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

STUDY AND ANALYSIS OF THYRISTOR CONTROLLED SERIES CAPACITOR FOR IMPROVING OF TRANSMISSION SYSTEM CAPACITY

(A Case Study on 500kV Dedesa Substation)

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

By

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DECLARATION

I, the undersigned, declared that this MSc thesis in titled as" **Study and Analysis of Thyristor Controlled Series Capacitor for Improvement of Transmission System Capacity"** is my original work, has not been presented for fulfillment of a degree in this or any other Universities, and all sources and materials used for the thesis work are acknowledged in this document.

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

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Advisor	Signature

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BS	Bypass switch
B_{TCSC}	Susceptance of TCSC
CB	Circuit Breaker
Ckt	Circuit
CT	Current transformer
DS	Line Disconnector
EEP	Ethiopian Electric Power
FACTS	Flexible AC Transmission Systems
FSC	Fixed Series Capacitor
GERD	Grand Ethiopian Renaissance Dam
H.E.P.P	Hydroelectric Power Plant
MOV	Metallic Oxide Varistor
MVAr	Mega Voltage Ampere reactive
OPF/T	Optimum Power Flow/Transfer
POD	Power Oscillation Damping
PTP	Power Transmission Project
PTC	Power Transfer Capacity
RMS	Root Mean Square
SG	Spark Gap
SSSC	Series Synchronous Static Compensator
SVC	Static Var Compensator
TCR	Thyristor Controlled Reactor
TCSC	Thyristor Controlled Series Capacitor
TPSC	Thyristor Protected Series Capacitor
TSSC	Thyristor Switched Series Capacitor
UPFC	Unified Power Flow Control
V_R	Receiving end Voltage
V_S	Sending end Voltage
X_C	Capacitive Reactance
X_L	Inductive Reactance
α	Firing Angle

ABSTRACT

An increase of power demand in recent years have 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. Flexible AC transmission system devices such as thyristor controlled series compensator can help increase power transfer capacity in heavily loaded networks because of its capability to control power flow flexibly. This is where TCSC device is very useful because of its low initial cost as compared to setting up a 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 thesis analyses the importance of TCSC which is Series Compensation for the improvement of transmission line utilization at Dedesa substation of 500kV transmission system stretched from GERD to Holeta substation and designed TCSC for the system as good alternative for power oscillation damping and SSR mitigation. The system is implemented using software. Steady and dynamic stabilities power, voltage and current of the system are improved using DigSILENT.

Generally, using TCSC the power capacity is increased from 5759 MW to 5916.35 MW, voltage regulation is decreased from 3.95% to 3.02% and it is 10% of the building of new transmission line which is cost effective method. With the firing control of the thyristors, its apparent reactance is changed smoothly and rapidly for stability system from 83.60-157.72Ohms.

KEY WORDS: Series Capacitor, FSC, TCSC, MOV, Stability, Dedesa Substation, power transfer capacity

CHAPTER ONE

1. INTRODUCTION

1.1 BACKGROUND OF THE STUDY

Power systems have to be planned, projected, constructed, commissioned and operated in such a way to enable a safe, reliable and economic supply of the load. The knowledge of the equipment loading at the time of commissioning, the prediction is necessary in the future for the design and determination of the rating individual equipment and power system as a whole. A grid of transmission lines operating at high or extra high voltages is required to transmit power from generating stations to load. In addition to transmission lines that carry power from source to load, modern power systems are highly interconnected for economic reasons. The large interconnected transmission networks are prone to faults due to the lightning discharges and reduce insulation strength. Changing of loads and atmosphere conditions are unpredictable factors. This may cause overloading of lines due to which voltage collapse takes place. These problems can be eased by introduction of fast dynamic control over reactive and active power by high power electronic controllers called flexible alternating current systems [1]. In recent years, the highly increasing cost of building new transmission lines, is compounded by the difficulty to obtain new transmission corridors, has led to a search for increasing the transmission capacity of existing lines. The Series compensation in transmission line is modeled in order to enhance power flow at the receiving end. Series compensation employs capacitors to compensate the inductive reactance of long lines. It is a highly effective and economical means of improving power transfer capacity suitable for both new and existing lines: series compensation increases power transfer capability by raising the transient stability limit as well as improving the voltage stability [2].

In Ethiopia, fixed series capacitor new technology that increase the power transfer capacity and to protect those problems occurred in long transmission systems using Series Compensation. Only shunt reactor was used which is incapable to improve and solve such problems properly. But nowadays FSC is installed at Dedesa Substation on 500kV which transmit the power generated from the GERD to the national grid.

The GERD - Dedesa - Holeta 500kV power transmission project is to transmit power of 6000MW from the future GERD hydroelectric power station through two 500kV double circuit transmission lines to the new Dedesa, then Holeta substations and then through a 400kV line from Holeta to Sebeta II, Holeta to Sululta II, and Holeta to Akaki II existing substations. In the second phase, a 400kV double circuit line from GERD to Beles and Bahir Dar is already under working. The project GERD is designed in such a way to supply power to the Ethiopian national grid, and the two corridors, especially the Southern Sudan and Northern Sudan. This simplified network is shown in Figure 1.1.

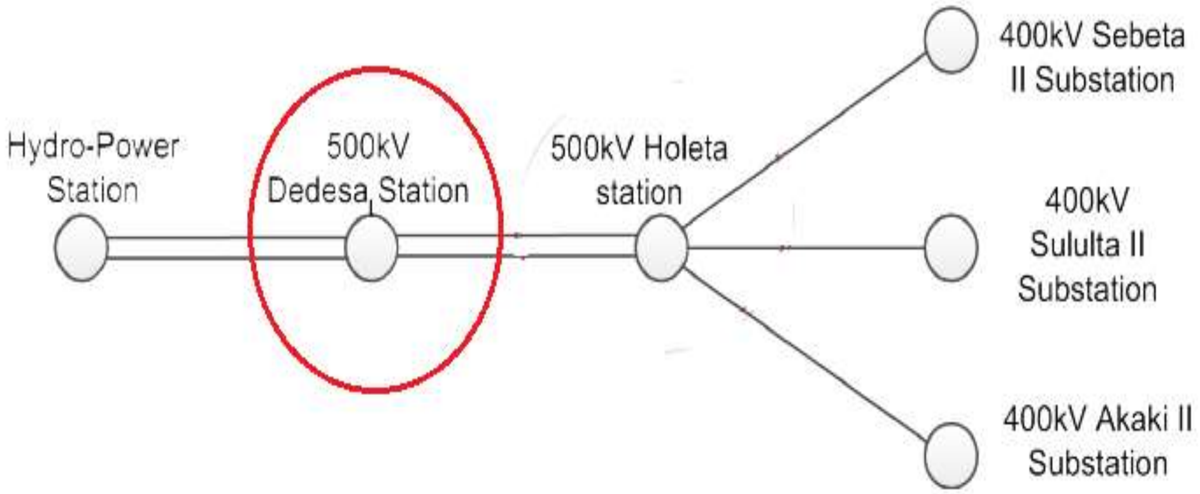


Figure 1.1**:** Simplified GERD-Dedesa- Holeta line path [4]

The SC is located at Dedesa substation at an overhead distance of 345km from GERD and **300**km far from Addis Ababa near city Nekemt in the Oromia region of Ethiopia. Series Capacitor technology in AC transmission system is to seriously connect the capacitor bank into power line to increase the transmission capacity, improve transmission system stability and save investment cost and time.

The current power grid is very weak and the voltage fluctuation along the transmission line remains to be solved. In April 26, 2013 held at the Sheraton Addis, Chinese company, State Grid of China Electric Power Equipment & Technology Co. Ltd (SGCC) won the contract for the installation of high-voltage electric transmission lines to provide Series Capacitor at Dedesa Substation in order to reduce the fluctuation and improve power transmission quality. A 516MVAr and 411MVAr SC system have been installed in the 500kV Dedesa Substation to supply power oscillation damping, to enhance dynamic voltage performance and improve power grid stability. Since this transmission line is very long, the power is weak when it is connected to the main national grid. Due to this reason, the line has also Static Var Compensator (Fixed Capacitor +Thyristor Controlled Reactor +Thyristor Switching Capacitor) at Holeta Substation with 900MVAr is already installed in the 500kV Holeta station to supply power oscillation damping, so as to enhance dynamic voltage performance and improve power grid stability but this is not the part of this thesis work [4].

Therefore, in this thesis, TCSC is studied and analyzed, design of TCSC for transmission system and also technical and economic aspects of the series compensated system at Dedesa substation is discussed and compared this with the new building of transmission line.

1.2 STATEMENT OF THE PROBLEM

Realizing maximum power transfer, 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 relieving power transmission bottlenecks. Modern energy transmission systems suffer in reduction power transfer capability and great voltage drop and due to the line reactance and thermal limits. Therefore, the construction of newer transmission lines is a tedious task owing to laws, environmental impacts, and prohibitive capital requirements. Therefore, the need arises to explore the various avenues for enhancing the power transfer capacity of the transmission lines. 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. The main aim of this thesis is to solve power transfer capacity, voltage drop and stability problem faced in GERD- Dedesa-Holeta lines.

1.3 OBJECTIVES OF THE STUDY

1.3.1 General Objective

The general objective of this thesis is to study and analysis of TCSC for improvement long power transmission system capacity based on series compensation at 500kV Dedesa substation and carried out the technical and economical aspects of TCSC.

1.3.2 Specific Objectives

i. To reduce the number of transmission line circuits to increasing power flow capacity 500kV transmission line by decreasing the effective series reactance of the line
ii. To study and analyze of TCSC Dedessa substation
iii. To analyze the steady state and dynamic stability of the transmission system
iv. To Design and model TCSC for the case study
v. To analyze power losses on the lines using DigSILENT
vi. To study the technical and economical aspect analysis of the TCSC in terms of the efficiency of power loss on the lines, voltage regulation and investment costs.

1.4 SIGNIFICANCE OF THE STUDY

This research study is worth doing because of the vital information it renders to future power system engineers and researchers. Therefore, enhancing power flow in transmission systems is important for efficient power supply because a modern day society requires a large amount of electrical energy for domestic, commercial and industrial purposes. Designing of TCSC over the FSC is the capability of controlling the reactance of the transmission line automatically using the back to back sandwiched bidirectional thyristors. This enables for effective cancelling the more inductive nature of GERD-Dedessa-Holeta line when impedance is variable and for damping power oscillation as well as SSR over the system. In technical and economical aspects, TCSC is taken similar to FSC only differ on the back to back thyristors. In general, implementing transmission lines with series capacitor have huge benefit for enhancing power transfer capacity and stability.

1.5 METHODOLOGY

Site Selection: Dedesa substation is selected as case study area since it has already installed the FSC controlled using thyristor which power will be transmitted from GERD to Holeta substation more than 620km long overhead line of 500kV with two double transmission line since 2013-2016 and the site is selected for series capacitor placement location since it is almost midpoint of the total transmission line of GERD to Ethiopian grids.

Data Collection: Data of this research has been conducted using the following methods.

i. Started from intensive literature reading about series compensation especially FSC/TCSC
ii. Technical data are collected from the design and construction office of Senior Engineers
iii. Gathered relevant data from the EEP, PTP office
iv. For the purpose of analysis Dedesa substation, data has been collected based on the existed structure of Dedesa substation system data's on EEP manual and agreement documents of as-built , data's on planning and design of EEP and data's from EEP project Office, PTP.

Data Analysis and Modelling: The study is modelled using DigSILENT in order to see the real effects of the TCSC on the transmission lines. The DigSILENT is used for determining the power losses on the lines as well as for system stability when disturbance due to the fault on the lines is occurred. Using this, the operating regions or modes of TCSC are studied and protection systems are also observed using the software.

Design of TCSC: In this part, all required equipment of TCSC are designed starting from the detailed modelling of variable reactance and firing angle control. The protection equipment are also designed having satisfied the specifications and also considered the rating of all parameters.

Technical and Economic Analysis of Series Compensated System: Technical aspect analysis is taken about the compensated system regarding that power transfer capacity and voltage drop and other related issues such as losses simply on the lines taking directly from the PSS simulation given by EEP and tried to calculate the efficiency.

Economical analysis of the compensated system mainly the investment costs of the transmission and TCSC is carried out by comparing with SC/TCSC and building new transmission system for GERD-Dedesa-Holeta transmission lines.

1.6 ORGANIZATION OF THE THESIS

The thesis is organized into six chapters which are briefly summarized as below.
Chapter One presents the introduction mainly consists of the background of the study, statement of the problem, objectives, significant and methodologies followed in the thesis work.

The **Second Chapter** discusses about the theoretical background and literature review of the study, mainly on electric power control using series capacitors, characteristics of TCSC on power system, stability of the system using TCSC and the protection of the series capacitor system.

Chapter Three deals with advantage of using TCSC in long transmission system, analysis and modelling the series capacitor of the system and make a clear explanation of TCSC for Dedesa substation and also deals TCSC design in detail, modelling of the power flow using the variable reactance and firing angle.

Chapter Four deals with the simulation results and discussions which mainly includes the modelling TCSC using the DigSILENT, steady state, dynamic stability and it also describes the results discussion of all of the outcomes thesis work.

Chapter Five discusses the technical and economic aspects of SC/TCSC system including benefits in terms of power transfer capacity, investment cost of transmission line and the cost of SC and whole transmission line.

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

CHAPTER TWO

2. THEORETICAL BACKGROUND AND LITERATURE REVIEWS

2.1 INTRODUCTION

Efficient and reliable electric power transmission have got more and more attention due to continuous increase in electric power consumption and electricity dependency of the society. Consequently, new solutions for increasing the electricity transmission capacity and stability of the transmission system have been developed. FACTS devices have become respectable alternative for construction of new transmission lines since by utilizing FACTS devices the existing transmission system can be utilized more effectively. This can be considered beneficial especially because construction of new transmission lines is coming increasingly restricted and expensive in the future.

On the other hand, global targets aiming for increasing energy efficiency of the society can also be considered to have positive effect on FACTS development projects [6]. The transmission of active power is mainly limited by the impedance of the transmission line, comprising the ohmic resistance plus the capacitive and inductive reactance.

Furthermore, the main purpose of installed FACTS devices is to improve the overall performance of the transmission network and thereby to increase the reliability and stability of the network extensive power system analysis should be executed always as new FACTS devices are installed in the network. Therefore, need for new extensive but at the same time user friendly analysis tools can be seen obvious. Increase of FACTS devices in the power system emphasizes also the importance of system development of FACTS in industry. Especially concern should be taken already in early state of the design project of the device on interaction phenomena between FACTS devices of the power system and between FACTS devices and other power system components [7]. FACTS devices includes Static Var Compensator, Unified Power Flow Controllers, Static Synchronous Series Capacitor, Thyristor controlled series capacitor, Thyristor switching series capacitor , Fixed series capacitor etc.

2.2 SERIES COMPENSATION SYSTEM

Series compensation has been in use since the early the 20th century. The first series capacitor for EHV power transmission application was installed in a 245 kV line back in 1951 in Sweden.

It was followed by a similar project in the USA in 1951. The first 400 kV series compensation project was energized in 1954 in Sweden. In 1960s the first 500 kV series compensation project was introduced in the USA. As a result of the success of these projects, series compensation has become a common practice to enhance the power transfer over long AC transmission lines [8].

Today's interconnected power network is very large and has many lines, perhaps most of the lines are uncompensated which leads to more reactive power losses subsequently poor voltage regulation. Sometimes it may leads to voltage instability and subsequently collapse due to disturbances, sudden variations of load and contingencies. The main reason for the voltage collapse is due to lack of reactive power in the heavily stressed systems, generator reactive power limits, the load characteristics, the action of the voltage control devices. All these factors may lead to: limit the power transfer capability of uncompensated lines, may exceed the line limits subsequently line outages and may cause the cascading outages, and voltage instability and voltage collapse which may leads to partial blackout or sometime total blackout of system [9].

With growing increases in demand for electrical power and the number of power plant facilities, additional transmission facilities have continually been constructed. The result increases in the total short circuit capacity of a power system have given rise to issues regarding system control and the complexity of system protection. Furthermore, geographical constraints and local civil complaints have become additional barriers, increasing the difficulty of constructing additional facilities. These problems might weaken the stability of the grid [10]. FACTs address such problems, and are widely used for electrical power systems in many countries. Some of the series FACTs are applications are the FSC, TCSC and TPSC. Series capacitors are applied to negate a percentage of reactance and hence reduce the overall reactance of a transmission line. The benefits of applying series capacitors on a transmission line include improved stability margins, better load division on parallel paths, ability to adjust line load levels, reduced transmission losses, and reduced voltage drop on the system during severe disturbances. The application of series capacitors is normally economical for line lengths greater than 200 miles. Series capacitors are applied to compensate for 25 to 75 percent of the inductive reactance of the transmission line [8]. Series FACTS devices are powerful controllers recognized for power flow, power oscillation damping and improving transient stability [10, 11]. Normally these devices are used for power flow control in transmission lines and also used to damp the power system oscillation.

In series compensation, the FACTS is connected in series with the power system. It works as a controllable voltage source. Series inductance exists in all AC transmission lines. In long lines, when a large current flows, this causes a large voltage drop. To compensate this, series capacitors are connected to decreasing the effect of the inductance and also by connecting series capacitors in series with the line, the inductive reactance between the receiving end and the sending end will be reduced due to this, the power systems of the system can be improved [10].

The impact of the series capacitors in an electrical sense to make the transmission distances between the generators and load seem shorter. This is the benefit to angular as well as voltage stability, enabling power transmission to take place at levels considerably exceeding the natural loading of the lines. Additionally, very important benefit of the series capacitors is an optimization of load sharing between the parallel lines. Since the lines were constructed at different times during three decades, impedances vary from one line to the next. The series capacitors, by the degree of compensation in each individual case, make up for these differences in line impedances and bring about the best possible load sharing between the lines. From the FACTS devices only series capacitor has been discussed in detail in this study, such as FSC and TCSC.

2.3 FIXED SERIES CAPACITOR COMPENSATION (FSC)

Series compensation is a well-established technology that is primarily used to reduce transfer reactance, most notably in bulk transmission corridors. The result is a significant increase in the transient and voltage stability in transmission systems [8].

FSC has long been the preferred solution for optimizing performance in very large bulk transmission corridors. Installing a capacitive reactance in series in a long transmission line reduces both the angular deviation and the voltage drop, which increases the loadability and stability of the line. Since the current through the transmission line directly "drives" the MVAr output from the capacitor, the compensation concept is "self-regulating”, and this straightforward principle ensures that series compensation is an extremely cost effective solution. Series compensation provides increased transient (angular) stability of a power corridor and increased voltage stability of the grid. It also improves the voltage profile along the power corridor and optimizes power sharing between parallel circuits [12].

Since series capacitors are installed in series on a transmission line, the equipment must be housed on a platform that is fully insulated for the system voltage. The capacitor together with the overvoltage protection circuits are located on this steel platform. Overvoltage protection is a key design factor, as the capacitor bank must be able to withstand the throughput fault current, even at a severe nearby fault. The primary overvoltage protection typically involves nonlinear metal oxide varistors, a gap, damping system and a fast bypass switch. Secondary protection is achieved with ground mounted electronics acting on signals from optical current transducers in the high voltage circuit [20].

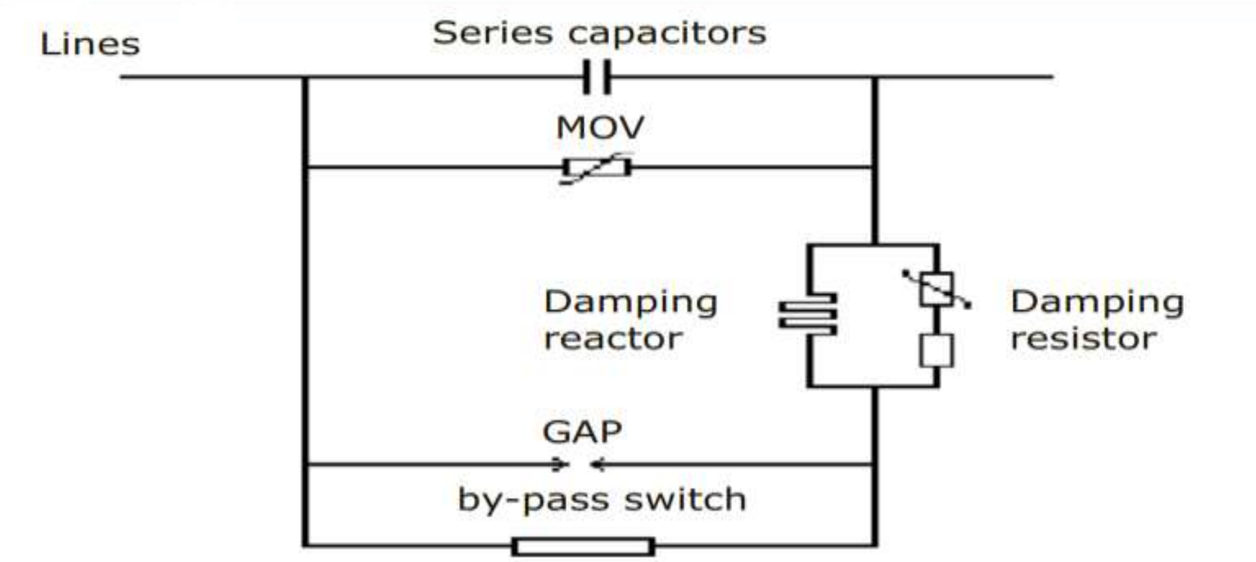


Figure 2.1: Fixed Series Capacitor [4]

A damping circuit is connected in series with the triggered spark gap and is not always stressed by the ac line current. In parallel to the spark gap, the bypass breaker is located to provide current commutation for times when the current capability of the Spark gap or MOV is exceeded [23].

The purpose of series compensation of long transmission line is to reduce inductive reactance of the transmission line and to enhance power transfer ability. The simplest and most cost effective type of series compensation is provided by FSC. FSC installations are protected against over voltages using MOVs and self/forced triggered gaps [11].

Advantages FSC

i. Increases transmission capacity and reduction in transmission angle
ii. Cost is much lower than building a new transmission circuit
iii. Improves stability by reducing the transmission phase angle
iv. Reduces line inductive reactance
v. Reduces system losses
vi. Provides desired load division between circuits.
vii. Reduces line voltage drops and limits load dependent voltage drops
viii. Influences load flow in parallel transmission lines
ix. Increases system stability
x. Reduce the Ferranti effect

2.4 THYRISTOR CONTROLLED SERIES CAPACITOR (TCSC)

TCSC is a power electronic-based device that provides a fast and controllable series compensation of transmission line reactance. It has great application potential in accurately regulating power flow a transmission line by increasing transfer power capability, damping inter-area power oscillation, mitigation sub synchronous resonance (SSR) and improving transient stability. Though very useful indeed, conventional series capacitors are still limited in their flexibility due to their fixed ratings. By introducing control of the degree of compensation, additional benefits are gained. In early types of controllable series capacitors, mechanical circuit breakers are used to switch segments of the capacitor in and out according to need. This is adequate in most situations for power flow control, but for applications requiring more of dynamic response, its usefulness is reduced due to the limitations associated with using circuit breakers as switches [7, 12].

Providing FSC on the parallel path to enhance power transfer capability appears to be a feasible solution, but it may increase the total system losses. Therefore, it is advantageous to install a TCSC in transmission paths, which can adapt its series compensation level to the instantaneous system requirements and provide a lower loss alternative to fixed series compensation. The series compensation provided by the TCSC can be adjusted rapidly ensure to specified magnitudes of power flow along designated transmission line. This condition is evident from the TCSC's effectively, that is, ability to change its power flow as a function of its capacitive reactance setting [13].

After introduction of TCSC in the late 1980s TCSC implementations have been installed in several locations in the world. As controllable series compensation device and with flexible control possibilities TCSC has found to be effective especially in damping electromechanical and sub synchronous oscillations [3]. Therefore replacing the existing FSC device or part of it with TCSC may become of interest especially in a case where controlling of series compensation degree of the transmission line and new control possibilities for stability enhancement of the power system are desired.

TCSC is used in power systems to dynamically control the reactance of a transmission line in order to provide sufficient load compensation. The benefits of TCSC are seen in its ability to control the amount of compensation of a transmission line, and in its ability to operate in different modes

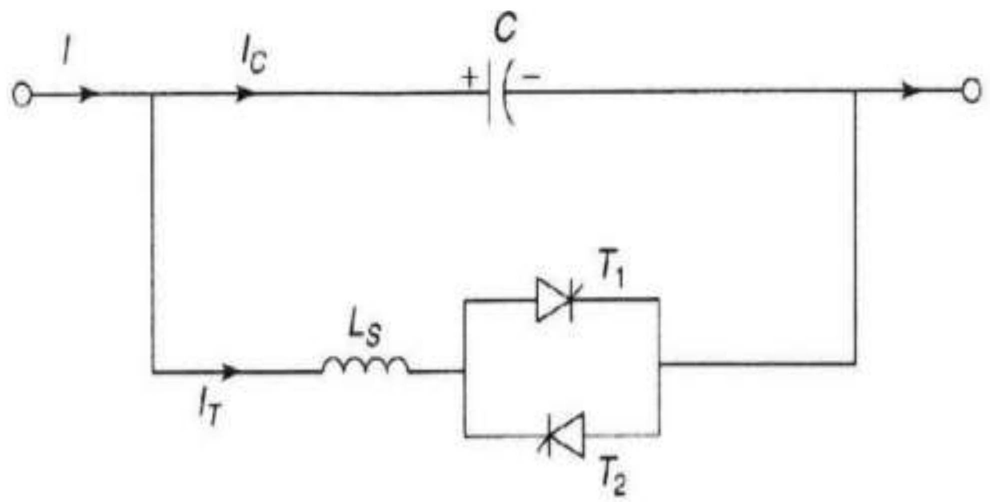


Figure 2.2: Basic Thyristor-Controlled Series Capacitor scheme

. These traits are very desirable since loads are constantly changing and cannot always be predicted [5]. Therefore, important added benefits of TCSC are the following [10, 14]

i. Increases dynamic stability of power transmission systems
ii. Improves stability
iii. Elimination of line overloads and reduction of loop flows
iv. Improves voltage regulation and reactive power balance
v. Elimination of sub synchronous resonance risks (SSR)
vi. Damping of active power oscillations and dynamic power flow control
vii. Minimizing system losses and optimizing load sharing between parallel circuits/lines

TCSC designs operate in the same way as FSC, but provide variable control of the reactance absorbed by the capacitor device. TCSC is one of the controllers used for series compensation. TCSC is a FACT device which is a combination of TCR parallel with capacitor. TCR is a variable inductive reactor X_L (α) controlled by firing angle α [15]. TCSC consist of back to back thyristor. By changing the firing angle of this back to back thyristor it is possible to vary the reactance of the TCSC as per TCSC characteristics. In inductive region power flow decreases and in capacitive region power flow is increasing [16].

For many years series compensation technique is used to adjust the power transfer between two stations by adjusting the net series impedance of the line. Installation of a series capacitor is a conventional and established method of increasing transmission line capacity, by reducing the net series impedance, thus increasing power transmission.

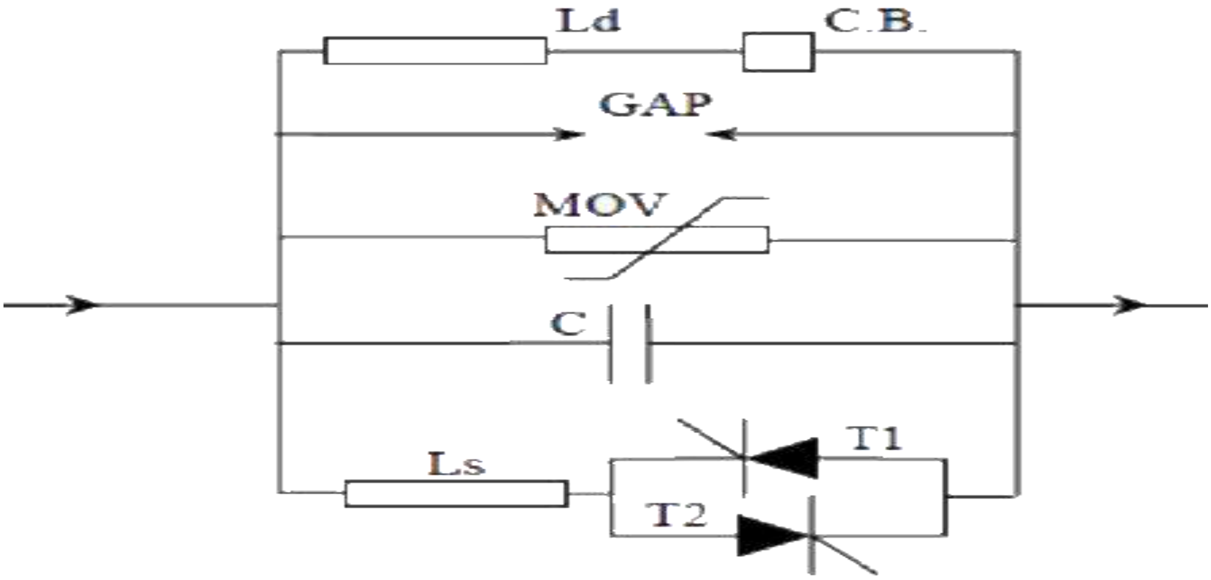


Figure 2.3: Basic Practical TCSC [14]

As this method is well established method but, due to the limitation of its slow switching time it is replaced by thyristor controllers, which are fast acting devices due to which rapid and continuous control of line compensation is possible [13]. The major benefits of TCSC are the abilities to schedule power flows along desired lines and to rapidly modulate the effective impedance in response to power system dynamics. It has been seen that with the increase in degree of compensation the power flow across the transmission line increases [16].

When the system want to decrease the power transfer from sending bus bar to receiving bus bar, it should have to operate the TCSC in inductive region. In such scenario the length of transmission line enlarged. In such mode the TCSC is rarely operated. If the system want to decrease the electric length of transmission line and want to amplify power transfer from sending bus bar to receiving bus bar, TCSC should be operated in capacitive region. Due to stability issues TCSC is not operated in resonance region.

2.5 CHARACTERISTICS OF TCSC ON TRANSMISSION SYSTEM

2.5.1 TCSC on Transmission Capacity

The main usable power in power system is the active or real power. Therefore, this should increase and control in order to decrease power outage and scarcity especially in long transmission using TCSC. Active and reactive power in a transmission line depends on the voltage magnitudes and phase angles at the sending and receiving ends as well as line impedance.

In a transmission system, the maximum active power transferable over a certain power line is inversely proportional to the series reactance of the line. Thus, by compensating the series reactance to a certain degree using a series capacitor, an electrically shorter line is realized and higher active power transfer is achieved. Since the series capacitor is self-regulated, that is its output is directly proportional to the line current itself, it will also partly balance the voltage drop caused by the transfer reactance. Consequently, the voltage stability of the transmission system is increased [17].

To facilitate the understanding of the basic issues in power flow control and to introduce the basic idea behind SC based FACTS controllers, the simple models given in

Figure *2.5* and

Figure *2.6* shown are used. The sending and receiving end voltages are assumed to be fixed and can be interpreted as points in large power systems where voltages are "stiff". The sending and receiving ends are connected by an equivalent reactance, assuming that the resistance of high voltage transmission lines is very small. The receiving end is modeled mostly as an infinite bus with a fixed angle of 0^0 [18].

The active power transfer of the system without series capacitor between the end lines is given below by neglecting the resistance value of the transmission line [19]. Assuming the line to be lossless and ignoring the effect of line charging, the real power flow, P is given

$$P_1 = \frac{V_S * V_R}{X_L} sin\delta \qquad (2.1)$$

Where;

P = active power transmittable

V_S= sending end voltage

δ= the transmission/load angle between the ends

V_R= receiving end voltage

X_L= inductive line reactance

The maximum power (Pmax) transmitted over a line is

$$P_{MAX} = \frac{V_S * V_R}{X_L} sin\delta_{MAX} \qquad (2.2)$$

Where, $sin\delta_{MAX}$ is selected depending on the stability margins and the stiffness of the terminal buses to which the line is connected. For line lengths exceeding a limit, Pmax is less than the thermal limit on the power transfer determined by the current carrying capacity of the conductors. As the line length increases, reactance increases in a linear fashion and P_{max} reduces as shown in Figure 2.4 [20].

SC compensation was first applied in the field of high voltage transmission technology, its technology development is more mature. The impact of series capacitor compensation on transmission line capacity is analyzed by a simple double machine system to observe the effects.

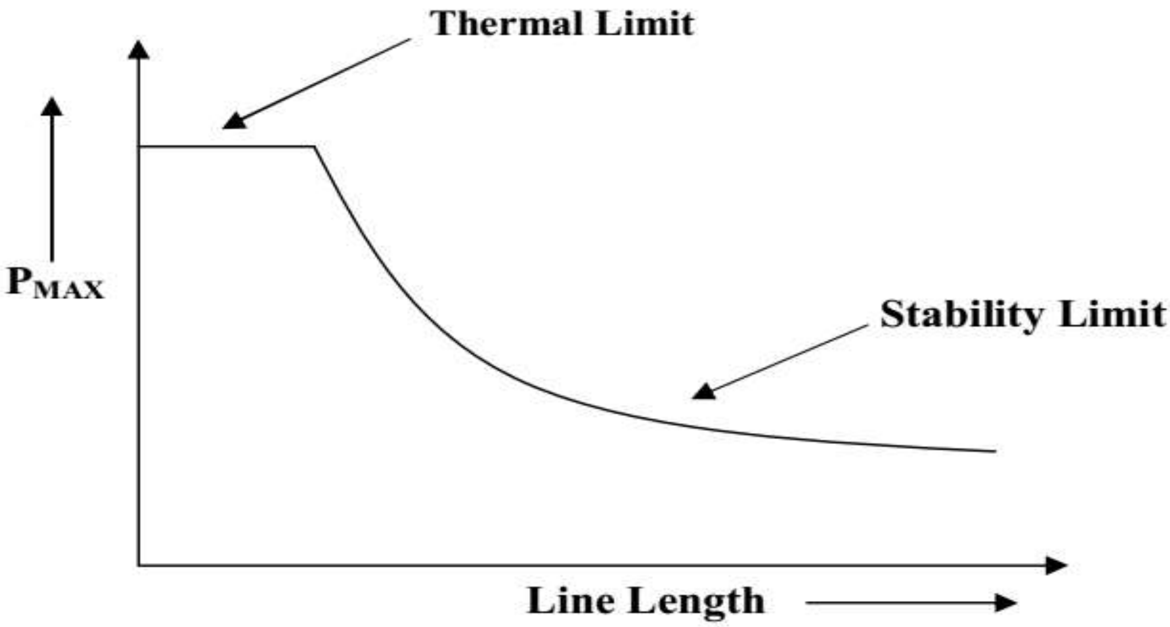


Figure 2.4 Power transfer capacity as a function of line length [20]

Series compensation is more effective in controlling the actual transmitted power which, at a defined transmission voltage, is ultimately determined by the series line impedance and the angle between the end voltages of line. It was always recognized that ac power transmission over long lines was primarily limited by the series reactive impedance of the line. Series capacitive compensation was introduced decades ago to cancel a portion of the reactive line impedance and thereby increase the transmittable power.

Subsequently, within the FACTS initiative, it has been demonstrated that variable series compensation is highly effective in both controlling power flow in the line and in improving stability. Controllable series line compensation is a cornerstone of FACTS technology. It can be applied to achieve full utilization of transmission assets by controlling the power flow in the lines, preventing loop flows and, with the use of fast controls, minimizing the effect of system disturbances, thereby reducing traditional stability margin requirement.

When the series capacitor is inserted on the line, the transmitted power in the TCSC compensated line is expressed as:

$$P_2 = \frac{V_S * V_R}{X_L - X_{TCSC(\alpha)}} sin\delta \qquad (2.3)$$

Where;

X_{TCSC}= Thyristor controlled series capacitive reactance

Since the denominator of the equation is decreased, it results in a higher power transfer for the given value V_S ,V_R and δ. From the transmission line data receiving and sending voltages are

500kV and the power angle is limited from $30^0 - 60^0$ to meet the synchronization and stability. A system is stable if the angle is suit for both transient and steady state stability [1].

2.5.1.1 Degree of compensation

The degree of compensation is defined by the ratio of capacitive reactance to the total inductive reactance of the transmission line as given by equation 2.4. At 100% compensation the effective line reactance would be zero and the line current and power flow would be extremely sensitive to changes in the relative angles of terminal voltages. In addition the circuit would be series resonant at the fundamental frequency. High compensation level also increases the complexity of protection circuit and probability of SSR. Therefore, a practical limit to the series compensation is up to 75% [20].

With the reactance of the capacitive element, i.e. the series capacitor equal to X_C and the inductive reactance of the line equal to X_L, it can be introduce a measure of the degree of series compensation, k. The degree of compensation k, is defined as [2]

$$k = \frac{X_C}{X_L} \tag{2.4}$$

And the power transfer capacity flow between the lines is expressed by using the degree of compensation.

$$P_2 = \frac{V_S * V_R}{X_L\,(1-k)} sin\delta \tag{2.5}$$

The increased power after inserting series capacitor on the line is written as

$$\frac{P_2}{P_1} = \frac{\frac{V_S * V_R}{X_L - X_C} sin\delta}{\frac{V_S * V_R}{X_L} sin\delta} = \frac{\frac{V_S * V_R}{X_L\,(1-k)} sin\delta}{\frac{V_S * V_R}{X_L} sin\delta} = \frac{1}{1-k} = 2 \text{ , for k=50\%}$$

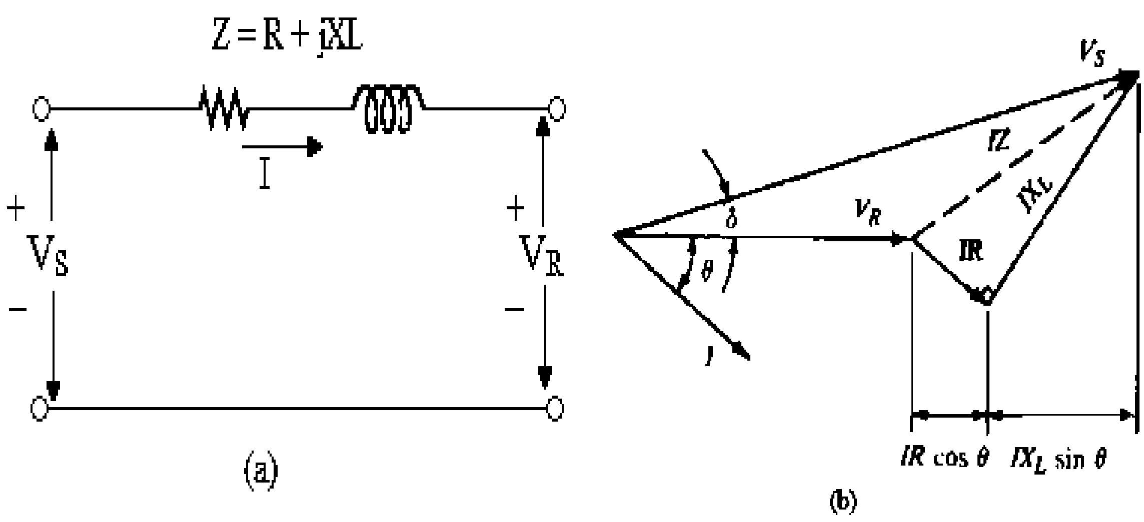


Figure 2.5: Model for calculation of real and reactive power flow without TCSC [20]

The power is doubled ideally using the series capacitor. In power transmission applications, the degree of compensation is usually chosen within the range 0.3 ≤k ≤0.7 which is less than unity and therefore, power is increased when series capacitor on the line is inserted. Since the denominator is less than unity, the power is increased after compensation process. Figure 2.4 and 2.5 are used for comparing system with TCSC and without TCSC [20].

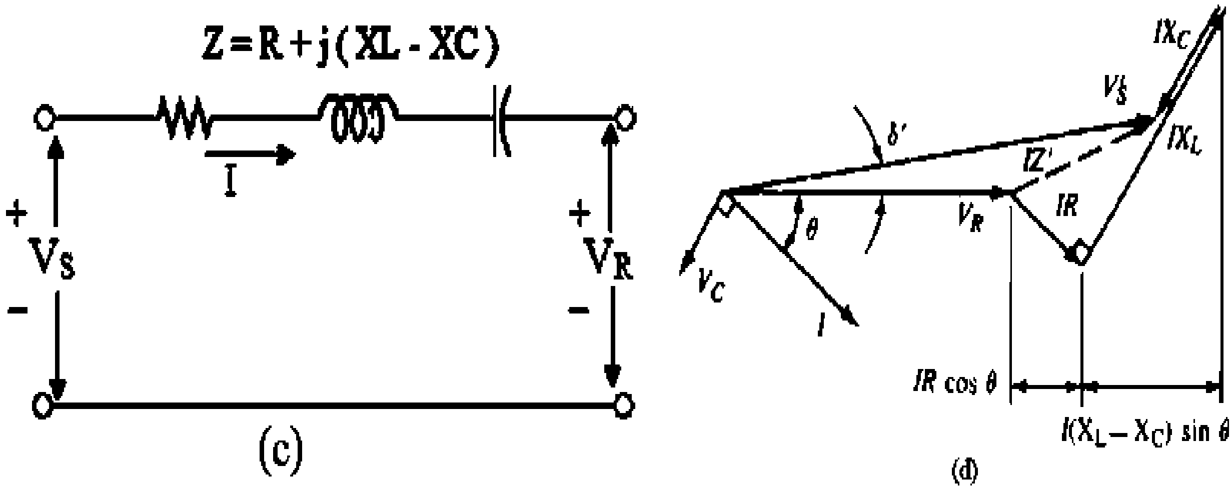


Figure 2.6: Model for calculation of real and reactive power flow with TCSC [20]

2.5.2 TCSC on Line Voltage

Reactive power is an important, but not an easy concept to understand in electrical power systems. Reactive power compensation is considered as a powerful tool for optimizing the power flow on transmission networks. Inadequate reactive power leads to voltage collapses and has been a major cause of several recent major power outages worldwide. Reactive power compensation can be provided by using FACTS devices, which are power electronics based devices that control and regulate the power flow within the power system. They are capable to reroute power through the optimum available paths regardless of the dynamics of the power system. Clear understanding of the principles of TCSC devices and how they affect the behavior of the power system becomes easier after grasping the fundamentals of designing primary building blocks of all thyristor based FACTS devices [2, 21] The voltage performance of the lines without series capacitors referring Figure 2.5 and 2.6 can be expressed as [17]

$$\Delta V = (IR_L cos\delta + IX_L sin\delta) \qquad (2.6)$$

$$\Delta V = \frac{P*R_L + QX_L}{V_S} \qquad (2.7)$$

Where;

I= current on the line

ΔV= voltage on the line

From the equation 2.6, when the load is inductive, the voltage at the end of the line is lower than the voltage at the head of the line. An inductive load causes a voltage reduction at the load side [17].

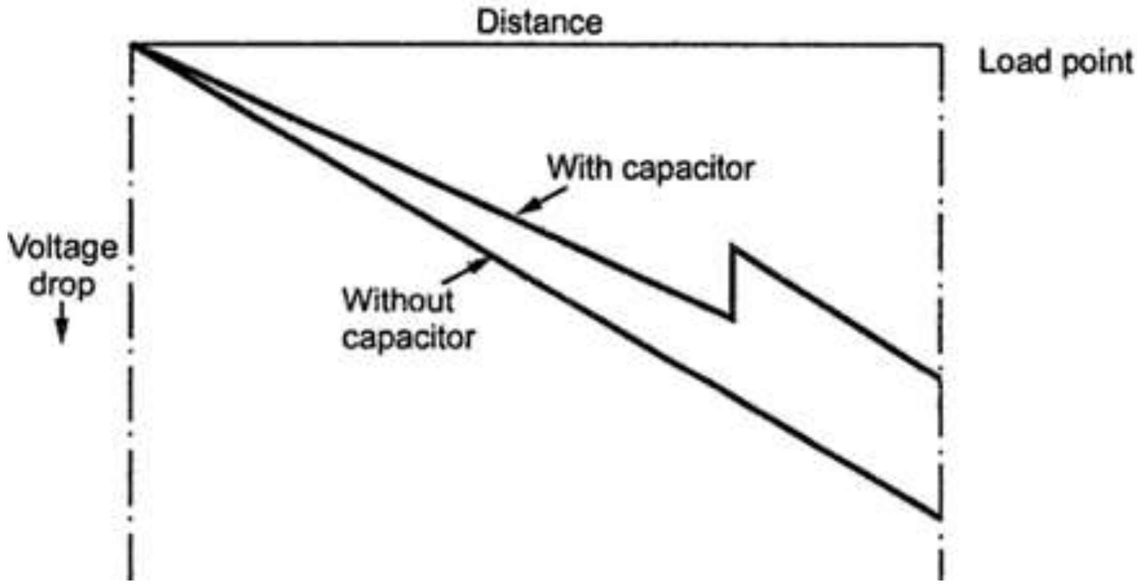


Figure 2.7: Effect of series capacitor on voltage drop [17]

Series reactive power compensation consists of controlling the reactive impedance of a transmission line to control line power flow. Series capacitive impedance was initially introduced to decrease the total line reactance and thus increases the power on the line; shunt compensation is ineffective in controlling the actual transmitted power, which at a defined transmission voltage, is ultimately determined by the series line impedance and the angle between the voltages of line. For the same level of compensation the Series Compensator size is quiet small compared to the shunt compensator perhaps the degree of series compensation is limited [22].

Reactive power compensation by means of series capacitors is an efficient way of improving power transfer in high voltage systems with long transmission lines. Series capacitors basically consist of capacitor banks connected in series with the transmission lines, thereby effectively reducing the inductive impedance of the lines. They also increase power transfer and dynamic system stability.

The voltage from source to load of the lines with series capacitors can be expressed as

$$\Delta V = (IR_L cos\delta + I(X_L - X_{TCSC})sin\delta) \quad (2.8)$$

$$\Delta V = \frac{P*R_L + Q(X_L - X_{TCSC})}{V_S} \quad (2.9)$$

The voltage collapse or drop is decreased by using the SC.

The reactive power generation or absorbed can be expressed by

$$Q = I^2 * (X_L - X_{TCSC}) \qquad (2.10)$$

$$Q = \frac{V_S(V_S - V_R cos\delta)}{X_L - X_{TCSC}} \qquad (2.11)$$

Where Q is reactive power and I is the RMS current of transmission line

2.5.3 Angular Stability Improvement

With regard to angular stability improvement, series compensation is highly efficient. By means of series compensation, the overall reactance between the line ends is reduced. From equation 2.1, it is evident that the flow of active power can be increased by decreasing the effective series reactance of the line. In other words, if a reactance of opposite sign (i.e. a capacitive reactance) is introduced in the denominator, a corresponding increase in power transmission is enabled without having to increase the angular separation of the end voltages, i.e. with the angular stability of the link unimpeded [2].

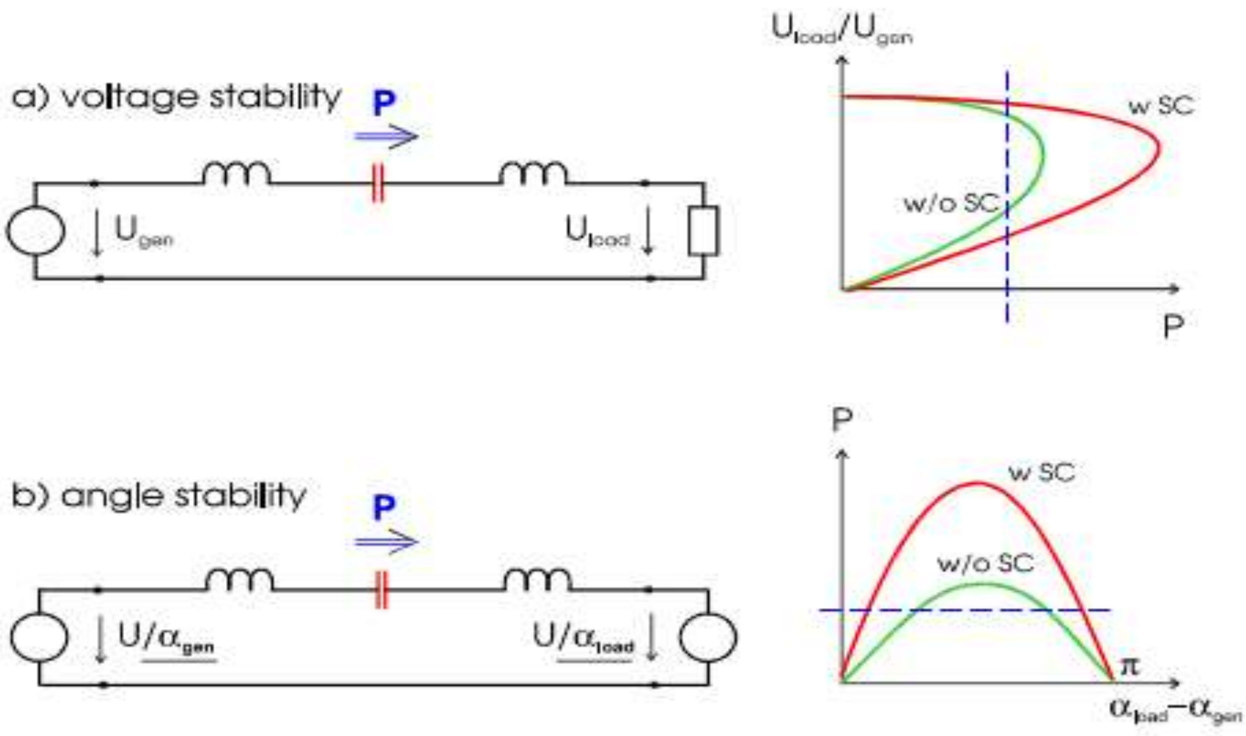


Figure 2.8: The impact of series compensation on (a) voltage and (b) angular stability [2]

Similarly it is demonstrated that by introducing a capacitive reactance in the denominator of equation 2.1, it is possible to achieve a decrease of the angular separation with power transmission capability unaffected, i.e. an increase of the angular stability of the link.

An alternative way of expressing the impact of series compensation is by means of an increase of synchronizing torque, equal to the slope of the power vs angle separation relationship given by Figure 2.8 (b). The influencing of transmission reactance by means of series compensation also opens up for optimizing of load sharing between parallel circuits, thereby bringing about an increase in overall power transmission capacity again.

2.6 OPERATION AND CONTROL OF TCSC

A TCSC is a series controlled capacitive reactance that can provide continuous control of power on the ac line over a wide range. The principle of variable series compensation is simply to increase the fundamental frequency voltage across a FC in a series compensated line through appropriate variation of the firing angle, α. A simple understanding of TCSC functioning can be obtained by analyzing the behavior of a variable inductor connected in parallel with an FC. The equivalent impedance, Z_{eq}, of this LC combination of both inductive and capacitive since the resistance is negligible [12].

$$Z_{eq} = \frac{-j}{\omega C - \frac{1}{\omega L}} \quad (2.12)$$

The impedance of the FC alone, is given by $-\frac{j1}{\omega C}$. If $\omega C - \frac{1}{\omega L} > 0$ or, in other words, $\omega C > \frac{1}{\omega L}$ the reactance of the FC is less than that of the parallel connected variable reactor and that combination provides a variable capacitive reactance.

The second criteria is if $\omega C - \frac{1}{\omega L} = 0$, a resonance develops that results in an infinite capacitive impedance an obviously unacceptable condition. And the last one is if $\omega C - \frac{1}{\omega L} < 0$, the LC combination provides inductance above the value of the fixed inductor. This situation corresponds to the inductive mode of the TCSC operation [20].

In the variable capacitance mode of the TCSC, as the inductive reactance of the variable inductor is increased, the equivalent capacitive reactance is gradually decreased. The minimum equivalent capacitive reactance is obtained for extremely large inductive reactance or when the variable inductor is open circuited, in which the value is equal to the reactance of the FC itself [13].

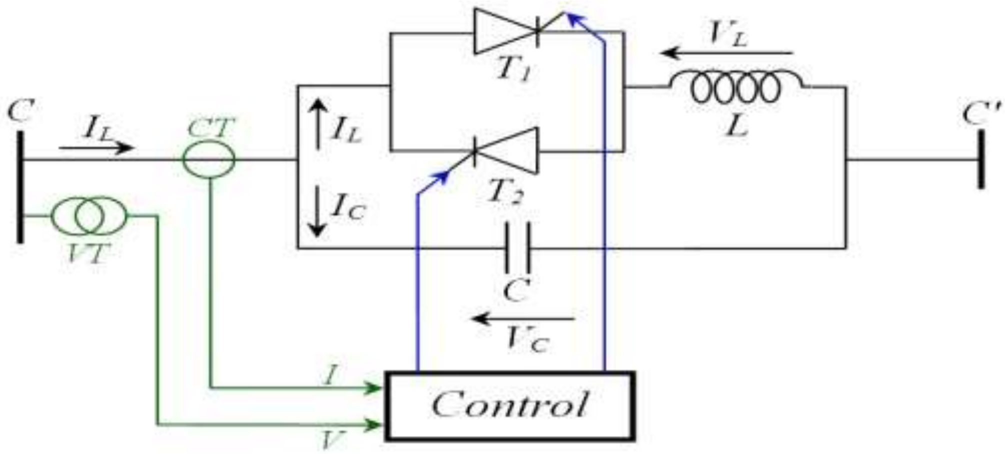


Figure 2.9: System configuration for TCSC system [22]

A general expression for the susceptance of the TCSC (B_{TCSC})

$$B_{TCR} = -j\,\frac{2\,(\pi-\alpha)+\sin 2\alpha}{\pi X_L} \qquad (2.13)$$

$$B_{TSC} = \,j\omega C \qquad (2.14)$$

$$B_{TCSC} = B_{TSC} - B_{TCR} = j\,\frac{X_L - \frac{X_C}{\pi}(2(\pi-\alpha)+\sin 2\alpha)}{X_C X_L} \qquad (2.15)$$

$$X_L = \omega L \qquad X_C = \frac{1}{\omega C}$$

For the interval of the firing angle between 0 and 90 degrees, the reactance is also given by

$X_L(\alpha) = \frac{1}{B_{TCR}} = X_L(\frac{\pi}{\pi-2\alpha-\sin2\alpha})$

The variable inductive impedance $X_L(\alpha)$ is therefore determined using by

$$X_L(\alpha) = \frac{X_L * \pi}{\pi-2\alpha-\sin 2\alpha} \qquad (2.16)$$

The impedance of TCSC:

$$X_{TCSC}(\alpha) = \frac{X_C * X_L(\alpha)}{X_L(\alpha)-X_C} \qquad (2.17)$$

There are three modes of operation of TCSC depending upon the firing angle of the pulses fed to the thyristor.

i. Thyristor blocked mode
ii. Thyristor bypassed mode
iii. Vernier or Partially Conducting Thyristor operating mode

2.6.1 Thyristor blocked Operating Mode

In this mode, also known as the waiting mode, the firing pulses to the thyristor valves are blocked. If the thyristors are conducting and a blocking command is given, the thyristors turn off as soon as the current through them reaches a zero crossing. The TCSC module is thus reduced to a FSC, and the net TCSC reactance is capacitive. In Thyristor blocked mode, the firing angle is 90 degree and thyristor are non-conducting. The TCSC's net or effective impedance is merely due to capacitive reactance. In such cases the line current is equal to capacitor current.

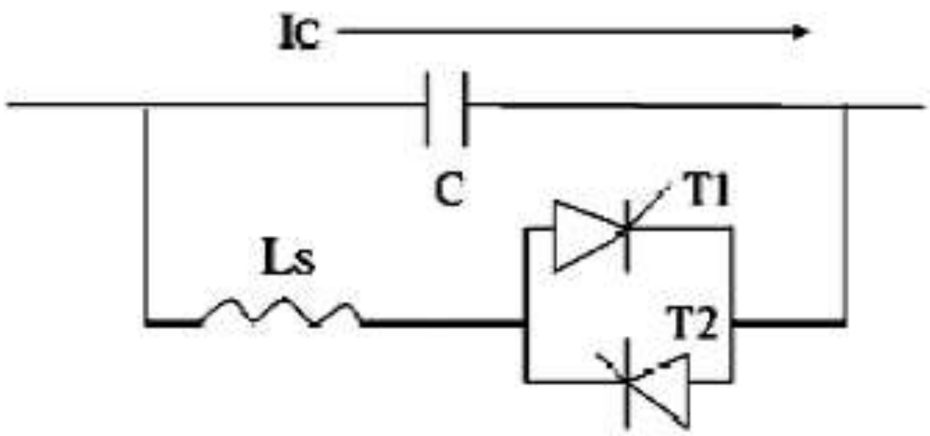


Figure 2.10: The Blocked thyristor mode [16]

2.6.2 Thyristor Bypassed mode

In this bypassed mode, the thyristors are made to fully conduct with a conduction angle of 90. Gate pulses are applied as soon as the voltage across the thyristors reaches zero and becomes positive, resulting in a continuous sinusoidal of flow current through the thyristor valves. The TCSC module behaves like a parallel capacitor–inductor combination. However, the net current through the module is inductive. Also known as the thyristor-switched-reactor (TSR) mode, the bypassed thyristor mode is distinct from the bypassed-breaker mode, in which the circuit breaker provided across the series capacitor is closed to remove the capacitor or the TCSC module in the event of TCSC faults or transient over voltages across the TCSC. This mode is employed for control purposes and also for initiating certain protective functions. A small amount of current flows through the capacitor [16].

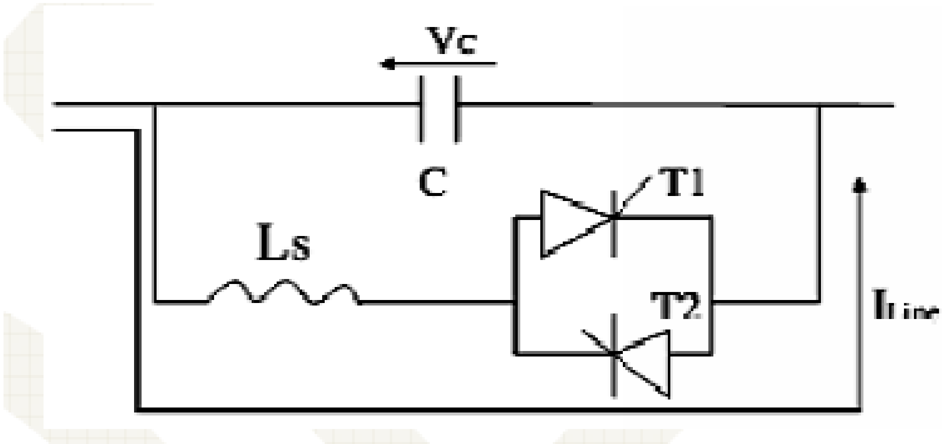


Figure 2.11: The Bypassed thyristor mode [16]

2.6.3 Vernier Operation mode

This mode allows the TCSC to behave either as a continuously controllable capacitive reactance or as a continuously controllable inductive reactance. It is achieved by varying the thyristor-pair firing angle in an appropriate range. However, a smooth transition from the capacitive to inductive mode is not permitted because of the resonant region between the two modes.

Based on the three modes of thyristor-valve operation, two variants of the TCSC 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 operation.

2.6.3.1 Capacitive Boost mode

In capacitive boost mode a trigger pulse is supplied to the thyristor having forward voltage just before the capacitor voltage crosses the zero line, so a capacitor discharge current pulse will circulate through the parallel inductive branch. The discharge current pulse adds to the line current through the capacitor and causes a capacitor voltage that adds to the voltage caused by the line current. The capacitor peak voltage thus will be increased in proportion to the charge that passes through the thyristor branch. The fundamental voltage also increases almost proportionally to the charge. From the system point of view, this mode inserts capacitors to the line up to nearly three times the fixed capacitor [11].

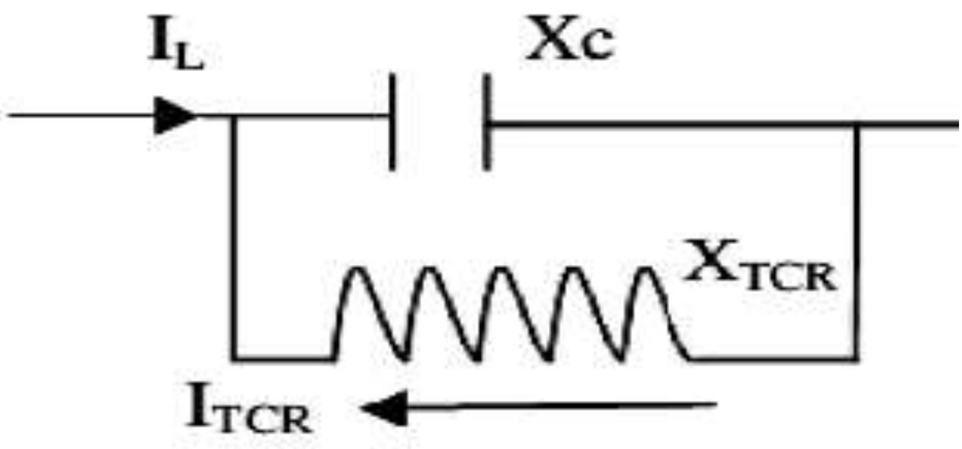


Figure 2.12: Capacitive vernier mode [16]

2.6.3.2 Inductive Boost Mode

In inductive boost mode the circulating current in the TCSC thyristor branch is bigger than the line current. In this mode, large thyristor currents result and further the capacitor voltage waveform is very much distorted from its sinusoidal shape. The peak voltage appears close to the turn on. The poor waveform and the high valve stress make the inductive boost mode less attractive for steady state operation [16].

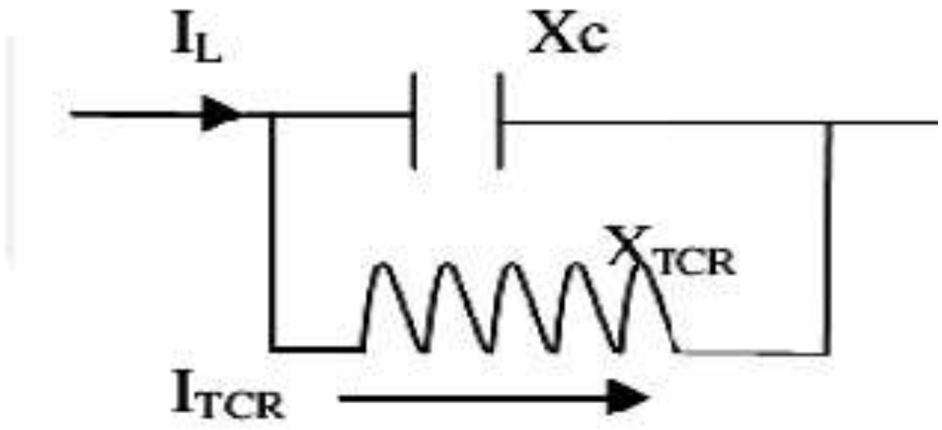


Figure 2.13: Inductive vernier mode [16]

The effective reactance of TCSC operates in three region as indicated below

i. Inductive region: - $0 \leq \alpha \leq \alpha_{L\ lim}$
ii. Capacitive region: - $\alpha_{C\ lim} \leq \alpha \leq 90$.
iii. Resonance region: - $\alpha_{L\ lim} \leq \alpha \leq \alpha_{C\ lim}$

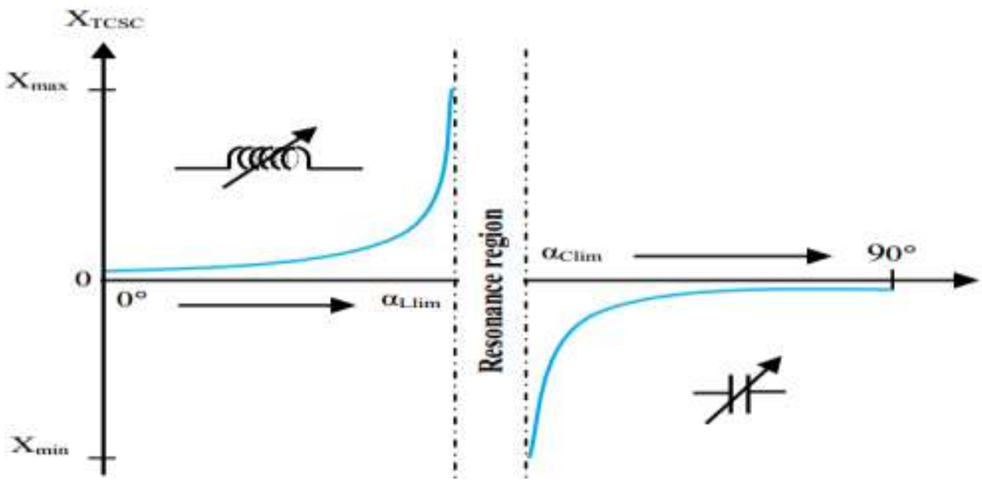


Figure 2.14: Impedance Vs firing angle characteristic curve [19]

2.7 TCSC PROTECTION METHODS

Protection is much more important in series compensation than in shunt. The main reason for this is fact that the capacitors are placed in series with the line thus making the device more susceptible to line currents than shunt capacitors. This need for additional protection is one of the main reasons why the series compensation is more costly than shunt compensation. One of the main disadvantages in using series capacitor is during the fault condition there is high reverse voltage impressed across the terminals of the capacitor, which in turn may damage the capacitor and may demand replacement. To protect this capacitor from this type of damage a special technique incorporating a MOV for the protection of capacitor. Approximately 40-50% of the total cost of a series compensation installation goes to system protection [11].

The discussion of each protection components are explained below.

MOV: They are connected with series capacitors in parallel, and can limit the over voltage of series capacitor at power frequency below the design level by non-line voltage current characteristic. Different ac system configurations as well as different fault types and point on wave fault inceptions need to be considered for the design, to establish the proper operation of the capacitor system also for future stages of the growing Ac network. There are two different types of faults which have to be considered for the design of the number of MOV housings [30].

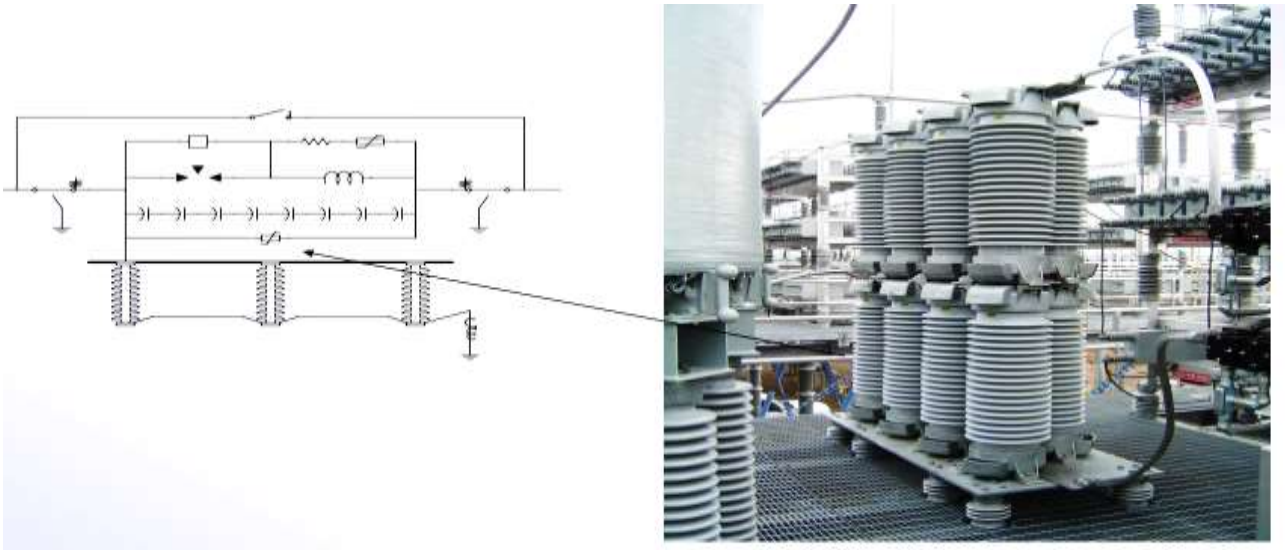


Figure 2.15: MOV protection diagram [30]

The first is external faults which are occurring outside the series compensated line terminated by breakers. The MOV must be designed to withstand external faults without damages, as the series capacitor will not be bypassed during external faults.

The second is internal faults are those occurring within the series compensated line terminated by breakers. When an internal fault is detected, the series capacitor is allowed to be bypassed by the triggered spark gap. This type of fault leads to the maximum overvoltage stress of MOV and capacitor. As soon as the instantaneous value of the MOV current.

The analyzed external fault locations taking into account different fault types like single and multiphase faults show that this type of fault leads to the highest MOV current stress without any allowed bypassing action.

Bypass switch: Common for all installations in electrical power systems is that there are protective systems for overloads and faults, and that parts of the installations can be removed from service. These are some of the reasons why series capacitors are equipped with a bypass system. This bypass system, which is connected in parallel with the capacitor bank, is designed to limit the voltage over the bank. The bypass system thus has a protective function but is also used to switch the series capacitor in and out during planned measures, such as regulation of series capacitance as well as any maintenance on the series capacitor bank or other component parts.

There are a number of different solutions for bypass systems. The economy aspect is naturally important, and the grid's configuration, its electrical properties and customer specific requirements for protective functions come into play when choosing a bypass system.

In addition to the above mentioned requirements, the bypass switch must be able to carry the rated current and the rated short circuit current in the closed position, as well as withstand the overvoltages specified across the open gap and phase to earth. It should be noted however, that the bypass switch is not intended to interrupt short circuit currents which may occur in the system.

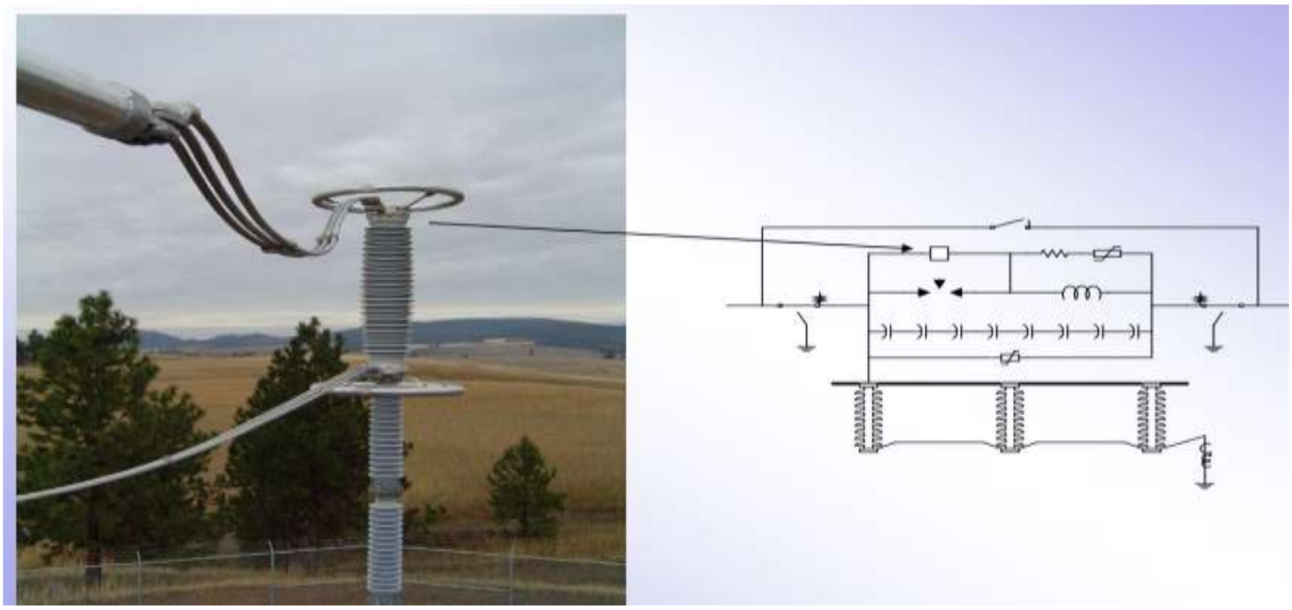


Figure 2.16**:** Bypass switch diagram [30]

Spark Gap: Protection spark gaps form an important part of series compensation schemes in high voltage transmission system. Their primary function is to safeguard the series capacitors from transient over voltages. In the event of fault, the line current may momentarily increase and the corresponding voltage across the capacitor banks may exceed the short time over voltage limit. The Gap, which is connected in parallel with the bank, is set to spark over when the voltage across the bank exceeds the permissible level. Thus the spark gap acts as a bypass for the capacitor during faults [25].

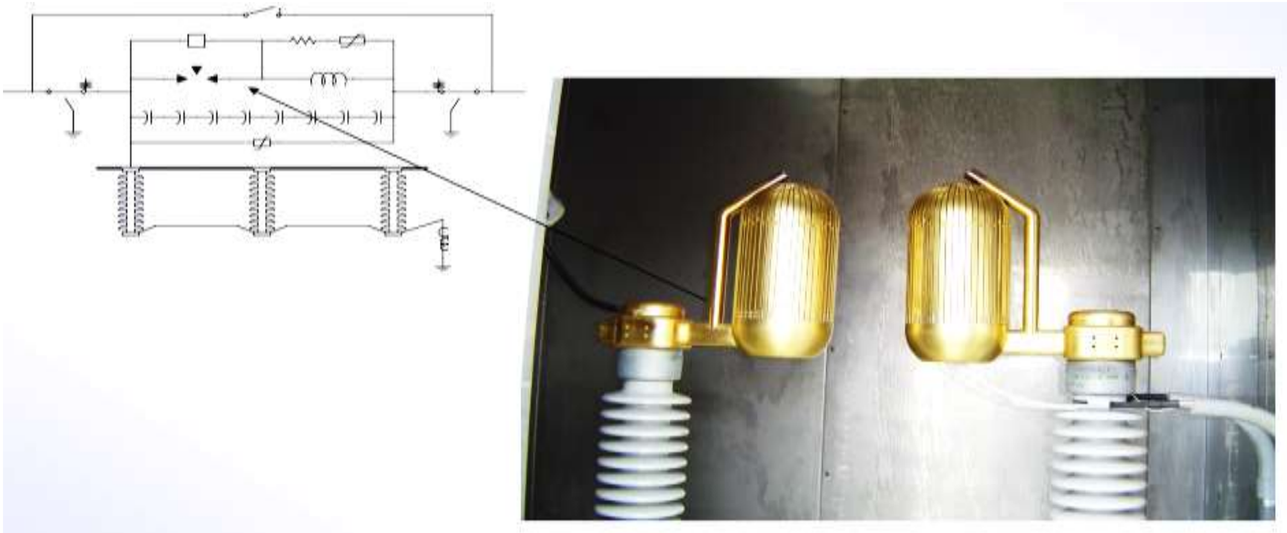


Figure 2.17: Spark Gap scheme [30]

Damping system: It can limit the discharge current amplitude and frequency of the capacitor banks, and provide appropriate damping during discharge process. The discharging damping circuit comprises primarily an air core reactor. In addition, it shall be capable of limiting the peak capacitor discharge current to less than the capability of the bypass switch.

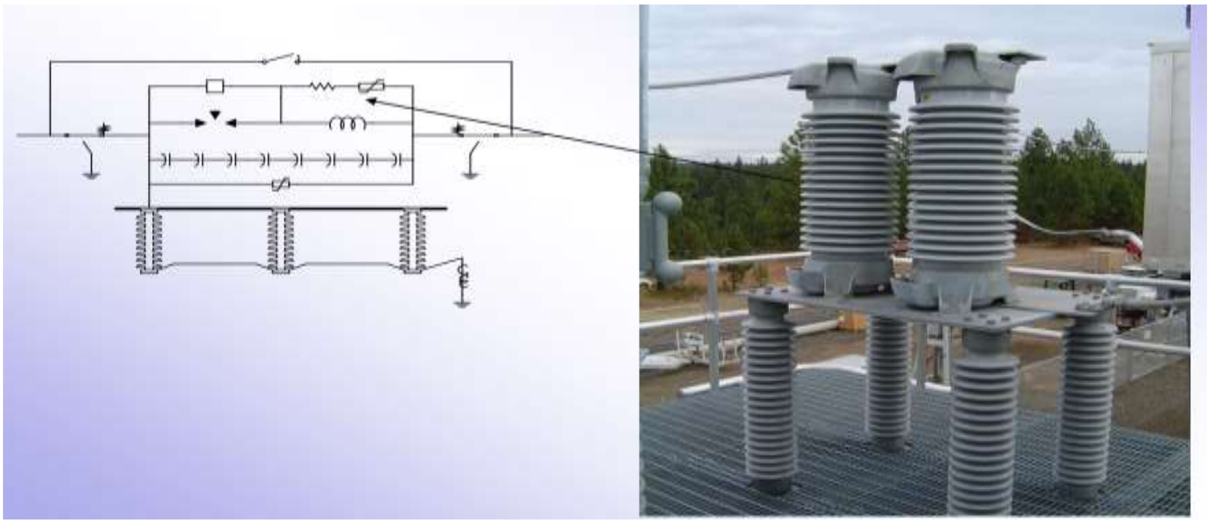


Figure 2.18: Damping system [30]

The following are some of the available protective functions of the series capacitors:

i. Capacitor unbalance protection
ii. Capacitor overload protection
iii. Line current supervision
iv. Flashover to platform protection

v. MOV overload protection
vi. MOV failure protection
vii. By-pass switch failure protection

2.8 DRAWBACKS FSC

Even if there are so many advantages of SC, there are also some drawbacks. As mentioned above, a SC is used to control power flow means to increase the transmittable power capacity. However, because the SC takes control by it decreasing impedance of the line, the following problems are caused during fault conditions. When the decreased line impedance contributes to an increased fault current, it becomes necessary to review the existing transmission line protection system and substitute a high performance circuit breaker, thereby resulting in loss of money and time. Moreover, the TCSC is inserted into the transmission lines in series; hence, when a fault takes place nearby, more than tens of kilovolts are applied because of the fault current. This voltage lays considerable stress on the TCSC, even causing dielectric breakdown in the facilities [26]. The main common causes are listed below.

i. Increases short circuit currents
ii. Increases line-to-ground voltages adjacent to bank
iii. Distance relays may trip for external faults - overreach
iv. Can create or amplify generator sub-synchronous resonance (SSR)

To overcome those problems it is necessary to control the impedance accurately and continuously according to the power demand or loads connected to the system. This can be controlled using TCSC by inserting I the same way as FSC rather than fixed it is uses variable reactance in the system.

2.9 LITERATURE REVIEW

Literature reviews related to this thesis study are summarized below.

The paper entitled "Power Flow Control in Power System Using FACT Device Thyristor Controlled Series Capacitor (TCSC)", by Priyanka Kathal, Arti Bhandakkar, ISSN: 2320-3331, Vol. 7, Issue 6 (Sep. - Oct. 2013), PP 72-83 proposed power flow control in a power system network by incorporating TCSC and SVC devices. The goal of the paper was achieved in power control and stability limits and simulated it using MATLAB/SIMULINK on two area four machine 11 bus test system model [18].

The literature indicated in [12], by using the TCSC Controller in transmission line the real power of transmission line is increased i.e power transfer capacity of EHV Transmission line increased.

Also the receiving end voltage increased to match the value nearly to the sending end voltage that increased the stability of the transmission network.

"Voltage Profile Improvement with Thyristor Controlled Series Capacitor" by Yadu Ram, Dr. Dharmendra Kumar Singh, Amit Agrawal : International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering (An ISO 3297:2007 Certified Organization) Vol. 4, Issue 6, June 2015 which Simulation has been done for 33kv 110 km medium transmission lines. During the power flow from sending to receiving end the losses of power and voltage drop appear and their objective is to minimize that drops and improve power transfer capability of the system and studied the voltage sag and swell is generated during sudden switching on/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/swell and harmonics can be compensated, and hence the power transfer capability of line can be improved [20].

The work entitled as "A review on Series Compensation of Transmission Lines and Its Impact on Performance of Transmission Lines" also discussed the insertion of series capacitor in transmission line reduces net transfer reactance of line and it gives greater power transfer capability of the lines. It also improves power flow control & voltage regulation of lines and at the end the authors achieved their goals and published it (ISSN: 2321-9939) [26].

The literature entitled under 'Modelling, Simulation and Performance Analysis of FACTS Controller in Transmission line.' The main objective of this study was to implement FACTS devices in a transmission line for dynamic reactive power compensation to increase the line capacity. All the simulations are carried out by using MATLAB/SIMULINK software. The simulation result shows the performance of FACTS devices in transmission line. The transmission line is considered to be a short transmission line hence capacitance of the line is neglected. The resistance of the line is 5Ω and the inductance is 0.06mH. The source impedance is (0.01+0.001) Ω and the load is kept constant at 25MW and 50MVAR .The current and voltage measurement blocks are used to measure the voltage and current at source. By the use of active and reactive power measurement block, the real and reactive power in the load is measured. This study concluded that using TCSC increases power flow through the system increases capacitance that both active and reactive power increases with the increase in capacitance value up to 30μF. Beyond this value both real and reactive power starts decreasing. So the better compensation is obtained at a capacitor value of 30μF [27].

CHAPTER THREE

3. DESIGN AND MODELLING OF TCSC

This chapter deals with modelling and design of main components of TCSC in the HVAC transmission system. Modelling of each component has been discussed based on bench mark FSC Dedessa substation model, which includes transmission line. The Generator ratings and Infinite bus (External Grid) data have been collected from EEP. According to this, each main component has been designed to meet the requirement of transmission system to transfer 6000 MW power from the Generation to the Holeta Substation. This chapter also includes the series capacitor data of Dedessa Substation and the transmission line parameters required to model the study.

3.1 ANALYSIS AND MODELLING OF DEDESA SUBSTATION FSC

3.1.1 Main Technical Parameters of Series Capacitor

The Dedesa 500kV substation has installed 8 sets of 500kV series compensation device which to H.E.P.P GERD each back to the outlet are installed 1 sets of 516MVar FSC. This is done to limit the design voltage of the series capacitor bank and to maintain a reasonable acceptable voltage profile on the transmission line. The degree of SC located on line GERD to Dedesa is 50%. The SC is departed into two segments, the degree of the two segments are 20% (206Mvar) and 30% (310Mvar) respectively which to Holeta each back to the outlet are installed 1 sets of 411 MVar FSC. The degree of SC located in line Dedesa to Holeta is also 50% which is departed into two segments, the degree of the two segments are 20% (164Mvar) and 30 % (247Mvar) respectively [4]. From Figure 3.1 and**Error! Reference source not found.**, there are four incoming and outgoing lines and each line has three phases. Each phase has series capacitor in both segments. Therefore, the total capacitors installed can be easily determined by multiplying with total lines and each tracks installed. The number of capacitor banks in a transmission line are dependent on the line length, percent compensation, rated line current etc. Basically, the intent is to maintain the bank RMS voltage and transient voltages to a manageable design level. For a typical 500 kV system it is desirable to keep the series capacitor bank RMS voltages below 100 kV (less than 20 %) and the transient voltages below 300kV (below 60 %). For more information Table 3.1 is given [4].

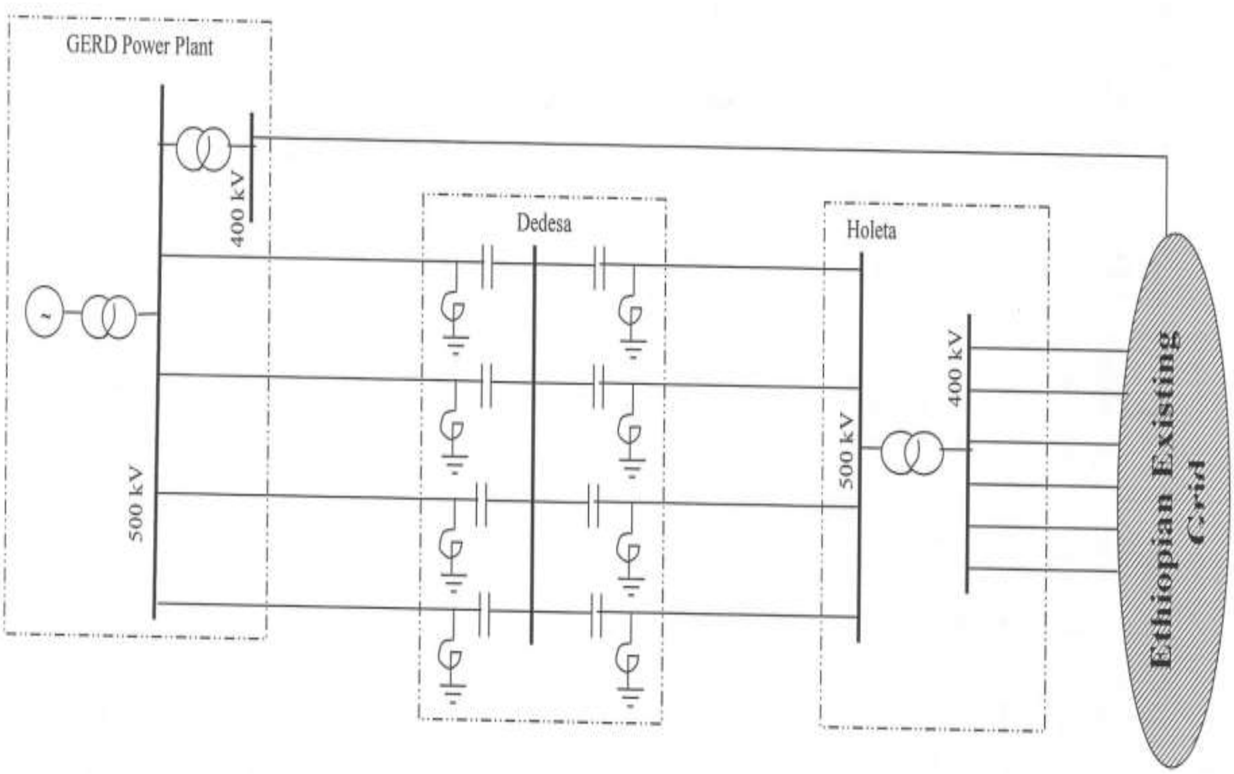


Figure 3.1: GERD-Holeta related system equivalent circuit [4]

From the FSC specification designed, the following rated data are given in Table 3.1.

Table 3.1: SC Rated Parameter Data [4]

Description	GERD-Dedesa Line	Dedesa-Holeta Line
Degree of compensation /%	50	50
Rated current /A	1900	1900
Rated reactance /Ω	47.6	38
Rated voltage /kV	90	72
Rated output of three-phase /MVAr	516	411
Rated energy of MOV(with spare) MJ/phase	35	35
Protective level (with spare) p.u	2.5	2.5
Rated reactive power at rated current (MVar/3 phase)	135	90
30 minute overload current profile of SC (A_{rms})	2565	2565

3.1.2 Single Line Diagram of FSC

Starting from the generation station, there are 16 units which have the capacity to generate each 375 MW power and two doubled transmission lines. The other necessary data are already mentioned in Table 3.1 above. The single line diagram comprising the main components is shown below. The capacitive reactance is 83.67425 ohms, for each of the four parallel lines, the series capacitor is 38.0335μF. The nominal continuous current all capacitor banks are designed for is 1900 A rms with temporary overload currents up to 2565A rms for 10 min.

Under normal condition the ac line current flows through the capacitor resulting in a steady state voltage drop across capacitor and varistor. In case of ac line faults the short circuit currents increases the voltage drop across the capacitor until it is clipped by the MOV. In this way the capacitor units are therefore, protected by voltage clipping. During voltage clipping the MOV dissipates energy. To protect the MOV against excessive energy dissipation a fast operating spark gap is connected in parallel to the capacitor performing an immediate bypass after gap triggering. To protect the gap against excessive arcing stresses the bypass switch closes about 50msec after gap firing. Depending on the severity of the ac line fault the capacitor units can be protected by different bypassing strategies.

The damping circuit consists of a reactor and a parallel small gap and series resistor is connected in parallel with the spark gap and bypass switch. Sufficient damping must be provided to limit the high frequency discharge current of the capacitor.

3.1.3 Layout Considerations

The SC components are installed on a platform which is connected to the high potential of the ac-transmission line. This helps to the lowest creepage distances and flashover voltages across the components. The platform itself is built up on reinforced structures of porcelain insulators to provide an appropriate line to earth creepage distance with a height of approximately 6 meters. The capacitor is built up in four racks in a differential protection scheme to detect capacitor unit unbalances. The damping circuit resistor is located within the damping reactor coil. The two spark gap housings are installed on top of each other to save platform space. The MOV housings including the spares per phase are built up in two stacks. The bypass switch is not installed on the platform but located beneath the platform on the ground. Figure 3.2 shows the platform layout and associated bypass switch for one phase.

Figure 3.2**:** Basic SC layout diagram

3.1.4 System Analysis of the Dedesa Substation

3.2.4.1 Analysis of Dedesa Substation without TCSC

The following assumptions are adopted to simplify the analysis:

- 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 [19].

Table 3.2: Transmission Line parameters [4]

Description	Values
Positive sequence of resistor	0.018627 Ω/km
Positive sequence of reactance	0.269975 Ω/km
Positive sequence of capacitance	13.67949 nF/km
Zero sequence of resistor	0.194014 Ω/km
Zero sequence of reactance	0.948489 Ω/km
Zero sequence of capacitance	8.706821 nF/km

The impedance of the transmission line GERD- Dedesa Holeta is calculated as follow.

- The positive sequence impedance, Z_1 is calculated as

$$Z_1 = R_1 + j(X_{L1} - X_{C1}) \qquad (3.1)$$

Let's see the effect of the line resistance (R) on the magnitude and compare without it.

Table 3.3: Transmission line length [4]

Transmission line section	Line length (km)	OPGW length (km)
GERD to Dedesa	345	355.35
Dedesa to Holeta	275	283.25
Holeta to Sululta	31.163	32.10
Holeta to Akaki II	49.27	50.75
Holeta to Sebet II	17.446	17.97

The sequence impedance of the GERD-Dedesa- Holeta transmission line is evaluated. Since the system has identical parameters and its total overhead length is 620km, the overall positive reactance of the line is determined below.

$$R_1=0.018627*620=11.55\Omega$$

$$X_{L1} = 0.269975*620=167.3845\Omega \text{ and}$$

$$L=\frac{167.3845}{100\pi} = 0.5328H = 0.8594mH/km$$

$$X_{C1}=\frac{1}{2\pi f C_1} \text{ and} \qquad (3.2)$$

$$C_1 = 13.67949*10^{-9}*620=8{,}481.13*10^{-9}$$

Inserting this value into the reactance formula, $X_{C1} = 375.31\Omega$

Subsisting those values in to equation 3.1, the positive sequence impedance is

$$Z_1 = 11.55 + j(167.3845 - 375.31)$$

$$\underline{Z_1 = 208.23\Omega}$$

Without the resistance $Z_1 = 207.91\Omega$ which is almost the same. This is why it is ignore most of time the resistance in long transmission lines and only accounts 6.9% of the inductance of the line.

Table 3.4: Summary of Transmission line sequence reactance

Sequence	R	L	C
Zero	120.89 Ω	1.872H	5.398Mf
Positive	11.55 Ω	0.5328H	8.481µF

Table 3.5: Inductive and Capacitive reactance

Sequence	Inductive reactance	Capacitive reactance
Zero	588.06 Ω	589.66 Ω
Positive	167.3845Ω	375.31 Ω

The equivalent reactance of the four line is determined by dividing to four. Therefore, $X_L = 41.846\ Ohms$. From this point of view, it is known that designed power already fixed and the sending and receiving voltages as well as the reactance of the transmission line. The active power transfer of the system without series capacitor between the end lines is given on equation 2.1. For practical stability issue, the power angle is limited to 30^0 to 60^0

$$P_1 = \frac{V_S * V_R}{X_L} sin\delta_{MAX} = \frac{500*500}{41.84} sin60$$

$$P = \underline{\underline{5,175MW}}$$

Even if it is the impossible to get the voltage in receiving end at 500kV and power angle at 60 degree, power is below the designed for GERD, and this is why it is important to implement the series capacitor in the line in order to increase the power transfer capacity.

The voltage at the receiving end of the lines without series capacitor is given in equations 2.6 and 2.7 and the angle is also calculated from the transmission lines.

$$\Delta V = (V_S cos\delta + V_R sin\delta)$$

$$\Delta V = (IR_L cos\delta + IX_L sin\delta)$$

The line current is calculated from the RMS current given in Table 3.1 of the series capacitor is

$$I_L = \sqrt{2} * I_{RMS} = \sqrt{2} * 1.9kA = 2.687kA \text{ So, the voltage is}$$

$$\Delta V = (2.687 * 11.55 + 2.687 * 167.3845 sin86)$$

$$\Delta V = \underline{\underline{479.5}}kV$$

3.2.4.2 Analysis of Dedesa Substation with FSC

If the series capacitor is inserted on the line to compensate the inductive reactance, the 3-phase transmitted power in the SC compensated line is expressed as:

$$P_2 = 3 * \frac{V_S * V_R}{X_L - X_{TCSC}} sin\delta$$

The rated data for the series capacitor are given in Table 3.1. For the compensation system, the capacitive reactance is obtained from the inductive reactance of the transmission line already calculated above. The degree of compensation is 50% and X_{L1} =167.3845Ω for 620km. Therefore,

$$X_C = 0.5 * 167.3485 = 83.67425\Omega$$

The series capacitor is $X_{CS} = 167.3485 - 83.67425 = 83.67425\Omega$. The capacitance is

$$Cs = \frac{1}{2\pi f X_{CS}} = 38.05\mu F$$

In this case the capacitive reactance and thyristor controlled series capacitor reactance are the same. The power transfer capacity flow between the lines can be also expressed by

$$\underline{I} = \frac{\underline{V_S} - \underline{V_R}}{jX_L(1-k)} = \frac{V_S\angle\delta - V_R}{jX_L(1-k)} \tag{3.3}$$

$$\underline{S}_{12} = 3.\underline{V_S}\,\underline{I}^* = 3.\frac{V_S V_R sin\delta + j(V_S V_R cos\delta - V_S R)}{X_L(1-k)} \tag{3.4}$$

$$\text{with } V_S = V_R = V \text{ and } X_C = k\,X_L$$

Since there are four incoming and outgoing line the equivalent capacitance is divided by four simply since these lines are identically rated.

$$P_2 = \frac{V_S * V_R}{X_L\,(1 - k)}\sin\delta = \frac{500 * 500}{20.923}\sin 30$$

$$P = \underline{\underline{5975}}\ MW$$

But all of the above calculations are ideally because there is not power angle 30^0 in practice and the receiving end voltage cannot be at its rated value of 500kV line since it depends on the loads connected and line parameters. So voltage drop can be occurred and we couldn't get this amount of power. From this, the capacity of power couldn't be increased above the designed power. But this line can be load until this power is reached when series capacitor is used without any thermal and other heating effects on the lines. When the power angle is taken as 60 degree, the power is increased.

The voltage from source to load of the lines with series capacitors can be expressed as using equations 2.9 to 2.11.

$$\Delta V = (V_S\cos\delta + (V_C - V_R)\sin\delta$$

$$\Delta V = (IR_L\cos\delta + I(X_L - X_{TCSC})\sin\delta$$

The voltage varies as the TCSC reactance varies. We can only calculate the voltage for the FSC.

3.1.5 Main Equipment of the TCSC

i. All engineering, manufacturing and supply of the components of the SC, their assemblies and accessories.
ii. All capacitor banks, including a numbers of capacitor units suitably connected in series and parallel, as required by the design.
iii. Overvoltage protection
iv. Surge protection
v. All circuit breakers including bypass, disconnect switches, and earth switches are required
vi. Complete SC platforms, fully insulated and supported as ground level.
vii. SC lighting protection are few of them

Series Capacitor banks for GERD and Holeta 1-4 lines includes the following equipment and accessories

[1] Four (4) 500kv ,single pole, vertical break disconnector with earthing switch at one ends, 50Hz, 500Amp,40kv/1sec, for three phase operation, outdoor operation installation, with drive mechanism for manual gang and motor operation.

[2] Three (3) 500kv ,single pole, vertical break disconnector with earthing switch at one ends, 50Hz, 5000Amp,40kA/1 sec, for three phase operation, outdoor operation installation, with drive mechanism for manual gang and motor operation.

[3] Twenty (20) post insulators, 500kv, outdoor

[4] Three single pole, bypass switch for three phase operation, SF_6 insulated, with pre insertion resistor, DC motor charged spring mechanism, outdoor, 50Hz, 5000Amp, 40kA/1 sec.

[5] Three (3) single phase configuration SC banks, 500kv, complete with current limiting and damping circuit , MOV, protective spar gap, insulators and bus works and instrument transformers and others

3.2 TCSC DESIGN FOR DEDESA SUBSTATION

Design Criterion of TCSC

The main reason to design TCSC at Dedesa substation is because the series capacitor already installed is fixed and it is difficult to response FSC when the impedance is variable. The TCSC advantage over other series compensating devices is that its reactance can be instantaneously and precisely controlled.

TCSC is used in power systems to dynamically control the reactance of a transmission line in order to provide sufficient load compensation. The benefits of TCSC are seen in its ability to control the amount of compensation of a transmission line, and in its ability to operate in different modes. These traits are very desirable since loads are constantly changing and cannot always be predicted. TCSC designs operate in the same way as FSC, but provide variable control of the reactance absorbed by the capacitor device.

The TCSC offers the following advantages over conventional fixed series compensation:

i. Usable for dynamic load-flow control
ii. Power Oscillation Damping
iii. Higher degree of compensation
iv. Better capacitor protection due to thyristors

The basic idea behind the TCSC scheme is to provide a continuously variable capacitor by means of partially canceling the effective compensating capacitance by the TCR. The TCR at the fundamental system frequency is continuously variable reactive impedance, controllable by delay angle α. The steady state impedance of the TCSC is that of a parallel LC circuit, consisting of a fixed capacitive impedance X_C. Therefore, using the firing angle, TCSC is able to control the variable impedance.

Sizing of MOV

The rated current of 1.9kA, equivalent to the transmission line capacity of 1500 MVA, is considered for sizing TCSC protection. For the sake of simplicity, only threshold values and their significance has been presented in this thesis. MOV rating after considering an overload factor of 2.5 is calculated as 562 kV. The protective level current of MOV I_{PR} corresponding to MOV rating of 550kV, I_{PR} is the RMS value of the minimum amount of the current through SC protection that would lead to MOV conduction. For protecting MOV against large fault currents, SC protection is set to immediately bypass the MOV through spark gap if the MOV instantaneous current is above the bypass current ($I_{BP} = kI_{PR}$) [29].

The protective level current, I_{PR} is calculated as

$$I_{PR} = \frac{V_{PK}}{\sqrt{2}X_{TCSC}} \tag{3.5}$$

$I_{PR}=\frac{550}{\sqrt{2}*83.67425} = 4.6478$kA the current bypass, I_{BP} is given by

$$I_{BP} = kI_{PR} \tag{3.6}$$

The safety factor, k is selected properly in order to protect the overload current during the fault and its value for GERD-Dedesa-Holeta series capacitor is 2.5 as given in Table 3.1. Therefore, the MOV protection level required to protect the capacitors at 2.5 times the nominal capacitor voltage.

$$V_{prot}= \sqrt{2} * 2.5 * I_{RMS} * X_{TCSC} \tag{3.7}$$

$$V_{prot}= \sqrt{2}* 2.5*1.9kA*83.67425= 562 \text{ kV}$$

For practical applications, MOV in spark-gap configurations is designed to tolerate the energy storage for four cycles of the worst possible case of external fault conditions without getting bypassed while for gapless scheme, MOV is sized corresponding to the most severe internal fault.

The maximum energy dissipation capacity of MOV is 40 MJ/phase as it would result in the bypass of MOV for considerable number of fault and is in the range of practical applications. The value of 40 MJ/phase for the maximum energy dissipation capacity of MOV is simulated using DigSILENT for different type faults and locations of the faults. The faulty duty of the MOV is summarize below.

Table 3.6: The time duration for faults external/internal to the line

Fault type	Time duration
Single phase to ground	5cycles, 0.5 sec dead time, 12 cycles*
Phase to phase	5cycles, 0.5 sec dead time, 12 cycles*
Three phase	12 cycles*

*The MOV may be bypassed after the 12 cycle period for external faults.

**The MOV may be bypassed during the 5/12 cycle period for internal faults.

The 12 cycle in the time duty cycle corresponds to 240ms at 50 Hz. This is equivalent to the backup breaker fault clearing time.

The 5 cycle in the time duty cycle corresponds to 100ms at 50 Hz. This is equivalent to main protection breaker fault clearing time.

There are different types of damping systems in addition to the MOV. These may be resistor only, reactor only, resistor and reactor and also MOV with resistor in parallel of reactor. Therefore, Dedessa Substation's damping system is MOV with resistor in parallel of reactor. These are taken directly from the transmission line data of GERD-Dedessa-Holeta line. Therefore, these values are specified as

R=4.6 Ω, L= 1.7mH

The purpose of the resistor is to add damping to the capacitor discharge current, and thus quickly reduce the voltage across the capacitor after a bypass operation and the purpose of the varistor is to avoid fundamental frequency losses in the damping resistor during steady state operation.

Bypass switch

The bypass switch shall be connected in parallel to the capacitor bank and overvoltage protective device. The switch is required for intentional or emergency by passing of the capacitor bank and its reinsertion. The type of the circuit breaker shall be the SF6 type with spring operated mechanism. It shall be designed and tested according to the standards of IEC62271-109,"High voltage switchgear and control gear of alternating current SC bypass switch [4]. The power frequency withstand voltage, 1 minute, kV is

i. To earth 620kv and across open contact 800kv and has rated short circuit current 40KA/1s.
ii. The maximum closing time for the bypass CB for TCSC bank is less than or equal to 32s.
iii. The maximum closing time for the bypass CB for TCSC bank is less than or equal to 65s.

Maximum closing time of the bypass circuit breaker for the TCSC bank is less than or equal to 32ms and the maximum opening time is less than or equal to 65ms. The bypass switch is used for bypassing and insertion of the series capacitor on the line.

[1]. Bypassing of series capacitor

The bypass switch is able to bypass the series capacitor bank when it is pre-charged to its protective level (limiting voltage of the overvoltage protector) and consequently withstand the associated inrush current from the capacitor bank superimposed on the line fault current.

[2]. Insertion of the series capacitor

The bypass switch is able to transfer the load current from the bypass circuit path to the SC path and withstand the associated recovery voltage, with peak values of up to its protective level.

Location of the TCSC

A series capacitor bank can theoretically be located anywhere along the line. But it is very important to be selective the location and size of the series capacitor. The addition of series compensation will result in higher short circuit duties and may require costly mitigation measures for SSR, if they are close to generators with SSR risk. Based on these considerations, a fixed level of series compensation is selected. Where there are several parallel paths or transmission lines, 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, and 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 [30].

i. Midpoint of the line.
ii. Line terminals
iii. 1/3 or 1/4 points of the line

Therefore, the Dedesa substation is located somewhat at the midpoint of the total transmission system and is better since the degree of compensation is also 50%.

The location of thyristor controlled series capacitor banks is selected based on the following factors.

i. The compensation “effectiveness” of the series capacitor varies as a function of the series capacitor location along the line.
ii. The series capacitor location affects the voltage profile along the line.

iii. The transmission line protection and the series capacitor main circuit equipment are affected by the series capacitor location.
iv. The series capacitor location affects the maintainability of the series capacitor.
v. For MOV protected series capacitors, the rating of the MOV is very dependent upon the series capacitor location.

The midpoint location has advantage that the relaying requirements are less complicated. If compensation is less than 50% in addition short circuit current is lower, however it is not very convenient in term of access for maintenance, monitoring, securities.

The location of series capacitor at Dedesa is given by

$$\frac{345}{345+275+45} * 100\% = 51.88\%$$

Which is almost 50%. This indicates the location is at the midpoint of GERD-Dedesa-Holeta total length of the transmission line.

3.3. POWER FLOW MODEL OF TCSC

Two alternative power flow models are used to the impact of TCSC. The simpler TCSC model exploits the concept of a variable series reactance. The series reactance is adjusted automatically, within limits, to satisfy a specified amount of active power flows through it. The more advanced model uses directly the TCSC reactance-firing angle characteristics, given in the form of a non-linear relation. The TCSC firing angle is chosen to be the state variable in the Newton-Raphson power flow solution.

3.3.1. Variable Series Reactance Power Flow Model

The TCSC power flow model presented in this section is based on the simple concept of a variable series reactance, the value of which is adjusted automatically to constrain the power flow across the branch to a specified value. The amount of reactance is determined efficiently using Newton's method. The changing reactance X_{TCSC}, shown in Figure 3.3, represents the equivalent reactance of all the series-connected modules making up the TCSC, when operating either in the in the capacitive or inductive regions.

Figure 3.3: TCSC equivalent capacitive reactance [15]

The transfer admittance matrix of the variable series compensator is given by

$$\begin{pmatrix} I_k \\ I_m \end{pmatrix} = \begin{bmatrix} JB_{kk} & JB_{km} \\ JB_{mk} & JB_{mm} \end{bmatrix} \begin{pmatrix} V_k \\ V_m \end{pmatrix} \quad (3.8)$$

For capacitive operation, we have

$$B_{kk} = B_{mm} = \frac{1}{X_{TCSC}} \quad (3.9)$$

$$B_{km} = B_{mk} = -\frac{1}{X_{TCSC}} \quad (3.10)$$

For inductive operation the signs are reversed. The active and reactive power equations at bus k are as follows:

$$P_k = V_k V_m B_{km} sin(\delta_k - \delta_m) \quad (3.11)$$

$$Q_k = V_k V_k B_{kk} - V_k V_m B_{km} sin(\delta_k - \delta_m) \quad (3.12)$$

The state variable X_{TCSC} of the series controller is updated at the end of each iterative step as given in equation

$$X_{TCSC}{}^{i} = X_{TCSC}{}^{(i-1)} + \left(\frac{\Delta X_{TCSC}}{X_{TCSC}}\right)^{i} X_{TCSC}{}^{(i-1)} \quad (3.13)$$

3.3.2. Firing Angle Power Flow Model

Consider the line reactance of the transmission line in per unit system. For 50% compensation, the value of the capacitor in the TCSC will be 50% of the line reactance. Now for capacitive compensation, the value of inductive reactance must be greater than capacitive reactance that is, $X_L > X_C$ [11, 15]. The TCR is formed by a reactor in series with a bidirectional thyristor valve with an angle ranging between 0^0 and 90^0 with respect to the capacitor voltage. It consists of three components: capacitor banks C, bypass inductor L and bidirectional thyristors T_1 and T_2. The firing angles of the thyristors are controlled to adjust the TCSC reactance in accordance with a system control algorithm, normally in response to some system parameter variations [14]. The value of the TCR reactor depends on the requirement of the operating range of TCSC. Normally X_R/X_C for practical purpose should be in the range of 0.1 to 0.3 [15].

The TCR at the fundamental system frequency is continuously variable reactive impedance, controllable by firing angle α. Thus, the total impedance of TCSC can be changed by changing the firing angle of TCR branch, in which the current through the reactor $i_L(\alpha)$ can be continuously controlled from maximum to 0. Considering voltage on reactor as $v(t) = V_m \cos\omega t$, value of current though the reactor is

$$i_l(t) = \frac{1}{L}\int v(t)dt = \frac{V_m}{\omega L}\sin\omega t \quad (3.14)$$

Using Fourier analysis the magnitude of the fundamental frequency current can be obtained

$$i_l(t)=\frac{1}{L}\int=\frac{V_m}{\omega L}(1-\frac{2\alpha}{\pi}-\frac{1}{\pi}sin2\alpha) \quad (3.15)$$

Where, Vm is the magnitude of voltage of reactor, ωL is inductance of reactor and ω is circular frequency of voltage.

Thus, it is possible to control the current flowing through the reactor

$$I_L = VB_{TCR} \quad (3.16)$$

$$B_L = \frac{1}{\omega L} \quad (3.17)$$

And from above equation it is possible to calculate the inductive susceptance of TCR which is the function of the firing angle α

$$B_{TCR}(\alpha)=\frac{1}{\omega L}(1-\frac{2\alpha}{\pi}-\frac{1}{\pi}sin2\alpha) = B_L(\frac{\pi-2\alpha-sin2\alpha}{\pi}) \quad (3.18)$$

Thus as current can be varied from the maximum value to 0 by controlling the firing angle the inductive susceptance of TCR branch $B_{TCR}(\alpha)$ can also be changed from the maximum value ($\alpha=0$, $B_{TCR}=B_L$) up to zero ($\alpha=\pi/2$, $B_{TCR}=0$). Thus from the above equation the TCR reactance can be obtained as

$$X_{TCR}(\alpha) = \frac{1}{B_{TCR}(\alpha)} = \frac{\pi X_L}{\pi-2\alpha-sin2\alpha} \quad (3.19)$$

$X_L(=\omega L) \leq X_{TCR}(\alpha) \leq \infty$

Now, as TCSC is the parallel combination of the fixed capacitive reactance, X_C, and the varying inductive reactance, $X_L(\alpha)$, it becomes

$$X_{TCSC} = \frac{X_{TCR}(\alpha)*X_C}{X_{TCR}(\alpha)-X_C} \quad (3.20)$$

Where $X_L \leq X_{TCR}(\alpha) \leq \infty$

The model presented above uses the concept of an equivalent series reactance to represent the TCSC. Once the value of reactance is determined using Newton's method then the associated firing angle TCSC can be calculated. However, such calculations involve an iterative solution since the TCSC reactance and the firing angle are non-linearly related. One way to avoid the additional iterative process is to use the alternative TCSC power flow model presented in this section [27].

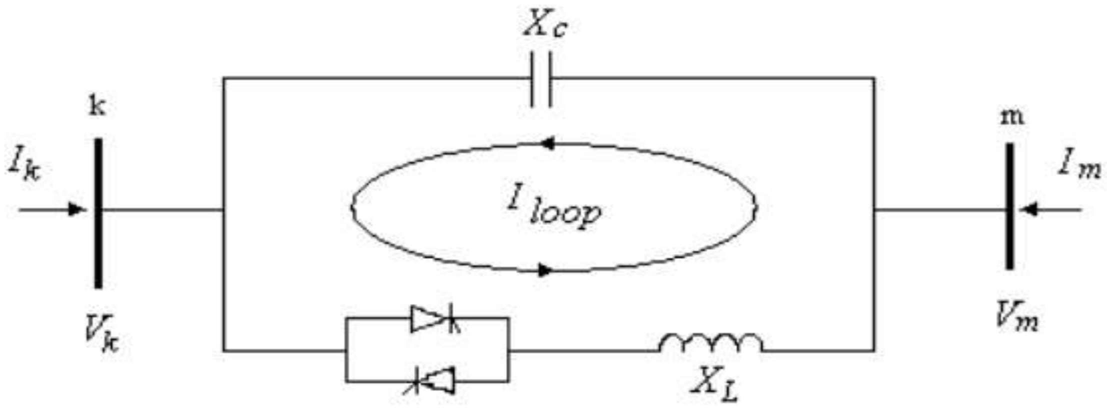


Figure 3.4: TCSC compensator firing angle modules [27]

The fundamental frequency equivalent reactance X_{TCSC} of the TCSC module shown in Figure 3.4 is given on equation 2.21. The TCSC reactance can be represented also as follows

$X_{TCSC\,(\alpha)}$=-$X_C + C_1(2(\pi-\alpha)+sin(2(\pi-\alpha))$)-$C_2cos^2(\pi-\alpha)\acute{\omega}\,tan\big(\acute{\omega}(\pi-\alpha)\big)-tan(\pi-\alpha)$ (Equation 3.21)

$$X_{LC}=\frac{X_C*X_L}{X_L-X_C} \quad (3.22a)$$

$$C_1=\frac{X_C*X_{LC}}{\pi} \quad (22b)$$

$$C_2=4\frac{X_{LC}}{X_L\pi} \quad (22a)$$

$$\acute{\omega}=\sqrt{\frac{X_C}{X_L}} \quad (22d)$$

The TCSC active and reactive power equations at bus k are as follows:

$$P_K= V_kV_mB_{km}sin(\delta_k-\delta_m) \quad (3.23)$$

$$Q_k=V_kV_kB_{kk}\text{-}V_kV_mB_{km}sin(\delta_k-\delta_m) \quad (3.24)$$

Where

$$B_{kk}=-B_{km}=B_{TCSC} \quad (3.25)$$

These equations are used to do load flow using the Newton's Raphson method.

CHAPTER FOUR

4. RESULTS AND DISCUSSIONS

4.1 INTRODUCTION

In this chapter, the modelling of TCSC, simulation parameters needed, simulation results and their discussions are made on TCSC results and its impacts on power transfer capacity, voltage drop/regulation, current behavior, steady state and dynamic stability of the system using DigSILENT software. The line is compensated using the series capacitors and shunt reactors, but only the effects of series capacitor are discussed and implemented using the modelling. In this thesis work, the power transfer capacity, voltage drop, and stability especially the dynamic stability results are explained clearly in this chapter. The EEP sets the voltage variation should be between 0.95 and 1.05 pu values. The GERD to Beles line is neglected for this study because, this study is focused only on the series capacitor installed at GERD- Dedesa-Holeta line.

4.2 MODELLING OF TCSC USING DigSILENT

From this modelling, the power losses in each components of the transmission lines is determined. Therefore, both power loss and voltage drop are evaluated and compared these values with the PSS results taken from the EPP and at the last conclusions are done based on the results. After all parameters are fed to each block the load flow is done using the DigSILENT. The results are found after the fourth iteration of Newton Raphson method. The modelling is simply taken the single bus bar for simplification purpose.

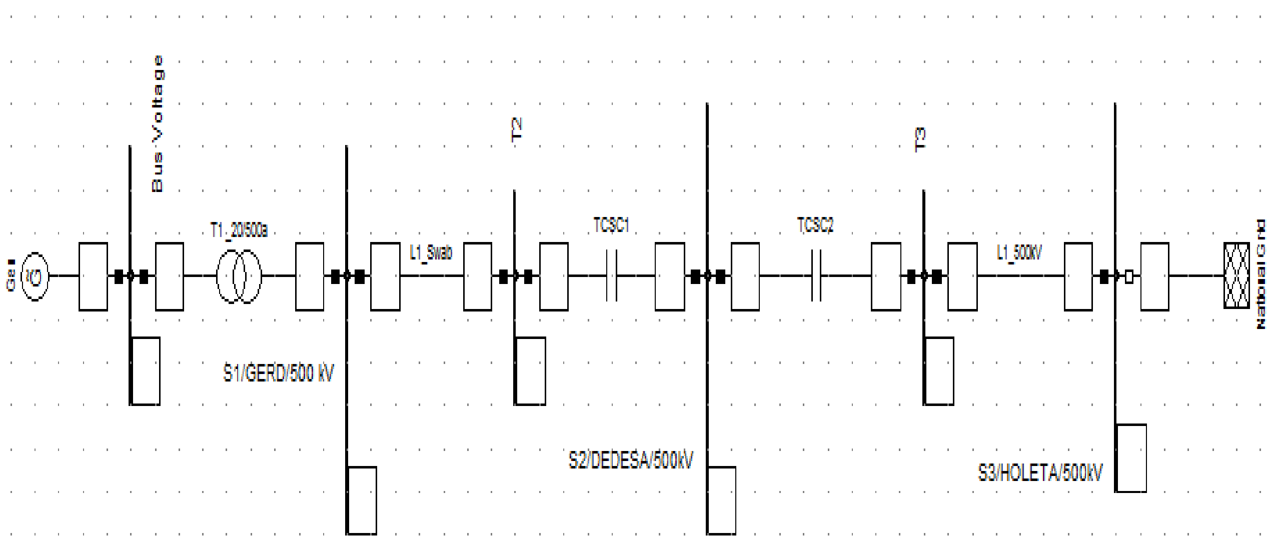


Figure 4.1: GERD -Holeta line modelling using DigSILENT

4.3 SIMULATION PARAMETERS

TCSC are connected in series of the transmission line. The TCSC is inserted at the midpoint of the transmission line to enhance controllability and increase power transfer capacity of transmission line. For the desired operation of TCSC proper selection of capacitor and reactor is required. Capacitor is selected based on the degree of series compensation required and it is the ratio of the effective reactance TCSC to the net reactance of transmission line [31].

To study the performance of TCSC, a transmission system is developed in DigSILENT for 500 kV, 620km long. The parameters are obtained from the GERD-Dedesa-Holeta 500KV line on which for the first time series controlled compensation project was commissioned in Ethiopia.

Technical Data of the transmission line:

Inductance / km L = 0.8597mH

Length of transmission Line 1 = 345km (4 lines)

Length of transmission Line 2 = 275km (4 lines)

Total inductance of the line = 0.5328H

Total line reactance of single line X_{TL} = 167.3845Ω.

Selection of TCSC parameters:

For 50% compensation

X_R = 11.643Ω for X_R/X_C = 0.25

Thus TCR reactor L_{TCR} = 0.0371H or 0.1074mH/km

Series capacitor C_S=38.05μF or 0.19812μF/km

External Grid: An infinite bus connected at the end is characterized by short circuit current and the short circuit power. This external grid represents the remaining network of the grid system of which the transmission line is connected.

In this thesis work the external grid represents the national grid at Holeta substation having bus bar voltage rating of 500 kV, 3 phase short circuit current Ik" max of 17.1604 kA, and short circuit-power Sk" max of 11,889.7 MVA and positive and negative sequence impedances are 0.101 at an angle of 86 because in order to investigate this problem using the power angle method, the bus voltage should have same bus voltages.

4.4 SIMULATION RESULTS AND DISCUSSION

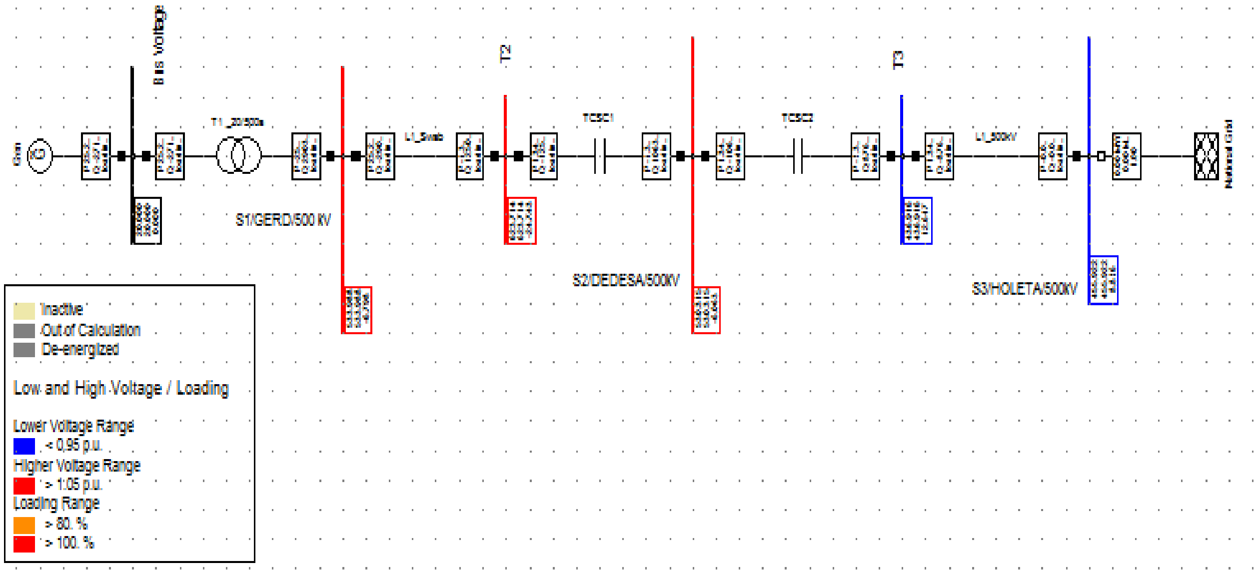
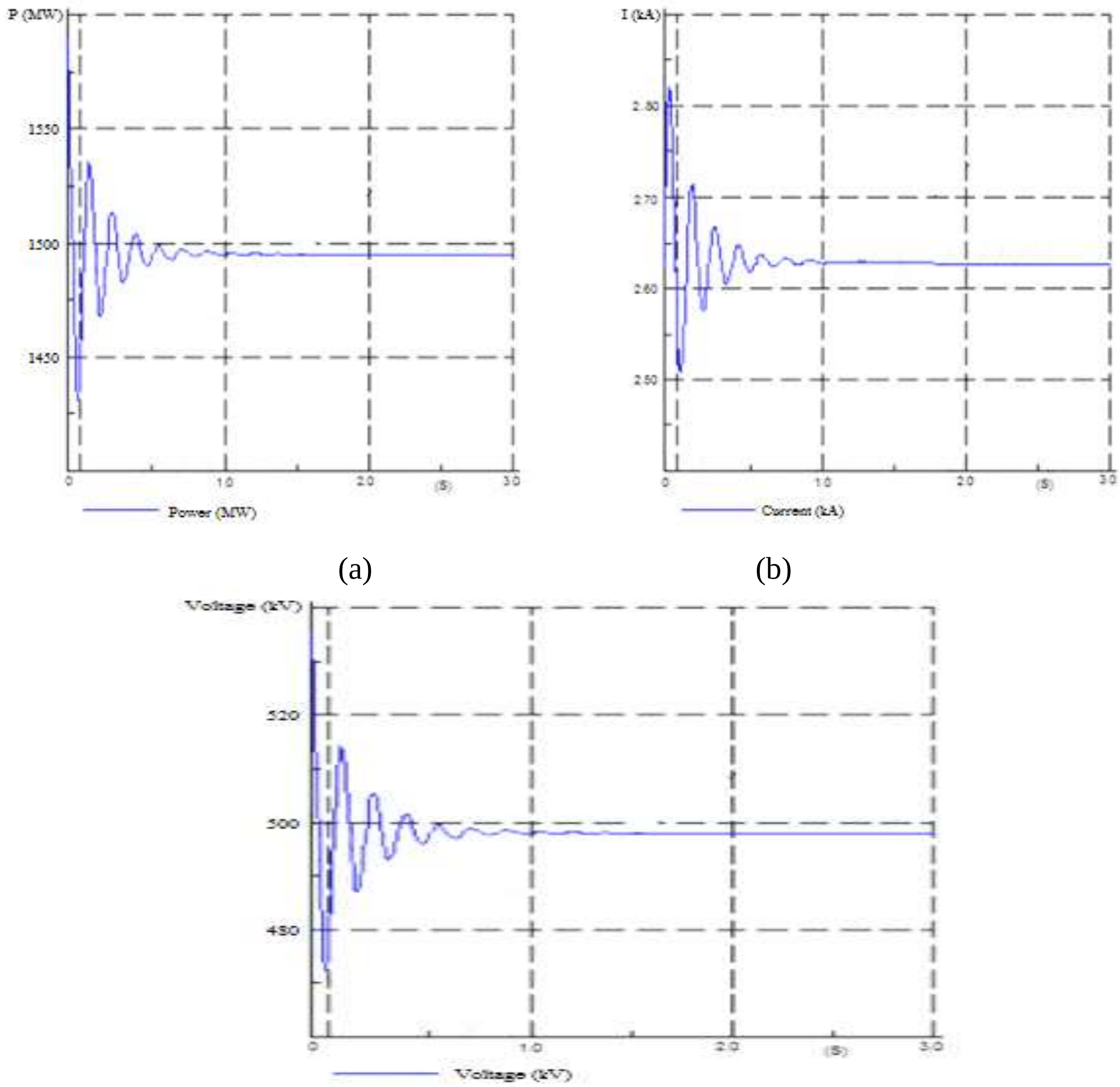


Figure 4.2: Voltage level loading on the Bus bars

4.4.1 Steady State load flow of the System

During the outage of a critical line in a large power system leads to flow in a parallel paths, which may become severely overloaded. Providing FC compensation on the parallel path to enhance the power transfer capability appears to be feasible solution, but it may increase the total system losses. Therefore, it is advantageous to install a TCSC in key transmission paths, which can adapt its series compensation level to the instantaneous system requirements and provide a lower loss alternative to the fixed.

A Steady State simulation assumes that the plant or system has reached steady operating conditions. Steady State simulation of an HVAC transmission system model is done on DigSILENT software tool without creating disturbances or faults on the system. The purpose of the steady state simulation is to evaluate the time response of the system output that has reached steady operating conditions. In this load flow simulation one line three phase voltage, current and power has been simulated at the receiving end of the transmission system. As it is seen on the wave shape outputs, these quantities come to their steady state values.



(a) (b)

(c)

Figure 4.3: Steady State Simulation at the Receiving End (a) Power (b) Current (c) Voltage.

In Figure 4.3, the AC voltage at the sending end of the transmission line is 498.0 kV or 1 p.u and the current flowing through each bus or line is 2.631 kA or 0.98pu which is nearly equal to the rating value of a single line i.e. 2.687 kA. The power loss within one line of the transmission line is 20.39 MW or 1.36%. For the two double 500kV transmission line the power loss become 81.65 MW or 5.44% which is shows improved power. All these parameters regained to their steady state stability after 50ms and they are all within the standards even if all are below their rated values.

Steady state stability is occurred due to overloading of transmission lines and voltage stability problems exhibited by a slow decline of the voltage profile with increases in power loading of the transmission system.

Oscillations of active power in power transmission systems arises in corridors between generating areas as a result of poor damping of the interconnection, particularly during heavy power transfer. Such oscillations can be excited by a number of reasons such as line faults or a sudden change of generator output. The presence of active power oscillations acts to limit the power transmission capacity of interconnections between areas or regions.

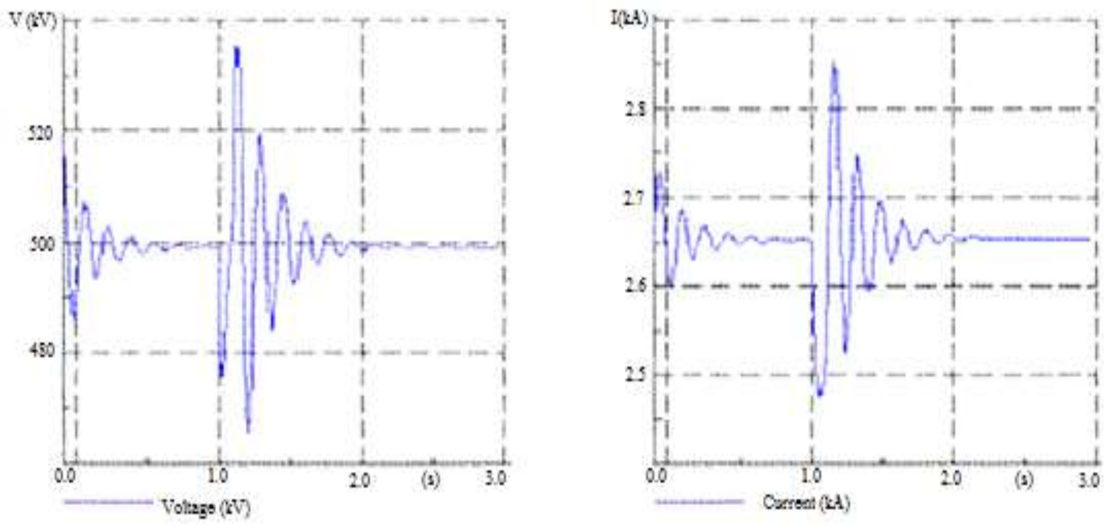
4.4.2 Dynamic Simulation of the System

A Dynamic simulation assumes that the plant or system is in a state of change. The specific objective of the dynamic simulation studies is to evaluate the stability and performance of the system after disturbances happening on the system. The dynamic simulation has also used for proper choice of circuit breakers and protection of relays. The magnitude of currents that would flow under short-circuit conditions shall be determined by fault analysis using the DigSILENT software. The majority of the system faults are not three-phase faults /symmetrical faults/ but faults involving one line-to-ground or occasionally two lines-to-ground/unsymmetrical fault/. Even though it is infrequent, the symmetrical three phase fault analysis has to be carried out, as it generally leads to most severe fault currents from which the system shall be protected. It is this value, which is usually referred to determine the breaking capacity of circuit breakers.

In this thesis work, a three-phase short circuit fault is used as the standard fault type applicable to 20 kV Generation bus bar and 500 kV Holeta bus bar which is carried out using the DigSILENT. Transient Stability of the system is analyzed as for one second run system without disturbance, apply disturbance at T = 1sec, clear fault within 100 ms and needs 4 cycles to reach steady state operation after the fault is cleared.

A grid code is a technical specification which defines the parameters of a facility connected to a public electric network has to meet to ensure safe, secure and economic proper functioning of the electric system. The facility can be electricity generating plant, a consumer, or another network. The grid code is specified by an authority responsible for the system integrity and network operation.

In Ethiopia there is no grid code. So, it is difficult to compare weather the quantities that are under study may fulfill the regulations of the power company. However, for the project under study a reference is taken from the PSS results given by EEP.



(a) (b)

Figure 4.4: Dynamic State Simulation (a) Voltage (b) Current

Dynamic instability characterized by negatively damped low frequency oscillation, caused by transferring a high level of power over a weak transmission link.

4.4.3 Sub Synchronous Reactance (SSR)

Damping of electromechanical oscillations between interconnected synchronous generators is necessary for a secure system operation. Power system stabilizers (PSSs) are effective for controlling system oscillations but are usually designed for damping local electromechanical oscillations. The behavior of low frequency inter-area oscillations is generally determined by global parameters of larger parts of the power system.

The limited influence on inter-area modes, however, leads us to the fact that they may not be considered as the only solution to damp inter-area oscillations. Flexible AC Transmission Systems are being increasingly used to improve the utilization capacity of the existing transmission systems.

The use of controllable series compensation is a very efficient and robust method to achieve improved damping of power oscillations. Adequate equipment for power oscillation damping utilizes thyristor control of the inserted capacitive reactance.

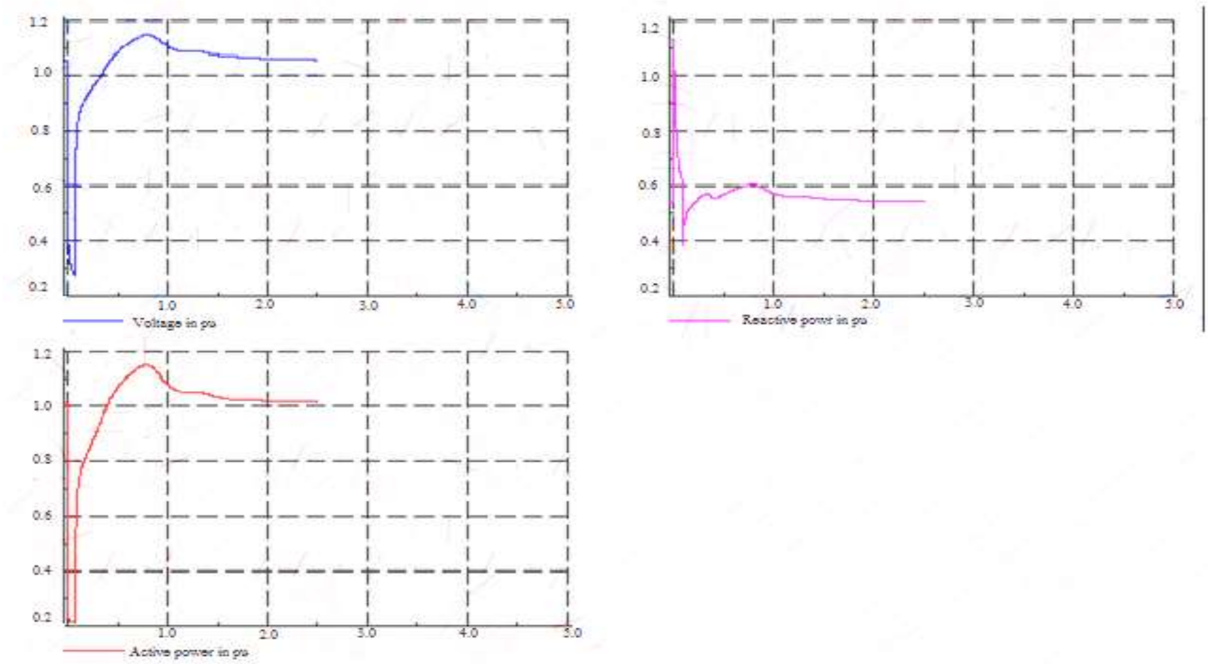


Figure 4.5: Damping of SSR in the line feeder

From Figure 4.8, the SSR is damped out at 1sec when the TCSC time operation is under talking. Therefore, using the TCSC, the power oscillation on the line is reduced, almost it become unity. The reactive power is controlled in order to voltage stability. Voltage stability problems exhibited by a slow decline of the voltage profile with increases in power loading of the transmission system.

4.4.4 MOV Protection

The MOV protection is one of the series capacitor protections. In this protection only the MOV current, MOV energy and voltage overloading are discussed.

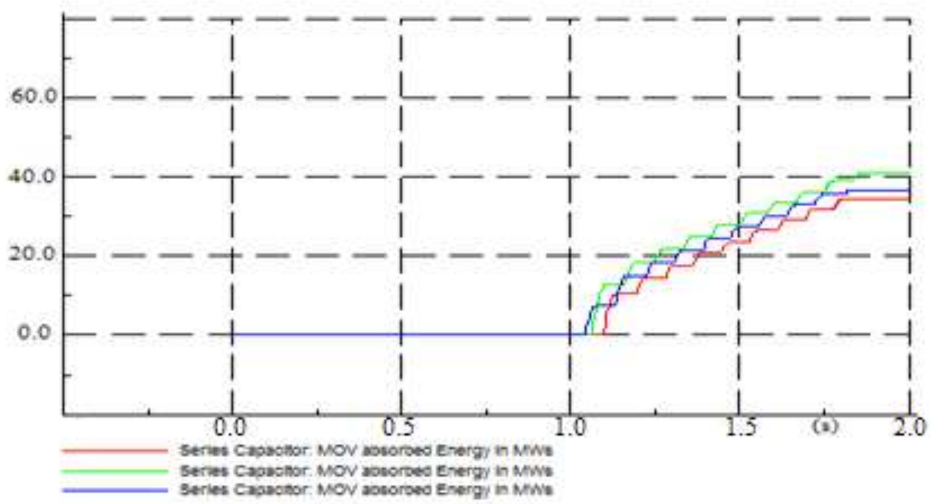


Figure 4.6: Energy absorbed by the MOV

From the Figure 4.7, the threshold energy is 40MJ/ phase, beyond this value the TCSC is bypassed by closing the line disconnector.

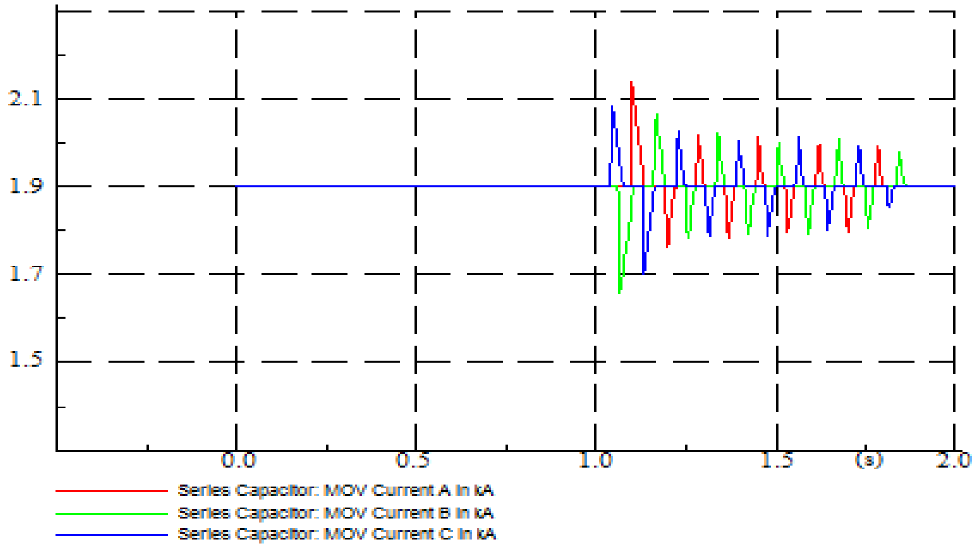


Figure 4.7: MOV RMS Current in kA

The current is increased from the normal load current of 1.9kA rms to 2.01kA and decreased to 1.79kA due to fault on the line after MOV is operated at 1sec, the current goes almost to its steady state. Therefore, the load current is increased by 15.56% due to the fault.

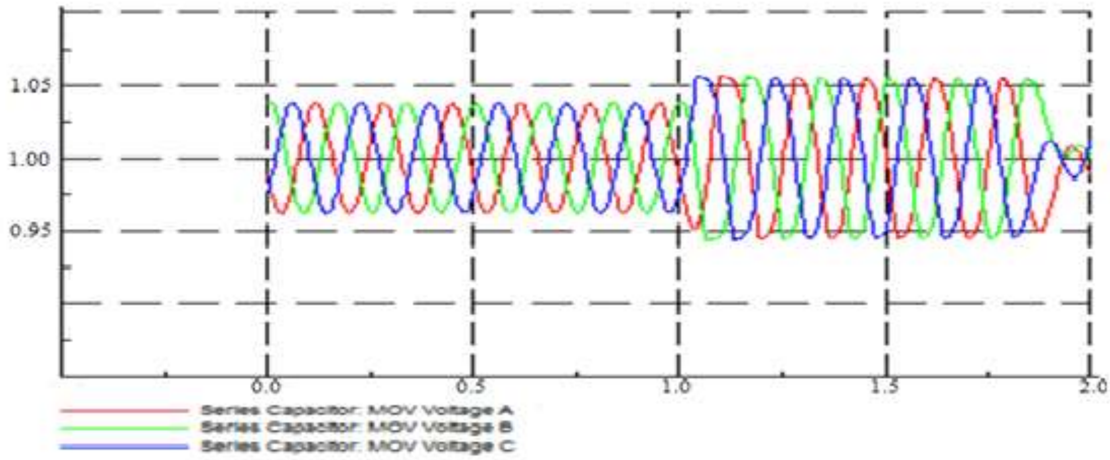


Figure 4.8: MOV voltage in pu

As shown above, after some point the voltage is fluctuated due to internal faults in the series capacitor. To prevent this fault, the MOV is installed and decreased the fluctuation of voltage to its steady state system. This MOV provided safe protection of series capacitor during the high capacitor voltage.

4.5 ANALYSIS OF TCSC

The behavior of the TCSC is similar to that of the parallel LC combination. The difference is that the LC-combination analysis is based on the presence of pure sinusoidal voltage and current in the circuit, whereas in the TCSC, because of the voltage and current in the FC and thyristor-controlled reactor (TCR) are not sinusoidal because of thyristor switching.

The TCSC is to be installed on a line with: 500 kV, X_L = 0.269975 Ω/km, 620 km, and is designed to achieve a degree of compensation (k) is 50 %. The reactance of the thyristor controlled reactance as a function of the firing angle (α) is given by the following relationship.

$$X_{TCR} = \omega L.\frac{\pi}{\pi - 2\alpha - \sin 2\alpha}, \text{ for } 0 < \alpha < \frac{\pi}{2}$$

Firing angle, α is variable according to the reactance needed in the transmission line allowed to designed power is obtained and required to be transfer along the line. Therefore, let the angle is varied from 0^0-90^0 and see the effects on the power transfer capacity. The TCSC operates in capacitive mode if X_{TCR} is greater than X_C.

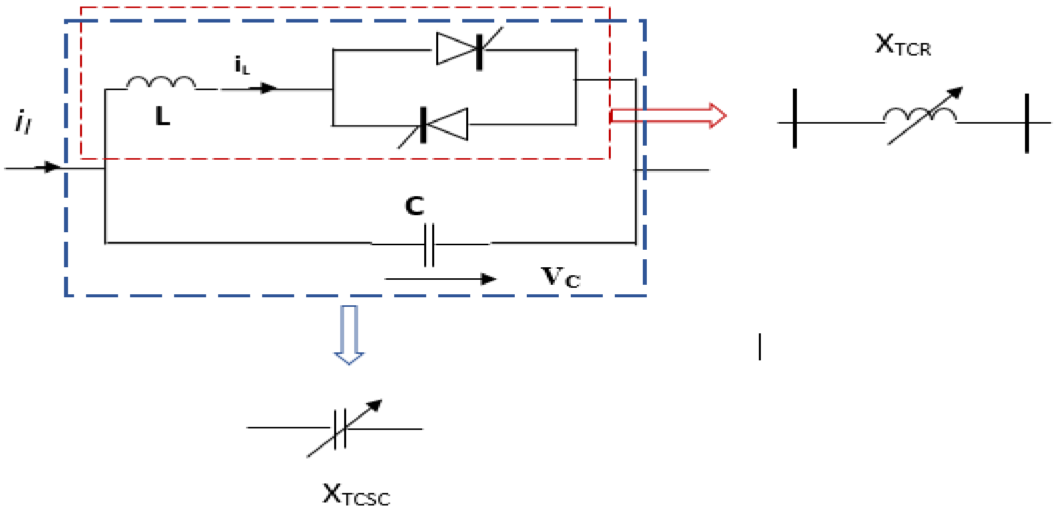


Figure 4.9: Configuration of a TCSC

Since the resistance is negligible, the impedance is the same as the reactance of the line. Therefore, total reactance of the line with TCSC from Figure 4.10 is

$$X = X_L - X_{TCSC} \tag{4.1}$$

$$\underline{Z}_{TCSC} = \frac{jX_L\,(-jX_C)}{jX_L - jX_C} = -j\,\frac{X_L\,X_C}{X_L - X_C} \rightarrow \text{impedance capacitive only for } X_L > X_C$$

This is only for fixed capacitor value

$$X_{TCSC} = \frac{X_{TCR}\,X_C}{X_{TCR} - X_C} \rightarrow X_{TCR} = \frac{X_{TCSC}\,X_C}{X_{TCSC} - X_C} \tag{4.2}$$

$$\text{with } X_C = \frac{1}{100 * \pi * 38.0334 \text{ x } 10^{-6}} = 83.69225\ \Omega$$

$$k = \frac{X_{TCSC}}{X_L} = \frac{X_{TCSC}}{0.2699975 \times 620} \rightarrow X_{TCSC} = 167.3845\Omega \times k = 83.69225\Omega \text{ for FSC}$$

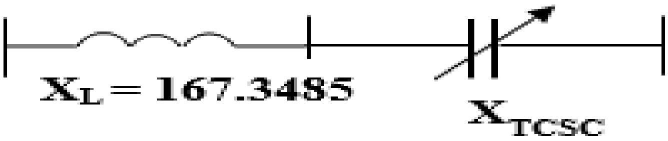


Figure 4.10: Simplified Single line diagram of transmission line

$$X_{TCSC} = \frac{jX_L\,(-jX_C)}{jX_L - jX_C} = -j\,\frac{X_L\,X_C}{X_L - X_C} \rightarrow \omega L = \frac{\omega}{C\,(2\pi\,100)^2} = 20.923\Omega$$

Resonant frequency, $f_R = \frac{1}{2\pi\sqrt{LC}} = 100\text{ Hz}$

The maximum power carrying capability for system is determined by

$$P_{max} = \frac{(500kV)^2}{X_L - X_{TCSC}(\alpha)}\,sin\delta_{MAX} = \frac{(500kV)^2}{41.846 - X_{TCSC(\alpha)}}\,sin\delta_{MAX}$$

Where, $sin\delta_{MAX}$ (30^o- 60^o) is selected depending on the stability margins and the stiffness of the terminal buses to which the line is connected. The transfer power capacity depends on the X_{TCSC} value as it varies based on the firing angle. Using the different values of firing angle, the reactance of both power and reactance for four lines are given in Table 4.1 and 4.2

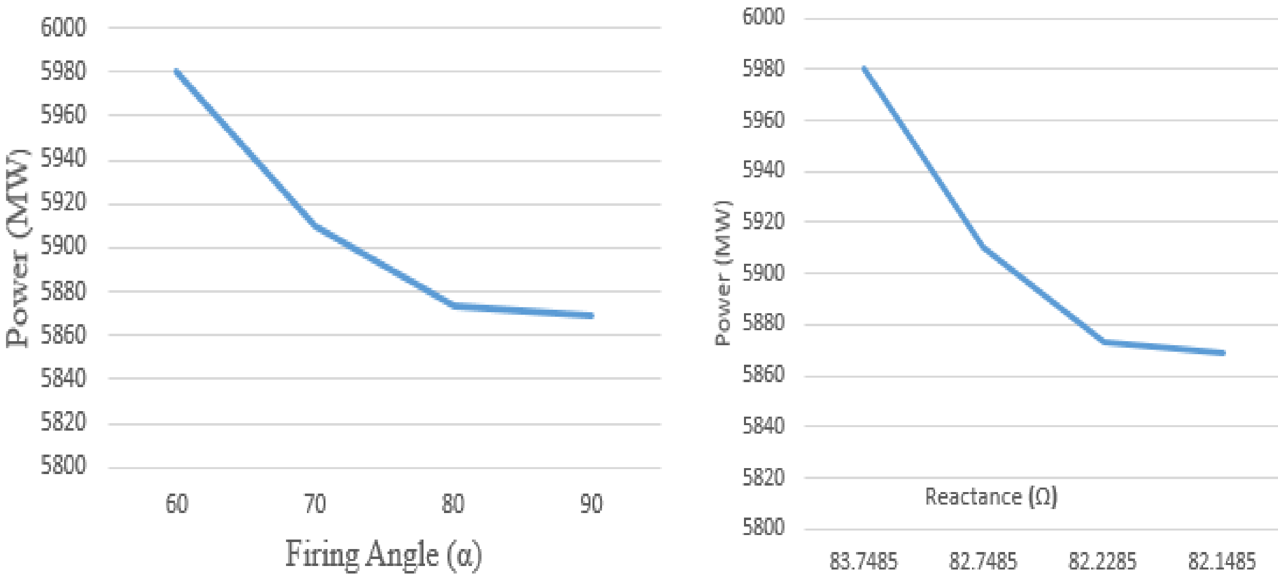
Table 4.1: Variation of power flow and the X_{TCSC} reactance in the inductive mode

Alpha (α)	$X_{TCSC}(\Omega)$	**Power (MW)**
0^0	42.1985	3995
10^0	37.2085	3842
20^0	29.0785	3616
30^0	9.63	3170

Table 4.2: Variation of power flow and the X_{TCSC} reactance in the capacitive mode

Alpha (α)	X_{TCSC} **(Ω)**	**Power (MW)**
60^0	83.7485	5980
70^0	82.7485	5910
80^0	82.2285	5873
90^0	82.1485	5868.7

Using the graph of the regions of operating with control angle alpha, it can be plotted below based on the calculated values above.



From Figure 4.12, it is observed that as the firing angle is varied from 90˚ towards the resonance region, the power flow is increased and again decreasing further the firing angle in the inductive region power flow increases.

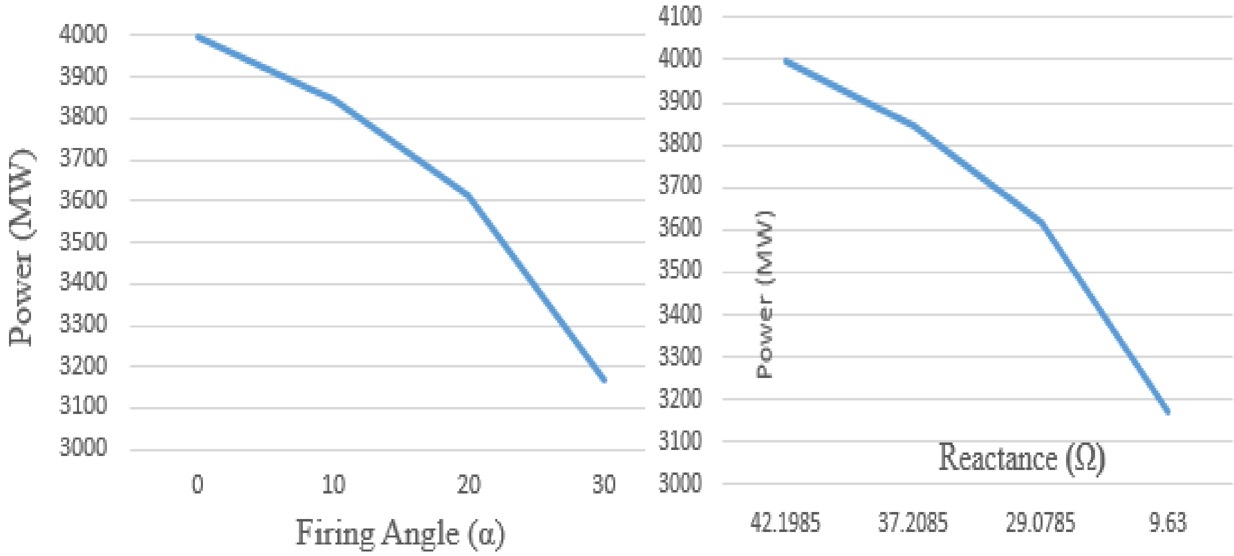


Figure 4.12: Power Vs Firing Angle and Reactance in Inductive Region

Referring to the Figure 4.13, it is observed that the power flow decreases in the inductive mode as firing angle is increased from 0˚ towards the resonance region because TCSC in the inductive mode acts as a variable inductance.

Since the resonance for this TCSC is around 50^0 firing angle, the operation is prohibited in firing angle range 35^0- 55^0. The capacitive mode is achieved with firing angles 60^0- 90^0.

The impedance is lowest at 90^0, and therefore, power transfer increases as the firing angle is reduced. The range for impedance values is approximately 83.60-157.72 Ohm. This range corresponds to approximately 3995MW-5980MW power transfer range.

CHAPTER FIVE

5. TECHNICAL AND ECONOMICAL ANALYSIS OF TCSC

In this chapter, the technical and economic analysis or aspects are discussed. Bulk power is transferred using HVAC transmission system from a remote generating station to the load center. Before implementation of those transmission systems, technical performance and cost comparison of series capacitor and building new transmission system needs to be carried out.

From the technical comparison point of view, each transmission system has been evaluated based on comparative parameters, like transmission line power, and voltage drop, to come up with an optimal transmission system. In order to compare the cost, all main system components must be taken into considerations. For the TCSC with its protection system components and overall cost investment TCSC cost and conclusion on the cost estimation based on ABB is carried out.

5.1 TECHNICAL ASPECTS

5.1.1 Transmission Lines loss

While designing a transmission line care must be taken on the loss of power within a transmission system to maintain the efficiency of the transmission system within desirable limit. This section covers comparison without and with TCSC on transmission systems in terms of the power transfer capacity, voltage drop and system stability of each transmission system components using the DigSILENT software. For HVAC major transmission system components are: step-up transformers at the generation side, transmission line, and step-down transformers at the Holeta side. The transmission line designed by EEP planning office employs two double circuit 500 kV transmission line. Each of 16 Generation units are connected to 16 (375 MVA) transformers which are used to step up the voltage from 20 kV to 500 kV. At the receiving end (Holeta), there are 8× (750 MVA, 500/400 kV) transformers that are used to step down the voltage level of the transmission line to the main grid voltage level i.e. 400 kV. Depending on the overall transmission system components, the performance of the transmission system with respect to power losses has been evaluated to determine the total power losses and voltage drop on the lines.

Table 5.1**:** PSS HVAC system simulation output data.

Parameters	Generation Station	Sending end	Receiving end
Power, MW	6000	5922	5759
Voltage, kV	20	500	481

The generation power is 6000 MW. From the results discussed above using Table 5.1 the power coming out from the step up transformers is 5922 MW. The power losses in these transformers become 78 MW. From the PSS simulation study of the HVAC transmission line developed by EEP, the power at the sending end of the transmission line is 5922 MW and the power at the receiving end of the transmission line is 5759 MW. So, the power loss in the transmission line is 163 MW. So the overall power loss on the lines is 241MW. The voltage regulation of the system without using the TCSC is calculated as

$$\frac{V_S - V_R}{V_R}*100\% = \frac{500-481}{481}*100=3.95\%$$

Table 5.2: DigSILENT HVAC system simulation output data.

Parameters	Generation Station	Sending end	Receiving end
Power, MW	5998	5986.86	5916.35
Voltage, kV	20	499	484.36

The generation power is 5998 MW and the power at the sending of the transmission line is 5986.86 MW. So, the power loss in the transformers become 11.14 MW. The power at the receiving end of the transmission line is 5916.35 MW and the power loss within the transmission line is 70.51 MW. Therefore, the total power loss on the system is 81.65 MW.

The overall power losses on the lines leads the system steady state stability problem as the power may not be enough as it is designed for future. Therefore, to solve such power loss TCSC is designed at Dedesa substation in order to increase the power transfer capacity. Using this TCSC the power is increased by 159.35 MW. The voltage regulation of the system with TCSC is determined as

$$\frac{V_S - V_R}{V_R}*100\% = \frac{499-484.36}{484.36}*100=3.02\%$$

From this result, the system with TCSC has better voltage regulation. The voltage regulation of the system for both methods, the values are within the standard [39].

Table 5.3: Comparison of transmission system results

System Parameters	Without TCSC	With TCSC
System efficiency	95.98	98.64%
Voltage regulation	3.95%	3.02%
Power loss	241 MW	81.65 MW

5.2 ECONOMICAL ASPECTS

The impact of TCSC on transmission system parameters such as power transfer capacity, voltage drop on the lines as well as power oscillation are compared. Based on this, TCSC has better performance with respect to efficiency. In addition to this evaluation made above, the system has been evaluated in terms of the investment cost of TCSC as follows.

5.2.1 Investment Cost of Transmission Line

The detail investment cost is found in Appendix B. Table 5.4 is only summarized the investment cost for the HVAC transmission system [4].

Table 5.4**:** Total investment cost of HVAC transmission line [4]

Items	Total Price (USD)
Total Substation Cost	460,490,000.00
Transmission line Cost	688,800,000.00
Total Cost	1,149,290,000.00
Engineering and Administration (5% of the Total cost)	57,464,500.00
Total Project Cost	1,206,754,500.00
Physical Contingency (5% of the Total Project cost)	60,337,725.00
Price Contingency (10% of the Total Project cost)	1,267,092,225.00
Grand Total Project Cost	**1,393,801,448.00**

5.2.1.1 Estimated Cost of the Transmission GERD - Holeta Line

The EEP signed a 1.2 billion dollar agreement with the Chinese company, SGCC for the installation of high voltage electric transmission lines. The estimated cost of the overall transmission line extending from the initial point to commissioning stage is tabulated below.

Table 5.5**:** The Total Cost of GERD- Dedesa-Holeta Transmission Lines [4, 5]

Lot No.	EPC price	Financing cost	Total cost
2.	56,893,770.26	13,407,436.07	70,301,206.33
3.	170,364,745.88	40,147,707.36	210,512,453.24
4.	209,420,511.73	49,351,486.28	258,771,998.01
5.	167,599,237.56	39,495,994.95	207,095,232.51
6.	215,721,734.57	50,836,415.86	266,558,150.43
Grand Total (USD)	820,000,000.00	193,239,040.52	**1,013,239,040.52**

The **lots** indicated in the above table represents the following transmission lines.

[1]. GERD- TL-Lot 2, construction of 400kv Holeta-Akaki II, Holeta-Sebeta II and Holeta-Sululta II transmission lines
[2]. GERD- TL-Lot 3, construction of 500kv GERD- Holeta transmission line 1
[3]. GERD- TL-Lot 4, construction of 500kv GERD-Dedesa transmission line 1
[4]. GERD- TL-Lot 5, construction of 500kv GERD -Holeta transmission line 2
[5]. GERD- TL-Lot 6, construction of 500kv GERD-Dedesa transmission line 2

5.2.2 Investment Cost of TCSC

The total cost of the TCSC in $/KVAr is given [41]

$$C_{TCSC} = 0.003S^2 - 0.3051S + 127.38 \quad (5.1)$$

The main objective is minimization of the total cost

$$\text{Min } f_s = C_{TCSC} * S * 1000 \quad (5.2)$$

$$S = Q_2 - Q_1 \quad (5.3)$$

Where Q1 and Q2 are the reactive power before and after the installation of TCSC and the estimated cost for series capacitor is given in Table 5.6.

Table 5.6: Cost of Thyristor Controlled Series Capacitor [4]

Items	Unit	Qty.	FOB price	Sea transportation	Local transportation	Insurance	Civil works	Erection & commissioning
			Unit price	Unit price	Unit price	Unit price	Unit price	Unit price
1.	No.	48	22,761.00	1,593.00	228.00	114.00	1,138.00	1,138.00
2.	No.	24	22,761.00	1,593.00	228.00	114.00	1,138.00	1,138.00
3.	No.	160	2,212.00	155.00	22.00	11.00	111.00	111.00
4.	No.	24	73,735.00	5,161.00	737.00	369.00	3,687.00	3,687.00
5.	No.	12	2,436,479.00	170,554.00	24,365.00	12,182.00	121,824.00	121,824.00
6.	No.	12	2,308,243.00	161,577.00	23,082.00	11,541.00	115,412.00	115,412.00
7.	No	48	19,500.00	1,480.00	150.00	250.00	-----	1,026,240.00
8.	No.	4	49,004.00	3,430.00	490.00	245.00	2,450.00	2,450.00
9.	No.	21	40,240.00	2,817.00	402.00	201.00	---	2,012.00
Grand Total (USD)						**74,515,388.00**		

The '**items**' are represented the following main components

1. 500kv, single pole, vertical break disconnector with earthing switch at one ends, 50Hz, 500Amp, 40kv/1sec, with earthing switch at one end

2. 500kv, single pole, vertical break disconnector with earthing switch at one ends, 5000Amp,40kA/1 sec, with earthing switch at one end
3. Post insulators, 500kv
4. Single pole, bypass switch (CB) for three phase operation, SF_6 insulated, with pre insertion resistor, DC motor charged spring mechanism, 5000Amp, 40kA/1 sec
5. Single phase configuration SC banks, 500kv, complete with equipment and accessories of current limiting and damping circuit, Varistor (MOV), Protective spar gap, Insulators and bus works and Instrument transformers and others
6. Single phase SC banks, 137 MVAr (411MVAr for three phase)
7. Thyristors including the series inductance, 500kV
8. Set of steel structure for equipment support including foundation anchor bolts, eyeballs and assembly nuts, bolts and washers etc. for each capacitor bay
9. Complete of set platform, support, insulators etc. for SC banks

When the series capacitor cost is compared to a building new transmission line cost in percent, it became as followed.

$$\frac{Total\ TCSC\ cost}{Total\ transmission\ line\ cost} = \frac{74,515,388.00}{763,106,230.00} = 9.8\% \qquad (5.4)$$

The cost of a series capacitor bank is approximately 10% of the cost of a new transmission line, thus providing a quick return on investment. Therefore, it fits to the literature review stated by ABB. From this it is recommended that installing series capacitor especially TCSC is better rather than building new transmission lines to accomplished those objectives stated above in this thesis work.

In this thesis, the cost of series capacitor is compared to the cost of total transmission system of the Dedesa substation, and check with literatures stated by ABB series capacitor installation guide. Cost of TCSC is almost same with SC with only differ in the thyristor cost and this shows it is very economic and better to use instead of the SC on the line under investigated study. Often the TCSC is combined with FC compensation to increase transient stability in the most cost effective way.

CHAPTER SIX

6. CONCLUSION, RECOMMENDATION AND FUTURE WORK

6.1 CONCLUSION

Series compensation improves line power handling capacity. In this thesis three bus power system has been modeled using the DigSILENT and the effect of TCSC for three bus system is analyzed. This thesis concluded that TCSC is the effective means of improving electrical characteristics of transmission line when the impedance is variable. Voltage profile, power transmission capability, steady state and dynamic stability are enhanced by using the TCSC. Location of TCSC is an important issue and the mid of the transmission line is the best location for series compensation.

In this study, the simulation of EHV transmission line using TCSC Controller is carried out. By using the TCSC Controller in transmission line the real power of transmission line is increased that means power transfer capacity of EHV transmission line increased. Also the receiving end voltage increases to match the value nearly to the sending end voltage that increasing the stability of the transmission network. The voltage drop due the line reactance is decreased. From the simulation results, TCSC can control the power at the different load condition and also in different firing angle of thyristors. As the degree of compensation increases, the voltage drop is improved and power transfer capacity is increased.

The thesis is discussed the operation of TCSC at the varying firing angle and thus concluded that TCSC improves the power transfer capability of system, if used with proper control techniques to fire the SCRs in proper region with proper conduction angle. It has been referred that in the inductive mode TCSC acts as a variable inductor leading to the increase in the overall inductance of the transmission line and thus decreasing the power flow whereas in the capacitive mode the TCSC acts as a variable capacitance decreasing the reactance of the transmission line depending on the firing angle and thus increasing the power flow. In short, TCSC provides dynamically variable series impedance to regulate the power on the line where it is connected.

Using the TCSC, the power loss of the transmission system GERD to Holeta line is decreased means the power transfer capacity is improved. From the DigSILENT result, the power loss on the lines is decreased by 2.805%, voltage regulation decrease by 0.93% and power efficiency is lines is increased by 2.66%. The steady and dynamic stability of power, voltage and current are improved and also the MOV protection for the TCSC is achieved. Cost of TCSC is 10% of the cost of build new transmission lines and this satisfies the ABB guide.

6.2 RECOMMENDATIONS

Based on the thesis work, it is recommended that the following points are to be considered.

[1]. EEP should be use the series capacitor for other long transmission lines instead of building and expansion of new transmission system network in order to save time and cost as well as the land it is consumed.

[2]. Both Ethiopian Universities and EEP should be work cooperatively when such a 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.

[3]. The power company, EEP has to develop Grid code which helps researchers to evaluate their designs to meet EEP's standard criteria's as a bench mark study.

[4]. To see the real effects of the TCSC on the transmission line more clearly, it is good to consider the SVC installed at Holeta Substation when power is interconnected to main Ethiopian grid.

6.3 FUTURE WORK

As it has seen from the results, series capacitor with TCSC can lead effectiveness such as power flow control, increase in transmission capacity, and improvement for system transient phenomena. But, reducing series impedances in transmission system, there are serious problems such as increase in fault current, transient stability deterioration and series voltage stress of TCSC in the transmission line. SFCL can be expected to protect the TCSC from a large transient current generated by lightning or switching surge in power transmission system. Therefore, for future it is better to design SFCL with TCSC for more protection of short circuit and stability of the system.

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LIST OF APPENDICES

A. EEP DATA

Table A.1 Generation Data [5]

System Parameter	Unit	Value
Synchronous Reactance		
X_d	Pu	2
X_q	Pu	2
Transient Reactance		
$X_{d'}$	Pu	0.3
Sub- Transient Reactance		
$X_{d''}$	Pu	0.2
$X_{q''}$	Pu	0.2
Zero sequence data		
X_0	Pu	0.1162
R_0	Pu	0.00145
Negative sequence data		
X_2	Pu	0.1932
R_2	Pu	0.02039
Inertia		
Inertia time constant (rated to Pgn) H	Sec	10
Mechanical Damping	Pu	0
Stator resistance/Leakage reactance		
Rstr	Pu	0
x_l	Pu	0.1
x_{rl}	Pu	0
Rotor type		
Salient pole	---	---
Transient time constants		
System parameter	Unit	Value
$T_{d'}$	Sec	1
Sub- Transient time constants		
$T_{d''}$	Sec	0.035

$T_{q''}$	Sec	0.035
Steady state short circuit current		
I_{kd}	Pu	1.2
Nominal frequency		
Frequency	Hz	50
Machine type		
IEC909/IEC60909	----	----
Generation Bus bar	kV	20

Table A.2**:** Distance between Relevant Towns (km) [4]

From/To	Addis Ababa	Sululta II	Sebeta II	Akaki II	Holeta	Dedesa
Addis Ababa	---	15	35	25	45	380
Sululta II	15	----	50	40	60	398
Sebeta II	35	50	-----	60	80	415
Akaki II	25	40	60	------	70	405
Holeta	45	60	80	70	-----	335
Dedesa	380	398	415	405	335	------
Djibouti	925	940	960	900	970	1305

Table A.3: EEPCO Main Grid data [5]

System Parameter	Unit	Value
Holeta substation rated voltage	kV	500
Short circuit current (Ik'') (10minutes) at the end of construction	kA	17.1604<-86^{o}
Short Circuit MVA power (Sk'') at the end of construction	MVA	11,889.7
MVA Base (for one line)	MVAs	1500
Z_1=Z_2	Ohm	16.822<86*

* The equivalent positive and negative sequence impedances are

$$Z_1=Z_2=\frac{500}{\sqrt{3}*17.1604}=16.822\text{Ohms}$$

The base impedance

$$Z_{Base}=\frac{V_{BaseLL}^2}{MVA_S}=\frac{500^2}{1500}=166.67\text{Ohms}$$

So, positive and negative sequence impedance of the line in pu is 0.101at an angle of 86^{o}.

The current flowing through the TCR or TCSC is calculated as using the current divider rule from the equivalent circuit for the FSC case.

$$I_{TCR} = \frac{jX_C I_L}{j(X_C - X_{TCR})} = I_{TCR} = \frac{I_L}{1 - \frac{X_{TCR}}{X_C}} = \frac{2.687}{1-0.25} = 3.5827\text{kA}$$

And the current flowing through the series capacitor is calculated as similar way

$$I_C = \frac{I_L}{1 - \frac{X_C}{X_{TCR}}} = \frac{2.687}{1-4} = -0.8957\text{kA}$$

The reactive power is therefore, defined by the following formula

$$Q_{TCSC} = (I_C^2 * X_C) - (I_{TCR}^2 * X_L)$$

$$Q_{TCSC} = 0.8957^2 * 83.69225 - 3.5827^2 * 167.3845 = -2{,}080.9\text{MVAr}$$

Negative reactive power generated means that reactive power is flowing from the utility grid (source) to the generator. This occurs whenever the generator field is under-excited or if an induction generator is being used.

Table A3: Rating of Shunt capacitor

Description	Rating
Type	China
Manufacturer	China
Unit capacitor	
Rated current of unit capacitor, Amp	85.2
Rated voltage of unit capacitor, kV	5.75
Rated output of unit capacitor, KVAr	490
Nominal capacitance and maximum permitted tolerance for each capacitor	Nominal capacitance 47.25μF and maximum permitted tolerance for each capacitor -3%
Insulation level of each capacitor	
Lighting impulse, kV	1,425
Power frequency withstand voltage, kV	1,050

Table A4**:** Voltage and Frequency Data [4]

Description	Values
Nominal voltage	500kV,$_{ph-ph}$
Minimum continuous voltage	475kV,$_{ph-ph}$
Minimum emergency short time voltage	450kV,$_{ph-ph}$
Maximum continuous voltage	525kV,$_{ph-ph}$
Maximum temporary overvoltage	650kV,$_{ph-ph}$ for 5s
Maximum emergency short voltage	550kV,$_{ph-ph}$
System frequency	50Hz

B. ESTIMATED COST

Table B1: Cost Estimate of Grid connection [5]

No.	Description	Unit	Qty.	Unit Cost (USD)	Total Cost (USD)
1	500 kV line bay, double bus	each	4	1,800,000	7,200,000
2	500 kV transformer bay, double bus	"	1	1,700,000	1,700,000
3	500kV 4X135 MVAr line connected shunt reactor	MVA	540	24,000	12,960,000
		Total			**21,860,000**

No.	Description	Unit	Qty.	Unit Cost (USD)	Total Cost (USD)
1	500 kV line bay, double bus	each	8	1,800,000	14,400,000
2	500 kV Bus coupler bay	"	1	1,700,000	1,700,000
3	500 kV shunt reactor bay	"	1	1,700,000	1,700,000
7	500 kV, series capacitor bay, double bus	"	16	1,800,000	28,800,000
4	500 kV 1X45 MVAr line connected reactor	MVA	45	24,000	1,080,000
6	500 kV Series Capacitor	"	4000	48,000	192,000,000
5	500 kV 8X135 MVAr line connected reactor	"	1080	24,000	25,920,000
8	Substation Basics	lot	1	1,600,000	1,600,000
9	General civil work	lot	1	500,000	500,000
		Total			**267,700,000**

No.	Description	Unit	Qty.	Unit Cost (USD)	Total Cost (USD)
1	500 kV incoming line bay, double bus	each	4	1,800,000	7,200,000
2	500 kV transformer bay, double bus	"	8	1,700,000	13,600,000
3	500 kV Bus coupler bay	"	1	1,700,000	1,700,000
4	500/400kV 750 MVA transformer	"	8	15,000,000	120,000,000
5	400 kV transformer bay, double bus	"	8	1,100,000	8,800,000
6	400 kV line bay, double bus	"	4	1,200,000	4,800,000
7	400kV shunt Capacitor bay	"	1	1,100,000	1,100,000
8	400 kV Bus coupler bay	"	1	1,300,000	1,300,000
9	400kV 3x90/1x45 MVAr Shunt Capacitor	MVA	315	22,000	6,930,000
10	Substation Basics	lot	1	4,200,000	4,200,000
11	General civil work	lot	1	1,300,000	1,300,000
		Total			**170,930,000**

No.	Description	Unit	Qty.	Unit Cost (USD)	Total Cost (USD)
1	Two Double Ckt, Steel Tower from GERD-500kV to Dedesa	km	345	1,200,000	412,800,000

2	Two Double Ckt, Steel Tower from Dedesa to Holeta Substation	km	275	1,200,000	276,000,000
	Total Transmission Line Cost				688,800,000
	Total Substation cost				460,490,000
	Total Cost				**1,149,290,000.00**
	Engineering & Administration cost			5.0%	57,464,500.00
	Total Project Cost				1,206,754,500.00
	Physical Contingency			5.0%	60,337,725.00
	Price Contingency			10.0%	1,267,092,225.00
	Grand Total Project (USD)				**1,393,801,448.00**

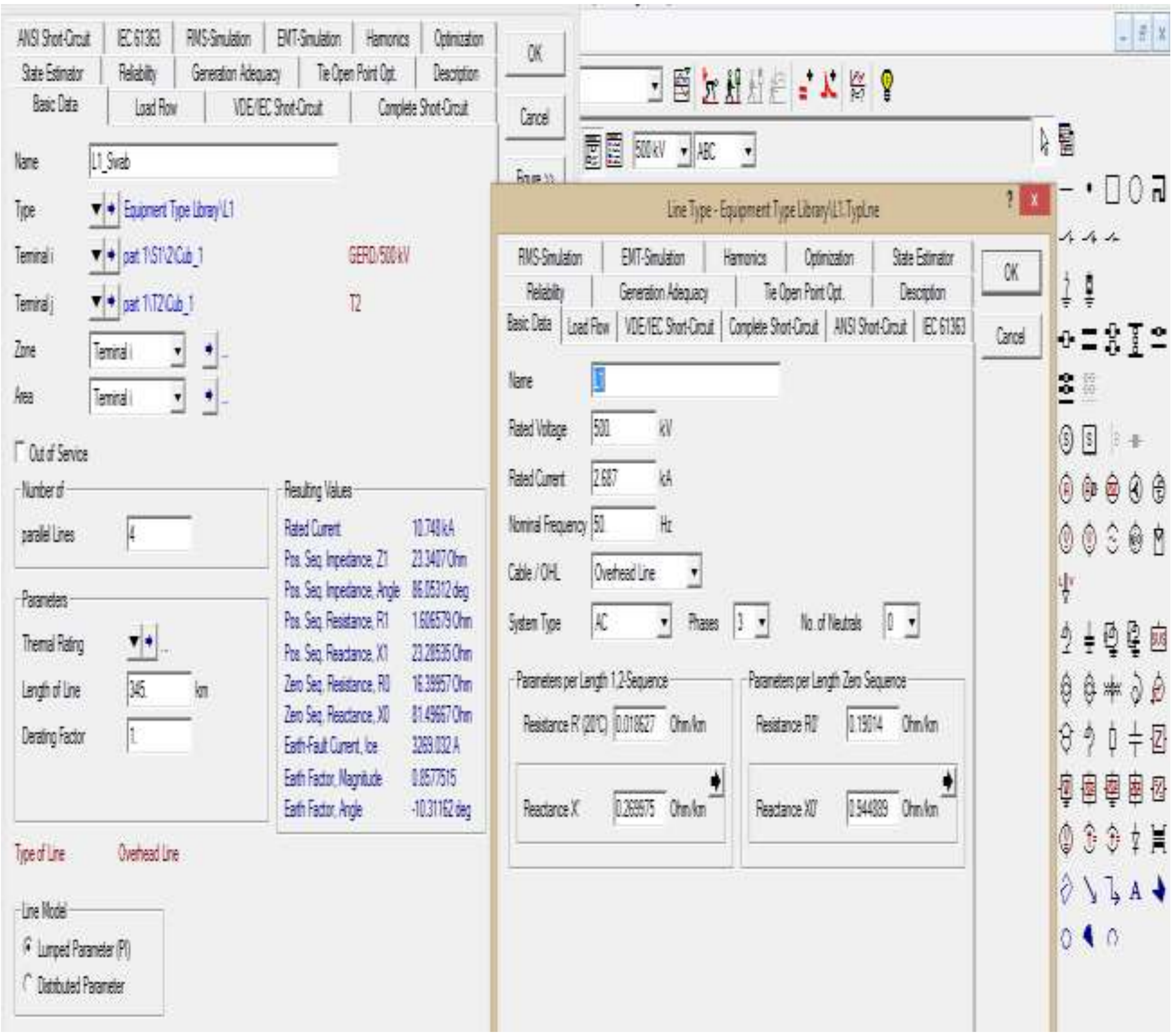

Figure B1: Input data to the DigSILENT

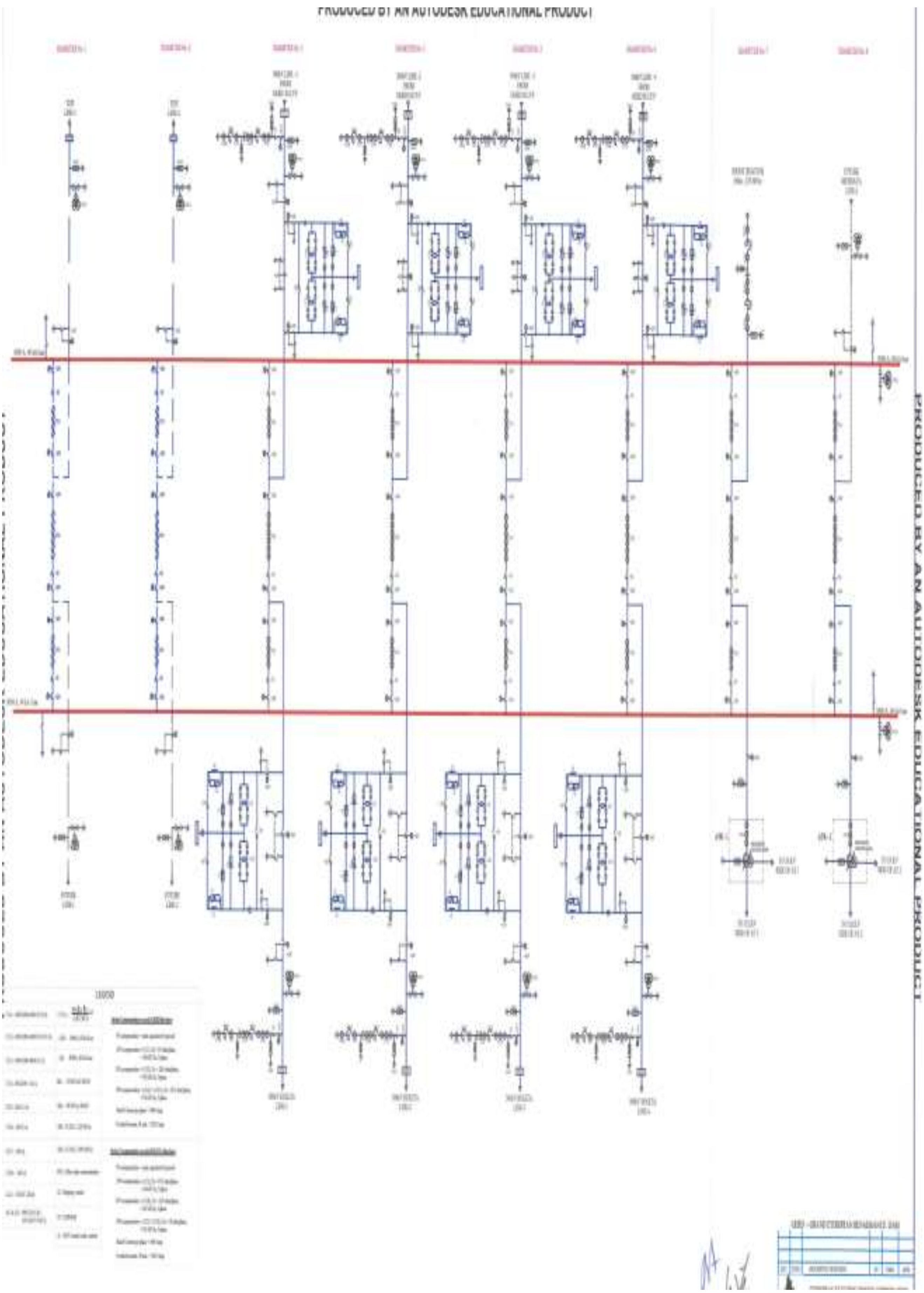

Figure B2: Total lines of GERD-Dedesa-Holeta transmission system