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Minimization of Losses on Electric Power Transmission Line Using UPFC (A Case Study of Bahir Dar to Debremarkos Transmission Line)

ASMAMAW, ADMAS TAREKEGN

BAHIR DAR UNIVERSITY

BAHIR DAR INSTITUTE OF TECHNOLOGY

SCHOOL OF RESEARCH AND POSTGRADUATE STUDIES

FACULTY OF ELECTRICAL AND COMPUTER ENGINEERING

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MSc. THESIS

BY:

ASMAMAW ADMAS TAREKEGN

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ADVISOR: TASSEW TADIWOSE (PHD)

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BY

Asmamaw Admas Tarekegn

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Advisor:

TASSEW TADIWOSE (PHD)

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DECLARATION

I, the undersigned, declare that the thesis comprises my own work. In compliance with internationally accepted practices, I have acknowledged and refereed all materials used in this work. I understand that non-adherence to the principles of academic honesty and integrity, misrepresentation/ fabrication of any idea/data/fact/source will constitute sufficient ground for disciplinary action by the University and can also evoke penal action from the sources which have not been properly cited or acknowledged.

Name of the student: Asmamaw Admas Tarekegn

Signature: _____________

Date of submission: ___________________

Place: Bahir Dar

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

Advisor Name: TASSEW TADIWOSE (PHD)

Advisor's Signature: ___________________

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FACULTY OF ELECTRICAL AND COMPUTER ENGINEERING

THESIS APPROVAL SHEET

Student: Asmamaw Admas ______ 13/07/2020

Name Signature Date

The following graduate faculty members certify that this student has successfully presented the necessary written final thesis and oral presentation for partial fulfillment of the thesis requirements for the Degree of Master of Science in Power Systems Engineering.

Approved by:

Advisor: Dr. Tassew Tadiwose ______ 28/07/2020

Name Signature Date

External Examiner: Yoseph Mekonnen Abebe (Ph.D) ______ 27/07/2020

Name Signature Date

Internal Examiner: Dr.-Ing. Belachew Bantyirga ______ 28/07/2020

Name Signature Date

Prog. Chair Holder: Mr. Biniyam Zemene ______ 28/07/2020

Name Signature Date

Faculty Dean: Mr. Tewodros Gera ______ 28/07/2020

Name Signature Date

iv

ABSTRACT

Power systems continuously subjected to various types of disturbances, which cause a lot of power system instability which lowers its efficiency. Power loss is the major one which decreases the efficiency of electrical machine, disturb the quality and stability of the system, decrease the revenue of the government, and affect customer satisfaction. Minimization this loss is very important to increase distribution and transmission power flow. Power loss reduction have been focused in this research to solve the challenges happens in transmission systems. The contribution of this work presents loss minimization of the Bahir Dar to Debremarkose power transmission using a unified power flow controller (UPFC) applied in North West Region of Ethiopian power system network. This method is selected for loss minimization due to its versatility or its ability to control all power system parameters like active power, reactive power, bus voltage, line impedance and load angle. The research is properly modeled and conducted using MATLAB/SIMULINK software. The SIMULINK model contains both North West Region power system network and the UPFC. Power loss measurement of the transmission line has been conducted in different scenarios. The power loss measurement of the transmission line under steady state condition is 2.048MW. However, when UPFC is connected to the power system network of the North West Region, the loss of the transmission line is reduced to 85.12kW and hence 1.69MW power is saved from the transmission line by using UPFC. When the power system network is exposed to three phase fault at 230kV distribution network and the fault sustained from 0.1-0.5seconds, the loss becomes 2.0482MW. However, when UPFC is used, the power loss becomes 82.21kW. Hence, at least 1.963MW power is saved from loss wasted by the transmission line using UPFC.

Keywords: Flexible AC Transmission System, MATLAB/SIMULINK, Power Loss, Unified Power Flow Controller.

LIST OF ABBREVIATION AND SYMBOLS

CSFSA	Chaotic Stochastic Fractal Search Algorithm
DER	Distribution Energy Resource
DG	Distribution Generation
DNR	Distribution Network Reconfiguration
DPFC	Distributed Power Flow controller
d-q	Direct and Quadrature Axis
DSS	Distribution System Simulator (DSS)
EEP	Ethiopian Electric Power
FACTS	Flexible AC Transmission Systems
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated Gate Bipolar Junction Transistors
IPFC	Interline Power Flow Controller
KCL	Kirchhoff’s Voltage Law
KVL	Kirchhoff’s current Law
NWR	North West Region
PCC	Point of Common Coupling
PI	Proportional Integral
PID	Proportional Integral and Derivative
PLL	Phase Locked Loop
PWM	Pulse Width Modulator
Se	Series
Sh	Shunt

SSSC	Static Synchronous Series Compensator
STATCOM	Static Synchronous Compensator
SVC	Static VAR Compensator
TCR	Thyristor Controlled Reactor
TCSC	Thyristor controlled Series Compensator
TEP	Transmission Network Expansion Planning
TSC	Thyristor Switching Capacitor
UPFC	Unified Power Flow Controller
Var	volt-ampere reactive
VSI	Voltage Source Inverter
I	Current
Ki	Integral Constant
Kp	Proportional Constant
P	Real Power
Q	Reactive Power
R	Resistance
S	Apparent Power
V	Voltage
X	Reactance
Y	Admittance
Z	Impedance

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CHAPTER ONE

1. INTRODUCTION

Electrical energy is considered as a basic infrastructure for the country as a whole and as a household level. Modern human life highly depends on the need of Electrical power. We can find small to big industry, agriculture, transportation, defense, public center, home and other places. Due to easy to use and controllability, cheapness, suitable and efficient transformation to other forms of energy, cleanness, greater flexibility, versatile forms, instant availability and consumer end cleanliness, electricity has become an indispensable, multi-purpose form of energy.

Power generated in power stations pass through large and complex networks like transformers, underground and overhead lines and other equipment to distribute to customers. Like all other systems, no matter how carefully the system is designed, losses are present and must be modeled before an accurate representation of the system response can be calculated. Due to the size of the area that the power system serves, most of the system components are dedicated to power transmission. This means, the unit of electric energy generated by Power Station does not match with the units distributed to the consumers. Some percentage of the units is lost in the transmission and distribution network. The difference in the generated and distributed units is known as Transmission and Distribution loss. Losses are the amounts that are not paid for by users. Therefore, it reduces the revenue that the power plant deserves of getting money. In addition, it reduces the customer satisfaction from the power supply company and reduces the total production of goods and services of the country. The ultimate result of power loss is unsustainable growth of the individuals, communities, and the economy of country.

A utility company engages in producing electric power in such a way that reduce complexity and lengthy of line joining the generation and the load. Therefore, transmission lines, distribution substation and generations are initially built to link remote generating power plants to load centers, thus allowing power plants to be located in regions that are more economical and environmentally suitable. However due to the accessibility of resources, generation plants and end users are normally located geographically far from each other and they are connected by transmission lines, which may go through desert, jungles or even mountains. Those up down land elongate the transmission line and affect the voltage quality; increase the power loss and the reliability of the power to the end user. These natural constraints make the power loss as the existing characteristics of power system defects.

There are two types of Transmission and Distribution Losses: - Technical Losses and non-Technical Losses (Commercial Losses). Each category has their own causes and have different impact as shown below in Figure 1.1.

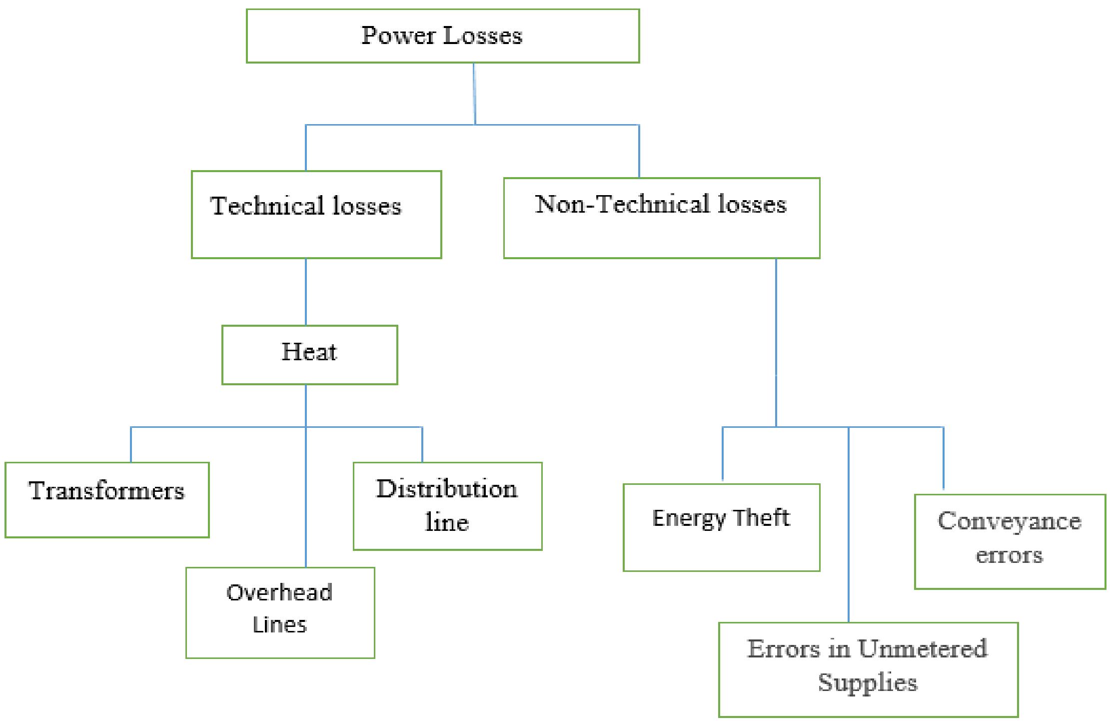


Figure 1.1 Classification of power loss

i. Technical Losses

These losses are due to energy dissipated in the conductors, in equipment used for transmission line, transformer, sub transmission and distribution line, and in magnetic losses of transformers [1]. These losses always come from the heat produced on the conductor, transformers generally in electrical equipment's and the heat is due to lengthy of conductor, corona, leakage current, dielectric losses, open circuit losses and losses due to continuous load of control elements. Some causes for technical losses are:

- **Lengthy Distribution lines**:- The power lines in rural areas are extended over long distances to feed loads scattered over large areas. Thus, the primary and secondary distributions lines in rural areas are largely radial laid usually extend over long distances. This long distance has high resistance and can have I^2R losses in the line.
- **Inadequate Size of Conductors**: - The size of the conductors should be selected based on the capacity of standard conductor for a required voltage regulation, but rural loads are usually scattered and generally fed by radial feeders. The conductor size of these feeders should be adequate (should have enough cross-sectional area to decrease the resistance of the conductor).
- **Installation of Distribution transformers away from load centers**: - In most case, Distribution Transformers are not located centrally with respect to consumers. Consequently, the farthest consumers obtain an extremity low voltage even though a good voltage levels maintained at the transformers secondary. This again leads to higher line losses (The reason for the line losses increasing because of decreased voltage at the consumer's end). Therefore, to reduce the voltage, drop in the line to the farthest consumers, the distribution transformer should be located at the load center to keep voltage drop within permissible limits.
- **Low Power Factor of Primary and secondary distribution system: -** For a given load, if the Power Factor is low, the current drawn is high and the losses proportional to square of the current will be more. Thus, line losses owing to the

poor PF can be reduced by improving the Power Factor. This can be done by application of shunt capacitors.

- **Bad Workmanship: -** Bad Workmanship significantly contributes role towards increasing distribution losses. Connections to the transformer bushing-stem, drop out fuse, isolator, and low-tension switch etc. should be periodically inspected and proper pressure maintained to avoid sparking and heating of contacts. Replacement of deteriorated wires and services should also be made timely to avoid any cause of leaking and loss of power.
- **Feeder Phase Current and Load Balancing: -** One of the easiest loss savings of the distribution system is balancing current along three-phase circuits. Feeder phase balancing also tends to balance voltage drop among phases giving three-phase customers less voltage unbalance.
- **Switching off transformers: -** One method of reducing fixed losses is to switch off transformers in periods of low demand. If two transformers of a certain size are required at a substation during peak periods, only one might be required during times of low demand so that the other transformer might be switched off to reduce fixed losses. This will produce some offsetting increase in variable losses and might affect security and quality of supply as well as the operational condition of the transformer itself. However, these trade-offs will not be explored and optimized unless the cost of losses are considered.

ii. Non-technical losses

These losses occur due to unidentified, misallocated, or inaccurate energy flows. They can be thought of as electricity that is consumed but not billed. It is important to differentiate this from electricity that is billed but where the bills are not paid. In the case of non-technical losses, the end user is unknown, or the amount of energy being consumed is uncertain. The three types of non-technical losses are:

- **Energy Theft**: - The energy that has been illegally taken from the network through tampering with meters or other network assets. This is taken without the knowledge of an energy company and leads to differences between estimated and actual electricity consumption. Energy Theft increases everybody's energy bills and creates serious electrical hazard.

- **Errors in Unmetered Supplies**: - Can occur due to inaccuracies in meter readings, unregistered meter points, errors in registration or faulty meters. These errors result in a discrepancy between actual and measured consumption, meaning energy is lost in the system.
- **Conveyance errors**: - Are commonly used for the communal areas in council owned buildings, streetlamps, bus stops and advertising boards. Unmetered supply customers provide inventories of their connected electrical equipment and estimated consumptions.

1.1 Statement of the Problem

Modern electric power system is facing many challenges due to day-to-day increasing complexity in their operation and structure. This is due to demand of electrical power is continuously rising at a very high rate due to rapid industrial development, urbanization, and population growth. One of the challenges is the unbalance between the generated power and the load demand. The unbalance may come from either excess demand than the generation or from losses on the transmission line. The power system losses in transmission line systems vary with numerous factors depending on system configuration of power system components and equipment's such as the transmission lines, transformers, capacitors, insulators, etc. Ethiopian government is building huge power plants like hydro, wind, solar and any other power plants. However, still research indicates that transmission and distribution losses are around wastes some percentage from the generated power. This makes crisis in power producer revenue, in domestic product, in customer satisfaction and extra. There are different techniques to solve power loss problem. For instance, using a low resistance cable in the transmission line like silver and copper is a simple logic regardless of their cost. It is the intent of this thesis to reduce this loses using UPFC. Among FACTS device UPFC is one of the more interesting and potentially the most versatile. It can regulate power flow, by controlling active power and reactive power; can improve the transmission line capacity of power system in power system transient state. It can realize fast-acting reactive power compensation, dynamically supporting the voltage at the access point and improving system voltage stability. The most preferred behavior of UPFC is, it can be changed from one mode of operation to the other without its hardware changing.

1.2 Objectives of the Thesis

1.2.1 General Objectives

To reduce the power loss of the transmission line having a length of 193.7km from Bahir Dar substation to Debremarkose substation by using UPFC.

1.2.2 Specific Objectives

- Reviewing literatures related to power loss minimization.
- Collecting data required for system modeling.
- Modeling and analysis of Bahir Dar to Debremarkose power system networks using MATLAB/SIMULINK
- Study the power lost on the line under existing system and in different scenarios.
- Design UPFC controllers, size UPFC and determine its placement on the North West region of Ethiopian electric power network.
- Apply UPFC on the modeled network.
- Analyze the performance of transmission line loss with and without UPFC

1.3 Methodology

To complete this work, tasks have been conducted based on the following steps.

- **Problem identification:** In Ethiopia especially in North West Region, power interruption is habitual. There are a lot of reasons for this and power loss is the major one. This loss is due to non-balancing of load demand and power flow on the peak load lines. Any fault on the power system network can also be the cause of power losses in the transmission and distribution losses. Power losses have lots of disadvantage for efficient use of any projects in individual, community, and the country level.

- **Literature review:** A number of published ideas about methods of reducing the power losses on the transmission line have been reviewed from books, papers, articles, journals, lecture notes, power points about the different methods and techniques used to improve power loss.
- **Data Collection and analysis:** The data's required for the thesis have been gathered from the concerned body. These data have been filled in the system and examined based on accepted standards.
- **Modeling of system design**: - In this work, UPFC has been selected and designed based on the existing system of North West Region power network. The design procedure is selected with its mathematical description. Lots of engineering work is conducted in this portion.
- **Simulation and discussion**: Simulation is done in matlab platform in different scenario and constraints. Finally, the result has been discussed and concluded the output obtained from the work based on internationally accepted terms and standards.

1.4 Scope of the Study and Significance of the Thesis

1.4.1 Scope of the Study

The North West Region of Ethiopian power system network has been modeled. Any disturbance, which affects the healthiness of this power network, has been checked. The power loss of the transmission line is analyzed in different situations. The analysis and modeling of UPFC for power loss mitigation of a transmission line extending from Bahir Dar substation to Debremarkose substation is conducted. Proper designing of UPFC in terms of its sizing and its dynamic response for every power disturbance system is carried out. The effect of using UPFC on the existing Ethiopian power system of North-West region in steady state condition is examined. The response of UPFC when the power system exposed to disturbance like three phase short circuit and load variation is tested. Finally, the power system responses without UPFC and using UPFC on the network have been analyzed. MATLAB\SIMULINK used as a tool to conduct the research.

1.4.2 Significance of the Thesis

Power loss mitigation is important from the viewpoint of increasing the efficiency of an electrical machine, decreasing the overloading of the transmission line and generally for maintaining the security of electrical network. UPFC, which is one of the versatile FACTS devices, can keep the loading of the transmission line in its optimum capacity by dynamically responding for any power system disturbance. Overloading of the transmission line is due to the disturbance of power system components. (i.e. over loading may be due to increment of high load on the distribution substation, faults on the other line of power system networks or due to high generation). Keeping the transmission line on its optimum loading capability decrease the power loss and increases the security of the power system network. Therefore, using UPFC for power loss mitigation of the transmission line extending from Bahir Dar substation to Debremarkose substation have the afore mentioned advantages.

1.5 Background of Case Study

Power development was introduced in Ethiopia as early as 1950s, and since then the Ethiopian electric power sector has served over 55 years. At the beginning of this electrical power for Ethiopia, the main energy source were hydropower plants, which are Tis Abay, Koka, Gilgel Gibe, Tana Beles to mention a few. Now a day many types of power source introduced including hydro, solar, wind, geothermal and others. Like the global challenges of power system defects, Ethiopia also suffered for it. Most of power system defects are power system stability, power system quality and power loss. Therefore, optimization of power system defect now a day takes the most priority for electrical engineers. This thesis case study area focuses on the power loss minimization of the transmission line extended from Bahir Dar substation to Debremarkose substation. The transmission line covers a length of 193.7km and caries 400kV. The transmission line loss is to be minimized by using the compensating device placed on the North West Region of Ethiopian power system network.

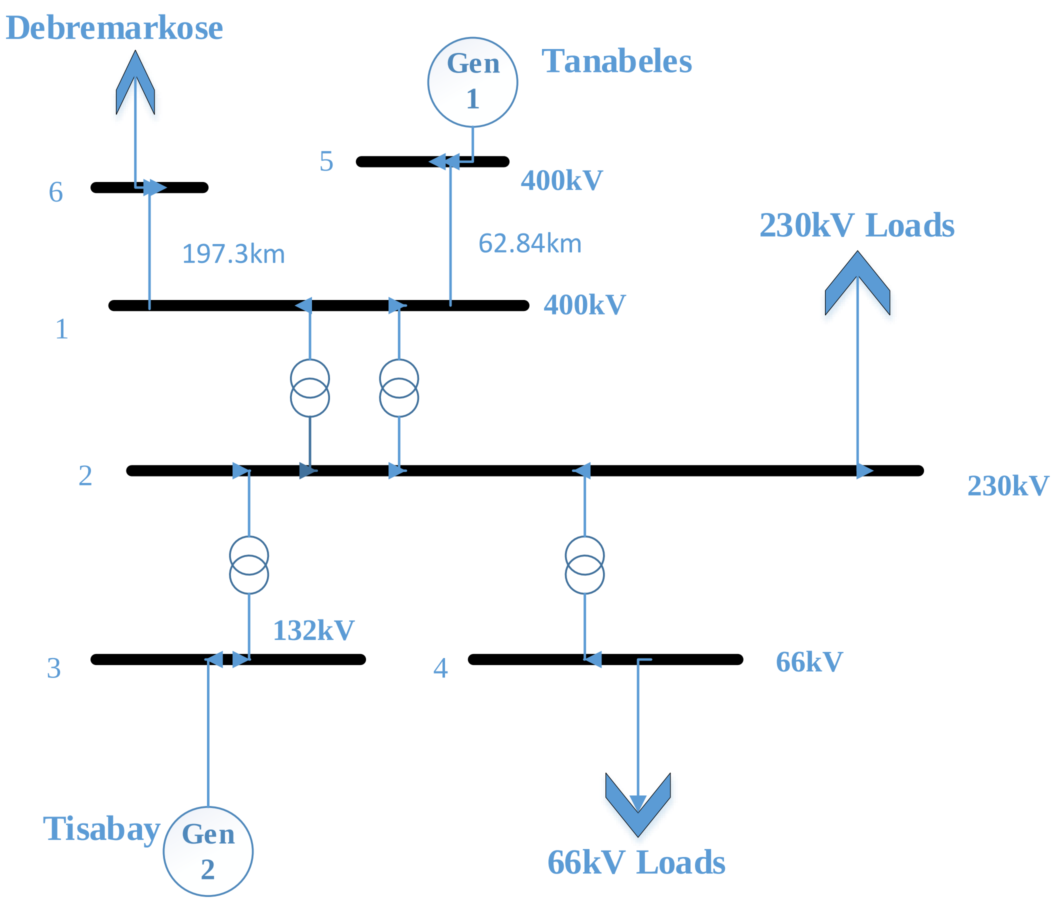


Figure 1.2 North-West Region, power system network

The case study is conducted on the power loss of the transmission line from Bahir Dar substation to Debremarkose substation (from bus bar 1 to bus bar 6). However, it covers the North West region of Ethiopian power system network because any new cases in the North West region of Ethiopian power system network can greatly affect the healthiness of the transmission line from Bahir Dar to Debremarkose substation. For instance, the fault on Gondar substation or Alamata line can greatly affect the congestion status of Bahir Dar to Debremarkose power line.

As shown in the Figure 1.2, the case study area contains generator, bus bars, transformers, transmission line and loads. Each component has its own loss and most of the power loss is usually occur in the transmission line, even if the cause for loss is may or may not be by the component itself or by the other component. This means that the change in one parameter of the one component will also change the parameters of other components. For example, change the quantity of the load will also change the percentage loading of the transmission line, transformers and the MVA output of generators.

Therefore, compensating the load variation in one of the North West Region (NWR) substation would amend the loss on the transmission line. In this thesis, the transmission line losses from Bahir Dar substation to Debremarkose substation would be improved by applying UPFC on the above electrical power network. If any load variation or faults occur in the North West, maximum or minimum power comes from the national grid UPFC can regulate the North West region and can reduce congestion on the line so that it can optimize power loss.

1.6 Thesis Organization

To make this work easy, the contents have been divided into five chapters. A brief overview of each chapter is given as follows.

Chapter-1: deals with an introduction about power loss in power system components and electrical equipment is in general. The cause and classification of power losses in power system have been discussed in this chapter. Statements in power losses problems, Objective of the thesis, significance of the thesis, limitation and scopes of the work are explained in this chapter.

Chapter-2: this chapter discussed about the power system loss mitigation mechanisms. The load flow equation used to determine power system parameters at each power system components is explained more to find the solution for each power system defects. Ways of reducing the power loss is discussed well in this chapter. Different literature has been reviewed which are essential for this work. From different literatures reviewed, the unified power flow controller has been selected to reduce the power loss of the transmission line from Bahir Dar substation to Debremarkose substation.

Chapter-3: this chapter contains the design procedures of UPFC used to reduce the power loss of the transmission line. In the design part of this portion, various concept has been included. Modeling of the North West region has been conducted. Mathematical modeling of UPFC, controller design of UPFC and placement techniques of UPFC has been conducted.

Chapter-4: this chapter contains simulations results and discussion of the power loss of the transmission line. A comparative analysis of the system simulation with UPFC and without UPFC is explained. The simulation and discussion scenario has been selected based on their contribution, which can change the magnitude of the power loss. For instance, different locations of UPFC have different impacts on the loss magnitude.

Chapter-5: conclusion has been conducted about results found from the simulation results. Conclusion and recommendation has been carried out about the overall impact of using UPFC in reducing power loss of the transmission line.

CHAPTER TWO

2. POWER LOSS

Power system in any country comprises of generating units that produce electricity, high voltage transmission lines that transport electricity over long distances, distribution lines that deliver the electricity to consumers, substations that connect the pieces to each other and energy control centers to coordinate the operation of the components. Therefore, activities relating to the management of existing generation, transmission and distribution of electrical energy needs to be given the highest priority in the national energy planning process of any nation.

There is no difference between a transmission line and a distribution line except for the voltage level and power handling capability. Transmission lines are usually capable of transmitting large quantities of electric energy over great distances and operate at high voltages while Distribution lines carry limited quantities of power over shorter distances. Voltage drops in line are in relation to the resistance and reactance of line, length and the current drawn. For the same quantity of power handling capacity of line, lowering the voltage increases the current drawn and higher the voltage drops. The current drawn is inversely proportional to the voltage level for the same quantity of power handled. High voltage transmission and distribution thus would help to minimize line voltage drop in the ratio of voltages, and the line power loss in the ratio of square of voltages. Lower voltage transmission and distribution also calls for bigger size conductor because of current handling capacity needed.

When a transmission line is subjected to electric power, electric current flows in the medium. This flow of current on the conductor always encounter opposition (resistance) from the conductor and consequently power losses occur as current flows through resistive materials and the magnetizing energy in the lines. The consequence of this loss disturbs the operating system of the electrical equipment, decrease the efficiency of electrical machine, and finally destabilize electrical network. It also increases the operating cost of electric utilities and consequently results in high cost of electricity. Therefore, reduction of system losses is of paramount importance because of its financial, economic, and socio-economic values to the utility company, customers and the host country.

Power system losses can be computed numerically using several formulae in consideration of power system network by taking resistance and reactance of transmission line as a determining factor for it. However, based on the types of power source (DC or AC) and the length of transmission line, the numerical computation can be conducted by two methods [2].

i. **Computing transmission losses by ohm's law:** when the power transmissions are DC system, there is no reactive impedance on the line. Again when the transmission line is short whatever the type of power (DC or AC), reactive impedance is negligible compared with resistive impedance. Hence, the only impedance is resistance and the loss due to this resistance can be calculated by ohm's law i.e. multiplying the square of the current passing through the transmission line with its resistance. It is written as: -

$$P_{loss} = I^2 R \qquad (2.1)$$

Where,

P_{loss} is the Power loss on the transmission line in kW.

I^2 is the square of the current passing through the line in A^2

R is the resistance of the transmission line in Ω.

ii. **By computing line flows and line losses:** - This computational method is the general numerical computation of power flow (load flow) for all types of power source (DC or AC) and for all types of transmission system (i.e. short, medium or long). The load flow calculation shows the magnitude of all power system parameters at each transmission line, at each bus, at each generator and at each load. It can calculate the bus

voltage at each bus bar, the active and reactive power at each bus bar at generation, the power angle at each bus bar and generation and the power loss at each transmission line.
The load flow equation works by nodal analysis of electrical circuit. For a given power, system network using the node equation, the current entering a node is always equal to the current leaving the node. To make the load flow equation simple, consider the single line diagram of the North West region, power system network as shown in the previous Figure 1.2.

From ohm's law, the current passing throw any circuit is proportional to the source voltage and inversely proportional to the resistance of the conductor. Mathematically written as;

$$I = \frac{V}{R} \tag{2.2}$$

Where,

I is the current passes through a circuit.

V is the source voltage for the circuit.

R is the resistance of conductor in a circuit.

For the power system network having long transmission line and carrying high voltage, the resistance R is replaced by impedance (Z). The impedance of the power system consists resistance, inductance, reactance and line admittance. Hence, the current for the power system network can be written as shown in equation 2.3 by replacing the resistance with impedance of equation 2.2.

$$I = \frac{V}{Z} \tag{2.3}$$

Where,

Z is the impedance of power line.

For load flow analysis, the admittance is preferred than impedance because of the characteristic of admittance matric is easier than impedance matrices in power system network. The main characteristics, which make admittance more preferable than impedance is that; there are more number of zeros in admittance matrix than impedance matrix. The admittance is the invers of impedance hence, equation 2.2 can be written as;

$$I = V * Y \tag{2.4}$$

Where;

Y is the admittance of the power system network.

For complex circuit having more nodes (connecting point), the current entering into a node and the current leaving the node can be calculated by using Kirchhoff's current law (KCL). KCL states that the current entering a node is always equal to the current leaving the node. Mathematically can be expressed as;

$$\sum I_{entering} = \sum I_{leaving}$$

From figure 1.2, the current entering in to a bus 1 is let I_1 and the current leaving bus 1 be I_2 and I_3. Then

$$I_1 = I_2 + I_3 \tag{2.5}$$

I_1 can be expressed in terms of admittance and voltage,

$$I_1 = V_1 Y_{11} + (V_1 - V_2)Y_{12} + (V_1 - V_5)Y_{15} + (V_1 - V_6)Y_{16} \tag{2.6}$$

Applying Kirchhoff's Current Law (KCL) equation to all buses gives the general formula to the currents at each bus. i.e. the current entering and leaving the bus is written in terms of self-bus admittance Y_{ii} and mutual bus admittance Y_{ik} as follows;

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \end{bmatrix} = \begin{bmatrix} Y_{11} & -y_{12} & 0 & 0 & -y_{15} & -y_{16} \\ -y_{21} & Y_{22} & -y_{23} & -y_{24} & 0 & 0 \\ 0 & -y_{32} & Y_{33} & 0 & 0 & 0 \\ 0 & -y_{42} & 0 & Y_{44} & 0 & 0 \\ -y_{51} & 0 & 0 & 0 & Y_{55} & 0 \\ -y_{61} & 0 & 0 & 0 & 0 & Y_{66} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \end{bmatrix} \qquad (2.7)$$

Where,

I_i is the current entering or leaving the bus i.

V_i is the voltage at the given bus i

Y_{ij} is the negative of admittance from bus i to bus j.

These Y_{ii} elements are known as self-admittance (driving point admittance) of the i^{th} node and it is equal to the sum of the admittance connected to the i^{th} node.

$$Y_{11} = y_{12} + y_{15} + y_{16}$$
$$Y_{22} = y_{12} + y_{23}$$
$$Y_{33} = y_{30} + y_{32}$$
$$Y_{44} = y_{4l} + y_{42}$$
$$Y_{55} = y_{50} + y_{51}$$
$$Y_{66} = y_{61} + y_{6l}$$

Each off-diagonal term Y_{ik} is known as mutual admittance (or transfer admittance) between i^{th} and k^{th} node and is equal to the negative of the sum of all the admittances connected directly between i^{th} and k^{th} node i.e. $Y_{ik} = Y_{ki} = -y_{ik}$. Therefore, equation 2.6 can be written in compact form as;

$$[I_{bus}] = [Y_{bus}]*[V_{bus}] \qquad (2.8)$$

Network equation can be formulated in a variety of forms. The network equations, which are in the nodal admittance form, results in complex linear simultaneous algebraic equation in terms of node currents. The load flow results give the bus voltage magnitude and phase angle and the power flow through the transmission line, line losses and power injection at all buses. Four quantities are associated with each bus. These are voltage magnitude $|V|$, phase angle (δ) real power P and reactive power Q. In a load flow study, two out of four quantities are specified and the remaining two quantities are to be found. Therefore the system buses are generally classified in to three catagories based on their known and unknown quantities as summarized shown in table 1.

Table 1 Classification of power system buses.

Bus type	Specified quantities	Unknown quantities
Slack buses	V, δ	P, Q
Load buses	P, Q	V, δ
Voltage controlled buses	P, V	Q, δ

Therefore, in a load flow study, two quantities are always known and the other two quantities are to be determined. Now let S_{Gi} and S_{Di} denote the power generated and power demanded into the i[th] bus, then the net complex power S_i injected into the bus is given as;

$$S_i = P_i + jQ_i = (P_{Gi} - P_{Di}) + j(Q_{Gi} - Q_{Di})$$

The complex power transferred from bus i to bus j can be expressed as by multiplying the magnitude of the two end bus bar voltage, the line admittance between the two bus bars, the phase angle difference between the two bus bars and the angle of line admittance.

$$P_i - jQ_i = \sum_{j=1}^{n} V_i V_j Y_{ij} < -(\delta_{ij} - \theta_{ij}) \qquad (2.9)$$

Decomposing this equation into real and imaginary part gives;

$$P_i = \sum_{j=1}^{n} V_i V_j Y_{ij} \cos(\delta_{ij} - \theta_{ij})$$
$$Q_i = \sum_{j=1}^{n} V_i V_j Y_{ij} \sin(\delta_{ij} - \theta_{ij})$$

The current injected into the i^{th} bus then obtained as;

$$P_i - jQ_i = I_i * V_i$$
$$I_i = \frac{P_i - jQ_i}{V_i^*}$$

From this, the following equation will be extracted.

$$\frac{P_i - jQ_i}{V_i^*} = Y_{ii} V_i + \sum_{\substack{k=1 \\ k \neq i}}^{n} Y_{ik} V_k$$
$$Y_{ii} V_i = \frac{P_i - jQ_i}{V_i^*} - \sum_{\substack{k=1 \\ k \neq i}}^{n} Y_{ik} V_k$$

The voltage at the given bus then can be found as;

$$V_i = \frac{1}{Y_{ii}} \left[\frac{P_i - jQ_i}{V_i^*} - \sum_{\substack{k=1 \\ k \neq i}}^{n} Y_{ik} V_k \right] \qquad (2.10)$$

Now consider the connecting bus i and k, the line and the transformer at each end can be represented by a circuit with series admittance Y_{ik} and tow shunt admittance Y_{ik}^0 and Y_{ki}^0 as shown in fig above 1.1. The power transferred from bus i to bus k is given by:

$$P_{ik} = -V_i^2 Y_{ik} \cos\theta_{ik} + V_i V_k Y_{ik} \cos(\theta_{ik} - \delta_i + \delta_k) \qquad (2.11)$$

Similarly, from equation (2.11), the power transferred from bus k to bus i is

$$P_{ki} = -V_k{}^2 Y_{ik} \cos\theta_{ik} + V_i V_k Y_{ik} \cos(\theta_{ik} - \delta_k + \delta_i)$$

Now real power loss bus i to bus k is the sum of real power flows determined from;

$$
\begin{aligned}
P_{LOSS_{ik}} &= P_{ik} + P_{ki} \\
&= -V_i^2 Y_{ik} \cos\theta_{ik} + V_i V_k Y_{ik} \cos(\theta_{ik} - \delta_i + \delta_k) - V_k^2 Y_{ik} \cos\theta_{ik} + V_i V_k Y_{ik} \cos(\theta_{ik} - \delta_k + \delta_i) \\
&= 2V_i V_k \cos(\delta_i - \delta_k) - [V_i^2] - [V_k^2] Y_{ik} \cos\theta_{ik}
\end{aligned}
$$

The power loss from Bahir Dar substation to Debremarkose substation (bus 1 to bus 6) is now written as

$$
\begin{aligned}
P_{LOSS_{16}} &= P_{16} + P_{61} \\
&= 2|V_1||V_6|\cos(\delta_1 - \delta_6) - |V_1|^2 - |V_6|^2 |Y_{16}| \cos\theta_{16}
\end{aligned}
$$

2.1 Power Loss Mitigation Technique

There have been different techniques developed on the past times in order to compensate this kind of power system losses. Among those methods used to mitigate the power losses on the transmission line, some of them are [3];

- Use of distribution generation
- Network reconfiguration
- Use of FACT devices
- Doubling the transmission line

2.1.1 Use Distribution Generator

The term distribution generation (DG) is generally defined as any source of electric energy of limited capacity that is directly connected to the existing network on the customer side or on the distribution substation and the source of electric power may be solar power, wind power, diesel power or hydropower. There is no consensus on what exactly the rating of DGs as well as the voltage level at the point of common coupling (PCC) to the grid should be. The magnitude of DG in kW somewhat vary from one research group to another research group and from one country to another country. For example, in France, DGs is defined in capacity as greater than 40 MW and connected at

225 kV voltage level while Portugal pegs the capacity limit of DGs to 10 MW that can be connected at any voltage level. Spain allows the DGs capacity to go up to 50% of the feeder capacity. So far, Australia has been able to install practically the largest size of 130 MW DGs at 132 kV on its power grid. Although the capacity limit is not clearly stated for Germany, United Kingdom (UK) and Netherlands, the voltage levels at PCC are defined as up to 132 kV for UK, up to 110 kV for Germany and up to 150 kV for the Netherlands. Based on these varying capacity limits, in suggested various classifications of DGs based on their capacities as micro DGs of 1 W to less than 5 kW, small DGs of 5 kW to less than 5 MW, medium DGs of 5 MW to less than 50 MW, and large DGs of 50 MW to less than 300 MW. This classification is a welcome idea since it encompasses all various definitions given by different groups/countries [4].

DG is one of the better alternatives to fulfill this ever-growing energy demand. Moreover, it reduces system energy loss, alleviates transmission congestion, improves voltage profile, enhances reliability, and provides lower operating cost. Because of small size compared with conventional generation units, DG is more flexible to install in terms of investment and time. As a result, integration of Distributed Energy Resources (DER) with distribution network offers a promising solution. Therefore, an intensive level of research is needed to understand the impacts of distributed resources on Distribution System. Before operating distributed and dispersed generation in power system, different technical, environmental, commercial, and regulatory issues should be analyzed properly. Most significant technical barriers are protection, power quality, stability, and islanding operation. However, there are some other issues, which should be analyzed before to maximize these technical benefits.

DG should be allocated in an optimal way such that it will reduce system losses and hence improve voltage profile. Improper DG size and inappropriate allocation of DER may lead to higher power loss than when there is no dispersed generation in the system at all. Therefore, detail and exact analysis method is required to determine the proper location and size of DG more accurately and precisely [4]. DG injects MW power to the bus bar where it is connected. Therefore, it increases the voltage profile of the bus bar.

Because of this, it increases the efficiency of the electrical equipment and the power transfer capacity of the transmission line.

2.1.2 Network Reconfiguration

To reduce the active power losses of the distribution system, one of the methods is the network reconfiguration. The process involved in network reconfiguration is the simultaneous operation of sectionalizing and tie switches in feeders, which varies its topological structure. The transmission network expansion planning (TEP) is as the problem of determining where to locate the new transmission line, when and how many additional new lines must be installed so as the network meet operational, economical, technical, and reliability criteria of the power system. Additional transmission capability is justified whenever there is a need to connect new generation plant to meet growing load demand or enhance system reliability or both.

The network reconfiguration works by controlling ON/OFF status of switches that pre-installed at each distribution lines. The reason for this approach is to reroute power flow at distribution network and for this purpose there are two types of switches installed in the distribution system, which is tie-switches (normally open) and sectionalize-switches (normally close). Even though the process of network reconfiguration looks simple, selections of ON/OFF combination are a complex decision-making process that needs to be done thoroughly [5].The main advantages of reconfiguration are, service restoration during feeder faults, network maintenance through outages planning, network overload relief, bus voltage improvement and loss minimization [5].

As discussed before, network reconfiguration is one way of loss mitigation technique by reducing the transmission line stress. Figure 2.1, which is taken from examples of power world simulator, indicates that reconfiguring the transmission line network can have different MW line loss. As shown in figure, the line stress from bus bar 2 to bus bar 3 in a is greater than in b because of the power sharing in Figure 2.1(a). In addition, the MW loss from bus bar 1 to bus bar 2 in figure a is 0.21MW while in be 0.04MW in Figure 2.1(b).

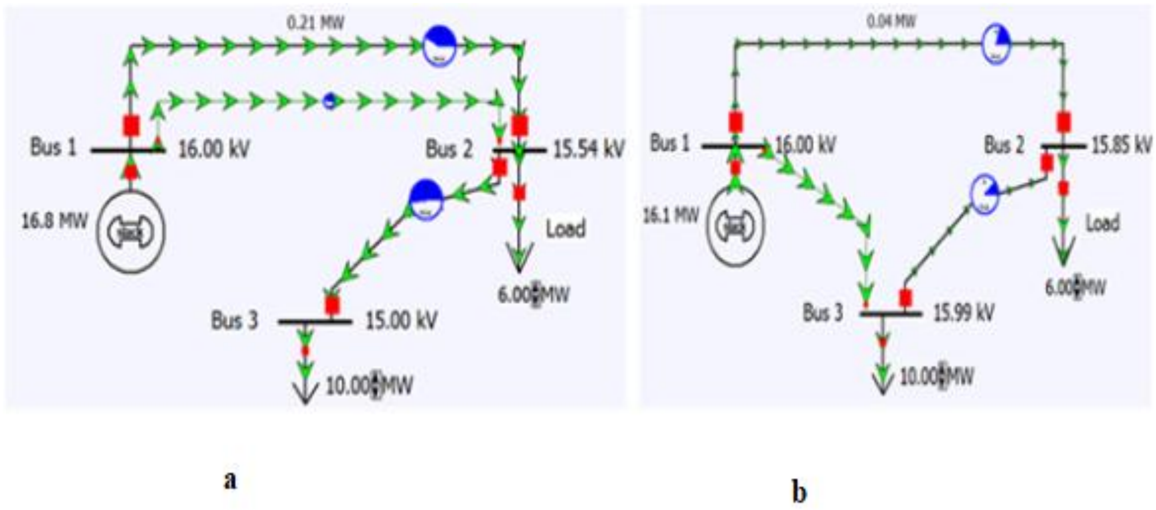


Figure 2.1 Network reconfiguration impacts on power loss

2.1.3 Use of FACT Devices

The term Flexible Alternating Current Transmission System (FACTS) devices describes a wide range of high voltage, large power electronic converters that can increase the flexibility of power systems to enhance AC system controllability, stability and increase power transfer capability [6]. The benefit brought by FACTS includes improvement of system dynamic behavior and thus enhancement of system reliability. They contribute to optimal system operation by reducing power losses and improving voltage profile.

Most of the FACT device contains capacitor with power electronics as a switching device therefore; it can generate reactive power to the bus bar where it is connected. The voltage injected to the bus bar is 90^o leading from the voltage incoming to the load. Therefore, it can alter the load angle difference between sending end to receiving end bus bar voltage. Changing the receiving end voltage and phase angle difference can alter the magnitude of the active power transfer between the two bus bar. To illustrate this explanation, take the power transfer between two end bus bars, which is given by the equation as [7];

$$P = \frac{V_s V_r \sin\theta}{X} \qquad (2.12)$$

Where,

P is the power transfer from sending end to receiving end.

V_s is the sending end voltage.

V_r is receiving end voltage.

X is the reactance of the line from sender to receiver.

θ is the phase angle difference between sender and receiver.

From equation (3.1), maximum power transfer between the two station hence depend on the receiving end voltage, sending end voltage line reactance and the phase angle difference between senders and receivers. The receiving end voltage and phase angle (θ) can be controlled by FACTS device therefore; the two parameters can determine the active power loss of the transmission line.

There are several kinds of FACTS devices, which can be classified according to their construction and their connection to the power system components [8], [9]. These are:

- Series FACTS Controllers
- Shunt FACTS Controllers
- Combined Series-Shunt FACTS Controllers
- Combined Series-Series FACTS Controllers

Series FACTS Controllers: The series controller could be variable impedance, such as a reactor, capacitor, etc. or power electronics based variable source of main frequency, sub synchronous and harmonic frequencies to serve the desired need. In principle, all series controllers inject voltage in series with the line. As long as the voltage is in phase quadrature with the line current, the series controller only supplies or consumes variable reactive power. Other than the quadrature with injected voltage and line current, the controller can involve itself for real power control [9, 10]. Members of this type of controller include Serial Synchronous Static Compensator (SSSC) and Thyristor-Controlled Series Capacitor (TCSC).

Shunt FACTS Controllers: The shunt FACTS Controllers may be variable impedance type i.e. reactor or capacitor adjustable source based on the power electronics, which is shunt connected to the line in order to inject variable current. In principle, all shunt controllers inject current into the system at the point of connection. Even variable shunt impedance connected to the line voltage causes a variable current flow and hence represents injection of the current into the line. As long as the injected current is in phase quadrature with the line voltage, the shunt controller only supplies or consumes variable reactive power [9, 10]. The controllers that belong to this category include Synchronous Static Compensator (STATCOM), Thyristor controlled reactor (TCR), and Static Var compensator (SVC) [11].

Combined Series-Series FACTS Controllers: These could be a combination of separate series controllers. The configuration of Combined Series-Series FACTS Controllers provides independent series reactive power compensation for each line but also transfers real power among the lines via power link. The presence of power link between series controllers names this configuration as “Unified Series-Series Controller. It is just a unified controller, in which the serial controllers provide reactive compensation for each line, thereby transferring active power between the lines via a power link. Active and reactive power balance is achieved either by the line feeder controller or through the transmission capacity of the active power that presents a unified serial controller. The unified nature therefore enables it to achieve active power transfer between each other by proper connection of the dc terminals of the converters of the controllers. A typical example of serial-serial controller is Interline Power Flow Controller (IPFC) [10], [11].

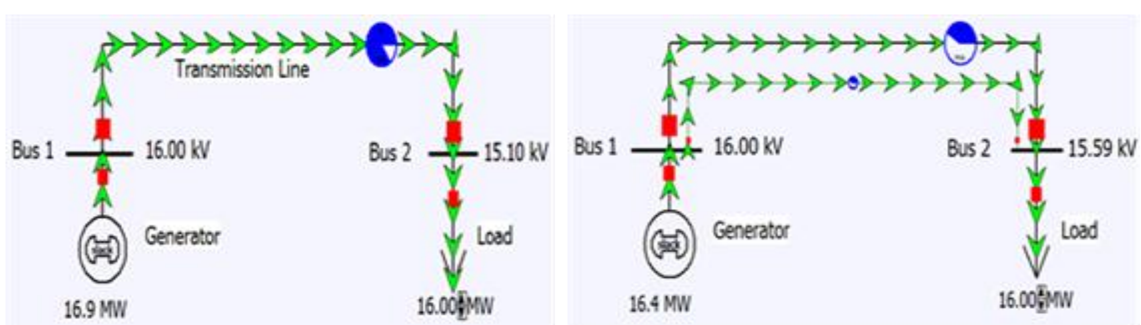
Combined Shunt-Series FACTS Controllers: These are arrangement of distinct arrangement of shunt and series controller and they connected in such way that the control of both is much-synchronized manner. The real or active power exchange is take place through the power dc link when these controllers are connected to each other and with the line. They work by injecting current into the system with the shunt part of the controller and voltage in series in the line with the series part of the controller. Thus the shunt and series part of the controllers are unified, in which case, real power exchange between the series and shunt controllers can be achieved via a proper link [9 - 11]. Members of this class of controllers include UPFC and DPFC.

The UPFC is advantageous for real-time control and dynamic compensation of the AC transmission system to provide the necessary functional flexibility required to solve many of the problems facing the power industry today. This opens up new opportunities for controlling the power, decreasing the losses and enhancing the usable capacity of existing transmission lines [12, 13]

2.1.4 Doubling the Transmission Line

The power loss is proportional to the square of the current, thus a small current greatly reduces power (heat) loss. For the same power handling of a line, small current can be achieved by using a high voltage. For example, doubling the transmission voltage can halve the current and the power loss would be reduced to a quarter (1/4), i.e. 25% of the original value. Keeping the voltage and the current constant, the power loss in the transmission line loss is directly proportional to the resistance R of the wire. Therefore, to reduce the resistance of the wire, the first consideration is the choice of material. Copper and aluminum are the most used metals in transmission wires. They are very good conductors, cheap, resistant to corrosion, and strong. The resistance of the transmission wire is lowered by making the wire thicker. Thicker wires have larger cross-sectional areas and therefore lower resistance. In addition to this doubling the transmission line of copper or aluminum wire can increase the cross-sectional area.

Doubling the transmission line in the power transmission will increase the cross-sectional area of the conductor as stated before. Hence, the I^2R loss reduces by half.



a b

Figure 2.2 Doubling the transmission line for power loss reduction

As shown in the figure above, doubling the transmission line reduce the percentage loading of the transmission line. This is because of doubling the cross-sectional area or parallel connecting two impedances reduce the net impedance of a line and the I^2R loss reduces.

2.2 Literature Review

From the time that modern distribution and transmission system is started, power loss was an issue raised as the shortcoming of the technology. Due to this, various scholars in different times have studied the causes and the effect of different types of losses found in a power system network. Among those losses, transmission line loss accounts a considerable part. As part of this study many papers related to transmission, loss and their respective mitigation techniques have been reviewed. Among many literatures, some of them, which are selected as the best input to this paper, is discussed below.

In 2016, U. Sultana et al. [14] performed a comprehensive study for optimum DG placement considering minimization of power/energy losses, enhancement of voltage stability, and improvement of voltage profile. An attempt has been made to summarize the existing approaches and present a detailed discussion, which can help the energy planners in deciding which objective and planning factors need more attention for optimum DG allocation for a given location or in a given scenario. It has presented the recent trend of Optimal Allocation of DG with different objectives function including voltage stability enhancement, voltage profile improvement, power loss reduction and their multi-objective approach. Optimal allocation techniques resolve the issues related to DG's sizing and suitable placement by imposing different objective functions with many forced technical/operational constraints, applying various computational methods with the consideration of different DG types based on power factor (PF) and multiple numbers of units. Nevertheless, the systematic principle to handle planning issues of distribution system is still an open question for researchers.

In 2019 Ibrahim. M [15] studied a novel graphically-based distribution network reconfiguration (DNR) to obtain the optimized radial configurations for power loss minimization. The proposed DNR is based on the graphical representation of the distribution system without any need for a radially check. Case studies were conducted on 16, 33, 70, 83 and many nodes distribution systems in order to minimize the total power loss. Results have proven the ability of the proposed graphical DNR for power loss minimization by obtaining fast radial configurations its ability to deal with large distribution systems efficiently. The proposed DNR succeeded in minimizing the total losses for large distribution systems up to 80%. Algorithmically, the proposed methodology can minimize power losses for any distribution system in a fast and efficient manner as validated by comparison with the results obtained from other previous studies. Therefore, applying the proposed DNR mathematical approach to modern distribution systems has fulfilled an economic aspect for different network types due to its ability to minimize the total power losses and in turn minimizing the investment costs to reinforce the existing distribution networks. However, this much power loss minimization may not be succeeding due to practical constraints

In 2016, Avani G. [5] explained the reduction of real power losses in the distribution network by a network reconfiguration. Reconfiguration is done by changing the status of the sectionalizing and tie switches provided in the network. The optimal configuration with minimum real power loss is to be determined. To determine the status of the switches optimization technique Genetic Algorithm is used. Reconfiguration is implemented on a standard 33-node distribution system. It is found that due to change in configuration of an existing network, active power losses are reduced considerably, and the system voltage is improved. After reconfiguration of the distribution network, the overall system losses have decreased also voltage is. If the same strategy, i.e. distribution network reconfiguration is applied for distribution system; it will be very much useful in reducing the power losses and improving the system voltage.

In 2019, Tung T. et.al [16] proposed a chaotic stochastic fractal search algorithm (CSFSA) method to solve the reconfiguration problem for minimizing the power loss and improving the voltage profile in distribution systems. Researchers have made tremendous efforts to find the optimal solution for the distribution network reconfiguration (DNR) problem with many approaches. This study has been successfully applied to the CSFSA method for the DNR problem with the objective function of power loss reduction and voltage profile improvement in distribution systems. The radial structure of distribution networks has been tested using the graph theory after the new configuration was created. The proposed CSFSA has been tested on the 33-bus, 84-bus, and large-scale systems including 119-bus and 136-bus systems. The obtained results from the CSFSA have confirmed the effectiveness and robustness of the proposed method to solve the reconfiguration problem in distribution networks by providing the better power loss reduction and voltage profile improvement than many other mature methods. Therefore, the proposed CFSFA can be a favorable method for solving the complex and large-scale reconfiguration problems in distribution systems.

In 2019, Jitender K. et.al [11] proposed Flexible AC Transmission System (FACTS) devices, which are used, for increasing the transmission line loading ability without changing its line parameters. The proposed model is demonstrated on modified IEEE 14 Bus System using MATLAB Simulation software. The research proposed that, the use of multiple combinations of FACTS devices online may help in reducing heavy load congestion on power system lines. This may be helpful in reduction of system losses, improve system stability in terms of a small signal as well as large signal analysis with the enhancement of power quality of the existing systems. This paper investigates the effect of multiple combinations of FACTS devices on load congestions mitigations with the application of weighted least square (WLS) technique. The system has been tested on two types of FACTS devices and observed from results that, while implementation of a single unit of large rating FACT device in IEEE System will not lead as much compensation as by using multiple small rating FACT devices at a different location in the system. This may lead to much more congestion relief of power system during its loading conditions. The use of Single SVC will lead to less voltage profile improvement while Double SVC is helping to improve voltage profile better than the single one. In addition, with triple SVC system will improve voltage profile better than the double one. With the same procedure with SVC, using triple STATCOM in in dispersed way provide best improvement than the double and single one. Therefore, from this paper the optimal size and allocation of individual and combination of FACTS devices will lead to minimize system congestion. Such type of arrangement of FACTS device will also lead to optimize the cost of entire power system with appropriate voltage profile and Reactive power compensation.

In 2014, Ogujor A. et.al [17] investigated the transmission line losses using the 5-bus Ring segment of Nigeria National Grid and the improvement that a unified power flow controller (UPFC) can create by simultaneous or individual controls of basic system parameters like distribution voltage, line impedance and phase angle. The network segment was analyzed using Newton-Rapson iterative method in MATLAB/ SIMULINK environment. The network was modeled using Simulink block sets. The power losses in the transmission lines were calculated using differential power flow with and without the unified power flow controller (UPFC). The simulation results showed that all the bus voltage is within acceptable limit (voltage measured in per unit) and incorporating the UPFC reduced real power losses and reactive power losses.

In 2015, Worku A. from Addis Ababa University [18] presented the problem in power system transmission line loss and voltage profile for eastern region of Ethiopia. He analyzes 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. It has 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. Generally, this paper showed that minimizing transmission line loss and improving voltage profile is advantageous in term of balancing the demand and supply. 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. He stated that when energy is to be transported over relatively larger distances with low load density, the transmission losses, in some cases, might amount to about 20–30% of the total load, but it is more realistic to consider then transmission line losses, which are about 5–15% of the total generation. He concludes that using Unified Power Flow Controller in the Eastern Region of Ethiopia can improve transmission line loss and voltage profiles.

In 2014, Adnan A. et.al supposed [4] Determination of appropriate size and location of DG is important to maximize overall power system efficiency. In most of the previous research of DG sizing and allocation, DG has been connected with grid directly. Significant risks are associated in connecting such equipment directly to utility distribution system. The insulation level of the machines may not synchronize with the system. Therefore, direct connection of DG is often discouraged. In this paper, an optimization method has been presented to determine the appropriate size and proper allocation of DG in a distribution network. Results obtained from this method have been compared with using the repeated load flow method. A new approach to perform repeated load flow by using simulation engine 'open DSS' COM server through MATLAB programming is also introduced here. Both optimized method and repeated load flow-based method have been compared for three IEEE distribution test systems. This analysis shows that using appropriate size and location of DG, total power loss in primary distribution system can be reduced significantly. However, more detail dynamic analysis is needed to understand the impact of proper allocation and size of DG properly.

In 2002, Peter Z. [19] presented a mathematical model and steady-state operational characteristics of a Unified Power Flow Controller (UPFC). The steady-state operational characteristics of the UPFC can be determined using the derived mathematical model or state space equation of the device. The mathematical description is based on the transformation of a three-phase system into an orthogonal synchronously rotating coordinate system, in which, under steady state conditions, all system quantities are constant values. The mathematical description based on the transformation of a three-phase system into an orthogonal synchronously rotating coordinate system under steady state conditions is done. Thus, at given parameters, it is generally possible to determine the dimensions of the device. The analysis of the steady-state operational characteristics resulted in key findings enabling derivation of control algorithms and further examination of the device operating under dynamic conditions. UPFC’s capabilities have been investigated in different areas such as; power flow control, voltage control, transient stability improvement, oscillation damping.

In 2013, Shameem A. et.al [20] proposed a dynamic model of Unified Power Flow Controller (UPFC) to improve the power transfer capability through the transmission line. Improvement of the bus voltages profiles along with the reduction of total power losses is also intended with UPFC’s presence. The proposed UPFC controller is tested by using IEEE-5 and 14 bus systems with various case studies. The performance of the proposed controllers is also compared with different control methods. The active power flow with proposed controller based UPFC has improved 4.86% and 14.26% compared to its nominal value in IEEE-5 and IEEE-14 bus networks respectively. In the same networks, real power capacity losses also reduced more with UPFC connected to the transmission line. Meanwhile, with UPFC the bus voltages across the networks are also improved to their respective nominal values and from the results, significant improvement has been achieved with the minimization of total power losses.

In this work, the unified power flow controller (UPFC) is suggested as one methods of resolving power system defects, which may be as a cause of power system disturbance, loss and blackout. Because, UPFC is one of the more interesting and potentially the most versatile member of FACTS [21]. It can provide simultaneous and independent control of important power system parameters, line active power flow, line reactive power flow, impedance and voltage [21]–[23]. Thereby, it offers necessary functional flexibility for the combined application of phase angle control with controlled series and shunt compensation.

The UPFC operation mode can be changed from one state into another without hardware alterations to adapt particularly changing system conditions. This feature makes UPFC today a competent and the best device for power flow regulation and load compensation than other FACTS device [21], [24].

CHAPTER THREE

3. SYSTEM DESIGN AND ANALYSIS

Today’s power systems are highly complex so that it requires careful monitoring of each power system component for its proper operation. Hence, it is not an easy task for more efficient use of already existing power system resources without reduction in system stability and security. Due to the complexity of power system networks, proper automatic monitoring mechanisms with best and efficient controllability should be established. For instance, most of the large power system blackouts, which occurred worldwide over the last twenty years, are caused by heavily stressed system with large amount of real and reactive power demand and low voltage condition. Therefore, before blackout occurred in power system, immediate action taker mechanisms should be designed as stated before.

The design criteria in this thesis include rating of each UPFC components and the placement of UPFC in the North-West region of Ethiopian power system network. UPFC rating depends on the rating of bus bars where it is connected in the powers system network. For instance, if UPFC is connected on 400kV bus bar, then the primary side transformer of UPFC should be at least 400kV. Once the primary side transformer of UPFC known, then its secondary side transformer voltage is 10% of the primary side according to the rating of UPFC from IEEE standard. This is true for both shunt and series converter of UPFC transformers. Other transformers parameters like transformer reactance X and resistance R are selected from EEP catalogue put in appendix A of transformer parameters.

The other component of UPFC is the DC link capacitor. The rating of this capacitor should withstand the difference between the active power difference coming from the shunt converter and passing through the series converters. Hence, the rating of the DC link capacitor depends on the maximum power or energy stored on it. From fundamental of electrical energy principle, the energy stored on the capacitor can be expressed mathematically as; $E = \frac{CV^2}{2}$

Power is the rate of doing work. Therefore, the rating of the capacitor can be found as; $S = \frac{E}{t} = \frac{CV^2}{2*t}$

Where,

E is the energy stored on the capacitor.

C is the capacitance of the capacitor.

V is the secondary side transformer of the shunt converter.

S is the power rating on the capacitor in k Var.

t is the duration of time required to store power.

The next design part of UPFC is its placement in the network. This portion is conducted by interpolation techniques to find the best effect position. As shown from Figure 3.1 below there are two figures, the north west region power network and UPFC assigned as a and b respectively. The UPFC is assumed to reduce the power loss of the transmission line from Bahir Dar substation to Debremarkose substation (bus number 1 to bus number 6) when it is connected somewhere on the network. The interpolation procedure is explained more in chapter four of this thesis.

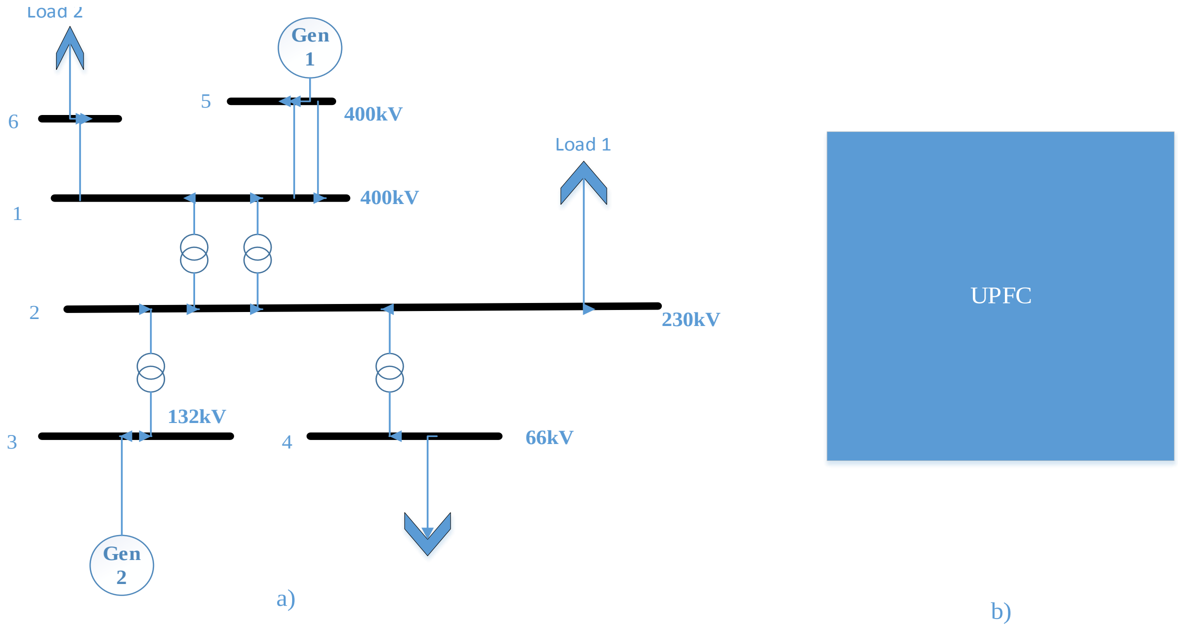


Figure 3.1 Overview of the system design

3.1. The Unified Power Flow Controllers

The term "unified power flow controller" concept was described in 1991 by L. Gyugyi from USA west room science and technology center, which can abbreviate as UPFC [25]. It is a FACTS family, the most complex and most attractive of a power flow regulator, which has synthesized a number of FACTS devices flexible control means, and the most powerful FACTS device having a value of a control system in the flexible AC transmission technology [21, 25 – 27]. It is an electrical device having two voltage source inverter (VSI) for providing fast-acting reactive power compensation on high-voltage electricity transmission networks. It is a representative of the third generation of FACTS devices, and by far the most comprehensive FACTS device, in power system steady state and in power system dynamic behavior. It can implement power flow regulation, reasonably controlling line active power and reactive power, improving the transmission capacity of power system in power system transient state. It can realize fast-acting reactive power compensation, dynamically supporting the voltage at the access point and improving system voltage stability. Moreover, it can improve the damping of the power angle stability [28, 29].

UPFC can control simultaneously or selectively all the parameters affecting power flow in the transmission line (i.e. voltage, impedance, and phase angle). Alternatively, it can independently control both the real and reactive power flows in the line [26, 30, 31, 32]. In terms of static and dynamic operation of the power system, UPFC offers advantages with the combined application of controlling phase angle with controlled series reactive compensations and voltage regulation. This enables the real-time change from one mode of compensation into another one to handle the actual system contingencies more effectively [21, 33].

UPFC consists of static synchronous compensator which is converter 1 (STATCOM) and a static synchronous series compensator which is converter 2 (SSSC) coupled via common DC link as shown below Figure 3.2 [34].

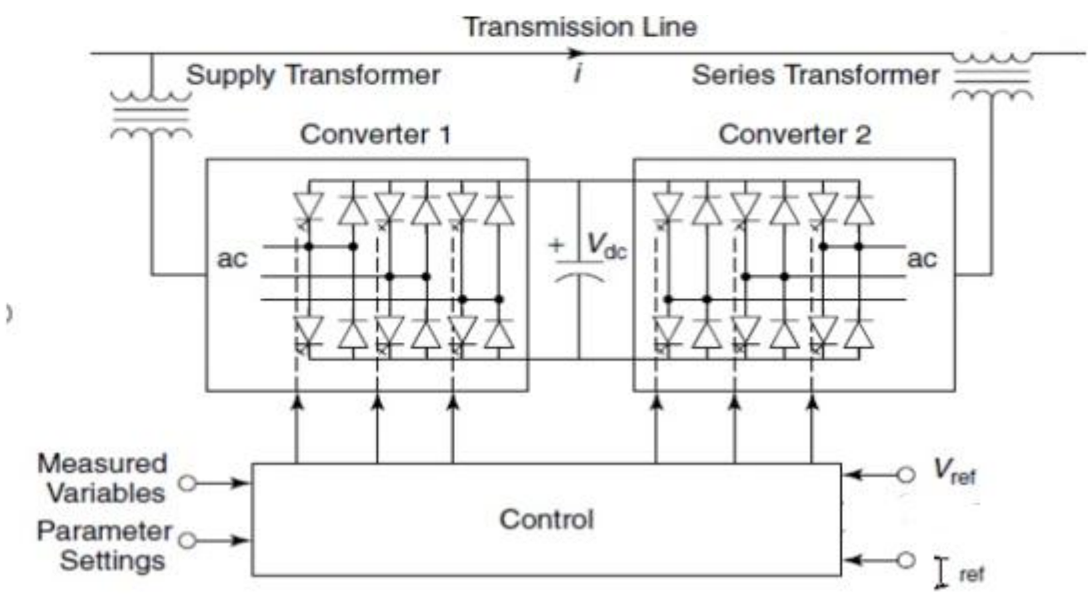


Figure 3.2 Overall system components of UPFC

As shown in the figure above, UPFC consists of two voltage source converters series and shunt converter. These converters are used to convert from AC to DC or vice versa and usually, they are either Thyristor or insulated gate bipolar junction transistors (IGBT). The two converters connected to each other with a common dc link and connected to the power system through coupling transformer. The coupling transformers are used to match the voltage levels between the power system of transmission line or bus bar and the power electronic inverters [31].

The two converters can work independently from each other. The shunt inverter is operating as a (STATCOM) and that is used primarily to provide the real power demanded by series converter through the common DC link terminal. An important role of the shunt converter of UPFC is a direct control of the DC capacitor voltage and regulation of the real power required by the series UPFC branch. It can also generate or absorb reactive power independent of the real power flow through it. The power absorbed from the line by UPFC is equal only to the losses of the inverters with their transformers and the real power required by the series converter. The remaining capacity of the shunt inverter can be used to exchange reactive power with the lines to provide a voltage regulation at the connection point. Hence, the shunt converter controls the dc voltage and the bus voltage through the shunt converter's transformer.

The series inverter is operating as (SSSC) that generates or absorbs reactive power to regulate the current flowing in the transmission line and hence regulate the power flows in the transmission line at the connection point. It generates the voltage and phase shift at the fundamental frequency. This voltage is used to add controlled voltage magnitude and phase angle at fundamental frequency in series with the line. Therefore, the injected voltage with their phase angle can increase the power transfer capability of the line.

3.1.1 Operating Mode of UPFC

The UPFC has many possible operating modes. In particular, 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 inverter, to absorb or generate respectively reactive power from the line. Generally, the operating mode can be discussed in more detail for both shunt and series converter.

3.1.1.1 Operating Modes of Shunt Converter

The shunt inverter is operated to absorb or generate reactive power to regulate the bus voltage at which UPFC is connected. The shunt converter used 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 inverter, to absorb or generate reactive power from the line. There are two operating (control) modes for the shunt converter [25].

i. **VAR Control Mode**: The reference input is an inductive or capacitive VAR request. The shunt inverter control translates the VAR reference into a corresponding shunt current request and adjusts gating of the inverter to establish the desired current. For this mode of control a feedback signal representing the dc bus voltage, V_{dc} is also required [25], [35].

ii. **Automatic Voltage Control Mode**: The shunt inverter reactive current is automatically regulated to maintain the transmission line voltage at the point of connection to a reference. For this mode of control, voltage feedback signals are obtained from the sending end bus feeding the shunt-coupling transformer [25], [35].

3.1.1.2 Operating Modes of Series Converter

The series converter operating mode depends on the relative phase angle and magnitude of the injected voltage, and they are controlled maintain or vary active and reactive power flow through the transmission line within a predetermined region. The series inverter controls the magnitude and angle of the voltage injected in series with the line [25], [35], [36]. This voltage injection is always intended to influence the flow of power on the line. The series voltage can be determined in different ways. This includes;

i. **Direct Voltage Injection Mode**: -The series inverter simply generates a voltage vector with magnitude and phase angle requested by reference input. A special case of direct voltage injection is when the injected voltage is kept in quadrature with the line current to provide purely reactive series compensation. The series inverter injects the appropriate voltage so that the voltage V is phase shifted relative to the voltage by an angle specified by reference input.

ii. **Automatic Power Flow Control Mode**: -Automatic power flow control mode where the reference inputs determine the required real power and the reactive power at a specified location in the line. Both real power and reactive power can be controlled independently of each other in a feasible region determined by the satisfaction of various constraints. The UPFC has the unique capability of independently controlling both the real power flow at a specific point. This capability can be appreciated by interpreting the series injected voltage, V_{se} as a controllable two-dimensional vector quantity. This injected voltage vector can be chosen appropriately to force any desired current vector (within limits) to flow on the line, hence establishing a corresponding power flow. In automatic power flow, control mode, the series injected voltage is determined automatically and continuously by a vector control system to ensure that, the desired real power and reactive power are maintained despite system changes.

iii. **Line impedance, emulation mode**: Line impedance emulation mode where the series injected voltage is controlled in proportion to the line current. The desired impedance is specified by reference input and in general, it may be complex impedance with resistive and reactive components of either polarity. The complex impedance (the injected voltage divided by the line current) seen by the line current is determined by the reference inputs. It is essential to take care (in employing this control mode) to avoid instability or resonance. A large value of the capacitive (negative) reactance can result in resonance.

iv. **Phase Angle Shifter Emulation Mode**: The reference input is phase displacement between the sending end voltage and the receiving end voltage [37].

3.1.2 Mathematical Modeling of UPFC

In this section, numerous mathematical equations are developed and synthesized on two bus electrical power system operations. This device’s characteristics are established in line with d-q transformation and very much compatible with small, large and multifaceted electrical power network operations [38, 39]. To design and understand its operation principle, consider the single line diagram with two machines connected by a transmission line of reactance X along with UPFC converters as shown in Figure 3.2. The two machines are assigned as a source and as a load of the transmission line [22, 25].

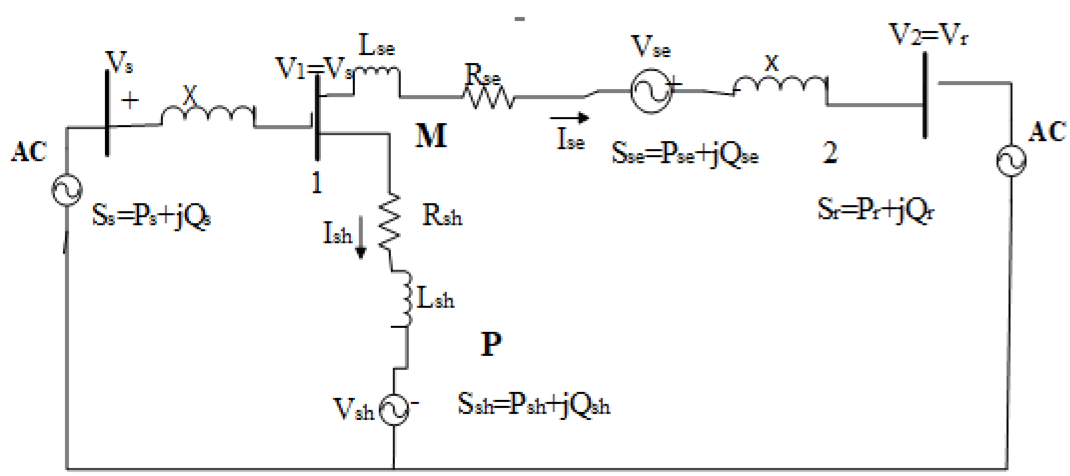


Figure 3.3 Equivalent Circuit of UPFC along with the power network

As shown here, the two voltage source converters of UPFC denoted by V_{sh} (shunt converter) and V_{se} (series converter), are connected in shunt and series respectively at the mid- point of the transmission line. V_{sh} and V_{se} are connected to the transmission line through a transformer having reactance represented as a reactance X_{sh} and X_{se} respectively. Based on the magnitude of the power on the two machines, V_{sh} and V_{se} have the capabilities of varying their magnitude and their phase angle.

To understand the operation of the shunt converter [25], source voltage V_{sh} is connected and the source voltage V_{se} is disconnected. If the magnitude of the voltage source V_{sh} is greater than the mid-point voltage $V_{\mathbf{M}}$, and the phase of them are the same, reactive power will flow from the voltage source V_{sh} to bus **M**. If the phase angle of the voltage source V_{sh} leads the phase angle of mid-point voltage $V_{\mathbf{M}}$ and the magnitude of V_{sh} is greater than $V_{\mathbf{M}}$, then real and reactive power will flow from the voltage source V_{sh} to the bus **M**. Conversely, if the magnitude of the shunt voltage V_{sh} is less than the midpoint voltage $V_{\mathbf{M}}$ but the phase angle difference between them is zero, then only reactive power will flow from the bus **M** to the bus **P**. In this process, the voltage source V_{sh} is consuming reactive power. If the phase angle of V_{sh} lags the phase angle of $V_{\mathbf{M}}$, then both real and reactive power will flow from bus **M** to bus **P** and the voltage source is said to be consuming both real and reactive power. Therefore, the direction of real and reactive power flow to the bus **M** can be controlled by controlling the magnitude and phase angle of the shunt voltage source V_{sh}. Alternatively, the voltage source V_{sh} can be made to function as a load or as a generator for the power system. In the above operation, if the phase angle difference between the voltage at bus **M** and that of V_{sh} is maintained at zero, then by varying the magnitude of V_{sh} reactive power can either be consumed or generated by V_{sh}. This operation can be compared with that of a Thyristor controller reactor with fixed capacitor (shunt compensator) that generates or absorbs reactive power by altering its shunt reactive impedance.

Similar to the operation of the shunt converter, consider only the operation of series voltage source V_{se} with the shunt voltage source V_{sh} isolated from the line. It is assumed that the magnitude and phase angle of the series voltage source V_{se} can be varied. The transmission line current I_{se} interacts with the series voltage source V_{se} causing real and reactive power to be exchanged between the series voltage source and the transmission line. If the voltage source V_{se} and the transmission line current I_{se} have a phase angle difference of 90 degrees and the voltage phasor of V_{se} leads the line current, then the voltage source (V_{se}) generates only reactive power. Conversely, if the voltage source V_{se} phasor lags the transmission line current I_{se} phasor by 90 degrees, then the voltage source V_{se} will consume reactive power. In summary, the function of series capacitor could be performed by the series voltage source V_{se} by maintaining its phase to lead the transmission line current I_{se} phasor by 90 degrees. Conversely, the function of a series inductor could be performed by the series voltage source V_{se} by adjusting its phase angle to be lagging the line current I phasor by 90 degrees.

By properly adjusting the phase angle of the series voltage source V_{se}, the operation of a phase shifter has obtained. In the case of a phase shifter, the phase angle of the series voltage source V_{se} leads or lags the voltage of the bus to which it is attached by 90 degrees. This causes the voltage phasor to shift depending on the magnitude of the injected voltage. In this case, if the series voltage source V_{se} has a 90 degrees leading or lagging phase relationship. Therefore, by adjusting the phase angle of the series voltage source V_{se} to be either leading or lagging the bus voltage M by 90 degrees, a phase shifter operation could be obtained. To vary the magnitude of phase shift, the magnitude of the series voltage source V_{se} could be varied.

The mathematical modeling of UPFC can be derived from Kirchhoff's current law (KCL) and Kirchhoff's voltage law (KVL) from its equivalent circuit of figure 4. Since UPFC is composed of three components, each component has their own dynamic mathematical modeling. As discussed before the three components are shunt converter, series converter and DC link capacitors. Therefore, mathematical modeling for each component will simplify the design procedure.

3.1.2.1 Mathematical Modeling of Shunt Converter

Thee voltage stored on the resister is given by i*R and the voltage stored in inductor is given by: $v = \frac{ldi}{dt}$. Therefore, from figure 3.3, the voltage stored on the shunt converter can be formulated using the circuital theory of KVL equation.

$$V_S = L_{sh}\frac{di_{sh}}{dt} + R_{sh}i_{sh} + V_{sh} \qquad (3.1)$$

Where,

R_{sh}, L_{sh} and i_{sh} are resistance, inductance and current of the shunt converter

V_{sh} is injected shunt voltage.

Rewriting equation (3.1) give as,

$$\frac{di_{sh}}{dt} = \frac{1}{L_{sh}}\left(-R_{sh}i_{sh} + V_S - V_{sh}\right) \qquad (3.2)$$

Equation (3.1) and equation (3.2) are established for sing phase circuit. However, the real system of the shunt converter is a three-phase system. Hence, equation (3.2) can be changed to three-phase system and can be written as;

$$\frac{d}{dt}\begin{bmatrix} i_{sha} \\ i_{shb} \\ i_{shc} \end{bmatrix} = -\frac{R_{sh}}{L_{sh}}\begin{bmatrix} i_{sha} \\ i_{shb} \\ i_{shc} \end{bmatrix} + \frac{1}{L_{sh}}\begin{bmatrix} V_{sa} - V_{sha} \\ V_{sb} - V_{shb} \\ V_{sc} - V_{shc} \end{bmatrix} \qquad (3.3)$$

Controlling two elements is easier than controlling three and more elements. Equation (3.3) has three voltage dependent currents and controlling this element is a little bit difficult. To reduce the complexity of the three-phase system control, reducing it into two-phase (d-q) frame of reference can minimize some work. Park’s transformation rule can transfer three-phase system in two-phase system and this two-phase system in other words known as d-q axis [40]. Let the parks transformation ratio be T(θ) and have the transformation ratio as expressed below;

$$T(\theta)=\frac{2}{3}\begin{bmatrix} \cos\theta & \cos\left(\theta-\frac{2\pi}{3}\right) & \cos\left(\theta+\frac{2\pi}{3}\right) \\ -\sin\theta & -\sin\left(\theta-\frac{2\pi}{3}\right) & -\sin\left(\theta+\frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$$

Voltage transformation from three phases (a, b, c) to two phases (d-q) is,

$$\begin{bmatrix} V_d \\ V_q \\ V_o \end{bmatrix}=\frac{2}{3}\begin{bmatrix} \cos\theta & \cos\left(\theta-\frac{2\pi}{3}\right) & \cos\left(\theta+\frac{2\pi}{3}\right) \\ -\sin\theta & -\sin\left(\theta-\frac{2\pi}{3}\right) & -\sin\left(\theta+\frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{3.4}$$

Current transformation from three phases (a, b, c) to two phases (d-q) is,

$$\begin{bmatrix} i_d \\ i_q \\ i_o \end{bmatrix}=\frac{2}{3}\begin{bmatrix} \cos\theta & \cos\left(\theta-\frac{2\pi}{3}\right) & \cos\left(\theta+\frac{2\pi}{3}\right) \\ -\sin\theta & -\sin\left(\theta-\frac{2\pi}{3}\right) & -\sin\left(\theta+\frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{3.5}$$

To get the d-q form of the voltages and the currents, which are written in equation (3.4) and (3.5) respectively, apply the derivative rules. In short, equation (3.4) can be written as;

$$V_{dqo}=T(\theta)V_{abc} \tag{3.6}$$

And equation (3.5 can be expressed as,

$$i_{dqo}=T(\theta)i_{abc} \tag{3.7}$$

Applying Park's transformation to equation (3.8) using derivative formula,

$$\frac{d}{dt}(i_{dqo})=\frac{d}{dt}(T(\theta)i_{abc})=\frac{d}{dt}(T(\theta))i_{abc}+T(\theta)\frac{d}{dt}i_{abc} \tag{3.8}$$

Substituting equation (3.3) to equation (3.8) results,

$$\frac{d}{dt}(i_{shdqo}) = T^{'}(\theta)i_{sh} + T(\theta)\frac{1}{L_{sh}}\left(-R_{sh}i_{sh} + V_S - V_{sh}\right) \qquad (3.9)$$

Simplifying equations (3.9) results equation (3.10).

$$\frac{d}{dt}\begin{bmatrix} i_{shd} \\ i_{shq} \\ i_{sh0} \end{bmatrix} = \begin{bmatrix} i_{shq} \\ -i_{shd} \\ 0 \end{bmatrix} - \frac{R_{sh}}{L_{sh}}\begin{bmatrix} i_{shd} \\ i_{shq} \\ i_{sho} \end{bmatrix} + \frac{1}{L_{sh}}\begin{bmatrix} V_{sd} - V_{shd} \\ V_{sq} - V_{shq} \\ V_{s0} - V_{sho} \end{bmatrix} \qquad (3.10)$$

Where,

$V_d\ V_q\ and\ V_o$ are direct axis, quadrature axis and zero axis voltages.

$i_d\ i_q\ and\ i_o$ are direct axis, quadrature axis and zero axis current, respectively.

There are only two axes are important hence the zero axis is omitted and equation (3.10) can be written as,

$$\frac{d}{dt}\begin{bmatrix} i_{shd} \\ i_{shq} \end{bmatrix} = \begin{bmatrix} i_{shq} \\ -i_{shd} \end{bmatrix} - \frac{R_{sh}}{L_{sh}}\begin{bmatrix} i_{shd} \\ i_{shq} \end{bmatrix} + \frac{1}{L_{sh}}\begin{bmatrix} V_{sd} - V_{shd} \\ V_{sq} - V_{shq} \end{bmatrix} \qquad (3.11)$$

Multiply equation (3.11) by $e^{j\omega t}$ both sides then

$$\frac{d}{dt}\left\{\left(i_{shd} + ji_{shq}\right)e^{j\omega t}\right\} = \left(i_{shq} - ji_{shd}\right)e^{j\omega t} - \frac{R_{sh}}{L_{sh}}\left(i_{shd} + ji_{shq}\right)e^{j\omega t}$$
$$+\frac{1}{L_{sh}}\left\{\left(V_{sd} + jV_{sq}\right) - \left(V_{shd} + jV_{shq}\right)\right\}e^{j\omega t} \qquad (3.12)$$

Simplifying equation (3.12) and writing in matrix form resulted equation (3.13).

$$\frac{d}{dt}\begin{bmatrix} i_{shd} \\ i_{shq} \end{bmatrix} = \begin{bmatrix} -\frac{R_{sh}}{L_{sh}} & 0 \\ 0 & -\frac{R_{sh}}{L_{sh}} \end{bmatrix} \begin{bmatrix} i_{shd} \\ i_{shq} \end{bmatrix} + \frac{1}{L_{sh}} \begin{bmatrix} V_{sd} - V_{shd} + \omega L_{sh}\, i_{shq} \\ V_{sq} - V_{shq} - \omega L_{sh}\, i_{shd} \end{bmatrix} \qquad (3.13)$$

3.1.2.2 Mathematical Modeling of Series Converter

Formulating the mathematical modeling of the series converter is the same as the shunt converter. Using KVL, the dynamic modeling of series converter from figure (3.3) is;

$$\frac{d}{dt}(i_{sep}) = -\frac{R_{se}}{L_{se}}(i_{se}) + \frac{1}{L_{se}}(V_s - V_{se} - V_r) \qquad (3.14).$$

Where,

L_{se} and R_{se} are the series resistance and inductance of transformer, respectively.

i_{se} is the current through the transmission line.

V_{se} , V_s *and* V_r are series injected, sending end, and receiving end voltages.

Keeping the producers of the shunt converter, the three-phase mathematical modeling of the series converter can be written as below in equation (3.15) which is obtained from equation (3.14).

$$\frac{d}{dt}\begin{bmatrix} i_{sep} \\ i_{seb} \\ i_{sec} \end{bmatrix} = -\frac{R_{se}}{L_{se}} \begin{bmatrix} i_{sep} \\ i_{seb} \\ i_{sec} \end{bmatrix} + \frac{1}{L_{se}} \begin{bmatrix} V_{sp} - V_{sep} - V_{rp} \\ V_{sb} - V_{seb} - V_{rb} \\ V_{sc} - V_{sec} - V_{rc} \end{bmatrix} \qquad (3.15)$$

Transferring from three phase in to two phase (d-q axis) using park transformation as did before in dynamic modeling of shunt converter, equation (3.16) can be obtained as below.

$$\frac{d}{dt}\begin{bmatrix} i_{sed} \\ i_{seq} \\ i_{se0} \end{bmatrix} = \begin{bmatrix} i_{seq} \\ -i_{sed} \\ 0 \end{bmatrix} - \frac{R_{se}}{L_{se}} \begin{bmatrix} i_{sed} \\ i_{seq} \\ i_{seo} \end{bmatrix} + \frac{1}{L_{se}} \begin{bmatrix} V_{sd} - V_{sed} - V_{rd} \\ V_{sq} - V_{seq} - V_{rq} \\ V_{s0} - V_{seo} - V_{ro} \end{bmatrix} \qquad (3.16)$$

Neglecting the zero components like dynamic modeling of shunt converter, the series converter is written as,

$$\frac{d}{dt}\begin{bmatrix} i_{sed} \\ i_{seq} \end{bmatrix} = \begin{bmatrix} -R_{se}/L_{se} & \omega \\ -\omega & R_{se}/L_{se} \end{bmatrix}\begin{bmatrix} i_{sed} \\ i_{seq} \end{bmatrix} + \frac{1}{L_{se}}\begin{bmatrix} V_{sd} - V_{sed} - V_{rd} \\ V_{sq} - V_{seq} - V_{rq} \end{bmatrix} \quad (3.17)$$

3.1.2.3 Mathematical Modeling of DC-link Capacitor

For maintaining the power flow in the capacitor, controlling the net input power should instantaneously meet the charging and discharging rate of energy in the capacitor. The input power to capacitor comes through shunt converter and output power pass through series converter [23], [25]. Thus, by applying the power balance equation, the net power in DC link capacitor becomes the difference between power in the shunt converter and power in series converter. Therefore, the power maintained in the capacitor is given by,

$$P_{dc} = P_{sh} - P_{se} \quad (3.18)$$

Where,

P_{dc} is the power store on the DC link capacitor.

P_{sh} is the power coming into the Dc link capacitor from the shunt converter.

P_{se} is the power injected into the transmission line from the series converter.

The power is the product of voltage and current hence, the power on the shunt converter on series converter and on the Dc link capacitor are written as,

$$\begin{aligned} P_{sh} &= V_{shd} i_{shd} - V_{shq} i_{shq} \\ P_{se} &= V_{sed} i_{sed} - V_{seq} i_{seq} \\ P_{dc} &= i_{DC} * V_{dc} \end{aligned} \quad (3.19)$$

The current in the capacitor is calculated as,

$$i_{dc} = C\frac{d}{dt}V_{dc}$$

Equation (3.18) can be written as.

$$CV_{dc}\frac{d}{dt}V_{dc} = \left(V_{shd}i_{shd} - V_{shq}i_{shq}\right) - \left(V_{sed}V_{sed} - V_{seq}i_{seq}\right) \qquad (3.20)$$

From the characteristics of derivatives, it is found that.

$$CV_{dc}\frac{d}{dt}V_{dc} = \frac{1}{2}C\frac{d}{dt}V_{dc}^{2}$$

Now substituting equation (3.20), by equation below

$$\frac{1}{2}C\frac{d}{dt}V_{dc}^{2} = \left(V_{shd}i_{shd} - V_{shq}i_{shq}\right) - \left(V_{sed}V_{sed} - V_{seq}i_{seq}\right)$$

The dynamic mathematical modeling of the DC link capacitor can be found as.

$$\frac{d}{dt}V_{dc}^{2} = \frac{2}{C}\left\{\left(V_{shd}i_{shd} - V_{shq}i_{shq}\right) - \left(V_{sed}V_{sed} - V_{seq}i_{seq}\right)\right\} \qquad (3.21)$$

3.2 Mathematical Modeling of UPFC Controller

As seen from the complete structure of UPFC from figure 3.2, it has a controller used for switching of the two converters. The controllers regulate the two converters when and what action is to be taken. Therefore, proper coordination between the series and shunt converter control system in the UPFC has to be established so that proper coordination of real and reactive power in the UPFC has to be maintained. There are two parameters to determine the action of the converters. These are the set value (reference) and measured values. The reference or set value is the value of power system parameters (voltage, current, power) at steady state condition at the connection point of UPFC and the system network. The measured value is the value of power system parameters at any instant of time at the connection point of UPFC with the system network.

The function of the UPFC controller is sending a switching signal to the converters. These switching signals are a pulse width modulator (PWM). Hence, shunt converter has its own controlling signals and a series converter too. The controller design for each converter can then be synthesized from their mathematical modeling.

Both the series and shunt converters mathematical modeling has state space equation form derived from their mathematical modeling [25]. The state space equation is written as;

$$\overline{X} = AX + BU\ .$$

3.2.1 Shunt Converter Controller Modeling

The shunt converter, control modeling is derived from equation (3.13). It can be written as in state space equation ‘ $\overline{X} = AX + BU$ and ‘ $Y = CX$ ’ form.

$$\frac{d}{dt}\begin{bmatrix} i_{shd} \\ i_{shq} \end{bmatrix} = \begin{bmatrix} -\frac{R_{sh}}{L_{sh}} & 0 \\ 0 & -\frac{R_{sh}}{L_{sh}} \end{bmatrix} \begin{bmatrix} i_{shd} \\ i_{shq} \end{bmatrix} + \frac{1}{L_{sh}} \begin{bmatrix} V_{sd} - V_{shd} + \omega L_{sh}\, i_{shq} \\ V_{sq} - V_{shq} - \omega L_{sh}\, i_{shd} \end{bmatrix} \qquad (3.22)$$

Where,

$$\overline{X} = \frac{d}{dt}\begin{bmatrix} i_{shd} \\ i_{shq} \end{bmatrix}, \qquad (X) = \begin{bmatrix} i_{shd} \\ i_{shq} \end{bmatrix}, \qquad (A) = \begin{bmatrix} \frac{-R_{sh}}{L_{sh}} & 0 \\ 0 & \frac{-R_{sh}}{L_{sh}} \end{bmatrix}$$

$$U = \frac{1}{L_{sh}} \begin{bmatrix} V_{sd} - V_{shd} + \omega L_{sh}\, i_{shq} \\ V_{sq} - V_{shq} - \omega L_{sh}\, i_{shd} \end{bmatrix} \qquad (B) = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

$$\text{output } (Y) = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix}, \qquad \text{output matrix } (C) = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

Then, equation (3.22) can be written as,

$$\frac{d}{dt}\begin{bmatrix} i_{shd} \\ i_{shq} \end{bmatrix} = \begin{bmatrix} -\frac{R_{sh}}{L_{sh}} & 0 \\ 0 & -\frac{R_{sh}}{L_{sh}} \end{bmatrix} \begin{bmatrix} i_{shd} \\ i_{shq} \end{bmatrix} + \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \tag{3.23}$$

Control variable from equation (3.23) can be written as;

$$\begin{bmatrix} V_{shd} \\ V_{shq} \end{bmatrix} = \begin{bmatrix} k_{psh} + \frac{k_{ish}}{s} & 0 \\ 0 & k_{psh} + \frac{k_{ish}}{s} \end{bmatrix} \begin{bmatrix} i^*_{shd} - i_{shd} \\ i^*_{shq} - i_{shq} \end{bmatrix} + \begin{bmatrix} V_{sd} + \omega L_{sh} i_{shq} \\ V_{sq} - \omega L_{sh} i_{shd} \end{bmatrix} \tag{3.24}$$

Where,

i^*_{shd} is the active component reference of UPFC shunt converter.

i^*_{shq} is the reactive component reference of UPFC shunt converter.

The inverter current I_{sh} split into real (in phase with bus voltage) and reactive components. AC-bus voltage regulator determines the reference for reactive component. Magnitude of the sending end bus voltage $|V_s|$ is controlled by shunt device reactive power injection.

Reference value of shunt reactive power is;

$$Q^*_{sh} = \left(\frac{K_{iV}}{s} + K_{pV}\right)\left(|V_s|^* - |V_s|\right) \tag{3.25}$$

Where;

$|V_s|^*$ is the sending end reference voltage magnitude.

K_{iV} , and K_{pV} are the integral and the proportional gain for the PI controller.

Then, the q-axis reference current in the shunt branch is:

$$i_{shq}^{*} = \frac{Q_{sh}^{*}}{|V_s|} \tag{3.26}$$

Substituting equation (3.25) into equation (3.26)

$$i_{shq}^{*} = \frac{\left(\frac{K_{iV}}{s} + K_{pV}\right)\left(|V_s|^{*} - |V_s|\right)}{|V_s|} \tag{3.27}$$

The d-axis reference current for the shunt branch has taken from the active power drawn by the series converter.

$$i_{shd}^{*} = \frac{P_{se}}{|V_s|} + \left(K_{pDC} + \frac{K_{iDC}}{s}\right)\left(V_{DC}^{*} - V_{DC}\right) \tag{3.28}$$

Where;

P_{se} is the instantaneous real power injected into the transmission line by the series converter.

V_{sed} and V_{seq} are the real and the reactive component of the injected voltages.

i_{sed} *and* i_{seq} are real and reactive components of the line current respectively

K_{iDC} *and* K_{pDC} are the integral and the proportional gain for the PI controller.

3.2.1.1 Series Converter Control Modeling

Similar to the controller design of shunt converter, the series converter, controller design can be synthesized from the mathematical modeling of the series converter. Therefor the mathematical modeling of the series converter can be remembered as below.

$$\frac{d}{dt}\begin{bmatrix} i_{sed} \\ i_{seq} \end{bmatrix} = \begin{bmatrix} -\frac{R_{se}}{L_{se}} & 0 \\ 0 & -\frac{R_{se}}{L_{se}} \end{bmatrix}\begin{bmatrix} i_{sed} \\ i_{seq} \end{bmatrix} + \frac{1}{L_{se}}\begin{bmatrix} V_{sd} - V_{sed} - V_{rd} + \omega L_{se}\, i_{seq} \\ V_{sq} - V_{seq} - V_{rq} - \omega L_{se}\, i_{sed} \end{bmatrix} \quad (3.29)$$

Where,

$$\overline{X} = \frac{d}{dt}\begin{bmatrix} i_{sed} \\ i_{seq} \end{bmatrix}, \qquad A = \begin{bmatrix} \frac{-R_{se}}{L_{se}} & 0 \\ 0 & \frac{-R_{se}}{L_{se}} \end{bmatrix}, \qquad X = \begin{bmatrix} i_{sed} \\ i_{seq} \end{bmatrix}$$

$$U = \frac{1}{L_{se}}\begin{bmatrix} V_{sd} - V_{sed} - V_{rd} + \omega L_{se}\, i_{seq} \\ V_{sq} - V_{seq} - V_{rq} - \omega L_{se}\, i_{sed} \end{bmatrix}, \qquad B = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

Applying a similar procedure as the shunt converter, the control variable U can then be written as,

$$\begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \frac{1}{L_{se}}\begin{bmatrix} V_{sd} - V_{sed} - V_{rd} + \omega L_{se} i_{seq} \\ V_{sq} - V_{seq} - V_{rq} - \omega L_{se} i_{seq} \end{bmatrix} \quad (3.30)$$

Now equation 3.29 can be written as;

$$\frac{d}{dt}\begin{bmatrix} i_{sed} \\ i_{seq} \end{bmatrix} = \begin{bmatrix} -\frac{R_{se}}{L_{se}} & 0 \\ 0 & -\frac{R_{se}}{L_{se}} \end{bmatrix}\begin{bmatrix} i_{sed} \\ i_{seq} \end{bmatrix} + \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \quad (3.31)$$

Where,

i^*_{sed} is the d- component reference current of series converter.

i^*_{seq} is the q- component reference current of series converter.

Therefore, the control variables of the series converter can be expressed in equation (3.32) as shown below.

$$\begin{bmatrix} V_{sed} \\ V_{seq} \end{bmatrix} = \begin{bmatrix} k_{pse} + \frac{k_{ise}}{s} & 0 \\ 0 & k_{pse} + \frac{k_{ise}}{s} \end{bmatrix} \begin{bmatrix} i_{sed}^{*} - i_{sed} \\ i_{seq}^{*} - i_{seq} \end{bmatrix} + \begin{bmatrix} V_{sd} - V_{rd} + \omega L_{se} i_{seq} \\ V_{sq} - V_{rq} - \omega L_{se} i_{sed} \end{bmatrix} \tag{3.33}$$

Series reference current can be calculated from the total power flow through the series converter.

$$S_{se} = V_r * i_{se} = P_{se} + jQ_{se} = \left(V_{rd} + jV_{rq}\right)\left(i_{sed} + ji_{seq}\right)$$

This resulted as;

$$S_{se} = V_{rd} i_{sed} - V_{rq} i_{seq} + j\left(V_{rd} i_{seq} + V_{rq} i_{sed}\right) \tag{3.34}$$

Then the active power on the series converter can be written as;

$$P_{se} = V_{rd} i_{sed} - V_{rq} i_{seq} \tag{3.35}$$

The reactive power on the series converter is;

$$Q_{se} = V_{rd} i_{seq} + V_{rq} i_{sed} \tag{3.36}$$

Thus, the series reference current can be calculated from equation (3.35) and (3.36.)

$$i_{sed}^{*} = \frac{P_{se}^{*} V_{rd} + Q_{se}^{*} V_{rq}}{V_r^2} \tag{3.37}$$

$$i_{seq}^{*} = \frac{-P_{se}^{*} V_{rq} + Q_{se}^{*} V_{rd}}{V_r^2}$$

The receiving end voltage can be split in to direct and quadrature axis.

$$V_r^2 = V_{rd}^2 + V_{rq}^2 \qquad (3.38)$$

Where;

P_{se}^* is the real power reference (base) of the bus bar.

Q_{se}^* is reactive power reference (base) of the bus bar.

V_{rd} *and* V_{rq} are the real and reactive components of receiving end voltages.

3.2.2 SIMULINK Model of Converters

UPFC converters as discussed before contain shunt converter, series converter, DC link capacitors and UPFC controllers. Both converters have transformers and a power electronics switches while DC link capacitor has capacitors used to store and release power for the two converters. Therefore, the MATLAB/SIMULINK for both converters contains only the transformers and power electronics switch connected in series with the transformer. Hence, MATLAB/SIMULINK in this work has been built for UPFC controllers from the mathematical modeling of shunt converters, series converters and DC link capacitors.

3.2.2.1 SIMULINK Model of Shunt Converter

Taking the mathematical modeling of shunt converter controller, MATLAB/SIMULINK model has been designed. The Simulink model shown in Figure 3.4, is developed from equation (3.24)

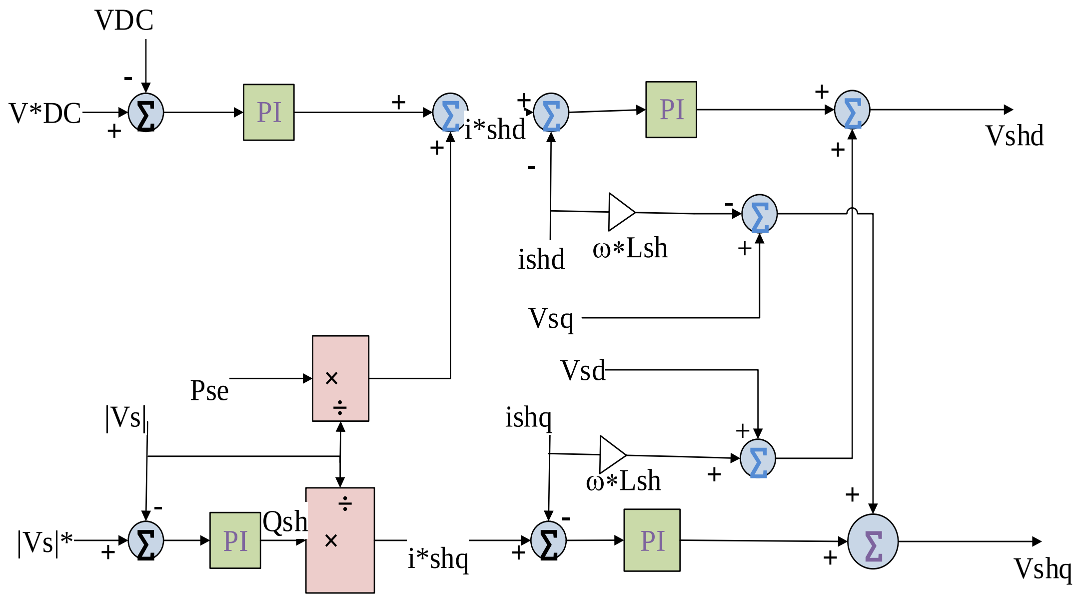


Figure 3.4 SIMULINK model of shunt converter controller

The Simulink model shown in figure 3.5 is developed from equation (3.27).

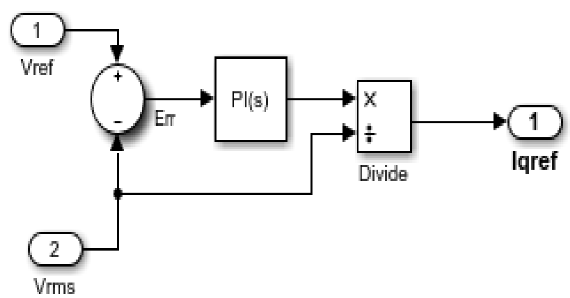


Figure 3.5 SIMULINK model of quadrature axis reference current

Figure 3.6 is the Simulink model developed from equation (3.28).

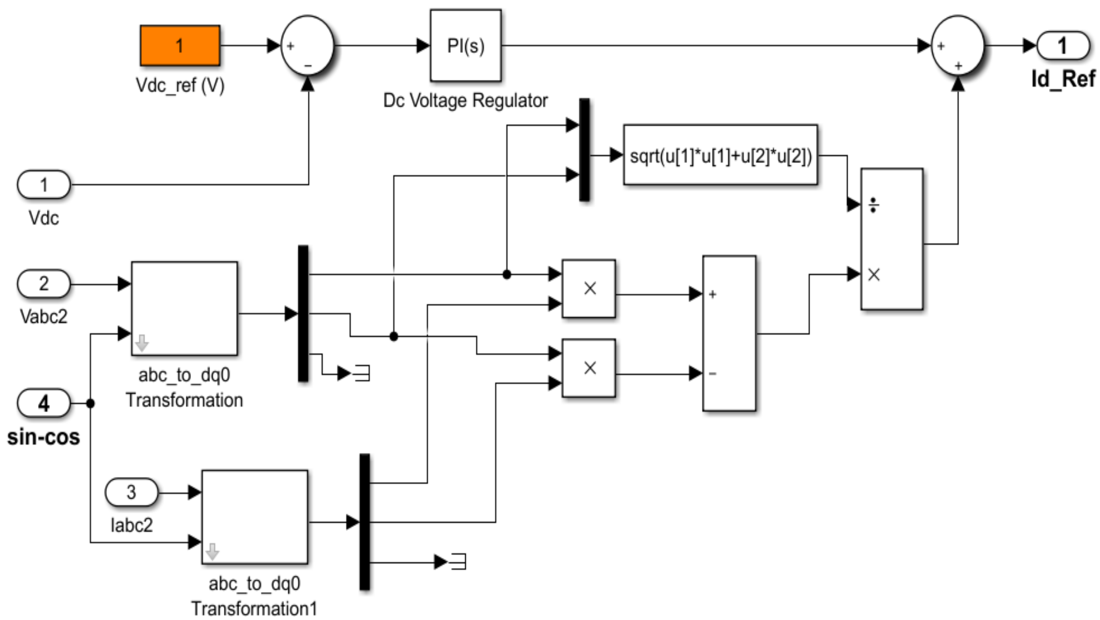


Figure 3.6 SIMULINK model of the direct axis reference current

The Figure 3.7 Shown below is the total SIMULINK model developed from the mathematical modeling of the shunt converter controller design. Some blocks are taken from IEEE block of UPFC models in the MATLAB/SIMULINK library.

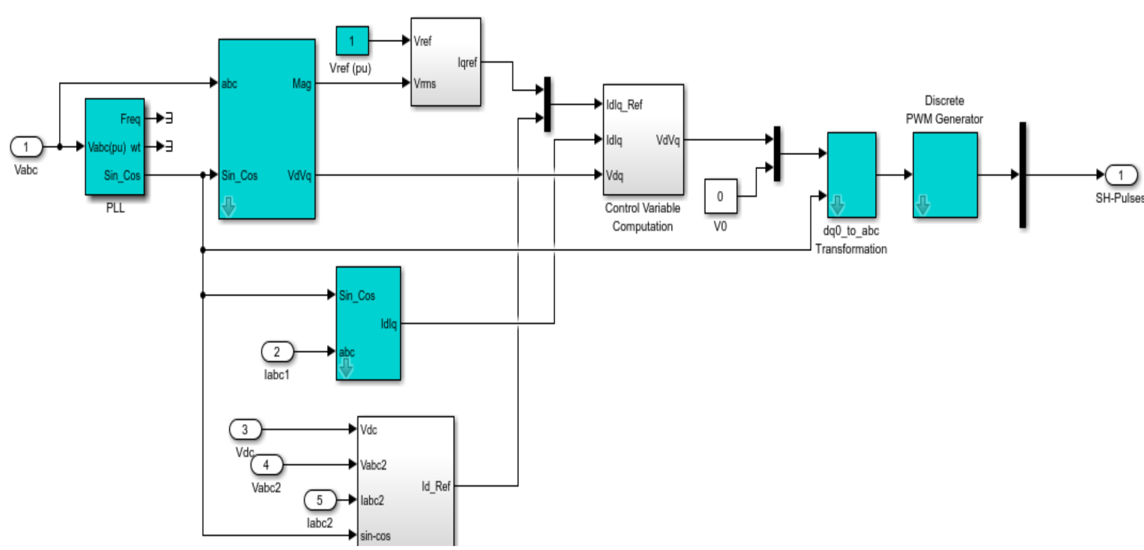


Figure 3.7 General SIMULINK model of the shunt converter controller

3.2.2.2 SIMULINK Model of the Series Converter

Like the Simulink modeling of the shunt converter, the models of the series converter have been developed from its corresponding mathematical modeling. The figure 3.8 below is the Simulink model of the series direct and quadrature axis voltages.

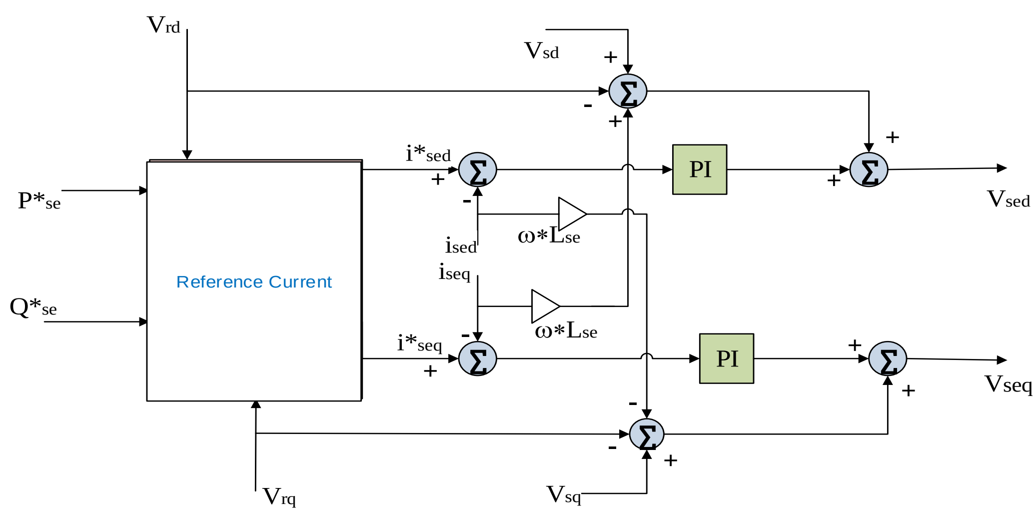


Figure 3.8 SIMULINK Model of d-q voltages

The Simulink model block is derived from equation (3.37).

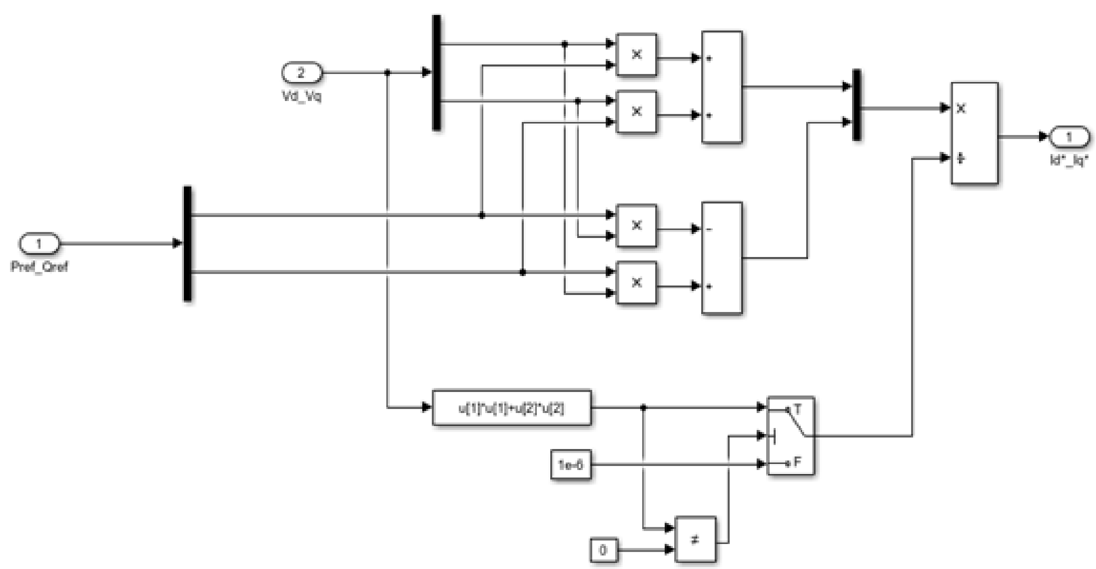


Figure 3.9 Block diagram of series converter reference currents

CHAPTER FOUR

4. SIMULATION RESULT AND DISCUSSION

4.1. General Overview of Simulation and Discussion

This chapter present simulation result and analysis of the transmission line loss from Bahir Dar substation to Debremarkose substation. The analysis of the simulation result has been conducted under different scenario. Those scenarios are chosen due to their contribution to line losses. As discussed in chapter two there are many causes for power loss of the transmission line. For ease of simulation analysis, these factors can be generalized as load variation at the consumer side, faults anywhere in the power system network, the impedance of the power lines at normal (steady state condition). Therefore, the analysis of the transmission line is conducted at two major classes (i.e. at steady state and at disturbance condition).

Power loss is measured by calculating or measuring the power difference at sending end bus bar to the receiving end bus bar of the power network. The power loss in this simulation is analyzed by subtracting the power reading of Bus 6 from Bus 1 from the figure 4.1 shown in below. The difference is natural; because power loss is a natural phenomenon and cannot be eliminated. However properly designing (sizing) of the transmission line and use of compensating device can minimize the amount of losses on the transmission line. The unit of the power loss measurement in this work is conducted on per unit measurement, taking 532MVA as the base MVA of North-West region, power system network.

As shown in the figure 4.1 below there are two power system networks represented by figure a and b. One shown in a, is existing power network of the North-West region while figure b is the power network of North-West region with UPFC connected to it. To know whether UPFC reduce the loss of the transmission line from Bahir Dar to Debremarkose substation (bus 1 to bus 6) or not, measurement is taken from the two systems by keeping the two system at the same situation except UPFC is added to **Error! Reference source ot found.** (b).

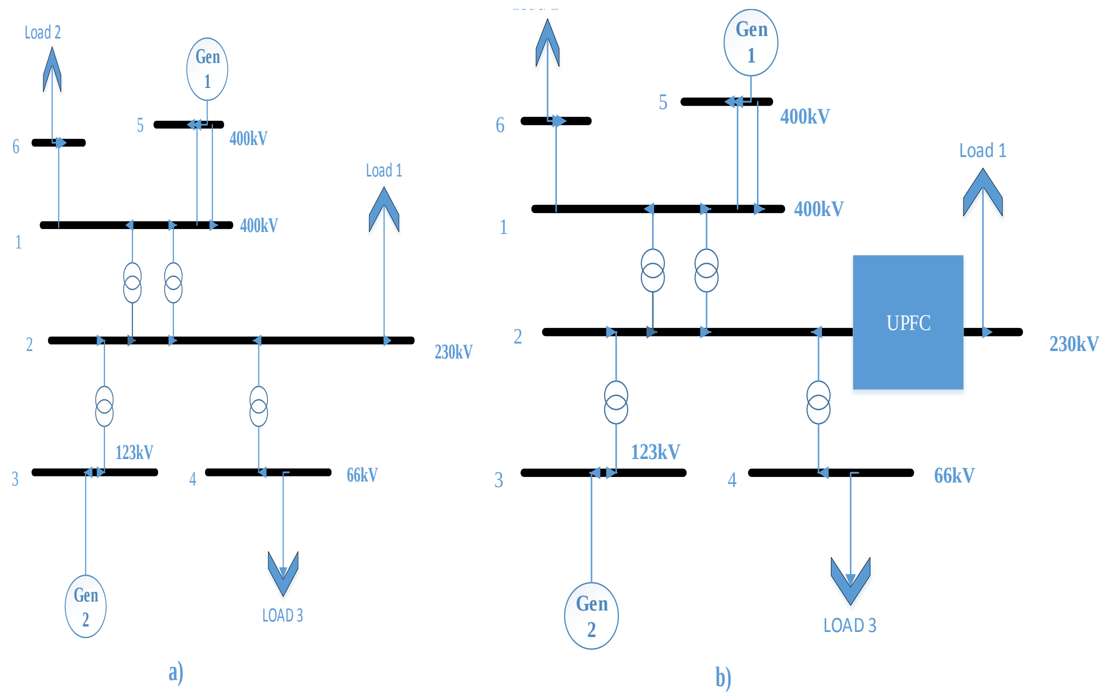


Figure 4.1 The North West region power system network with and without UPFC

The simulation result can be analyzed in different position of UPFC on the power network. The placement can be tested at bus 1 at bus 6, between the midpoint of bus 1 and bus 6, at bus 3, at bus 2, at between the midpoint of bus 1 and bus 2 generally anywhere in the network. Many tests can be conducted and using interpolation techniques, the preferred position is determined. Placement of UPFC has been determined after comparing the simulation results in different position so that choosing the minimum loss of the transmission line obtained as the best performance of the UPFC.

4.1.1. System Simulation at Different Position

The effectiveness of controller device especially FACTS device on the power system can vary from one position to the other position. Therefore, to determine the placement where the controller should be located on the power system network, various mechanisms forwarded by many scholars. From those methods, particle swarm optimization and artificial intelligence are the most common. For simple and less complicated power system network, using interpolation method to identify the best placement is preferred than developing another algorism.

The term interpolation is, taking two different positions randomly for the solution of some problem and finding the solution based on the result found from the test point. In this case placing the controller at the beginning of the transmission line and at the end of the transmission line and test the effectiveness of the controller for the two placements individually. If sufficient output is not obtained, then test the placement at the middle of the two positions. If the result is not approaching for the intended point, check the placement anywhere away from the path that from previously tested. The interpolation procedure continues in this method until best result is obtained.

In this research, interpolation begins from the two terminals, which are at the beginning of the generation station and at the distribution substations. The generation substation is from Tanabeles and the distribution substation is the Debremarkose substation and the 230 kV bus bar of Bahir Dar substation.

After many interpolation experiments is conducted, some locations brought into discussion for analyst clarity of this work. These locations for UPFC placement in North West region of Ethiopian power system are in Bahir Dar substation, in Debremarkose substation, between Bahir Dar and Debremarkose substation and at the beginning of transmission line from Tan abeles generation station.

4.1.1.1. UPFC Applied at 400KV of Bahir Dar substation

In Bahir Dar substation, there are different voltage level bus bars, which are 400kV bus bar, 230kV bus bar, 132kV bus bar and 66kV bus bar. In this scenario, the simulation of the power loss measurement of the transmission line is conducted from both figures a and b with the same power system parameters except UPFC is added in figure b. For both a and b, the system is at steady state (i.e. no fault and with power system balanced)

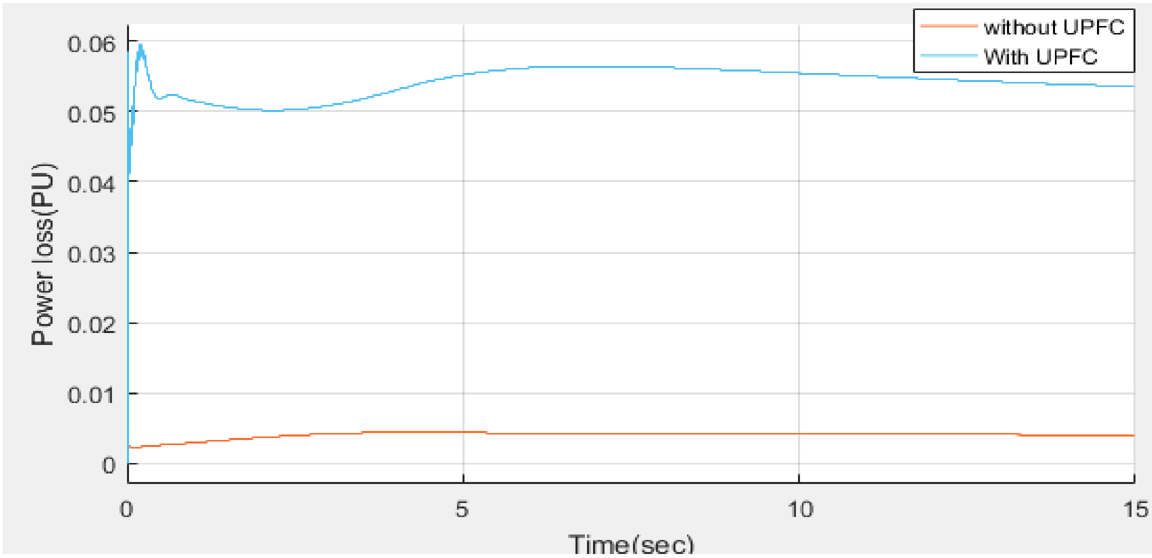


Figure 4.2 Power loss when UPFC is at 400kV bus bar.

The graph shown in fig: 4.2 is the power loss measurement of the transmission line from Bahir Dar substation to Debremarkose substation (bus bar 1 to bus bar 6). As shown in the figure 4.2, there are two-power loss readings having different magnitudes. The graph shown in the blue colored is the power loss of the transmission line of the system shown in fig: 4.1 b, with magnitude 0.06Pu at the beginning of the simulation and 0.054Pu at steady state hence, the maximum loss is 0.06Pu. However, when UPFC is used as power loss controller and placed on Bahir Dar substation at 400kV bus bar, the transmission line loss shown in red color become 0.0043Pu. The power loss difference of the two graphs is 0.0557Pu, which is 29.63MW. From the two graphs, the system with UPFC has more loss than the system without UPFC. Therefore, bus bar 1 cannot be the location of UPFC.

4.1.1.2. UPFC applied at Bus Bar 6

Debremarkose substation is one of distribution substation, which reduces the incoming 400kV to 230kV. When UPFC is located in the 400kV side of this substation and simulation is tested to reduce the transmission line loss, the result is found as shown in figure 4.3 below.

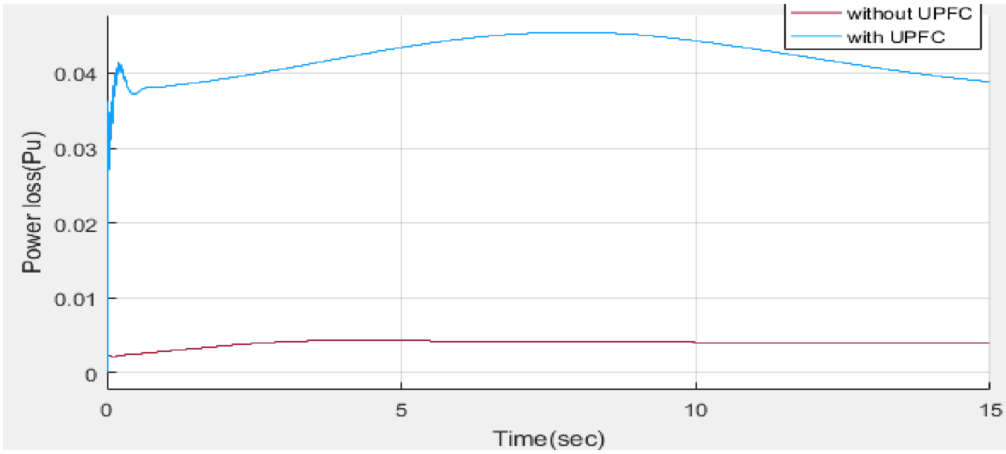


Figure 4.3 Power loss simulations when UPFC is located at bus bar 6

As shown in the figure 4.3, power loss measurement is conducted in two systems. One is power loss of the transmission line without UPFC and the other is power loss using UPFC which is located on the Debremarkose substation. The blue colored graph is the power loss of the transmission line using UPFC in the system which is located at bus bar 6 and the loss of the transmission line become 0.046Pu while the graph colored with red one is the power loss of the transmission line when the system is without UPFC having power loss of 0.0043Pu. In this simulation, the power loss difference in the two graphs is 0.0417Pu which is 22.1844MW. Therefore, UPFC has negative impact when it is located on Debremarkose substation.

4.1.1.3. UPFC Applied at the Middle bus bar 1 and bus bar 6

As observed from the above two-simulation result, bus bar 1 and bus bar 6 cannot be the location of UPFC in the North-West region of Ethiopian power system network. The middle point of the two location is tested to check that, whether the path from bus bar 1 to bus bar 6 can be the location or not. i.e. the middle of the transmission line is selected to find better power loss reduction if the previously tested outputs are not satisfactory or the two solutions are far apart from the intended output in their result. Now placing UPFC on the middle of the transmission line provides the loss of the transmission line as shown in figure 4.4 below.

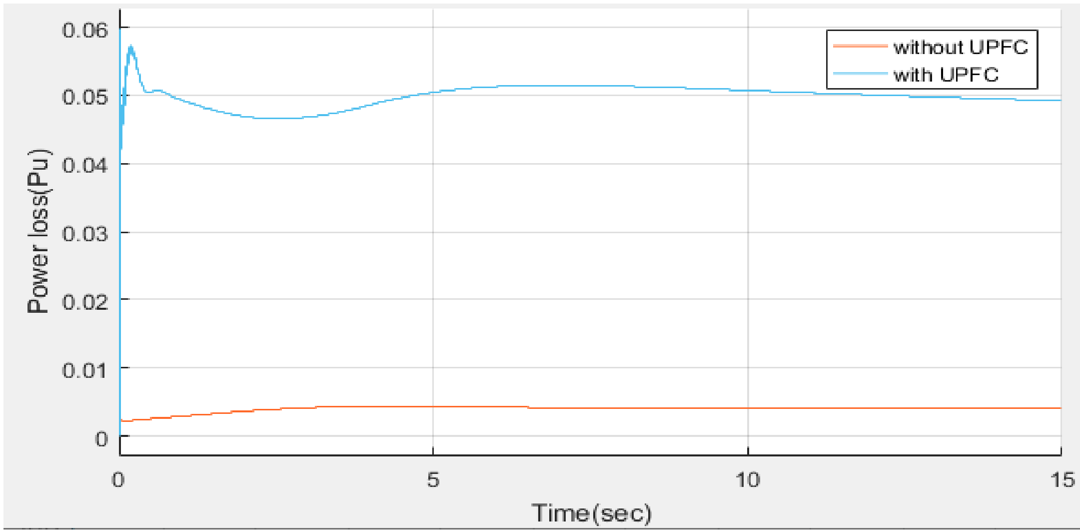


Figure 4.4 System simulation when UPFC is between bus1 and bus6

From the figure 4.4, the power losses of the transmission line in two systems are different in magnitude. The graph in the blue color is the power loss of the transmission line when UPFC is located in the middle of the transmission line having the maximum power loss of 0.058Pu. The graph shown in the red color is the power loss of the transmission line without UPFC is added to the network. The line has maximum power loss of 0.0537Pu which is very low compared to the blue graph. Therefore, UPFC should not be connected at anywhere from bus 1 up to bus bar 6.

4.1.1.4. UPFC Applied at Bus Bar 2

If the placement of UPFC on the line between Debremarkose and Bahir Dar substation is not the solution for power loss reduction, searching other place in the other point of the North West region of Ethiopian power system network is the next step. Therefore, 230kV (bus bar 2) of the power system network can be the next step. Notice that when the location of UPFC is changed from one voltage level to the other, its rating also changed. Here UPFC is connected with 230kV bus bar hence; the sizing of UPFC transformers and DC link capacitors is also changed based on the concepts discussed in chapter three (in sizing of UPFC part).

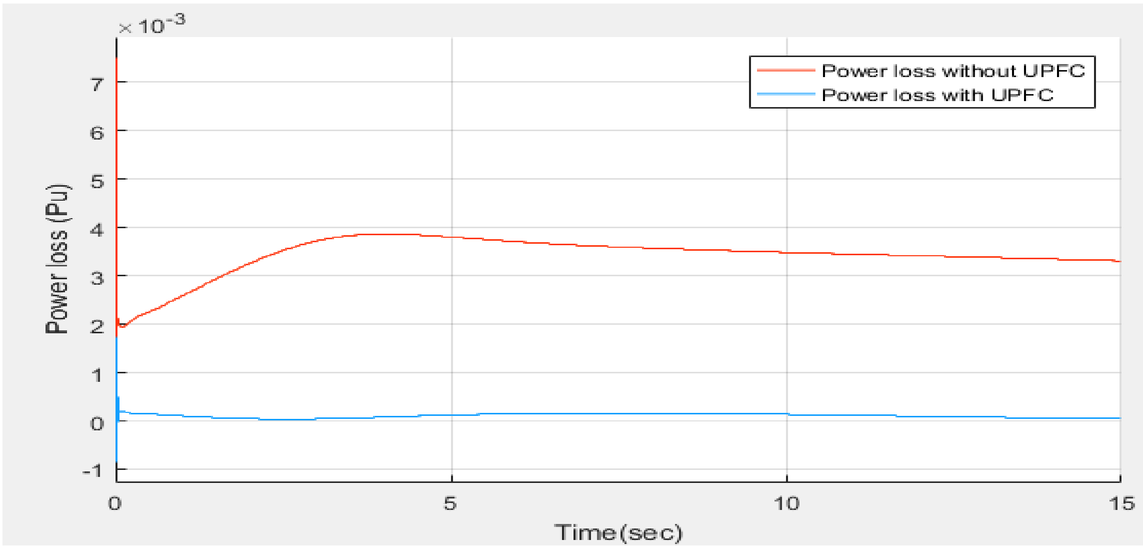


Figure 4.5. Power loss when UPFC is at 230kV of Bahir Dar substation

As shown in the figure 4.5, the power loss of the transmission line shown in red color is 0.00385Pu. However, when UPFC is connected to the network at 230kV (at bus bar 2), the power loss becomes 0.00016Pu. Using UPFC in the power system network at bus 2 reduce the existing power loss by 0.00369Pu. Therefore, using UPFC at bus 2 in the network can save the power loss by 0.00369Pu or 1.693MW.

From the results found in figure 4.5, the location of UPFC in North-West region is at 230kV of the Bahir Dar substation. To see the performance of UPFC for power loss reduction of the transmission line, it should be tested at different power system disturbance by keeping its location at bus bar 2.

4.1.2. System Simulation at Different Scenarios

Since the location of UPFC is known based on trial-error and interpolation techniques, then its effectiveness is also examined for different scenarios. As discussed earlier, there are factors for power loss variation for transmission line. These factors can be categorized in faults and in load variation. The above three location scenarios are held, by keeping the network at steady state i.e. no fault and no load variation occur on the system.

4.1.2.1. System Simulation at Three Phase Fault

Any fault on the Ethiopian power system network especially on North West region disturb the normal power handling of the transmission line and may leads to congestion. This congestion leads more power loss online due to heating of the transmission line and the increment of impedance on the line. The duration of fault has different impacts on the power loss of the transmission line.

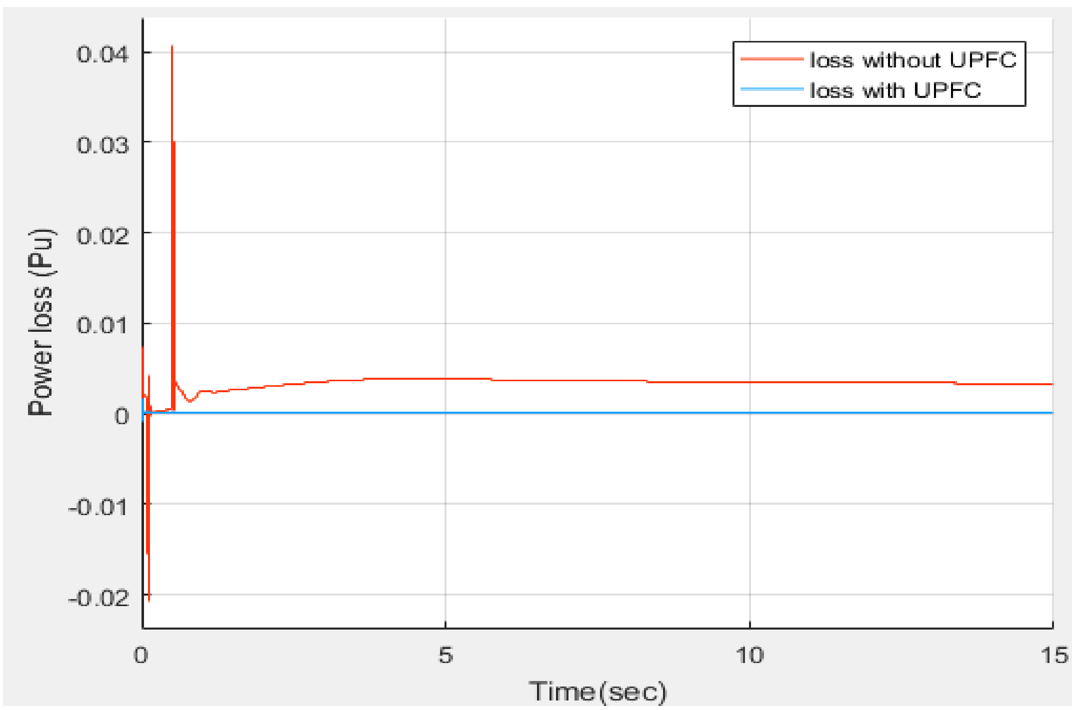


Figure 4.6 power losses at three phase fault

The figure shown in figure 4.6 is the power loss of the transmission line when the power system network is exposed to three phase fault at a transmission line from bus 1 to bus 6 and the fault sustained from 0.1-0.5 seconds. The graph shown in the red color is the power loss of the transmission line. As seen the loss increases up to 0.04Pu during the fault condition and the loss becomes 0.00385Pu after the fault is cleared. However, when UPFC is used, the power loss becomes 0.00016Pu. Hence, at least 0.00369Pu or 1.963MW power is saved from loss by the transmission line.

If the duration of fault increases, the power losses either increase or differ from the result obtained from figure 4.6. When the fault sustained in the power system it will create cascading fault to other power system components or equipment's. This resulted as either power flow interruption or blackout in the power system network. Immediately clearing the fault is advisable for the healthiness of the electrical equipment. To see how sustained fault can have an influence, let the fault sustained up to 2 second and test the simulation.

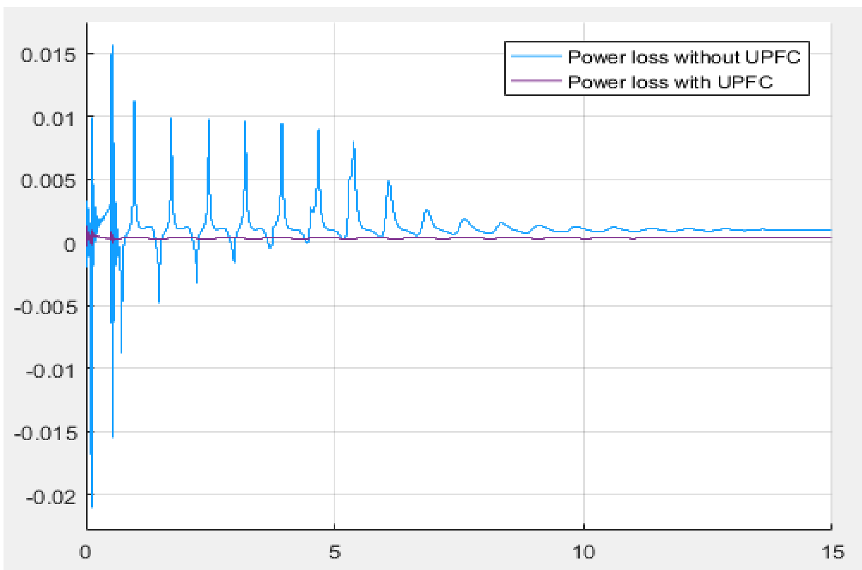


Figure 4.7 power loss at sustained faulted

In the figure 4.7, the blue colored graph is fluctuated and has a high magnitude power loss 0.015Pu. However, when UPFC is used for power loss mitigation, the power loss become constant and has a magnitude of 0.00016Pu. As seen from the result power loss is reduced by 0.01484Pu or 7.89MW. Therefore, using UPFC has great advantage for power loss reduction.

4.1.2.2. System Simulation for Load Variation

Load variation is one of the main defects for overall performance of the power system quality, stability efficiency and losses. Hence, the load demand should always be equal to the generated power. Under load or overload in load demand causes the power system network unhealthy. Load variation may be either under loaded or over loaded of electrical equipment. Both overloaded or under loaded equipment have great contribution to the power loss. When the power demand is greater than the expected one, congestion on the transmission line, reduction in generator's rotor speed, inefficient energy supply in electric equipment and other problems can be occurred. When 50MW load is added at 230kV, the power loss of the transmission without and with UPFC is as depicted in figure 4.8.

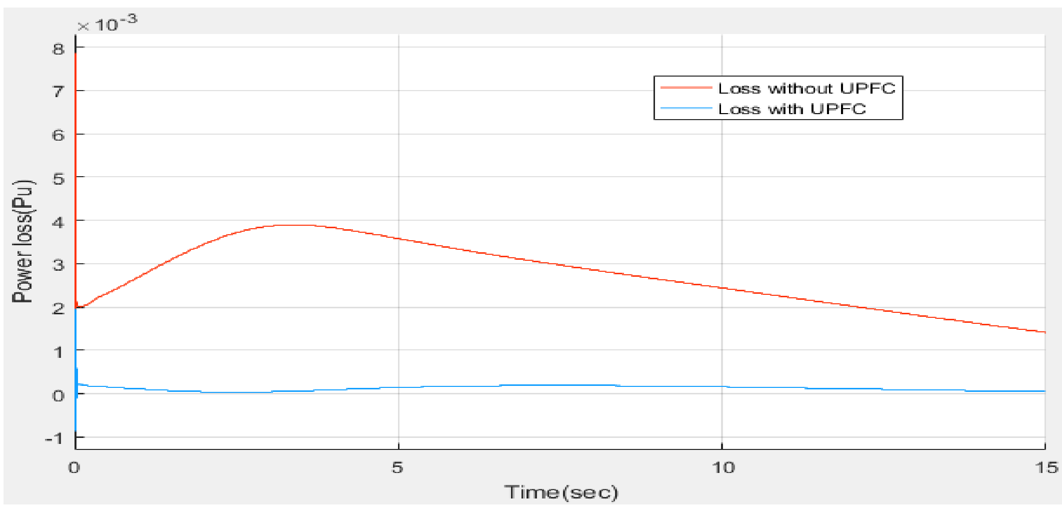


Figure 4.8 Power loss with increasing 50MW load.

Figure 4.8 show that, the power loss in the red lined graph is greater than the power loss shown with blue one. As shown in the figure, the maximum power loss of the transmission line has shown with red line $3.89*10^{-3}$ Pu. However, when UPFC is connected with power system, the power loss is 0.00021Pu. as observed from the result, 0.00368Pu or 1.9577MW power is saved from the loss by using UPFC on the power system network.

When the load at Debremarkose distribution substation increases for instance increase by 70MW, the power loss of the transmission line become as follows.

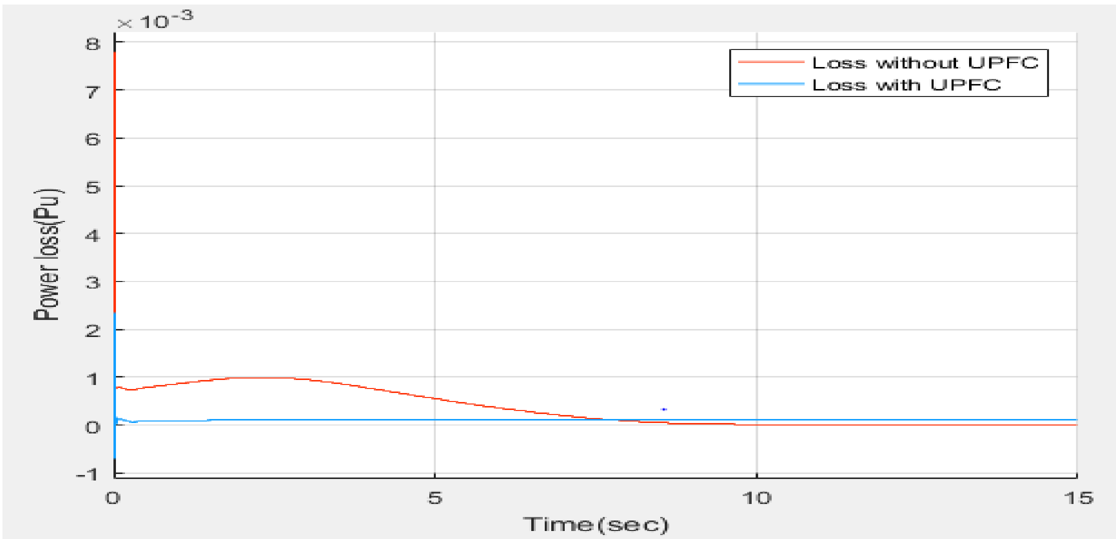


Figure 4.9 Power loss with 70MW load increment

As shown in figure 4.9, the maximum power loss of the transmission line becomes 0.001Pu. However, when UPFC is added to the power system network of the North-West region, the power loss of the transmission line reduced to 0.0002Pu. Hence 0.0008Pu or 425.6kW power is saved from the loss by using UPFC.

CHAPTER FIVE

5. CONCLUSIONS AND FUTURE WORK

5.1 Conclusion

This thesis is focused on power loss reduction of the transmission line from Bahir Dar substation to Debremarkose substation by using UPFC. Several issues and problems have been considered during the UPFC designing process. The issues are the location, sizing, and controller design of UPFC. The location of UPFC, on the North West-Region of Ethiopian power system network is conducted by trial-error and interpolation techniques. The sizing of UPFC is dimensioning of its component. The ratings of the shunt and series transformers have been done based on the location of UPFC i.e. if the location of UPFC is on 230kV bus bar, then the primary side of shunt and series transformer is 230kV. The design of the DC link capacitor of UPFC is carried out based on energy storage principles of capacitor. The complex part in designing of UPFC is its controller design and it has been performed based on the state space equation techniques. MATLAB/SIMULINK has been selected to model the system and conduct the research.

The simulation result shows that, UPFC can reduce the power loss of the transmission line. This is because; UPFC can regulate power system parameters such as load angle and bus voltage. Controlling load angle and bus voltage can enhance the power transfer capacity of the transmission line. Therefore, whatever the disturbance occurred in the power system network, UPFC can regulate and adjust some power system parameters. This enables UPFC to reduce the disturbance and power congestion on the transmission line. As seen from the simulation result, the transmission line power loss has been reduced by using UPFC, even if fault, load variation and power congestion occurred on the power system.

However, the optimum location of UPFC should be identified. As seen from the experiment, when UPFC is located anywhere other than the 230kV, it aggravates the transmission line losses this is due to UPFC is a load by itself. Hence, exact location is a must for effective controlling of the power parameters by UPFC.

5.2 Recommendations

Based on the studies and results found in this thesis, it is strongly recommended that the North West Region of Ethiopian power system should use UPFC to increase the quality and stability of the power system. It secures the power system and increase the efficiency of the power system components by reducing the power losses on the transmission line. Using UPFC in Bahir Dar substation is important for minimizing the number of overloaded lines and the voltage regulation. Therefore, it is highly recommended that the North West Region of EEP should use UPFC on Bahir Dar substation for power system healthy.

Very little research has been done in designing a control system and operation of UPFC. In addition, the system design is done in this paper for the transforms having constant primary and secondary voltage. Therefore, the design process should include for autotransformers or the UPFC should be designed for having auto transformer on its shunt and series converter. The main difficulty in designing UPFC is the complexity of its controller. Therefore, scientists should do a lot for reducing the complexity of its controller.

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APPENDICES

Appendix A: System SIMULINK model

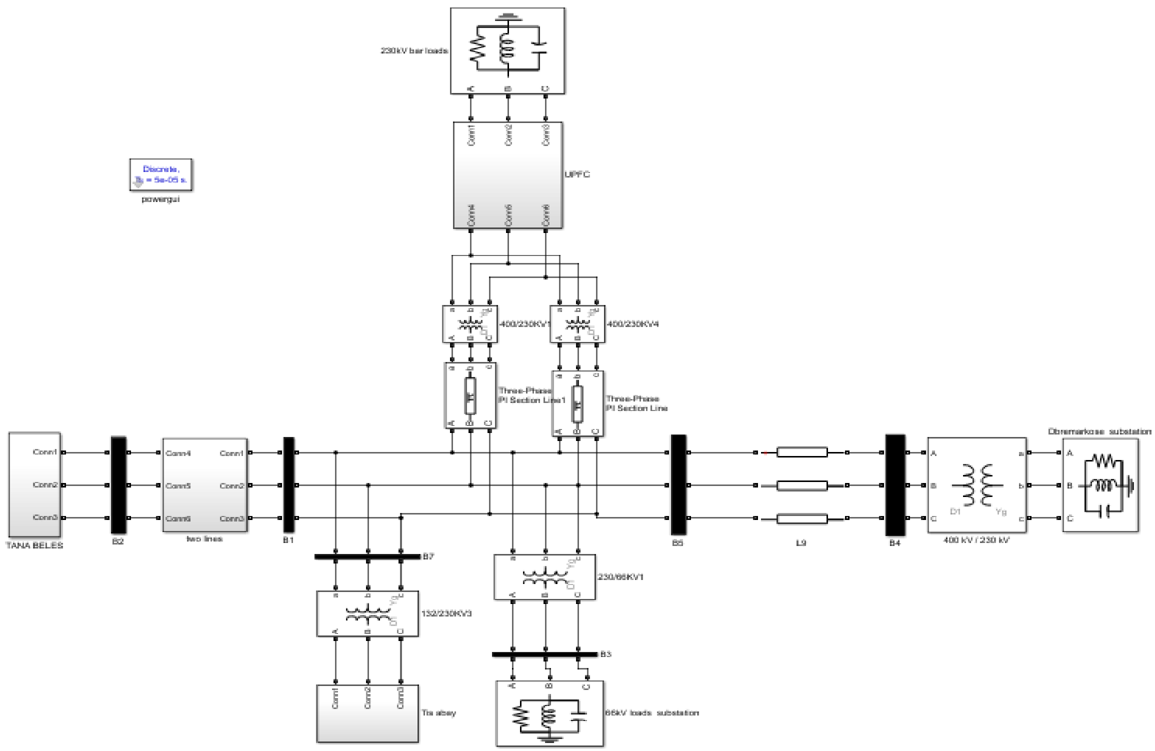

Figure 1: MATLAB/SIMULINK model of the system

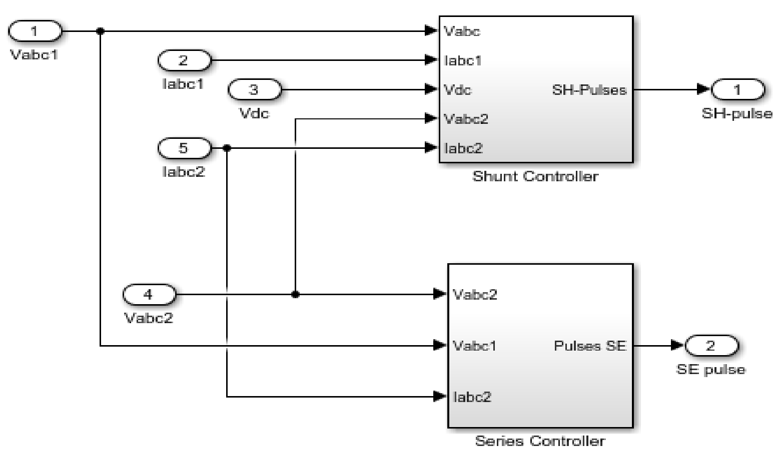

Figure.2: UPFC controller

Appendix B: Parameters of the Power System

Table 2 Generator Parameters of the system

Generators	voltage (kV)	MVA	Inertia H(s)	T'do	T"do = T"qo	Xd	Xq	X'd	X"d=X"q
Tisabay1	6	4.8	2	5.4	0.05	1.21	0.7	0.3	0.18
Tisabay2	10.5	40	2.5	7.1	0.12	1	0.6	0.29	0.365
Tanabeles	15	133	3.14	9.2	0.1	1.03	0.7	0.31	0.25

Table 3 Transmission Line Parameters

Transmission line parameters						
From Bus	To Bus	Length (km)	MVA	R(pu)	X(pu)	B(pu)
Bahir Dar II	D/Markos	193.7	1341	0.002095	0.0285	0.7905
Bahir Dar II	Tanabeles	62.84	1341	0.000679	0.0087	0.2704

Table 4 Transformer Parameters

Voltage (kV)	**Rating (MVA)**	**R (%)**	**X (%)**	**X/R ratio**
400/230	133	0.176	12.045	68.44
400/15	133	0.215	13.5	62.79
230/132	133	0.233	13.36	57.33
230/66	133	0.43	12.368	28.76
230/33	6.3	0.302	8.4	27.78
132/10.5	24	0.257	7.8	30.35
132/6	6.3	0.3221	6.387	28.85

Table 5 Peak Load Parameters

No	Bus name	Active power (MW)	Reactive power (MVAR)	Voltage level (kV)
1	Alamata	-117.81	-57.08	230
2	Bahir Dar II	-88.46	-30.762	66
3	Dangila	-4.2	-2.1	66

4	D/Markose	-18.4	-8.22	230
5	Gondar II	-37	-18	230
6	Motta	-3.45	-1.7	230
7	Tana Beles	460	-	15
8	Tis Abay	14.8	-	6
9	Tis Abay II	73	-	10.5