	1.00	0.039	0.057
			Sebeta-1-45kv-A	-2.923	0.257	-1.00	0.039	0.057
Line(3)	Lne	11.06	Geff-132kv-BB	-29.331	7.721	-0.97	0.133	0.332
			Gefersa-132KV	29.331	-7.721	0.97	0.133	0.332
Line(9)	Lne	13.15	Gefersa-230kv-B(1)	52.254	-3.956	1.00	0.132	0.132
			geff230kv	-52.254	3.949	-1.00	0.132	0.132
Line-Tap	Lne	19.05	Geff230kv	51.969	-4.070	1.00	0.131	0.190
			geff 230kv	-51.968	4.066	-1.00	0.131	0.190
Twinish ASH/16.7KM	Lne	82.49	sululta-230kv-BB	127.175	32.582	0.97	0.327	0.820
			Gefersa-230kv-B(1)	-126.599	-34.113	-0.97	0.329	0.825
line-2	Lne	82.43	sululta-230kv-BB	127.045	32.700	0.97	0.327	0.819
			Geff-230kv-A-BB	-126.469	-34.233	-0.97	0.329	0.824
line-3	Lne	17.53	Geff-230kv-A-BB	40.906	-25.093	0.85	0.120	0.175
			Gefersa-230kv-B(1)	-40.906	25.086	-0.85	0.120	0.175
line-4	Lne	17.53	Geff-230kv-A-BB	40.906	-25.093	0.85	0.120	0.175
			Gefersa-230kv-B(1)	-40.906	25.086	-0.85	0.120	0.175
2-Winding Transformer	Tr2	163.35	sebeta-1 132kv	58.758	27.171	0.91	0.286	1.634
			sebeta-15kv-BB	-58.602	-23.972	-0.93	2.515	1.634
2-Winding Transformer(1)	Tr2	125.59	Addis South-II-132KV	23.050	-6.496	0.96	0.110	1.256
			Addis South-II-15KV..	-23.050	7.442	-0.95	0.967	1.256
2-Winding Transformer(11)	r2	36.36	Gefersa-132KV	6.933	5.893	0.76	0.040	0.364
			Gef15kv	-6.929	-5.794	-0.77	0.350	0.364

Grid: PF-peak-after.		System Stage: PF-peak-after.		Study Case: Study Case			Annex: / 3	
Name	Type	Loading [%]	Busbar	Active Power [MW]	Reactive Power [Mvar]	Power.- factor [-]	Current [kA]	[p.u.]
2-Winding Transformer (2) Tr2		125.03	Gefersa-45kv	-10.244	-4.334	-0.92	0.144	0.450
			Mekanisa-132KV-BB	32.948	17.118	0.89	0.172	1.250
2-Winding Transformer (24) r2		125.03	Mekanisa-15kv BB	-32.924	-15.641	-0.90	1.516	1.250
			Mekanisa-132KV-BB	32.667	17.648	0.88	0.172	1.250
2-Winding Transformer (26) r2		117.50	Mekanisa-15kv BB	-32.667	-16.170	-0.90	1.516	1.250
			Addis South-II-132KV	19.230	8.479	0.91	0.103	1.175
2-Winding Transformer (3) Tr2		41.51	Addis South-II-15KV..	-19.199	-7.651	-0.93	0.905	1.175
			Geff230kv	47.775	20.243	0.92	0.130	0.415
2-Winding Transformer (4) Tr2		41.47	Geff-132kv	-47.764	-19.597	-0.93	0.227	0.415
			geff 230kv	47.731	20.213	0.92	0.130	0.415
2-Winding Transformer (5) Tr2		72.81	Geff-132kv	-47.721	-19.568	-0.93	0.227	0.415
			Sebeta-1 -230kv	77.595	45.729	0.86	0.228	0.728
2-Winding Transformer (6) Tr2		72.81	sebeta-1 132kv	-77.563	-43.741	-0.87	0.398	0.728
			Sebeta-1 -230kv	77.595	45.729	0.86	0.228	0.728
63MVA	Tr2	62.33	sebeta-1 132kv	-77.563	-43.741	-0.87	0.398	0.728
			sululta-230kv-BB	36.254	15.853	0.92	0.099	0.623
63MVA (1)	Tr2	62.33	Sululta-132kv-BB	-36.235	-15.119	-0.92	0.172	0.623
			sululta-230kv-BB	36.254	15.853	0.92	0.099	0.623
3-Winding Transformer	Tr3	167.43	Sululta-132kv-BB	-36.235	-15.119	-0.92	0.172	0.623
			sebeta-1 132kv	17.561	8.743	0.90	0.088	0.802
3-Winding Transformer (1) Tr3		172.89	Sebeta-1-45kv-A	-14.600	-6.514	-0.91	0.215	1.674
			15kv (1)	-2.961	-1.188	-0.93	0.127	0.331
			Sululta-132kv-BB	41.212	24.241	0.86	0.209	0.956
3-Winding Transformer (10) r3		137.93	sululta-33kv	-4.011	-2.102	-0.89	0.080	0.184
			sululta-15kv	-37.201	-19.633	-0.88	1.664	1.729
			sebeta-1 132kv	21.833	11.610	0.88	0.111	1.011
3-Winding Transformer (2) Tr3		13.57	Sebeta-1-45kv-B	-10.290	-3.934	-0.93	0.148	1.154
			Seb-15kv BB-1	-11.544	-6.233	-0.88	0.531	1.379
			Gefersa-132KV	1.656	0.944	0.87	0.008	0.080
3-Winding Transformer (3) Tr3		25.10	33KV (4)	-0.257	-0.128	-0.89	0.005	0.024
			15KV (2)	-1.399	-0.808	-0.87	0.063	0.136
			Gefersa-132KV	4.432	1.414	0.95	0.020	0.117
3-Winding Transformer (6) Tr3		16.76	66kv (1)	-0.744	0.132	-0.98	0.007	0.048
			45kv (3)	-3.688	-1.509	-0.93	0.052	0.251
			Gefersa-132KV	1.294	0.321	0.97	0.006	0.067
3-Winding Transformer (7) Tr3		25.10	66kv (1)	-1.294	-0.315	-0.97	0.012	0.168
				-0.000	-0.000	-1.00	0.000	0.000
			Gefersa-132KV	2.216	0.707	0.95	0.010	0.117
			66kv (1)	-0.372	0.066	-0.98	0.003	0.048
			45kv (3)	-1.844	-0.755	-0.93	0.026	0.251