ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING
(POWER ENGINEERING)

TRANSMISSION LINE LOSS MINIMIZATION AND IMPROVEMENT OF VOLTAGE PROFILE USING UNIFIED POWER FLOW CONTROLLER

(CASE STUDY: EASTERN REGION OF ETHIOPIA)

A Thesis Submitted to Addis Ababa Institute of Technology, School of Graduate Studies, Addis Ababa University, in Partial Fulfillment of the Requirements for the Degree of Master of Science in Electrical and Computer Engineering (Power Engineering)

By

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ADDIS ABABA, ETHIOPIA

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Addis Ababa University
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DECLARATION

I, the undersigned, declared that this MSc thesis in titled as **"Transmission Line Loss Minimization and Improvement of Voltage Profile Using Unified Power Flow Controller"** is my original work, has not been presented for fulfillment of a degree in this or any other Universities, and all sources and materials used for the thesis work are acknowledged in this document.

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Place	Date of Submission

This thesis work has been submitted for examination with my approval as a University Advisor.

Dr.Mengesha Mamo	______________
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LIST OF ABREVIATIONS

EEP	Ethiopian Electric Power
FACTS	Flexible AC Transmission Systems
MVAr	Mega Voltage Ampere reactive
kV	kilo Volt
MVA	Mega Volt Ampere
MW	Mega Watt
SSSC	Series Synchronous Static Compensator
SVC	Static Var Compensator
TCR	Thyristor Controlled Reactor
TCSC	Thyristor Controlled Series Capacitor
TSSC	Thyristor Switched Series Capacitor
UPFC	Unified Power Flow Controller
STATCOM	Static Synchronous Compensator
IPFC	Interline Power Flow Controller
AC	Alternating Current
DC	Direct Current
p.u	Per unit
HVCD	High Voltage Direct Current

LIST OF NOTATIONS

P	Active Power
Q	Reactive Power
S	Apparent Power
I	Current
V	Voltage
Ω	Ohm
X	Reactance
R	Resistance
C	Capacitance
L	Inductance
P_G	Generated Power
V_G	Generated line to line voltage
CosØG	generator power factor
VR	Voltage regulation
V_R	Receiving end Voltage
V_S	Sending end Voltage

ABSTRACT

Electrical power system is very complex and it requires very careful design of new equipment's which are needed to improve electric power utilization, enhancing power system stability, power loss minimization and power transfer capability. The existing power transmission network of Ethiopia consists of 45kV, 66kV, 132kV, 230kV and 400kV lines. This thesis mainly focused on 132kV transmission line of Eastern region of Ethiopia.

Transmission Line loss minimization and voltage profile improvement in the transmission line are challenging problems. This thesis analyze the impact of using unified power flow controller (UPFC) in the transmission line. The UPFC is the most versatile and complex power electronics equipment's that has emerged for control and optimization of power flow in electric power transmission systems. It is a combination of series and parallel compensation and can therefore provide active and reactive control to achieve maximum power transfer, system stability, and voltage profile improvement and minimize transmission line loss.

Unified Power Flow Controller is designed for the transmission line to increase power transfer capability, reduce power loss and improve voltage profile. The UPFC has been simulated using DIgSILENT Power Factory Software. The simulation results showed that all the bus voltages are within acceptable limit which is above 0.95p.u. After incorporating the UPFC the total active power loss is reduced from 4.295MW to 1.908, from 2.387MW to 1.306MW and from 1.166MW to 0.454MW for peak load condition, average load condition and minimum load condition respectively. The total reactive power loss is reduced from 9.2MVAr to 3.3MVAr, from 6.1MVAr to 2MVAr and from 4.6MVAr to 0.9MVAr for peak load condition, average load condition and minimum load condition respectively.

Therefore, by incorporating the designed Unified Power Flow Controller voltage profiles in the Eastern Region of Ethiopia is improved and transmission line loss is minimized.

Key words: Load Flow analysis, UPFC, FACTS, Power loss minimization, Voltage Profile improvement, DIgSILENT Power Factory.

CHAPTER ONE

1. INTRODUCTION

1.1. BACKGROUND

In recent years, electric power transmission line has become more constrained due to continuous load growth. There is an urgent need to increase the power carrying capacity of the power transmission lines in order to minimized losses and reduce voltage instability, there by maintaining reliability, power quality and security of power system as whole. Power generating stations are mostly situated far away from the load center due to environmental challenges such as pollution hazard to human and regulatory policies. With a specific objective to meet the perpetually increasing power demand, utilities depend on the existing arrangements of power generation and transmission lines as opposed to building new transmission line that are subject to economic and environmental issues. Also certain transmission line is well operating below their rated thermal limit; some other lines are over loaded, resulting in voltage collapse there by reducing the system reliability and stability. This general circumstance requires the investigation of different methods or techniques of reducing transmission line losses and the application of available methods, which would allow the existing transmission line function up to their full capacity without reducing power system security, stability and power transfer. It is imperative to note that the increasing of reactive power in the system cause power losses and reduce the transmission line power transfer capacity. It also brings about a large voltage amplitude variation at consumer’s end. Compensating reactive power is there by important in controlling and minimizing losses in electric power systems [1]. Load ability of existing systems can be improved by reducing real power loss in the line with the help of Flexible AC Transmission System devices.

UPFC is a versatile FACTS device; has the unique capability to control simultaneously both an active and reactive power flows on the transmission line [2]. So, there has been increasing interest in the analysis of UPFC in power system. The UPFC can provide simultaneous control of all basic power system parameters such as transmission line voltage, impedance and phase angle. The controller can fulfill the functions of shunt compensation, series compensation and phase shifting meeting multiple control. In Ethiopia the generating units are increasing with no corresponding increase in the transmission network. The existing transmission network has more transmission line losses due to overloading and aging problems. When there is a disturbance in existing 132kV transmission line, bus voltage instability and power loss will be occurred. This leads to poor voltage regulation problems. Therefore, it is necessary to design appropriate controlling devices in order to enhance improvement of voltage profile of the transmission network. In Ethiopia, a commonly used transmission line ratings are 45kV, 66kV, 132kV, 230kV and 400kV lines whereas for distribution system either 33kV or 15kV transmission lines are used. This thesis focused on 132kV transmission network of the Eastern region of Ethiopia. The losses in this transmission line are more, since this transmission line covers large distances and most of this transmission line is aged.

1.2. STATEMENT OF THE PROBLEM

Electric power systems play important roles in the industrial and socioeconomic development of any nation. Electrical energy is generated and transported from remote generating stations to the load centers through transmission lines. These transmission lines are susceptible to losses and to voltage profile problems, which affect the ability to deliver the same amount of power generated at the receiving end. This has become a problem that needs to be solved through research.

The Ethiopian government currently gives much emphasis to increase more generating units to balance with power demand without corresponding increase in the transmission network and transmission line is not efficiently utilized up to their maximum limit. It has to be understood that the result of any increase in the transmission power losses in a network is further loading of the system elements which intends to shorten their life as the losses are dissipated in the form of heat. Higher losses also require a higher rate of the generation sources commitment, which in other words means a higher installed power. Consequently, more transmission line losses will imbalance the energy demand and the power supply. Due to the power loss problem and poor voltage regulation problem the area in the Eastern part is not receive sufficient energy from the main supply.

Power flow calculation is key to evaluate the operation state of any power system therefore; a power flow study using the Newton- Raphson algorithms was adopted with and without UPFC placement in the power system, while different load condition scenarios were considered to understand how increasing in power demand and ageing of transmission line contribute to transmission line loss and poor voltage profile problem.

Therefore, to solve the transmission line loss and the voltage profile problem, the Ethiopian Electric Power plans to build new transmission line, even if it is not easy and financially affordable. So, it is necessary to have a compensation mechanism for reducing power loss and improving voltage profile in Easter region of Ethiopia by using Unified Power Flow Controller.

1.3. OBJECTIVE OF THE STUDY

1.3.1. General Objective

The main objective of this thesis is to minimize transmission line loss, improvement of voltage profile and enhance power transfer capacity of the existing transmission line using Unified Power Flow Controller (UPFC).

1.3.2. Specific Objective

i. To study performance analysis , identify the transmission line losses and voltage profile of the existing transmission network for three load condition scenarios
ii. To design and model UPFC control strategies for transmission network
iii. To analyze the impact of UPFC in the transmission line
iv. To Evaluate the performance of the transmission network of Eastern region of Ethiopia By incorporating UPFC Using DigSILENT Power Factory software

1.4. SIGNIFICANCE OF THE STUDY

The study will be useful for power system planners, load forecasting and decision makers since it presents a concern on how much primary power is lost on the transmission network and also show the voltage deviation of buses. As EEP is exporting electrical energy and on the way to increase the export of energy, an additional energy from loss reduction will benefit the EEP to earn more profit. The electrical system losses of EEP should have to be investigated so that appropriate loss minimization and improvement of voltage profile measures can be undertaken. Thus the result of this thesis work will be best input for those study groups and researchers who are working on the implementation of bulk power transmission system loss minimization and maintain voltage profile constant.

1.5. SCOPE OF THE STUDY

The scope of this research is to analysis, design, simulate and evaluate the performance of the transmission line without UPFC and with UPFC in order to minimize the transmission line losses and improve bus voltage profile of the selected case study using Unified Power Flow Controller.

1.6. METHODOLOGY OF THE STUDY

In order to achieve the main aim of the study there are various procedural tasks followed. The first method towards processing the work is started with reviewing different literatures where all the theoretical information regarding the transmission line losses and voltage profile improvement. Alongside with literature reviewing, the collection and verification of data for the analysis is performed. This is followed by studying the characteristic and modeling transmission lines of the Eastern region of Ethiopia. Once the model is developed using DIgSILENT Power Factory v15 software, the analysis of the system is performed. Finally, the performance of the UPFC is analyzed and a comparison is made.

1.7. ORGANIZATION OF THE THESIS

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

Chapter One Presents the introduction mainly consists of the background, statement of the problem, objectives, significant, scope, methodologies and organization of the thesis followed in the thesis work.

Chapter Two discusses about the theoretical background and literature review of the study, mainly on transmission line losses, voltage drop and electric power control using UPFC, TCSC, SVC, STATCOM, TSSC, SSSC and IPFC.

Chapter Three modelling of the transmission line of the existing the eastern region of Ethiopia and modelling UPFC and design of UPFC.

Chapter Four system simulation and their result discussion without UPFC and with UPFC.

The last chapter, **Chapter Five** deals with the conclusions, recommendations and also the future works. At the end of this thesis references and Appendix are added.

CHAPTER TWO

2. THEORETICAL BACKGROUND AND LITERATURE REVIE

2.1. ELECTRICAL POWER SYSTEMS

For a very long time, there has been a significant increase in demand for electric power energy and as a result electrical power transmission networks are experiencing limitation in power transmission [7]. These limitations are due to balancing supply, allowed level of voltage and maintaining the network stability. These have resulted in lesser practical operation capacity of the power system compared to the full capacity. The consequence is non-optimal operation of the power transmission systems. Among the many option to solve the increase problem of power transmission capacity is to construct new transmission line, which is not practical nor economical viable. Researchers have worked in the last two decades to develop models and new algorithms for power system stability by incorporating Flexible AC Transmission System (FACTS) devices for a reliable, fast and continuous control of power flow in the transmission system. These devices have been applied in different areas of power system security, improvement in the damping ration of power system and economic power dispatch so that power may be made available without violating system constraints to the consumers [8].

2.2. CONFIGURATION OF ELECTRICAL POWER SYSTEMS

Generally, the goal of an electric power system is to transport electrical energy to the load, in a secure, economical, and reliable manner. Before the loads can consume this energy, electrical power must be generated and then transported. There are two different ways to transport electric power: transmission and distribution. The primary task of power system is the generation, transmission and distribution of electrical power. There is a secondary task apart from the three main function; this includes metering and protection. These tasks are carried out by the primary and secondary systems respectively. The primary configuration of an electrical power system is illustrated schematically in figure. Electrical power systems are much more complex than the graphic illustration in the figure below, because they consist of a network of meshed transmission lines that cut across regions and to which a great number of power plants and loads are connected.

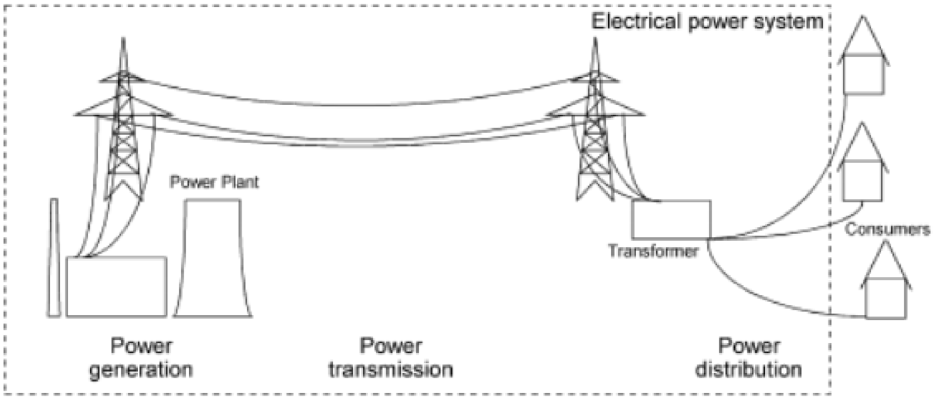

Figure 2.1: Schematic diagram of a primary configuration of electrical power system [9]

2.3. ELECTRIC SYSTEM LOSSES

Electric power has to be moved from generation place to the consumer's place through some wires for consumption. Along the way, some portion of the generated power is lost due to several reasons. Whether this loss is at its lowest possible range is the question of modern energy efficiency issues. To make it easier to investigate losses it is helpful to divide electric system losses into different categories. Common classification is to use two categories; technical losses and non-technical losses [10].

2.3.1. Technical Losses

As power is transferred from one point to another, some of the power is dissipated along the route due to the natural properties of the conductors and equipment the power is carried upon. Technical losses incurred over individual elements, shorten the elements operational life on one hand, and dictates greater dimensioning of the power system on the other hand. There are different ways to classify technical losses [10].

Depending on their origin, technical losses can be divided into resistive, leakage and corona losses. Resistive (copper) losses are the I^2R losses that are inherent in all conductors because of the finite resistance of the conductors. The leakage losses are losses due to the finite resistance of the insulation materials. Corona losses are caused by partial discharges in the air surrounding overhead lines. The air molecules become ionized and conductive as the voltage level is increased. The ionization generates light, audible noise, radio noise, conductor vibration, ozone and cause a dissipation of energy that result in line losses. Heavy rain or wet snow results in a dramatic increase in corona due to droplets clinging to conductor which act as sources of point of discharge [11]. One common classification of technical losses is to use the categories to be (Load losses) and Fixed (No-load losses). This classification method is useful when studying the dependence of losses on power flow [12].

2.3.1.1. Load Losses

Load losses are system load dependent and occur in any system element through which the electric current flow. Variable losses vary with the amount of electricity distributed and are proportional to the square of the current. They are simply copper or I^2R losses of branch or equipment. Between 2/3 and 3/4 of technical losses are variable [12].

2.3.1.2. No-Load Losses

No-load losses are the result of the readiness state, i.e. presence of electric voltage on elements. The share of the constant losses in the total peak load losses is small. It should nevertheless be remembered that constant losses are load-independent and occur throughout the element operation. Fixed losses are present all the time, this means 8760 hours a year; the only problem affecting the calculation accuracy is determination of the scope of the power losses [10].

Sources of no-load losses include the iron cores of transformers due to hysteresis and eddy current losses, resistive losses in the primary winding of transformers, corona discharges and voltage coils of energy meters. Iron loss has been regarded as the major area for improvement in transformer efficiency since the earliest design were built and tremendous strides have been made in reducing iron losses over the last century, mainly due to improvements in the core steel [13]. No-load losses are very identifiable on any electric systems and range from 20% to 40% of total energy [14].

Technical losses can be calculated based on the natural properties of components in the power system, i.e. resistance, inductance, capacitance, voltage, current, and power, which are routinely calculated by utility companies as a way to specify what components will be added to the system in order to reduce losses and improve the voltage levels.

2.3.2. Non- technical Losses

Non-technical losses are not related to the physical characteristics and functions of the electrical system. These losses are not actually losses in terms of consumption loss. What makes them to be grouped under losses is that the consumption is not paid for. They can be evaluated on the basis of the difference between the generated and sold energy on one hand and the calculated technical losses on the other hand. Illegal energy consumption (theft), incorrect meter reading, energy meter failures and shortfalls in billing are known sources of non-technical losses [15].

2.4. FACTOR INFLUENCING SYSTEM LOSSES

The factors that influence system losses are circulating current, phase balancing, power factor and voltage regulation. Flow of circulating current is the failure to maintain a flat voltage a profile across modern highly interconnected networks. Therefore, to minimize losses it is important to maintain voltage limits to its specified values for a transmission network. Heavily loaded lines can be balanced with other phase by using phase balancing systems, the deviation from the average values below 10% [16]. At unity power factor there will be minimum current flow but any reactive component will cause the current to increase as a result real power losses also increases. When the current increases in the transmission system the voltage drop due to line resistance is high and the transmission network voltage reduce at receiving end side when comparing to unity power factor. It is necessary to reduce energy losses in transmission lines by maintaining the system voltage profile [16].

2.5. ANALYSIS OF LOSSES IN POWER SYSTEM

Electrical system losses can be determining by using different techniques. The losses incurred in resistive materials can be reduced by means of reducing the current, the resistance and the reactance of the line and regulating system voltage [17]. Electric power system losses can be computed using several formulae/techniques by including the arrangement of generation station and loads, [17], by means of any of the following methods:

i. Computing transmission losses as I^2R
ii. Differential power loss method
iii. Computing line flows and line losses

2.5.1. Computing Transmission Losses I^2R

Consider a simple three-phase radial transmission line between two points of generating and receiving ends as illustrated in one line diagram of figure2.2 below, including the generated power P_G, line resistance R, line reactance jx and load [17].

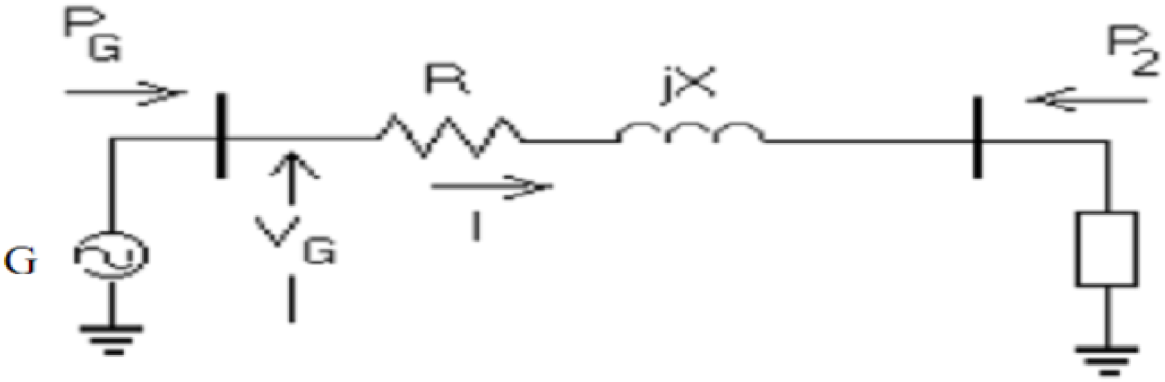

Figure 2.2: One-line diagram with one generation and one load (source: [17])

Transmission line real power loss is calculated as,

$$P_{loss} = 3I^2 R \tag{2.1}$$

Then the current which is flowing through the line can be determined as,

$$|I| = \frac{P_G}{\sqrt{3}V_G \cos\emptyset_G} \tag{2.2}$$

Where, I = the line current

R= the resistance of the transmission line in ohms per phase

P_G = the power generated

V_G = the magnitude of the line to line generated voltage

$\cos\emptyset_G$ = the generator power factor.

Substituting equation 2.2 into equation 2.1

$$P_{Loss} = \frac{P_G{}^2 R}{V_G{}^2 (\cos \emptyset_G)^2} \tag{2.3}$$

Assuming constant generator voltage and power factor, the loss can be define as

$$P_{Loss} = BP_G{}^2 \tag{2.4}$$

Where,

$$B = \frac{R}{V_G{}^2 (\cos \emptyset_G)^2} \tag{2.5}$$

2.5.2. Differential Power Loss Method

Real power loss in the transmission network can be expressed as the difference between the transmitted power and received power [17] [18].

$$P_{Loss} = P_{Sent} - P_{Received} \tag{2.6}$$

As expressed in equation 2.6 the transmission line losses can be easily determined by subtracting the receiving end power from the sending end power. But this method is used only if both sending end power and receiving end power are known only. This method may not be applicable for large interconnected system because the system will be complex.

If we have buses i and k, then the complex power leaving bus-i is given by [18],

$$S_i = P_i + jQ_i = V_i i_i{}^* \tag{2.7}$$

The complex power which is entering bus-k is also given by [13],

$$S_k = P_k + jQ_k = V_k i_k{}^* \tag{2.8}$$

Therefore, from equation 2.7 and 2.8 the real power loss due to I^2R on the transmission line between bus-i and bus-k is determined as [18],

$$P_{Loss,i-k} = P_i - P_k \tag{2.9}$$

Similarly, the reactive power loss due to I^2X on the transmission line between Bus-i and bus-k is determined as [18]

$$Q_{Loss,i-k} = Q_i - Q_k \tag{2.10}$$

2.5.3. Computation of Load Flows

Computation of transmission line losses for the given network as shown in the figure 2.3 that shows a line connecting i_{th} and k_{th} buses [17], [19].

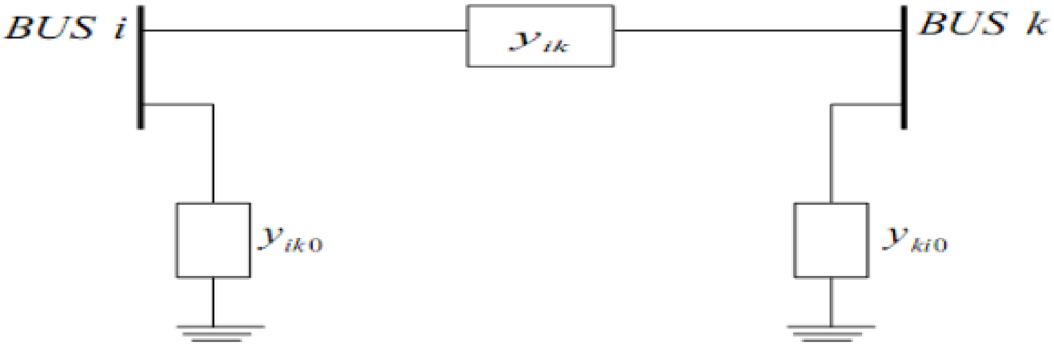

Figure 2.3: Transmission line between two buses (source: [17] [19]).

The current flowing from bus-i towards bus-k is given by,

$$I_{ik} = (V_i - V_k)Y_{ik} + V_i Y_{iko} \tag{2.11}$$

Where V_i and V_k are the bus voltages at the buses i and k respectively.

The power flow in the line i-k at bus-i is given by [17] [19]

$$S_{ik} = P_{ik} + jQ_{ik} = V_i I_{ik}^* \tag{2.12}$$

Substituting equation 2.11 into equation 2.12

$$S_{ik} = V_i(V_i^* - V_k^*)Y_{ik}^* + V_i V_i^* Y_{iko}^* \tag{2.13}$$

Similarly, the power flow in the line i-k at bus k is given by,

$$S_{ki} = P_{ki} + jQ_{ki} = V_k I_{ki}^* \tag{2.14}$$

$$S_{ki} = V_k(V_i^* - V_K^*)Y_{ki}^* + V_k V_k^* Y_{kio}^* \tag{2.15}$$

Where,

S_{ik}= apparent power injection from bus i to the line between bus i and bus k

S_{ki}= apparent power injection from bus k to the line between bus i and bus k

I_{ik}^*= complex conjugated of current I_{ik}

I_{ki}^{*}= complex conjugated of current I_{ki}

Then apparent power flow over all the lines can be computed by using the above equations 2.13 and 2.15. The apparent power losses of (i-k)th line is given by the sum of the power flows determined from above equations which is expressed as,

$$S_{Lik} = S_{ik} + S_{ki} \tag{2.16}$$

Where, S_{Lik}= apparent power loss in a single line between bus-i and bus-k

Therefore, the total apparent power loss in all lines can be calculated as the sum of losses in all lines.

$$S_{Loss} = \sum S_{Lik} \tag{2.17}$$

Where, S_{Loss} = the total apparent power loss of all the transmission lines.

2.6. VOLTAGE DROP IN TRANSMISSION LINE

The important consideration in design and operation of a transmission line are determination of voltage drop, line loss and efficiency of a transmission. These values are greatly influenced by the line constants R, L, C of the transmission line for instance the voltage drop in the line depends upon the value of the above three line constants. Similarly, the resistance of a transmission line conductor is the most important cause of power loss in the line and determines the transmission efficiency [20].

2.6.1. Long Transmission Lines

In power systems, long lines with voltage uncontrolled buses at the receiving ends create major voltage problem during light load or heavy load condition. When the loading level is low the receiving end voltage rises while for heavy loading conditions (much above) the receiving end voltage drop (this evident from the reactive power characteristics of a line). The receiving end voltage case of heavy loading conditions, the series reactive drop may be very high causing voltage depression at the receiving end. In extreme cases, the reactive power demand (i.e series reactive loss) of the line may be enormously high, causing severe voltage control problem. This voltage depression cumulatively increases due to the lower charging capacity and higher reactive current in take in the induction motor loads.

2.6.2. Radial Transmission Line

In a power system, most of the parallel high voltage networks are composed of radial transmission lines. Any loss of a high voltage line in the network causes an enhancement in system reactance. In case a condition appears where the increase in reactive power deliver by lines to the load for given drop in voltage is less than the increase in reactive power required by the load for the same voltage drops, a small increase in load puts the system in an unstable. On load tap changing, transformer improve or maintains the distribution voltage while there is no improvement in transmission voltage. This also affects the voltage stability.

2.6.3. Shortage of Local Reactive Power

The reactive power generation and the reactive power demand at any buses must be match to have stability at any buses. However, there may be a disorganized combination of outage and maintenance schedule that may cause localized reactive power shortage and lead to voltage control problems. In reactive constrained system, the reactive power reserve in the network is low. A disturbance in a load bus may cause a shortage of reactive power supply and/or an increase in reactive power demand. The result is a voltage drop in the transmission line. This gives rise to the problem of voltage control and also reduce the charging capacity of reactive power support; any attempt to import reactive power through the long high transmission lines is not successful and does not serve the purpose.

2.6.4. Voltage Regulation

When a transmission line is carrying current, there is a voltage drop in the line due to resistance and inductance of the line. The result is that receiving end voltage (V_R) of the line is generally less than the sending end voltage (V_S). This voltage drops ($V_S - V_R$) in the line is expressed as a percentage of receiving end voltage V_R and is called voltage regulation mathematically.

$$\%\text{age of voltage regulation} = \frac{V_S - V_R}{V_R} * 100 \tag{2.18}$$

Voltage regulation can be defined as the proportional change in voltage magnitude at the load bus due to change in load current (say from no load to full load). The voltage drop is caused due to feeder impedance carrying the load current as illustrated in Fig. 2.4(a). If the supply voltage is represented by Thevenin’s equivalent, then the voltage regulation (VR) is given by,

$$\mathrm{VR} = \frac{\overline{\mathrm{E}}-\overline{\mathrm{V}}}{\mathrm{V}} = \frac{\overline{\mathrm{E}}-\mathrm{V}}{\mathrm{V}} \tag{2.19}$$

$\overline{\mathrm{V}}$, being a reference phasor. In absence of compensator, the source and load currents are same and the voltage drop due to the feeder is given by,

$$\Delta\overline{\mathrm{V}} = \overline{\mathrm{E}} - \overline{\mathrm{V}} = \mathrm{Zs}\overline{\mathrm{I}_1} \tag{2.20}$$

The feeder impedance, Z_S = R_S+ jX_S. The relationship between the load powers and its voltage and current is expressed below

$$\overline{\mathrm{S}_1} = \overline{\mathrm{V}}(\mathrm{I}_1)^* = \mathrm{P}_1 + \mathrm{jQ}_1 \tag{2.21}$$

Since $\overline{\mathrm{V}}$ = V, the load current is expressed as following

$$\mathrm{I}_1 = \frac{\mathrm{P}_1 - \mathrm{jQ}_1}{\mathrm{V}} \tag{2.22}$$

Substituting, I1 from the above equation in 2.20)

$$\Delta\overline{\mathrm{V}} = \overline{\mathrm{E}} - \overline{\mathrm{V}} = (R_S + \mathrm{j}X_S)(\frac{P_1 - \mathrm{j}Q_1}{\mathrm{V}}) \tag{2.23}$$

$$= \frac{\mathrm{R_S P_1 + X_S Q_1}}{\mathrm{V}} + \mathrm{j}\,\frac{\mathrm{X_S P_1 - R_S Q_1}}{\mathrm{V}} \tag{2.24}$$

$$= \Delta\mathrm{V_R} + \mathrm{j}\Delta\mathrm{V_X} \tag{2.25}$$

Thus, the voltage drop across the feeder has two components, one in phase $\Delta\mathrm{V_R}$ and another is in phase quadrature $\Delta\mathrm{V_X}$ this is illustrated in Fig. 2.4a.

From the above, it is evident that load bus voltage $\overline{\mathrm{V}}$ is dependent on the value of the feeder impedance, magnitude and phase angle of the load current. In other words, voltage change (ΔVx) depends upon the real and reactive power flow of the load and the value of the feeder impedance.

When the compensator is added parallel with the load, the question is whether it is possible to make $\overline{\mathrm{E}} = \overline{\mathrm{V}}$ in order to achieve zero voltage regulation irrespective of change in the load, the answer is yes, if the compensator consisting of purely reactive component has enough capacity to supply the required amount of the reactive power. This situation is shown using phasor diagram in Fig. 2.4b.

The net reactive load bus is now $\mathrm{Qs} = \mathrm{Q\gamma} + \mathrm{Ql}$ the compensator reactive power (Qγ) has to be adjusted in such a way as to rotate the phasor ΔV until $\overline{\mathrm{E}} = \overline{\mathrm{V}}$ [21].

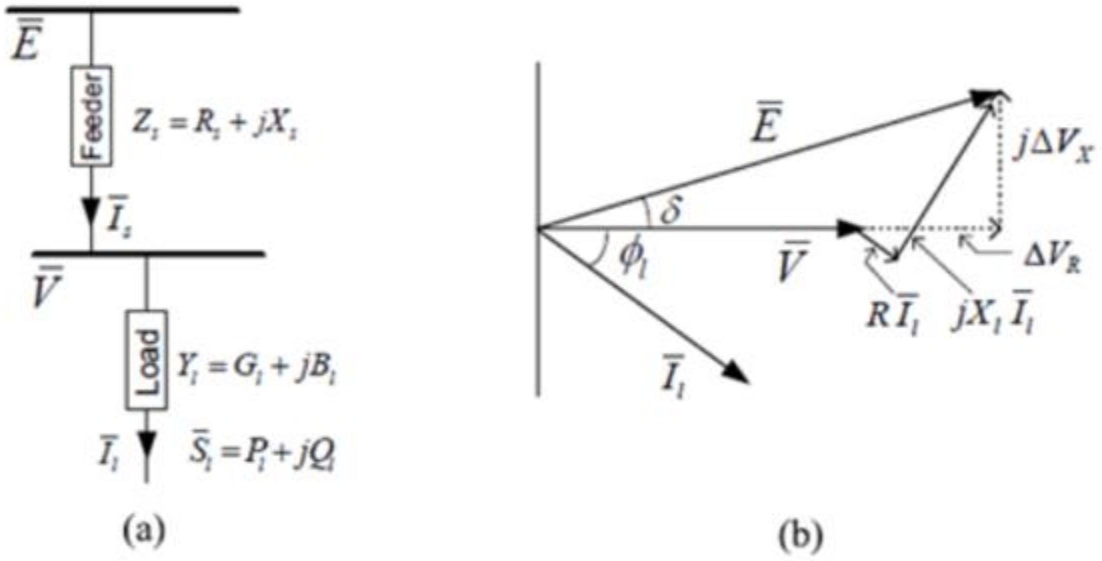

Figure 2.4a: Single phase system with feeder impedance, Figure 2.4b Phasor diagram [20]

2.7. APPLICATION OF POWER ELECTRONICS IN POWER SYSTEM

The use of power electronics devices has grown significantly in the last decade. It uses has significantly increased both in the transmission and distribution system. Power electronics devices used in the transmission system are High Voltage Direct current (HVDC) links and Flexible Alternating Current Transmission Systems (FACTS). The HVDC links serve as an alternative means of transmitting electrical power, while the FACTS devices an applied to compensate and improve AC systems. The device used in the distribution system are employed to improve the system power quality and they are usually referred to as custom power devices, while the devices on the transmission system are optimized to reduce losses by balancing the reactive power [22].

2.7.1. Overview of Major FACTS Devices

Flexible AC Transmission Systems, called FACTS, got in the recent years a well-known term for higher controllability in power systems by means of power electronic devices. Several FACTS-devices have been introduced for various applications worldwide. A number of new types of devices are in the stage of being introduced in practice. Even more concepts of configurations of FACTS-devices are discussed in research and literature.

In most of the applications the controllability is used to avoid cost intensive or landscape requiring extensions of power systems, for instance like upgrades or additions of substations and power lines. FACTS-devices provide a better adaptation to varying operational conditions and improve the usage of existing installations. The basic applications of FACTS-devices are:

- ✓ Power flow control,
- ✓ Increase of transmission capability,
- ✓ Voltage control,
- ✓ Reactive power compensation,
- ✓ Stability improvement,
- ✓ Power quality improvement,
- ✓ Power conditioning,
- ✓ Flicker mitigation,
- ✓ Interconnection of renewable and distributed generation and storages.

The influence of FACTS-devices is achieved through switched or controlled shunt compensation, series compensation or phase shift control. The devices work electrically as fast current, voltage or impedance controllers. The power electronic allows very short reaction times down to far below one second.

In the following a structured overview on FACTS-devices is given. These devices are mapped to their different fields of applications. The left column in Figure 2.5 contains the conventional devices build out of fixed or mechanically switchable components like resistance, inductance or capacitance together with transformers. The FACTS-devices contain these elements as well but use additional power electronic valves or converters to switch the elements in smaller steps or with switching patterns within a cycle of the alternating current. The left column of FACTS-devices uses Thyristor valves or converters. These valves or converters are well known since several years. They have low losses because of their low switching frequency of once a cycle in the converters or the usage of the Thyristors to simply bridge impedances in the valves.

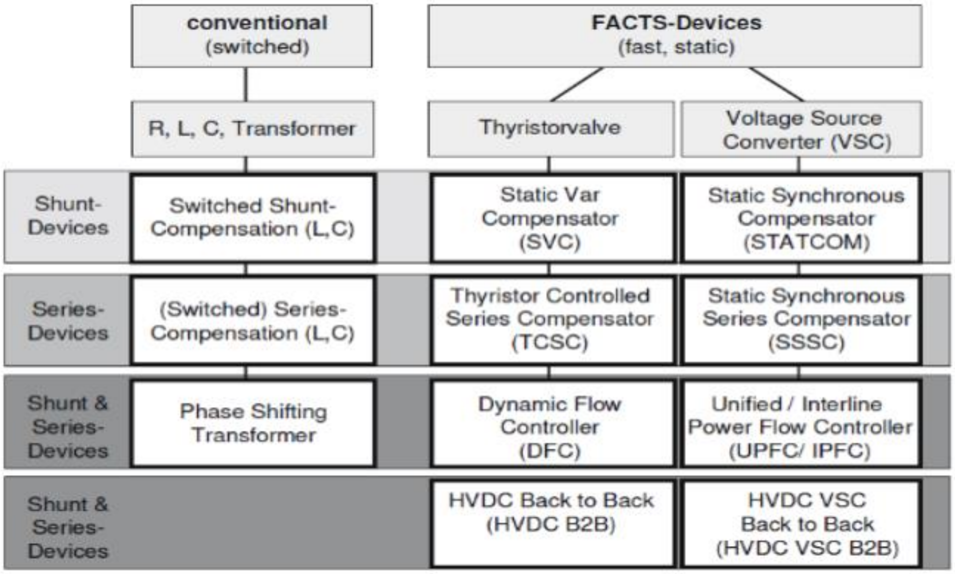

Figure 2.5: Overviews of major FACTS Device [23]

The right column of FACTS-devices contains more advanced technology of voltage source converters based today mainly on Insulated Gate Bipolar Transistors (IGBT) or Insulated Gate Commutated Thyristors (IGCT). Voltage Source Converters provide a free controllable voltage in magnitude and phase due to a pulse width modulation of the IGBTs or IGCTs. High modulation frequencies allow to get low harmonics in the output signal and even to compensate disturbances coming from the network. The disadvantage is that with an increasing switching frequency, the losses are increasing as well. Therefore, special designs of the converters are required to compensate this.

In each column the elements can be structured according to their connection to the power system. The shunt devices are primarily for reactive power compensation and therefore voltage control. The SVC provides in comparison to the mechanically switched compensation a smoother and more precise control. It improves the stability of the network and it can be adapted instantaneously to new situations. The STATCOM goes one step further and is capable of improving the power quality against even dips and flickers.

The series devices are compensating reactive power. With their influence on the effective impedance on the line they have an influence on stability and power flow. These devices are installed on platforms in series to the line. Most manufacturers count Series Compensation, which is usually used in a fixed configuration, as a FACTS-device. The reason is that most parts and the system setup require the same knowledge as for the other FACTS-devices. In some cases, the Series Compensator is protected with a Thyristor-bridge. The application of the TCSC is primarily for damping of inter-area oscillations and therefore stability improvement, but it has as well a certain influence on the power flow [23].

2.7.2. Types of FACTS Devices

There are two types of reactive power compensating device [24][25].The first type engage conventional thyristor switched reactors and capacitors, while the other type engages a Gate Turn-Off (GTO) thyristor , Integrate Gate Bipolar Transistor (IGBT), Integrated Gate Commutated Thyristor (IGCT), Injection Enhanced Gate Transistor (IEGT) converters as voltage source converters (VSC) [26].The ideas of FACTS and its controllers was defined in [27] as an alternating current transmission system made up of power electronic-based static controllers to improve the control of system parameters and power transfer ability of an electric power transmission system. Electronics-based FACTS devices have replaced many mechanically controlled reactive power compensators; more importantly they are playing a major role in the operation and control of modern systems. FACTS devices can be grouped into four categories;

i. Series devices
ii. Shunt devices
iii. Combined Series-Series devices
iv. Combined Series-Shunt devices

2.7.2.1. Series Devices

This device could be a variable impedance such as thyristor switched, capacitor, reactor or a power electronics based variable source that inject voltage in series with line as shown in figure 2.6. The injected variable series voltage in the line is represented by the variable impedance multiplied by the current flowing through it. In this case, the device requires an external energy source. This device either supplies or absorbs variable reactive power when the voltage is more or less than 90^0 out of phase with the line current.

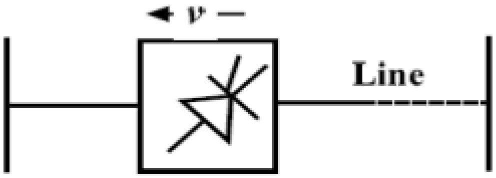

Figure 2.6: Basic Series FACTS devices [24]

The series FACTS device are used to enhance power system stability and loadability; it operates as a variable capacitive or inductive impedance that can be adjusted in series with the transmission line to damp oscillation in the system as shown in figure 2.7. This is accomplished by injecting a proper voltage phasor in series with the transmission line and is seen as the voltage across an impedance in series with the line. In the event that the line voltage is in phase quadrature with the line current, the controller sink or generate reactive power, otherwise the device sink or produce active and reactive power. The power flow is controlled according to equation (2.26) and (2.27) below.

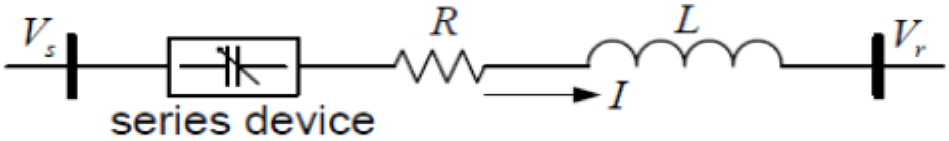

Figure 2.7: Series FACTS device Operation Principle [27]

$$P_r = \frac{|V_r|\,|V_S|}{X}\sin\theta \tag{2.26}$$

$$Q_r = \frac{|V_r|\,|V_S|}{X}\cos\theta - \frac{|V_r|}{X} \tag{2.27}$$

When the device acts in capacitive mode, it balances a fraction of the transmission line reactance. In the case of an inductive mode, the reactance will be increased to limit the power flow.

2.7.2.1.1. Thyristor Controlled Series Capacitor (TCSC)

Thyristor Controlled Series Capacitors (TCSC) addresses specific dynamical problems in transmission systems. Firstly, it increases damping when large electrical systems are interconnected. Secondly it can overcome the problem of Sub Synchronous Resonance (SSR), a phenomenon that involves an interaction between large thermal generating units and series compensated transmission systems. The TCSC's high speed switching capability provides a mechanism for controlling line power flow, which permits increased loading of existing transmission lines, and allows for rapid readjustment of line power flow in response to various contingencies. The TCSC also can regulate steady-state power flow within its rating limits.

From a principal technology point of view, the TCSC resembles the conventional series capacitor. All the power equipment is located on an isolated steel platform, including the Thyristor valve that is used to control the behavior of the main capacitor bank. Likewise, the control and protection is located on ground potential together with other auxiliary systems. Figure 2.8 shows the principle setup of a TCSC and its operational diagram. The firing angle and the thermal limits of the Thyristors determine the boundaries of the operational diagram.

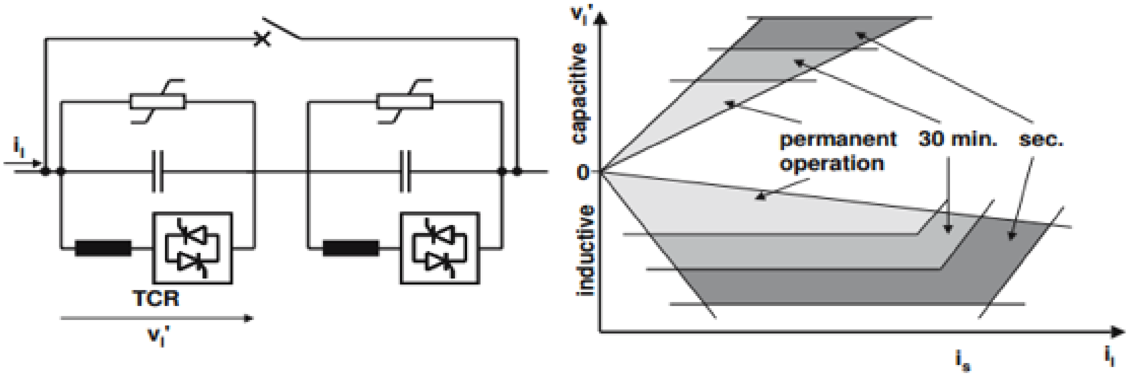

Figure 2.8: Principle setup and operational diagram of thyristor controlled series compensation [23]

The main principles of the TCSC concept are two; firstly, to provide electromechanical damping between large electrical systems by changing the reactance of a specific interconnecting power line, i.e. the TCSC will provide a variable capacitive reactance. Secondly, the TCSC shall change its apparent impedance (as seen by the line current) for sub-synchronous frequencies, such that a prospective sub synchronous resonance is avoided. Both objectives are achieved with the TCSC, using control algorithms that work concurrently. The controls will function on the Thyristor circuit in parallel to the main capacitor bank such that controlled charges are added to the main capacitor, making it a variable capacitor at fundamental frequency but a “virtual inductor” at sub-synchronous frequencies.

2.7.2.1.2. Thyristor Switched Series controller (TSSC)

A Thyristor Switched Series Capacitor (TSSC) is “a capacitive reactance compensator which consists of a series capacitor bank shunted by a thyristor switched reactor to provide a step-wise control of series capacitive reactance” [27]. The TSSC utilize the thyristor switch the capacitor bank and it has a faster response than compensator that are mechanically switched. The TSSC as shown in the figure below can only inject capacitance into the line; it cannot limit the line current.

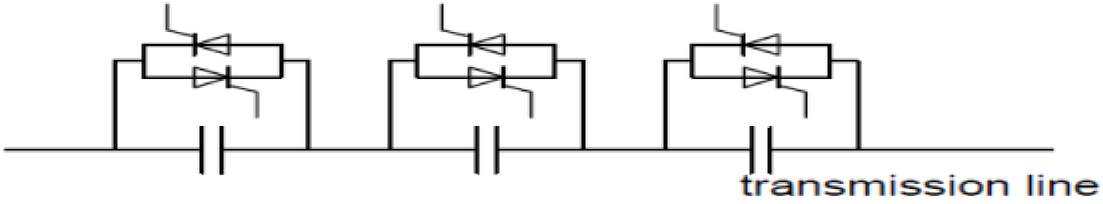

Figure 2.9: TSSC configuration [28]

2.7.2.1.3. Static Synchronous Series Compensator (SSSC)

The Static Synchronous Series Compensator (SSSC) is connected in series with transmission line. It injects a controlled voltage magnitude at an angle into the line. The voltage injected is dependent on the mode selected for the SSSC to control the transmitted electric power. “The SSSC operates without an external energy source as a series compensator whose output voltage is in quadrature with, and controlled independently of the line current. The purpose of this is to increase the overall reactive voltage drop across the line, thereby controlling the power flow” [27].

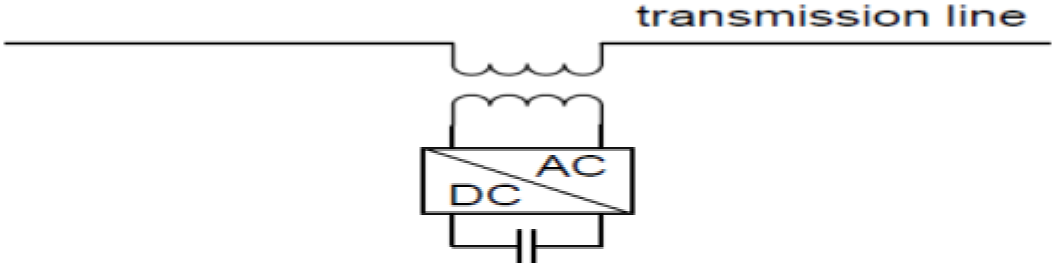

Figure 2.10: A SSSC line configuration [28]

2.7.2.2. Shunt Devices

The shunt devices can have variable impedance, variable current or voltage source, capacitor, reactor or a power electronics based variable source that is connected in shunt to the system so as to inject variable current in to the line in figure 2.11. The shunt device either supplies or absorbs variable reactive power when the injected current is more or less than 90^0 out of phase with the line voltage.

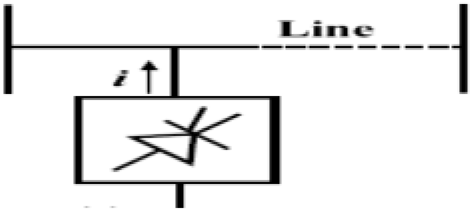

Figure 2.11: Basic Shunt FACTS device [24]

The operational principle of a shunt device is to supply reactive power that is required at the load, by varying its impedance, to inject reactive current I_{sh} thereby it indirectly control the line current$I$. By Ohm's law, the difference between the sending end voltage and the receiving end voltage (V_s-V_r) being the voltage drop across the transmission line correlate to the line current I. We can assume the voltage at the sending end (V_s) to be constant value, the magnitude of voltage at the receiving end $|V_r|$ can be controlled by a shunt device [28].

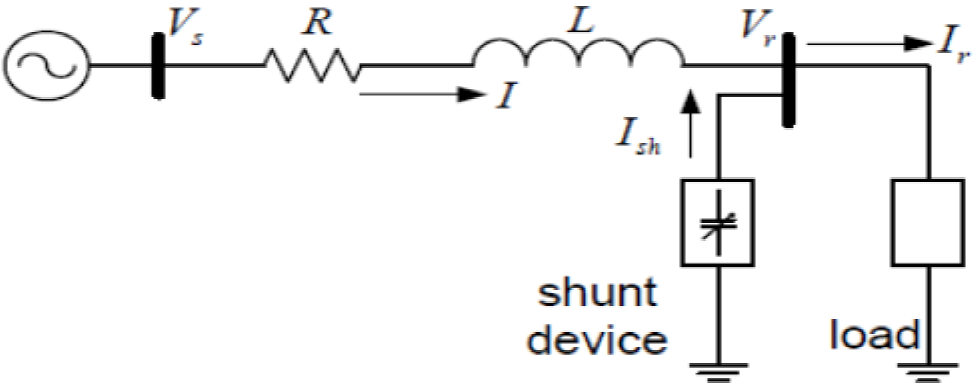

Figure 2.12: Shunt device Operating principle [28]

The link between the injected current $I_{sh}$by the shunt device and the voltage at receiving end V_r can be found in the equation below:

$$V_r = V_s - IZ \qquad (2.28)$$

$$= V_s - (I_r - I_{sh})\,Z \qquad (2.29)$$

Where Z=R + jωL

As seen in equation (2.28), the shunt device can control the voltage magnitude by varying it impedance. The line current I in heavy load condition leads to a voltage drop and is reduce by the shunt current I_{sh} partial compensation for the large load current I_r. The three types of shunt controllers are switched shunt inductor and capacitor devices, Static Var Compensator (SVC) and Static Synchronous Compensator (STATCOM).

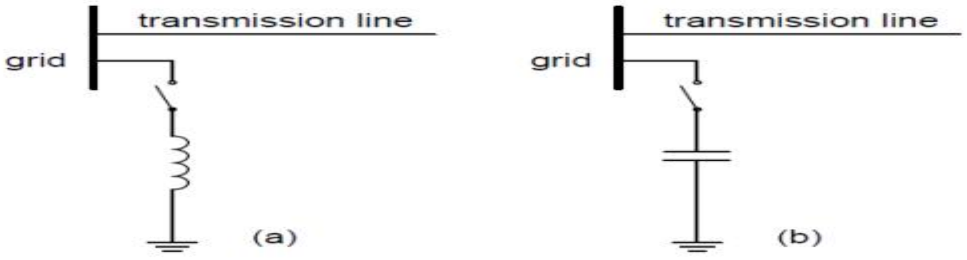

Figure 2.13: Configuration of Switched Shunt inductor and capacitor:
(a) Inductor; (b) Capacitor [28]

2.7.2.2.1. Static Var Compensator (SVC)

Electrical loads both generate and absorb reactive power. Since the transmitted load varies considerably from one hour to another, the reactive power balance in a grid varies as well. The result can be unacceptable voltage amplitude variations or even a voltage depression, at the extreme a voltage collapse. A rapidly operating Static Var compensator (SVC) can continuously provide the reactive power required to control dynamic voltage oscillations under various system conditions and thereby improve the power system transmission and distribution stability. Installing SVC at one or more suitable points in the network can increase transfer capability and reduce losses while maintaining a smooth voltage profile under different network conditions. In addition, an SVC can mitigate active power oscillations through voltage amplitude modulation. SVC installations consist of a number of building blocks. The most important is the Thyristor valve, i.e. Stack assemblies of series connected anti-parallel Thyristors to provide controllability. Air core reactors and high voltage AC capacitors are the reactive power elements used together with the Thyristor valves. The step-up connection of this equipment to the transmission voltage is achieved through a power transformer. The Thyristor valves together with auxiliary systems are located indoors in an SVC building, while the air core reactors and capacitors, together with the power transformer are located outdoors.

In principle the SVC consists of Thyristor Switched Capacitors (TSC) and Thyristor Switched or Controlled Reactors (TSR / TCR).

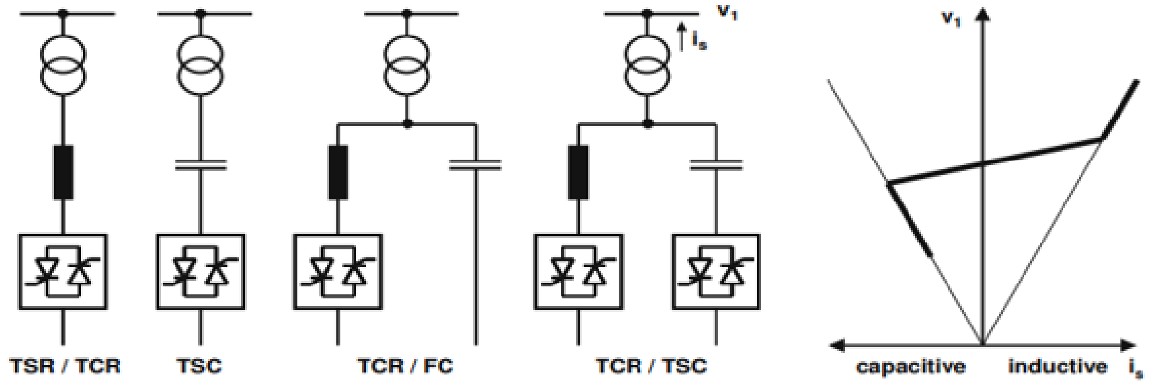

Figure 2.14: SVC building blocks and voltage / current characteristic [23]

2.7.2.2.2. Static Synchronous Compensator (STATCOM)

The Static Synchronous Compensator (STATCOM) is Synchronous Voltage Generator (SVG) that is power electronics based. It is a shunt connected FACTS device that provides capacitive or inductive output current for reactive power compensation to solve variety of power system voltage stability and fluctuation conditions independent of the AC system voltage [18]. STATCOM is a shunt VSC that is connected to the gird as shown in figure 2.15. The device controls the line reactive power via the output reactive current without interfering with the AC voltage. It control line voltage, the power delivery capacity of the transmission lines and improve the stability angle. The device consists of DC Voltage Source Converter, Self-Commutated converters using a Gate Commutated Turn–off (GCT) thyristor and step-up transformer [25].From the DC capacitor; it generates a three-phase voltage in synchronous with the grid voltage via a coupling transformer, it improves the static and dynamic voltage stability of bus on power network, and keeps the voltage of the electric system in receivable operating mode [29].Figure 2.15 show the configuration and terminal characteristic of STATCOM.

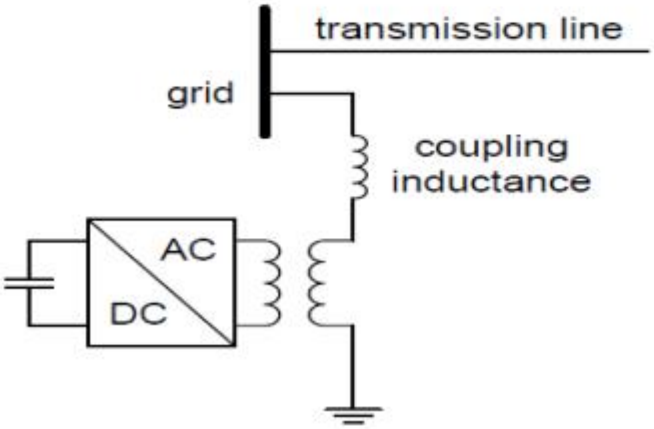

Figure 2.15: The configuration of STATCOM [28]

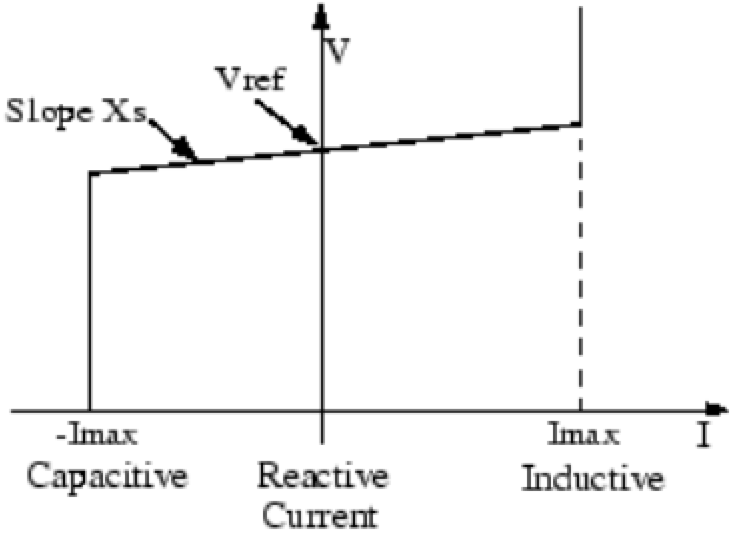

Figure 2.16: Terminal characteristic of STATCOM [30]

2.7.2.3. Combined Series-Series Devices

Combined series-series FACTS device is a combination of two different series FACTS devices with coordinated manner. A combined series-series controller has two circuits. One consists of series controllers operating in a coordinated manner in a multiline transmission network and the other provides independent reactive power control for each line of a multiline transmission network and, at the same time facilitates real power transfer through the power link. The family of such devices is Interline Power Flow Controller (IPFC) that balances real and reactive power flows on the transmission lines [31], [32].

2.7.2.3.1. Interline Power Flow Controller (IPFC)

The Interline Power Flow Controller (IPFC) consists of two series converters in different line that are inter-connected by a common DC link. It is a device that provides a comprehensive power flow control for a multi-line transmission system and consists of multiple number of DC to AC converters, each providing series compensation for a different transmission line. The converters are linked together to their DC terminals and connected to the AC systems through their series coupling transformers. With this arrangement, it provides series reactive compensation in addition any converter can be controlled to supply active power to the common DC link from its own transmission line. Unlike other FACTS controls and compensate power flow in a multiple line transmission systems as shown in figure 2.17.

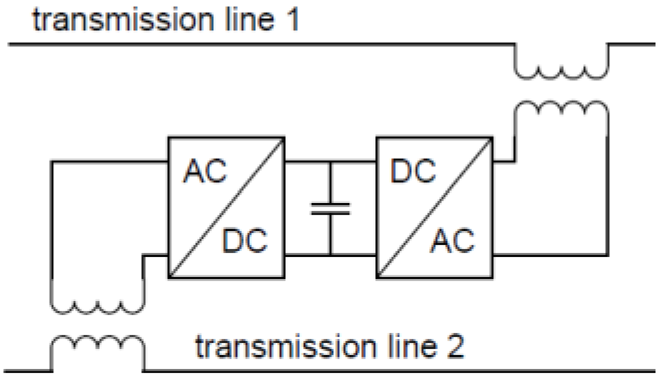

Figure 2.17: Interline Power Flow Controller Configuration [28]

Both converters have the capacity to provide series compensation on their line as a SSSC. The converters can provide active compensation just as the can exchange active power through a common DC link. This allows the controller to provide both active and reactive compensation for the transmission line lines and thereby optimize the operation of a multi-line transmission systems [33].

2.7.2.4. Combined Series-Shunt Devices

These are devices that combine separate series and shunt controllers in a coordinated manner. The combined series and shunt controllers inject voltage in series in the line with series part, and current into the systems with the shunt part. The series-shunt device is shown in figure 2.18.

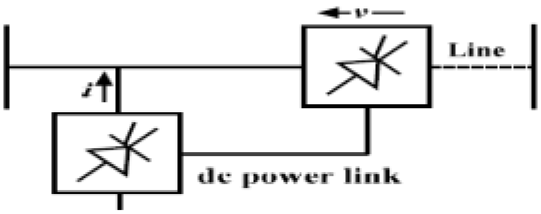

Figure 2.18: Basic Series-Shunt FACTS Device [24]

2.7.2.4.1. Unified Power Flow Controller (UPFC)

The Unified Power Flow Controller is a combination of Static Synchronous Compensator (STATCOM) and Static Synchronous Series Compensator (SSSC) which are linked by a common DC-link; this allow bi-direction flow of active power between the series and shunt output terminals of SSSC and STATCOM respectively, and are controlled to provide real and reactive series line compensation concurrently without an external electric energy source [34]. The device with two converter of shunt and series transformer operates from a DC link provide by DC Storage capacitor as represent in figure 2.19.

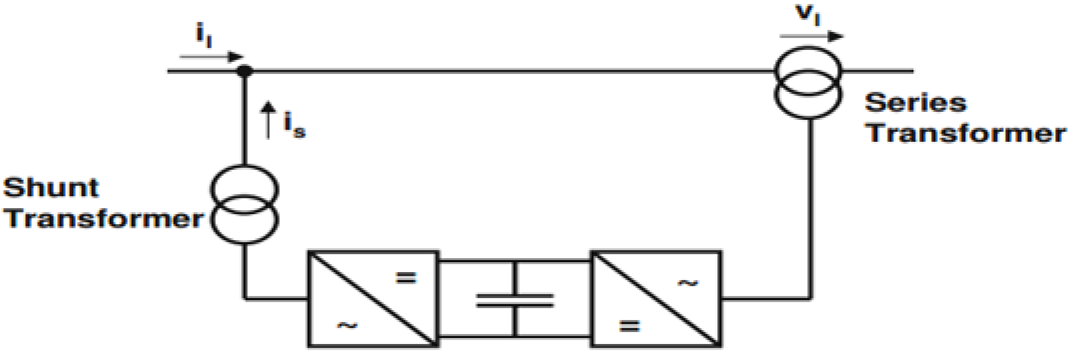

Figure 2.19: Principle configuration of an UPFC [17]

The shunt converter provides the real power demand of the second converter at the common DC link from the AC power system. It can also generate or absorb reactive power at its AC terminal, which not dependent on the active power that it transfers to the DC terminal. With proper control, it can execute indirect voltage stability at the input terminal of UPFC by providing reactive power compensate for the transmission line. The Series Converter generates a voltage source at the basic frequency with variable amplitude and phase angle, which is injected into the AC transmission line by the series connected booster transformer. Therefore, the converter voltage output added in series with the line can be used for direct series compensation, voltage control and phase shift.

2.8. LITERATURE REVIEW

Literature reviews related to this thesis study are summarized below.

M.Z.EL-Sadek, M.Abo-Zahhad, A.Ahamed, H.E. Zidan (2007) [5], this paper devoted to the incorporating of the steady-state model of the unified power flow controller in the power flow program using UPFC injection model. The adopted UPFC injection model is based on the representation of UPFC in steady state condition by two Voltage source in series with certain reactance. Using this UPFC power flow model, total system losses, slack bus generated active and reactive power and the injected reactive power from voltage controlled buses are illustrated

A.Anbarasan, M.Y. Sanavullah and S. Ramesh. (2014) [2], this paper presents a method to reduce the transmission line losses in the power system network using FACTS devices. They have tried to propose identification of suitable location of these FACTS devices. The effectiveness of the proposed work is analyzed using IEEE 14-bus test system. The proposed method identifies suitable devices, on suitable lines at suitable location. In this paper the existing transmission line facility are utilized effectively and economically to transfer the power to the consumer but the continuation power flow method is used to identify weakest bus in the system. Generally it is possible to say in one way or the other the above transmission line loss minimization and voltage regulation includes ; 1) all the parameters are not controlled 2) The voltage deviation is not as required level.3) Uses the evolutionary optimization techniques. The proposed MATLAB/Simulink model for transmission line loss minimization and voltage regulation using UPFC avoids the above discussed issues

Thomas John (2011) [3] has done a research on Line loss minimization and voltage regulation using UPFC. This paper presents a method for achieving line loss minimization and voltage regulation in the given power system. In order to achieve these two objectives simultaneously he has used UPFC.

D. BalaGangi Reddy and M. Suryakalavathi (2011) [4], concerns on modeling, analysis and optimal location of UPFC for real power loss minimization. In this paper, an improved UPFC steady-state mathematical model for the implementation of the device in the conventional Newton Raphson (NR) power flow algorithm has been developed from a two-voltage source equivalent of UPFC. An advantage of this model is that the model is capable of taking the losses of UPFC into account. GA is used for optimal placement of UPFC to minimize the total system losses. The proposed approach is tested on IEEE-14 bus test system. For different loadings this researcher tried to show that using optimal placement and optimal settings of UPFC, system line losses are reduced significantly.

M. Kowsalya et.al (2009) [6] has used particle swarm optimization technique in order to loss optimization for voltage stability enhancement incorporating UPFC. In this paper voltage stability enhancement with the optimal placement of UPFC using stability index such as nodal analysis, Voltage Phasor method is made and the loss minimization including UPFC is formulated as an optimization problem. This paper proposed particle swarm optimization for the exact real power loss minimization including UPFC and the implementation of loss minimization for the optimal location of UPFC was tested with IEEE-14 and IEEE-57 bus system. But the drawback of this system is it uses the evolutionary optimization techniques and the algorithm is only used to determine the optimal location of the UPFC.

Mark Ndubuku Nwohu (2010) [7] has discussed on the optimal location of unified power flow controller in Nigerian Grid system. On his research he tried to present an approach to find and choose the optimal location of UPFC based on the sensitivity of the total system active power loss with respect to the control variables of the UPFC. He has developed the control system of the UPFC's injection model to avoid a voltage collapse which is explored by analyzing multi-machine test system. The software MATLAB/Simulink was used in this study to evaluate voltage stability of the system and to determine optimal placement of UPFC in order to provide better damping during transient and dynamic control. Even though the idea is transmission line loss minimization but it chooses the optimal location based on sensitivity of the total active power loss only and not for steady state analysis.

CHAPTER THREE

3. METHODOLOGY AND DATA ANALYSIS

3.1. DATA COLLECTION

For this thesis work primary data was collected from EEP. The collected data includes line resistance, line reactance, line length, bus description, and bus nominal voltage, and transformer data, actual voltage level of the line, peak load, average load and minimum load of the transmission network of case study.

3.2. LOAD FLOW ANALYSIS

Load flow analysis forms the core of power system analysis. Load flow analysis used to determine the voltage, current, real power, reactive power, losses and power factor in a power system. Load flow analysis should be used to confirm adequate voltage profile during different operating conditions, such as heavily loaded and lightly loaded system conditions.

Planning the operation of power system under existing conditions, its improvement and also future expansion requires the load flow studies. However, the load flow studies are very important for planning, control and operation of existing systems as well as planning its future expansion as satisfactory operation of the system depends upon knowing the effect of interconnection, new load, new generation stations or new line transmission, change of network configuration before they are installed. Load flow studies also help to select power electronics based devices and locate them at optimal location in order to minimize the losses and improve voltage profile.

Generally, load flow analysis solves for any unknown bus voltage and unspecified generation and finally form complex power flow in the network components for a given power system network, with known loads and some set of specifications or restrictions on power generation and voltages. A load flow analysis can be utilized to determine total transmission loss in a system as well as losses in individual components. It provides real and reactive powers at different buses. Total transmission loss can be calculated from the algebraic sum of powers injected at all buses.

In this study load flow analysis was used to determine the bus voltages profiles, active power flows, reactive power flows and transmission line losses on all lines and transformers of the eastern region of EEP’s high voltage transmission network.

3.3. ONE-LINE (SINGLE LINE) DIAGRAM

The first step of any power system problem is the development of a single-line diagram of the interconnected power system, from which computer solutions can be obtained. The one line diagram of the case study network, eastern region of Ethiopian Transmission line, was thus drawn on the DIgSILENT Power factory for this study. All the organized data were then fed to the one-line diagram.

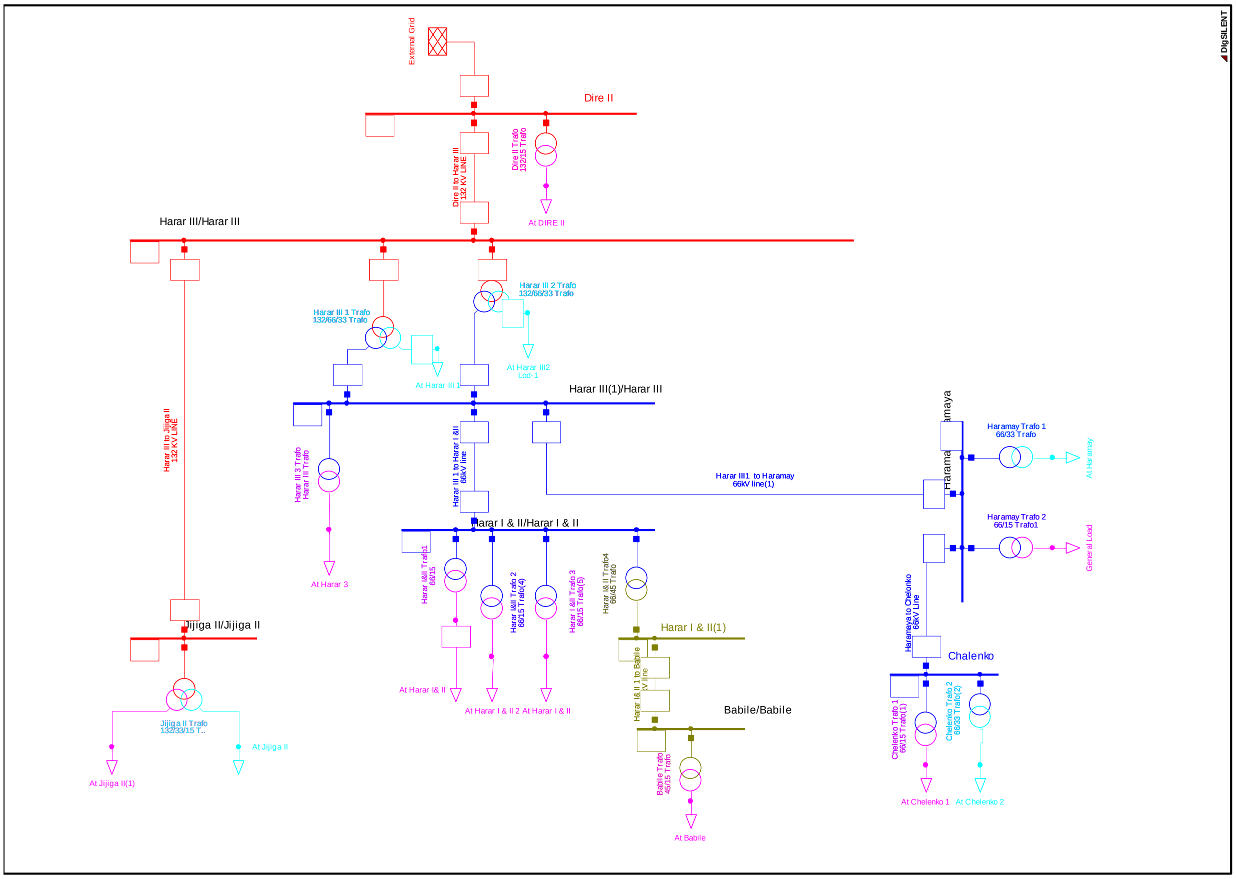

Figure 3.1: One-line diagram of EEP eastern region transmission network

3.4. EEP'S HIGH VOLTAGE SYSTEMS

All necessary data of EEP eastern region of Ethiopia high voltage transmission line network were collected from the concerned offices of EEP and analyzed in this section to make it ready for the software.

3.4.1. Transmission Line Data

The study area existing EEP transmission network consisting around 6 transmission lines. From these the 132 kV network constitute 2 lines, the 66 kV constitutes 3 lines and the 45 kV network constitutes 1 line.

The collected EEP data consists of transmission line length (km), resistance of a line (ohm/km), reactance of a line (ohm/km) and shunt capacitance (nF/km).The flexibility of DIgSILENT Power Factory software.

Table 3.1: Transmission line Data

From Bus	To Bus	L(km)	R(ohm/km)	X(ohm/km)	C(nf/Km)	Y(mohm/km)
Dire II- 132kV	Harar III -132kV	43.8	0.1835	0.4242	8.6	0.0000027
Harar III- 132kV	Jijiga II- 132kV	95.1	0.1835	0.4242	8.6	0.0000027
Harar III -66kV	Harar I&II -66kV	2.7	0.1906	0.4208	8.6	0.0000027
Harar I&II -45kV	Babile -45kV	26	0.1835	0.4012	8.9	0.0000028
Haramaya -66kK	Chelanko -66kV	49.8	0.1906	0.4231	8.6	0.0000027
Harar III -66kV	Haramaya- 66kV	16	0.1906	0.4231	8.6	0.0000027

3.4.2. Transformer Data

EEP’s transmission line considered in this study consists 11 two winding and 3 three winding transformers. Three phase winding transformers are widely used in power systems. When the VA rating of the third winding is appreciably lower than the primary or secondary winding ratings, the third is called a tertiary winding. The most common reason for the additional third set of windings to a three phase transformer is to provide path for the third harmonics. Other purpose of tertiary windings are to provide connection for reactive power compensation such as shunt reactors, shunt capacitor, static variable compensators or synchronous compensators or synchronous condensers

Table 3.2: Two winding transformer data

S.N	From Bus	To Bus	MVA	Pri(kV)	Sec(kV)	X (%)	R (%)
1	Babile -45kV	Babile -15kV	3.0	45	15	6.00	0.90
2	Haramaya- 66kV	Haramay-15kV	6.3	66	15	7.050	0.59
3	Chelenko -66kV	Chelenko15kV	6.3	66	15	7.160	0.59
4	Dire II -132kV	Dire II -15kV	40.0	132	15	8.990	0.33
5	Harar I & II -66kV	Harar I & II-15kV	6.0	66	15	7.170	0.50
6	Harar I& II -66kV	Harar I&II- 15kV	6.3	66	15	7.220	0.42
7	Harar I& II -66kV	Harar I& II- 15kV	6.3	66	15	7.990	0.43
8	Harar III -66kV	Harar III- 15kV	9.6	66	15	7.190	0.42
9	Harar I& II -66kV	Harar I & II 45-kV	6.0	66	45	7.170	0.50
10	Chelenko- 66kV	Chelenko- 33kV	9.6	66	33	7.160	0.59
11	Haramaya -66kV	Haramaya -33kV	9.6	66	15	6.000	0.90

Table 3.3: Three winding transformer data

Node1	Node2	Node3	Prim. kV	Sec. kV	Tert. kV	Prim. MVA	Sec. MVA	Tert. MVA	% Rps	%Rpt	%Rst	%Xps	%Xpt	%Xst
Harar III	Harar III	Harar III	132	66	33	100	50	50	0.38	0.24	0.17	8.0	6.9	2.4
Harar III	Harar III	Harar III	132	66	33	100	50	50	0.38	0.24	0.17	8.0	6.9	2.4
Jijiga II	Jijiga II	Jijiga II	132	33	15	25	25	12	0.38	0.24	0.19	8.4	6.82	2.16

3.4.3. Load Data

The peak load data of each substation buses is summarized as shown in the following table.

Table 3.4: For Substation peak load

Substation name	Transformer		Peak load(MW)		Peak load(MVAr)		Peak load (MVA)	
	MVA	Voltage ratio	15kV	33kV	15kV	33kV	15kV	33kV
Dire II	40	132/15	9.70		4.22		10.58	
Harar I and II	6.	66/15	1.77		1.32		2.21	
	6.3	66/15	4.43		2.98		5.43	
	6.3	66/15	3.43		2.31		4.13	
Harar III	100/50/50	132/66/33		2.24		1.68		2.80
	9.6/12	66/15	10.00		7.50		12.50	
Haramaya	6.3	66/15	4.44		2.75		5.22	
	9.6/12	66/33	3.46		2.14		4.07	
Jijiga II	25/25/12	132/33/15	7.40	2.20	4.97	1.65	8.92	2.75
Babile	3	45/15	1.77		1.68		2.21	
Chelenko	6.3	66/15	3.82		2.10		4.49	
	9.6/12	66/33		4.40		2.56		5.18

The minimum load data of each substation buses is summarized as shown in the following table**.**

Table 3.5: For Substation minimum load

Substation name	Transformer		Minimum load(MW)		Minimum load(MVAr)		Minimum load (MVA)	
	MVA	Voltage ratio	15kV	33kV	15kV	33kV	15kV	33kV
Dire II	40	132/15	2.20		1.48		2.65	
Harar I and II	6	66/15	1.77		1.32		2.21	
	6.3	66/15	2.75		1.85		3.31	
	6.3	66/15	2.75		1.85		3.31	
Harar III	100/50/50	132/66/33		2.24		1.68		2.80
	9.6/12	66/15	4.89		3.28		5.89	
Haramaya	6.3	66/15	2.40		1.61		2.89	
	9.6/12	66/33	2.10		1.41		2.53	
Jijiga II	25/25/12	132/33/15	5.10	1.10	3.44	0.74	6.15	1.33
Babile	3	45/15	1.10		0.74		1.33	
Chelenko	6.3	66/15	1.80		1.22		2.17	
	9.6/12	66/33		2.12		1.42		2.55

The average load data of each substation buses is summarized as shown in the following table.

Table 3.6: For Substation average load

Substation name	Transformer		Average load(MW)		Average load(MVAr)		Average load (MVA)	
	MVA	Voltage ratio	15kV	33kV	15kV	33kV	15kV	33kV
Dire II	40	132/15	5.95		2.85		6.62	
Harar I and II	6	66/15	1.77		1.32		2.21	
	6.3	66/15	3.59		2.41		4.33	
	6.3	66/15	3.09		2.09		3.73	
Harar III	100/50/50	132/66/33		2.24		1.68		2.80
	9.6/12	66/15	7.45		5.39		9.20	
Haramaya	6.3	66/15	3.42		2.11		4.07	
	9.6/12	66/33	2.78		1.72		3.27	
Jijiga II	25/25/12	132/33/15	6.25	1.65	4.2	1.20	8.16	2.04
Babile	3	45/15	1.44		1.21		1.77	
Chelenko	6.3	66/15	2.81		1.75		3.31	
	9.6/12	66/33		3.26		2.03		3.84

3.5. UNIFIED POWER FLOW CONTROLLER MODELING

3.5.1. Basic Structure and Operation of Unified Power Flow Controller

Unified power flow controller is designed by the combination of SSSC and STATCOM coupled with a common DC capacitor. UPFC has the ability to control all the transmission parameters such as voltage, impedance and phase angle of power system simultaneously. It consists of two voltage source converters one connected in series with the transmission line through series inserted transformer and the other one connected in shunt with the transmission line through a shunt transformer. These converters are operated from a common DC link provided by a DC storage capacitor as shown in figure 3.2 below [35].

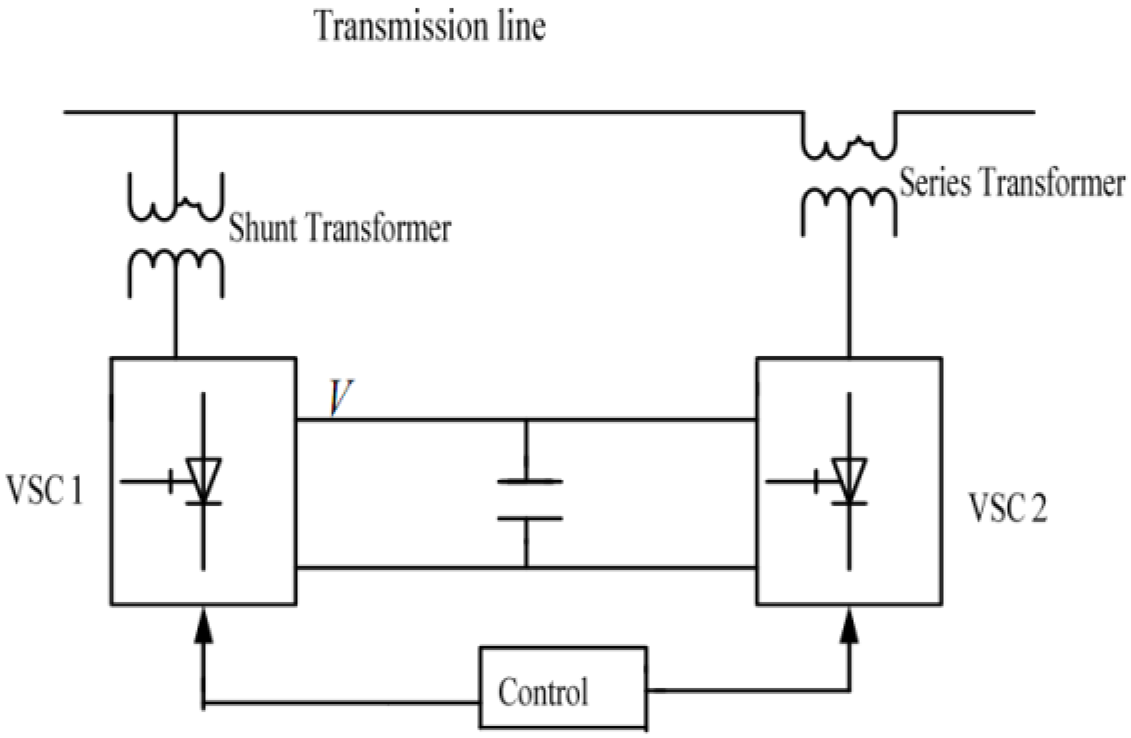

Figure 3.2: Structure of UPFC [35]

Different scholars identified that Unified Power Flow Controller is the most flexible of the FACTS controller. It can not only perform the function of the STATCOM, SSSC and the phase angle regulator but also provides additional flexibility by combining some of the function of the above controller. The main function of the UPFC is to control the flow of real and reactive power by injection of a voltage in series with the transmission line by controlling its magnitude and the phase angle of injected voltage.

The basic components of the UPFC are two voltage source converters (VSC's) sharing a common dc storage capacitor and connected to the system through coupling transformers. The voltage source converter 2 (VSC 2) provide the main function of the UPFC by injecting an AC voltage with controllable magnitude and phase angle in series with the transmission line via a series transformer. The basic function voltage source converter 1 (VSC 1) is to supply or absorb the real power demand by converter 2 at the common dc link. It can also generate or absorb controllable reactive power and provide independent shunt reactive compensation for the line. Converter 2 supplies or absorbs locally the required reactive power and exchanges the active power as a result of the series injection voltage [35].

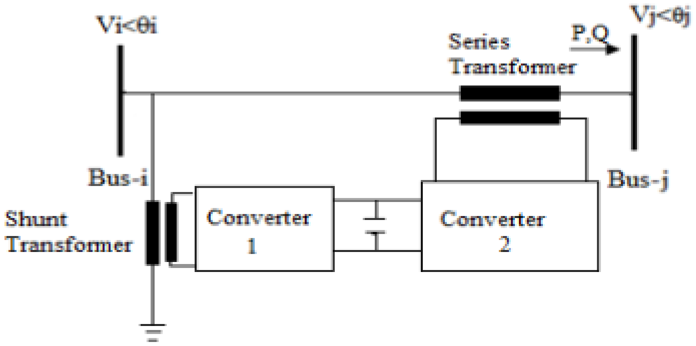

Figure 3.3: Basic Circuit arrangement of UPFC [3]

Controlling the angle of the converter output voltage with respect to the AC system voltage controls the real power exchange between the converter and the AC system. The real power flow from the DC side to AC side (inverter operation) if the converter output voltage is controlled to lead the AC system voltage. If the converter output voltage is made to lag the AC system voltage the power will flow from the AC side to DC side (rectifier operation). Inverter action is carried out by the Get Turn Off Switches (GTOs) while the rectifier action is carried out by the diodes. From practical power transmission system operation, change in real power from a specified value at a bus is more dependent on changes in voltage angle at the specified bus whereas change in reactive power is more dependent on change in voltage magnitude of the bus i.e. controlling the magnitude and phase angle of the converter output voltage controls the active and reactive and real power exchange between the converter and the AC system respectively. The converter generates reactive power for the AC system if the magnitude of the converter output voltage is greater than the magnitude of the AC system voltage. If the magnitude of the converter output voltage is less than that of the AC system, the converter will absorb reactive power to regulate the bus voltages where the UPFC installed.

The series inverter is controlled to inject a symmetrical three phase voltage system, V_{se} of controllable magnitude and phase angle in series with the line to control active and reactive power flows on the transmission line. So, this inverter will exchange active and reactive power with the line. The reactive power is electronically provided by the series inverter and active power is transmitted to the DC terminals. The shunt rectifier is operated in such a way as to demand the DC terminal power (positive or negative) from the line keeping the voltage across the storage capacitor constant. So, the net real power absorbed from the line by the UPFC is equal only to the losses of the two converters and their transformer. The remaining capacity of the shunt rectifier can be used to exchange reactive power with the line to provide a voltage regulation at the connection point of the line. The two VSC's can work independently of each other by separating the DC side. In short rectifier is operating as a STATCOM that generates or absorb reactive power to regulate the voltage magnitude at the connection point whereas, the series inverter is operating as SSSC that generates or absorbs reactive power to regulate the current flow.

The UPFC has also another possible operating mode; the shunt inverter is operating in such a way to inject a controllable current into the transmission line. This current consists of two components with respect to the line voltage: the real or direct component, which is in phase or in opposite phase with the line voltage and the reactive or quadrature component, which is in quadrature. The direct component is automatically determined by the requirement to balance the real power of the series inverter. The quadrature component, instead, can be independently set to any desired reference level (inductive or capacitive) within the capability of the rectifier, absorb or generate respectively reactive power from the line.

3.5.2. Unified Power Flow Controller Injection Model

In this thesis, at steady state power system operation the UPFC injection model is derived. In steady state condition UPFC can represent by two voltage sources representing fundamental components of output voltage waveforms of the two converters and impedances being leakage reactance of the two coupling transformers. The impact of UPFC on transmission network at steady state condition is understandable by using this model. Furthermore, the UPFC injection model can be easily incorporated in the steady state power flow model [38]. Figure 3.4 shows that the two voltage –source model of UPFC.

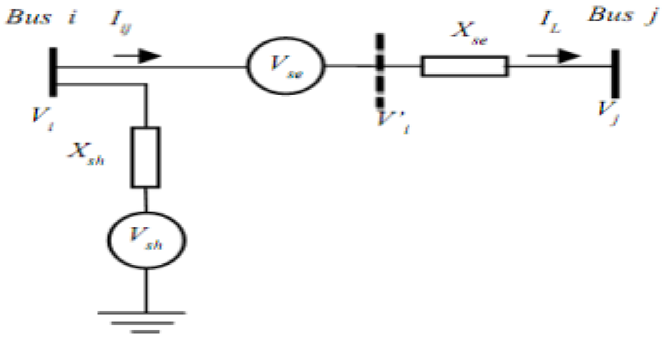

Figure 3.4: Voltage source model of UPFC [36]

Bus-i voltage is taken as reference$V_i = |V| \angle 0^0$. All other bus voltage angles are taken with respect to this bus angle. The voltage source, V_{se} and V_{sh} are controllable in both magnitude and phase angle.

Therefore, the voltage up to UPFC is given by,

$$V_i' = V_i + V_{se} \tag{3.1}$$

Then Series voltage source converter V_{se} is defined in terms of reference bus voltages as,

$$V_{se} = rV_i e^{j\gamma} \tag{3.2}$$

The values of Series voltage Source coefficient r and Series Voltage Source angle γ are defined within the limits of $0 \leq \gamma \leq 2\pi$. where r is per unit value of output voltage of series branch of UPFC and γ is the phase angle difference between V_i and V_{se}.

In UPFC injection model there are two voltage source converter models. These are series connected voltage source converter model and shunt connected voltage source converter model. Using superposition theorem it is easy to determine the power fed by the UPFC. Since the series connected voltage source converter does the main function of the UPFC, it is appropriate to discuss the modeling of a series connected voltage source converter first and then the shunt connected voltage source converter model.

3.5.2.1. Series Connected Voltage Source Converter Model

Consider that a series connected voltage source is located between bus-i and bus-j in a power system. The series voltage source converter can be modeled with an ideal series voltage V_{se} in series with a reactance X_{se} as shown in figure 3.5 the voltage V_i' represents the voltage behind the series reactance.

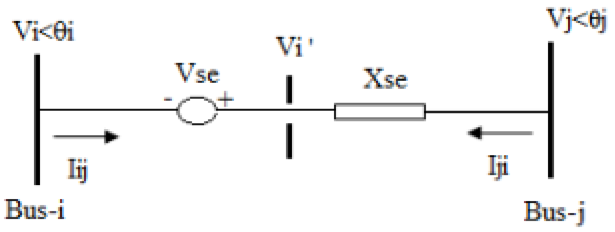

Figure 3.5: Representation of Series connected VSC [3]

Using duality principle the series voltage source V_{se} represented by a current source to develop the steady-state UPFC mathematical model. Figure 3.6 shows that current source which is connected in parallel with the transmission line. [38].

$$I_{se} = -jb_{se}V_{se} \tag{3.3}$$

Where, $b_{se} = {}^{1}/_{X_{se}}$

The negative sign in equation 3.3 indicates that the current is leaving bus-i, since the current which is leaving the node is represented by negative and the current which is entering the node is represented by positive by using convention of current flow.

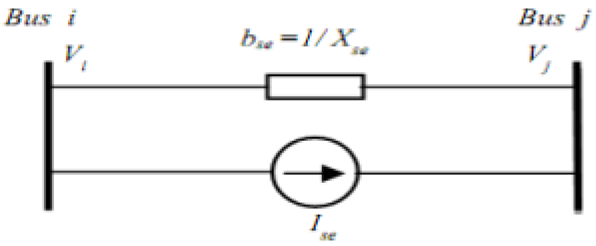

Figure 3.6: Replacement of Series Voltage Source by Current Source [38]

The current source I_{se} can be modeled by injection powers S_{ise} and S_{jse} at the two buses which are expressed by,

$$S_{ise} = V_i\ (-I_{se})^* \tag{3.4}$$

$$S_{jse} = V_j\ (I_{se})^* \tag{3.5}$$

Substituting equations 3.2 and 3.3 into equation 3.4 injected power S_{ise} can be simplified as,

$$S_{ise} = V_i\ (jb_{se}rV_ie^{j\gamma})^* \tag{3.6}$$

$$S_{ise} = V_i\ (-jb_{se}rV_i^*e^{-j\gamma}) \tag{3.7}$$

where $-j = e^{-j90}$ (3.8)

Substituting equation 3.8 in to 3.7,

$$S_{ise} = V_i\ (b_{se}rV_i^*e^{-j(\gamma+90)}) \tag{3.9}$$

By using Euler Identity, i.e.$e^{j\gamma} = \cos\gamma + j\sin\gamma$, equation 3.9 cab simplified as,

$$S_{ise} = V_i^2b_{se}r(\cos(-\gamma - 90) + j\sin(-\gamma - 90)) \tag{3.10}$$

As $\cos(-\gamma - 90) = -\sin\gamma$ and $\sin(-\gamma - 90) = -\cos\gamma$

By using trigonometric identities equation 3.10 can be simplified as,

$$S_{ise} = -rb_{se}V_i^{\,2}\sin\gamma - jrb_{se}V_i^{\,2}\cos\gamma \tag{3.11}$$

Since $S_{ies} = P_{ise} + jQ_{ise}$, then separating the real and imaginary part,

$$P_{ise} = -rb_{se}V_i^{\,2}\sin\gamma \tag{3.12}$$

$$Q_{ise} = -rb_{se}V_i^{\,2}\cos\gamma \tag{3.13}$$

Similarly, substituting equation 3.2 and 3.3 into equation 3.5 the injected power S_{jse}can be modified as,

$$S_{jse} = V_j(-jb_{se}rV_ie^{j\gamma})^* \tag{3.14}$$

But the voltage at each bus is given by $V_j = V_j\angle\theta_j$ and $V_i = V_i\angle\theta_i$

$$S_{jse} = V_j\angle\theta_j\ (-jb_{se}\ rV_i\angle\theta_ie^{j\gamma})^* \tag{3.15}$$

$$S_{jse} = V_je^{j\theta_j}(-jb_{se}rV_ie^{j\theta_i}\ e^{j\gamma})^* \tag{3.16}$$

$$S_{jse} = V_je^{j\theta_j}jb_{se}rV_i^{\,*}e^{-j\theta_i}\ e^{-j\gamma} \tag{3.17}$$

$$S_{jse} = V_je^{j\theta_j}e^{j90}b_{se}rV_i^{\,*}e^{-j\theta_i}\ e^{-j\gamma} \tag{3.18}$$

Where , $j = e^{j90}$ (3.19)

$$S_{jse} = rV_jV_ib_{se}e^{j(90+\theta_j-\theta_i-\gamma)} \tag{3.20}$$

$$S_{jse} = rV_jV_ib_{se}(\cos(90 + \theta_j - \theta_i - \gamma) + j\sin(90 + \theta_j - \theta_i - \gamma)) \tag{3.21}$$

$$S_{jse} = rV_jV_ib_{se}(\cos(90 - (-\theta_j + \theta_i + \gamma)) + j\sin(90 - (-\theta_j + \theta_i + \gamma))) \tag{3.22}$$

Where,

$$\cos\left(90 - (-\theta_j + \theta_i + \gamma)\right) = \cos 90\cos(-\theta_j + \theta_i + \gamma) + \sin 90\sin(-\theta_j + \theta_i + \gamma) \tag{3.23}$$

$$=\mathrm{Sin}(-\theta_j + \theta_i + \gamma) \tag{3.24}$$

And

$$\sin(90 - (-\theta_j + \theta_i + \gamma)) = \sin 90\cos(-\theta_j + \theta_i + \gamma) + \sin(-\theta_j + \theta_i + \gamma)\cos 90 \tag{3.25}$$

$$=\mathrm{Cos}(-\theta_j + \theta_i + \gamma) \tag{3.26}$$

Then by substituting equation 3.24 and 3.25 into equation 3.22 and equation 3.22 is simplified as,

$$S_{jse} = rb_{se}V_jV_i \sin(\theta_i - \theta_j + \gamma) + jrb_{se}V_jV_i \cos(\theta_i - \theta_j + \gamma) \tag{3.27}$$

But $\theta_{ij} = \theta_i - \theta_j$substituting this values into equation 3.27 then the final equation can be written as,

$$S_{jse} = rb_{se}V_jV_i \sin(\theta_{ij} + \gamma)+jrb_{se}V_jV_i \cos(\theta_{ij} + \gamma) \tag{3.28}$$

Since $S_{jse} = P_{jse} + jQ_{jse,}$ then separating the real and imaginary part,

$$P_{jse} = rb_{se}V_jV_i \sin(\theta_{ij} + \gamma) \tag{3.29}$$

$$Q_{jse} = rb_{se}V_jV_i \cos(\theta_{ij} + \gamma) \tag{3.30}$$

The above equations 3.12, 3.13, 3.29 and 3.30 shows that power injection model of the series connected voltage source can be seen as two independent loads at the buses i and j as shown in figure 3.7.

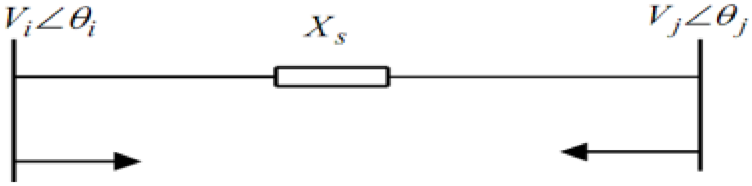

Figure 3.7: Power injection model for a series connected VSC [37]

$$P_{ise} = -rb_{se}V_i^2 \sin\gamma \qquad P_{jse} = rb_{se}V_iV_j \sin(\theta_{ij} + \gamma)$$

$$Q_{ise} = -rb_{se}V_i^2 \cos\gamma \qquad Q_{jse} = rb_{se}V_iV_j \cos(\theta_{ij} + \gamma)$$

3.5.2.2. Shunt Connected Voltage Source Converter Model

The shunt connected converter of UPFC is used mainly in order to provide both the active power demand of the series connected voltage source converter, which is injected to the system, and the losses within the UPFC. The total switching of the two converters is estimated to be about 2% of the power transfer for the converters. If the losses in the active power injection of the shunt connected voltage source converter at bus-i, Pconv1 is equal to 1.02 times the injected series active power Pconv2 through the series connected voltage source converter to the system.

$$\mathrm{P_{conv1}} = -1.02\mathrm{P_{conv2}} \tag{3.31}$$

The apparent power supplied by the series converter is given by,

$$\mathrm{S_{conv2}} = \mathrm{V_{se}I_{ij}}^{*} \tag{3.32}$$

$$\mathrm{I_{ij}} = \frac{\mathrm{V_i}' - \mathrm{V_j}}{\mathrm{jX_{se}}} \tag{3.33}$$

Substituting equation 3.2 and 3.33 into equation 3.32 it is modified as,

$$\mathrm{S_{conv2}} = \mathrm{rV_i}e^{j\gamma}\left(\frac{\mathrm{V_i}' - \mathrm{V_j}}{\mathrm{jX_{se}}}\right)^{*} \tag{3.34}$$

Substituting equation 3.1 into equation 3.34 it is simplified as,

$$\mathrm{S_{conv2}} = \mathrm{rV_i}e^{j\gamma}\left(\frac{\mathrm{V_i} + \mathrm{V_{se}} - \mathrm{V_j}}{\mathrm{jX_{se}}}\right)^{*} \tag{3.35}$$

Again substituting equation 3.2 into equation 3.35 it is simplified as,

$$\mathrm{S_{conv2}} = \mathrm{rV_i}e^{j\gamma}\left(\frac{\mathrm{V_i} + \mathrm{rV_i}e^{j\gamma} - \mathrm{V_j}}{\mathrm{jX_{se}}}\right)^{*} \tag{3.36}$$

But the voltage at each bus is given by $\mathrm{V_j} = \mathrm{V_j}\angle\theta_j$ and $\mathrm{V_i} = \mathrm{V_i}\angle\theta_i$

$$\mathrm{S_{conv2}} = \mathrm{rV_i}\angle\theta_i e^{j\gamma}\left(\frac{\mathrm{V_i}\angle\theta_i + \mathrm{rV_i}\angle\theta_i e^{j\gamma} - \mathrm{V_j}\angle\theta_j}{\mathrm{jX_{se}}}\right)^{*} \tag{3.37}$$

$$\mathrm{S_{conv2}} = \mathrm{rV_i}e^{j\theta_i}e^{j\gamma}\left(\frac{\mathrm{V_i}\,e^{j\theta_i} + \mathrm{rV_i}e^{j\theta_i}e^{j\gamma} - \mathrm{V_j}e^{j\theta_j}}{\mathrm{jX_{se}}}\right)^{*} \tag{3.38}$$

$$\mathrm{S_{conv2}} = \mathrm{rV_i}e^{j\theta_i}e^{j\gamma}\left(\frac{\mathrm{V_i}e^{-j\theta_i} + \mathrm{rV_i}e^{-j\theta_i}e^{-j\gamma} - \mathrm{V_j}e^{-j\theta_j}}{-\mathrm{jX_{Se}}}\right) \tag{3.39}$$

$$\mathrm{S_{conv2}} = \mathrm{rV_i}e^{j(\theta_i+\gamma)}\left(\frac{\mathrm{V_i}e^{-j\theta_i} + \mathrm{rV_i}e^{-j(\theta_i+\gamma)} - \mathrm{V_j}e^{-j\theta_j}}{-\mathrm{jX_{se}}}\right) \tag{3.40}$$

Substituting $b_{se} = {}^{1}/_{X_{se}}$ in to the above equation 3.40 it gives,

$$\mathrm{S_{conv2}} = \mathrm{rb_{se}V_i}e^{j(\theta_i+\gamma)}\left(\frac{\mathrm{V_i}e^{-j\theta_i} + \mathrm{rV_i}e^{-j(\theta_i+\gamma)} - \mathrm{V_j}e^{-j\theta_j}}{-j}\right) \tag{3.41}$$

Multiplying the numerator and denominator of equation 3.41 by conjugate of $-\mathrm{j}$ and it can be simplified as,

$$\mathrm{S_{conv2}} = \mathrm{jrb_{se}V_i e^{j(\theta_i+\gamma)}(V_i e^{-j\theta_i} + rV_i e^{-j(\theta_i+\gamma)} - V_j e^{-j\theta_j})} \tag{3.42}$$

Then the above equation can be simplified as,

$$\mathrm{S_{conv2}} = \mathrm{jrb_{se}V_i}^2 \mathrm{e^{j\gamma}} + \mathrm{jb_{se}r^2V_i}^2 - \mathrm{jrb_{se}V_iV_j e^{j(\theta_i-\theta_j+\gamma)}} \tag{3.43}$$

By using Euler identity, i.e. $e^{j\gamma} = \cos\gamma + j\sin\gamma$

And $\mathrm{e^{j(\theta_i-\theta_j+\gamma)}} = \cos(\theta_\mathrm{i} - \theta_\mathrm{j} + \gamma) + \mathrm{j}\sin(\theta_\mathrm{i} - \theta_\mathrm{j} + \gamma)$ equation 3.43 is simplified as,

$$\begin{aligned}\mathrm{S_{conv2}} = {} & \mathrm{jr^2b_{se}V_i}^2 + \mathrm{jrb_{se}V_i}^2(\cos\gamma + \mathrm{j}\sin\gamma) - \mathrm{jrV_jb_{se}}\,\mathrm{V_i}(\cos\big(\theta_\mathrm{i} - \theta_\mathrm{j} + \gamma\big) \\ & + \mathrm{j}\sin(\theta_\mathrm{i} - \theta_\mathrm{j} + \gamma))\end{aligned} \tag{3.44}$$

$$\begin{aligned}\mathrm{S_{conv2}} = {} & \mathrm{jr^2b_{se}V_i}^2 + \mathrm{jrb_{se}V_i}^2\cos\gamma - \mathrm{rb_{se}V_i}^2\sin\gamma - \mathrm{jrV_jb_{se}}\,\mathrm{V_i}(\cos\big(\theta_\mathrm{i} - \theta_\mathrm{j} + \gamma\big) \\ & + \mathrm{rV_jb_{se}}\,\mathrm{V_i}\sin(\theta_\mathrm{i} - \theta_\mathrm{j} + \gamma))\end{aligned} \tag{3.45}$$

Therefore, separating the real and imaginary part the active power and reactive power at converter-2 as follows,

$$\mathrm{P_{conv2}} = \mathrm{rb_{se}V_iV_j}\sin(\theta_\mathrm{i} - \theta_\mathrm{j} + \gamma) - \mathrm{rb_{se}V_i}^2\sin\gamma \tag{3.46}$$

$$\mathrm{Q_{conv2}} = -\mathrm{rb_{se}V_iV_j}\cos(\theta_\mathrm{i} - \theta_\mathrm{j} + \gamma) + \mathrm{rb_{se}V_i}^2\cos\gamma + \mathrm{r^2b_{se}V_i}^2 \tag{3.47}$$

Then the active power injected at converter-1 is determine by substituting equation 3.46 into equation 3.31 as,

$$\mathrm{P_{conv1}} = -1.02\mathrm{rb_{se}V_iV_j}\sin\big(\theta_\mathrm{i} - \theta_\mathrm{j} + \gamma\big) + 1.02\mathrm{rb_{se}V_i}^2\sin\gamma \tag{3.48}$$

The reactive power delivered or absorbed by voltage source converter 1 is independently controllable by UPFC and can be modeled as a separate controllable shunt reactive source. In the view of above, it is assumed that the reactive power of converter-1 is equal to zero. The UPFC injection model is constructed from the series connected voltage source converter model with the addition of a power equivalent to $\mathrm{P_{conv1}} + \mathrm{j}0$ to bus-i [36] [37].

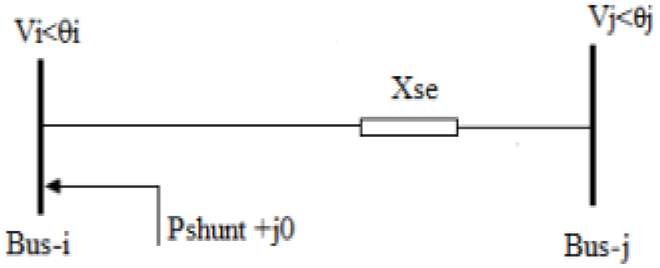

Figure 3.8: Power injection model of shunt connected voltage source converter [36] [37]

Therefore, the steady-state UPFC mathematical modeling can be constructed by combining the series power injection and shunt power injection at bus-i and bus-j.

The element of power injection model of UPFC can be expressed as follows,

$$P_{i,UPFC} = -rb_{se}V_i^2 \sin\gamma - 1.02rb_{se}V_iV_j \sin(\theta_i - \theta_j + \gamma) + 1.02rb_{se}V_i^2 \sin\gamma$$

$$=0.02\ rb_{se}V_i^2 \sin\gamma - 1.02rb_{se}V_iV_j \sin(\theta_i - \theta_j + \gamma) \quad (3.49)$$

$$Q_{i,UPFC} = -rb_{se}V_i^2 \cos\gamma \quad (3.50)$$

$$P_{j,UPFC} = rb_{se}V_iV_j \sin(\theta_i - \theta_j + \gamma) \quad (3.51)$$

$$Q_{j,UPFC} = rb_{se}V_iV_j \cos(\theta_i - \theta_j + \gamma) \quad (3.52)$$

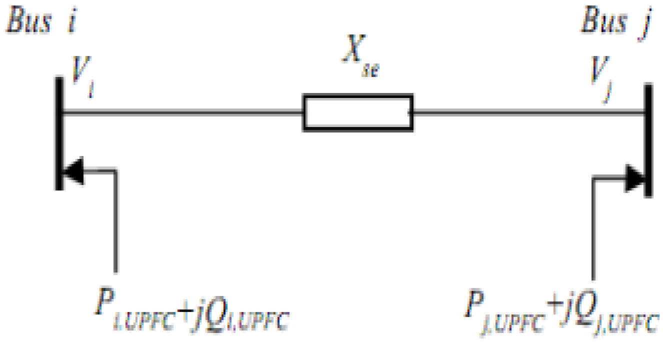

Figure 3.9: The overall System steady state UPFC mathematical model [37]

3.5.3. System Parameters of Unified Power Flow Controller

A ± 40MVAr UPFC is modeled for this thesis work. The size of the UPFC device is determined based on different parameters which is governed by the amount of reactive power to be injected in to the systems. The block of UPFC control system, the parameters of the shunt coupling transformer are as following: the ratio is 132kV/15kV, the capacitance is 50MVA, the leakage reactance is 10%, and the connection type is Y/Δ to decrease the current flow to the converter.

- The controller parameters for shunt current controller are $\mathrm{Kr} = 0.1, \mathrm{Ki} = 0.1, \mathrm{Ti} = 1$ and $\mathrm{Tm} = 0.01$.
- The controller parameters for VDC are $\mathrm{K} = 100$ and $\mathrm{Ti} = 6$

The parameters of the series coupling transformer are set as following the ratio is 132kV/15kV, the capacitance 50MVA, and the leakage reactance is 5%. The DC capacitor: 1MVAr, Vdc=25kV.

- The controller parameters for series current controller *are* $\mathrm{Ki} = 0.1, \mathrm{Ti} = 0.17, \mathrm{Kr} = 0.1$ $\mathrm{Tr} = 0.17$ and Tm=0.01.
- The controller for PQ controller are $\mathrm{KP} = 0.01, \mathrm{TiP} = 5, \mathrm{KQ} = 0.1, \mathrm{TiQ} = 5$ and $\mathrm{Tr} = 0.1$.

CHAPTER FOUR

4. RESULTS AND DISCUSSION

4.1. LOAD FLOW ANALYSIS

Load flow analysis remain a principal tool used in power system studies. The planning and operation of a power system require such computation, to dissect the steady-state performance of the power system under different working conditions and to consider the impact of change in equipment configuration. Load flow solutions produced for these reasons, where analyzed utilizing computer programs. The fundamental aim of load flow performance is to generate the load power utilization at all buses of a known electric power systems, and power (active and reactive) at every bus.

4.2. LOAD FLOW ANALYSIS OF THE EXISTING TRANSMISSION NETWORK OF THE EASTERN REGION

In this section, the active power flow, reactive power flow, power loss and voltage profile of each bus for eastern region of EEP network were analyzed. Figure 4.1 show that the overall existing interconnected transmission network of eastern region of EEP without incorporating UPFC. With a specific objective to verify the model and outline the effect of UPFC, three distinctive operating scenarios were considered as stated below.

i. Scenario 1: Peak Load condition without and with UPFC
ii. Scenario 2: Average Load condition without and with UPFC
iii. Scenario 3: Minimum Load condition without and with UPFC

4.2.1. Scenario 1: Peak Load Condition without UPFC

After filling all the necessary data in to the transmission network diagram of the existing eastern region of EEP network, load flow simulation was run for the peak load condition. From the load flow result, active and reactive power at each bus, active and reactive power flow over each transmission line, total transmission active and reactive line loss and bus voltages profile were identified. Table 4.1 shows that the overall DIgSILENT Power Factory result of the existing transmission network of eastern region of EEP without UPFC.

From table 4.1 the bus voltages profile of all buses are less than 95%. This indicated that there is more real and reactive power losses on the transmission line and the voltage profile of the buses are with poor voltage regulation. Due to this power delivered to the load side is not as required level i.e the power transmitted does not meet the demand power at each substation because of poor voltage regulation attained at the buses for weakest bus voltage regulation 28%. The simulation results shown in figure 4.2 quantifies that the bus voltage are not improved.

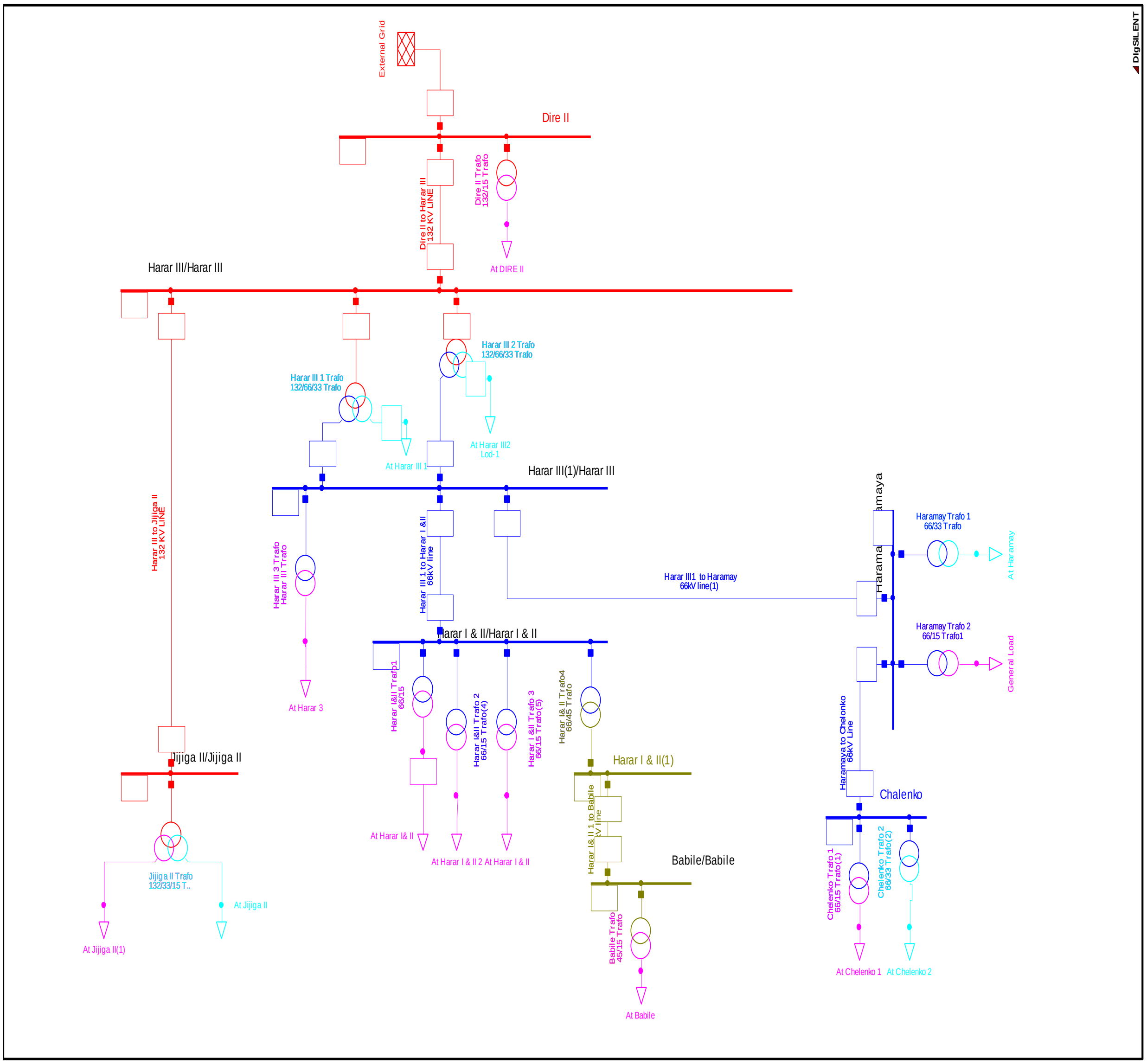

Figure 4.1: Overall existing transmission network of Eastern Region of EEP without UPFC

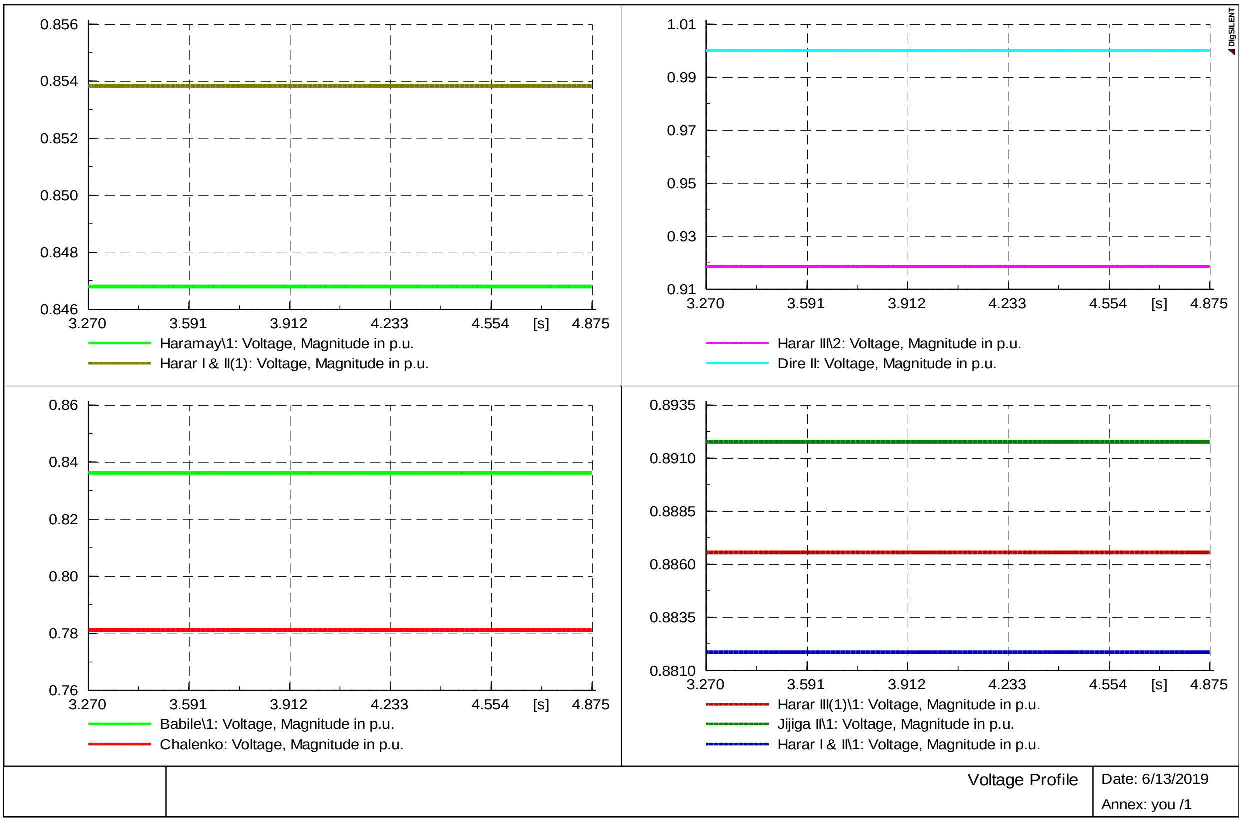

Figure 4.2: Bus Voltage in per unit without UPFC at peak load

Table 4.1: Ethiopian Eastern Region Transmission Network Bus Voltage and Power without UPFC at peak load

Bus No.	Bus Name	Bus Voltage (p.u)	Bus Voltage (kV)	Real Power(MW)	Reactive Power (MVAr)	Bus Voltage(% nominal)
1	Dire II-132kV	1.000	132.00	66.20	50.06	100.00
2	Jijiga II-132kV	0.892	117.71	9.630	6.860	89.20
3	Harar III-132kV	0.918	121.24	53.38	41.97	91.80
4	Haramaya-66kV	0.847	55.890	16.72	12.25	84.70
5	Chalenko-66kV	0.781	51.560	8.290	5.890	78.10
6	Babile-45kV	0.836	37.630	1.800	1.890	83.60
7	Harar I& II-66kV	0.882	58.200	11.53	9.430	88.20
8	Harar I &II 1-45kV	0.854	38.420	1.830	1.830	85.40
9	Harar III1-66kV	0.887	58.510	39.00	32.00	88.70

Table 4.2: Real power and reactive power losses of each transmission line without UPFC at peak load

Line Number	From Bus	To Bus	Real power loss(MW)	Reactive Power loss (MVAr)
1	Dire II-132kV	Harar III-132kV	3.0668	3.80
2	Harar III-132kV	Jijiga II-132kV	0.1846	3.40
3	Harar III1-66kV	Harar I & II-66kV	0.0416	0.10
4	Harar I & II 1-45kV	Babile-45kV	0.0276	0.10
5	Harar III1-66kV	Haramaya-66kV	0.5182	1.00
6	Haramaya-66kV	Chalenko-66kV	0.4565	0.80
Total loss			4.295	9.20

The real power demand of total eastern region of Ethiopia is 66.2MW at peak load condition but the total power delivered to load is reduced to 61.33MW due to transmission line and transformer losses. The total transmission line loss is 4.295MW real loss and 9.2MVAr reactive loss as shown in table 4.2 and the total transformer real power loss is 0.575MW and reactive power loss is 6.23MVAr. Therefore, UPFC is incorporated between two buses of eastern region transmission network in order to improve bus voltage and minimize the transmission line loss.

4.2.2. Scenario 2: Average Load Condition without UPFC

After filling all the necessary data in to the transmission network diagram of the existing eastern region of EEP network, load flow simulation was run for the average load condition. From the load flow result, active and reactive power at each bus, active and reactive power flow over each transmission line, total transmission active and reactive power losses and bus voltages were identified. Table 4.3 shows that the overall DIgSILENT Power Factory result of the existing transmission network of eastern region of EEP.

From table 4.3 the bus voltages profile of all buses are less than 95%.This indicated that there is more real and reactive power losses on the transmission line and the voltage profile of the buses are not improved. Due to this power delivered to the load side is not as required level i.e the power transmitted does not meet the demand power at each substation because of poor voltage regulation attained at the buses for weakest bus voltage regulation is 18.21%. The simulation results shown in figure 4.3 quantifies that the bus voltage are not improved.

Table 4.3: Ethiopian Eastern Region Transmission Network Bus Voltage and Power without UPFC at average load

Bus No.	Bus Name	Bus Voltage (p.u)	Bus Voltage (kV)	Real Power(MW)	Reactive Power (MVAr)	Bus Voltage (% nominal)
1	Dire II-132kV	1.00	132.00	50.70	35.30	100.00
2	Jijiga II-132kV	0.919	121.24	7.930	5.950	91.80
3	Harar III-132kV	0.94	124.02	43.00	30.08	94.00
4	Haramaya-66kV	0.889	58.700	12.60	8.700	88.90
5	Chalenko-66kV	0.846	55.830	6.110	4.140	84.60
6	Babile-45kV	0.883	39.710	1.460	1.330	88.30
7	Harar I & II-66kV	0.913	60.260	9.980	7.810	91.30
8	Harar I & II 1- 45kV	0.895	40.260	1.470	1.240	89.50
9	Harar III1- 66kV	0.917	60.510	30.32	23.24	91.70

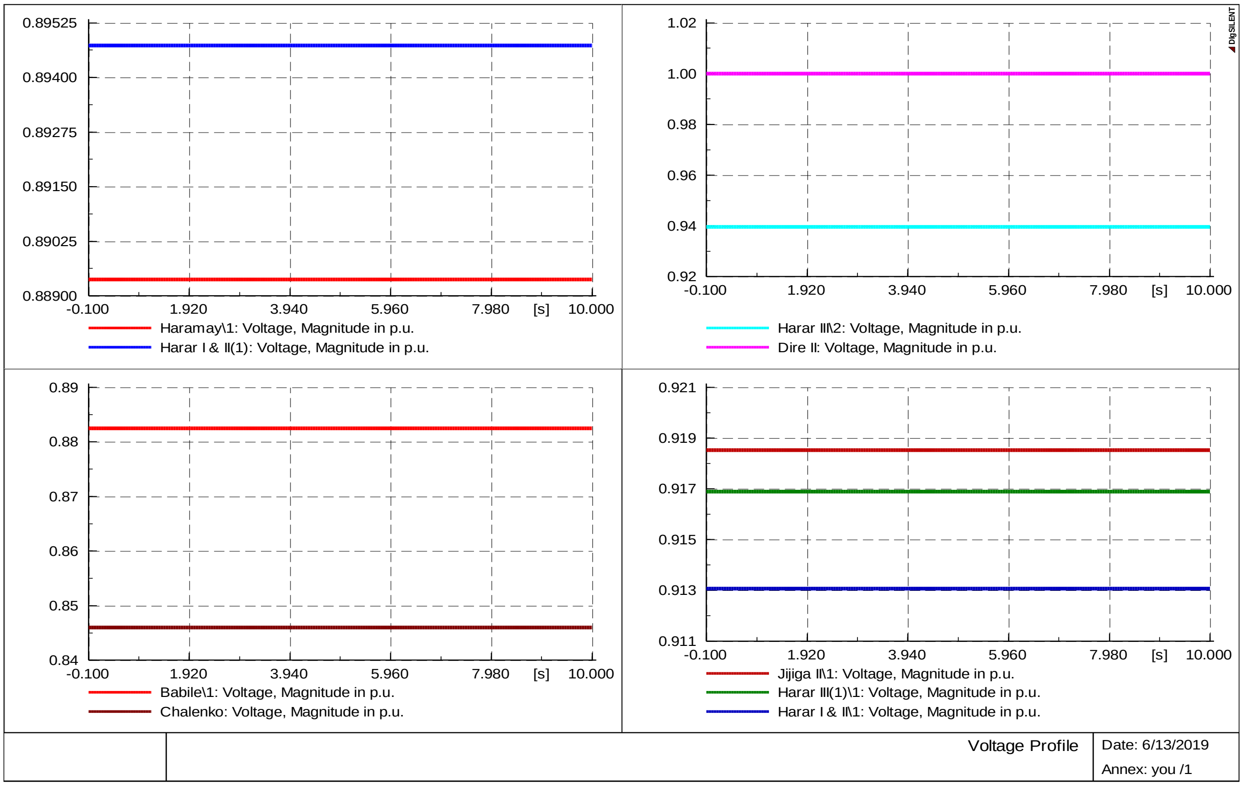

Figure 4.3: Bus Voltage in per unit without UPFC at average load

Table 4.4: Real power and reactive power losses of each transmission line without UPFC at average load

Line Number	From Bus	To Bus	Real power loss(MW)	Reactive Power loss (MVAr)
1	Dire II-132kV	Harar III-132kV	1.7682	1.40
2	Harar III-132kV	Jijiga II-132kV	0.1164	3.70
3	Harar III1- 66kV	Harar I &II-66kV	0.0281	0.00
4	Harar I & II 1-45kV	Babile-45kV	0.014	0.10
5	Harar III1-66kV	Haramaya-66kV	0.2551	0.50
6	Haramaya- 66kV	Chalenko-66kV	0.2049	0.40
Total loss			2.387	6.10

The real power demand of total eastern region of Ethiopia is 50.7MW at average load condition but the total power delivered to load is reduced to 47.95MW due to transmission and transformer losses. The total transmission line loss is 2.387MW real power loss and 6.1MVAr reactive loss as shown in table 4.4 and the total transformer real power loss is 0.364MW and 2.32MVAr reactive power loss. Therefore, UPFC is incorporated between two buses of eastern region transmission network in order to improve bus voltage and minimize the transmission line loss.

4.2.3. Scenario 3: Minimum Load Condition without UPFC

After filling all the necessary data in to the transmission network diagram of the existing eastern region of EEP network, load flow simulation was run for the minimum load condition. From the load flow result, active and reactive power at each bus, total transmission active and reactive power losses, active and reactive power flow over each transmission line and bus voltages were identified. Table 4.5 shows that the overall DIgSILENT Power Factory result of the existing transmission network of eastern region of EEP.

From table 4.5 the bus voltages profile of some buses are less than 95%. This indicated that there is more real and reactive power losses on the transmission line and the voltage profile of the buses are unregulated. Due to this power delivered to the load side is not as required level i.e the power transmitted does not meet the demand power at each substation because of poor voltage regulation attained at the buses for weakest bus voltage regulation is 6.74%. The simulation results shown in figure 4.4 quantifies that the bus voltage are not improved.

Table 4.5: Ethiopian Eastern Region Transmission Network Bus Voltage and Power without UPFC at minimum load

Bus No.	Bus Name	Bus Voltage (p.u)	Bus Voltag e(kV)	Real Power(MW)	Reactive Power (MVAr)	Bus Voltage (% nominal)
1	Dire II-132kV	1.000	132.00	37.20	23.10	100.00
2	Jijiga II-132kV	0.943	124.50	7.44	4.720	94.30
3	Harar III-132kV	0.959	126.55	34.10	21.60	95.90
4	Haramaya-66kV	0.925	61.04	8.50	6.100	92.50
5	Chalenko-66kV	0.898	59.26	3.90	2.800	89.80
6	Babile-45kV	0.922	41.50	1.10	0.800	92.20
7	Harar I& II-66kV	0.940	62.05	8.40	6.200	94.00
8	Harar I & II 1-45kV	0.930	41.84	1.11	0.690	93.00
9	Harar III1- 66kV	0.943	62.25	22.02	16.20	94.30

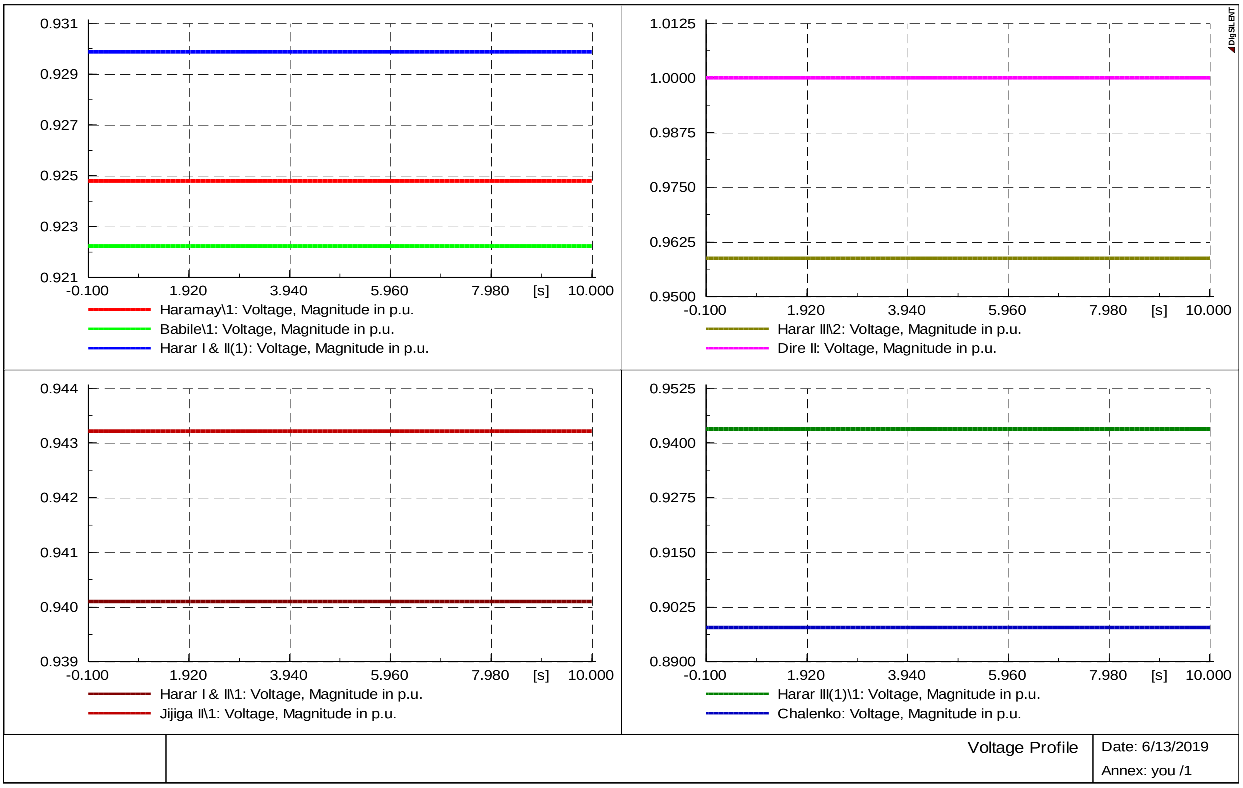

Figure 4.4: Bus Voltage in per unit without UPFC at minimum load

Table 4.6: Real power and reactive power losses of each transmission line without UPFC at minimum load

Line Number	From Bus	To Bus	Real power loss (MW)	Reactive Power loss (MVAr)
1	Dire II-132kV	Harar III-132kV	0.8744	0.20
2	Harar III-132kV	Jijiga II-132kV	0.0776	3.90
3	Harar III1-66kV	Harar I &II-66kV	0.0182	0.10
4	Harar I & II 1-45kV	Babile-45kV	0.0061	0.10
5	Harar III1-66kV	Haramaya-66kV	0.1119	0.20
6	Haramaya-66kV	Chalenko-66kV	0.0778	0.10
Total loss			1.166	4.60

The real power demand of total eastern region of Ethiopia is 37.2MW at minimum load conditions but the total power delivered to load is reduced to 35.79MW due to transmission and transformer losses. The total transmission line loss is 1.166MW real power loss and 4.6Mvar reactive loss as shown in table 4.6 and the total transformer real power loss is 0.244MW. Therefore, UPFC is incorporated between two buses of eastern region transmission network in order to improve bus voltage and minimize the transmission line loss.

4.3. LOAD FLOW ANALYSIS WITH UPFC BETWEEN DIRE II-132 BUS AND HARAR III -132 BUS

The UPFC incorporated between Dire II bus and Harar III bus in transmission network of Eastern region of Ethiopia as shown in figure 4.5 below. In this section, the active power flow, reactive power flow, power loss and bus voltage of each buses for eastern region of EEP network were analyzed. Figure 4.5 show that the overall modified interconnected transmission network of eastern region of EEP with incorporating UPFC between Dire II -132 bus and Harar III 132 bus

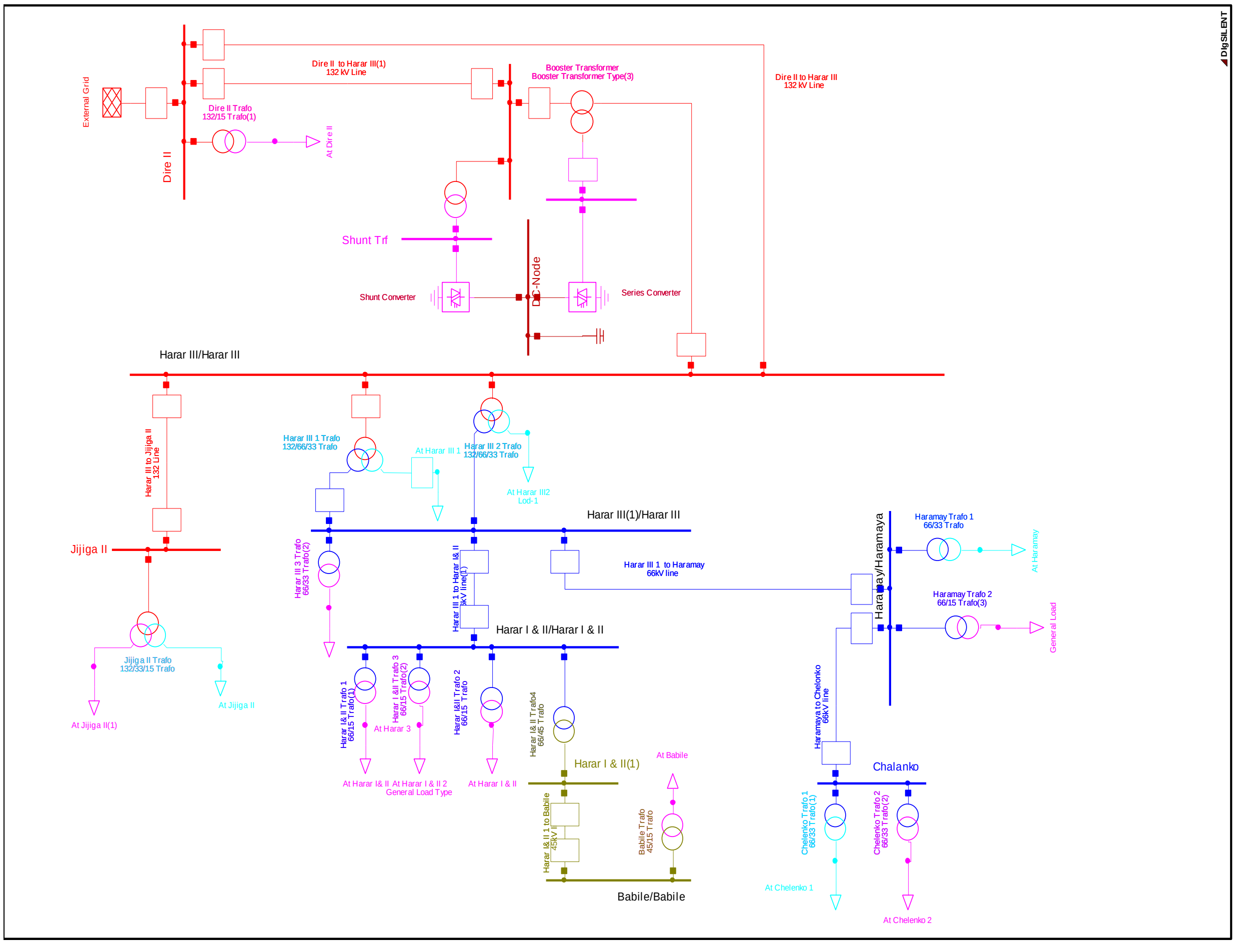

Figure 4.5: Transmission network of Eastern region of EEP with UPFC between Dire II bus and Harar III bus

4.3.1 Scenario 1: Peak Load Condition with UPFC

After filling all the necessary data in to the transmission network diagram of the eastern region of EEP network, load flow simulation was run for the peak load condition. From the load flow result, active and reactive power at each bus, total transmission active and reactive power losses and bus voltages were identified. Table 4.7 shows that the overall DIgSILENT Power Factory result of the transmission network of eastern region of EEP with UPFC.

Table 4.7: Ethiopian Eastern Region Transmission Network Bus Voltage and Power with UPFC at peak load

Bus No.	Bus Name	Bus Voltage (p.u)		Bus Voltage(kV)		Active Power(MW)	Reactive Power (MVAr)
		Without UPFC	With UPFC	Without UPFC	With UPFC		
1	Dire II-132kV	1.00	1.00	132.00	132.00	63.70	6.100
2	Jijiga II-132kV	0.892	0.998	117.71	131.80	9.600	6.800
3	Harar III-132kV	0.918	1.026	121.24	135.40	53.00	43.00
4	Haramaya-66kV	0.847	0.967	55.890	63.810	16.50	11.00
5	Chalenko-66kV	0.781	0.913	51.560	60.280	8.300	5.700
6	Babile-45kV	0.836	0.957	37.630	43.060	1.800	1.800
7	Harar I & II-66kV	0.882	0.995	58.200	65.690	11.50	9.200
8	Harar I &II 1-45kV	0.854	0.972	38.420	43.730	1.800	1.700
9	Harar III1-66kV	0.887	0.999	58.510	65.960	38.60	30.00

From table 4.7 the bus voltages profile of all buses are greater than 95% accept Chelanko. This indicated that there is less real and reactive power losses on the transmission line and the voltage profile of the buses are improved. Due to this power delivered to the load side is as required level i.e. the power transmitted meet the demand power at each substation because of improved voltage profile is attained at each bus. The simulation results shown in figure 4.6 and figure 4.7 quantify that the bus voltages are improved.

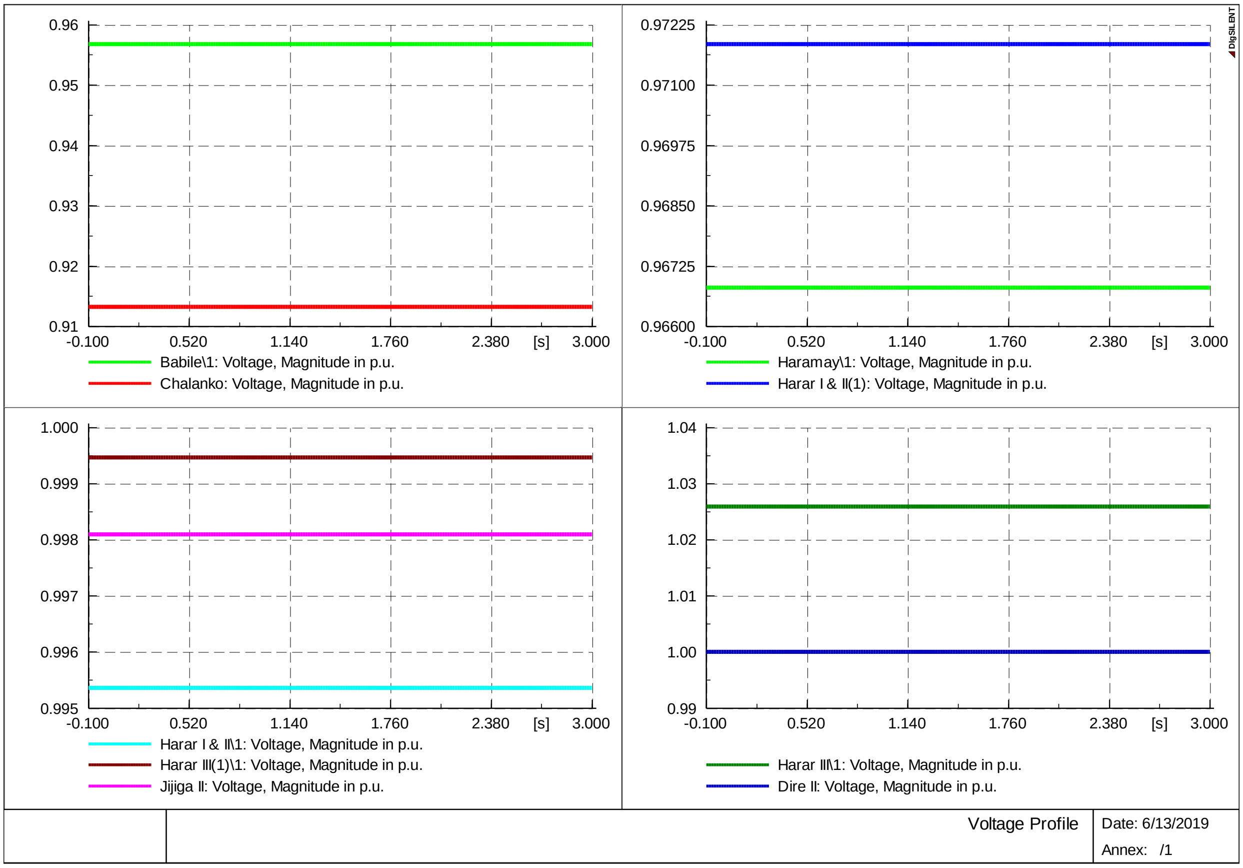

Figure 4.6: Bus Voltage in per unit with UPFC at peak load

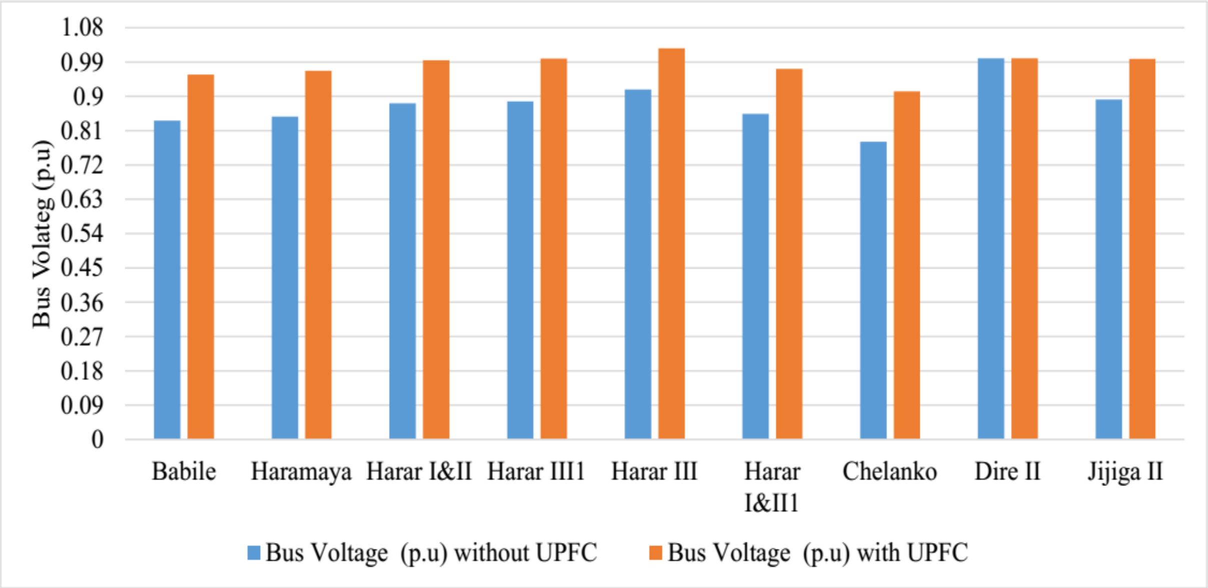

Figure 4.7: Comparison of buses voltage with and without UPFC at Peak load

Table 4.8: Rael power and reactive power losses of each transmission line with UPFC at peak load

Line Number	From Bus	To Bus	Active power loss(MW)		Reactive Power loss (MVAr)	
			Without UPFC	With UPFC	Without UPFC	With UPFC
1	Dire II-32kV	Harar III-132kV	3.0668	1.0010	3.80	2.20
2	Harar III-132kV	Jijiga II-132kV	0.1846	0.1730	3.40	0.40
3	Harar III1-66kV	Harar I & II-66kV	0.0416	0.0321	0.10	0.10
4	Harar I & II 1-45kV	Babile-45kV	0.0276	0.0203	0.10	0.10
5	Harar III1-66kV	Haramaya-66kV	0.5182	0.3658	1.00	0.50
6	Haramaya-66kV	Chalenko-66kV	0.4565	0.3162	0.80	0.00
Total loss			4.2950	1.9080	9.20	3.30

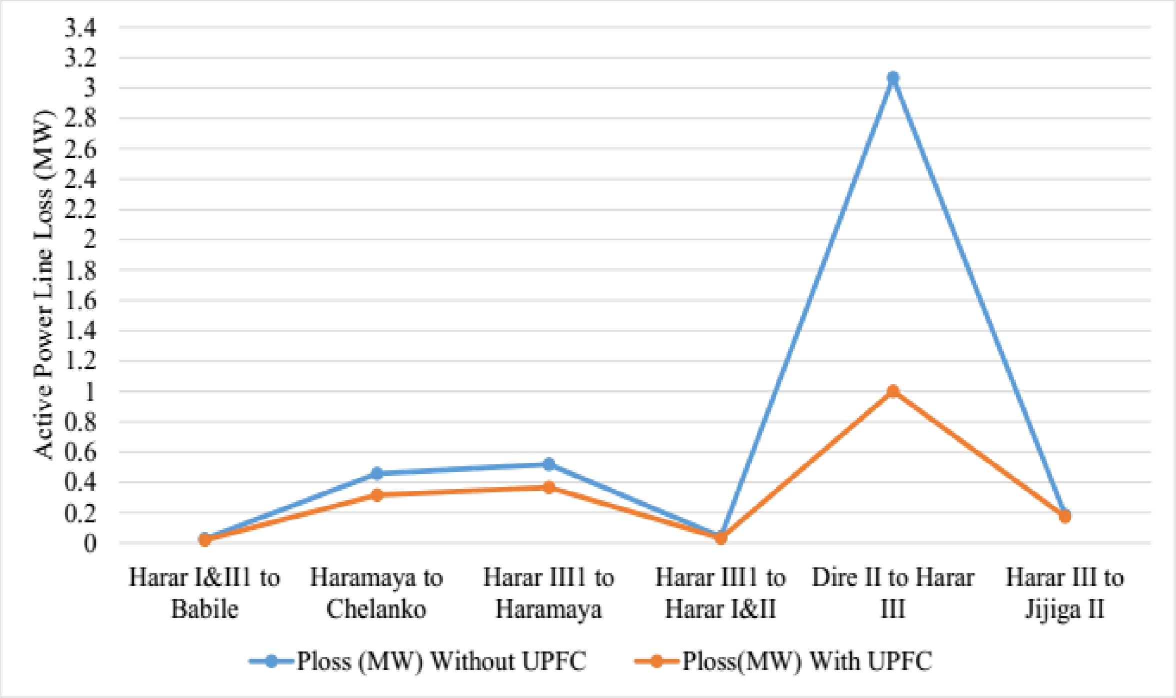

Figure 4.8: Comparison of active power loss on each line with and without UPFC at peak load

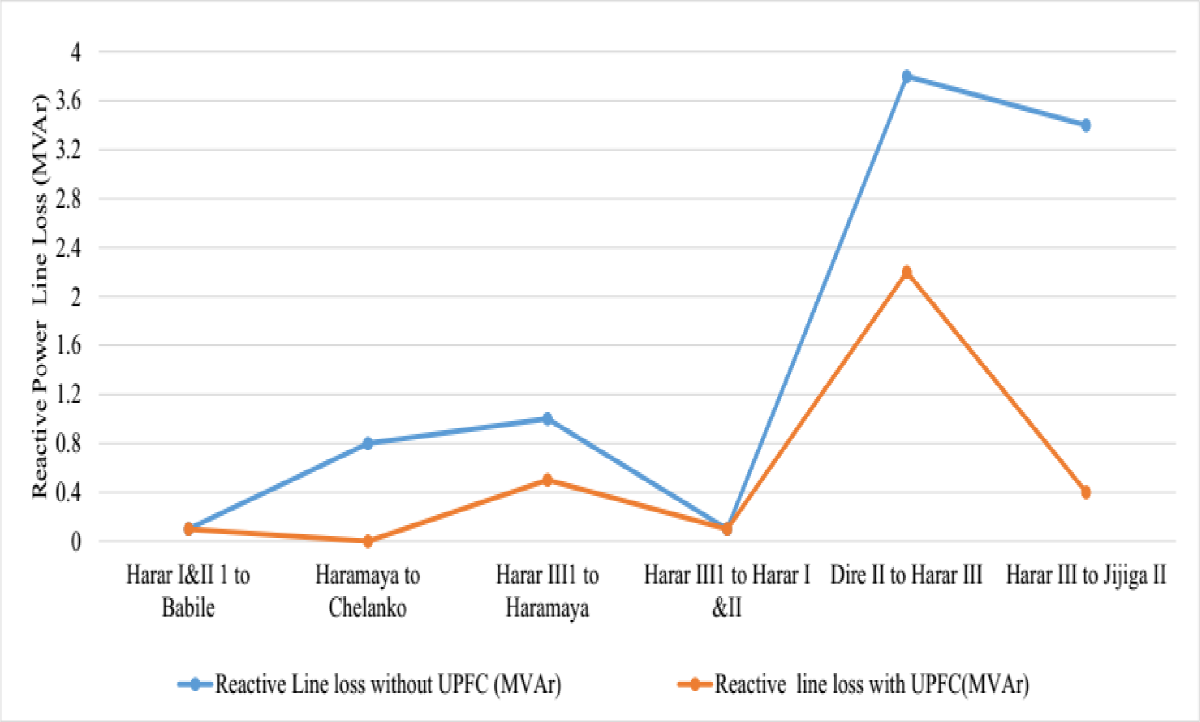

Figure 4.9: Comparison of reactive power loss on each line with and without UPFC at peak load

The addition of UPFC between Dire II bus and Harar III bus improved the real power delivered to all substations. The total transmission line active power loss is 4.295MW before incorporating UPFC which accounts 6.49% of peak load demand. After incorporating the total real power is reduced to 1.908MW which is accounts 2.88% of peak load demand. The total transmission line reactive power loss is 9.2MVAr before incorporating UPFC after incorporating UPFC it is reduced to 3. 3MVAr.The total active and reactive power losses are minimized by 55.57% and 64.13% respectively when UPFC is incorporated between Dire II bus and Harar III bus of Eastern region of Ethiopian transmission network.

4.3.2. Scenario 2: Average Load Condition with UPFC

After filling all the necessary data in to the transmission network diagram of the eastern region of EEP load flow simulation was run for the average load condition. From the load flow result, active and reactive power at the buses, total transmission active and reactive power losses and bus voltages were identified. Table 4.9 shows that the overall DIgSILENT Power Factory result of the transmission network of eastern region of EEP with UPFC.

From table 4.9 the bus voltages profile of all buses are greater than 95%. This indicated that there is less real and reactive power losses on the transmission line and the voltage profile of the buses are improved. Due to this power delivered to the load side is as required level i.e the power transmitted meet the demand power at each substation because of improved voltage profile is attained at each bus. The simulation results shown in figure 4.10 and figure 4.11 quantify that the bus voltages are improved.

Table 4.9: Ethiopian Eastern Region Transmission Network Bus Voltage and Power with UPFC at average load

Bus No.	Bus Name	Bus Voltage (p.u)		Bus Voltage(kV)		Active Power(MW)	Reactive Power (MVAr)
		Without UPFC	With UPFC	Without UPFC	With UPFC		
1	Dire II -132kV	1.000	1.000	132.00	132.00	49.00	5.300
2	Jijiga II -132kV	0.919	1.008	124.24	133.00	7.900	5.500
3	Harar III -132kV	0.940	1.030	124.02	135.95	42.80	32.70
4	Haramaya-66kV	0.889	0.987	58.70	65.150	12.50	7.900
5	Chalenko-66kV	0.846	0.950	55.83	62.710	6.100	4.090
6	Babile-45kV	0.883	0.980	39.71	44.110	1.500	1.300
7	Harar I& II-66kV	0.913	1.007	60.26	66.470	10.00	7.700
8	Harar I &II 1-45kV	0.895	0.991	40.26	44.600	1.470	1.190
9	Harar III1-66kV	0.917	1.010	60.51	66.690	30.20	20.90

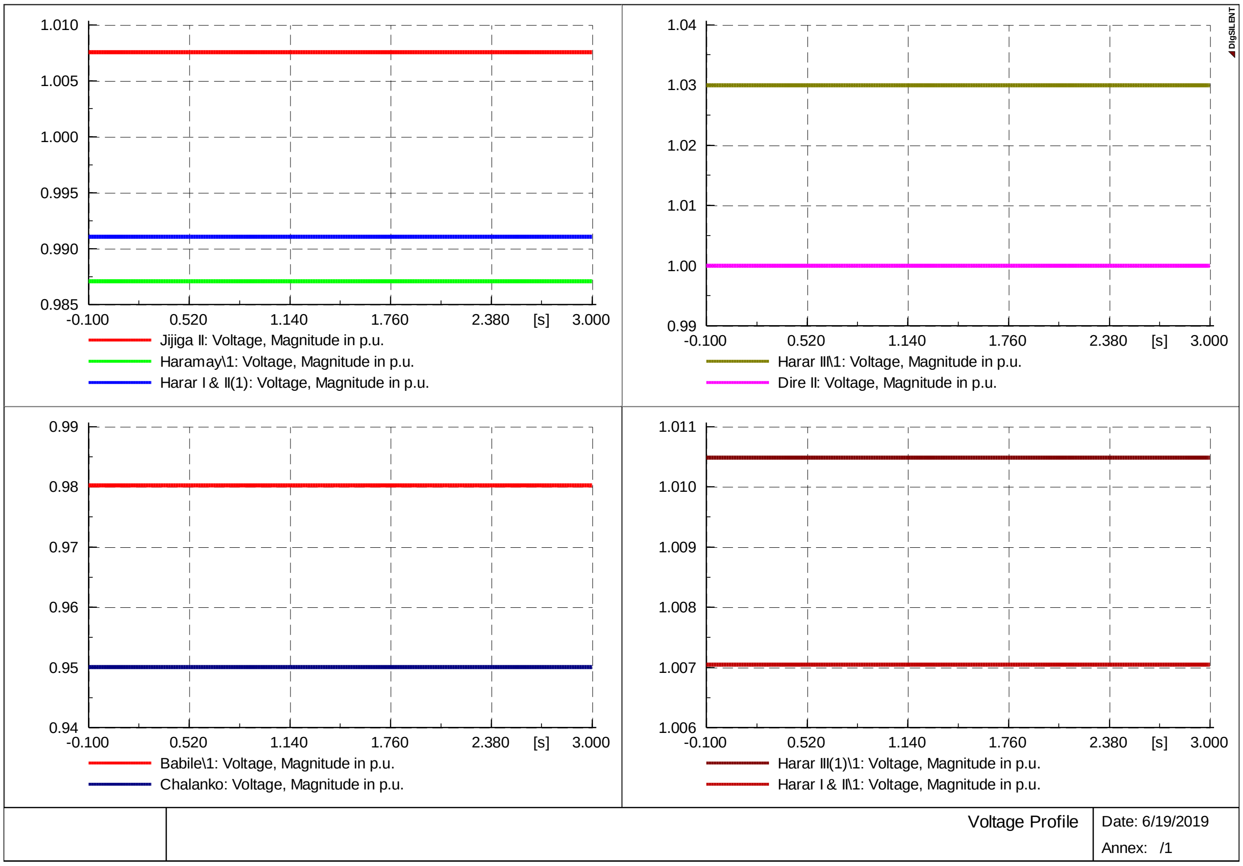

Figure 4.10: Bus Voltage in per unit with UPFC at average load

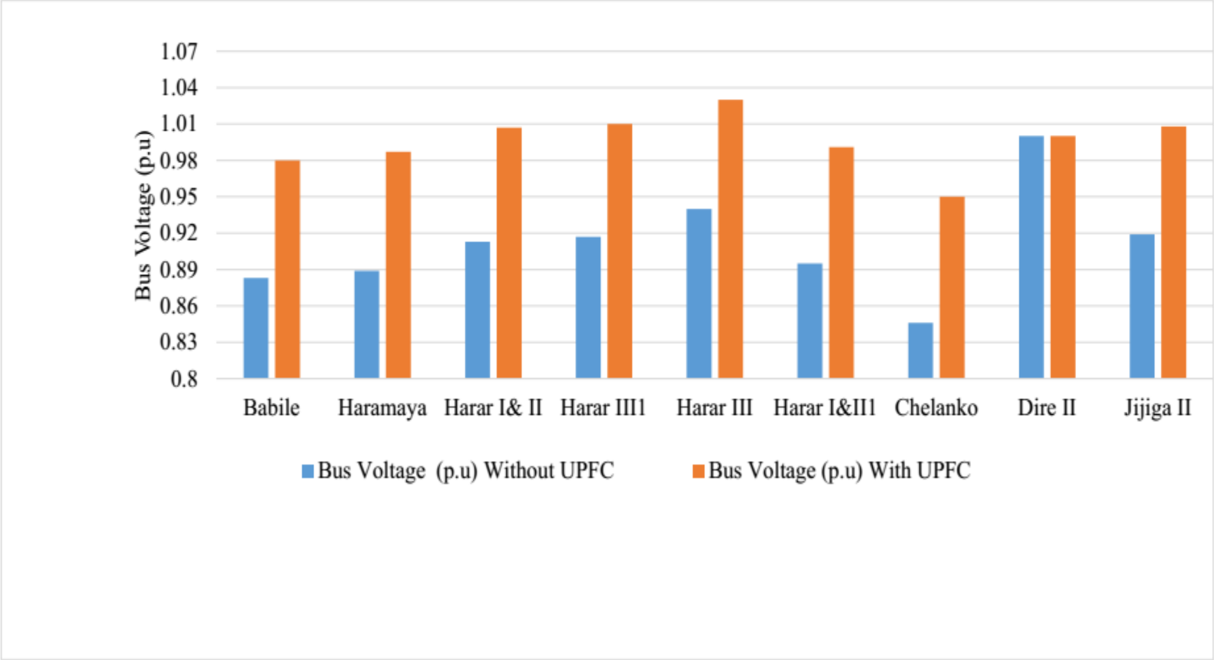

Figure 4.11: Comparison of buses voltage with and without UPFC at average load

Table 4.10: Rael power and reactive power losses of each transmission line without UPFC at average load

Line Number	From Bus	To Bus	Active power loss(MW)		Reactive Power loss (MVAr)	
			Without UPFC	With UPFC	Without UPFC	With UPFC
1	Dire II-32kV	Harar III-132kV	1.7682	0.8102	1.40	1.20
2	Harar III-132kV	Jijiga II-132kV	0.1164	0.1132	3.70	0.20
3	Harar III1-66kV	Harar I &II-66kV	0.0281	0.0228	0.00	0.00
4	Harar I & II 1-45kV	Babile-45kV	0.0140	0.0111	0.10	0.10
5	Harar III1-66kV	Haramaya-66kV	0.2551	0.1934	0.50	0.20
6	Haramaya-66kV	Chalenko-66kV	0.2049	0.1548	0.40	0.30
Total loss			2.3870	1.3060	6.10	2.00

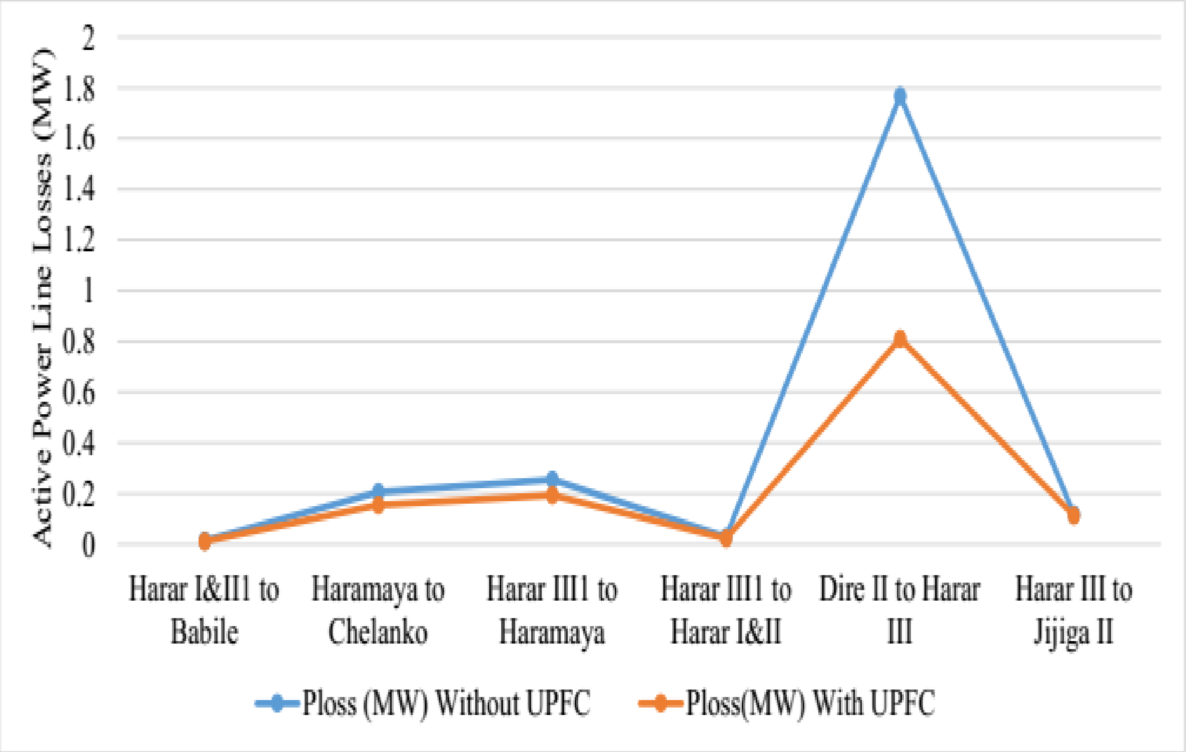

Figure 4.12: Comparison of active power loss on each line with and without UPFC at average load

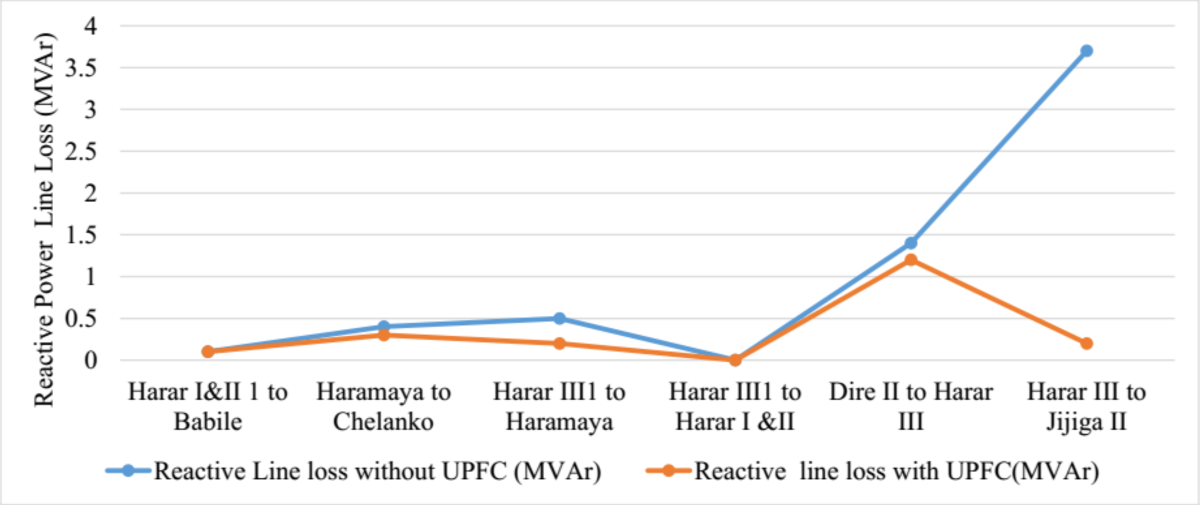

Figure 4.13: Comparison of reactive power loss on each line with and without UPFC at average load

The addition of UPFC between Dire II bus and Harar III bus improved the real power delivered to all substations. The total transmission line active power loss is 2.387MW before incorporating UPFC which accounts 4.71% of average load demand. After incorporating the total real power is reduced to 1.306MW which is accounts 2.58% of average load demand. The total transmission line reactive power loss is 6.1MVAr before incorporating UPFC after incorporating UPFC it is reduced to 2MVAr.The total active and reactive power losses are minimized by 45.29% and 67.21% respectively when UPFC is incorporated between Dire II bus and Harar III bus of Eastern region of Ethiopian transmission network.

4.3.3. Scenario 3: Minimum Load Condition with UPFC

After filling all the necessary data in to the transmission network diagram of the eastern region of EEP network load flow simulation was run for the minimum load condition. From the load flow result, active and reactive power at each bus, total transmission active and reactive power losses and bus voltages were identified. Table 4.11 shows that the overall DIgSILENT Power Factory result of the transmission network of eastern region of EEP with UPFC.

From table 4.11 the bus voltages profile of all buses are greater than 95%. This indicated that there is less real and reactive power losses on the transmission line and the voltage profile of the buses are improved. Due to this power delivered to the load side is as required level i.e the power transmitted meet the demand power at each substation because of improved voltage profile is attained at each bus. The simulation results shown in figure 4.14 and figure 4.15 quantify that the bus voltages are improved.

Table 4.11: Ethiopian Eastern Region Transmission Network Bus Voltage and Power with UPFC at minimum load

Bus No.	Bus Name	Bus Voltage (p.u)		Bus Voltage(kV)		Active Power(MW)	Reactive Power (MVAr)
		Without UPFC	With UPFC	Without UPFC	With UPFC		
1	Dire II -132kV	1.000	1.000	132.00	132.00	35.30	13.60
2	Jijiga II -132kV	0.943	0.990	124.50	130.70	6.200	4.300
3	Harar III -132kV	0.959	1.008	126.55	133.10	32.90	24.00
4	Haramaya-66kV	0.925	0.978	61.040	64.520	8.530	5.600
5	Chalenko-66kV	0.898	0.954	59.260	62.940	3.940	2.800
6	Babile-45kV	0.922	0.974	41.500	43.840	1.110	0.800
7	Harar I& II-66kV	0.940	0.991	62.050	65.400	8.530	6.200
8	Harar I &II 1-45kV	0.930	0.981	41.840	44.170	1.110	0.900
9	Harar III1-66kV	0.943	0.994	62.250	65.600	22.08	15.00

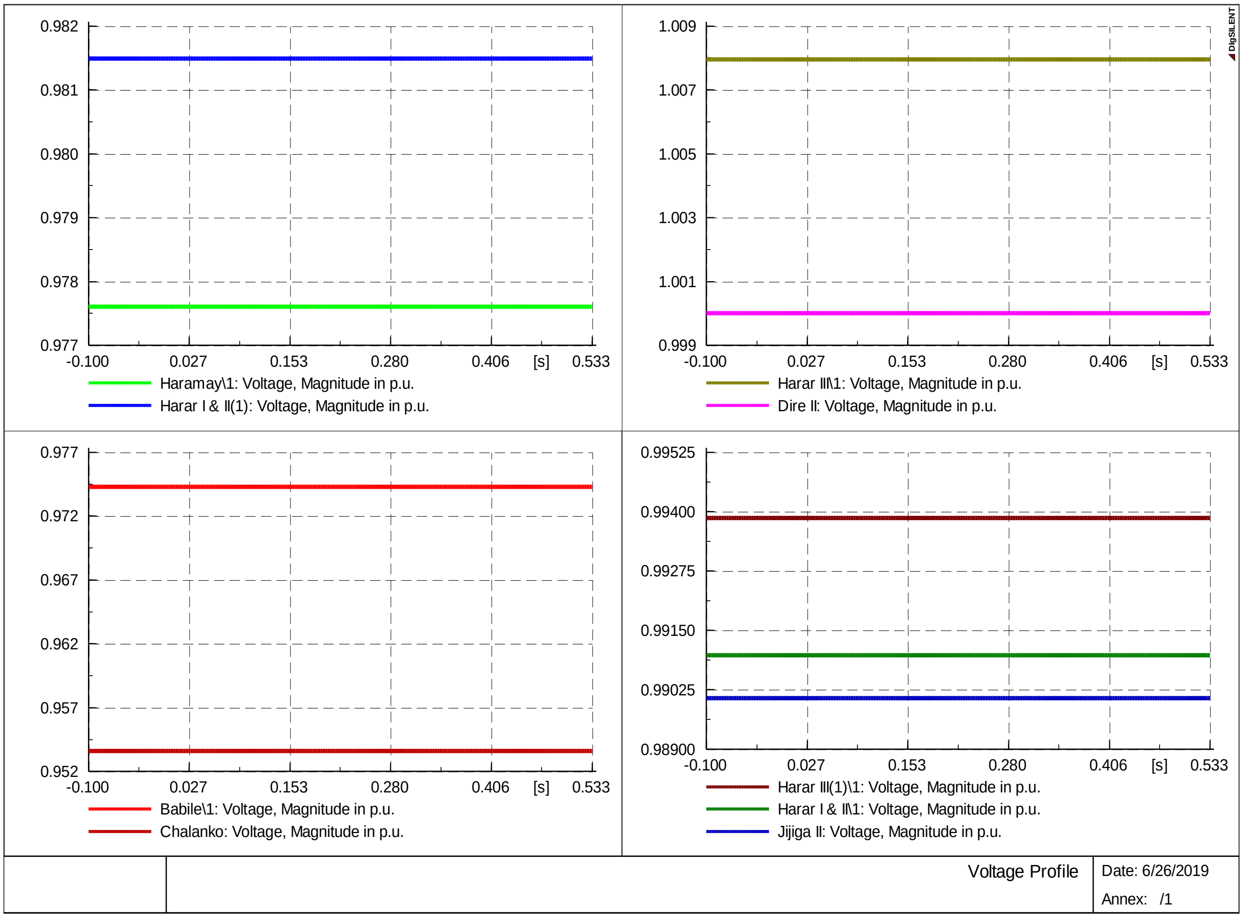

Figure 4.14: Bus Voltage in per unit with UPFC at a minimum load

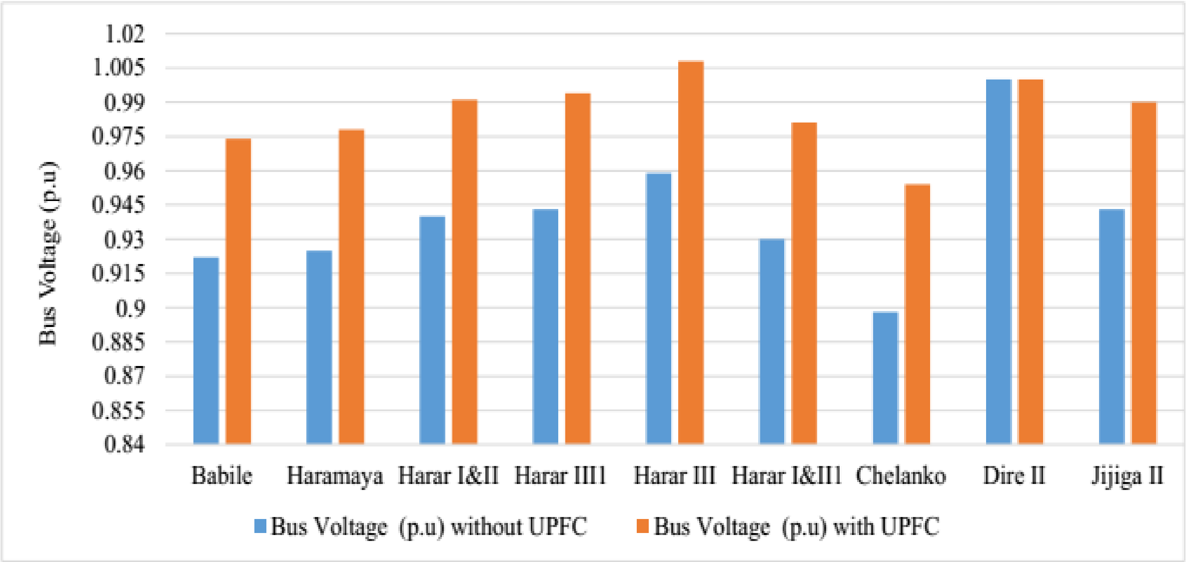

Figure 4.15: Comparison of buses voltage with and without UPFC at minimum load

Table 4.12: Rael power and reactive power losses of each transmission line without UPFC at minimum load

Line Number	From Bus	To Bus	Active power loss(MW)		Reactive Power loss (MVAr)	
			Without UPFC	With UPFC	Without UPFC	With UPFC
1	Dire II-32kV	Harar III-132kV	0.8744	0.202	0.20	0.30
2	Harar III-132kV	Jijiga II-132kV	0.0776	0.0722	3.90	0.10
3	Harar III1-66kV	Harar I &II-66kV	0.0182	0.0166	0.10	0.00
4	Harar I & II 1-45kV	Babile-45kV	0.0061	0.0054	0.10	0.10
5	Harar III1-66kV	Haramaya-66kV	0.1119	0.0928	0.20	0.00
6	Haramaya-66kV	Chalenko-66kV	0.0778	0.0648	0.10	0.40
Total loss			1.166	0.454	4.60	0.90

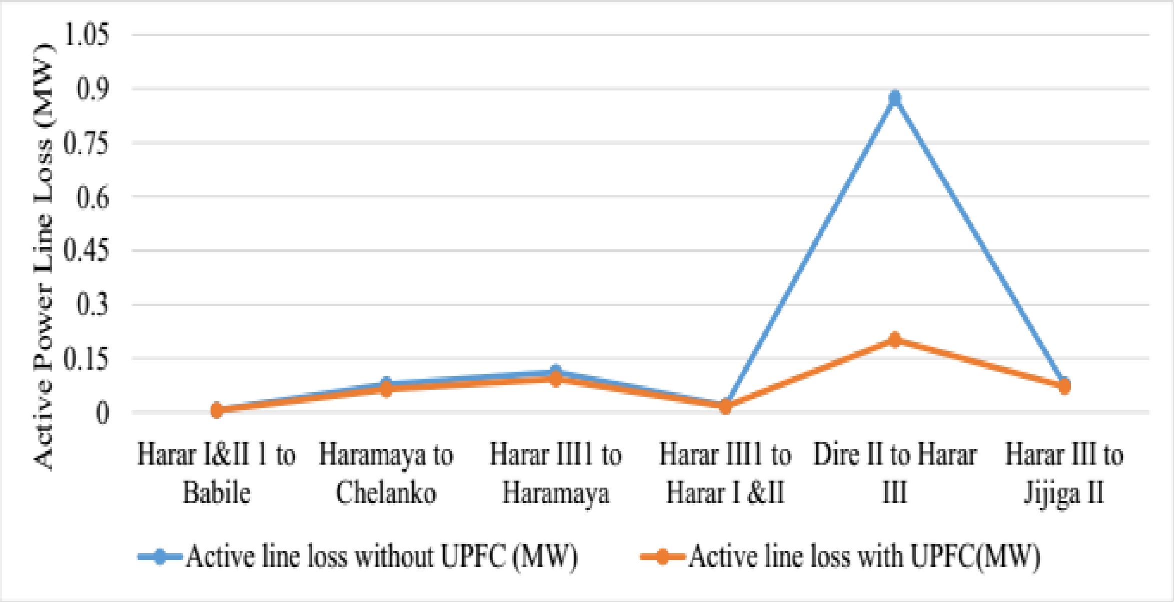

Figure 4.16: Comparison of active power loss on each line with and without UPFC at minimum load

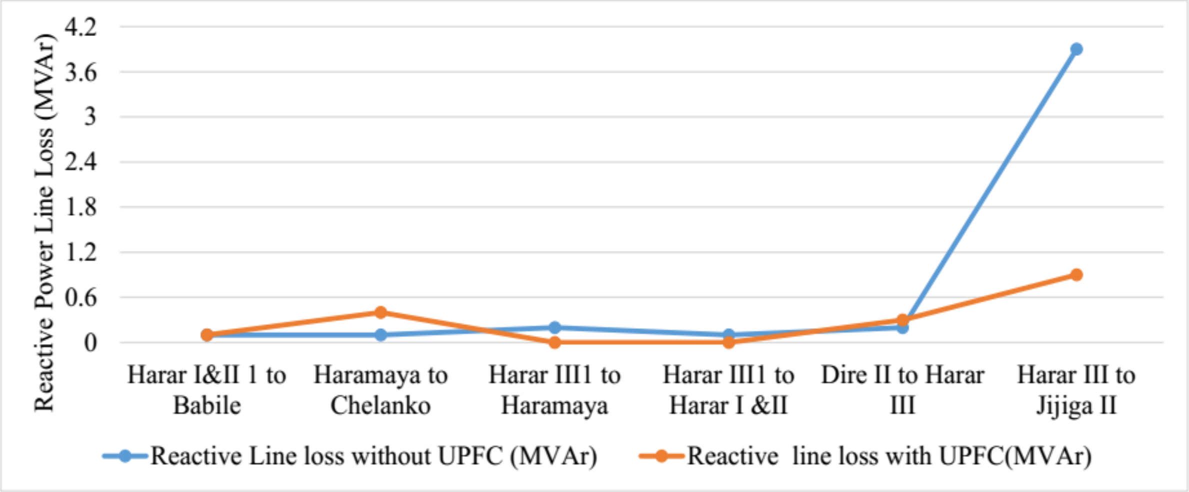

Figure 4.17: Comparison of reactive power loss on each line with and without UPFC at minimum load

The addition of UPFC between Dire II bus and Harar III bus improved the real power delivered to all substations. The total transmission line active power loss is 1.166MW before incorporating UPFC which accounts 3.13% of minimum load demand. After incorporating UPFC the total real power is reduced to 0.454MW which is accounts 1.22% of minimum load demand. The total reactive power loss is 4.6MVAr before incorporating UPFC after incorporating UPFC it is reduced to 0.9MVAr. The total active and reactive power losses are minimized by 61.06% and 80.43% respectively when UPFC is incorporated between Dire II bus and Harar III bus of Eastern region of Ethiopian transmission network.

Table 4.13: Total active and reactive power loss

Load condition	Active power loss (MW)		Reactive power (MVAr)	
	Without UPFC	With UPFC	Without UPFC	With UPFC
Peak Load	4.295	1.908	9.20	3.30
Average Load	2.387	1.306	6.10	2.00
Minimum Load	1.166	0.454	4.60	0.90

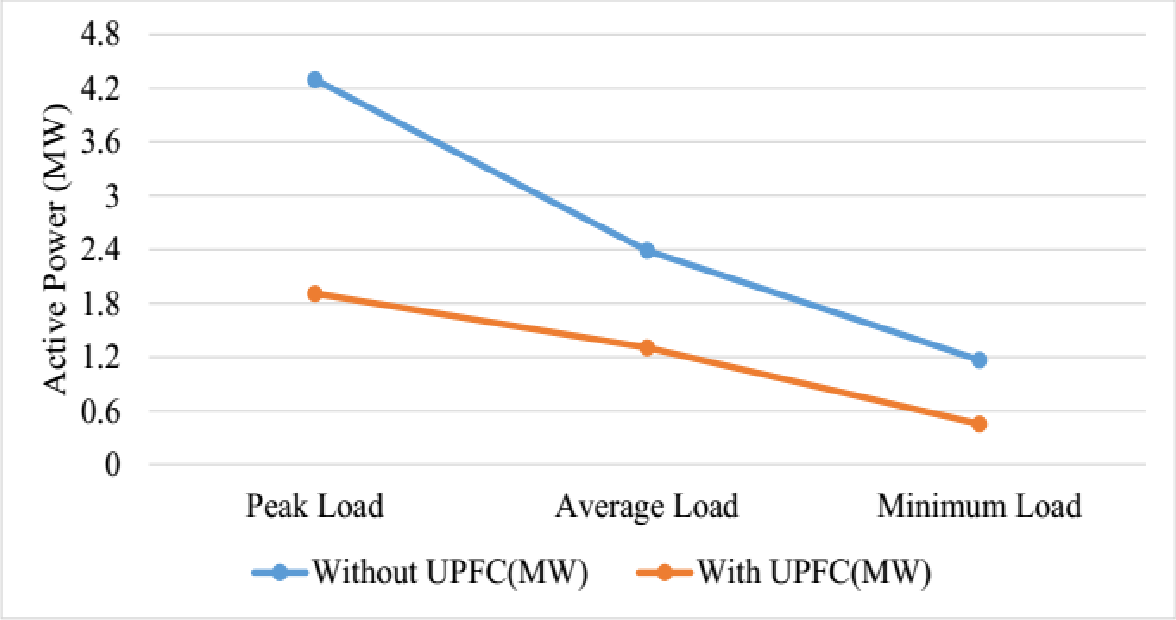

Figure 4.18: Comparison of total active power loss with and without UPFC

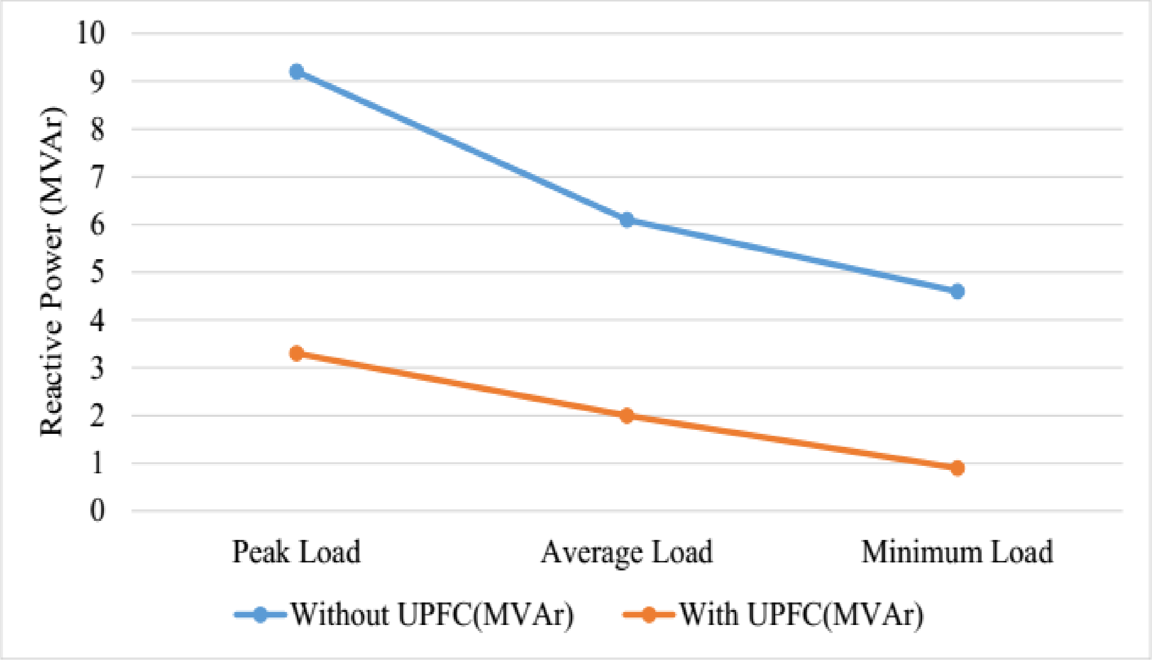

Figure 4.19: Comparison of total reactive power loss with and without UPFC

CHAPTER FIVE

5. CONCLUSIONS, RECOMMENDATION AND FUTURE WORKS

5.1. CONCLUSIONS

This thesis presents problem in power transmission line loss and voltage profile for eastern region of Ethiopia. The minimization of transmission line loss and improving voltage profile is analyzed in this thesis without and with UPFC.

The simulation result of the existing transmission network of eastern region of Ethiopia EEP with peak load condition delivered power having total transmission line active power loss of 4.295MW which is 6.49% peak load demand. For average load condition it delivered power having total transmission line active power loss of 2.387MW which is 4.71% average load demand and for minimum load condition it delivered power having total transmission line active power loss of 1.166MW which is 3.13% minimum load demand. The reactive power loss before incorporating UPFC is 9.2MVAr, 6.1MVAr and 4.6MVAr for peak load condition, average load condition and minimum load condition respectively.

The addition of UPFC between Dire II bus and Harar III bus improved the real power delivered to all substations. The total active power loss is reduced to 1.908MW, 1.308MW and 0.454W for peak load condition, average load condition and minimum load condition respectively. The total reactive power loss is also reduced to 3.3MVAr, 2MVAr and 0.9MVAr for peak load condition, average load condition and minimum load condition respectively. The total active power loss is minimized by 55.57%, 45.29% and 61.06% for peak load condition, average load condition and minimum load condition respectively. And also the voltage profile of all buses are with acceptable range after incorporating UPFC. Hence the existing transmission line facility will be utilized effectively and economically to transfer the power to the costumers.

The simulation result showed that the placement of UPFC present the best benefit on power losses minimization, improvement of bus voltage profile and power flow. The numerical results for the eastern region transmission network of EEP have been presented with and without UPFC and the comparative analysis was made.

The placement of UPFC is based on the system active power loss, transfer capability of the line, improvement of voltage profile and ease of accessibility for maintenance work.

Generally, this thesis shows that minimizing transmission line loss and improving voltage profile is advantageous in term of balancing the demand and supply. And also it has an advantage of using the existing transmission line rather than constructing new transmission line which requires long time planning and high investment cost. The result of this thesis encourage EEP to take advantage of incorporating UPFC in to the transmission network of Ethiopia.

5.2. RECOMMENDATION

The Ethiopian Electric Power is recommended to minimize the power loss and improve voltage profile of eastern region of Ethiopia. Based the thesis work it is recommended that the EEP should be use the UPFC for transmission lines instead of building and expansion of new transmission system network in order to save time and cost as well as the land it is consumed. The power company, EEP has to develop grid code which helps research to evaluate their designs to meet EEP's standard criteria's as a bench mark study.

5.3. FUTURE WORK

Future work on UPFC should consider the performance analysis of the device under different fault conditions. Cost analysis of this method is can be considered as future work.

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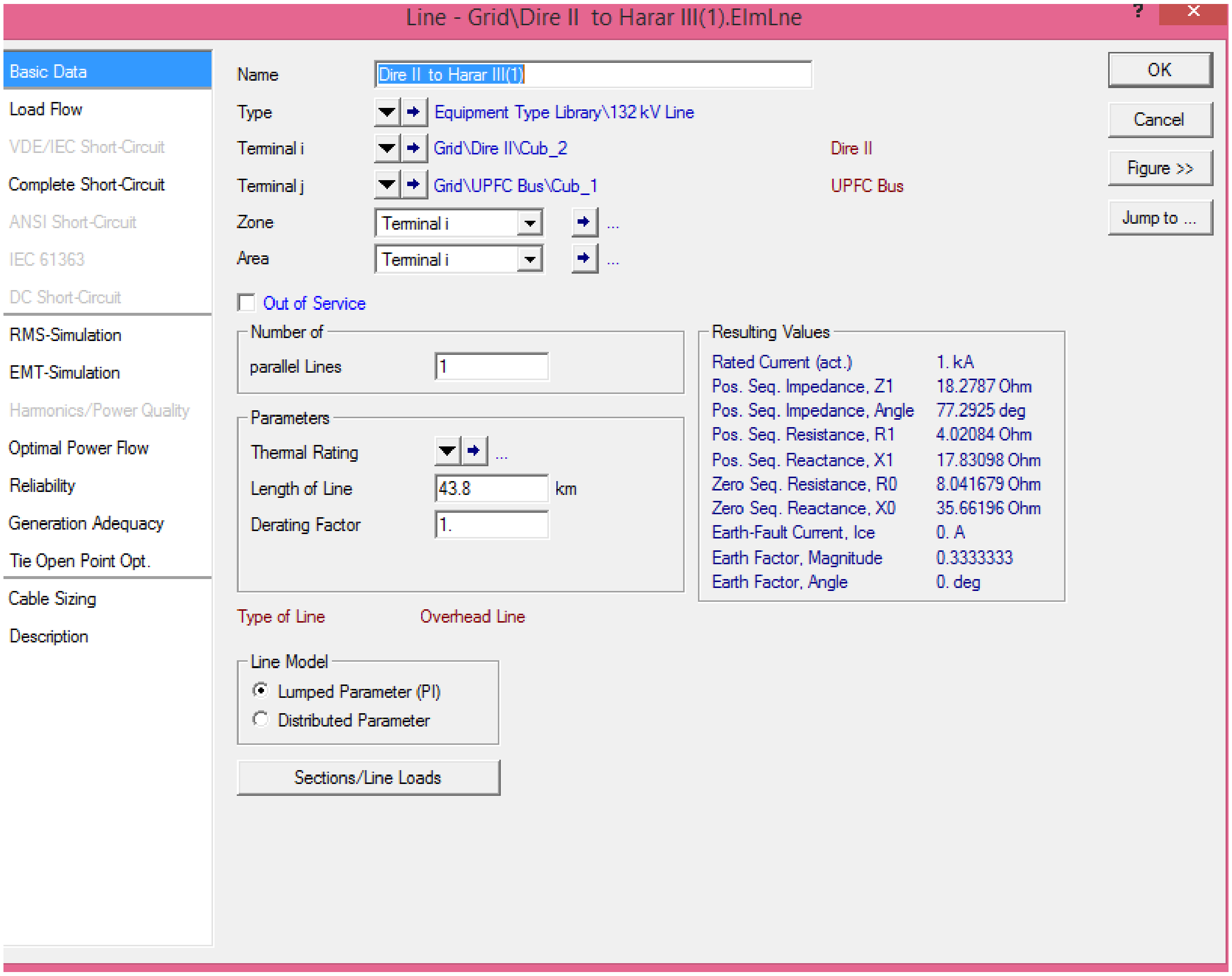
LIST OF APPENDICES

APPENDIX 1: LINE MODEL IN DIgSILENT Power Factory



Name: Dire II to Harar III(1)
Type: Equipment Type Library\132 kV Line
Terminal i: Grid\Dire II\Cub_2 Dire II
Terminal j: Grid\UPFC Bus\Cub_1 UPFC Bus
Zone: Terminal i
Area: Terminal i
☐ Out of Service

Number of
parallel Lines: 1

Parameters
Thermal Rating: ...
Length of Line: 43.8 km
Derating Factor: 1.

Type of Line: Overhead Line

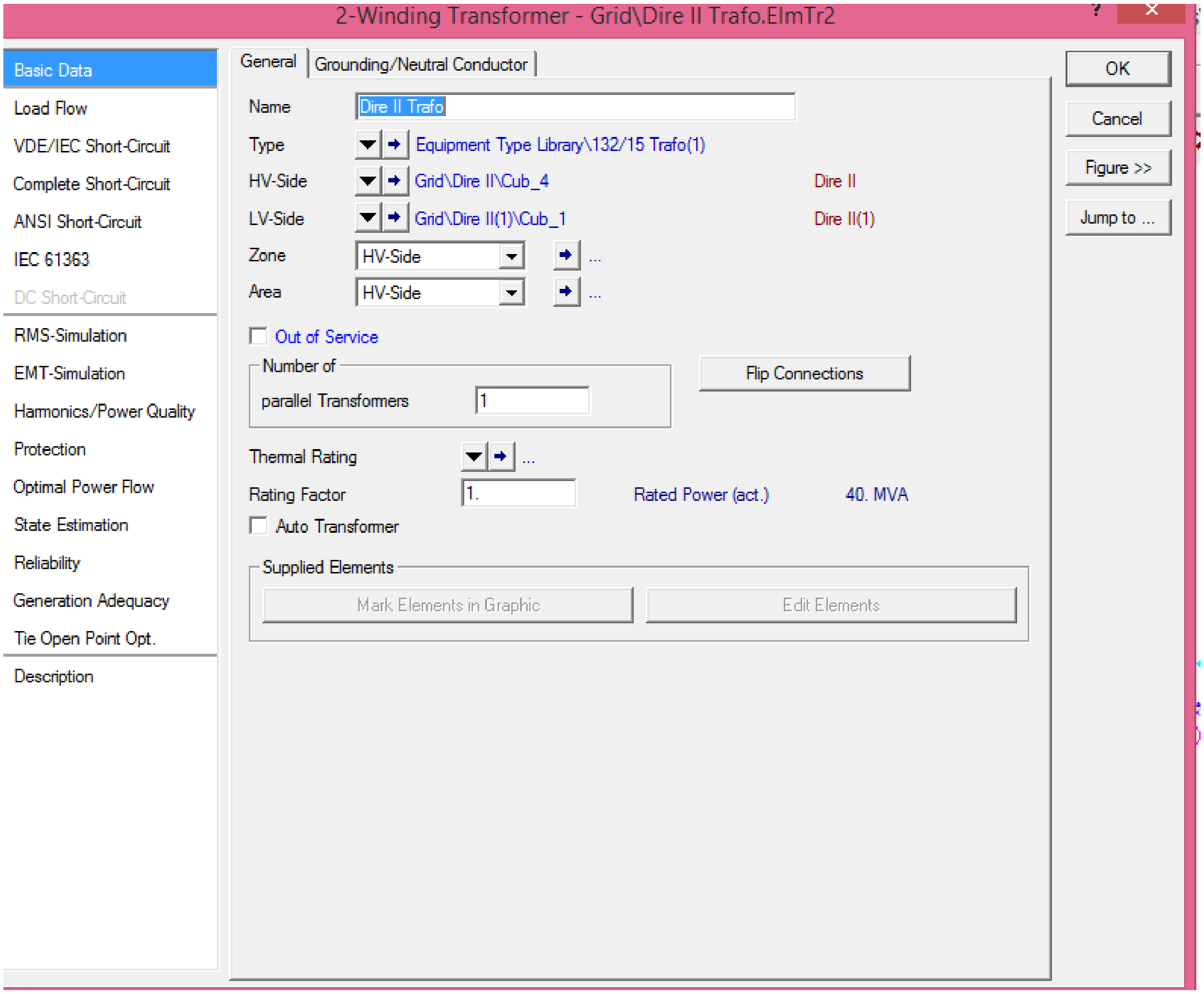
Line Model
● Lumped Parameter (PI)
○ Distributed Parameter

Resulting Values

Rated Current (act.)	1. kA
Pos. Seq. Impedance, Z1	18.2787 Ohm
Pos. Seq. Impedance, Angle	77.2925 deg
Pos. Seq. Resistance, R1	4.02084 Ohm
Pos. Seq. Reactance, X1	17.83098 Ohm
Zero Seq. Resistance, R0	8.041679 Ohm
Zero Seq. Reactance, X0	35.66196 Ohm
Earth-Fault Current, Ice	0. A
Earth Factor, Magnitude	0.3333333
Earth Factor, Angle	0. deg

Figure 1: Line model in DIgSILENT power factory

APPENDIX 2: POWER TRANSFORMER IN DIgSILENT Power Factory



2-Winding Transformer - Grid\Dire II Trafo.ElmTr2

Name: Dire II Trafo
Type: Equipment Type Library\132/15 Trafo(1)
HV-Side: Grid\Dire II\Cub_4 Dire II
LV-Side: Grid\Dire II(1)\Cub_1 Dire II(1)
Zone: HV-Side
Area: HV-Side
☐ Out of Service
Number of parallel Transformers: 1
Thermal Rating
Rating Factor: 1.
Rated Power (act.) 40. MVA
☐ Auto Transformer

Figure 2: Power transformer in DIgSILENT power factory

APPENDIX 3: BLOCK DIAGRAM OF SERIES CONTROLLER

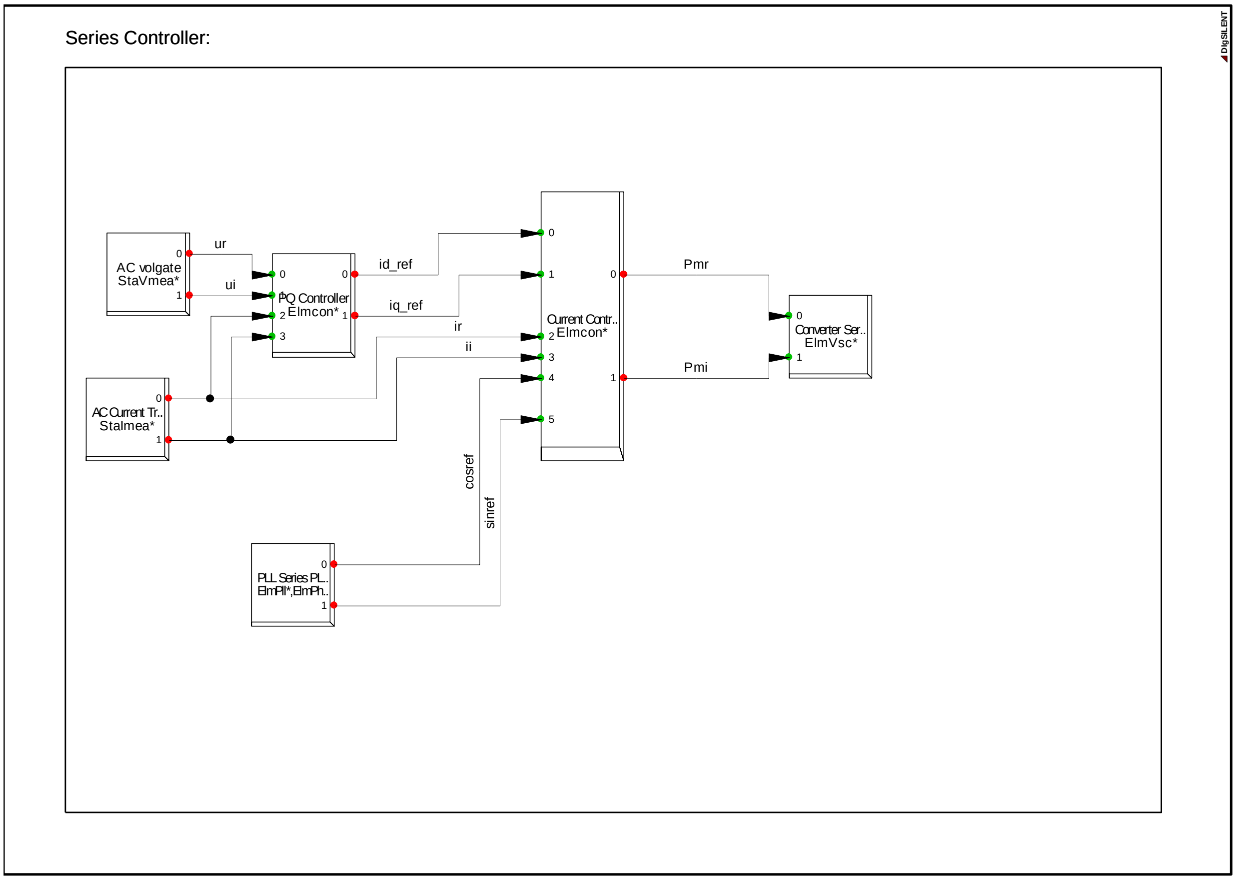


Figure 3: Block diagram of series controller

APPENDIX 4: BLOCK DIAGRAM OF SHUNT CONTROLLER

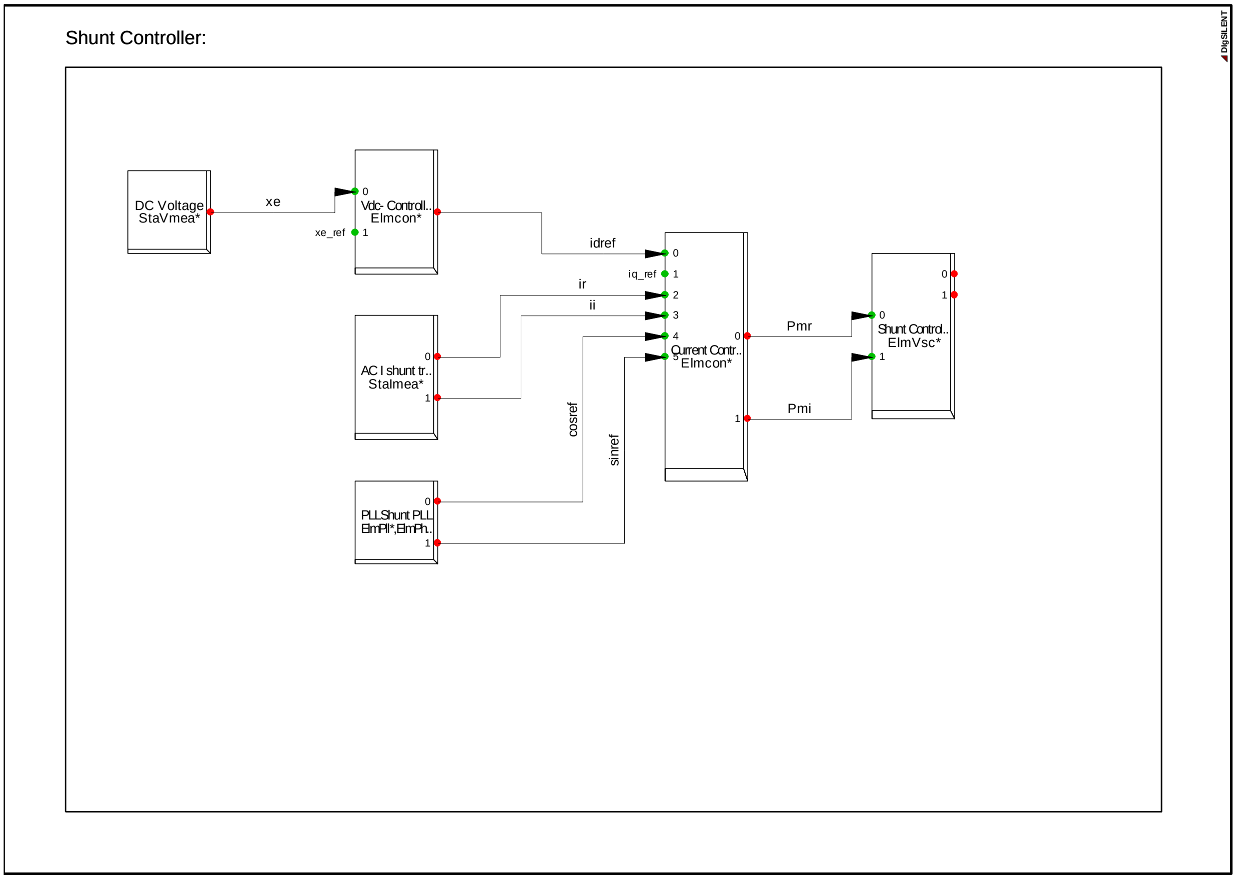


Figure 4: Block diagram of shunt controller

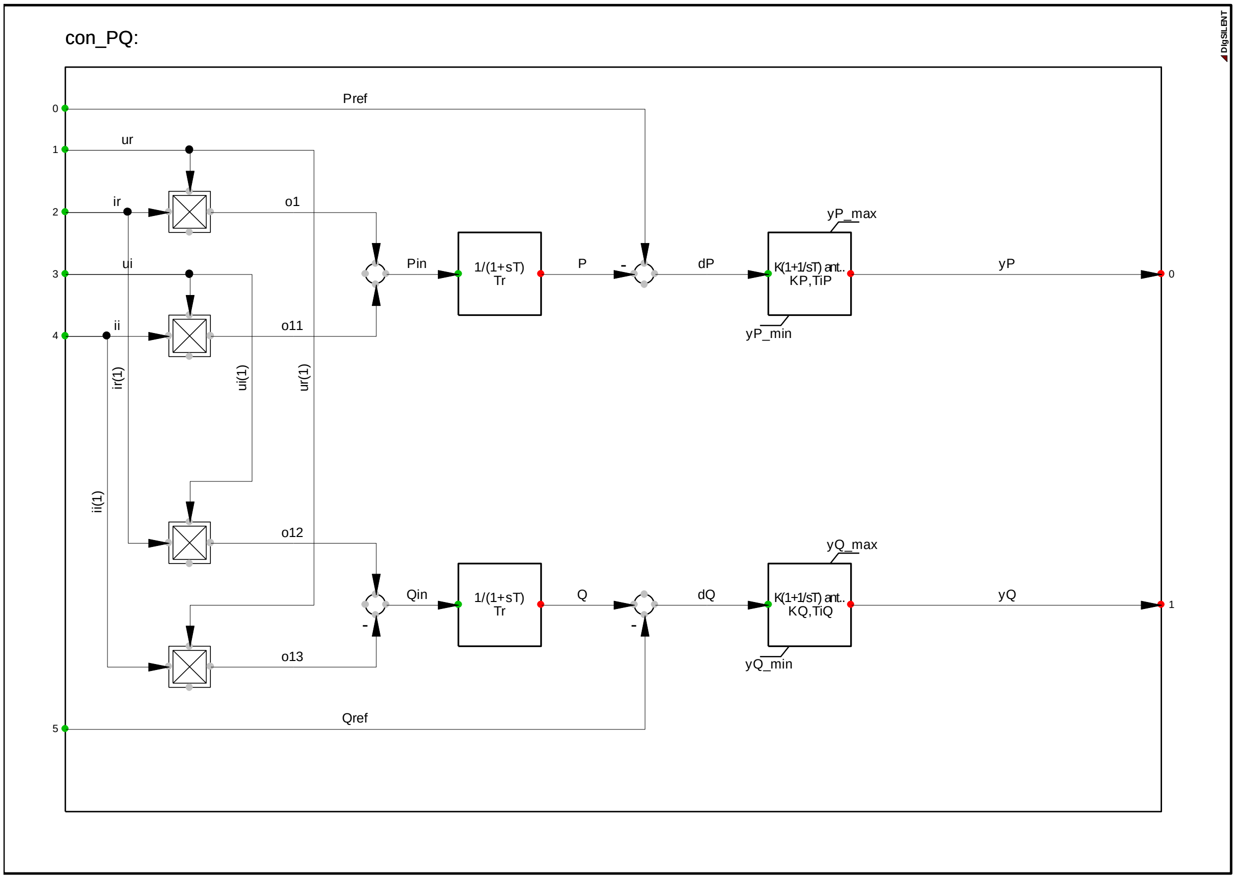


Figure 5: PQ controller

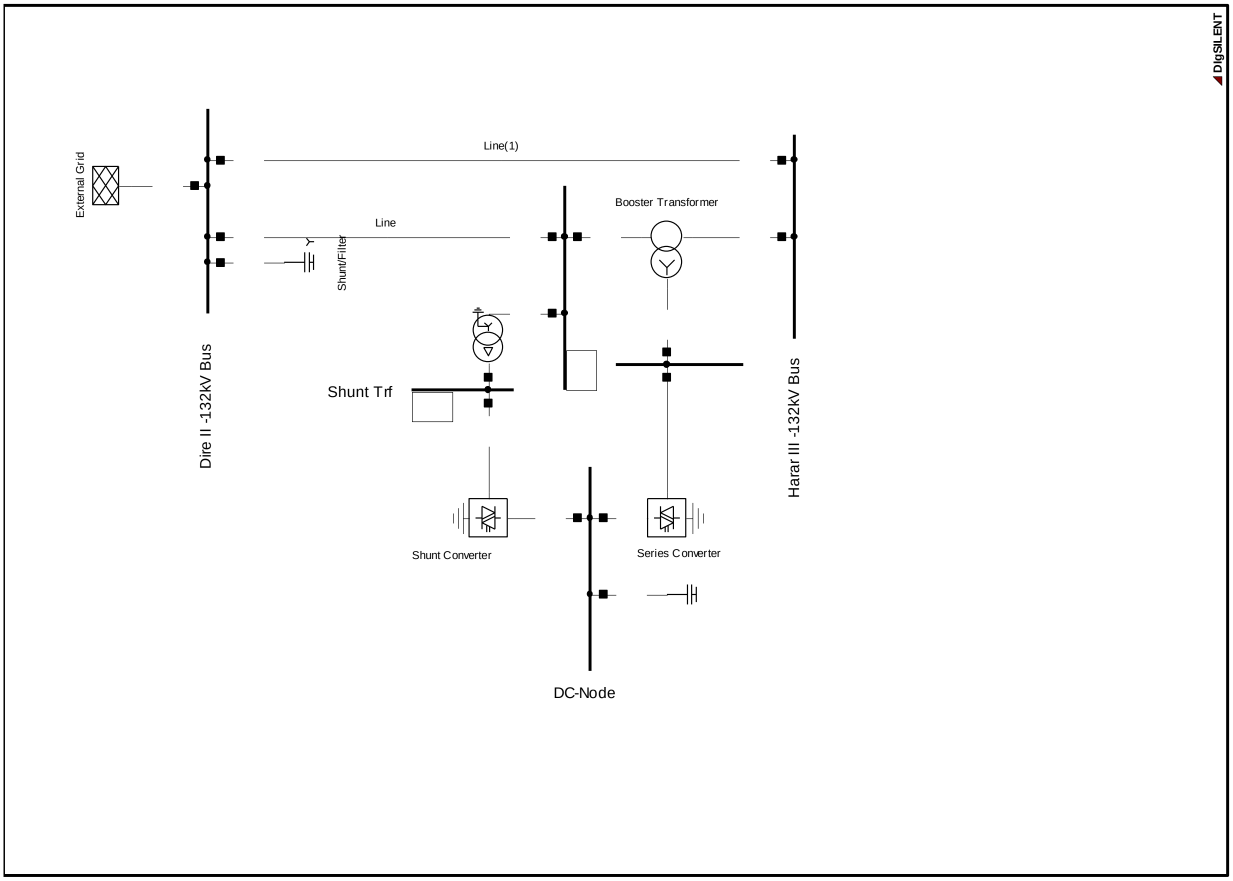


Figure 6: Basic Structure of Unified Power Flow Controller