Power Flow Study for Transient Stability Problems and its Enhancement Using Thyristor Controlled Series Capacitor (Case Study in Gilgel gibe-II to Sebeta-II High Voltage Transmission Line)

Desu Demsses Badrga

A Thesis Submitted to

The Department of Electrical Power and Control Engineering

School of Electrical Engineering and Computing

Presented in a Partial Fulfilment of the Requirement for the Degree of Master's of science in Electrical Power and Control Engineering (Electrical Power)

Office of Graduate Studies
Adama Science and Technology University

Adama, ETHIOPIA

July, 2021

Power Flow Study for Transient Stability Problems and Its Enhancement Using Thyristor Controlled Series Capacitor (Case Study in Gilgel Gibe-II to SEBETA-II High Voltage Transmission Line)

Desu Demsses Badrga

Advisor:-Dr. Milkias Berhanu

A Thesis Submitted to

The Department of Electrical Power and Control Engineering

School of Electrical Engineering and Computing

Presented in a Partial Fulfilment of the Requirement for the Degree of Master's of science in Electrical Power and Control Engineering (Electrical Power)

Office of Graduate Studies
Adama Science and Technology University

Adama, ETHIOPIA

July, 2021

APPROVAL SHEET

I/we, the advisors of the thesis entitled "Power Flow Study for Transient Stability Problem and its Enhancement Using Thyristor Controlled Series Capacitor (Case Study in Gilgel Gibe-II to SEBETA-II High Voltage Transmission Line**)**" and developed by Desu Demsses Badrga, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Dr. Milkias Berhanu ______________ ________________

Advisor Signature Date

We, the undersigned, members of the Board of Examiners of the thesis by Desu Demsses Badrga have read and evaluated the thesis entitled "Power Flow Study for Transient Stability Problem and its Enhancement Using Thyristor Controlled Series Capacitor (Case Study in Gilgel Gibe-II to SEBETA-II High Voltage Transmission Line)" and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in electrical power engineering

Mr. Mesfin megra	_____________	_______________
Chairperson	Signature	Date
Dr. Mola Biweta	_____________	_______________
Internal Examiner	Signature	Date
Dr. ing. Getachew Biru	_____________	_______________
External Examiner	Signature	Date

Finally, approval and acceptance of the thesis is contingent upon submission of its final copy to the Office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and School Graduate Committee (SGC).

Mr. Mesfin megra	______________	_______________
Department Head	Signature	Date
____________________________	_______________	________________
School Dean	Signature	Date
____________________________	________________	________________
Office of Postgraduate Studies, Dean	Signature	Date

DECLARATION

I hereby declare that this MSc thesis entitled "Power Flow Study for Transient Stability Problems and Its Enhancement Using Thyristor Controlled Series Capacitor (Case Study in Gilgel Gibe-II to SEBETA II High Voltage Transmission Line)" is my original work and has not been presented for a degree in any other university, and all sources of material used for this thesis have been duly acknowledged through citation.

Name: Desu Demsses Badrga

Signature: ______________

Date of submission: July 2021

RECOMMENDATION

I/we, the advisor(s) of this thesis, hereby certify that I/we have read the revised version of the thesis entitled "Power Flow Study for Transient Stability Problems and Its Enhancement Techniques Using Thyristor Controlled Series Capacitor (Case Study in Gilgel Gibe-II to SEBETA II High Voltage Transmission Line)" prepared under my/our guidance by Desu Demsses Badrga submitted in partial fulfillment of the requirements for the degree in Masters of Science in electrical power engineering.

Therefore, I/we recommend the submission of a revised version of the thesis to the department following the applicable procedures.

Dr. Milkias Berhanu ______________________ _______________

Advisor Signature Date

ACKNOWLEDGEMENTS

First of all, I would like to thank Our Almighty God for everything and helps me to reach this time. Secondly, I am heartily thankful to my advisor, Dr. Milkias Birhanu for his commitment and patience to guide me in discussing every aspect of this thesis. I also thank my lecturers, especially those who have supported me as a co-advisor during the study starting from the beginning. Thirdly, my thank goes to the department of electrical power and control staff members, officials and professionals in private as well as in sectors, and also the Ethiopian electric power office staff and workers to give supportive ideas, guidance, and necessary data useful for my thesis research to the study case. Finally, I express my gratitude and pleasure to my family, classmates, staff members, and others who have given me their inspiration including all-rounded technical and moral supports during this period.

Table of Contents

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

AC	alternating current
AVR	Automatic voltage regulator
CB	Circuit breaker
DC	Direct current
EHV	Extra high voltage
EEP	Ethiopian electric power
ELC	Electro consult
EPC	Engineering procurement and construction
FACTS	Flexible alternating current transmission system
FSC	Fixed series capacitor
GGII	Gilgel gibe two
GERD	Great Ethiopian renaissance dam
G.C	Gregorian calendar
HVDC	High voltage direct current
HMI	Human machine interface
IEEE	International electrical and electronics engineering
L-G	Line to ground
MATLAB	Matrix laboratory
MOV	Metal oxide varistor
MMF	Magneto motive force
MVA	Mega volt ampere
NERC	North America electric reliability council
NLDC	National load dispatch center
PSS	Power system stabilizer
PLC	Programmable logic control
PLC	Private limited corporate
PU	Per unit
RPM	Revolution per minute
SMIB	Single machine infinite bus
SVC	Static var compensator
STATCOM	Static synchronous compensator

SSSC	Static synchronous series compensator
SCR	Silicon controlled reactor
SSR	Sub synchronous resonance
SNNP	Southern nation nationality and people
TSM	Transient stability margin
TCSC	Thyristor controlled series capacitor
TCR	Thyristor controlled reactor
TSR	Thyristor switched reactor
TSSC	Thyristor switched series capacitor
UPFC	Unified power flow controller
USA	United states of America

SYMBOLS

a, b, c	Stator phase windings
f_d	Field winding
Kd	d-axis damper circuit
Kq	q-axis damper winding
K	Number of damper circuits
Ωr	Rotor angular velocity
E	Terminal voltage
Efd	Field voltage
Ifd, Ikd, Ikq	Field and damper circuit currents
Rfd, Rkd, Rkq	Field and damper circuit resistances
Ra	Armature resistance
P	Active power
Q	Reactive power
Xc	Capacitive reactance
Cs	Capacitor
Uprot	Protective voltage of MOV
Ta	Accelerating torque
Tm	Mechanical torque
Te	Electromechanical torque
Pa	Accelerating power
Pm	Mechanical power
Pe	Electromechanical power
ωn	Synchronous speed
J	Moment of inertia
D	Damping constant
M	Angular momentum
H	Inertia constant
Ψ	Flux linkage
I	Current
r	Winding resistance

ABSTRACT

The stability problem is an important issue that explains the stable and reliable operation of an electrical power system. A stability problem is either a steady-state or transient stability problem. An increase in power demand in recent years has developed a number of challenges for power system engineers, for increasing the power transfer capability of the already installed transmission system without the expansion of the existing or building new transmission networks. Conventional methods adopted for the enhancement of transient stability include circuit breakers, fast-acting exciters, and reduced total transfer reactance of the system. However, the modern technology Flexible AC transmission system devices such as thyristor controlled series compensator (TCSC) can help to increase power transfer capacity in heavily loaded networks because of their capability to control power flow effectively. This is where the TCSC device is very useful because of its low initial cost as compared to setting up completely new transmission networks. The TCSC technology makes use of the already installed generating and transmission systems with minimum line losses and maximum use of the existing system. The most common causes of transient stability are fault, lightning, power line switching, and others. The severity of problems that occur due to the source of transient disturbances occur in a transmission line can be mitigated by using FACTS device controllers. Thus, taking the consideration of the above facts into account in resolving the transient stability problems in the high voltage transmission systems, this thesis aimed to focus on Flexible AC Transmission System Controller (FACTS) devices to be used as an effective utilization and minimization means of power losses in the transmission line. This controller improves the performance of transient stability in the transmission line. FACTs devices are best for steady-state, dynamic, and transient stability improvement. From the different types of FACTS devices, this thesis has used thyristor controlled series capacitor FACTs device because of its effectiveness, cost and used for many applications like transient and dynamic stability improvement, voltage control, etc. For further improving the Transient Stability Margin (TSM), FACTs devices have been employed, and the results of Gilgel Gibe (GG)-II to SEBETA-II transmission line have been obtained and verified using MATLAB Simulink software. From the results, the power transfer capacity is increased from 417.89MW to 611.38MW with TCSC and the suitability and effectiveness of the selected FACTs device for enhancing the transient Stability of the power system have been discussed and optimal results are obtained.

Keywords: FACTS controllers, MATLAB Simulink, Stability Margin, Thyristor controlled series capacitor, Transient Stability

CHAPTER ONE

INTRODUCTION

1.1. Background

The stability problem in the power system is concerned with the nature of the synchronous machines after they have been disturbed or perturbed. If the disturbance does not involve any net change in the power system, the machines should return to their original state of operation. If an unbalance between the supply and demand is created by a change in load on the power system network, in the generation station, or in-network conditions, a new operating state is necessary. In any case, all interconnected power system synchronous machines should remain in the condition of synchronism if the system is in a stable state, i.e., they should all remain operating in parallel and at the same operating synchronous speed. If the oscillation response of a power system during the transient period of the system following a disturbance on the power system is damped and the system settles in a finite time to return a new steady-state operating condition, we say the power system is in a stable state. This primitive definition of stability requires elaboration depending on the nature of disturbance and the nature of the power system [1]. Power systems have to be planned, constructed, commissioned, and operated in such a way to enable a safe, reliable, and economic supply of the load. A grid of transmission lines operating at high or EHV is required to transmit power from generating stations to load. In addition to transmission lines that carry power from the source to load, modern power systems are highly interconnected for economic reasons.

The large interconnected transmission networks are subject to faults due to lightning discharges and reduce insulation strength. Changing in loads and atmosphere conditions and power line switching are unpredictable factors. This may cause overloading of lines due to voltage collapse happened on the system. These problems can be eased by the introduction of fast dynamic control over the reactive and active power by high-power electronic controllers called flexible alternating current systems (FACTS). In recent years, the highly increasing cost of building new transmission lines is compounded by the difficulty in obtaining new transmission corridors, which has led to a search for increasing the transmission capacity of existing lines. The Series compensation in the transmission line is modeled to enhance power flow at the receiving end. Series compensation employs capacitors to compensate for the inductive reactance of long lines. It is a highly effective, efficient, and economical means of improving the power transfer capability of the power system or transient stability improvement suitable for both new and existing transmission lines.

Series compensation devices increase power transfer capability by raising the transient stability limit as well as improving the voltage stability. In Ethiopia, new technology fixed series compensator and static var compensator installed at holeta sub station that increases the power transfer capability of the system and to protect those problems occurred in long transmission systems. Only a shunt reactor was used in most of the grid in Ethiopia which is incapable to improve and solve such stability problems properly [2].

Power system transmission networks grow rapidly and continuously with a large number of interconnections with national and international power system networks. The complicated connected structure of such a network has exposed the power system to various contingencies and fault conditions that could lead to the power system instabilities such as steady-state, dynamic, or transient stability problems. Transient stability analysis is important in evaluating the network's ability to regain an acceptable state of equilibrium after being subjected to sudden or large disturbances.

An electric power system is a network of electrical power system components used to supply, generate, transmit, distribute, and use electric power for different applications. With the wide range of access to renewable energy sources, the electrical power system is becoming increasingly complicated, and highly interconnected, thus the calculation of transient stability limits is more significant. The development and use of accurate methods to predict transient stability is crucial in preventing such complicated conditions and therefore of special approach in the field of electrical power system protection, control, and planning. Generally, the electrical power system is a highly non-linear system that operates in an eternally modifying and improving the environment with generator power outputs, load demands, and key power system operating parameters are updated/modified regularly. However, when subjected to a disturbance, the stability of the system depends on initial operating conditions and the nature of the disturbance.

Power utilities are increasingly called upon to operate transmission lines at high power transfer levels due to the steadily growing demand for electric power. As the power transfer levels increase, the margins of the stability of the power system at steady-state stability and transient stability state decrease. Traditionally known solutions to upgrade or increase the transmission system infrastructure performance has been primarily in the form of adding new transmission lines, substations, and associated equipment to the system. However, as experiences have been proven over the past decades of years, the process to permit, site, and construct new transmission lines on the power system of the grid has become extremely difficult, expensive, time-consuming, and controversial [3]. Moreover, because of natural conditions, environmental protection, and the economic standard of the suppliers, it is difficult to construct more lines or substations at present.

This situation has led to a review of the traditional power generation and transmission system theory and practice to address the issue of how to operate the existing power system much closer to its stability limits without compromising and losing synchronization to the security of the system itself.

Historically, the safe and stable operation of an electric power system has been achieved by operating the system far away from its theoretical stability limits, in part because of a limited capacity to control the transmission system itself under dynamic conditions. However, it has been recognized that improved dynamic control of ac power systems would allow better utilization of these systems [4]. These circumstances and significant developments in the area of power electronics devices have led to the emergence of the Flexible AC Transmission systems or FACTS power electronics-based controller's concept. FACTS devices are aim to bring the factors which influence the transfer of power in a transmission system under rapid control employing modem, power-electronic-based compensating devices to allow the system safely and stably to be pushed closer to its stability limits.

1.2. Statement of The Problem

Realizing the maximum power transfer capacity of an electric power system, stable and steady-state system at the lowest possible cost is one of the greatest challenges today for transmission system operators. In meeting this challenge, Series compensation systems represent a very cost-effective and reliable means of increasing bulk power transfer and the performance of power transmission networks. This is mainly due to losses in an electric transmission line. Modern energy transmission systems suffer in reduction power transfer capability and great voltage drop due to the line reactance, thermal limits, and corona effect.

Based on the interview conducted at the site under the study and the interruption data collected from the station, I came to realize that the transmission line is subject to various kinds of faults that cause transient disturbances to the system. The general method adopted to avoid or clear the fault are fast-acting exciter, circuit breaker, and reduction in system transfer reactance.

However, on the other hand, the modern trend is applying Flexible AC Transmission System (FACTS) devices in the transmission line for effective improvement and enhancement of losses in the line. Therefore, this thesis tries to explore the various techniques for enhancing the power transfer capacity of the transmission lines using thyristor controlled series capacitor FACTS devices. By improving this ability, the existing transmission line will be more efficient and easy to control the variables depending on the demands. Power interruption is common in our country, this interruption of power is due to stability and other factors on the transmission systems mentioned in the above paragraphs. Besides, the main aim of this thesis is to improve power transfer capacity, voltage drop and stability problem, and power flow study for transient problems faced in Gilgel Gibe-II to SEBETA-II 400 kV transmission line.

1.3. OBJECTIVES OF THE STUDY

1.3.1. General Objective

The general objective of this thesis is power flow analysis for transient stability problems and its enhancement using Thyristor Controlled Series capacitor FACTS controller for improvement of long power transmission system capacity at 400kV GG-II to Sebeta-II transmission line.

1.3.2. Specific Objectives are to:

- ✓ analyze the power flow study for the transmission line.
- ✓ model a 400kV transmission line system of GG-II – SEBETA-II.
- ✓ select an appropriate FACTS device for the system under study.
- ✓ analyze the transient stability effect on the high voltage transmission system with and without TCSC controllers.
- ✓ determine power losses and line power flow and the transient stability condition of voltage and current on the lines by using MATLAB Simulink software**.**

1.4. Scope of the Study

An investigation will be carried out starting from knowing the total electric power transmission line power transfer capacity, analyzing the power flow study of the system, improving the transient stability, and increase the capacity of GG-II to Sebeta-II line by using series compensating FACTS devices and finally analyze simulation using MATLAB Software.

1.5. Limitation of the Study

The thesis is limited to the simulation of the system using MATLAB Simulink toolbox by showing how the different components of the system interact with each other. This is because the implementation of a real system is difficult to install components. Along with it takes the additional time and cost incurred in making the actual prototype implementation. And there is no high voltage testing laboratory in Ethiopia.

1.6. Significance of the Study

Enhancing transient stability and power flow study in transmission systems is important for efficient power supply because a modern-day society requires quality, reliable, and stable electrical energy for domestic, commercial, and industrial purposes. Designing FACTs devices over the shunt reactor is the capability of controlling the reactance of the transmission line automatically using the back-to-back sandwiched bidirectional thyristor. This enables for effective removing the more inductive nature of GG-II to Sebeta-II lines when the impedance is variable and for damping power oscillation as well as Sub Synchronous Resonance over the power system network.

1.7. Thesis Organization

This thesis has been organized in five chapters.

The first chapter presents on introduction of the thesis, statement of the problems, objectives of the thesis, significance the thesis, scope, and limitation of the thesis.

The second chapter discusses on literature review on the background of transient stability study using FACTS devices and different theoretical concepts of power system components, stability analysis, and FACTS controllers.

The third chapter describes the methodology that I have guided to work on this thesis and mathematical modelling of the power system.

The fourth chapter Presents the proposed model results and discussions.

The last chapter of the thesis describes all about conclusion and recommendations.

CHAPTER TWO

LITERATURE REVIEW

2.1. Theoretical Background

Many pieces of research have been conducted in dynamic stability, voltage stability and regulation, and transient stability improvement using different methods all over the world. Different scholars used different Technology options and approaches to evaluate the various configurations of transmission line resources performance, such as bus bar parameters, line parameters, substation parameters using FACTs controller.

2.1.1. Components of Power System

The Power system is a large interconnected system that consists of the following main components

- Power generating station.
- Transmission lines
- Distribution system
- Utilization

A generation station is a part of a power system component in which electricity is generated or produced by converting the mechanical energy appearing on the shaft of the turbine or more in the engine into electrical energy. This conversion is achieved by the use of a synchronous generator. The electrical energy is transferred through the transmission line, substation, or on the distribution lines with high voltage, medium voltage, and low voltage level networks to bring energy to the customers. The main advantage of electrical energy is the energy is produced through a water reservoir and it can transmit over a long distance to the load center.

Transmission lines are an interconnected electric energy path which contains different components based on the length of the transmission line.

Constants of transmission lines: - an overhead transmission line consist of a conductor running in parallel. These conductors are carried on the support that provides insulation from the conductor and earth.

The transmission line is characterized by its resistance, inductance, capacitance, and line shunt conductance. These constants are affected by different parameters that mean the resistance of the transmission line is affected by frequency, spiraling, and temperature.

Due to the stranding of the conductor, the length of the transmission line exceeds more than the actual length which in turn increases the transmission line resistance.

Ac resistance of the overhead transmission line increase due to the frequency of the transmitted signal. The magnetic field from the alternating current also increases a conductor's resistance relative to its dc resistance. The inductance of the transmission line is calculated as flux linkages per ampere. If the permeability of the material is constant, sinusoidal current produces sinusoidal varying flux in phase with the current. The capacitance of the transmission line is the result of the voltage between the transmission line conductors. It causes them to be charged in the same condition as the plates of a capacitor when there is a voltage between the conductors. The capacitance between the line conductors is the charge per unit of voltage through the line.

2.1.2. Stability Analysis

Electrical power system stability: is the ability of an electrical power system network for a given steady-state initial operating condition of the power system to regain an equilibrium operating state of the system after being subjected to a common disturbance, with most system state variables bounded so that practically the entire power system remains intact. Stability involves the study of dynamics of the power system about an equilibrium initial operating condition. Stability depends upon both the initial operating conditions and the size of the disturbance that occurred on the system. The power system is highly non-linear. A stability study is the study of the non-linear dynamics of a large system. It is also defined in terms of initial operating condition and nature and magnitude of disturbances. A typical power system will consist of a large number of devices having dynamic characteristics such as generators, AVRs, speed governors, FACTS devices, and transformers, etc.

The power system is considered as a large multivariable dynamic system with varying characteristics (linear or non-linear) and response rates that means some of the devices have a fast response like FACTS devices whereas the other has slow response time like on-load tap changing devices.

Stability is the ability of the system to withstand disturbances occurred on the power system. In other words, its ability to tolerate disturbances so that the normal operating condition is not disturbed. It is also the ability of the power system it returns to its stable state after subject to some form of disturbances. Disturbances in a power system may be load change, switching operation, generation failure, faults occurred in the power system network, Stability is the behavior of the system which if the input of the system is bounded the output must be bounded, then the system is said to be stable.

In general power system stability divided into two categories. These are steady-state stability and transient stability.

If the disturbance occurred on the power system is slow that means in gradual small steps and the system that withstands these disturbances like gradual change in load and perform satisfactorily the system is said to be steady-state stability. On the other hand, if the disturbance is sudden, even though the system withstands that sudden disturbance and performs satisfactorily, the system is in transient stability. There is a limit that is beyond the system to withstands the given disturbance limit, this condition is said to be a stability limit. This thesis research mainly focused on the power flow study and transient stability analysis of the system. It is discussed in detail on the next topic.

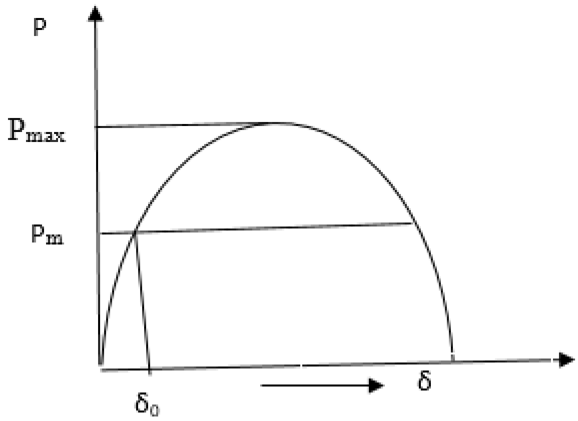


Figure 2.1 The swing curve to study the transient stability limit

From the above swing curve the electric power flow through the power system network is given by

$$Pe = \frac{|E||V|}{x}\sin\delta \qquad (2.1)$$

The electrical power and mechanical power are equal an angle (δ) is equal to δ0 and in this point, both electrical torque and mechanical torque are equal due to this condition the net torque is equal to zero, angular acceleration is zero, angular speed zero that means if speed is constant is known as synchronous speed. This condition is a normal operating condition. If the load (mechanical power) increases slowly the mechanical power dominates electrical power at an angle (δ0) the machine starts at decelerating or accelerating speed. This change in load is adjusted up to Pmax is done by increasing the mechanical power at load sides in the shaft of the synchronous motor and it withstands up to maximum mechanical power, this condition is steady-state stability limit. Besides, the load increases suddenly up to some point which is less than maximum mechanical power it will tolerate for a small-time up to Pmax, this limit is said to be transient stability limit [5].

2.1.3. Transient Stability Analysis

All the machines in the power system are synchronized which means run at a common frequency. The power system is operating in synchronous mode and it is subject to a wide range of disturbances which is a small disturbance from large disturbance.

Transient stability at the given power level

If it is a small disturbance the system is subject to small-load and generation change and network changes, and outages of equipment are cause large disturbances. Power system stability has involved the study of the dynamics of the power system under disturbances.

Under the classical point of view, power system instability can be seen as a loss of synchronism that means some synchronous machine going out of step when the system is subject to a particular disturbance.

For small disturbances, the swing equation can be linearized leading to the concept of steady-state stability. There are no available generalized criteria for explaining the system stability with large disturbances. The operating characteristics of induction and synchronous machines are presented by a set of differential equations. The solution of network equations retains the identity of the system and hence contributes to the system currents and voltages during the transient period.

Inability to maintain the stability of a power system makes the ability of a power system to transmit power to be impaired. The stability problems are hindrances to effective power transfers within the system. It is, therefore, necessary to design and operate power systems so that transient events (i.e. probable contingencies), can be withstood without the loss of load or loss of synchronism in the power system [6]. Different solutions can improve the stability of power systems so that increased power transfer capability can be achieved. Dynamic performance analyses are very crucial tools to identify system stability problems and demonstrate the effectiveness of stability improvement solutions [7].

Power system dynamics analysis involves the study of the behavior of a power system under the conditions of the system before and after sudden changes in system load or power generation, during faults and system outages from the normal operating condition. Hence, power system dynamics analysis is an important part of power system operation and planning.

2.1.4. Need for Classification of Stability Analysis Problems

These are based on the following considerations [6]

- The physical nature of the resulting instability problems related to the main power system parameter in which instability can be observed on it.

- The size and nature of the disturbance considered indicate the most appropriate method of calculation and prediction of stability problems.
- The devices, processes that are used, and the period must be taken into consideration in order to determine stability problems.

There are three different kinds of stability problems depending on what phenomena I have to interested to study these are discussed as follows.

Power system stability is essentially a single problem. For a given network topology, initial operating condition depending on nature and magnitude of disturbance, the imbalance between different sets of opposing forces may lead to different types of instability.

A. Rotor Angle Stability

A balanced three-phase system and balanced system disturbances will have considered. Deviation of machine frequencies from synchronous frequency is small, dc offset current and harmonics are neglected, network and impedance loads are at steady state, and voltage current and powers can be computed from the power flow equation.

Rotor angle stability is concerned with the ability of highly interconnected synchronous machines of an electrical power system to remain in synchronism condition under normal operating conditions of the system and, after being subjected to a large disturbance. The real power system imbalance means mechanical system input and electrical system output will result in rotor angle instability of the power system. It depends on the ability of the system to maintain or restore an equilibrium condition between electromagnetic torque and mechanical torque of each synchronous machine in the power system.

The instability that results occurs in the form of increasing angular components of swings of some power generators leading to their loss of synchronism with other generators.

It should be noted that loss of system synchronism can occur between one electrical machine and the rest of the power system, or between groups of electrical machines, possibly with system synchronism maintained within each group after separating from each other.

For convenience in analysis and for gaining useful inspection into the nature of power system stability problems, it is important to characterize this rotor angle stability in terms of the following two main categories:

Small signal (or steady-state) stability is concerned with the ability of the power system network to maintain synchronism under small system disturbances. The disturbances are considered to be very small that linearization of the power system equations is permissible for purposes of system analysis.

Such disturbances are continuously encountered in normal system operation conditions, such as small changes in system loads. Small signal stability depends on the initial state operating condition of the power system.

Large disturbance rotor angle stability (transient stability) is concerned with the ability of an electrical power system to maintain synchronism when the power system is subjected to a severe or large transient disturbance. The resulting power system response involves large excursions of generator rotor angles and is influenced by the nonlinear power-angle relationship. Transient stability depends on both the initial state operating condition of the power system and the severity of the system disturbance.

B. Voltage Stability

Voltage stability deals with the ability of the power system network to maintain steady-state voltages at all system buses in the power system under a normal state of operating conditions, and after being subjected to a system disturbance. The reactive power imbalance on the power system network results to voltage instability conditions. The possible result of voltage instability is loss of system load in the area where voltages reach unpredicted low values or a loss of integrity of the power system network.

Voltage stability problems are also experienced at the terminals of HVDC links. They are usually related to HVDC links connected to weak AC power systems.

As in the case of rotor angle stability, it is important to classify voltage stability into the following subcategories:

Large disturbance voltage stability is concerned with a power system's ability to control voltages following large system disturbances such as power system faults, loss of generation, or circuit contingencies.

Determination of large disturbance stability requires the application of the nonlinear dynamic performance of a system over a period of time sufficient to capture the interactions of such devices as under-load transformer tap changers and generator field-current limiters.

Small disturbance voltage stability is concerned with a power system's ability to control voltages following small perturbations such as incremental changes in system load.

This voltage stability is determined by the nature of system loads, continuous controls, and discrete controls at a given instant of time.

C. Frequency Stability

Frequency stability is the ability of a power system network to maintain steady-state frequency within a nominal system operating range following a large system upset resulting in a significant imbalance between generation and system load.

Large system upsets generally result in large disturbance of frequency, power flows, voltage, and other system state variables, thereby taking action of processes, controls, and protections that are not modeled in transient stability or voltage stability studies.

This condition may be very slow, such as boilers dynamics, or only triggered for high system conditions, such as volts=hertz protection tripping power generators.

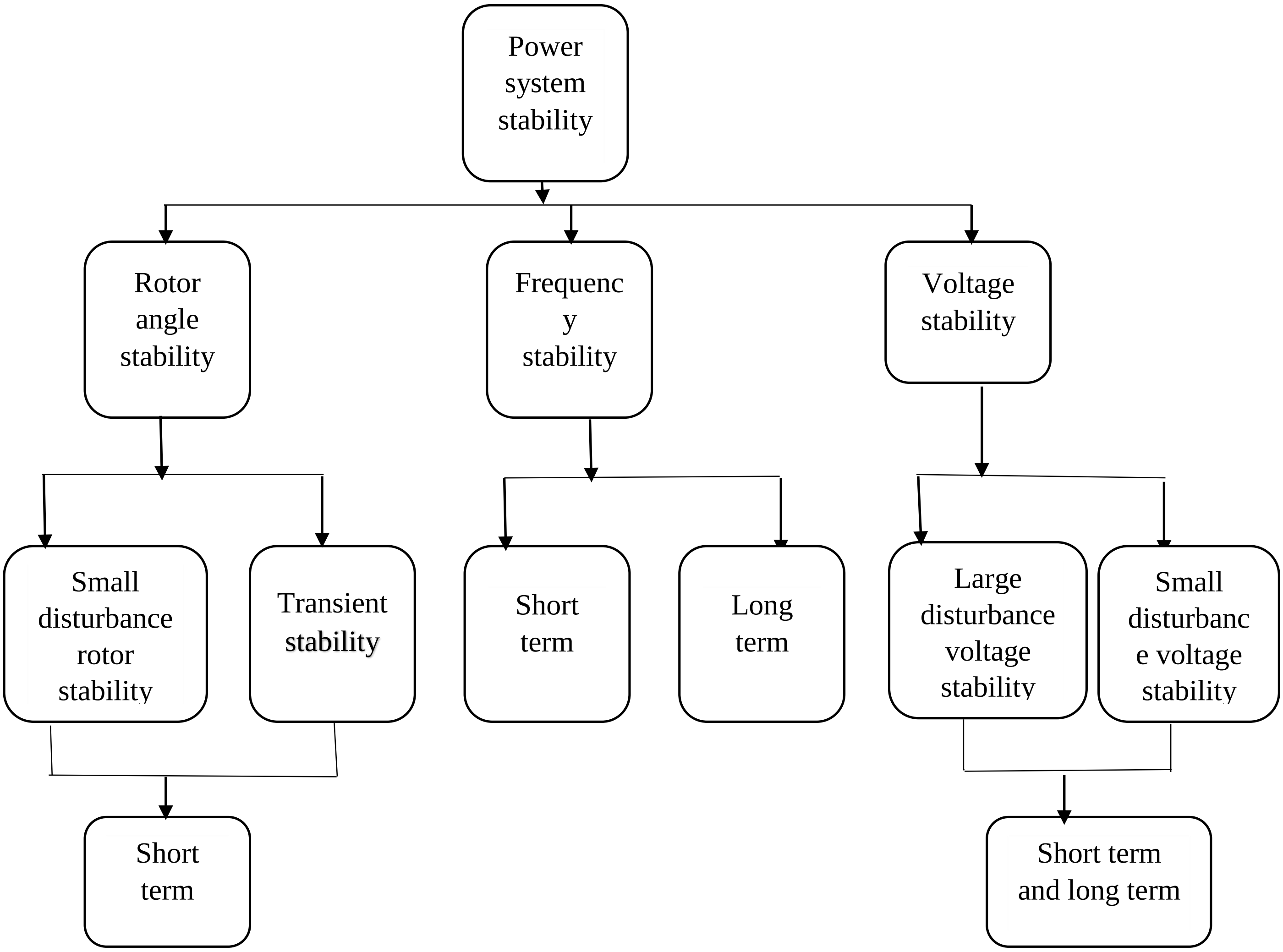


Figure 2.2: Classification of power system stability

The quality and reliability of a power system refer to the probability of its satisfactory operation over the long run. It denotes the ability to supply adequate electric service on a nearly continuous basis, with few interruptions over an extended period.

Security of a power system refers to the degree of risk in its ability to survive imminent disturbances without interruption of customer service. It relates to the robustness of the system to overcome or minimize disturbances and, hence, depends on the system operating condition as well as the contingent probability of disturbances.

NERC (North American Electric Reliability Council) defines power system reliability as reliability in a bulk electric power system, which is the degree to which the performance of that system results in power being delivered to consumers within accepted standards and the amount desired.

2.1.5. Power Flow Study

The flow of active and reactive power is known as power flow or load flow. It is one of the most fundamental problem analyses in the power system. The load in the power system is varying with the time change. Power flow aims to find out the voltage at different bus bars on the nodes at the substation and the flow of power on the line. In AC power systems, the electrical generation and load must be balanced at all times. If voltage is propped up with reactive power support, then the load will go up, and consequently, the frequency will keep dropping, and the system will collapse. Alternately, if there is insufficient reactive power, the power system can have voltage collapse on the power system.

When adequate generation is available active power flows from surplus generation areas to the deficit areas, and it flows through all parallel paths available which frequency involve extra-high-voltage and medium-voltage lines.

The power flow studies are very important for: [9]

- ✓ planning, control, operation, and expansion of existing power system.
- ✓ To know the effect of interconnection, adding new loads, new generation, lines, etc.
- ✓ help to select, size, and location of VAR equipment's on the system.

For planning and control the operation of existing power system networks, their improvement and, future expansion requires following studies such as load flow studies, short circuit studies, and stability studies in the power system network. Power flow studies are used to ensure that electrical power transfer from generation station to consumers or load side through the grid system is stable, reliable, and economic advantage. Power flow studies are most useful for all power system analysis because these are used in planning studies of power system networks to determine when specific elements will become overloaded condition.

The objectives of any power-flow study are to provide the following important information

- ✓ To determine voltage magnitude and phase angle at each bus bars.
- ✓ To determine real and Reactive power flowing through each element.

Once the system bus voltage magnitudes and phase angles are computed using the power flow, the real and reactive power flow through each transmission line can be computed. Also based on the difference between power flow in the sending end and receiving ends, the transmission line network losses in any particular transmission line can also be calculated. It helps to determine the best location as well as the optimal capacity of the proposed power generating station, distribution substation, and new transmission lines.

In the power flow problem, it is assumed that the real power (P) and reactive power (Q) at each Load Bus are known and these Buses are also known as PQ Buses. For Generator Buses, it is assumed that the real or active power generated (P) and the voltage magnitude (V) are known.
For the Slack Bus, it is assumed that the voltage magnitude (V) and its phase angle of the buses (δ) are known. In this thesis, the Newton Raphson method for power flow study is used, because of its reliability towards convergence and not sensitive nature to the starting solution. In high voltage network power flow studies, the Newton Raphson has proved most successful and effective because of its strong convergence characteristics. The power flow Newton Raphson algorithm is expressed as on the following relationship [10]

$$P_i = \sum_{k=1}^{n} |V_i||V_k||Y_{ik}|\cos(\theta_{ik} - \delta_i + \delta_k) \quad (2.2)$$

$$Q_i = -\sum_{k=1}^{n} |V_i||V_k||Y_{ik}|\sin(\theta_{ik} - \delta_i + \delta_k) \quad (2.3)$$

2.1.6. Power System Transient Stability Improvement Strategies

The transient stability of power systems depends on the active and reactive power balance between generation and load within the system. Losing this balance or loss of synchronism leads to loss of system integrity leading to system collapse which has a damaging impact on daily economic activities. To avoid such devastating impacts there should be an effective mechanism for maintaining this balance [7]. Nowadays' different solution mechanisms are continued to be employed by power utilities worldwide for insuring this balance and bring about improved system stability.
Strategies for power system stability improvement are implemented at two levels. The first is at generating units through the action of power system stabilizers (PSSs), automatic voltage regulators (AVRs) and, other supplementary controllers.
The power utilities worldwide are currently implementing PSSs and AVRs as excitation controllers to enhance power system stability. However, due to limited capacity and large system voltage variations introduced during disturbances upon utilizing them, they are getting insufficient to create system-wide influences [11]. The other solution group is through the application of FACTS devices and HVDC controls at the transmission level.
Coming to the EEP power system, the mechanisms employed for stability control are generator level AVR controls and manually switched shunt reactors at substations to reduce Ferranti over voltages and overvoltage that arise due to load rejection. However, these mechanisms are not sufficient and hence, it can be said that the EEP power system doesn't have effective stability controlling mechanism.

2.2. FACTS Device

FACT controllers are used for dynamic control of voltage, impedance, and phase angle of high voltage ac transmission lines. FACTS incorporating current power electronic-based and other static controllers to enhance controllability and increase the power transfer capability. It is a power electronics-based system and other static equipment that provide control of one or more AC transmission system parameters. This is one of the transmission techniques because there is more power demand. Within this flexible AC transmission system (FACTS) we have to interconnect the different AC systems in order to maintain constant voltage and frequency on the transmission line. The need for interconnection of transmission lines is to pool power plants, pool load centers, minimize power generation capacity, minimize fuel cost, diversity of load, more economical, integrate transmission planning, reduced cost of transmission line, reduced losses, transmission capacity, reliable electric service, enhanced power transfer capability, high-speed control, enhanced security, etc.

Application of high power semiconductor devices to control different parameters and electrical variables such as voltage, impedance, phase angle, current, active power, and reactive power. According to Siemens, “FACTS devices increase the reliability and performance of ac power grids and reduce power delivery costs in the system. They improve transmission quality and efficiency of power transmission lines by supplying inductive or reactive power to the grid. A desirable attribute of FACTS devices solution: -

- Controllable output
- Instant response
- Smooth adjustable
- Allowing frequent variation of output

The benefits of using FACTS devices are

1. Improve power transfer capacity, when we need to transfer more power than the transmission line is originally designed for, we need to build a new transmission line. This is economically more expensive because of the cost of right-of-way. Now FACTS devices provide an alternative solution.
2. Improve availability of power, this indicates that most blackouts occurred in the grid system is occurred due to lack of proper reactive power management, this problem is mitigating by the use of FACTS devices.
3. Improve stability, FACTS technology can be used to effectively improve steady-state and transient stability of interconnected power system.

4. Improve power quality, FACTS device on the distribution side also known as custom power device can be designed to improve the power quality of the system.
5. Optimal power system operation by reduction in power system losses.
6. Improve voltage profile.

The controllable parameters using FACTS controllers are

1. $P_1 = P_2 = \frac{V_1V_2\sin\delta}{x}$; $\delta = \delta_1 - \delta_2$ (2.4)

2. $Q_1 = \frac{V_1^2}{x} = \frac{V_1V_2\cos\delta}{x}$ (injected into sending end bus) (2.5)

3. $Q_2 = \frac{V_2^2}{x} = \frac{V_1V_2\cos\delta}{x}$ (injected into receiving end bus) (2.6)

By increasing or decreasing the reactance x value the active power (P_1 and P_2) can be controlled. By controlling the phase angle (δ), which controls the current flow through the line and active power flow if the phase angle is not large.

Broad-spectrum performances are: -

- Transient stability
- Increasing power transfer capability of the system
- Power oscillation damping capacity
- Preventing voltage collapse on the system

There are different FACTS devices used in the power system in the world currently for the maximum benefit of the transmission system, for increasing transmission system availability, utilization of existing transmission line assets, improving the transient stability of the transmission system, and enabling environmental benefits. Now according to Ranjit Kumar Binda the work that is done on benefits of FACTS devices in power system, because they are pollution-free and more economical for large interconnected power system network to transfer power from the sending end to receiving end of the line. The advantage of commonly used FACTS devices in the power system are discussed in the table 2.1.

Table 2.1: Benefits of facts devices in power system transmission system. [29]

Facts device	Power flow control	Voltage control	Transient stability	Dynamic stability
TCSC	++	+	+++	++
STATCOM	+	+++	++	++
SVC	+	+++	+	++
UPFC	+++	+++	+++	+++

Where + indicates good, ++ indicates better, +++ indicates best

Based on the benefits of FACTS devices described on table 2.1 above for power flow control and transient stability study TCSC series FACTS device is preferable for this thesis study.

It is cost effective and easily installed on the power system network. The UPFC FACTS device is in the criteria fulfills best operation for all criteria mentioned on the table, but it contains both series and shunt FACTS devices due to this condition it is complex, expensive, take time, and its rating is high for installing on the power system I have to select for the case study area.

FACTS controllers can be divided into four categories: [12]

The basic types of facts devices are

- Series controller
- Shunt controller
- Combined series - series controller
- Combined series – shunt controller

2.2.1. Shunt Controller FACTS Devices

Shunt controllers inject current into the system at the point of connection. They (static var compensator or SVC), variable source (STATCOM) or a combination of these. If the injected current is in phase quadrature with the bus voltage, the shunt controller only supplies or consumes variable reactive power. Some examples of shunt controllers FACTS device are explained as follow.

A. Static Var Compensator

SVC will be outlined as a shunt connected static volt-ampere generator or absorbent material whose output is adjusted to exchange capacitive or inductive current thus on maintain or management specific parameters of the electrical power system components (typically bus voltage and angle). SVCs are primarily employed in power systems for voltage control or for improving or rising system stability.

Static Volt-ampere Compensator composed of thyristor controlled reactor (TCR), thyristor switched capacitor (TSC) and harmonic filters connected in parallel to provide dynamic shunt compensation.

The current in the thyristor controlled reactor is controlled by the thyristor valve that controls the fundamental current by ever-changing the fire angle, making certain the voltage limited to an appropriate range at the injected node.

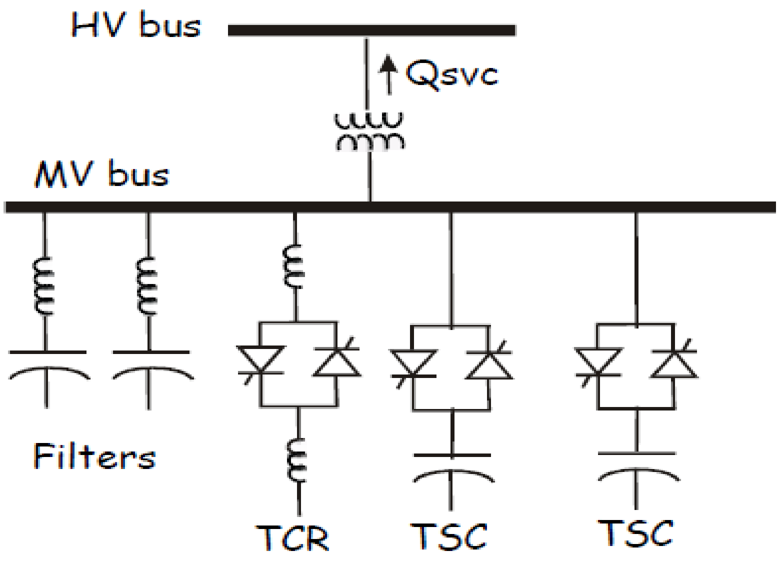


Figure 2.3: Circuit diagram of SVC[14]

Static synchronous compensator operated as shunt connected devices FACTS device whose capacitive or inductive output current can be controlled independent of the ac power system voltage. Which consists of shunt connected transformer and voltage source controllers. It is voltage source convertor which converts dc power into ac power of variable phase angle and magnitude. For industrial application the unity power factor can be obtained using the FACTS controller STATCOM.

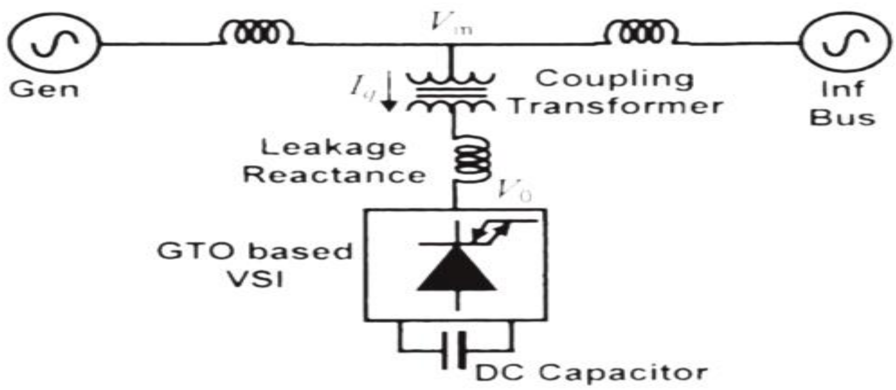


Figure 2.4: Basic structure of STATCOM [14]

2.2.2. Series-Connected FACTS Controllers

The power transfer capacity of long transmission lines networks depends on the line reactive impedance of the system. By using a series capacitor, the line reactive impedance of the system can be reduced, thus increasing the transfer power in the transmission system network.

Fixed capacitors provide a constant series impedance (−jXc), and makes the transmission line virtually shorter. This leads to an increase of the transient stability of the power system.

When needed, a controlled variable impedance can be obtained by using series-connected FACTS controllers such as the Thyristor-Controlled Series Capacitor (TCSC) and Static Synchronous Series Compensator (SSSC). This gives the advantage of power flow control and power oscillation damping that cannot be achieved when using uncontrolled compensation.

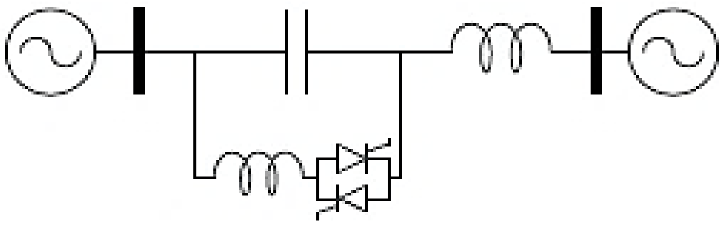


Figure 2.5: Thyristor controlled Series Capacitor (TCSC)

The benefits of using FACTS device controllers in transmission system are

- ✓ Increased transmission system reliability and performance.
- ✓ Better utilization of existing power transmission system network.
- ✓ It damps out power oscillations and increases the transient stability.

This paper addresses the static modeling of Thyristor Controlled Series Compensator (TCSC), and their capabilities to improve the voltage profile and power flow of the bus in power system to that it is connected is evaluated.

2.2.3. Thyristor Controlled Series Capacitor

According to IEEE standard definition TCSC can be defined as a capacitive reactance compensator which consists of a series capacitor bank shunted by a thyristor-controlled reactor in order to provide a smoothly variable series capacitive reactance. The basic important TCSC module consists of a series capacitor, C, in parallel with a thyristor-controlled reactor, LS.

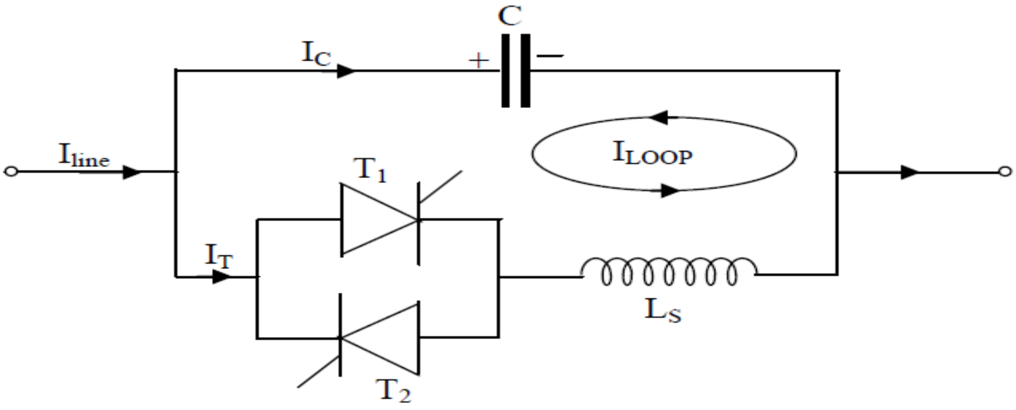


Figure 2.6: Structure of TCSC [6]

Thyristor controlled series capacitor (TCSC) is the most important and best known FACTS device controllers which has been used to increase the power transfer as well as to enhance power system stability.

The main advantage of TCSC are includes increase the real (active) power transferred in the power system, increase power oscillation damping, sub synchronous damping, power flow line control.

It consists of the following main components

- ✓ Capacitor bank C
- ✓ Bypass inductor L and Bidirectional thyristor SCR1 and SCR2

1.Analysis of the Power System without TCSC

The assumptions that are adopted to simplify the analysis are explained as follow:

Since the active resistance of transmission lines is small due to their inductive reactance, in the following description it is not considered (R= 0). The impedance of a transmission line consists mainly of inductive reactance, with resistance accounting for only 5–10% of impedance [13]

2. Principle of Operation (TCSC)

A thyristor controlled series capacitor FACTS device (TCSC) is a series-controlled capacitive reactance that can give continuous control of power on the AC transmission line network over a wide range of power system. From the system context view, the principle of variable series compensation is simply to increase the fundamental frequency voltage across a fixed TCSC capacitor (FC) in a series compensated line through appropriate variation of the firing angle α [14].

This improved voltage changes the effective value of the series-capacitive reactance value. An easy understanding of TCSC FACT device functioning can be obtained by analyzing the behavior of a variable inductor connected in parallel with a fixed capacitor.

In the variable-capacitance mode of the TCSC as the inductive reactance of the variable inductor is increase, and the equivalent capacitive-reactance is gradually decrease, that means decrease in the inductive value increases the capacitive value.

The minimum equivalent capacitive reactance is obtained for extremely large inductive reactance or the variable inductance of the system is open circuited the value is equal to the reactance of fixed capacitor itself.

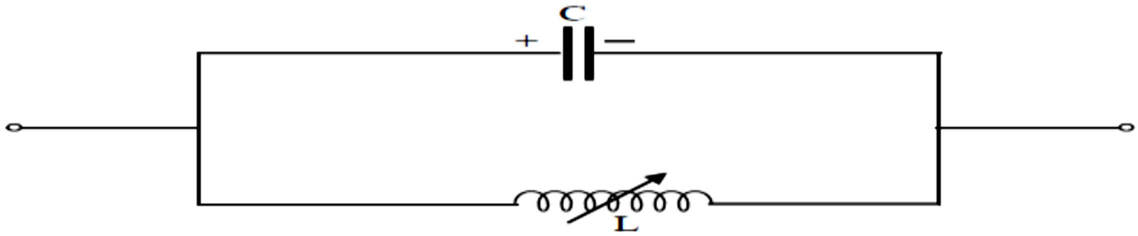


Figure 2. 7: A Variable Inductor in shunt to FC

3. Modes of Operation of TCSC

Different modes of operation

1. By pass thyristor operating mode
2. Blocked thyristor operating mode
3. Partially conducting thyristor mode or Vernier operating mode

Because of the TCSC is capable of operating on different operating modes depending on the power system requirements, TCSC is desired for many reasons. In addition to all of the merits of FSC, TCSC allows for increased system compensation simply by using a different mode of operation, as well as limitation of line current in the event of a fault condition. A benefit of using TCSC is the damping of sub synchronous resonance caused by torsional oscillations and inter-area oscillations. The ability to dampen these oscillations of damping is due to the control system controlling the compensator.

This results in the ability to transfer more power through the system, and the possibility of connecting the power systems of several areas over long distances [15].

i. By pass Thyristor Operating Mode

In this TCSC mode of operation, the thyristors are made to fully conduct with 180 degrees a conduction angle. Gate pulses are applied immediately the voltage across the thyristors valve reaches zero level and becomes positive, resulting in a continuous sinusoidal current flow through the thyristor valves. The TCSC FACT device module behaves like a parallel inductor–capacitor combination. However, the net current flow through the module is inductive mode, also represented as the thyristor-switched-reactor (TSR) operating mode.

The bypassed thyristor operating mode is different compared to the bypassed-breaker operating mode, in which the circuit breaker is provided across the series capacitor is closed to remove the capacitor or the TCSC module in the condition of TCSC faults or transient over-voltages across the TCSC FACT device. This operating mode is practicable for controlling purposes and also for initiating certain equipment protective functions. A small amount of current flows through the capacitor bank [16].

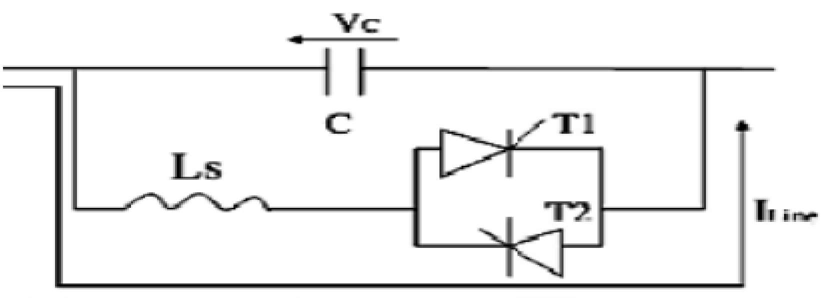


Figure 2.8: The Bypassed thyristor mode [17]

ii. Thyristor Blocked Operating Mode

This operating mode is also known as the waiting operating mode, the firing pulses to the thyristor valves are blocked.

If the thyristors are conducting and a blocking command is given the device, the thyristors turn off as soon as the current through them reaches a zero crossing. The TCSC module is thus reduced to a fixed series capacitor (FSC), and the net TCSC reactance is in capacitive mode. In Thyristor blocked mode, the firing angle is 90 degrees and thyristor are non-conducting. The TCSC's net or effective impedance is only due to capacitive reactance. In such cases the line current flow is equal to capacitor current.

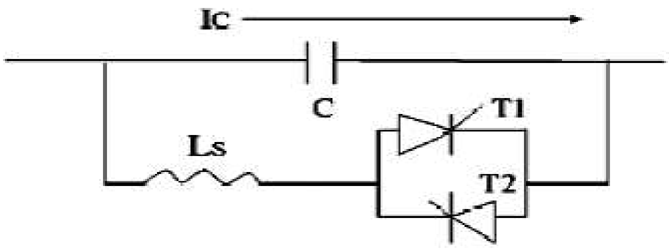


Figure 2.9: The Blocked thyristor operating mode [17]

iii. Partially Conducting Thyristor Mode or Vernier Operating Mode

This operating mode allows the TCSC device to behave either as a continuously controllable capacitive reactance or as a continuously controllable inductive reactance mode. It is successful by varying the thyristor-paired firing angle in an appropriate range of value.

However, a perfect transition from the capacitive mode to inductive mode is not allowed because of the resonant region between the two modes operation. Depend on the three operating modes of thyristor-valve operation, two variants of the TCSC device emerged.

These are TSSC which permits a discrete control of the capacitive reactance and TCSC which offers a continuous control of capacitive or inductive reactance.

Practically the mode operation used for TCSC is Vernier operating mode. It is operating as both capacitive boost mode or inductive boost mode.

iv. Capacitive Boost Mode

In capacitive boost operating mode a triggering pulse is given to the thyristor having forward voltage just before the capacitor voltage crosses the zero crossing line, so a capacitor discharge current pulse will flow through the shunt inductive branch. The discharge current pulse adds to the line current through the capacitor bank and causes a capacitor voltage that adds to the voltage caused by the line current. The capacitor peak voltage value thus can be increased in the same manner to the charge that crosses through the thyristor branch.

The basic or fundamental voltage also increases almost proportionally to the charge on the thyristor. From the system point of view, this operating mode adds capacitors to the line up to nearly three times the fixed capacitor [17].

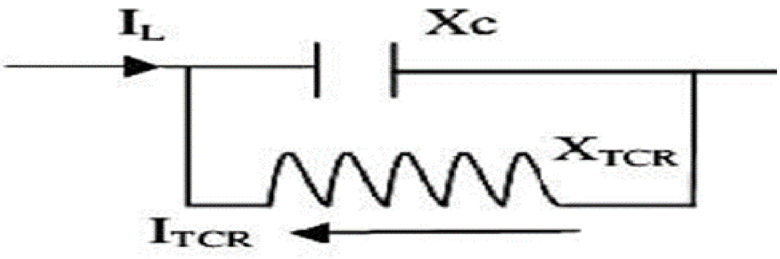


Figure 2.10: Capacitive Vernier operating mode [17]

v. Inductive Boost Mode

In this inductive boost operating mode the circulating current in the TCSC device thyristor branch is higher than the line current flow. In this mode, large thyristor currents result and further the capacitor voltage waveform is very much disturbed from its sinusoidal wave shape.

The peak or maximum voltage appears close to the turn on. The poor waveform and the high valve stress make the inductive boost operating mode less attractive for steady state operation of the system [22]

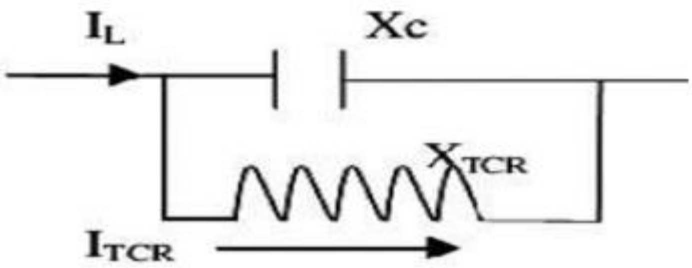


Figure 2.11: Inductive Vernier operating mode[17]

4. Location of the TCSC

A series capacitor bank can theoretically be located anywhere along the transmission line. But it is very important to be selective the location and size of the series capacitor in the power system network. The addition of series compensation will result in higher short circuit duties to the system and may require costly mitigation measures for sub synchronous resonance (SSR), if they are close to generators with SSR risk. Based on these criteria's, a fixed level of series compensation system is selected. Where there are several parallel paths or transmission lines networks, the level of series compensation should be selected to either equalize the flows on the parallel circuits or to optimize the power flow based on each circuit thermal capability. Factors influencing the choice of location include cost, accessibility, fault level, maintainability of series capacitor, protective relaying consideration, voltage profile and, effectiveness in improving power transfer capability. When a series capacitor is to be installed in a transmission line mainly following locations are considered [18].

i. Midpoint of the line.

ii. Line terminals

iii. 1/3 or 1/4 points of the line

For this case study area, the TCSC is installed between bus 2 and bus 3 of the transmission line because the line loss is maximum at that line.

2.3. Literature Review

Several studies' results have been published, some of the thesis papers, journals and, conferences are reviewed and elaborated in the following paragraph. Approaches suited for remote positioning of the variable series compensator and the appropriate types of input signals to the controller are discussed.
In May, 2019 Abebaw Yalew Mengistu [19]: study on power transfer capability and voltage stability improvement using static var compensator case study in holeta 500 /400 kV substation.

This thesis focuses to investigate the impact of the SVCs in HOLETA 500 /400kV substation on voltage stability control. Using the SVCs in the network improves the voltage stability margin in the 500 kV network at the GERD bus bar in the case of over voltage and under voltage. This is achieved by controlling the reactive power together with the shunt reactor installed on the network. However, to improve the capacity of the substation as well as the transient stability study is very important included in the thesis work.
In June 2015 Yadu Ram, Dr. Dharmendra Kumar Singh, Amit Agrawal [20]: study on voltage Profile Improvement with Thyristor Controlled Series Capacitor. The authors which has been done for 33kv

110 km medium transmission lines voltage profile improvement. During the power flow from sending end to receiving end the losses of power and voltage drop occur on the system. Their objective is to minimize drops and improve power transfer capability of the medium transmission system and they studied the voltage sag and swell generated during sudden switching on or off of heavy loads. With the help of TCSC these problems could be solved and finally they concluded that with the use of series compensator the sag or swell and harmonics can be compensated, and hence the power transfer capability of line can be improved. However, they don't study about large disturbance stability on the system.

In July – 2015 Sunil Kumar Singh, Lobzang Phunchok and Y.R. Sood [21] "Voltage Profile and Power Flow Enhancement with FACTS Controllers" In this paper, they have done the comprehensive modeling of FACTS devices for power flow study and its impact on system voltage. The effectiveness of modeling has been tested and analyzed on the IEEE-5 bus system.

The countries like India with the increasing demand for electric power day by day it is difficult to expand the existing transmission system due to difficulties in right of way and cost problem in transmission network expansion. So, they need power flow controllers to increasing transmission capacity and controlling power flows. Flexible alternating current transmission system (FACTS) controllers are capable of controlling power flows and enhancing the usable capacity of existing transmission lines.

According to work of Dr. Tarlochan Kaur and Sandeep Kakran [22] the transmission lines of power systems are becoming progressively more stressed because of increasing demand and limitations on building new transmission lines. One of the consequences of such a stressed system is the risk of losing stability following a disturbance. So in order to enhance a transmission line stability they use FACTS controller, static var compensator (SVC) as aiding device for stability enhancement.

According to their work a rapidly operating static var compensator (SVC) can regularly provide the reactive power necessary to control dynamic voltage swings under different system conditions and there by improve the power system transmission and distribution performance.

According to their conclusion installing static var compensator (SVC) at one or more appropriate points in the network will enhance transfer capability through improved voltage stability, while maintaining a smooth voltage profile under different network conditions.

In this work they model system in MATLAB/Simulink which consists of 1000MW power plant – 1 which is connected with another 1200MW power plant – 2 through along 400KV, 400Km transmission line and static var compensator (SVC) is connected to a middle of line and near power plant – 2. From the simulation of system with and without SVC for all three cases when three phase fault is applied to system they conclude that large transients occur in rotor angle difference of machines, in line voltage, line active power and in line reactive power for system without SVC compared to for system with SVC. In their study they also state that the transient stability of the system is highly affected by SVC. After clearing the fault high transients had appeared in rotor angle difference of two machines, in transmission line voltage and power when SVC was not connected in the line. But after connecting SVC in the line, transient period has decreased to a significant value. The problem on this journal is that it focuses on voltage profile of the system by providing reactive power to control dynamic voltage swing but does not focus on by providing active power controlling the rotor angle stability and they don’t study about power flow analysis.

According to Sonam Rai [23] transient stability has been given much attention by power system researchers and planners and it is being one of the major sources of power system insecurity. Flexible ac transmission system (FACTS) devices play an important role in improving transient stability.

Increasing transmission capability and damping low-frequency oscillations providing fast control of active and reactive power flow through the transmission line. In the work of the author transient stability of transmission line has been improved by using a unified power flow controller (UPFC), in this work author model of single machine infinite bus (SMIB) one without and one with unified power flow controller (UPFC) to show steady-state and dynamic stability improvement by using unified power flow controller (UPFC), a model consisting of a three-phase source of 400KV connected with the three-phase load of 250MW through a medium 150Km transmission line and simulation for the line to ground fault (L-G) is performed for two cases, by keeping unified power flow controller at end line for the system with equipment. According to the conclusion of the author, the voltage stability is improved when UPFC is inserted.

The author focused on line-to-ground faults but the other faults like symmetrical and unsymmetrical faults must be identified but he does not discuss them. It is also focused on the line with medium length but it must be studying on long transmission line etc.

according to Pankaj Kumar[1], Ankit Sachan[1], Dr. Pankaj Rai[2] [24] Power system stability is defined as the ability of power system network to regain its steady state stability or recover the initial steady state after any deviation of the system’s operation. The recent power systems are being operated nearest to their stability limits due to economic and environmental reasons.

Maintaining a stable, reliable and, secure operation of a power system is therefore a very important and challenging issue in the power system network.

According to the authors discussion Shunt FACTS devices play an important role in improving the transient stability, voltage control, reactive power compensation, increasing transmission capacity, and damping low frequency oscillations. In this work 11-bus power system network has been modeled using MATLAB SIMULINK software. The power system network under study consist of three units of power plant each producing 20 KV and step up by two winding transformer to 230 KV. For parallel operation of three different power plants, the frequency and the terminal voltage has been kept constant to avoid circulating current in the existing network. A Static VAR Compensator and a series compensator have been used in the considered network for improving the transient stability and to increase the transmission capacity of the system.

According to Ghazanfar Shahgholian*, Mohammad Reza Yousefi [25] discussion flexible ac transmission system (FACTS) controller can play an important role in mitigating voltage stability problems and power transfer capability. The unified power flow controller (UPFC) is one of the FACTS controller that combines both series and shunt compensators, and offers more specific characteristics compared to other devices controller.

In this paper, a unified power flow controller (UPFC) is applied to improve dynamic performance of electrical power system network by using power flow study control techniques. The phasor model of UPFC is used in this system. All the simulations for this work have been carried out using MATLAB/SIMULINK tool box environment. In summary, FACTS devices controllers are used to achieve the following main goals: controlling of power flow along desired transmission line corridors, increase transmission line capacity without requiring new transmission line infrastructure, improve dynamic stability, transient stability and voltage stability of the system, and provide damping for inter-area oscillations.

CHAPTER THREE

METHODOLOGY AND MATHEMATICAL MODELLING OF THE SYSTEM

Introduction

This chapter deals with data collection and analysis, mathematical modeling of the power system network from generation station to load. Then modeling of the overall transmission line network is performed. Finally, the system is simulated by using MATLAB/2015a software both in Simulink and script.

3.1. Materials

In this thesis work, software such as MATLAB/2015a, Microsoft office 2016, and Math Type 6.0 equation are used. MATLAB is the computing software which consists of technical toolboxes and Simulink. Microsoft office is used for editing the thesis documentation. Math Type 6.0 is used for writing mathematical formulas and equations in Microsoft offices word and PowerPoint presentation tools.

3.2. Methods

The method used in this thesis work to achieve the required task is shown in Figure 3.1 below. The closely related papers and literatures are reviewed. Then the necessary data used throughout this thesis are collected and analyzed. The generation data, transmission line data, bus data, and load data are collected from recorded sheets and template data of the machines obtained in the generation station and the national load dispatch center (NLDC).

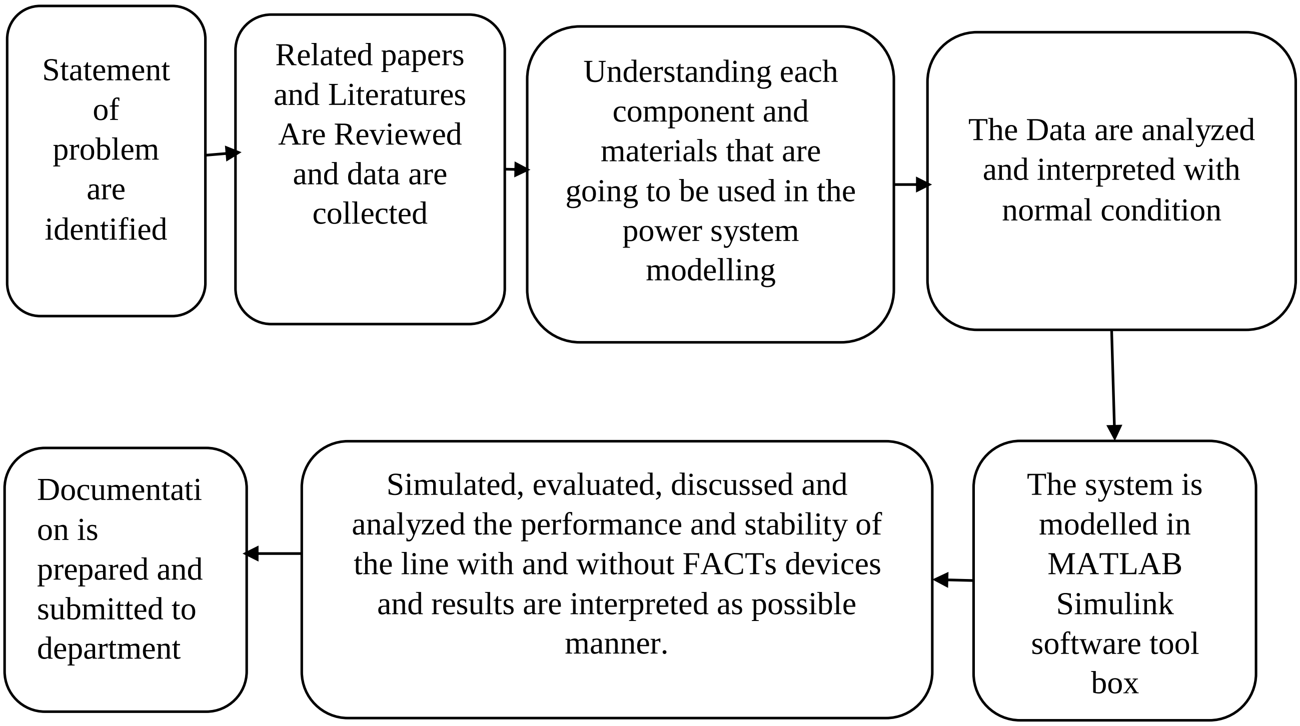


Figure 3.1: The block diagram of the proposed system

The explanation of the above methodology diagram of the overall thesis works are: -

1. The problem faced under the study area has been identified.
2. Literatures are reviewed to get ideas from the previous researchers related to the title I have to select.
3. Secondary data are collected from the case study sites from generation station, substation, and NLDC.
4. The collected data are analyzed using MATLAB Simulink.
5. The components and materials used to model the system have been identified and modelled on MATLAB Simulink.
6. Modelling the whole system using MATLAB software.
7. Simulate, evaluate, discus and analysis the performance and stability of the system with and without FACTS device.
8. The documentation for the thesis is prepared and submitted to the department.

3.3. Data Collection

The main collected data is obtained from the Ethiopian Electric Power (EEP) head office, some of it was taken from power plant station, the grid disturbance reports and recorded data of the National Load Dispatch Centre (NLDC) in the Ethiopian Electric Power, some interviewing the expert those who portioned on that area, by referring the other researcher have thought about the generation plant station especially the feature and characteristics of the station and browsing from internet for more clarification are the main sources of data for the research. Techniques such as interviewing and review of records and/or reports are employed for more.

Literature reviewing were also used to get further idea about the theoretical, conceptual and numerical ideas regarding to the topic and the methodology of the analysis of results.

3.4. Site Selection

Gilgel Gibe-II hydroelectric power plant which is located in two regional states Oromia and Southern Nation, nationalities and peoples (SNNP). The intake is located some 250Km from South West of Addis Ababa ,80Km North-East of Jima town. The outlet and power house in yem special woreda of SNNP regional state. This project is born as cascade of Gilgel Gibe-I hydroelectric power plant. The water that generates 184MW at Gilgel Gibe-I power plant is diverted via a 26Km long tunnel and generates additional 420MW of electric power at Gilgel Gibe-II power plant. It is fairly plateau about 937m.a.s.l consisting of a series of gently sloping high hills and bread plains surrounded by hills or mountains. The Gilgel Gibe crossing the region from SW to NE is a tributary of the great Gibe or Omo River downstream of the confluence and is extremely variable in course and gradient. The geographical feature is suitable for construction of reservoir with a considerable storage capacity, able to regulate most of the river flow thus keeping unsuitable spills to a minimum. At the end of plain, the river bank become steeper and the section of the valley is the suitable site for the construction of the dam. Given the storage volume, which will be obtained the height and the length of the dam embankment are modest. To provide adequate and quality electricity generation, transmission through continuous improvement of management practices responsive to the socio-economic development and environmental protection need of the public. Gilgel gibe two hydroelectric power plant is among the largest generation station in Ethiopia which generates about 420MW power transmit to the national grid through 400kV high voltage transmission line.

The implementation of the project was executed under an EPC (Engineering, procurement and construction) type of contract, in which the contractor, by Salini Costruttori of Italy Project Company.

ELC –Electro consult of Italy is engaged, under a separate consultancy contract agreement as the Employer's representative to review project design and assure quality of the workers. Gilgel Gibe II hydroelectric power project, the PEC main contractor is saline costruttori of Italy. Sub sequently, a Voith-Hydro of Germany related to electro mechanical works of the power house and switchyard. ATB-Riva Calzoni of Italy related to hydraulic steel structures and penstocks installation works. Power transmission and substations project: - KEC International; for 400kV and 230kV transmission lines. CYMI&SOCOIN, for the power transformers, shunt reactors and substation equipment [26].

Grace General contractor, for civil works. Sigma PLC, for electro mechanical erection works. Gilgel Gibe-II is brought in-service since 2010 G.C., currently the third largest power plant in Ethiopia. This project is born as a cascade of Gilgel Gibe-I hydroelectric power plant.

The water a tributary of Gibe River for Gilgel Gibe-I power plan generates 184 MW using 3 Generating units rated at 70 MW each at an operating head of 223.4 meters inside an Underground Power house comprising of Vertical Francis Turbines driving the synchronous generator at 428.50 RPM (Revolution per Minute) is diverted via a 26km long tunnel and generates additional 420 MW of electric power at Gilgel Gibe-II power plant. The powerhouse consists of four pelton turbines each having a rated power of 105 MW for a total of 420MW. The difference in elevation between intake and the powerhouse is about 485m. It is this head that allows generating 420MW of electric power with 4 pelton turbines driven Gilgel Gibe-II generators. The water is sprayed through six nozzles on the paddle wheel of the turbine and then it is released into the Omo River. Activities relative to the realization of the Gilgel Gibe II Hydroelectric project were commended in January 2002 E.C by Excellency former Prime minister Ato Meles Zenawi prime minster of the federal democratic republic of Ethiopia.

Designed Mechanical Power(PM) in Gilgel Gibe II

Given data: -flow rate (Q) =25.1m^3/s; height (H) =505m; gravity (g) =9.81m/s^2

Efficiency (η) =0.85; density of water (ρ) =1000kg/m3

Solution $p_m = \rho H \eta Q$

P_m =1000*505*25.1*0.85*9.81

P_m =106MW this power is generated from one generating unit, the generation station has four units and the total generating mechanical power is 420MW power.

Designed Electrical Power (PE) in Gilgel Gibe II HEPP

Given data: -rated current (I) = 4811A; rated voltage (V) = 15kV = 15000V

Cos(ϕ) =0.85; number of Phase = 3

Solution: $Pe = \sqrt{3} * VI\cos(\phi)$

$Pe = \sqrt{3}$ *15000v*4811A*0.85

Pe = 106MW the generating electrical power through one units of the generating station. The co-operation Established between the government of Ethiopia and the government of Italy and the plant was expected to come on-line in 2004 E.C. Due it's high capacity the station faces different unstable condition on the grid because of different fault conditions on the line like symmetrical and unsymmetrical faults, overloading, under loading, over frequency and under frequency are the major problems. Among these problems line to ground fault is occurring on the line from Gilgel gibe two to sebeta two high voltage transmission line.

The place of high voltage networks of EEP of these specific area is the one it makes preferable. These are so called the generation plants and transmission lines under the network. These the high voltage can be helpful to select the health and power supply capacity of the grid highly depends on the save and stable running of these circuits.

3.5. Data Analysis

The data were in general analyzed, through descriptions and simulations. Based on these the plan for data analysis was done in two advanced steps as follows

Step I. On this phase, the data collection, identification & analytical manipulation of the system data for status clarification are done. The data were organized and put in desired manner for analytical manipulation.

Step II. Modelling & simulation

The dynamic modelling of synchronous machine and dq0 or park transformation model of electrical machine is used in the interconnected form of power system networks. And different components of a power system network like generators, transmission lines, loads & transformers were loaded from the data by using MATLAB Simulink software tool box. The analyses of the current Ethiopian Power System of Gilgel gibe II to sebeta II transmission network with regard to the physical phenomena of transiently instable conditions are highly elaborated.

3.6. Mathematical Modelling of Power System Components

A modern power system is highly interconnected to each other. This interconnection result in operating economy and reliability through mutual assistance. They also contribute to stability problems, and these stability problems are a big challenge for power system engineers because of the large scale interconnections. For power system stability analysis, a mathematical model of a system is required to develop. The mathematical model a set of non-linear differential equations and a set of algebraic equation. For these two form of equation there is no formal solution available, these equations are to be solve using numerical techniques, and it takes a lot of time to solve the equations.

To get the correct assessment of power system stability a detail model of power system is need to be developed.

In late 1950 the analogue computer was developed, these was used to simulating the power system stability problems. Before 1950 there is no any computer problems are solved by hand calculations.

In late 1950G.c a digital computer was developed and the first computer program for transient stability problems analysis was developed in 1956 G.c, the program is mainly analyzing the transient stability of the system. After that there is development of high response excitation system resulted into a problem of power damping of the system oscillation.

This power damping oscillation has been overcome by using power system stabilizers. The mathematical modelling of power system components is as follow.

3.7. Synchronous Machine Modelling

The synchronous machine is model as a constant voltage behind direct axis transient reactance. The synchronous machine modeling has been a challenge or true a lot of work over the year to get accurate models of the synchronous machine. In this thesis research I have to develop the basic equations of synchronous machine and the dqo transformation or park transformation. Synchronous generator has two major parts of stator and rotor parts. The stator is divided into three windings and assume these windings are sinusoidaly distributed. On the rotor we have field winding on the direct axis and damper windings which represented by considering the damping located on the d-axis or on the q-axis.

The convention in this modelling is the dq-axis leads d- axis by 90 degrees. In some cases, the q-axis has leading the d-axis but in IEEE standards considering the q-axis leading the d-axis by 90 degrees.

A three phase synchronous machine is modelled in the rotor frame of reference as shown in Figure 3.2. The figure shows two fictitious d and q stator windings representing three phase armature windings on the stator.

The figure also depicts two rotor windings, including the field winding `fd' and damper rotor coil ‘k’ along d-axis and damper rotor coils ‘k’ along q-axis. The short circuited coils, one along d-axis (`k') and one along q-axis (`k') represent the effect of damper windings and eddy currents induced in the rotor mass.

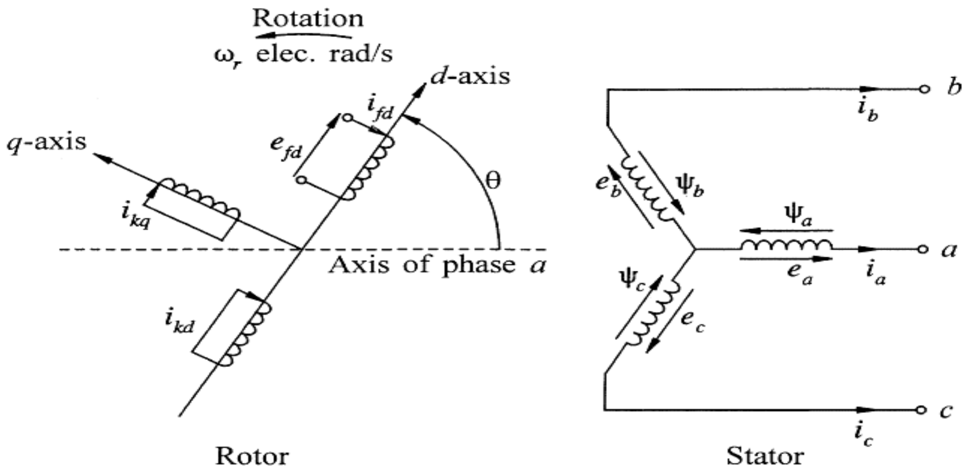


Figure 3.2: Model of a synchronous machine [6]

Let us consider a rotating synchronous machine the shaft of turbine is connected to a generator,

1. From the turbine the turbine exerts torque in one direction which causes the shaft to rotate. This is called mechanical torque Tm.
2. From the generator, the generator exerts torque in the direction opposite to the mechanical torque which retard the motion caused by Tm. This is called electromagnetic torque Te.

Tm and Te are equal in magnitude but opposite in direction, if Tm is equal to Te the machine is in synchronism. We have to consider the swing equation with nonlinear differential equation of the power angle to analyses the transient stability of the power system. Therefore, the numerical techniques have been developing to solve the equations. There are two methods to solve the swing equations on the power system these are method one and method two are used. In point by point solution of the swing equation consists of two process which are carried out alternatively.

1. The first process is the computation of the angular positions and angular speeds at the end of each interval from the knowledge of angular positions and speeds at the beginning of the time interval and the accelerating power assumed for the interval.
2. The second process is the computation of accelerating power of each machine from the angular position of all the machines of the system. The second process requires the knowledge of network solution.

In the swing curve if the δ-t curve response is depicted with increase δ, δ reach maximum and then decrease. The system is transiently stable. On the other hand, if the rotor angle increases indefinitely, the system is transiently instability.

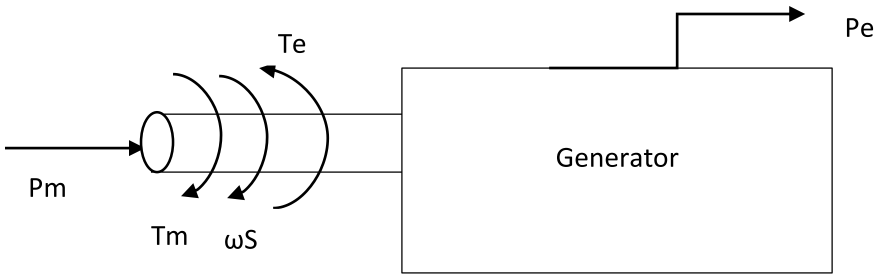


Figure 3.3: Flow of power in synchronous generator

The amount of accelerating torque is defined as,

$$Ta = Tm - Te \tag{3.1}$$

And also the mechanical and electrical powers are given by

$$P_m = \omega_m * T_m \text{ and } P_e = \omega_m * T_e \tag{3.2}$$

where, P_m is the mechanical power in which it is gotten from the prime mover and P_e is the electromechanical power, which is the sum of the output of the generator to that of the electrical losses. It is more convenient to measure the angular position of the rotor with respect to the synchronously rotating frame of reference.

$$\delta_m = \theta_m - \omega_n * t = \Delta\delta_m \tag{3.3}$$

where ω_n is a synchronous speed of the generator in revolution per minute or radian per second.

$$\frac{d\delta m}{dt} = \omega m - \omega n = \Delta\delta m \tag{3.4}$$

$$\frac{d^2\theta_m}{dt^2} = \frac{d^2\delta_m}{dt^2} \tag{3.5}$$

The accelerated torque of the generator can be formulated from the general torque equation which is the product of moment of inertia and the rotational acceleration (Second derivative of the angular position) With the consideration of the damping torque, the mechanical and electrical torque mismatch or the accelerating torque can be represented by

$$J\frac{d^2\delta}{dt^2} = D\frac{d\delta_m}{dt} = T_m - T_e = T_a \tag{3.6}$$

where D is damping coefficient, it is the coefficient of a rotating machines mechanical losses and in most practical implementation, it is considered as negligible.

$$J*\omega m*\frac{d^2\delta_m}{dt^2} = \omega m * T_m - T_e \qquad (3.7)$$

In the description J*ω_m is defined as the angular moment of the moving body and distinguished by capital letter M, where J is the moment of inertia.

$$M*\frac{d^2\delta_m}{dt^2} = \omega m\left[T_m - T_e\right] \qquad (3.8)$$

$$M\frac{d^2\delta_m}{dt^2} = p_m - p_e = p_a \qquad (3.9)$$

where $M = J\omega_m = \frac{2H}{\omega_m}$

δi-is angular displacement of rotor with respect to stationary reference and H is inertia constant

$$\delta_i(s) = \frac{\omega_m}{2Hs^2}[p_{mi}(s) - p_{ei}(s)] \qquad (3.10)$$

$$\frac{d^2\delta_i}{dt^2} = \frac{\omega_m}{2H}[pmi - \sum_{k=1}^{n} E_i E_k Y_{ik} \cos(\theta_{ii} + \delta_k - \delta_i)] \qquad (3.11)$$

This aforementioned subsequent equation would finally result in developing the so called the equation of motion or swing equation of the machine as depicted in (3.11).

The equations represented in (3.10) and (3.11) along with the reduced bus admittance matrices and the load flow result will be used for the evaluation of the transient stability of the system.

From the equivalent circuit of synchronous machine on figure 3.2 above in the rotor frame of reference (dq frame), The terminal voltage of any armature winding is given by the following matrix equation [6].

$$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = \frac{d}{dt}\begin{bmatrix} \psi_a \\ \psi_b \\ \psi_c \end{bmatrix} - r\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \qquad (3.12)$$

where e, terminal voltage

Ψ, total flux linkage

i, current through winding

r, winding resistance

In equation 3.12 the stator voltage and flux linkage relationship is

$$\psi_a = -L_{aa}i_a - L_{ab}i_b - L_{ac}i_c + L_{afd}i_{fd} + L_{akd}i_{kd} + L_{akq}i_{akq} \qquad (3.13)$$

And similarly equation 3.13 is apply for phase b and c.

$$\psi_{abc} = -[L_{ss}i_{abc}] + L_{sr}i_r \qquad (3.14)$$

The rotor circuit voltage and linkage flux in matrix equation is given by equation 3.15

$$\begin{bmatrix} e_{fd} \\ 0 \\ 0 \end{bmatrix} = \frac{d}{dt}\begin{bmatrix} \psi_{fd} \\ \psi_{kd} \\ \psi_{kq} \end{bmatrix} - \begin{bmatrix} r_{fd} * i_{fd} \\ r_{kd} * i_{kd} \\ r_{kq} * i_{kq} \end{bmatrix} \qquad (3.15)$$

The linkage flux interms of inductance and current is given by

$$\begin{bmatrix} \psi_{fd} \\ \psi_{kd} \\ \psi_{kq} \end{bmatrix} = \begin{bmatrix} L_{ffd}i_{fd} + L_{fkd}i_{kd} + L_{afd}[i_a\cos\theta + i_b\cos(\theta - \frac{2\pi}{3}) + i_c\cos(\theta + \frac{2\pi}{3})] \\ L_{fkd}i_{kd} + L_{kkd}i_{kd} + L_{afd}[i_a\cos\theta + i_b\cos(\theta - \frac{2\pi}{3}) + i_c\cos(\theta + \frac{2\pi}{3})] \\ L_{kkd}i_{kq} + L_{akq}[i_a\sin\theta + i_b\sin(\theta - \frac{2\pi}{3}) + i_c\sin(\theta + \frac{2\pi}{3})] \end{bmatrix} \qquad (3.16)$$

If the voltage produced by three phase armature current are resolved along the direct and quadrature axis current proportional to resultant voltage in the direct and quadrature axis defined interms of three phase current as

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin\theta & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \qquad (3.17)$$

The magnitude of phase current is obtained by multiplying both sides by inverse of coefficient of phase current i.e.

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & 1 \\ \cos(\theta - 120) & -\sin(\theta - 120) & 1 \\ \cos(\theta + 120) & -\sin(\theta + 120) & 1 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ 0 \end{bmatrix} \qquad (3.18)$$

Generally synchronous machine specified interms of nominal power, voltage, frequency and impedances.

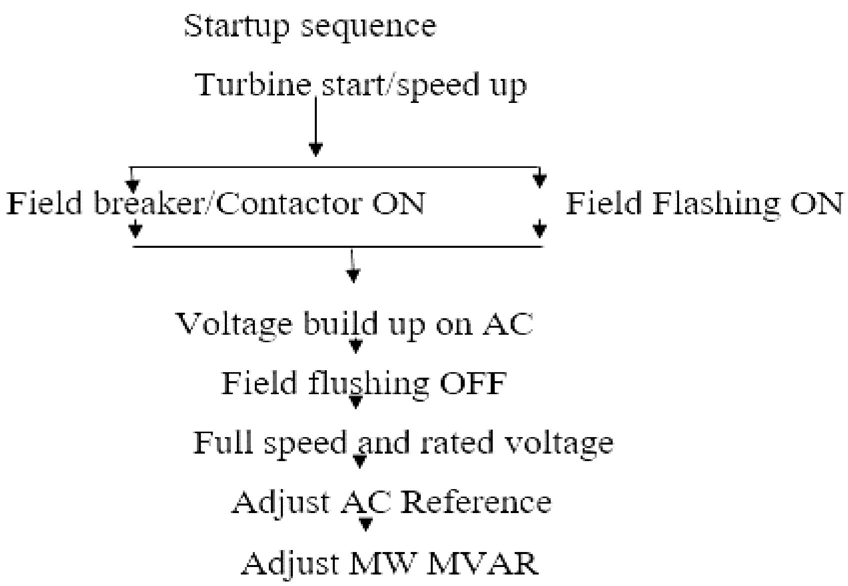
3.8. Exciter Modelling

An excitation system is a system that is used to supply, control, and monitoring of dc supply. The generator needs an excitation system for starting purposes by using Faraday's First Law. Faraday's first law states that the stator is stationary and the field is rotating. At speed reaches 90% field flush circuit breaker is off and supply gets continuously from DC system. It is a system supply that variable DC current to rotor winding for producing flux, which generates e.m.f.in stator winding.

The main function of an excitation system in a power system is to provide DC power to the field winding of a synchronous generator.

The excitation system performs control functions such as control of voltage level and reactive power shared by the generator, and provides means to improve dynamic and transient stability performance of the power systems by controlling the field voltage and thereby the field current.

Normal sequence of excitation system



3.8.1. Elements of Excitation System

The functions of each of the excitation element have been highlighted below [29]

1. Exciter: Exciter constitutes the power stage of the excitation system and it Provides dc power to the synchronous machine field winding.
2. Regulator: Regulator that processes and magnifies input control signals to a level and forms appropriate for control of the exciter. This includes both regulating and excitation system stabilizing functions.
3. Terminal voltage transducer and load compensator: Senses the generator terminal voltage, rectifies and filters it to DC quantity, and compares and contrast it with a reference that represents the desired terminal voltage and, load compensation may be provided.
4. Power System Stabilizers: Power System Stabilizers provides an additional input signal to the regulator to damp power system oscillations.
5. Limiters and Protective Circuits: These include a wide array of control and protective functions which ensure that the capability limits of the exciter and synchronous generators are not exceeded.

Some of the commonly used functions are the field-current limiter, maximum excitation limiter, terminal voltage limiter, volts-per-hertz regulator and protection, and under excitation limiter.

3.8.2. Types of Excitation System

The excitation system is classified into the following three broad categories based on the excitation power source [27]

1. DC Excitation System
2. AC Excitation System
3. Static Excitation System

A. DC Excitation Systems

The excitation systems of this type utilize dc generators as sources of excitation power and provide current to the rotor of the synchronous machine through slip rings. The exciter may be driven by a motor or the shaft of the generator. It may be either self-excited or separately excited. When separately excited, the exciter field is supplied by a pilot exciter comprising a permanent magnet generator.

B. AC Excitation Systems

The excitation systems of this type utilize alternators (ac generators) as sources of the main generator excitation power supply. Usually, the exciter is on the same shaft as the turbine generator.

The ac output of the exciter is rectified by either controlled or non-controlled rectifiers to produce the direct current needed for the generator field flushing.

AC exciters can be classified as follows:

1. Field-controlled alternator with non-controlled rectifiers
    - (a) Rotating rectifier arrangements- Brushless excitation system.
    - (b) Stationary rectifier arrangements.
2. Alternator-supplied controlled-rectifier excitation systems.

C. Static Excitation Systems

All components in these static excitation systems are static or stationary in system. Controlled or uncontrolled Static rectifiers supply the excitation current directly to the field windings of the main synchronous generator through slip rings. The supply of electric power to the rectifiers circuit is from the main generator (or through station auxiliary buses) through a transformer winding to step down the voltage magnitude to an appropriate level, or in some cases from auxiliary windings in the generator.

The Static Excitation system is mainly composed by:

- Voltage Regulator (Excitation panels)
- Excitation Transformer
- Potential and Current Transformers
- Interconnections

The different parts of Gilgel gibe-II hydroelectric power plant excitation system are discussed as follow [27].

Potential and Current Transformers are used to transform the generators voltage and current into values that can be read by the Voltage Regulator. In Thyricon there are transducers that convert the signals to electronic levels. Both the Potential and Current transformers and the transducers share the task of adapting signals from the machine to electronic signal levels.

The Excitation Transformer is a step down transformer used to feed the rectifier bridge and consequently the field. The Standard Excitation Transformer is a dry three-phase, Y / Δ or Δ /Y, which is dimensioned to guarantee 110% of maximum excitation system power.

Thyricon Voltage Regulators are compact standard products which are used in small, medium or large Hydro Power Plants. The selection of Thyricon model and type depends on the current and field voltage. Thyricon 500 is limited on 1000V by Simoreg converter.

The concept of redundancy in Thyricon 500 is 1+1 which can be executed in a cold or hot standby. Voltage Regulators are normally divided in two parts: the control and the power part.

The following are the two major types of static excitation systems:

1. Potential-source controlled rectifier systems.
2. Compound-source rectifier systems.

In Gilgel gibe II hydroelectric power plant the excitation system is static excitation it explained in detail as follow:

3.8.3. Static Excitation Systems

It is a type of excitation system; the generator field is fed from a thyristor network. It is just sufficient to adjust the thyristor firing angle to vary the excitation level. A major advantage of such system is that, when required the generator field voltage can be varied through a full range of positive value to negative values very rapidly with the major benefit of generator Voltage regulation during transient stability disturbances in the system. The thyristor network consists of either 3-phase semi or fully controlled bridge rectifiers. Field suppression resistor dissipates Energy in the field circuit while the field breaker ensures field isolation during generator stop.

A. Potential-Source Controlled Rectifier Systems

In this system, the excitation electrical power is supplied through a transformer from the generator terminals or the station auxiliary bus, and is regulated by a controlled rectifier. This type of excitation system is also known as a transformer-fed or bus-fed static system. A functional block schematic of this type exciter is shown in Figure 3.4.

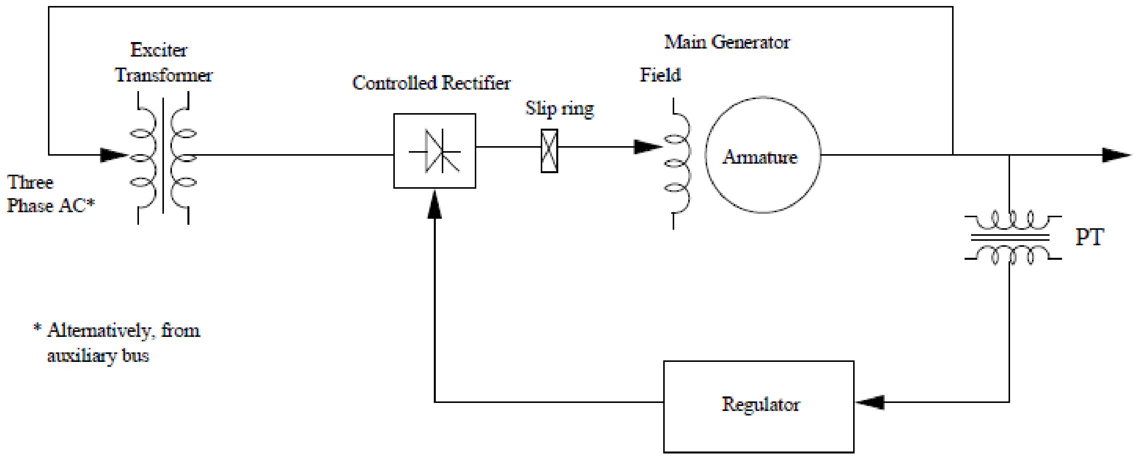


Figure 3.4: Potential-source controlled rectifier excitation system [27]

B. Compound-Source Rectifier Systems

In this case, the power to the excitation system is formed by utilizing the current as well as the voltage of the main generator. This may be achieved by means of a power potential transformer and a saturable current transformer as depicted in Figure 3.5.

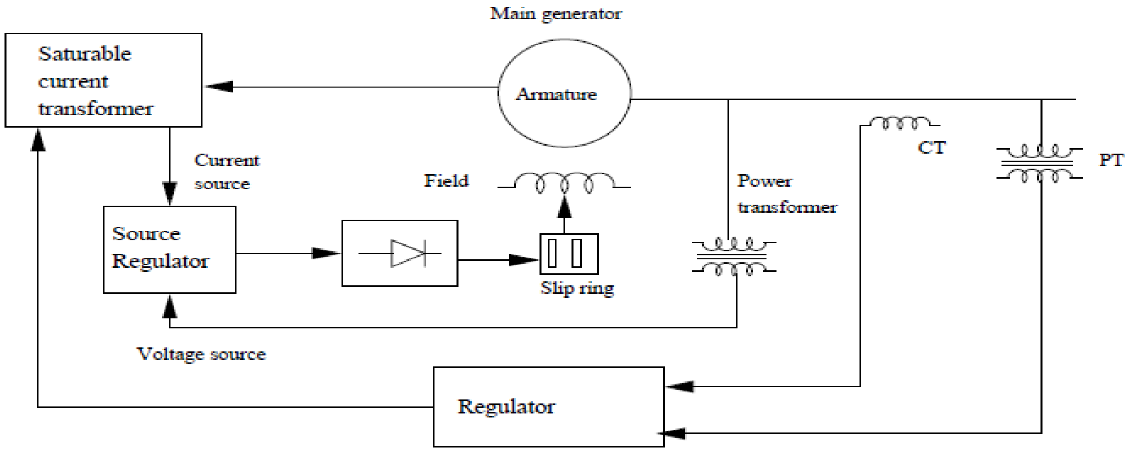


Figure 3.5: Compound-source rectifier excitation system [27]

3.9. Transmission Line Modelling

Modelling and representing transmission line is important to analysis and look the condition of transmission line under different cases of transients.

The parameters required to model transmission line depend up on length, spacing between conductors and nature of the conductors used. I have to use lumped parameter model of transmission line.

An overhead line represented as distributed constant where the line resistance(R), inductance(L), capacitance(C) and leakage conductance(G) were distributed uniformly over the line length.

Transmission network mainly consists of transmission lines, line support, insulators, distance protection relay, and transformers. Since the time constants of these elements are relatively small compared to the mechanical time constants, the network transient's problems are neglected and the network is assumed to be in sinusoidal steady state. The modelling of these components are briefly discussed in the next sections:

The power produced by the plant will be delivered to the ICS (Inter Connected System) through a 400 kV transmission line which connects the Gilgel Gibe II Plant to a substation located in the area of Addis Ababa at a distance of about 183.5 km. The Inter Connected System is a relatively small network, which serves the major towns and industrial centers in Ethiopia.

The generating capacity of the plants that currently supply the ICS (8 hydroelectric and 2 thermal plants), including also the Gilgel Gibe I, is about 767 MW with an average energy capability of about

3,250 GWh/y. However, the dependable capacity is reduced to less than 676 MW due to derating and unit unavailability due to forced outages.

According to demand forecast studies, envisaged in the Ethiopian Power System Expansion Plan - April 2004, the peak load demand expected in years 2013 is 2,547 MW, while the electricity demand expected for the same year is 10,690 GWh/y.

The ratio between the highest unit capacity (61 MW, Gilgel Gibe I) and the total network capacity (676 MW) is already high (about 9%) and should not be increased in order to limit network disturbances in case of sudden shut-down of one of the major units.

Since the new capacity brought by Gilgel Gibe II will increase the total network capacity to about 1,080 MW, the maximum unit size should not exceed 100 MW. The above mentioned ratio will decrease in the future since more capacity is expected to be added to the Ethiopian Grid in the next decades.

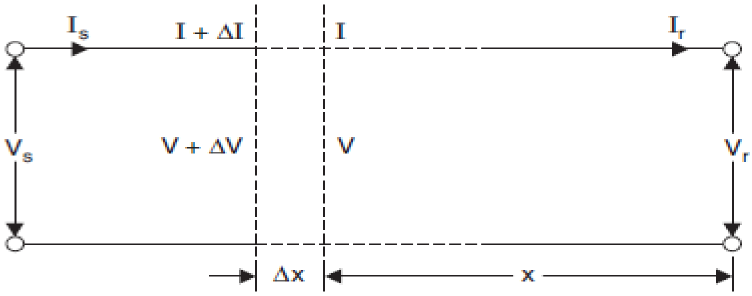


Figure 3.6: The equivalent circuit of long transmission line

For clarity the elemental length dx is redrawn in figure below

For analysis I shall take the receiving end as the reference for measuring distances. I have the transmission line impedance it consists of the inductance of the line and the resistance of the line and also consists of the capacitance of the line connected to ground which provides shunt admittance of the line and conductance most of the time it is negligible Take an elemental length dx of the line at a distance of x from the receiving end. Say the voltage and current at a distance x are V and I and at a distance x + dx, V + ΔV and I + ΔI respectively.

$$\Delta V = Iz\Delta x$$

$$\Delta I = Vy\Delta x \qquad (3.19)$$

From the above equation I have to get

$$\frac{\Delta V}{\Delta x} = Iz \qquad (3.20)$$

$$\frac{\Delta I}{\Delta x} = Vy$$

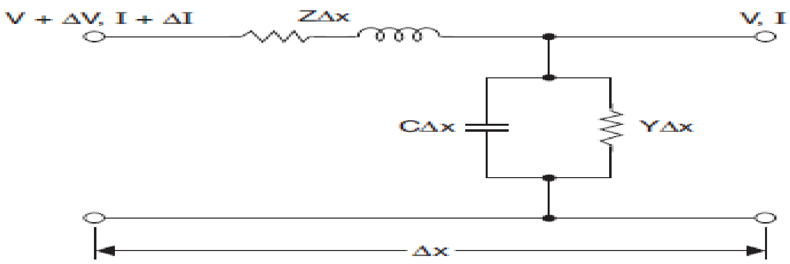


Figure 3.7: Impedance circuit diagram of transmission line

For sinusoidal waves on an overhead transmission line

$$\lambda = \frac{c}{f}; \qquad (3.20)$$

where c= $3*10^8$m/s^2

For f = 50Hz and λ=6000km

Since the line with 50Hz frequency can have current and voltage wave of 6000km but in most cases the transmission lines are few hundreds kilometers.

If the line length is greater than 150km long, one can neglect the distributed parameters effect of the transmission line and it is sufficient to consider lumped parameter model for transmission lines.

To model long transmission line, I have to consider the two port network on the line shown in below.

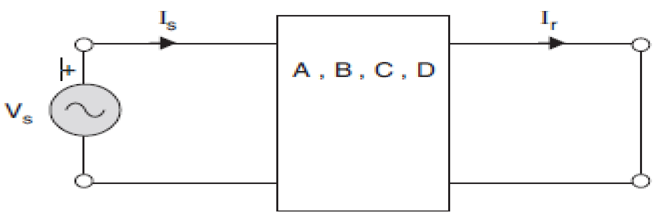


Figure 3.8: Two port network of long transmission line

For this two port network I have to write the relation between sending end voltage and current interms of receiving end voltage and current by the equation given in below

$$V_s = AV_R + BI_R \text{ volt} \qquad (3.20)$$

$$I_s = CV_R + DI_R \text{ A} \qquad (3.21)$$

This relationship is valid for linear bilateral two port network

The general ABCD transmission parameters model of any two port network transmission line are: -

$$\begin{bmatrix} Vs \\ Is \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix} \qquad (3.22)$$

AD-BC=1

The transmission line is very long it is used in extra high voltage transportation from the generation station to the receiving end or load center. In this the distributed model of a line we have to consider small change of length(Δx), series impedance(zΔx), total shunt admittance(yΔx), and the conductance for 50Hz or 60Hz frequency is negligible. The voltage at a distance x from the receiving end is V(x) and the current is I(x), similarly the voltage and current from receiving end to sending end are given by V (x+ Δx) and I (x+ Δx) respectively. From the equivalent circuit of long transmission line shown in above figure the modelling equations to find the parameters of the line are show as follow

$$Z = R + j\omega L \ \ \Omega / m \qquad (3.23)$$

$$Y = G + j\omega C \ \ S / m \qquad (3.24)$$

where Z and Y are the series impedance and shunt admittance per length of the line respectively
The voltage at sending end by Kirchhoff's voltage law is given by

$$V(x+\Delta x) = v(x) + (z\Delta x)\, I(x) \ \text{volts} \qquad (3.25)$$

This equation is referring the voltage at the receiving end is equal to the voltage at the sending end plus the voltage drop through the line due to series impedance. By rearranging the above equation, I have to get

$$\frac{V(x+\Delta x) - V(x)}{\Delta x} = zI(x) \qquad (3.26)$$

The limit Δx approaches to zero the derivative of the above equation is

$$\frac{dV(x)}{dx} = zI(x) \qquad (3.27)$$

The current at the sending end by using Kirchhoff's current law is

$$I(x+\Delta x) = I(x) + (y\Delta x)V(x+\Delta x) \qquad (3.28)$$

$$\frac{I(x+\Delta x) - I(x)}{\Delta x} = yV(x+\Delta x); \lim\Delta x® 0 \qquad (3.29)$$

$$\frac{dI(x)}{dx} = yV(x) \qquad (3.30)$$

From the derivative equation of voltage and current by equating them given as

$$\frac{d^2V(x)}{dx^2} = z\frac{dI(x)}{dx} = zyV(x) \qquad (3.31)$$

Substituting equation 1 into equation two and collect like terms given by

$\frac{d^2V(x)}{dx^2} - zyV(x) = 0$ it is second order homogenous equation and its solution is obtained by

$$V(X) = A1e^{\gamma x} + A2e^{-\gamma X} \ \text{volts} \qquad (3.32)$$

where $\gamma = \sqrt{zy}$ m^{-1}

Differentiating the above equation rewritten as

$$\frac{dV(x)}{dx} = \gamma A1e^{\gamma x} - \gamma A2e^{-\gamma X} = zI(x) \qquad (3.33)$$

From this equation the current at the receiving end is given by

$$I(x) = \frac{A1e^{\gamma x} - A2e^{-\gamma X}}{z/\gamma} \text{ or} \qquad (3.34)$$

$$I(x) = \frac{A1e^{\gamma x} - A2e^{-\gamma X}}{zc} \qquad (3.35)$$

where zc is the characteristics impedance given by

$$zc = z/\gamma = \frac{z}{\sqrt{zy}} = \sqrt{\frac{z}{y}}\Omega \qquad (3.36)$$

Using the boundary condition by making x is equal to zero

$$V_R = V(0)$$

$$I_R = I(0)$$

The receiving end voltage and current are given by

$$V_R = A1 + A2 \qquad (3.37)$$

$$I_R = \frac{A1 - A2}{zc} \qquad (3.38)$$

From the above two voltage and current equation we can calculate the value of A1 and A2 as

$$A1 = \frac{V_R + zcI_R}{2} \qquad (3.39)$$

$$A2 = \frac{V_R - zcI_R}{2} \qquad (3.40)$$

Substituting the value of A1 and A2 into the equation V(x) and I(x) we get

$$V(x) = (\frac{V_R + zcI_R}{2}) + (\frac{V_R - zcI_R}{2})e^{-\gamma X} \qquad (3.41)$$

$$I(x) = (\frac{V_R + zcI_R}{2zc})e^{\gamma X} - (\frac{V_R - zcI_R}{2zc})e^{-\gamma X} \qquad (3.42)$$

Rearrange the equation of V(x) and I(x) interms of V_R and I_R are

$$V(x) = (\frac{e^{\gamma X} + e^{-\gamma X}}{2})V_R + zc(\frac{e^{\gamma X} - e^{-\gamma X}}{2})I_R \qquad (3.43)$$

$$I(x) = \frac{1}{ZC}\left(\frac{e^{\gamma X} - e^{-\gamma X}}{2}\right)V_R + zc\left(\frac{e^{\gamma X} + e^{-\gamma X}}{2}\right)I_R \qquad (3.44)$$

These equations are also rewritten as hyperbolic functions interms of receiving end voltage and current as follow

$$V(x) = \cosh(\gamma x)V_R + zc\sinh(\gamma x)I_R \qquad (3.45)$$

$$I(x) = \frac{1}{ZC}\sinh(\gamma x)V_R + \cosh(\gamma x)I_R \qquad (3.46)$$

The voltage and current at any distance from the receiving end of the transmission line the ABCD parameters interms of receiving end voltage and current in the matrix form is given as

At sending end x = l

$$\begin{bmatrix} V_s \\ I_s \end{bmatrix} = \begin{bmatrix} A(x) & B(x) \\ C(x) & D(x) \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix} \qquad (3.47)$$

Then the value of ABCD parameters are

$$A = D = \cosh(\gamma x)pu$$

$$B = zc\sinh(\gamma x)\Omega \qquad (3.48)$$

$$C = \frac{1}{ZC}\sinh(\gamma x)S$$

From this AD-BC = 1

3.10. Transformer Modelling

Transformer are a static device which has magnetic core on which windings are placed. This magnetic core provides the path for alternating magnetic flux. Based on the construction there are two types of transformer 1, shell type transformer and 2, core type transformer.

A. Shell type transformer

In this type of transformer, the windings are put in the central limb of the transformer and we have the flux paths from both the primary and secondary windings of the transformer.

The transformer has two windings from the two windings when we have to energize the primary side of the transformer an alternating current is flowing through the windings and this alternating current setup alternating flux cuts the winding because it is alternating. According to Lenz's law, the alternating flux cuts the winding induces a voltage on the primary and secondary windings of the transformer which is nearly equal to terminal voltages.

B. Core Type Transformer

In this type of transformer, the windings are on the two extreme limbs of the primary and the secondary windings of the transformer. And also a flux path is provided on the core of transformer.

The working principle of this transformer is when the primary winding of the transformer is energized due to the voltage V1 the alternating current is flowing through the winding which sets up an alternating flux in the core.

Now the flux is alternating it cuts the winding produces a voltage on the primary e1 by Lenz's law which opposes the voltage V1 and is very nearly equal to each other and this also appears on the secondary side of the transformer.

There are practical and ideal transformers

C. Ideal Transformer

The transformer core has infinite permeability

a. Zero MMF is required to create magnetic flux on the core that means a negligible current which set up a magnetic flux in the core. If the core reluctance is zero its permeability is infinite.
b. All flux is will be confined on the core

Transformer winding has zero resistance

a. Zero ohmic power loss on the windings
b. Zero voltage drop on the winding

Transformer has zero core losses

Ideal transformer at no load according to lenze's law the voltage induced on the primary and secondary are given equation (3.49) and (3.50) respectively

$$V1 = e1 = N1\frac{d\phi}{dt} \qquad (3.49)$$

$$V2 = e2 = N2\frac{d\phi}{dt} \qquad (3.50)$$

The flux is the time varying flux, assume zero permeability all the flux set up in the primary winding also links the secondary winding.

The transformation ratio is given by the equation

$$\frac{V1}{V2} = \frac{E1}{E2} = \frac{N1}{N2} = a \qquad (3.51)$$

The source is sinusoidal the phasor relationship is given in equation (3.51), rearrange the equation the voltage at the primary winding is given by

$$V1 = \sqrt{2}\left|V1\right|\sin\omega t \qquad (3.52)$$

The time rate of change of flux linkage is given by

$$\frac{d\phi}{dt} = \frac{\sqrt{2}}{N1}\left|V1\right|\sin\omega t \qquad (3.53)$$

The flux linked to the windings of the transformer is given by

$$\phi = \frac{\sqrt{2}}{\omega N1}|V1|\cos\omega t \qquad (3.54)$$

$$\phi = \frac{\sqrt{2}}{\omega N1}|V1|\sin(\omega t - \frac{\pi}{2}) \qquad (3.55)$$

The maximum flux linked to the transformer is

$$\phi_{max} = \frac{\sqrt{2}}{\omega N1}|V1| \qquad (3.57)$$

The ratio of the induced voltage to the number of turn through the primary winding is

$$\frac{|V1|}{N1} = \frac{\omega\phi_{MAX}}{\sqrt{2}} \qquad (3.58)$$

$$\phi_{max} = \frac{2\pi f}{\sqrt{2}} ABmax \qquad (3.59)$$

The simplified equation to calculate the maximum flux linkage interms of maximum flux density and the cross sectional area of the transformer winding is

$$\phi_{max} = 4.44AB_{max} \qquad (3.60)$$

Thyristor controlled series capacitor analysis for the modelled power system

Table 3.1: Parameters of transmission line sequence

Description	Values
Zero sequence resistance	0.033626 pu
Zero sequence reactance	0.09511 pu
Zero sequence conductance	0.78563 pu
Positive sequence resistance	0.26 pu
Positive sequence reactance	0.22 pu
Positive sequence conductance	1.11 pu
Negative sequence resistance	0.0125 pu
Negative sequence reactance	0.2 pu
Negative sequence conductance	1.11 pu

The sequence impedance of the Gilgel gibe-sebeta 2 transmission line is evaluated. Since the system has identical parameters and its total overhead length is 183.5km, the overall positive reactance of the line is determined below.

R1= 0.033626*183.5 = 6.170371Ω

Xl1=0.09511*183.5 = 17.452685Ω

The inductance is calculated as

Xl1= 2πfL

L1= Xl1/2πf=17.452685/314 = 0.0556H

B1=0.78563*183.5 = 144.163105Ω^{-1}

TCSC Design for Gilgel Gibe II to Sebeta II Line

The TCSC important and advantageous compared to the other series compensating FACTS devices is that its reactance value can be instantaneously and clearly controlled. TCSC is used in power systems to control the reactance of a transmission line to provide sufficient load compensation to the system.

The important or advantages of the TCSC FACT device are observed in its ability to control the amount of compensation of a transmission line and in its ability to operate in different modes that mean in capacitive mode and inductive mode. These phenomena are very desirable since loads are constantly changing and cannot always be predicted. TCSC FACT device design is the same as other series FACTS devices like FSC, and it provides variable control of the reactance value absorbed by the capacitor device in the device.

The TCSC offers advantages over other conventional fixed series compensation such as usable for dynamic load-flow control, Power Oscillation Damping, a Higher degree of compensation, and Better capacitor protection due to thyristors.

The basic concept behind the TCSC FACTS device scheme is to provide a continuously variable capacitor value by means of partially canceling the effective compensating capacitance by the thyristor controlled reactor (TCR).

The thyristor controlled reactor (TCR) with the fundamental system frequency is continuously variable reactive impedance value, controllable by delay angle α. The steady-state reactive impedance of the TCSC FACT device is that of a parallel LC circuit, consisting of a fixed capacitive impedance XC. Therefore, using the firing angle, TCSC is able to control the variable impedance.

Total line reactance in positive-sequence:

$Xl = 2*pi*f*l$ *length of line, (inductive reactance)

X1 = 0.9337e-3*(2*pi*50) *183.5 = 53.67988 ohms

Capacitance required for 50% compensation:

Required series capacitance:

Xc=0.5*53.67988 = 26.8399 ohms or Cs= 115.39 μF

MOV protection level required to protect the capacitors at 2.5 times the nominal capacitor voltage. (The nominal capacitor voltage is taken at 2 kA rms line current)

Uprot. = 2.5*2kA*26.889*sqrt (2) = 190.134 kV

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1. Modelling of Power Flow Study of the Three Bus System of Gilgel gibe-II to Sebeta-II Transmission Line

The power system network has three buses with 400kv bus 1 on the switchyard of the generation station, the other 400kv bus bar, and 230kv bus bar on the sebeta-II substation. All three buses have input voltage sources coming from the Gilgel gibe two-generation station. Now the overall system buses modeling is given on the following modeling diagram. From the power flow model, I have to determine the voltage on each buses with phase angle and the active and reactive power flow through the power system and also determine the power loss on the system.

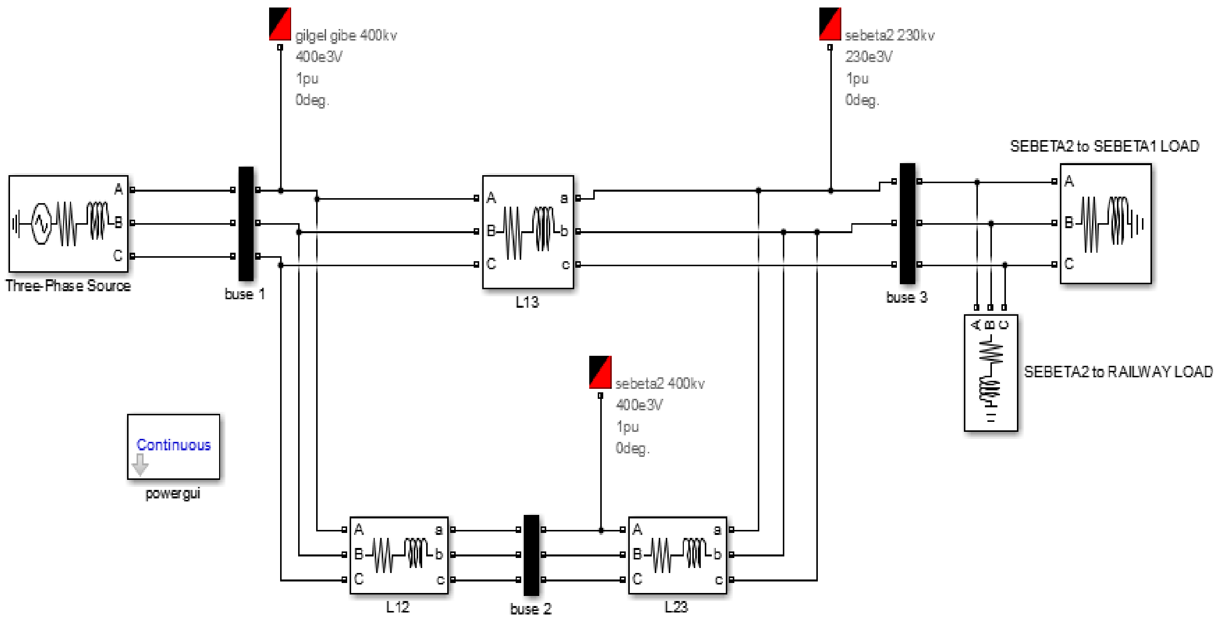


Figure 4.1: Load flow model of the three bus system of Gilgel gibe 2 to sebeta 2 line

Table 4.1: Generalized power flow result of the three bus power system

Frequency(Hz) = 50 base power(MVA) = 100 Max. iteration = 50 PQ tolerance(pu) = 0.0001				
	1	2	3	4
Bus type	Swing	PV	PQ	PQ
Bus id	Gilgel gibe2 400kV	Sebeta2 400kV	Sebeta2 230kV	Sebeta2 230Kv
Vbase(kV)	400	400	230	230
Vref(pu)	0.8097	0.9967	0.9869	0.9869
Vangle(deg)	-40.75	-40.75	54.84	54.84
P(MW)	0	0	16.97	71.58
Q(Mvar)	0	0	8.49	35.83
V_LF (pu)	0.8097	0.8096	1.4081	1.4081
Vangle LF(deg)	-40.75	-40.75	-40.75	-40.75
P_LF(MW)	417.89	0.00	16.97	71.58
Q_LF(Mvar)	44.38	0.00	8.49	35.83

The simulation result indicates that the load flow across each bus means the voltage magnitude, phase angle, active power flow, and reactive power flow of the three buses of the network.

The Load Flow converged in 5 iterations!

SUMMARY for each subnetwork

Table 4.2: The overall power flow analysis result of the three buses of the power system

Parameter	Active power (MW)	Reactive power(Mvar)
Total generation	417.89	44.38
Total PQ load	250.47	28.67
Total Zshunt load	167.39	0.17
Total losses	0.18	0.18
BUS1 Gilgel gibe 400kV V= 0.810pu/400kV -40.75 deg swing bus		
Generation	417.89	44.38
PQ load	0.00	0.00
Z_shunt	-0.16	-0.01
Sebeta 2 230kv	160.73	-16.07
Sebeta 2 400kv	257.22	60.47
BUS2 sebeta 2 400kV V= 0.810pu/400kV -40.75 deg		
Generation	0.00	0.00

PQ_load	0.00	-0.00
Z_shunt	192.78	107.84
Gilgel gibe 400kv	-257.21	-60.45
Sebeta2 230kv	-83.58	-47.40
BUS3 sebeta2 230kV V= 1.408pu/230kV -40.75 deg		
Generation	0.00	0.00
PQ_load	250.47	28.67
Z_shunt	-25.23	-107.80
Gilgel gibe 400kV	-160.73	16.08
Sebeta2 400kV	83.61	47.41

From the power, flow results in table 4.2 with the total generation power of 417.89MW the two loads sebeta-I and railway uses about 250.47MW, the shunt impedance connected to the system transmit to the grid about 167.39MW and, from the generated power about 0.18MW is lost. At bus B1 the bus is a swing bus the magnitude and phase angle of the voltage is the same so the PQ load is zero and at the bus, B2 is PV bus is connected to a generator and the voltage is kept constant by adjusting the field current on the synchronous generator.

The voltage in bus B1 and bus B2 is almost equal in magnitude and phase angle V= 0.810pu at an angle of -40.75 but in the load side on the power system that means on bus three (B3) the voltage magnitude is increased to the maximum value or over voltage in per unit value of V= 1.408pu at an angle of -40.75 deg so it needs to control the magnitude and this causes increasing of the reactive power. If the reactive power increase the power loss is also increased. Reactive power control is an important task that is done frequently within the transmission system. The system voltage is dependent on the reactive power provision within the system. Hence in order to ensure system voltage stability, there should be an effective control mechanism of reactive power. The reactive power control can also be used to damp out system power oscillations that arise following disturbances. To control the reactive power, I have to use series compensation. This series compensation reduces the magnitude of the line reactance within some specified compensation percentage. In this thesis, the series compensator is 50% of the line reactance it has also a metal oxide varistor (MOV) for the protection of the series capacitor on the compensating device. The overall modeling diagram with all components of the system with and without series compensation and its output result is shown in Figures 4.2 and 4.12.

Table 4.3: The voltage magnitude and phase angle with and without series compensator TCSC

Bus No	Voltage without TCSC		Voltage with TCSC	
	Magnitude in pu	Phase angle in degree	Magnitude in pu	Phase angle in degree
1	0.810	-40.75	0.820 pu	34.73
2	0.810	-40.75	0.825 pu	35.75
3	1.408	-40.75	0.710 pu	6.62

From the above table without a series compensator, the voltage through bus 3 is higher than the other two buses but the transmitting voltage at bus 1 and 2 are higher than bus 3. To transfer a small load through a long transmission line, the transmission line sending the end side must be higher than the receiving end side. By increasing the voltage on the transmission line the power loss through the transmission line is low.

4.2. Power Flow Solution by Newton-Raphson iteration method

Power Flow Solution by Newton-Raphson Method

Maximum Power Mismatch = 9.76038e-08

No. of Iterations = 4

Table 4.4: Power flow out put result for the three bus buses by using MATLAB code script

Bus No	Voltage mag.	angle	Load		Generation		Injected
	Pu	degree	MW	Mvar	MW	Mvar	Mvar
1	1.050	0.000	0.000	0.000	89.838	-258.032	0.000
2	1.080	-1.369	71.575	-35.830	0.000	0.000	0.000
3	1.065	-0.871	16.972	8.486	0.000	0.000	0.000
Total			88.548	-27.344	89.838	-258.032	0.000

This result indicates the amount of power generated and loaded and the voltage magnitude and phase angle of the three system buses. Bus one is the bus that is connected to the generation station which receives 89.838MW power from the one unit of the generation station. The other two buses are load buses which are found in the receiving end of the power system networks.

Table 4.5: Power flow out put result for each line and the total loss on the network by using MATLAB code script

Line		Power at bus and line flow			Line loss		Transformer
From	To	MW	Mvar	MVA	MW	Mvar	Tap
1	1	89.838	-258.032	273.224			
	2	65.186	-202.187	212.436	0.305	-232.832	
	3	24.652	-55.845	61.044	0.507	1.183	
2	2	-71.575	35.830	80.043			
	1	-64.881	-30.645	71.754	0.305	-232.832	
	3	-6.694	66.474	66.811	0.478	0.961	
3	3	-16.972	-8.486	18.975			
	1	-24.145	57.028	61.928	0.507	1.183	
	2	7.172	-65.514	65.905	0.478	0.961	
Total loss					1.290	-230.688	

From this result, the line flow and the line loss are identified by the newton Raphson iteration method. Now the line loss from bus 1to bus 3 is 0.507MW, bus 1 to bus 2 is 0.305MW, and bus 2 to bus 3 is 0.478MW. The total loss of the power system for all buses is about 1.290MW. The series compensator is installed between bus 2 to bus 3 because it has a large line loss due to the load is connected to bus 3 and the length of the line is long, this needs compensation of the line. So the series compensating FACTS device (TCSC) is connected and located at the third bus B3 of the transmission line.

4.3. Modelling the Power System with Real System Simulation Data of the Case Study Area.

From this simulation system, I have to consider if the system is a stable operating state that means without any fault on the system what looks like the output voltage, current on bus 1 and bus 2, and the overall fault current on the system. After that, I have to consider the fault on the system that appears on the system most of the interruption period.

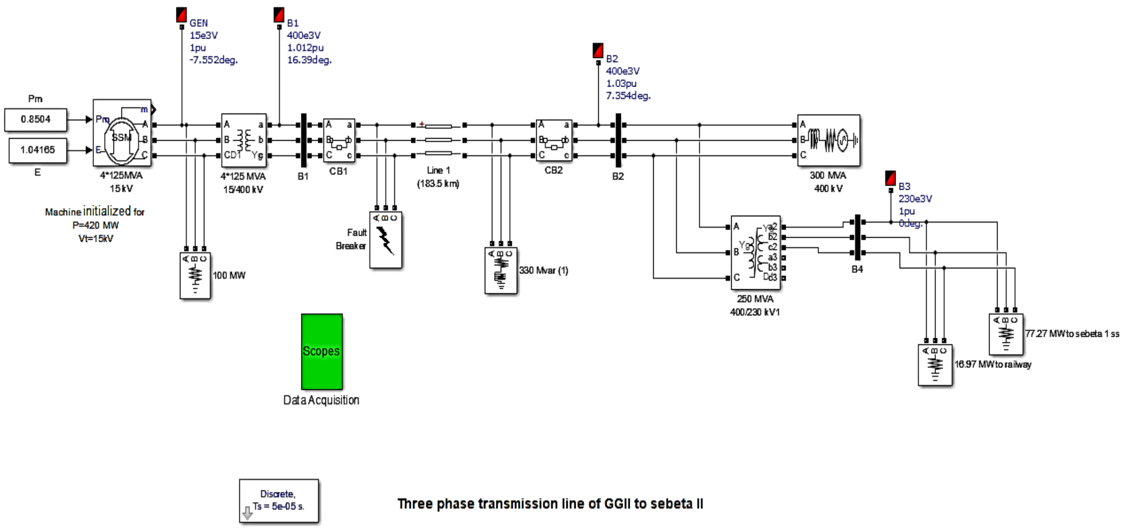


Figure 4.2: The real system simulation modeling diagram of Gilgel gibe2-sebeta 2 line

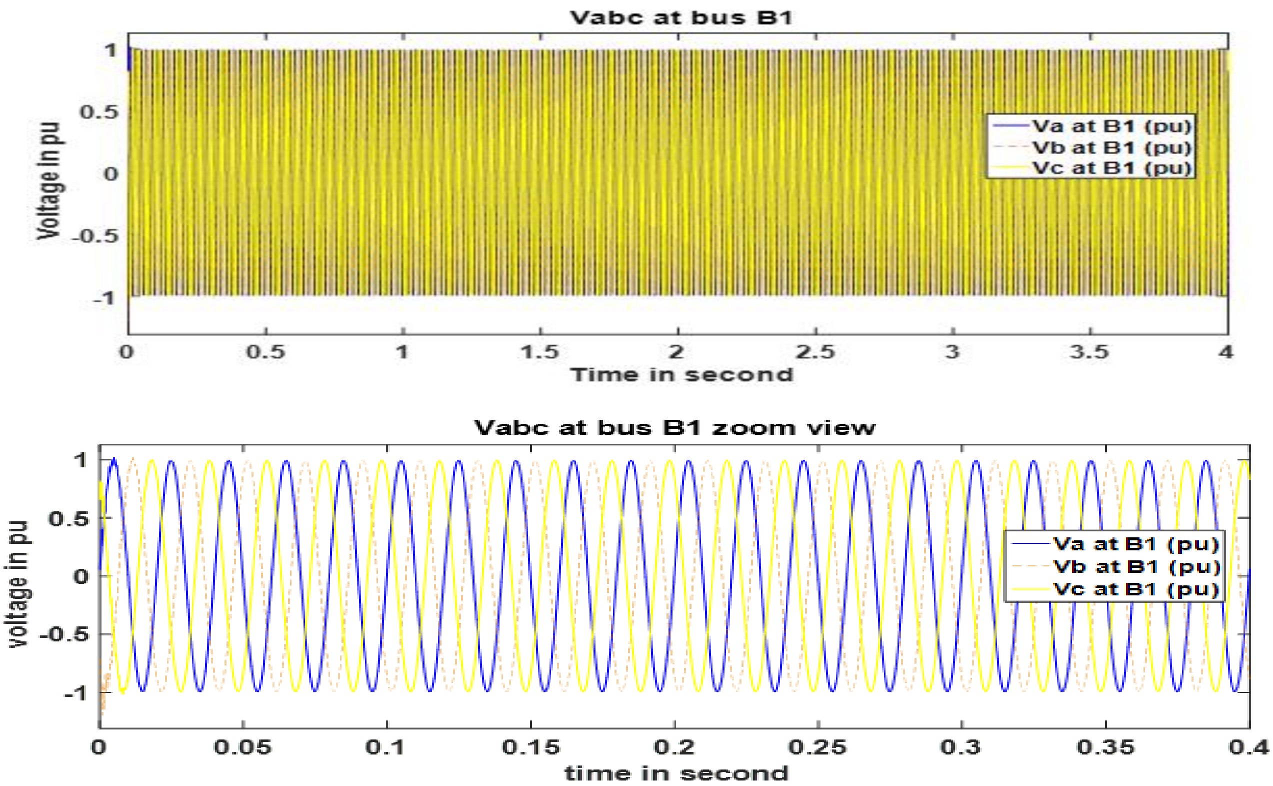


Figure 4.3: The wave form of voltage on bus B1 voltage in pu versus time in second wave graph

The amplitude of the voltage on the three phases is running in the sinusoidal waveform. The magnitude is free from any disturbances which slow down the voltage on the power system.

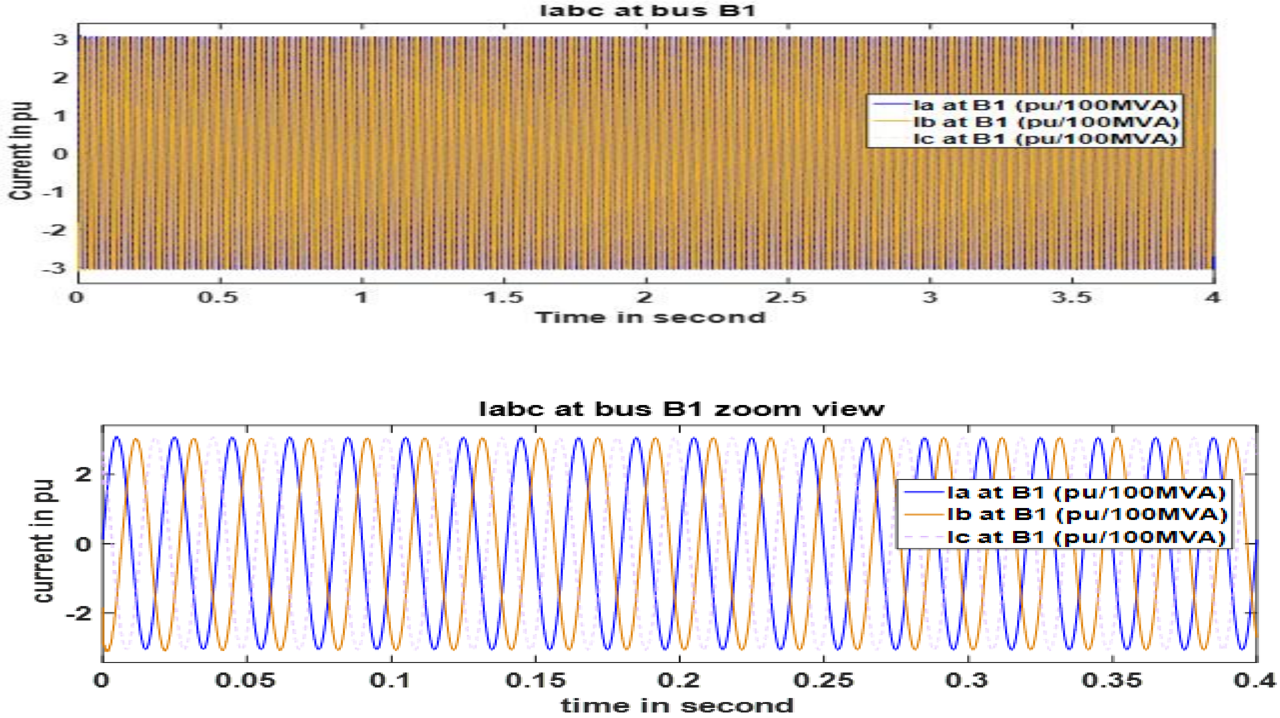


Figure 4.4: The wave form of current on bus B1 in pu versus time in second wave graph

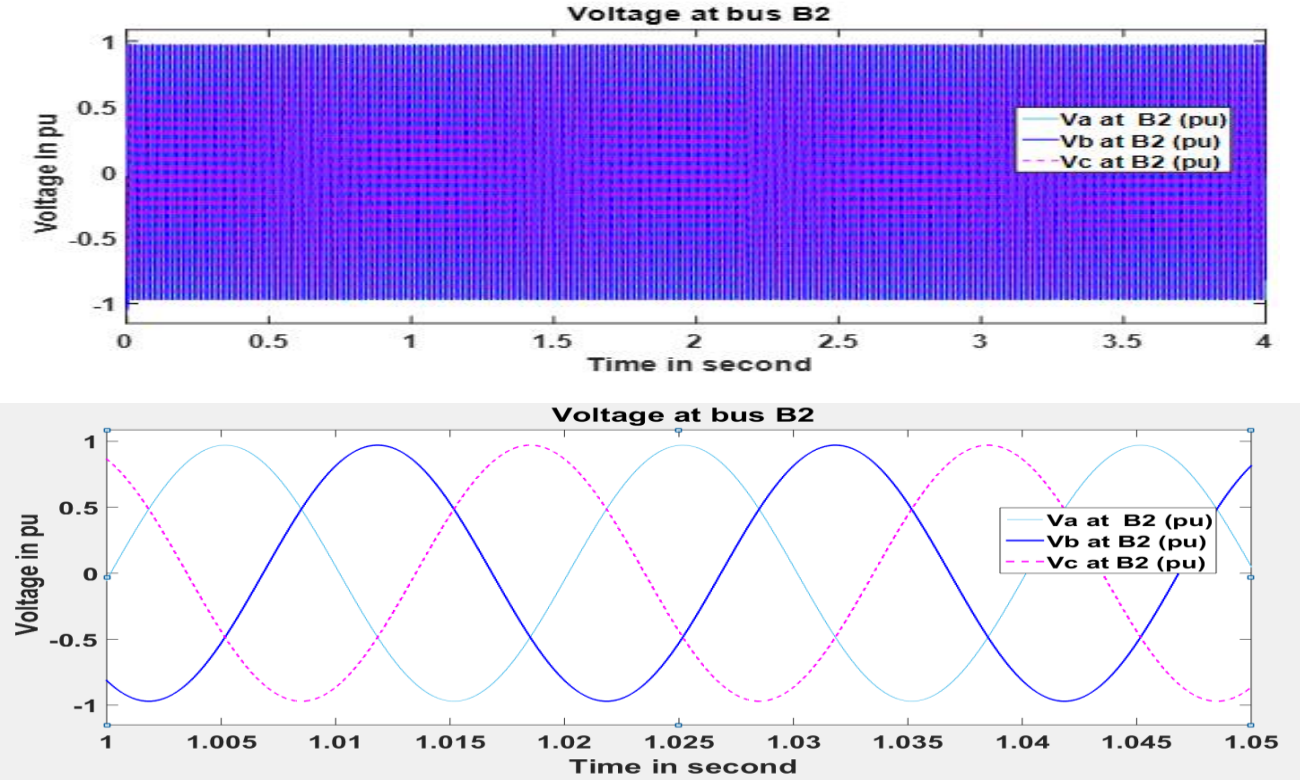


Figure 4.5: The wave form of voltage on bus B2 in pu versus time in second wave graph

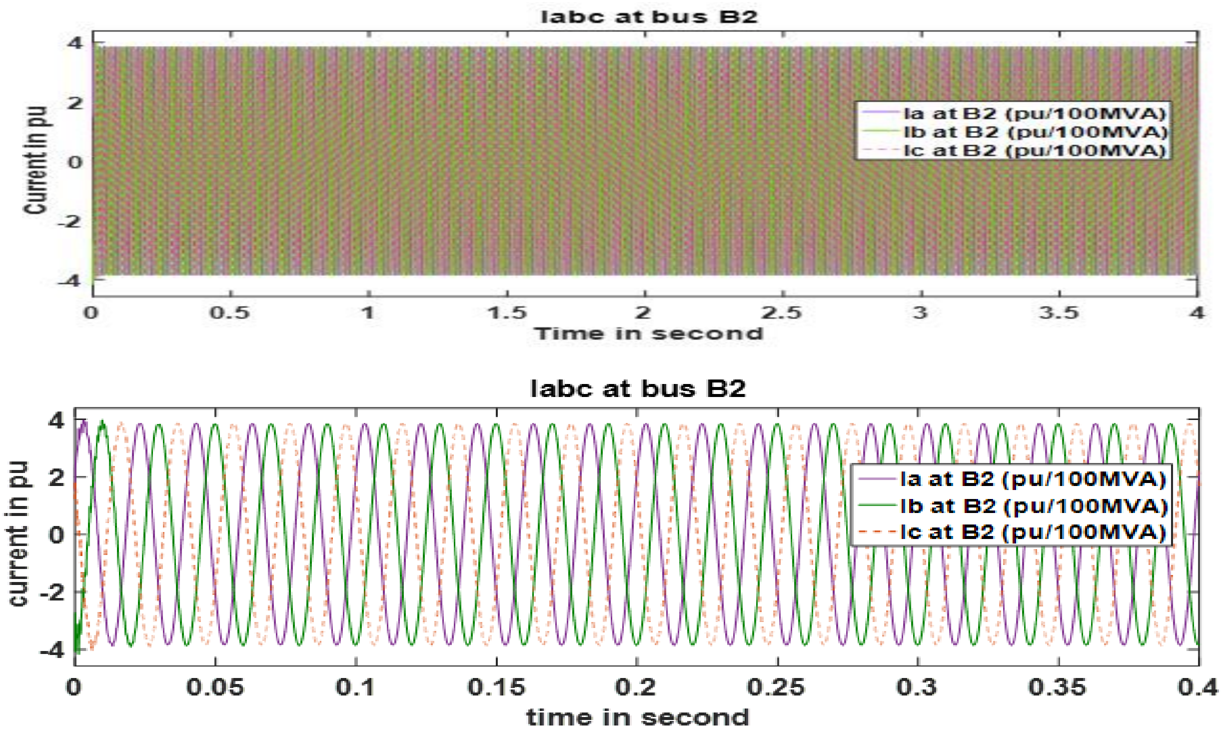


Figure 4.6: The wave form of current on bus B2 in pu/MVA versus time in second

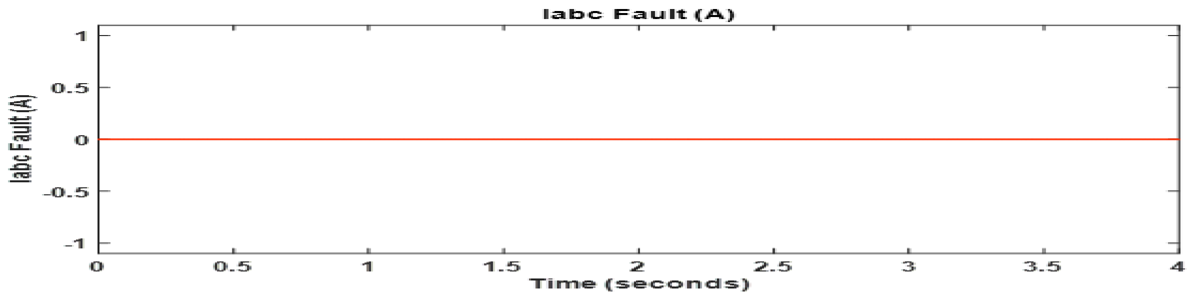
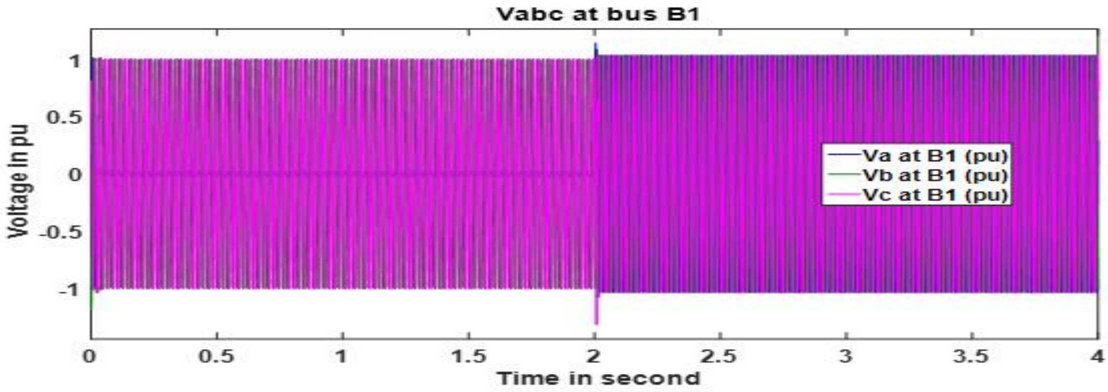


Figure 4.7: The wave form of fault current on the transmission line in ampere

From the above simulation result, the characteristics of the three phase load are purely resistive so the magnitude of voltage and current on each phase of the power system is in phase with each other, which mean the magnitude of phase current and phase voltage are equal in bus one and bus two. And also the nature of the wave for the three phases are sinusoidal at bus B1 and B2 as shown in figure 4.3, 4.4, 4.5 and, 4.6. The fault current is zero on the real system simulation network as shown in figure 4.7 above. All the values in the graph are in per unit (PU) values because in the power GUI block of the modeling diagram the input values to the synchronous machine of mechanical power (Pm) and excitation voltage (E) used to drive the machine are converted into per unit value during the machine initialization. This explanation is valid for the diagram with and without series compensation.



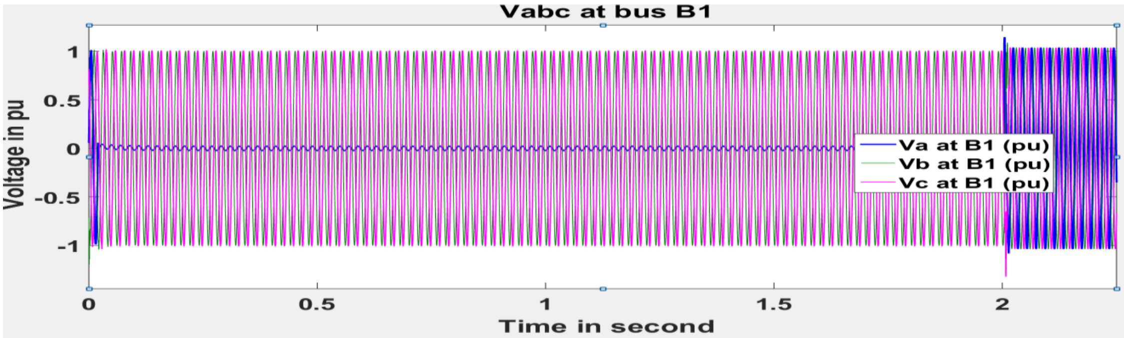


Figure 4.8: The wave form of voltage on bus B1 in pu with L-G fault versus time in second

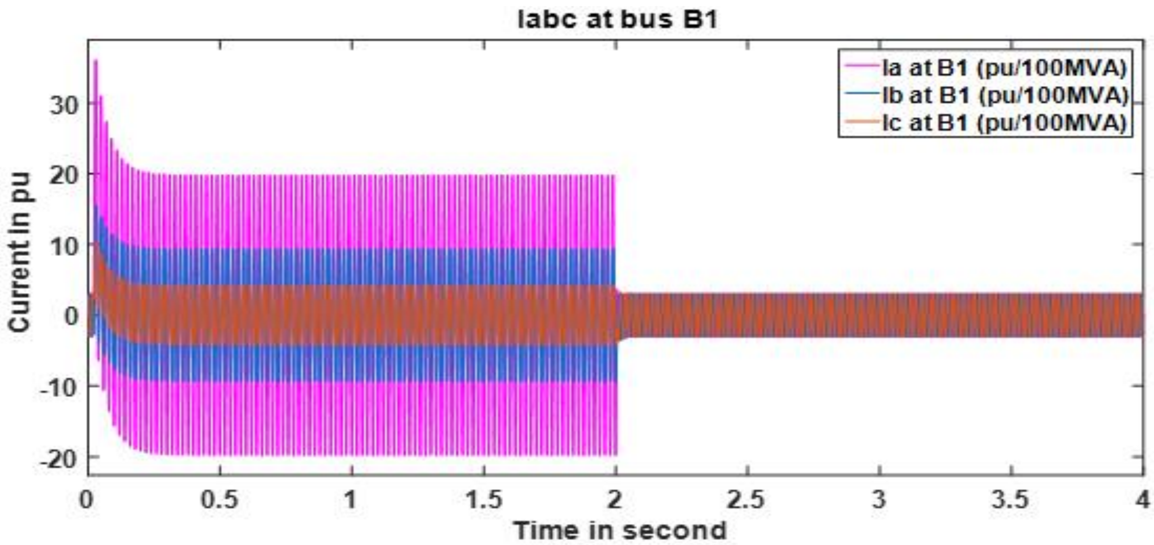


Figure 4.9: The wave form of current on B1 in pu with L-G fault versus time in second.

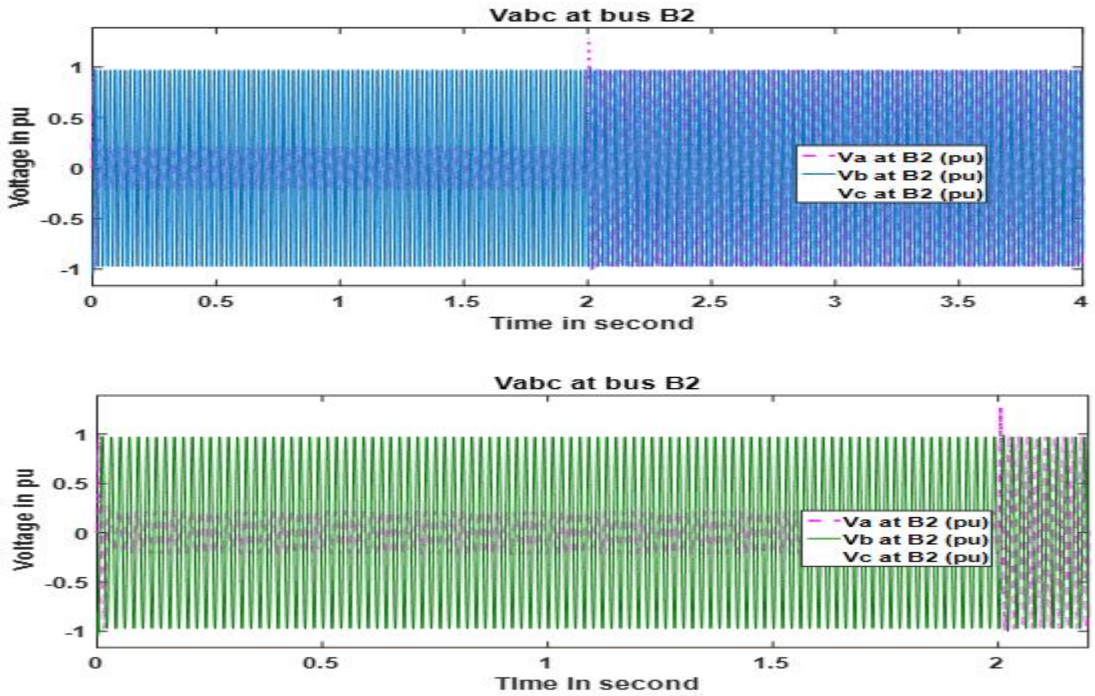


Figure 4.10: The wave form of voltage on bus B2 in pu with L-G fault versus time in second

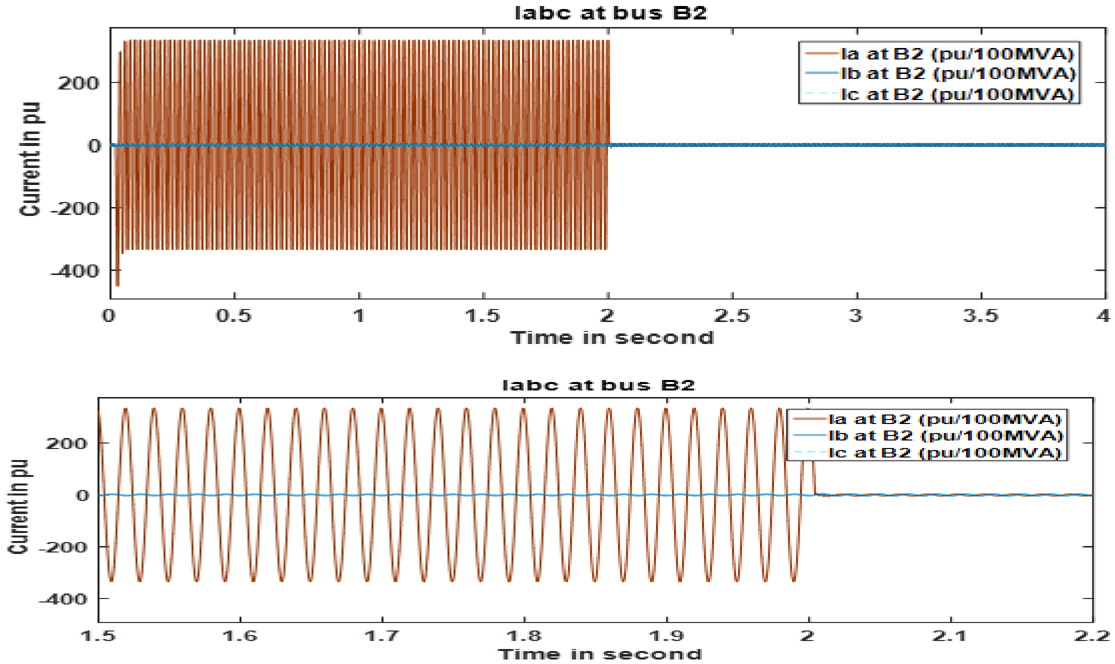


Figure 4.11: The wave form of current on bus B2 in pu/MVA with L-G fault vs time in second.

When a fault or overload occurs on the transmission line the large current will flow across the line the sinusoidal oscillation waveform is disturbed and loses its synchronism due to the fault on the power system. As shown in Figures 4.8 and 4.9 the magnitude of voltage and current peak amplitude during the occurring of the fault reaches 1.315 PU and 46.66 PU per 100MVA on the faulted line at bus B1 respectively Thus the excessive voltage drop occurs on the transmission line. The same is true for the values change on bus B2.

The fault on the transmission line causes abnormal voltage conditions, spark gaps and, power loss on the transmission line. The aim of modeling the real system simulation model is to compare the normal and faulted conditions of the power system.

The above simulation is done for the power system with real system simulation and by applying fault to the real system than to improve such abnormal conditions and to improve the transient stability of the power system it is simulated with series compensator FACTS device (TCSC) on the next modeling diagram.

4.4. Modelled Block Diagram for Transient Stability Study and its Enhancement Using Series Compensated System.

From the power flow study on the above modeling diagram figure 4.1, the voltage through bus three is high which means over-voltage produces a high amount of reactive power on the bus it causes a high amount of power loss on the system. To control the overvoltage, increase the power transfer capacity of the system, and improve the transient stability of the power system, I have to model the power system with series compensating FACTS device as shown on the modeling diagram in figure 4.12 below.

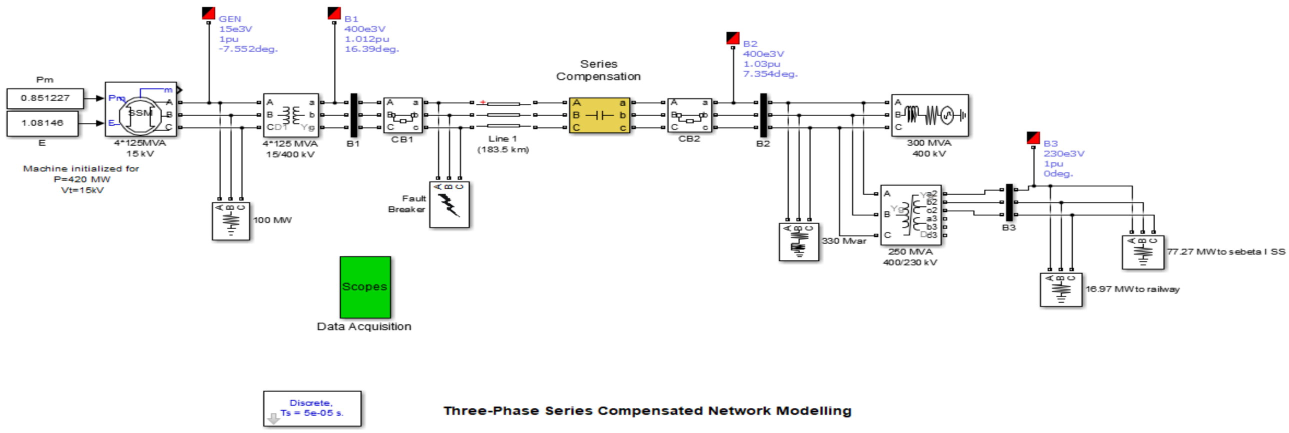


Figure 4.12: Modelling of the power system network with series compensation in the middle of line.

To increase the transmission line capacity, the line is series compensated by capacitor representing 50 percent of the transmission line reactance.

The line is also shunt compensated by 330 Mvar shunt reactance which is used to minimize voltage drop through the line and increase the transmission power transfer capacity. Each series compensation bank is protected by a metal-oxide varistor (MOV).

The two circuit breakers of the line are shown as CB1 and CB2 they are initially closed and during the faulty condition, both circuit breakers are returned to normally open conditions to protect the fault on the power system. The fault is applied online on the line side of the capacitor bank. Open the dialog boxes of the Three-Phase Fault block and the Three-Phase Breaker blocks CB1 and CB2. See how the initial breaker status and switching times are specified. A line-to-ground fault is applied on phase A at t = 20 cycles. The two circuit breakers that are initially closed are then open at t = 60cycles, simulating a fault detection and opening time of 40 cycles.

The fault is eliminated at t = 62.5cycles, 2.5cycle after the line opening.

Before studying the transient stability of the power system modeled on the above first I have to study the power flow analysis of the system. To study the power flow on this modeling the machine initialization must be set up. The machine initialization needs the input parameters active generated power and the machine terminal voltage must be set up. The value of the active power is a total of 420MW and the generated terminal voltage of 15KV. After setting this value I have to get the input mechanical power used to drive the machine and the required excitation voltage in PU is given as follows.

Pm = 0.851227 PU

E = 1.08146 PU

These parameters are connected to the input of the machine and inside the dialog box of the machine, the value of initial speed deviation, internal angle theta, current magnitude, and phase angle are automatically transferred to the line. Once the power flow is set up the measurements of current and voltage at each bus can be obtained.

The phasor for phase A voltage at buses B1, B2 and the current entering the transmission line through B1 and B2 are as follow

'VA/B1 = 304771.88 V -2.84°, 'VB/B1= 304771.88 V -122.84°, 'VC/B1= 304771.88 V 117.16°, 'VA/B2= 291980.33 V -1.45°, 'VB/B2= 291980.33 V -121.45°, 'VC/B2= 291980.33 V 118.55°, 'V/capacitor Phase A/VCsa ' = 110090.34 V -15.77°, 'V/capacitor Phase B/VCsb' = 110090.34 V -135.77°, 'V/capacitor Phase C/VCsa' = 110090.34 V 104.23°, 'I A/B1= 2787.76 A 77.18°, 'I B/B1= 2787.76 A -42.82°, 'I C/B1= 2787.76 A -162.82°, 'I A/B2= 2426.79 A 75.45°, 'I B/B2= 2426.79 A -44.55°, 'I C/B2 = 2426.79 A -164.5°

The load flow is for this modelled diagram is shown in table 4.6.

The Load Flow converged in 6 iterations!

Table 4.6: Summary for networks of the line by applying faults to the system

Parameter	Active power (MW)	Reactive power (Mvar)
Total generation	611.36	543.46
Total PQ load	0.00	0.00
Total Z_shunt load	595.10	225.44
Total losses	16.26	318.01
1. B1 V=0.820 pu/400kV 34.73 deg		
Generation	0.00	0.00
PQ load	0.00	0.00
Z_shunt load	0.34	0.34
1	284.37	3388.63
GEN	200.08	3387.26
2. B2 V= 0.825 pu/400kV 35.75 deg swing bus		
Generation	0.00	0.00
Z_shunt load	1.64	341.40
2	212.50	19.77
3	-256.50	4080.47
6	0.52	2.40
3. GEN V = 1.00pu/15kv -24.69 deg		
Generation	420.00	2032.02
PQ_load	0.00	0.00
Z_shunt load	100.50	0.50
B1	319.50	2032.52
4. B3 V= 0.710 pu/230kV 6.62 deg		
Generation	0.00	0.00
PQ_load	-0.00	-0.00
Z_shunt load	212.31	-0.01
6	-0.76	-2.30
B2	-211.55	2.32
5. *3* V=1.706pu/400kv 0.19 deg		
Generation	0.00	0.00
PQ_load	-0.00	0.00
Z_shunt load	3.84	960.58
4	-230.38	3119.89
B2	226.54	4080.47
B2	-11.84	2294.68
B3	11.84	-2294.68

To study the transient stability of the system applying the line to a ground fault to the transmission line at bus B2 through the fault breaker connected to the line. To speed up the simulation time the power GUI block has been in discrete mode and setting the simulation time 4 sec settling time. From the power flow model in figure 4.1, the per-unit value of the voltage on the high voltage side buses is low but on the low voltage, side is highly increased the per-unit value of the power flow. As explained above to control the highly increased voltage and the reactive power of the power system I have to use the series compensating FACTS device. Due to the series compensating device the voltage on the 230KV side is controlled to V= 0.710 PU/230kV 6.62 deg from V= 1.408pu/230kv -40.75 deg.

From these results, the reactive power is controlled and active power transfer capacity is increased and the power loss is compensated by the series capacitor. Because of the line to ground fault applied on the modeled transmission line network, the loss is high compared to the normal simulation without a series compensation device that means about 16.6MW but the total generation power is about 611.36MW is above the maximum designed power of 420MW. The increased generation power is because of the use of series compensating FACTS device. From the series compensating facts device thyristor controlled series capacitor (TCSC) is used in this thesis work. The thyristor is used to triggering of the firing angle to control the value of reference impedance on the power system model. Now the waveforms of the power system output are given in below.

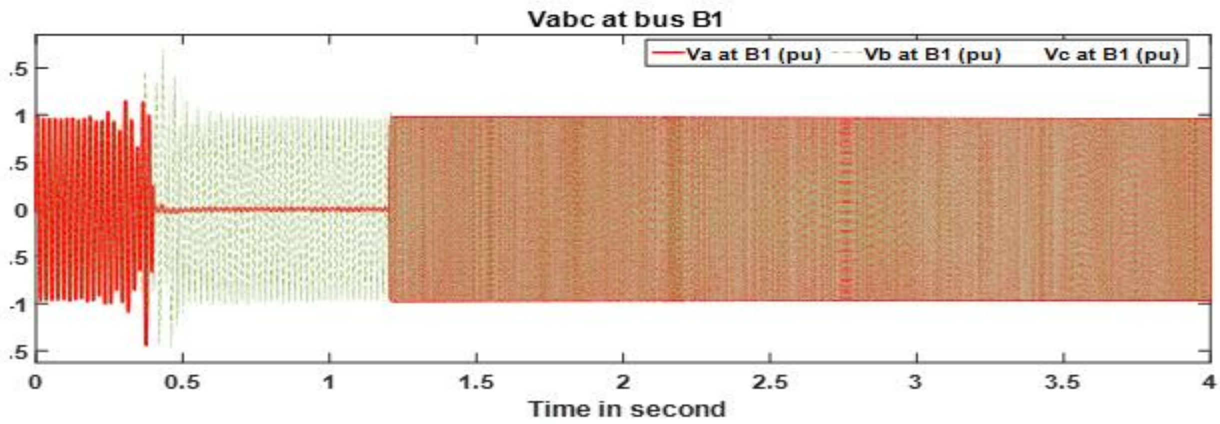


Figure 4.13: The output voltage wave form in PU at B1 versus time in second

From the graph the line to ground fault applies at 20cycle causes the sudden disturbance on the power system network this is a big problem faced to the system, and during occurring of fault the magnitude of the voltage at phase A fails to zero value from the time 0.4 second to 1.25 second and also during the fault on phase A, the magnitude of both phase B and phase C fluctuated and disturbed as shown on the output graph of figure 4.13 above this interruption on the power system losses its steady-state operation. The time that the fault occurs is at 0.4 second or 20cycle of the system frequency and the faults stay for the time about 0.85second then clear at the time 1.25second and the system maintain stable state because of the series compensator installed on the model. When the system voltage shoots to the maximum peak amplitude above the steady-state limit this causes a sudden disturbance on the power system and the fault current also increases to the maximum limit as shown in figure 4.17. At the occurrence of fault after a few-cycle, the voltage amplitude of the faulted line decreases in magnitude and falls to zero compared to the other phases. The circuit breakers on the power system initially are closed and after 60cycles they open to protect the fault on the line. The circuit breaker opens after 2.5cycle the fault is clear. During the opening of the circuit breaker, the current is falls to zero because at the open circuit network the current is blocked and only voltage is passed through the power system network due to electric field strength as shown in figure 4.14 below.

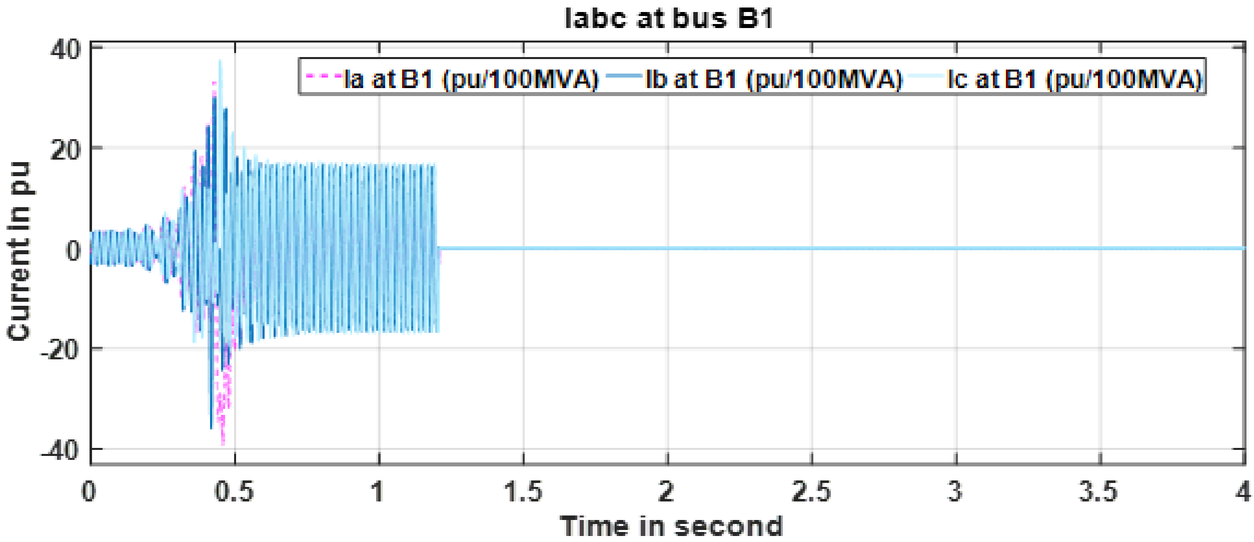


Figure 4.14: The output current wave form in PU at B1 versus time in second

From the result, I have analyzed that due to the line to ground unsymmetrical fault applied to the transmission line on phase A with the problem or interruption on the line at the length of around 95km, and the simulation starts at 20 cycle the magnitude of the voltage on phase A decreases, the two circuit breaker initially closed and open in 60 cycle the fault is cleared at 62 cycle or 1.25sec. The opening of the circuit breaker was applied after 2.5cycle. The fault current also exceeds to above 63KA as shown in figure 4.17 and the energy transferred dissipated in the metal oxide varistor to protect the capacitor in the series compensator is reached about 30MJ of maximum energy as shown in figure 4.20.

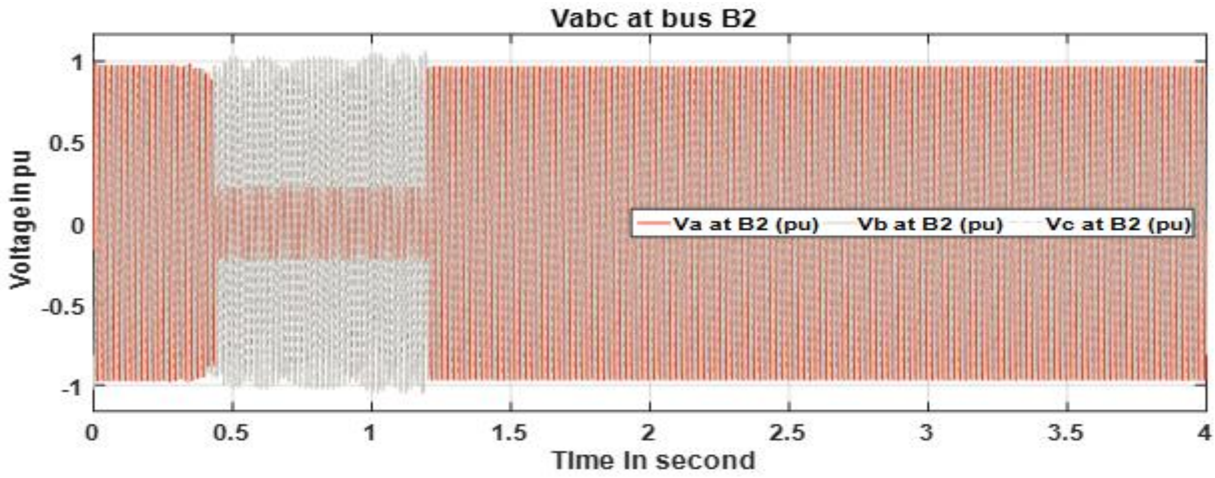


Figure 4.15: The output voltage wave form in PU at B2 versus time in second

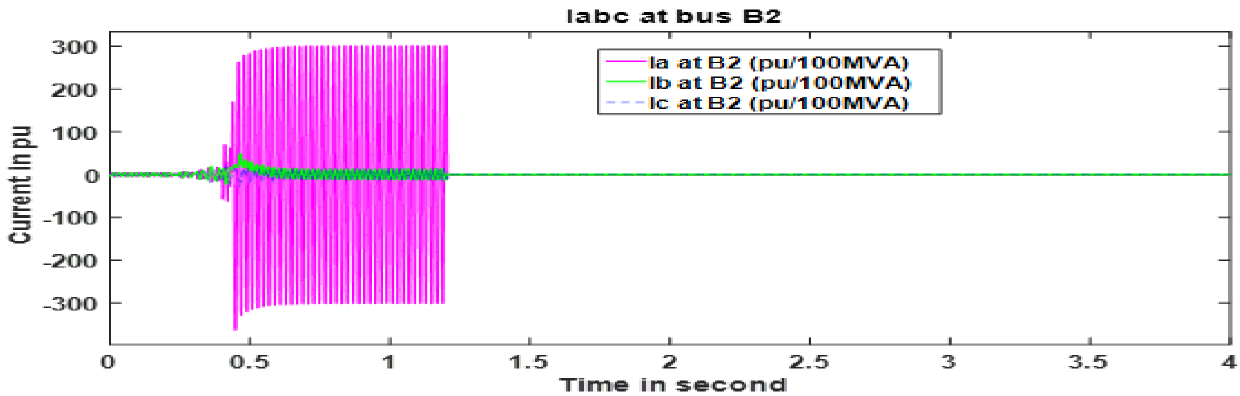


Figure 4.16: The output current wave form in PU at B2 versus time in second

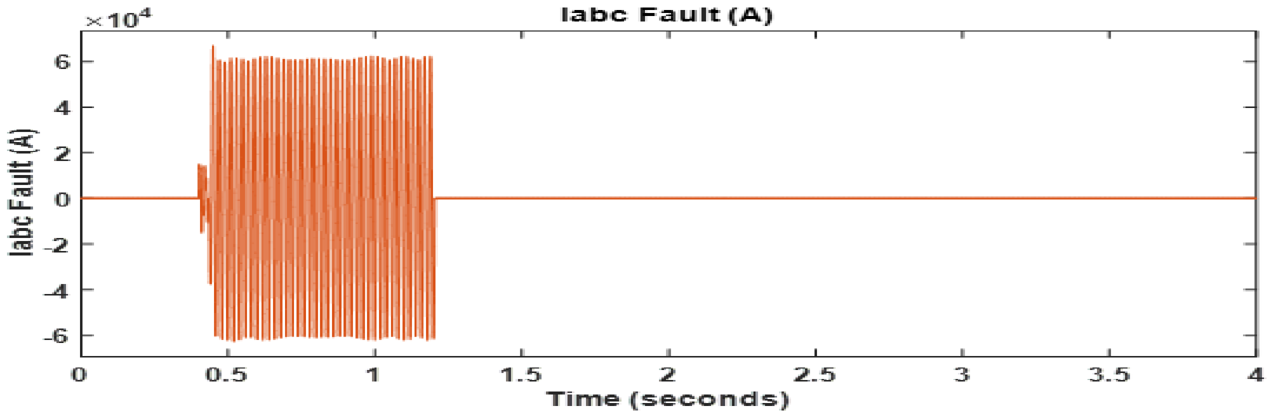


Figure 4.17: The output three phase fault current wave form

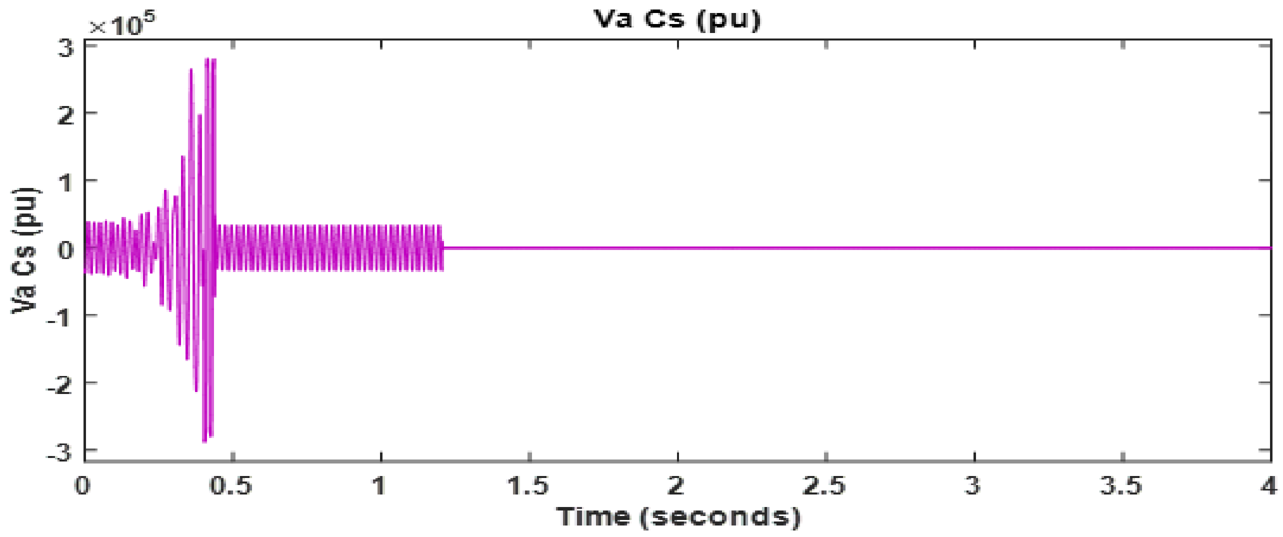


Figure 4.18: The output wave form of voltage through capacitor in pu

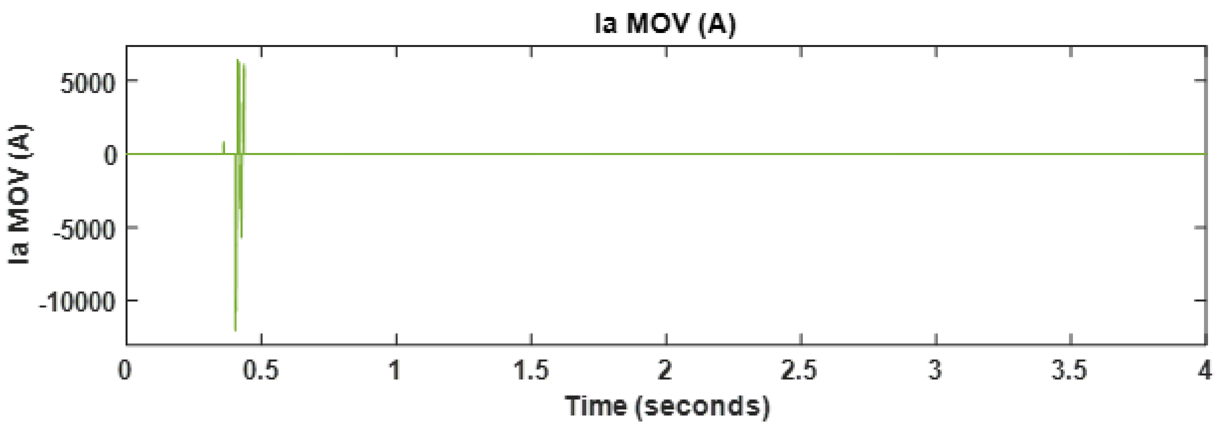


Figure 4.19: The output wave form of current in MOV in ampere

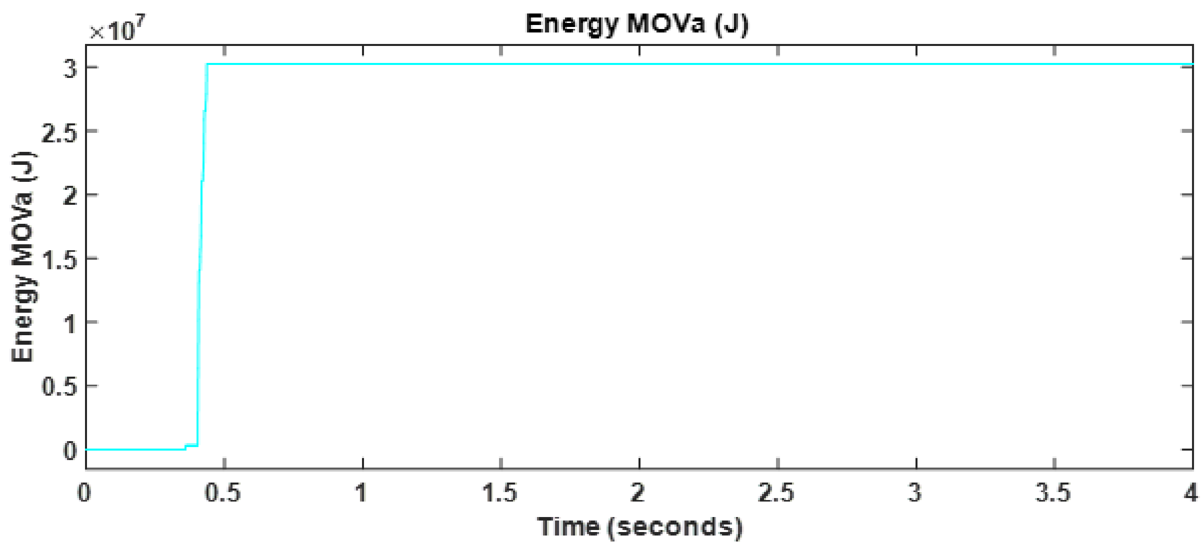


Figure 4.20: The output wave form of energy in the MOV in joule

The transmission line is 50% series compensated by a 115.39 µF capacitor. The capacitor is protected by the MOV block. If we open the dialog box of the MOV block, notice that it consists of 60 columns and that its protection level (specified at a reference current of 500 A/column or 2KA total) is set at 190.134 kV. This voltage corresponds to 2.5 times the nominal capacitor voltage obtained at a nominal current of 2 kA RMS. A gap is also connected in parallel with the MOV block. The gap is fired when the energy absorbed by the surge arrester exceeds a critical value of 30 MJ as shown on the output graph in figure 4.20 above. To limit the rate of rise of capacitor current when the gap is fired, a damping RL circuit is connected in series. Open the Energy & Gap firing subsystem.

It shows how you calculate the energy dissipated in the MOV by integrating the power (product of the MOV voltage and current). When the energy exceeds the 30 MJ threshold, a closing order is sent to the Breaker block simulating the gap.

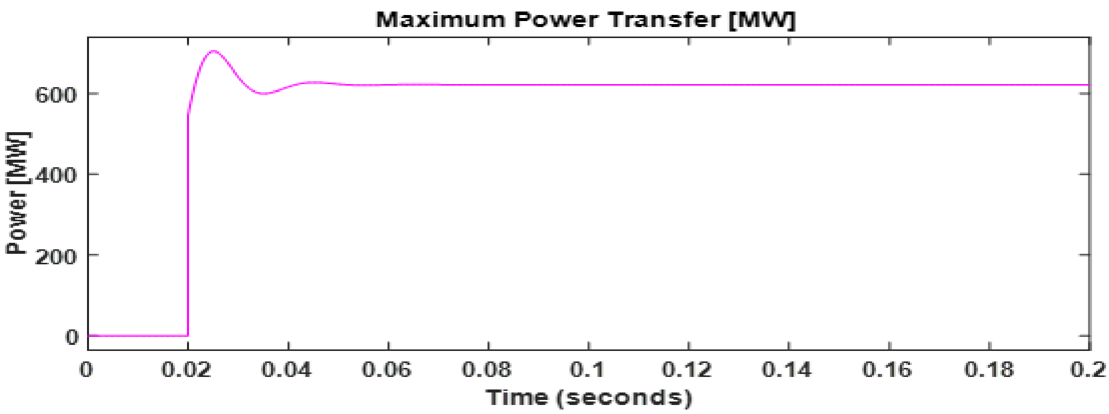


Figure 4.21: The output wave form of the maximum power transfer with TCSC

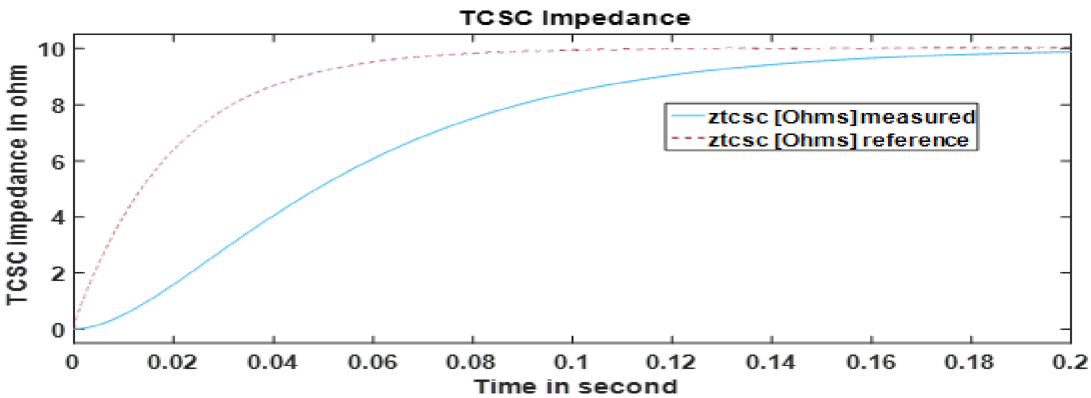


Figure 4.22: The output wave form of TCSC measured and reference impedance

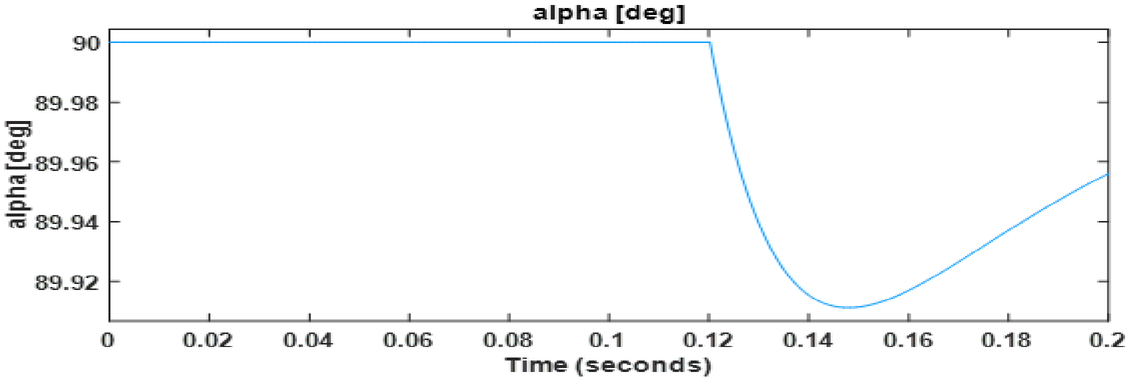


Figure 4.23: The output wave of the firing phase angle of TCSC

From the result in figure 4.21 with the TCSC FACTS device the power transfer capacity of the power system is increase to the maximum value of 610MW with the firing angle of 90 degrees and increasing the TCSC impedance so the installation of the device on the power system grid network is advantageous and it saves power, cost, and minimize power loss on the system. This condition is characterized by the transfer of stable, reliable, and enough power to the customer.

CHAPTER FIVE

CONCLUSIONS and RECOMMENDATIONS

5.1.Conclusion

In this thesis, the transient performance of the transmission line is discussed and improved. For analyzing the transient stability condition of the system the simulation was performed by subjecting the system to a different source of transients. Depending upon the result of the simulation the case which creates high transient disturbances are identified as switching of load, lightening, and fault-like line to ground (L-G) at the center of the line, three-phase line switching at the end. The indicator that is used for analyzing the transient stability condition is voltage level, rotor angle change, power factor change. According to the simulation result recorded for a system with series compensating FACTS device and without this FACTS device table 4.3 the deviation that occurs is due to voltage level change on each bus on the transmission line without TCSC. Now the system without TCSC the power loss is 0.04MW and the power transfer through the line is with power flow solution is about 417.89MW but with TCSC the line is subject to unsymmetrical fault the power loss on the line is about 16.26MW and the power transfer capacity of the transmission line is about 611.36MW this indicates that without series compensating the loss is low but the power transfer capacity is less than the maximum designed value of the line but with series compensating device (TCSC) the high amount of loss is controlled by the series capacitor by controlling the line reactance with 50% and the maximum power transfer is about 611.36MW is higher than the maximum designed power of the line and with the modeling of the TCSC the maximum power transfer is increased to 610MW as shown in figure 4.21. From the output wave graph due to the line to ground the voltage and current at each bus are disturbed because of the fault and after the addition of series compensating FACTs device, it returns to synchronism. The thesis is limited to simulation results only because to implement the system prototype the components are expensive, time-consuming, and complicated system, and also there is no high voltage testing equipment in our country.

5.2.Recommendation

In the future and now run on our country Ethiopia has planned to send power to other neighboring countries so that working on transmission line performance under any transient condition is a very important concern to the country. In addition to transient stability is the improvement of the equipment selected and improve the steady-state stability capacity is important, so that I recommended the

Ethiopian electric power (EEP) to identified the stressed line and faulted area on the load side of sebeta-II substation side of 230kV.

To improve the system disturbance, the EEP uses different techniques of improving the system's stable condition, among the techniques series and shunt devices must be installed on the line.

- EEP should use the series capacitor for other long transmission lines instead of building and expanding of new transmission system network in order to save time and cost as well as the land it is consumed
- Both Ethiopian Universities and EEP should be work cooperatively when such large transmission lines are build and new technologies are introduced to the country since it is very vital for both and in large benefit for the country development in electric power.

For the future, the grid system is interconnected to different national and international networks of the power systems. This condition on the network is subject to different fault conditions or abnormal operating conditions and loss of synchronism. To clear the fault and improve the power transfer capacity of the transmission line different FACTS device controllers must be installed on all the system networks. To protect the FACTS device from problems the researchers must study the protection techniques of these controlling devices.

Research Fund Acknowledgement

This research paper is funded by Adama Science and technology university under the grant number ASTU/SM-R/173/2020, Adama, Ethiopia.

References

[1] D.DAS electrical power system book 483-page, new age international (p) ltd publisher,2006.

[2] G/Michael Gebrie master thesis on “study and analysis of thyristor controlled series capacitor for improving of transmission system capacity” Jan 20, 2017.

[3] Paserba J. J., "How FACTS Controllers Benefit AC Transmission Systems", Proceedings of the IEEE PES Transmission and Distribution Conference and Expo, Dallas, TX, USA, 2003.

[4] Gyugsyi L., "Solid-State control of AC Power Transmission", Proceedings of the EPRI FACTS conference 1, Cincinnati, 1990, pp. (1.7-1) -(1.7-44).

[5] Rajiv Gandhi, Anish Anand, YK. Sehgal, M. Krishna Kumar, and Anand Mohan Enhancement of power transfer capability of existing 400KV transmission lines at NPSC in 2002.

[6] P.Kundur, Power System Stability and Control, McGraw-Hill Inc., New York, 1994.

[7] Daniel J. Sullivan, “Improvements in Voltage Control and Dynamic Performance of Power Transmission Systems Using Static Var Compensators (SVC)”, MSc thesis,BSEET, Pennsylvania State University, 1995.

[9] Voltage Profile and Power Flow Enhancement with FACTS Controllers by Sunil Kumar Singh, Lobzang Phunchok and Y.R. Sood. International Journal of Engineering Research & Technology (IJERT) ISSN: 2278-0181 Vol. 1 Issue 5, July – 2012.

[10] T.T. Nguyen and C.T. Vu. Complex-Variable Newton-Raphson Load flow analysis with FACTS devices, IEEE 2006.

[11] M. A. Abido, “Power System Stability Enhancement Using FACTS Controllers”, MSc thesis, King Fahd University of Petroleum & Minerals Dhahran 31261, Saudi Arabia,2008.

[12] Voltage Profile and Power Flow Enhancement with FACTS Controllers by Sunil Kumar Singh, Lobzang Phunchok and Y.R. Sood. International Journal of Engineering Research & Technology (IJERT) ISSN: 2278-0181 Vol. 1 Issue 5, July – 2012.

[13] Priyanka Kathal, Arti Bhandakkar, Power Flow Control in Power System Using FACT Device TCSC, ISSN: 2320-3331, Vol.7, Issue 6 (Sep. -Oct. 2013), PP 72-83.

[14] Fuerte-Esquivel, C.R. Acha, E. Ambriz-Perez, H. ― A Thyristor Controlled Series Compensator Model for the Power Flow Solution of Practical Power Network‖, IEEE Trans. Power System Vol.15 No.1Feb- 2000, pp.58-64.

[15] SHAIK RAZIA SULTHANA1, B. BADDU NAIK2 "Analysis of Classical and Intelligent Controller by using Facts Devices for Power System Damping" IJATIR ISSN 2348–2370 Vol.07, Issue.03, Pages:0315-0321 March-2015.

[16] Chauhan Chandkuwarbaa Hitendrasinh, Dr. Vijay Ma kwana, THYRISTOR CONTROLLED SERIES CAPACITOR: SIMULATION AND ANALYSIS, Volume2, Issue 5, May -2015.

[17] C. HEYMAN S., WILLFORSS R., Field Experience of Encapsulated Fast Protective Device for Series Capacitors, May 20th to 23rd, 2012.

[18] R. Grünbaum, G. Ingeström, 765 kV Series Capacitors for Increasing Power Transmission Capacity to the Cape Region, IEEE PES, South Africa, 09-13 July 2012.

[19] Abebaw Yalew Mengistu, "study on power transfer capability and voltage stability improvement using static var compensator case study: holeta 500 /400 kv substation" master thesis in May, 2019.

[20] Yadu Ram, Dr. Dharmendra Kumar Singh, and Amit Agrawal Voltage Profile Improvement with Thyristor Controlled Series Capacitor, ISSN (Online): 2278 – 8875, Vol. 4, Issue 6, June 2015.

[21] Voltage Profile and Power Flow Enhancement with FACTS Controllers by Sunil Kumar Singh, Lobzang Phunchok and Y.R. Sood. International Journal of Engineering Research & Technology (IJERT) ISSN: 2278-0181 Vol. 1 Issue 5, July – 2012.

[22] Dr. Tarlochan Kaur and Sandeep Kakran, "transient stability improvement of long transmission line system by using SVC", international journal of advanced research in electrical, electronics and instrumentation engineering vol. 1, issue 4, October 2012.

[23] Sonam Rai, "improvement of transient stability of transmission line" international journal of electrical and electronic research ISSN 2348 – 6988 Vol. 2, Isue2, April – June 2014.

[24] Pankaj Kumar1, Ankit Sachan1, Dr. Pankaj Rai2 “Series Compensation to Mitigate Voltage Sag and Transient Stability Analysis by Using SVC of 11- Bus System” IJAR in Electrical,Electronics and Instrumentation Engineering Vol. 5, Issue 1, January 2016.

[25] Ghazanfar Shahgholian*, Mohammad Reza Yousefi “Performance Improvement of Electrical Power System using UPFC Controller” International Journal of Research Studies in EEEng (IJRSEEE) ISSN 2454-9436 (Online) Volume 5, Issue 3, 2019, PP 5-13.

[26] Gilgel Gibe-II hydroelectric project Environmental Impact Assessment Main Report 0512/81/0001 E del 29/03/2004.

[27] EEP “Gilgel gibe-II hydroelectric power plant design and maintainace manual data”, 2004.

[28] Paserba J. J., "How FACTS Controllers Benefit AC Transmission Systems", Proceedings of the IEEE PES Transmission and Distribution Conference and Expo, Dallas, TX, USA, 2003.

[29] Ranjit Kumar Binda, “a review of benefits of FACTS devices in power system”, international journal of engineering and advanced technology (IJEAT) volume-3, issue-4, April 2014.

[30] C.L. Wadhwa, Electrical Power Systems, New Age International Publisher, 2009.

Appendixes

Appendix A: Parameters of synchronous generator

Parameter	Value
Rated frequency	50Hz
Number of poles	18
Rated speed	333.33 RPM
Rated output power	125MVA
Rated terminal voltage	15KV
Number of phase	3
Rated current	4811A
Rated torque	304KN
Rated power factor	0.85
Stator winding connection	Y
Class of insulation	F
Type of excitation	**Static excitation system**

Source: Nameplate and designed data of synchronous machine installed on GGII HEPP

Appendix B: Gilgel gibe two to sebeta two line dada

Parameters	Values
Voltage at sending end	400KV
Voltage at receiving end	230
Current through the line	115.91A
Transmission line length	183.5km
Active power	78.84MW
Reactive power	12.81MVAR
Apparent power	79.87MVA
Angle ϕ	9.2^0
Cosϕ	0.987
Sinϕ	0.160
Frequency	**50.12Hz**

Source: from relay reading data in sebeta two substation control panel board

Appendix C: Load data from sebeta two to sebeta one substation

Parameters	Values
Voltage sebeta2	230KV
Voltage at sebeta1	132KV
Current through the line	195.51A
Active power	77.27MW
Reactive power	-3.56MVAR
Apparent power	77.36MVA
Angleϕ	-2.6^0
Cosϕ	0.999
Sinϕ	-0.046
Frequency	**50.08Hz**

Source: from relay reading data at sebeta two substation out going feeder control panel board

Appendix D: Auto transformer and power transformer data installed in sebeta two substation

Transformer parameters	Values		
Type of transformer	OSFPZ-250000/400-230TA		
Number of phase	3		
Rated power	250/250/80MVA		
Rated frequency	50Hz		
Rated voltage and tap range	(400±10x1.5%)/230/36KV		
Vector group	YNa0+d		
Type of cooling	ONAN/ONAF/OFAF/52%/72%/100%		
NO load current	0.04%		
No load loss	63.77kw		
Load loss(KW)	MAX.	Rated	Min
H.V. – L.V.	444.63	424.70	482.17
Short circuit impedance(%)	Max	Rated	Min
H.V. – L.V.	12.64	12.29	12.81
Maximum duration of short-circuit	MAX. R.M.S Short circuit-current(KA)		
	H.V. Terminal	L.V. Terminal	
3 SEC	**2.9**	**5.02**	

Source: The auto transformer nameplate data installed in sebeta two substation

Appendix E: Interruption data of Gilgel gibe two hydroelectric power

Table GGII HEPP 2013EFY Hamle to Tahisas 21 Units Number Of Outages					
Quarters	Month	Gilgel gibe II UNIT 1			
		Internal Cause	External Cause	Total Outages	Remarks
1St Quarter	Hamle	8	3	8	The unit internal cause of interruption was related to the decrease in cooling water pressure and flow on the cooling system and stopped forcefully. And external causes are over load on wolayta line and earth fault at sebeta line.
	Nehase	1	3	4	The unit all external tripping occurred due to system disturbance earth fault at sebeta line and (O/U frequency & reverse power)
	Puagume	-	-	-	
	Meskerem	1	1	2	The internal power outage was due to planned maintenance work. But, the external fault was due to earth fault at Sokuro line (10.6Km)
2nd Quarter	Tikimit	1	1	2	The internal power outage was due to planned maintenance work. But, the external fault was due to system disturbance (Total shutdown or total blackout)
	Hidar	4	1	5	Four-unit outage occurs due to internal fault. The two are related to cooling water pump system.
	Tahisas	-	-	-	The unit was stand-by and didn't operate due the LDC load demand. But now, it is undergoing power nozzle maintenance on the generation station and can't operate until the maintenance work finished.
1St Six Month		15	9	21	• Average 3.5 times per month

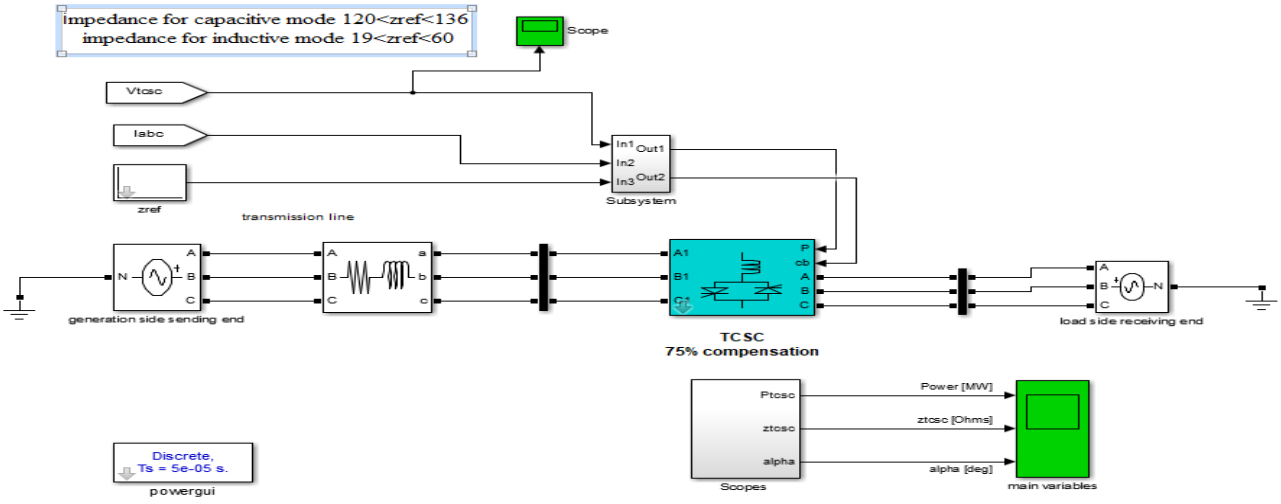
Appendix F: Machine data of Gilgel gibe two hydroelectric power plant.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Bus Name	Area Num	Area Name	Zone Num	Zone Name	Code	VSched (pu)	Remote Bus Number	In Service	PGen (MW)	PMax (MW)	PMin (MW)	QGen (Mvar)	QMax (Mvar)
2	ABA SAMUEL 6.3000	1	ADDIS ABABA	4	OROMIA	-2	1	701007	1	1.0836	1.15	0.115	0.1	0.1
3	ABA SAMUEL 6.3000	1	ADDIS ABABA	4	OROMIA	-2	1	701007	0	0	1.15	0.115	0.1	0.1
4	ABA SAMUEL 6.3000	1	ADDIS ABABA	4	OROMIA	-2	1	701007	0	0	1.15	0.115	0.1	0.1
5	ABA SAMUEL 6.3000	1	ADDIS ABABA	4	OROMIA	-2	1	701007	1	2.2864	3.15	0.315	0.25	0.25
6	KALITI-1-D 11.000	1	ADDIS ABABA	14	ADDIS ABABA	4	1	0	0	0	3.5	0	-0.1167	2.3
7	KALITI-1-D 11.000	1	ADDIS ABABA	14	ADDIS ABABA	4	1	0	0	0	3.5	0	-0.1167	2.3
8	KALITI-1-D 11.000	1	ADDIS ABABA	14	ADDIS ABABA	4	1	0	0	10	10	0	-0.4669	5.3
9	KALITI-1-D 11.000	1	ADDIS ABABA	14	ADDIS ABABA	4	1	0	0	0	3.5	0	-0.1167	2.3
10	KALITI-1-D 11.000	1	ADDIS ABABA	14	ADDIS ABABA	4	1	0	0	0	3.5	0	-0.1167	2.3
11	REPPIE WE 10.500	1	ADDIS ABABA	14	ADDIS ABABA	-2	1	0	1	12.5764	25	0	8	8
12	REPPIE WE 10.500	1	ADDIS ABABA	14	ADDIS ABABA	-2	1	0	1	12.5764	25	0	8	8
13	BELES-1 15.000	7	NORTH WEST	3	AMHARA	2	1	407002	1	115.3311	117	0	-23.6551	19.3285
14	TIS-ABA2-1 10.500	7	NORTH WEST	3	AMHARA	4	1	107002	0	14.8209	36	4	-6.9658	22.2358
15	TIS-ABAY1-1 6.3000	7	NORTH WEST	3	AMHARA	4	1	0	0	0	4.2	0.5	-0.149	3.2
16	BELES-2 15.000	7	NORTH WEST	3	AMHARA	2	1	407002	1	115.3311	117	0	-23.6551	19.3285
17	TIS-ABA2-2 10.500	7	NORTH WEST	3	AMHARA	2	1	107002	1	14.9115	36	4	-10.393	22.2177
18	TIS-ABAY1-2 6.3000	7	NORTH WEST	3	AMHARA	4	1.05	0	0	0	3.8	0.5	0	3.2
19	BELES-3 15.000	7	NORTH WEST	3	AMHARA	2	1	407002	1	115.3311	117	0	-23.6551	19.3285
20	TIS-ABAY1-3 6.3000	7	NORTH WEST	3	AMHARA	4	1	0	0	0	3.8	0.5	0	3.2
21	BELES-4 15.000	7	NORTH WEST	3	AMHARA	2	1	407002	1	115.3311	117	0	-23.6551	19.3285
22	WELKAYT 33.000	9	NORTH	1	TIGRAY	-2	1	0	0	0	9999	-9999	-23.1608	9999
23	AWASH-7D1 11.000	2	CENTRAL	2	AFAR	4	1.04	0	0	0	3.5	0	1.2333	2.3
24	AWASH-7D1 11.000	2	CENTRAL	2	AFAR	4	1.04	0	0	0	3.5	0	1.2333	2.3
25	AWASH-7D1 11.000	2	CENTRAL	2	AFAR	4	1.04	0	0	0	3.5	0	1.2333	2.3
26	AWASH-7D1 11.000	2	CENTRAL	2	AFAR	4	1.04	0	0	0	3.5	0	1.2333	2.3
27	AWASH-7D1 11.000	2	CENTRAL	2	AFAR	4	1.04	0	0	0	3.5	0	1.2333	2.3
28	AWASH-7D2 11.000	2	CENTRAL	2	AFAR	4	1	0	0	0	3.5	0	-1.248	2.3
29	AWASH-7D2 11.000	2	CENTRAL	2	AFAR	4	1	0	0	0	3.5	0	-1.248	2.3
30	AWASH-7D2 11.000	2	CENTRAL	2	AFAR	4	1	0	0	0	3.5	0	-1.248	2.3
31	AWASH-7D2 11.000	2	CENTRAL	2	AFAR	4	1	0	0	0	3.5	0	-1.248	2.3
32	AWASH-7D2 11.000	2	CENTRAL	2	AFAR	4	1	0	0	0	3.5	0	-1.248	2.3
33	AWASH7KL-1_113.800	2	CENTRAL	4	OROMIA	4	1.045	0	0	22	30	0	-15	15.8
34	ALUTO-LANG 111.000	2	CENTRAL	4	OROMIA	4	1.0219	0	0	0	4.5	3.5	2.1336	3.1
35	ALUTO-LANG 211.000	2	CENTRAL	4	OROMIA	4	1.02	0	0	0	4.5	3.5	1.9044	3.1
36	AWASH2-1 10.500	2	CENTRAL	4	OROMIA	-2	1	102014	1	6.4617	16	1.6	12.8538	12.8538
37	AWASH3-1 10.500	2	CENTRAL	4	OROMIA	-2	1	102015	1	6.4617	16	1.6	12.8538	12.8538
38	KOKA1 10.500	2	CENTRAL	4	OROMIA	-2	1	102018	1	6.1634	14.4	0.5	13.1006	13.1006
39	KOKA3 10.500	2	CENTRAL	4	OROMIA	4	1	102018	0	0	14.4	0.5	6.4922	13.5
40	M-WAKENA1 13.800	2	CENTRAL	4	OROMIA	2	1	202012	1	8.7715	38.25	0	0.6214	30
41	AWASH2-2 10.500	2	CENTRAL	4	OROMIA	-2	1	102014	1	6.4617	14.4	1.6	12.8538	12.8538
42	AWASH3-2 10.500	2	CENTRAL	4	OROMIA	-2	1	102015	1	6.4617	16	1.6	12.8538	12.8538
43	KOKA2 10.500	2	CENTRAL	4	OROMIA	-2	1	102018	1	6.1634	14.4	0.5	13.1006	13.1006
44	M -WAKENA2 13.800	2	CENTRAL	4	OROMIA	4	1	202012	0	0	38.25	0	30	30
45	M-WAKENA3 13.800	2	CENTRAL	4	OROMIA	2	1	202012	1	10.5258	38.25	0	0.6214	29.5959
46	M-WAKENA4 13.800	2	CENTRAL	4	OROMIA	2	1	202012	1	10.5258	38.25	0	0.6214	29.5959
47	ADAMA WF-I 33.000	2	CENTRAL	4	OROMIA	-2	1	102030	1	7.9119	15	0	5	5
48	ADAMA WF-I 33.000	2	CENTRAL	4	OROMIA	-2	1	102030	1	9.4943	18	0	6	6
49	ADAMA WF-I 33.000	2	CENTRAL	4	OROMIA	-2	1	102030	1	9.4943	18	0	6	6
50	ADAMA WF-II 33.000	2	CENTRAL	4	OROMIA	-2	1	202015	1	9.4889	16.5	0	0	5.357
51	ADAMA WF-II 33.000	2	CENTRAL	4	OROMIA	-2	1	202015	1	11.2142	19.5	0	0	6.331
52	ADAMA WF-II 33.000	2	CENTRAL	4	OROMIA	-2	1	202015	1	11.2142	19.5	0	0	6.331
53	ADAMA WF-II 33.000	2	CENTRAL	4	OROMIA	-2	1	202015	1	11.2142	19.5	0	0	6.331
54	ADAMA WF-II 33.000	2	CENTRAL	4	OROMIA	-2	1	202015	1	11.2142	19.5	0	0	6.331
55	ADAMA WF-II 33.000	2	CENTRAL	4	OROMIA	-2	1	202015	1	11.2142	19.5	0	0	6.331
56	ADAMA WF-II 33.000	2	CENTRAL	4	OROMIA	-2	1	202015	1	11.2142	19.5	0	0	6.331
57	ADAMA WF-II 33.000	2	CENTRAL	4	OROMIA	-2	1	202015	1	11.2142	19.5	0	0	6.331
58	D DAWA-DIESL15.000	3	EAST	10	DIRE DAWA	4	1	103009	0	0	10	0	6.3603	6.6
59	D DAWA-DIESL15.000	3	EAST	10	DIRE DAWA	4	1	103009	0	0	10	0	-3.8966	6.6
60	D DAWA-DIESL15.000	3	EAST	10	DIRE DAWA	4	1	103009	0	0	10	0	-3.5069	6.6
61	D DAWA-DIESL15.000	3	EAST	10	DIRE DAWA	4	1	103009	0	0	10	0	-3.5069	6.6
62	D DAWA-DIESL15.000	3	EAST	10	DIRE DAWA	4	1	103009	0	0	10	0	-3.8966	6.6
63	FINCHA1 13.800	4	WEST	4	OROMIA	2	1.03	204001	1	30.2207	36.3	3	9.0021	21.074
64	NESHE-1 13.800	4	WEST	4	OROMIA	-2	1	204004	1	44.8837	47.7	2	-8.5609	16.9391
65	FINCHA2 13.800	4	WEST	4	OROMIA	2	1.03	204001	1	30.2207	36.3	3	9.0021	21.074
66	NESHE-2 13.800	4	WEST	4	OROMIA	-2	1	204004	1	44.8837	47.7	2	-8.5609	16.9391
67	FINCHA3 13.800	4	WEST	4	OROMIA	2	1.03	204001	1	30.2207	36.3	3	9.0021	21.074
68	FINCHA4 13.800	4	WEST	4	OROMIA	2	1.03	204001	1	10.6369	35	3	9.0021	24.5
69	GENALE-III 13.800	5	SOUTH	4	OROMIA	-2	1	405003	1	50.0775	100	0	-39	65.8
70	GENALE-III 13.800	5	SOUTH	4	OROMIA	-2	1	405003	1	50.0775	100	0	-39	65.8
71	GENALE-III 13.800	5	SOUTH	4	OROMIA	-2	1	405003	1	50.0775	100	0	-39	65.8
72	GENALE-III 13.800	5	SOUTH	4	OROMIA	-2	1	405003	0	0	100	0	-78.1	131.7
73	G-GIB3 1 15.000	5	SOUTH	7	S.N.N.P	3	1.05	0	1	135.3187	187	5.61	23.1039	108.4841
74	G-GIB3 2 15.000	5	SOUTH	7	S.N.N.P	3	1.05	0	1	134.9952	187	5.61	22.9089	108.6137
75	G-GIB3 3 15.000	5	SOUTH	7	S.N.N.P	3	1.05	0	1	136.2039	187	5.61	23.1888	108.1295
76	G-GIB3 4 15.000	5	SOUTH	7	S.N.N.P	3	1.05	0	1	136.3121	187	5.61	23.0594	108.0861
77	G-GIB3 5 15.000	5	SOUTH	7	S.N.N.P	3	1.05	0	1	134.6854	187	5.61	23.0178	108.7378
78	G-GIB3 6 15.000	5	SOUTH	7	S.N.N.P	3	1.05	0	1	134.6852	187	5.61	22.8719	108.7379
79	G-GIB3 7 15.000	5	SOUTH	7	S.N.N.P	3	1.05	0	1	143.7252	187	5.61	26.4636	105.1175
80	G-GIB3 8 15.000	5	SOUTH	7	S.N.N.P	-2	1	405004	0	0	187	5.61	88.6095	136.51
81	G-GIB3 9 15.000	5	SOUTH	7	S.N.N.P	-2	1	405004	0	0	187	5.61	55.7348	136.51
82	G-GIB3 10 15.000	5	SOUTH	7	S.N.N.P	-2	1	405004	0	0	187	5.61	55.7348	136.51
83	G-GIBE2-1 15.000	8	SOUTH WEST	7	S.N.N.P	2	1	408001	1	67.599	105	2	-35.8297	62.0802
84	G-GIBE1-1 13.800	8	SOUTH WEST	4	OROMIA	2	1.02	208005	1	57.437	70	1.84	22.0483	29.4218
85	G-GIB2-2 15.000	8	SOUTH WEST	7	S.N.N.P	2	1	408001	1	67.599	105	2	-35.8297	62.0802
86	G-GIBE1-2 13.800	8	SOUTH WEST	4	OROMIA	2	1.02	208005	1	14.3592	70	1.84	22.0483	38.6082
87	G-GIB2-3 15.000	8	SOUTH WEST	7	S.N.N.P	2	1	408001	1	71.5754	105	2	-35.8297	61.2849
88	G-GIBE1-3 13.800	8	SOUTH WEST	4	OROMIA	2	1.02	208005	1	57.437	70	1.84	22.0483	29.4218
89	G-GIB2-4 15.000	8	SOUTH WEST	7	S.N.N.P	2	1	408001	1	71.5754	105	2	-35.8297	61.2849
90	TEKEZE1 13.800	9	NORTH	1	TIGRAY	2	1.03	209006	1	58.7084	78	0	-1.3731	99.37
91	TEKEZE4 13.800	9	NORTH	1	TIGRAY	2	1.03	209006	1	58.7084	78	0	-1.3731	99.37
92	TEKEZE2 13.800	9	NORTH	1	TIGRAY	4	1	209006	0	0	78	0	-2.7066	109.2
93	TEKEZE3 13.800	9	NORTH	1	TIGRAY	2	1.03	209006	1	58.7084	78	0	-1.3731	99.37
94	ASHEGODA-WF 33.000	9	NORTH	1	TIGRAY	2	1	209013	1	2.0795	3	0	4.9093	0.97
95	ASHEGODA-WF 33.000	9	NORTH	1	TIGRAY	2	1	209013	1	1.7364	25.05	0	4.0993	8.1111
96	ASHEGODA-WF 33.000	9	NORTH	1	TIGRAY	2	1	209013	1	2.3152	33.4	0	5.4657	10.8148
97	ASHEGODA-WF 33.000	9	NORTH	1	TIGRAY	2	1	209013	1	2.1994	31.73	0	5.1924	10.2741
98									1					
99														
100														

Appendix G: Bus data of Gilgel gibe two to sebeta transmission line

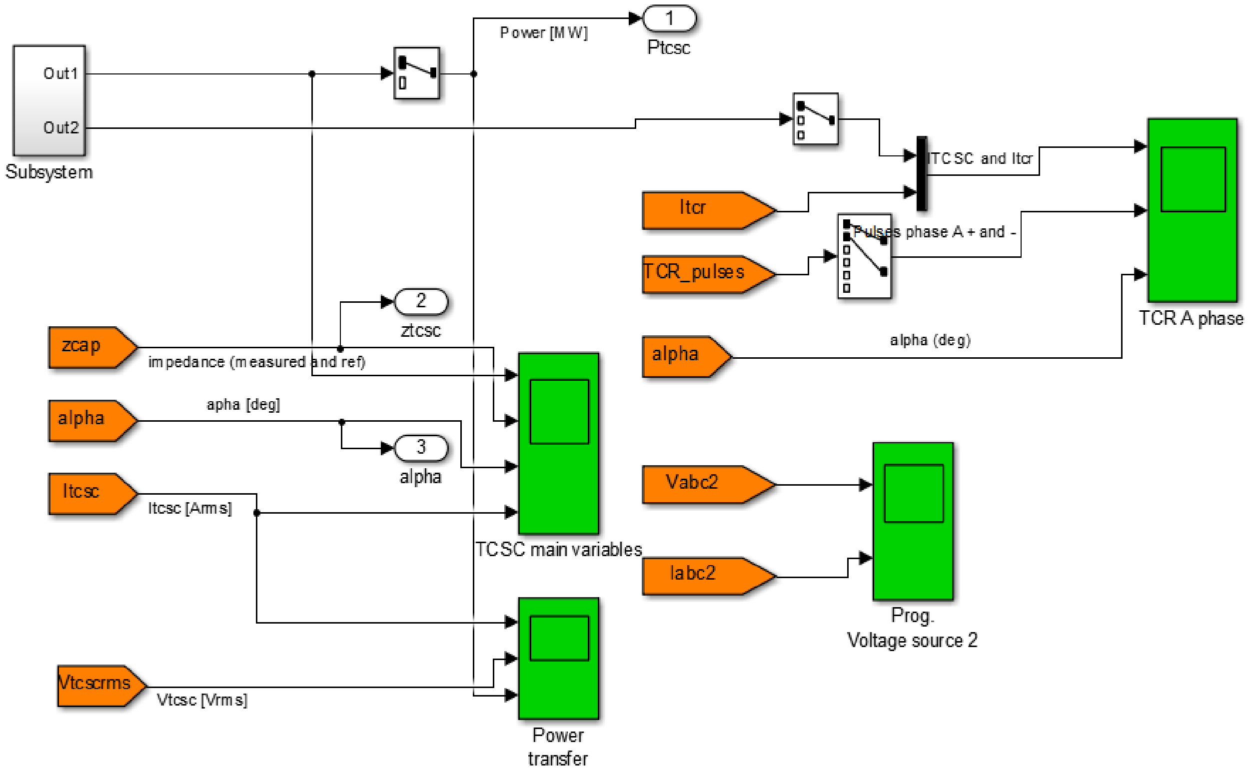
Bus Name	Base kV	Area Nun	Area Name	Zone Nun	Owner N	Owner Na	Code	Voltage (	Angle (de	Normal V	Normal V	Emergenc	Emergency Vmin (pu)
ADD EAST-II	132	1	ADDIS ABABA	14	1	TRANSMI:	1	0.9181	-60.1	1.05	0.95	1.1	0.9
B.WGN-TP	132	1	ADDIS ABABA	14	1	TRANSMI:	1	0.9186	-59.94	1.05	0.95	1.1	0.9
COTEBEI-I	132	1	ADDIS ABABA	14	1	TRANSMI:	1	0.9243	-59.84	1.05	0.95	1.1	0.9
SULULTA-132	132	1	ADDIS ABABA	4	1	TRANSMI:	1	0.9795	-57.4	1.05	0.95	1.1	0.9
WERGENU	132	1	ADDIS ABABA	14	1	TRANSMI:	1	0.9109	-60.21	1.05	0.95	1.1	0.9
LEGETAFO	132	1	ADDIS ABABA	14	1	TRANSMI:	1	0.9394	-59.41	1.05	0.95	1.1	0.9
ADDIS-E1	132	1	ADDIS ABABA	14	1	TRANSMI:	1	0.9238	-59.86	1.05	0.95	1.1	0.9
SHEGOLE	132	1	ADDIS ABABA	14	1	TRANSMI:	1	0.9412	-58.9	1.05	0.95	1.1	0.9
AYAT	132	1	ADDIS ABABA	14	1	TRANSMI:	1	0.9328	-59.59	1.05	0.95	1.1	0.9
BOLE-LEMI TP	132	1	ADDIS ABABA	14	1	TRANSMI:	1	0.9176	-59.8	1.05	0.95	1.1	0.9
BOLE-LEMI MB	132	1	ADDIS ABABA	14	1	TRANSMI:	1	0.9173	-59.82	1.05	0.95	1.1	0.9
ADDIS-NORTH	132	1	ADDIS ABABA	14	1	TRANSMI:	1	0.9316	-59.19	1.05	0.95	1.1	0.9
GEFERSA	132	1	ADDIS ABABA	4	1	TRANSMI:	1	0.9485	-58.68	1.05	0.95	1.1	0.9
MINILIK TS	132	1	ADDIS ABABA	14	1	TRANSMI:	1	0.9374	-59.02	1.05	0.95	1.1	0.9
ADDIS CENTER	132	1	ADDIS ABABA	14	1	TRANSMI:	1	0.882	-60.46	1.05	0.95	1.1	0.9
GOFA	132	1	ADDIS ABABA	14	1	TRANSMI:	1	0.9132	-59.85	1.05	0.95	1.1	0.9
KALITI1	132	1	ADDIS ABABA	14	1	TRANSMI:	1	0.9077	-59.57	1.05	0.95	1.1	0.9
KALTI-NORTH	132	1	ADDIS ABABA	14	1	TRANSMI:	1	0.9068	-59.67	1.05	0.95	1.1	0.9
KALITI TWO	132	1	ADDIS ABABA	14	1	TRANSMI:	1	0.9002	-59.89	1.05	0.95	1.1	0.9
KLT.N-TP	132	1	ADDIS ABABA	14	1	TRANSMI:	1	0.9073	-59.65	1.05	0.95	1.1	0.9
MEKANISA	132	1	ADDIS ABABA	14	1	TRANSMI:	1	0.9153	-59.76	1.05	0.95	1.1	0.9
YESU	132	1	ADDIS ABABA	4	1	TRANSMI:	1	0.9044	-59.75	1.05	0.95	1.1	0.9
GELAN	132	1	ADDIS ABABA	14	1	TRANSMI:	1	0.909	-59.59	1.05	0.95	1.1	0.9
INDODE TS	132	1	ADDIS ABABA	14	1	TRANSMI:	1	0.9068	-59.61	1.05	0.95	1.1	0.9
NEFASILK	132	1	ADDIS ABABA	14	1	TRANSMI:	1	0.8957	-60.04	1.05	0.95	1.1	0.9
KALITI GIS	132	1	ADDIS ABABA	14	1	TRANSMI:	1	0.9045	-59.71	1.05	0.95	1.1	0.9
SEBATA -I	132	1	ADDIS ABABA	14	1	TRANSMI:	1	0.951	-58.71	1.05	0.95	1.1	0.9
ADDIS WEST 2	132	1	ADDIS ABABA	14	1	TRANSMI:	1	0.9416	-59.37	1.05	0.95	1.1	0.9
BLACK-LION	132	1	ADDIS ABABA	14	1	TRANSMI:	1	0.9438	-59.11	1.05	0.95	1.1	0.9
REPPIE WE	132	1	ADDIS ABABA	14	1	TRANSMI:	1	0.9363	-59.07	1.05	0.95	1.1	0.9
SEBATA-1	230	1	ADDIS ABABA	14	1	TRANSMI:	1	0.9849	-55.45	1.05	0.95	1.1	0.9
SEBETA-2	230	1	ADDIS ABABA	4	1	TRANSMI:	1	0.9869	-54.84	1.05	0.95	1.1	0.9
SEBETA-2	400	1	ADDIS ABABA	4	1	TRANSMI:	1	0.9956	-51.67	1.05	0.95	1.1	0.9
GI GIBE-2	400	8	SOUTH WEST	7	2	GENERAT	1	1	-40.75	1.05	0.95	1.1	0.9

Appendix H: TCSC model for compensation of the power system to improve power transfer capacity of the system.



Thyristor controlled series capacitor (TCSC)

Appendix I: The sub system model of the scopes the above model



Appendix J: power flow study using MATLAB script code the solution by newton Raphson iteration method

```
baseMVA = 100; accuracy = 0.001; accel = 1.6; maxiter = 200;

%        3-BUS SYSTEM of GGII to sebeta line
%        Bus Bus  Voltage Angle   ---Load---- -------Generator----- Static Mvar
%        No  code Mag.    Degree  MW    Mvar  MW  Mvar   Qmin    Qmax    +Qc/-Ql
bus data= [1   g400    1.05    0.0     0.0    0.0    0.0  0.0   0       0       0
         2   s400    1.0     0.0   71.5754 -35.8297 0.0  0.0 -79.7076 62.0802 0
         3   s230    1.0     0.0    16.9722 8.4861   0.0  0.0   0      0      0];

%                                        Line code
%         Bus bus   R       X        1/2 B    = 1 for lines
%         nl  nr  p.u.     p.u.      p.u.     > 1 or < 1 tr. tap at bus nl
line data=[1   2   0.002839  0.037756   1.04419      1
          1   3   0.015      0.035       0.0        1
          2   3   0.0125    0.0251      0.0        1];

Lf ybus                % form the bus admittance matrix
Lf newton               % Load flow solution by Newton-Raphson method
Bus out               % Prints the power flow solution on the screen
Line flow           % Computes and displays the line flow and losses
```

This script is used calculate power flow solution using newton Raphson method, form bus admittance matrix, show the output of the three buses of the line and compute line flow and line loses of the system. All lf ybus, lf newton, bus out, and, line flow has their own script.