Reactive Power Compensation Analysis and Its Determination on 132/15 kV Transmission Substation System Using Appropriate SVC Devices
[A Case Study at Mekannisa Substation, Addis Ababa]

Yibbabie Tilahun Alemu

A Thesis Submitted to the Department of Electrical Power and Control Engineering

School of Electrical Engineering and Computing

Presented in Partial Fulfillment of the Requirement for the Degree of Master's
in Electrical Power and Control Engineering (Power System Engineering)

Office of Graduate Studies
Adama Science and Technology University

July 2022
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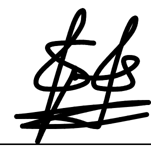
Declaration

I hereby declare that this Master Thesis entitled "Reactive Power Compensation Analysis and Its Determination on 132/15 kV Transmission Substation System Using Appropriate SVC Devices [A Case Study at Mekannisa Substation, Addis Ababa] is my original work. That is, it has not been submitted for the award of any academic degree, diploma, or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.



Yibbabie Tilahun Alemu		12/07/2022
Name of Student	Signature	Date

Recommendation

I, the advisor of this thesis, hereby certify that I have read the revised version of the thesis "Reactive Power Compensation Analysis and Its Determination on 132/15 kV Transmission Substation System Using Appropriate SVC Devices [A Case Study at Mekannisa Substation, Addis Ababa]" prepared under my/our guidance by Yibbabie Tilahun Alemu submitted in partial fulfillment of the requirements for the degree of Masters' of Science in Electrical Power and Control Engineering. Therefore, I recommend the submission of a revised version of the thesis to the department following the applicable procedures.

________________________	____________________	_______________
Advisor	Signature	Date

Approval Sheet

I, the advisor of the thesis entitled "Reactive Power Compensation Analysis and Its Determination on 132/15 kV Transmission Substation System Using Appropriate SVC Devices [A Case Study at Mekannisa Substation, Addis Ababa]" and developed by Yibbabie Tilahun Alemu, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Advisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the thesis by Yibbabie Tilahun Alemu have read and evaluated the thesis entitled "Reactive Power Compensation Analysis and Its Determination on 132/15 kV Transmission Substation System Using Appropriate SVC Devices [A Case Study at Mekannisa Substation, Addis Ababa]" and examined the candidate during the open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Electrical Power and Control Engineering.

Chairperson	Signature	Date
Internal Examiner	Signature	Date
Dr. Yeshitela Shiferaw	[signature]	22/07/2022
External Examiner	Signature	Date

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

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ACRONYMS AND ABBREVIATIONS

B_C	Capacitive Susceptance
B_L	Inductive Susceptance
B_{SVC}	Static Var Compensator Susceptance
B_{TCR}	Thyristor Controlled Reactor Susceptance
B_{TSC}	Thyristor Switched Capacitor Susceptance
FACTS	Flexible Alternating Current Transmission System
FC-TCR	Fixed Capacitor – Thyristor Controlled Reactor
HVAC	High Voltage Alternating Current
I_{TCR}	Thyristor Controlled Reactor Current
L_{eff}	Effective Inductance
K	System gain
kA	kilo Ampere
K_P	Proportional gain
K_{SL}	The current Droop
kV	kilo Volt
MATLAB	Matrix Laboratory
MVA	Mega Volt Ampere
MVAR	Mega Volt Ampere Reactive
MW	Mega Watt
n_{cap}	number of capacitors
P.F	Power Factor
PLL	Phase-Locked Loop
p.u	per unit
Q_C	Capacitive Reactive Power
Q_L	Inductive Reactive Power
SVC	Static VAR Compensator
Trafo	Transformer
TSC-TCR	Thyristor Switched Capacitor – Thyristor Controlled Reactor
X_C	Capacitive Reactance
X_L	Inductive Reactance

Abstract

Reactive power compensation is extremely crucial to implementing the development of power quality-related issues related to the consumers. The robust use of Static VAR Compensators under shunt FACTS devices plays a significant role in voltage regulation because of their fast response and high capability. Thus, it becomes necessary to review the utilization of SVCs for transmission system voltage control under normal operating conditions. This research investigates the reactive power compensation of the Mekannisa 132/15 kV transmission substation using Static VAR Compensators (SVCs). Data assortment and analysis are allotted to study the reactive power that is absorbed and supplied during peak load conditions and increment the specified voltage level of the Mekannisa transmission substation. The modeling and simulation studies are applied using MATLAB Simulink software. Simulation studies with and without SVCs have been performed for various situations of SVCs Configurations, like FC-TCR (Fixed Capacitor-Thyristor Controlled Reactor) and TSC-TCR (Thyristor Switched Capacitor Thyristor Controlled Reactor) hybrid configuration, to investigate its impact on voltage profile. The simulation outputs indicate the substation reactive power is compensated by implementing the shunt controlling SVCs that are absorbing (inductive) and generating (capacitive) in MVAR. This supports the voltage level to be incremented by inserting the desired SVCs into the system so that it is within the acceptable range. Consequently, the measured source voltage (V_{meas}) is improved from a reference voltage value of 1.0 p.u to 1.081 p.u. In the same manner, the voltage level of the outgoing lines improved from 0.949 p.u to 1.023 p.u. Furthermore, the power factor is corrected by adding the two SVC types in the 15 kV load bus such that it is near the unity power factor i.e. 0.998 p.u. Thus, supported by the findings of this research, it's concluded that Static VAR Compensators are also implemented to enhance the regulation of the voltage profile of transmission substations.

Keywords: FACTS, FC-TCR, MATLAB, Reactive power compensation, SVC, TSC-TCR.

CHAPTER ONE

INTRODUCTION

1.1 Background

Deregulation and instability of the transmission system lead to a loss of required power transfer for the electrical transmission network. Therefore, all actions must be taken to confirm that reactive power doesn't impede the transmission capacity. In addition, power loss in vital transmission systems must be avoided to eliminate the danger of jeopardizing the grid stability, and reliability additionally as an advantage for business operations. Moreover, to supply the best flexibility, the transmission system should make sure the maximum safe operative margins permit power injection from its buses while not endangering stable operation. Thus, the outcomes of transmission operations depend upon providing the utmost out there transmission capability on the substation. The advancements in power-electronics technology currently offer controllers that give fast responses such that FACTS controllers assure this desirable flexibility. The research matter was an integration of classic power systems, power electronics, and control aspects throughout the development and implementation of control systems for good power stability. Reactive power compensation is taken into account as a robust tool for optimizing the power flow on transmission networks. Inadequate reactive power results in voltage collapse, resulting in an uncontrolled power network in the area. Reactive power compensation is provided by FACTS devices, which are power electronic-based devices that control and regulate the electrical power flow inside the power system. They're capable to reroute power through the optimum out there ways despite the dynamics of the power system. Ethiopian Electric Power Corporation has a lot of substations including distribution and transmission networks. Mekannisa substation is one of the transmission substation systems located around Lebu, Addis Ababa. It has two incoming lines one from the Kality-I substation and Sebeta/Geffersa substation as well as one outgoing line to the Gofa substation which carries 132 kV. The substation has two power step-down transformers with ratings of 50 MVA and 20 MVA respectively as well as two buses i.e. 132 kV on bus one and 15 kV on bus two. It had seven-line feeders from the substation and connected to the distribution transformers that reach the load. The outgoing feeders from 15 kV trafo reached seven places in Addis Ababa namely: Hanamariam, Lebu, Lafto, Mekannisa, Sebeta, C.G.C, and one for the water pump.

1.2 Statement of the Problem

The low voltage levels and uncompensated reactive power problems associated with the substation which has no capacitor banks and shunt reactors are required to compute the injection and absorption of the MVARs on the bus of the system. As a result, they need a reactive power compensation and voltage stability analysis that supports the feeders which give the specified amount of power with fewer transmission losses. As a general truth, reactive power range and voltage levels are interrelated to each other. So that once reactive power is compensated, the voltage will be controlled in the other way by using a combination of hybrid SVC configurations. The analysis depends on the case of the Mekannisa substation that has a lower voltage level in which how much reactive power is injected and absorbed by the inductive loads that influence and determine the voltage. This preference has done through which total losses in MW and MVAR including external in feed without the static var compensators which brought a constant voltage reading to 15 kV bus connected loads that fed the seven chosen areas with the line feeders. The problem depends upon the voltage deviation in the absence of TSC-TCR and FC-TCR SVC models. For instance, the loads with 15 kV tapped on their bus with reactive power loading vary every one hour. If the hybrid TSC-TCR or FC-TCR shunt controller is not applied further, the voltage will also vary throughout the months of each coming year and become unstable on account of the reactive power that comes and goes from and to the incoming and outgoing lines which adversely affects the load. Consequently, this reactive power needs to be compensated to support the voltage and to improve the stability of the substation in the power system network.

1.3 Objective of the Thesis

1.3.1 General Objective

The main objective of the research is to perform studies on the reactive power compensation and voltage control techniques by using the static VAR compensators.

1.3.2 Specific Objectives

- To analyze voltage control methodologies and stability power flow studies using shunt controlling FACTS devices.
- To compute and model the substation using MATLAB Simulink software.

- To simulate the system under dynamic load variation and compare the results with and without the static VAR compensators.
- To maintain the voltage levels and compensate for the reactive power depending on the peak load of the substation.
- To analyze and compare the voltage profile of Mekannisa 132/15 kV transmission substation with and without SVCs.
- To model the power factor correction of the substation using MATLAB.
- To analyze the appropriate data and associate the voltage-related problems of the Mekannisa transmission substation.

1.4 Scope of the Thesis

This thesis has been completed on the compensation of reactive power for the voltage stability based on the analysis of the Mekannisa 132/15 kV transmission substation by following the modeling of static VAR compensators and simulating the results by MATLAB/Simulink software and comparing the results before and after adding these shunt controlling techniques.

1.5 Limitations and Delimitations of the Thesis

The thesis is limited to only simulation of the system using MATLAB/Simulink. Thus the substation has no capacitor bank and shunt reactor, it is difficult to obtain the system component devices in real life rather than in simulation.

1.6 Significance of the Thesis

Reactive power compensation and voltage control are the most important factors that need investigation and analysis to support the power system network. So, this thesis improves the voltage level of the Mekannisa 132/15 kV transmission substation depending on the system bus which is too weak that affects the load, interruption of frequency, and uncontrolled voltage ups and downs. Consequently, it addresses the assurance of good voltage stability techniques including shunt compensation components of variable impedance type static VAR generators such that thyristor switched capacitor-thyristor controlled reactor and fixed capacitor-thyristor controlled reactor under FACTS devices involvement in the system. The study delivers to answer questions about the necessity of response formulations including which system bus is absorbing/ injecting reactive power or not. At which values that the 15 kV bus affected by low voltage levels? How many line feeders are affected by the system? Where did a short-circuit or the fault occur? How does the dynamic variation of the loads affect the line feeders? What are the effects of adding the static VAR compensators to the bus? Will the shunt controller give an increase in bus voltage? Will the interruptions persist after adding the SVCs? Will the SVC devices vary the system values according to peak, and minimum loads? These questions must be properly investigated to make the system lie on stability. Further calculations of reactive power ratings for the capacitor banks and reactors issue the modeling and simulation of the substation more accurately to improve the voltage levels. These shunt-controlling SVCs are designed for fast voltage regulation and control operated with a given reactive power under normal characteristics. Later, they refer to the minimization of reactive power flow to the step-down transformers and giving voltage support to the outgoing line feeders of the substation.

1.7 Thesis Outline

The organization of the thesis is comprised of five chapters namely:

Chapter one presents the introduction, statement of the problem, objectives of the study, and significance of the study leading towards the completion of the thesis.

Chapter two deals with a brief explanation of the static VAR compensators in the power system network and reactive power control which relates to voltage stability.

Chapter three examines the research methodology, mathematical analysis and modeling of the static VAR compensators, an overview of the substation, data organization, Simulink modeling as well as cost determination of the SVC ratings.

Chapter four presents the simulation results and discussion part of the research.

Chapter five discusses the conclusions, recommendations, and suggestions for future work.

CHAPTER TWO
LITERATURE REVIEW

2.1 Theoretical Background

For economical and reliable operation of power systems, the management of voltage and reactive power ought to satisfy the subsequent objectives are needed to be implemented in the power system. Voltages at the terminals of all devices within the power system network need to be within acceptable limits. On the utility and consumer side, devices are designed to control at a definite voltage rating. Prolonged operation of the equipment at voltages outside the allowable limit might adversely affect their performance and presumably cause them damage. System stability and reliability are increased to maximize the use of the transmission system. Voltage regulation and reactive power control have a major impact on system stability. This ensures that the transmission operates efficiently such that primarily used for active power transfer. The concern of maintaining voltages inside the desired limits is affected by the fact that the power system provides power to an enormous variety of loads and is fed from several generating units. As loads vary, the reactive power in the transmission system varies consequently (J.E Miller, 1982, and R. Mohan Mathur, and K.M. Kavita, 2016).

(J.E Miller, 1982, and S. Daiva, and V. Radziukynas, 2022) Since reactive power cannot be transmitted over long distances, voltage control should be accomplished by exploiting special devices distributed throughout the system. This is often in distinction to the control of frequency that depends on the electrical power system’s active power balance. The right choice and coordination device for controlling reactive power and voltage are among the most important challenges in the power system engineering discipline. The modern power system is complicated and it's essential to fulfilling the demand with higher power quality. Advanced technologies are today getting used for maintaining power system reliability, security, and stability because of this power quality is improved. Voltage stability, voltage security, and power profile improvement are essential for power quality assurance. Also to realize the optimum performance of the power system, it is needed to regulate reactive power flow within the network which supports the voltage levels accordingly. Construction of recent transmission lines and power substations will increase the matter of system operation in addition to the overall cost, and restrictive limitation on the enlargement of the system network has resulted in an exceedingly reduction in stability margin thereby increasing the risk of voltage collapse. Voltage collapse or voltage instability happens in a power grid once the system is faulted, and heavily loaded. Thus, there's an increment in the demand for reactive power. Voltage instability in a power system occurs when the system is unable to satisfy the reactive power demand. And then, reactive power imbalance occurs when the system is faulted, heavily loaded and voltage fluctuation is there. Therefore, reactive power balance may be regained by connecting a device with the conductor which might inject or absorb reactive power based on system needs. FACTS is also outlined as a power electronic-based semiconductor device that may inject or absorb reactive power in a system as per requirement.

(R. Pratheeksha, and K.M. Kavitha, 2016, and Sen K.K., and Sen M.L, 2009) put their suggestions on this device permits the “Flexible” operation of an AC system while not stressing the system and giving support to the main applications within the specified areas such that power generation, power transmission, power distribution, railway grid support, and also for a distributed generation like wind, and solar. With FACTS, the subsequent advantages are often earned in AC systems that are improved power transmission capability, improved system stability, and availability, improved power quality, reduced environmental impact, and minimized transmission losses. FACTS are a family of devices that might be inserted into a power system network in series, in shunt, or a hybrid model of the two controllers. On the other hand, a static volt-ampere-reactive compensator (SVC) is a device for providing reactive power on transmission networks and stabilizing the voltage within the prescribed levels. The term “static” refers to the fact that the SVC has no moving elements (other than circuit breakers and disconnectors) that don't move under normal operating ranges.

(Sen K.K., Sen M.L, 2009, and K. Chaurasiya et al., 2018) discussed the SVC which brings the system nearer to the unity power factor. The device uses a synchronous voltage supply (SVS). The shunt-connected reactors comprised of the compensator to scale back the line overvoltages by intense the reactive power, whereas shunt-connected capacitors are used to maintain the voltage levels by compensating the reactive power to the transmission line. The overall requirement for compensation is voltage control, power system network stabilization, and reactive power flow control. There are some approaches to compensation. Among them, the fundamentals are passive compensation with mounted shunt susceptance, inductors, and capacitors, passive compensation with mounted series capacitors, and active or dynamic shunt compensation with synchronous condensers or static volt-ampere systems. Dynamic reactive power compensation therefore typically utilized at the HVDC/HVAC interface. Once the ac system resistance is so high that enormous ac voltage swings accompany little HVDC power swings. Compensation within the type of switched or fixed capacitor compensation, synchronous condensers, static VAR systems, or a combination of all forms is beneficial to resolve this problem.

Table. 2.1 FACTS devices functions in the power system (R. Mohan, 2002).

Shunt Capacitors	Shunt Reactors	Series Capacitors	Synchronous Condensers
Steady-state voltage control	Steady-state voltage control	Power transfer	Steady-state and dynamic voltage control
Reactive power flow control		Stabilization	Reactive power flow control
		Reactive power flow control	Power transfer and stabilization

The SVCs play three distinct roles:

1. Highly fast responsiveness implying reactive compensation changed in 0.5 to two cycles of the power frequency.

2. Individual or balanced three-phase control.

3. Continuous reactive compensation, which means adjusting it every 0.5 cycles of the power frequency.

(Majeed Rashid Zaidan & Saber Izadpanah Toos, 2021) demonstrated a research on the reactive power compensation which needs detailed analysis as one major issue with reactive power is that a suitable amount of it is necessary to provide the loads and losses within the network; nevertheless, having an excessive amount of reactive power flowing along in the network generates excess heating and undesired voltage drops. The common approach is to provide reactive power sources, especially at the location where reactive power is consumed. And, because reactive power does not require any "fuel," it should be possible to spread reactive power sources (such as capacitors) throughout the network to prevent heating the conductors and causing voltage drops. Unfortunately, this is not feasible in the extreme because there are numerous lines and loads connected to the grid, necessitating the use of vast numbers of reactive power sources, all of which must be mainly controlled to supply absolutely the right amount of reactive power at the exact right time every second of every day. Most cases will be neutralized by figuring out some kind of load aggregation at important connection points and transformers. This also leads to the question of the contrast between power quality management (attempting to exactly provide the appropriate amount of reactive power required to equal that which is used) and voltage control (trying to stay voltage levels at precisely the right level regardless of what proportion reactive power it takes). Each concern is reactive power, and hence the response to network voltage stability. The electrical characteristic of lines causes a dip that must be adjusted independently of whether the specific line flow is transferring active or reactive power (or both). The reactance also consumes reactive power, which should come from though. Serving reactive power to several is difficult since the reactive power must be delivered from the source to the load, increasing reactive losses and necessitating a large amount of reactive power from the source. The system response of reactive power sources ranges between milliseconds and seconds.

(Rengin Idil Cadabag, 2019) recommends the contribution in the modern circumstances, integrating SVC devices to enhance the power network voltage stability is crucial as it determines the power system engineering discipline. The TSC-TCR and FC-TCR configurations of the SVC contribute a role to play in supporting voltage on the weakest bus. The TSC is activated using two thyristors coupled back-to-back in the TS-TCR at a point in the cycle when the voltage across the value is minimum and positive, leading to decreased switching transient conditions. TSC does not produce any harmonics in steady-state, hence it is applied to generate reactive power. When the current through the thyristors falls below the holding currents, the gate pulses are blocked and the thyristors turn off. It should be noticed that multiple pairs of thyristors are arranged in series because the thyristor's voltage rating is inappropriate for the voltage necessary level. To adjust the rate of change of current in a TSC, a small reactor must be added in series with the capacitor. While the TCR can absorb reactive power from the bus, the TCR compensator's effective inductance can be achieved by altering the firing angle of the thyristors. If the thyristors are fired properly at the source's voltage peak level, They will then operate in a continuous step. Some of the numbers of TSC branches needed to be turned into suitable required capacitive output current with positive surplus and measure the amplitude of the inductive current required to eliminate the excess capacitive current To switch the capacitor banks, a logic must first detect two events: when the voltage across the thyristor valve is zero or when the voltage across the thyristor valve is at its highest. The real firing angle generation for the thyristors in the TSC valve is similar to that used for TCR, with the exception that continuity is provided to maintain the conduction state when the current is transferred from one thyristor string with positive polarity to another string with negative polarity. One of the most efficient approaches is the TSC-TCR, which senses the line voltage and preserves consistency by introducing capacitance and inductance to the system.

SVC TSC Control:

- Step-wise control.
- Average delay of a one-half cycle (maximum one cycle) in the execution of a command from the regulator.
- Very low inrush transients.
- No generation of harmonics.
- Low losses.

SVC TCR Control:

- Continuous control.
- Maximum delay of a one-half cycle in the execution of a command from the regulator.
- Practically no transients.
- Generation of harmonics.

2.2 TSC-TCR FACTS Controllers

(Rengin Idil Cadabag, 2019) puts the idea on the most common SVS features in high voltage electrical transmission systems are voltage stability along the line, where the VARs supplied by a line equal the VARs absorbed by the line, and net VARs are zero only when the load is close to the natural load. If the load exceeds the normal load, the line consumes net VARs. To maintain equal voltages across both ends of the line, each endpoint must supply an equivalent quantity of VARs. If the load on the line is less than the natural load, which happens naturally during high point conditions, the line produces net VARs. These VARs must be absorbed by employing shunt reactors at both ends of the line to maintain equal voltages. Improved stability when two or more locations are connected by lines in network topologies. System errors and power outages impact negatively system stability. According to research, adjusting the VARs supply at an appropriate point in the network can increase reliability. Thyristor switched shunt capacitors are very effective for this kind of concern. Overvoltage functions at which shunt compensation can regulate overvoltages under temporary and dynamic circumstances, allowing for a reduction in specified insulation levels. This function necessitates SVS rapidly flipping into absorption mode, which is best accomplished using a thyristor-controlled reactor. Lowering of VARs flow occurs when the availability of shunt compensating loads causes a reduction in the essential flow of VARs in the network, resulting in lower system losses and enhanced system availability.

(R. Mohan Mathur, Rajiv K. Varma, 2002, and Sen K.K, Sen M.L, 2009) suggest the operation of the TSC – TCR which comprises several TSCs and typically one TCR. It can also manipulate the reactive output using its complete rated power. Its process is equivalent to the FC-TCR instead of just the constant capacitive VAR output. Many TSCs have a step-wise characteristic curve to meet the reactive power need with suitable capacitive net reactive power and a markedly low inductive reactive power output of TCR instead of a continuous capacitive var output (QTCR). The TCR must be capable of changing for each capacitive step and, if necessary, provide an inductive VAR output. Assuming that TSCs ncap have the same nominal values, the desirable capacitive VAR range QC is separated into ncap intervals. The reactor can be variously switched into the circuit via thyristors to provide continuously variable VAR absorption to the electrical power system network. The capacitors supply the voltage in this setup, while the thyristor-controlled reactor affords simple modulation and control.

(Jahnavi Lakkireddy, 2014, and Filipovic Grcic, B. et al., 2021) explicitly mentioned the thyristor-controlled capacitor switching can provide smoother control and greater versatility. The static VAR compensator's thyristor switched capacitors can be switched in or out most accurately. As a result, the quantity of reactive power supplied via TSCs is best adjusted in steps by transforming the number of TSCs that may be switched on at the same time. The greater the number of TSCs that can be activated, the greater the amount of reactive power delivered by the TSCs. The TCR, on the other hand, can be adjusted as needed from a fully conducting state (TCR firing angle $\alpha=90^0$) to a non-conducting state (TCR firing angle $\alpha=180^0$), designed to allow for unique and continuous adjustment of the amount of reactive power conveyed by the static VAR compensator with the alternating current power system to that which is connected.

(Divyam, A. Saxena et al., 2020) implied a point of view on the amount of reactive power needed to adjust for the voltage within the alternating current power system connected to an SVC of the TSC-TCR type is zero, all TSCs are turned off and the TCR is ready to conduct (TCR firing angle equals to180^0). When the SVC is required to deliver reactive power to enhance the voltage inside the ac power system, a number of TSCs are switched so that the reactive power delivered exceeds the amount of reactive power. To control for the ac system voltage, the SVC must supply. As a result, the TCR firing angle is altered so that the amount of reactive power consumed through the TCR directly affects the amount of reactive power generated by the TSCs. The firing angle is adjusted so that the thyristor-controlled reactor consumes the adequate and significant amount of reactive power provided by the TSCs at the specific measured amount of reactive power that the SVC has to deliver to well compensate for the ac power system voltage will increase or decrease.

(Jinbo Che, and WenYu Hu, 2021) drawn out the value of reactive power that the SVC should deliver to modify the voltage within the ac transmission system exceeds the reactive power rating of the TSCs that are currently switched in the TCR firing angle is around 180^0. Another TSC must be activated in this instance. On the other hand, when the amount of reactive power that the SVC has to supply to balance the voltage dips below the level of reactive power that the SVC delivers, the thyristor-controlled reactor absorbs the most reactive power. i.e. When the TCR firing angle reaches 900, the TSC should be turned off. In each scenario, the TCR firing angle is then changed, resulting in the TCR absorbing only a considerable amount of reactive power supplied by the TSCs to meet the reactive power demand of the alternating current power system to which the SVC is linked.

(M. Maheshkumar, 2016) construed an implication when all TSCs are turned on and the thyristor-controlled reactor is about to enter a non-conducting state, the SVC of the TSC-TCR architecture provides a substantial quantity of reactive power (the TCR firing angle is set to 180^0). It will request TSC to enable or disable block control. For example, if one TSC branch responds to a request, it will follow this control block and activate TSC. If two TSC branches must be turned on at the same time, another request will be sent to the same block, which will generate the firing pulses for switching in or turning on the second TSC branch. The effects of SVC devices defined TSC-TCR configuration insertion on system impedance have a direct influence, as well as an injected variable susceptance of B_{TCR} and B_{TSC} that is ready to maximize network performance and acquire to minimize sudden circuit breaker tripping. Because an SVC compensator is implemented, the number of TSC branches "n" is set by subjective considerations such as the operating voltage level, maximum limit volt-ampere output, and current rating of the thyristor valves. By adding more TCR branches, the inductor value can be increased to any maximum rating. Within the first interval, the entire capacitive output range is divided into n-intervals. As a result, the reactive power generator's output ranges from zero to Qcomp/n. When Qcmax matches the overall rating generated by all TSC branches. During this period, one capacitor bank is switched on by firing and synchronously, and this in the TCR is ready by the appropriate firing delay angle, such that the aggregate of the volt-ampere outputs of TSC (negative) and TCR (positive) equals the capacitive output required. Thus, these FACTS devices are used to control reactive power flows in transmission systems by adjusting their parameters and improving the system's sensitivity and stability.

2.2.1 Thyristor Switched Capacitor

(Rengin Idil Cadabag, 2019) analyzes the response of TSC that is made up of many capacitors, yet the number of parallel capacitors is limited due to the expensive property of thyristors in their wide range of operations. This instructs efficient step-by-step regulation of reactive power. Unlike the TCR, the TSC cannot be manipulated continuously, but rather in a somewhat discrete manner. Once the thyristor valves are conducting, the capacitive current is used to switch the capacitor into the system. The switching-off event will occur only when there is a zero-current crossing, resulting in the least conducting time of half a phase length. The detached capacitor should ideally remain charged at this maximum value. To avoid the voltage across the thyristor switches Vsw reaching the peak-to-peak voltage, the capacitor is normally discharged upon disengagement. To ensure minimal temporary perturbation, the reconnection must occur when Vsw=zero. Because of these switching conditions, the TSC has restricted controllability. Each TSC contains a current limiting reactor whose purpose is to regulate the rate at which the current through the thyristors rises and to prevent resonance with the network (usually X_L/X_C). The current flowing through the capacitor varies according to the applied voltage. This results in a lower reactive power compensation once there's a dip within the system voltage. To approximate continuous current variations, many TSC branches in parallel are also used. Once all TSCs are switched on and therefore the valves are conducting however the voltage remains decreasing the output of the compensator also decreases.

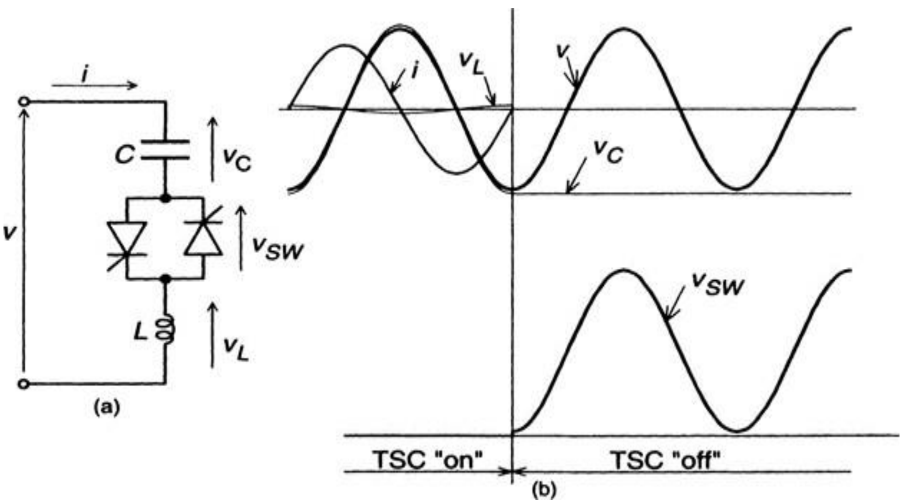

Fig. 2.1: V-I characteristic during TSC switching time.

2.2.2 Thyristor Controlled Reactor

The operation of a thyristor-controlled reactor (TCR), for firing delay angle, can constrain the current in the reactor i_{TCR} indefinitely. The TCR has a controlled range of $\alpha=90^0$ to $\alpha=180^0$. In the TCR, a firing angle of $\alpha=90^0$ results in a steady sinusoidal current flow. For this condition, the most intense responsive current and, as a result, the maximum reactive power is drawn. The current flows as discontinuous pulses uniformly distributed in the positive and negative half-cycles as the firing angle fluctuates from $\alpha=90^0$ to $\alpha=180^0$. The instance of $\alpha > 90^0$ causes the valves to open slowly, reducing reactive power absorption. The TCR behaves like a variable susceptance. Variety in the α changes the susceptance B_{TCR} and, subsequently, the fundamental current component, which prompts a variety of reactive power consumed by the reactor since it is accepted that the applied AC voltage is consistent. For α=90°, the TCR addresses a shunt reactor with its full inductive rating. Notwithstanding, as the α is expanded past 90°, the current becomes non-sinusoidal, and harmonics are produced. Expecting a consistent inductivity and steady system frequency, the reactive current drawn by the TCR is relative to the system voltage and lies on the α of the thyristors (D.I. Panifilov, A.E El Gebalv et al., 2018, and Rengin Idil Cadabag, 2019).

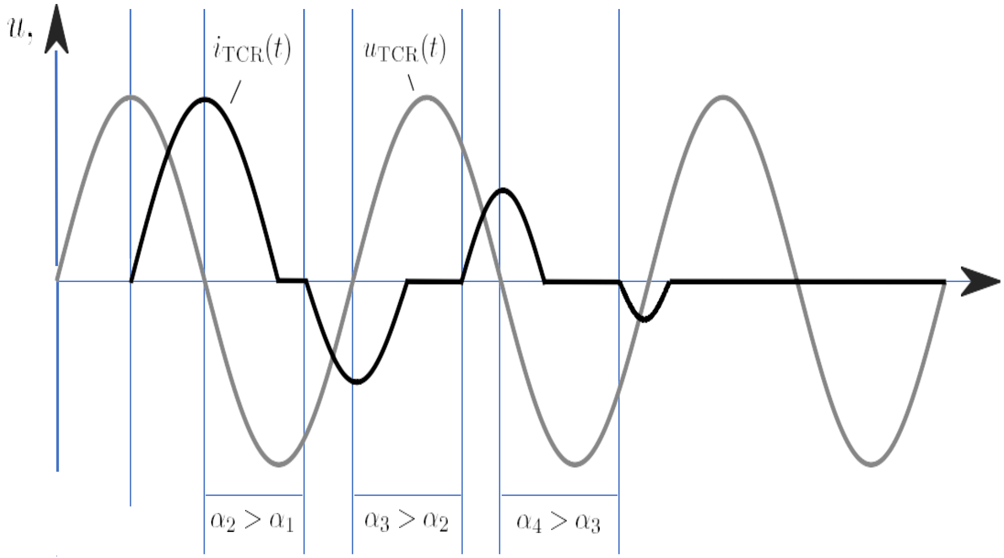

Fig. 2.2: Voltage controlling mechanism using thyristor controlled reactor on angle α.

2.2.2.1 The Thyristor-Controlled Reactor Operation

(A. Pekdemir, and A.B Yildiz, 2018) brought out the susceptance characteristics that depict the change in total SVC susceptance when the TCR susceptance is altered. TCR susceptance is negative, showing that the TCR is a reactive component that consumes. Because these features are most valuable to monitoring assessment, the controller governs the TCR firing angle, whereas the overall susceptance BSVC affects the power grid. Current characteristics for a lot of sophisticated SVC arrangements, notably those likewise to TSCs, it' difficult to examine. The many branches, however, contribute to the overall SVC current. As a result, these characteristics demonstrate that branch currents run the whole SVC current and are critical for determining the steady-state current ratings of the individual components. If the influence of voltage management is integrated, the operating feature is reduced to at least one characteristic of functional points, allowing the supposition that the compensator is equipped with voltage control. The system voltage is detected, and the feedback mechanism changes the thyristor controller reactor susceptance to maintain the system reference voltage. This control action is represented among the operating characteristic by the horizontal branch marked because the control range. This means the overvoltage control of the compensator that stabilizes the system voltage exactly to the setpoint reference voltage. The general action of the thyristor controller on the linear reactor of the TCR and capacitor of the TSC is to change the reactor to act as a controllable susceptance within the inductive mode which could be a performance of the angle. A firing angle of 90^0 leads to full thyristor conduction with a continual sinusoidal current flow within the TCR because the firing angle is varied from 90^0 to close to 180^0, and the current flows in the form of discontinuous pulses symmetrically located in the positive and negative half-cycles. Once the thyristor valves are fired, the discontinuity of current happens at its natural zero crossing. A method referred to as the line commutation. The current reduces to zero for a firing angle of 180^0. Thyristor firing at angles below 90^0 introduces dc elements within the current and perturbing the symmetrical operation of the two antiparallel valve branches. A characteristic of the line-commutation process with that the TCR operates is that after the valve conduction has commenced, any modification in the firing angle will solely be implemented in the next half-cycle, resulting in the supposed thyristor deadtime.

The TCR’s reactance doesn't change once the firing angle α is a smaller amount than 90^0, that's a result of the thyristors are in continuous conduction mode because of the impact of the reactor of the TCR. Therefore, the reactance of the TCR is capable of X_L as large because the firing angle α is less than 90^0. On the opposite hand, the TCR’s reactance approaches infinite value as the firing angle α tends to 180^0. One on both sides of the anti-parallel–connected thyristor pair, to stop the complete ac voltage across the thyristor valves and damage them if a short-circuit fault happens across the reactor’s two ends terminals. If the reactor units are identical, and also if all the thyristors are discharged bilaterally with equal firing angles in each phase, then the symmetric current pulses occur in each positive and negative half-cycles, and therefore, the generation of only odd harmonics will have happened. The proportion values of harmonic currents regarding fundamentals both within the phases and in the lines are the same.

2.3 TSC-TCR Closed-Loop Operation

The closed-loop operation has four major blocks namely the voltage regulator, allocator, measurement block which uses linearization, and the pulse generator. The capacitance values for each compensator will be applied to TSC-TCR hybrid configurations to keep up the reactive power within the range of compensated values and to maintain the voltage values at a stable and improved level. The SVC can improve stability with fast-acting voltage regulation. It may also increase power transfer in long lines with damp low frequency oscillations because of swing modes. These devices could affect the measured impedance directly of the protected line. The SVC controls voltage wherever it's connected by adjusting its susceptance to provide or absorb the desired reactive power (Q_{comp}). The SVC consists of TCR and a group of TSC in parallel and associated controlling systems. The controlling system operates to control the voltage at its connecting point.

Measuring circuit: The best method for those circuits is to regulate voltages and currents at completely different locations of the power network, which provides important data for static VAR compensator control and protection. The detected signals are reliant on certain conditions to provide appropriate control to alternative control system blocks.

Voltage regulator: It maintains the voltage in a closed loop. Because the control error signal to a PI (Proportional- Integral) regulator supplies the overall SVC susceptance reference necessary to attenuate the error, the difference between the voltage reference and the voltage measured at the point of connection of the SVC is fed.

Power oscillating damping: Once the power modulation control circuit is housed in the SVC controller, this high-level control function takes the power controller parameters as input and works on voltage regulation to dampen slow electrical and mechanical oscillations in the electrical network.

Allocator: This block converts the voltage regulator's susceptance reference into particular data, which is subsequently processed to determine the number of reactive banks that must be turned on as well as the required firing angle.

Linearizer: It transforms the allocator susceptance to a firing angle to maintain a consistent system reaction over the whole static VAR compensator operational limits. The angle is determined by a non-linear function of the susceptance reference order.

Hunting detection and gain adjustment: The voltage controller is monitored by the stability controller. Improper operations (hunting) will be identified during poor specified operating parameters. To ensure steady functioning, the gain of the PI controller would be lowered by half.

(Acha E., Fuerte- Esquivel et al., 2004) suggests the Q_{comp} (TSC-TCR) provided by TSC is larger than the specified load reactive power Q_L and if the distinction between them is greater than desired value then TCR can acquire the action. once Q_{comp} (TSC-TCR) supplied by TSC is greater than the required load reactive power Q_L. Consequently, if the difference between them is greater than the required value then TCR will come into the action. TCR controller will generate the firing pulses consistent with the error signal between Q_{comp} (TSC) and Q_L. As a result, additional leading volt-ampere-reactive is consumed by the thyristor-controlled reactor, and exact reactive power at PCC (Point common coupling), i.e., Q_{actual}, is stabilized on the Q_{ref} point. As a result, the reactive power drawn by TCR is proportionate to the inductor current iL(. The firing delay angle method of control may regulate the current within the reactor from the highest (thyristor-valve closed) to zero (thyristor-valve open). In the same manner, the angle becomes $90^0 \leq \alpha \leq 180^0$; it can't be able to change from 0^0 to 180^0, unlike the AC voltage controller. For this reason, additional current flow to the circuit (I) into ωL has an impact on the voltage level and proportional VAR will be absorbed. The current within the reactor may be controlled by most thyristor valves near 0^0 into the open state that's 180^0.

Waveform: The closure of the thyristor valve is delayed regarding the sharp point of the applied voltage every 0.5 cycles, and therefore the period of this conductivity interval is controlled.

So, the current that α is needed to be 90^0 then compensates for the inductive current. Hence, it'll have a phase lag of the current by 90^0 since alpha becomes 90^0. Thereafter, it will provide a delay to the value (α), then the conduction for the number of "δ" gives a response for what ought to be the value of the current. And the way abundant reactive power is been absorbed or produced? This is managed within the reactor by converting the firing angle from maximum to zero. The thyristor valve's closed state is delayed by the maximum of the applied voltage. It is intended to represent a 90^0 phase shift and an inductor current of 0^0. The existence of the characteristics of the thyristor-controlled reactor indicates that the shunt reactor is controlled by the valves.

By calculation, the current can begin the delay angle α is given as:

During the positive half cycle,

The current is by an offset of the $\frac{-V_m}{\omega L}\sin(\alpha)$.

This equation is valid only for αt varying from $\alpha \leq \omega t \leq \pi - \alpha$.

Likewise, the conduction angle for the negative half cycle is $\delta=2\pi-\alpha$. The delay angle rises, and the accordingly rising offset occurs in a lowering of the value's conduction angle, and hence a lowering of the reactive current. At the maximum delay of $\frac{V_m}{\omega L}$, at which both the conduction angle and the reactor current become zero. Because the two parameters, delay angle α, and conduction angle δ, are equal, TCR may be defined by either of them.

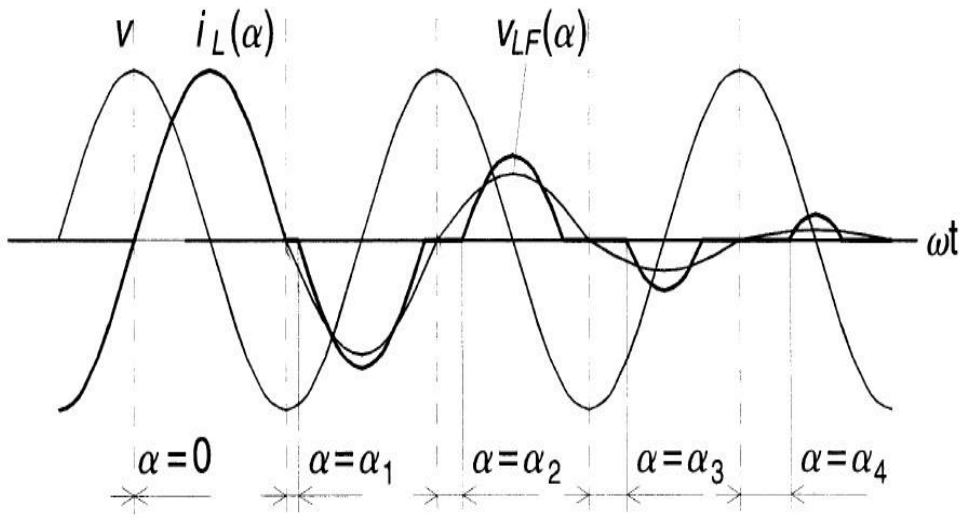

Fig. 2.3: By continuous varying of the firing angle; $0 < \alpha_1 < \alpha_2 < \alpha_3 < \alpha_4$.

If the firing angle increases, the TCR susceptance (B_L) will be reduced then consequently reactive power absorbed will be minimized and vice versa. Further to this, by varying firing angle (α) smooth control of reactive power absorption is achieved by TCR. One thyristor is fired according to the requirements (firing angle), and then the other is released 180^0 after the first where α is the firing angle of the second thyristor). Both thyristors cannot conduct at the same time because if one is conducting, the other is reversely biased, which means that even if it is given a response to conduct, it would be unable to perform. This limiting degree (90^0) is the impedance angle of the system, which is an inductor throughout this situation.

The TCR SVC is made up of a TCR and shunt capacitors that are incorporated. The capacitor banks provide fixed leading reactive power under steady alternating current voltage, while the TCR provides controlled lagging reactive power based on the thyristor valve's firing angle. In each half cycle, the firing of the thyristor valve is interrupted by an electrical angle with particular regard to the phase of the alternating current voltage.

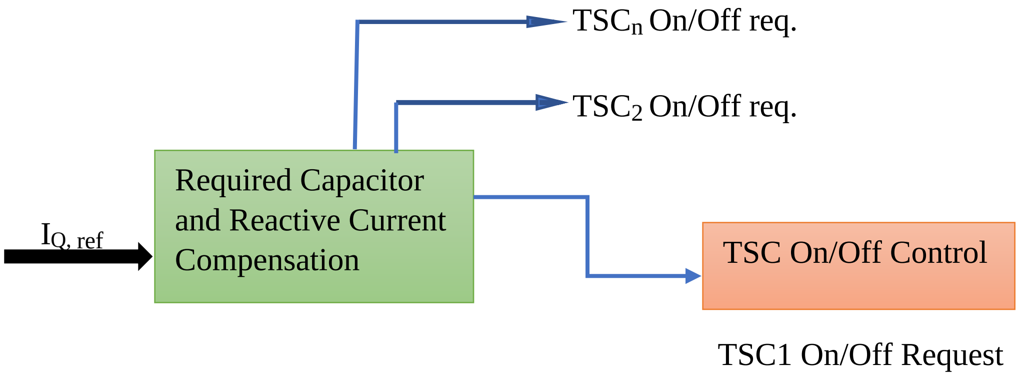

Fig. 2.4: The functional control scheme for TSC.

It will send a request to TSC to turn on/off block control. E.g. If one TSC branch has to be tuned on a request will go to this control block and it will turn on TSC1 if two TSC branches have to be turned on that another request will go to a similar block and that will generate the firing pulses for the switching in or for turning on second TSC branch. Similarly, there may be an "n" number of TSC branches. How many TSC branches can be turned on at a time will be decided by $I_{Q, ref}$ means how much reactive power compensation has to be done.

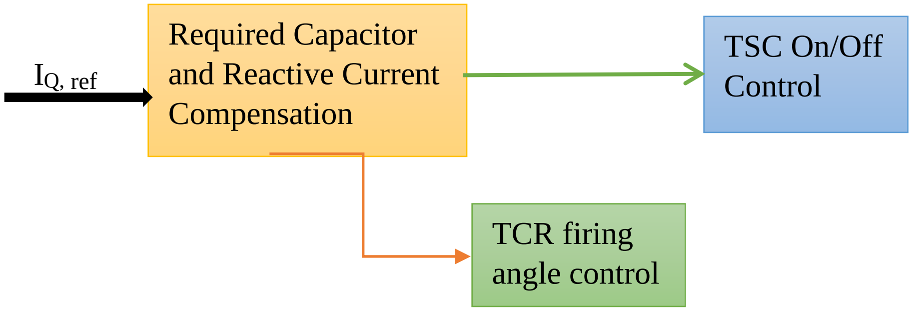

Fig. 2.5: TSC switching with TCR firing angle control.

To address this enormous issue, switching is performed when the voltage imbalance between the capacitor terminals and the voltage at the TSC terminals is minimal, leading to the lowest switching voltage. This will result in a transient period following switching that is minimized in accordance with the technique used to minimize the switching voltage V_{sw}. Another shortcoming is the existence of an inductor and a capacitor, resulting in a regulated LC circuit that will cause vibrations. However, because it can be switched off, the TSC is a more effective method than the FC. The firing angle is either 0 or π/2, with no through the values, implying that the TSC could only completely be on or off. Stability in the capacitive range is still inefficient in this manner.

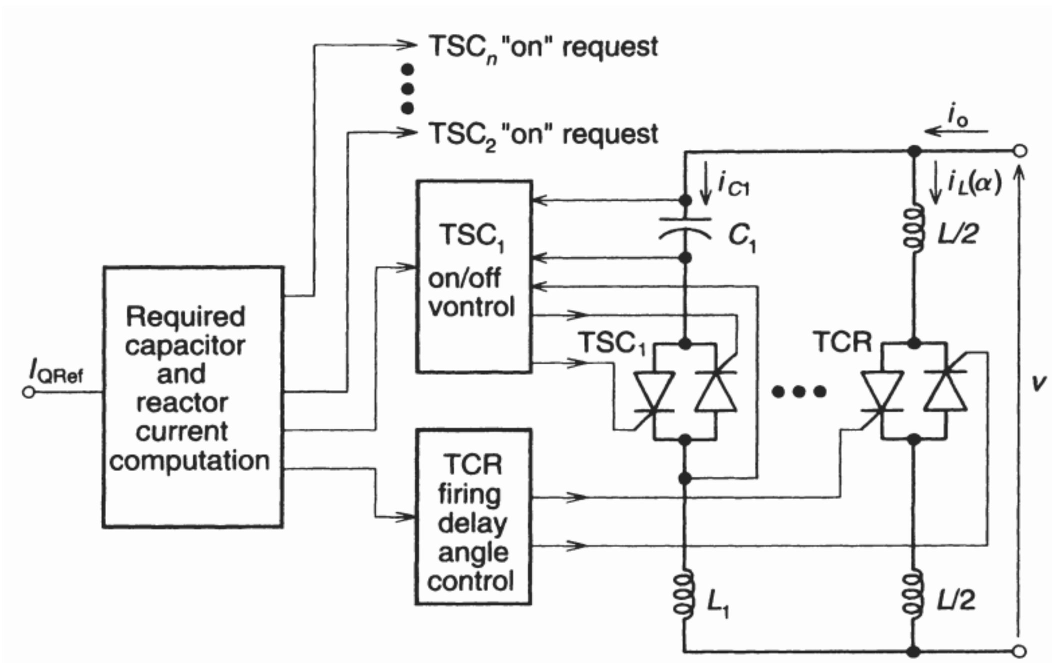

Fig. 2.6: The functional control scheme for TSC-TCR [29].

The TSC on/off control will issue the control pulses for the firing of TSC 1. And, the control pulses will move to the gates of the two thyristors anti-parallel connected. Then it will be switched on. At $\alpha = 90^0$, TSC activates fully. Similarly, the other branch is turned on if another TSC on/off request goes to the second form of a block (TSC 2), then the control pulse will go to another TSC-TCR, and the control block signal will be given to the gates of the thyristors (SCRs) that are connected in an anti-parallelizing way. The capacitor voltage with the help of a voltage sensor is detected and it's fed to the current block. At constant time, the voltage across the switch is sensed by another voltage sensor then the signal conjointly goes to this block again. A specific value of α depends on how much reactive power needs to be absorbed by this TCR. Any static compensator, regardless of the reactive power control range required, is frequently built from one or more of the preceding schemes (i.e. TSC and TCR), as illustrated in Fig. 2.6. In these circumstances, wherever a switched capacitor system is employed, the reactive power is split into an adequate range of steps, allowing for stepwise modification. The inclusion of a thyristor-controlled reactor might potentially provide continuous control. If reactive power must be consumed, the entire capacitor bank is disconnected, and the counterbalancing reactor is also found liable to perform the given response. Thus, the thyristor valves can be controlled in one and another way by their switching responses.

It is possible to achieve fully step-wise control by coordinating the control between the reactor and capacitor stages. Static VAR compensators of the combined TSC and TCR type are distinguished by continuous control, minimal harmonic production as a result of the regulated reactor rating being modest in comparison to the entire reactive power, and adjustability in control and operation. The cost of the TSC-TCR is a significant drawback when compared to individual TCR or TSC type compensators. A lower TCR rating results in certain potential savings. However, the price of the capacitor switches, as well as the additional advanced control, more than compensates for these savings. The aforementioned functional control method has the benefit of calculating the number of TSC branches to be turned on for capacitors in terms of current compensation by replying to various inquiries such as: How much reactive current capacity is required to be created or produced? What is the load's total reactive power demand? How much inductive reactive power does a load require? What is the total reactive power flowing through the transmission substation system? What is the amount of reactive power delivered into the transmission system? What is the total load connected? What is the power factor of the load? These above-mentioned inquiries must be responded to by the SVC applications in the given power system network.

It also governs the switching of all TSC branches in a very temporary disturbance-free manner that likewise determines the firing angle control or delay firing angle of the thyristor-controlled reactor.

The first function: Number of TSC branches to be turned on.

$I_{Q, ref}$ = n (rounded off to nearest highest integer).

I_C = current drawn by one TSC.

$I_{TCR} = I_C - I_{Q, Ref}$, where surplus reactive current = $I_{Q, Ref}$ – injected current absorbed by TCR.

The second function: Transient-free switching off TSCs.

Rule-I $\rightarrow V_C < V$

When $V_{ins} = V_C$ i.e., when $V_T = 0$, where V_T is the voltage across the thyristor valve.

$V_T = V - V_C$, for $V = V_C$.

In this case, the voltage sensor has got to be placed across the thyristor valve whenever this voltage sensor provides a signal to the controller specified $V_T = 0$.

Rule -II $\rightarrow V_C \geq V$, TSC switched on when $V_T = V_{Tmin}$. In this scenario, firing pulses ought to be issued at the sharp endpoint of the bus or applied voltage. Then, the controller issues the firing pulse at a negative peak, and an oversized transient current will follow as a result of the capacitor voltage being V_C. However, the applied voltage is $+V_C$. This leads to a greater extent large transient current that will follow which will instantly destruct the thyristor valves of the thyristor switched capacitor branch. Therefore, the voltage sensing element should sense not only to the maximum point but additionally realize the polarity of the applied voltage whether or not the applied voltage is at a positive peak or the negative peak.

If the capacitor has a positive voltage then firing needs to be done at the peak of the applied voltage. On the opposite hand, if the capacitor voltage is negative, then the firing pulses have to be compelled or the TSC branch has to be switched in at the negative peak of the applied voltage. TCR must be in non-conducting mode, α=180°, to produce a substantial quantity of capacitive reactive output. As previously stated, after the capacitive and inductive currents cancel out, there is no VAR output. A drop in near 90° causes an increase in inductive reactive output. It can also regulate the reactive output over its whole rating. The TCR must be likely to absorb the excess capacitance for each capacitive step and, if necessary, provide inductive VAR output.

Given a ncap of TSCs with equal ratings, the required capacitive VAR range Q_C is subdivided into ncap intervals. The TCR is intended to eliminate more than just the Q_C/ncap. However, it also provides enough for a steady operation. Furthermore, if the AC reaches zero, it will immediately block until the gate signal is restored. The firing delay angle control technique is frequently used to regulate the current in the reactor from maximum (SCR closed) to zero (SCR open). In other words, the SCR conduction is delayed concerning the applied voltage peak in each half-cycle, and therefore the duration of the current conduction interval is regulated. This technique of current regulation is demonstrated in Fig. 2.7. On an individual basis for the positive and negative current cycles, where the applied voltage V and therefore the reactor current (i_L) are displayed at zero delay angle (completely closed) and an impulsive delay angle. The delaying of the firing angle causes the thyristors to activate and switch off their nature of capability to inject and consume the specified amount of reactive power.

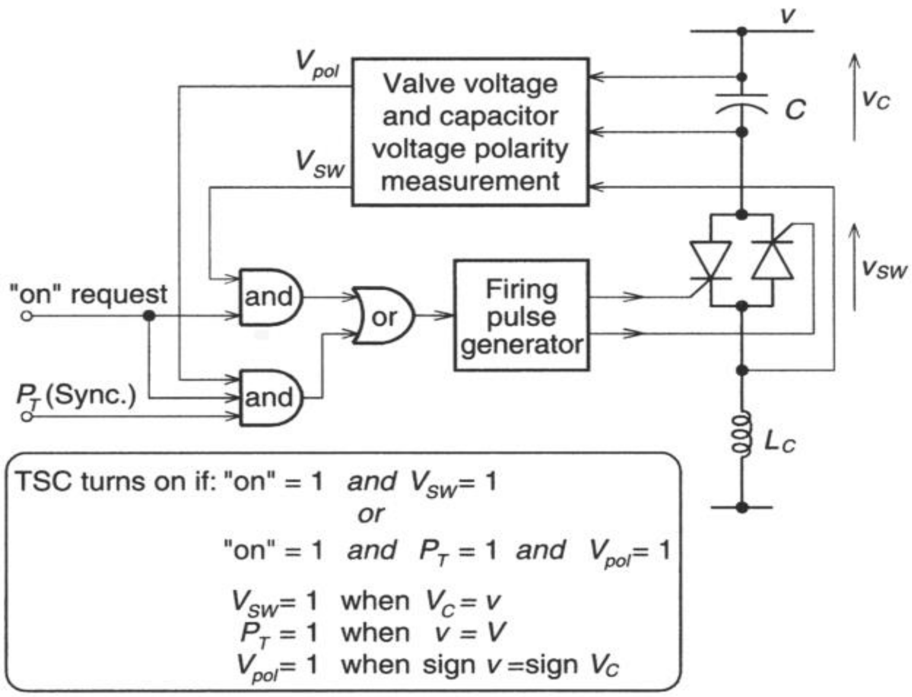

Fig. 2.7: Functional block diagram of transient free switching of a TSC branch.

When α=0, the SCR closes at the applied voltage's peak, and the output current within the reactor is identical to that achieved in an extremely steady state with a closed permanently switch. Once the thyristor's gating is delayed by an angle ranging from 0 to 90 degrees concerning the peak point of voltage. Because the thyristor, by definition, opens when the current reaches zero, it is valid for the interval $\alpha \leq \omega t \leq \pi-\alpha$. The sign of $V/\omega L$ becomes opposite for consequent negative half-cycle intervals. The offset in the equation $V/\omega L \sin \alpha=0$ is adjusted down for positive current half-cycles and up for negative current half-cycles found at $\alpha=0^0$.

Because thyristors automatically turn off when the present zero-crossing of the thyristor is reached, this approach adjusts the thyristor's conduction intervals or angle. That is, the delay angle ($\sigma = \pi - 2\alpha$) specifies the predominant conduction angle. Hence, when the delay angle rises, the associated rising offset causes the thyristor's conduction angle to decrease, and thus the reactor current decreases. At the maximum delay of $\alpha = \pi/2$, the offset also reaches its maximum of $V/\omega L$, at which both the conduction angle and also the reactor current becomes zero. Because the two parameters, delay angle and conduction angle, are equal, TCR may be defined by any of them; their application is just a subject of preference. As a result, the computation of the TCR may be represented in terms of α and σ. If the voltage bus falls below its set point range, the SVC can inject reactive power (Qnet) into the system within its control limits, restoring the bus voltage to its intended level. If the bus voltage rises, the SVC can inject less or the TCR will absorb more reactive power within its control limits, resulting in the appropriate bus voltage.

2.4 SVC Controller Block Diagram

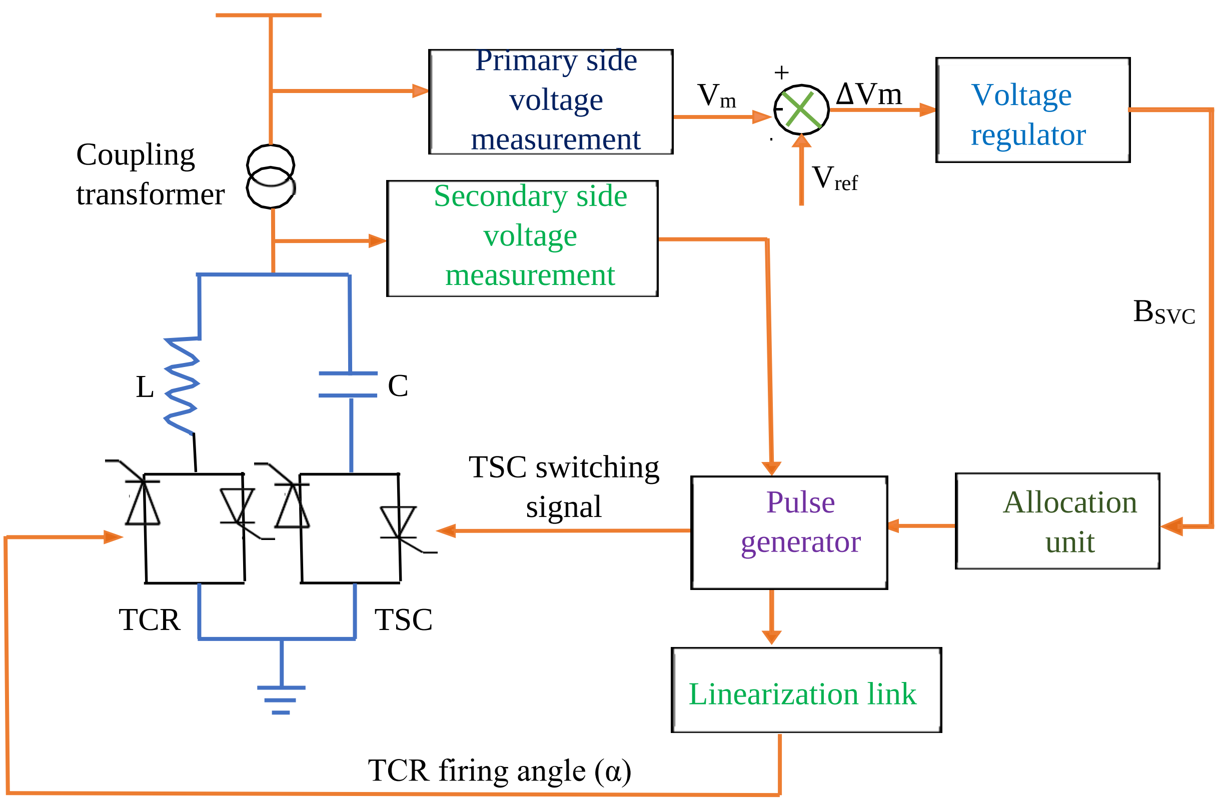

Fig. 2.8: TSC-TCR controller block diagram.

Figure 2.8 shows the control principle diagram of the TSC- TCR SVC. The first and secondary voltages measured by the V-I measurement module at each end of the transformer are sent to the SVC controller. The SVC controller is principally composed of 4 parts: a measurement system, a voltage regulation system, a distribution unit, and a trigger unit. The first aspect is that the voltage is distributed to the measurement subsystem to get the measured voltage, and also the distinction between the measured voltage and the reference voltage is sent to the voltage regulation system to obtain the susceptance value needed for reactive power compensation. The susceptance value is sent to the distribution unit, and then the distribution unit determines the specified trigger angle of the TCR branch thyristor and the number of TSC branches. Consequently, the trigger unit sends a trigger pulse in keeping with the trigger angle of the TCR branch thyristor and the number of TSC branches obtained by the allocation unit to regulate the on and off of the TCR branch and the switching of the TSC branch. The capacitance of the TSC branch is controlled by switching, and the inductance is controlled by controlling the firing angle of the thyristor for the TCR branch. Once the voltage of the power system is low, the capacitive reactive power is compensated by inputting the TSC branch. Once the capacitive reactive power input is just too much, it's necessary to input the TCR branch to absorb the surplus capacitive reactive power.

Voltage Controller: The magnitude of the balanced AC voltage V_{AC} is consistently compared to the voltage reference ($V_{AC,ref}$). A proportional-integral (PI) controller processes and increases the error, V_{AC}, to evaluate an appropriate control signal. It depicts a lag-block with a measurement time constant Tm and a rotating PI controller with proportional gain K_P, integral gain K_I, and time constant T_P. Within B_{max} and B_{min}, the SVC looks and acts like a monitored susceptance B_{SVC}, and its performance in regulating voltage profile is generally a function strength of the connected AC system. Whenever some "droop" is permitted, the SVC's system response becomes more reliable. This is extremely crucial for sinusoidal systems, which may be swinging around an operating point with a constantly shifting amount of TSC branches.

2.5 The Fixed- Capacitor - Thyristor - Controlled Reactor (FC–TCR)

The Fixed Capacitor Thyristor-Controlled Reactor (FC-TCR) is a VAR generating scheme that uses a set capacitor in conjunction with a thyristor-controlled reactor. The FC-TCR mainly comprises a tunable reactor controlled by an FC. To acquire the complete needed reactive power, the steady capacitive reactive power production Q_{FC} of FC is inhibited by dynamic reactive power consumption Q_{TCR} of TCR, as shown in Fig. 2.9 (a). The total losses of the FC-TCR hybrid combination raised as TCR current increased and dropped as capacitive VAR output increased. This type of loss feature is beneficial when the aggregate capacitive VAR output in a substation demands appropriate power factor correction. However, in the case of dynamic compensation of electric power systems, it cannot operate well when the average VAR output is low. To deliver the necessary capacitive impedance and filter the harmonics, the fixed capacitor is typically replaced entirely or partially by a filter circuit. An unfavorable feature is that the TCR repeats itself over time by switching and conducting (A. Pedemir et al., 2018).

To broaden the dynamic controllable range to the leading power-factor domain, the TCR provides configurable reactive power without intervention inside the lagging power factor range. In shunt with the TCR is a mounted-capacitor bank. If a lagging power-factor functioning is needed, the TCR MVAR is rated higher than the fixed capacitor to compensate (cancel) the capacitive MVAR and supply net inductive-reactive power. The fixed-capacitor banks, which are occasionally coupled in a star configuration, are divided into more than one 3-phase group. Each capacitor has a small turning inductor linked in series that switches the branch to operate as a filter for a specific harmonic order. For example, one capacitor bank is set to the fifth harmonic, another to the seventh, and still another to serve as a high-pass filter. The adjustable reactors reduce the net MVA rating of the attached capacitors slightly at a basic frequency. The voltage versus reactive power characteristic for this sort of SVS is that the locus of the attainable steady-state operational purposes for the SVS once connected to a power system. The precise operating point at any time is set by the SVS control settings and therefore the operations of the power system. The TCR-FC approach to SVS has several advantages. Its speed of response to dynamical system conditions is very quick at intervals of 2 to 3 cycles of the power frequency wave for the biggest voltage disturbances. At intervals within the considerable range, the control character is smooth and continuous. The associated control logic and equipment are comparatively easy as compared to the opposite two approaches. In addition, the technology and FACTS device concerned have the best operational feature within the application of any sort of equipment to a power system. Therefore, a part of the consideration is equipment losses.

The characteristic of the steady-state losses versus reactive power operational purpose for this SVS approach is shown as a percentage of the capacitive MVAR rating. This characteristic doesn't comprise transformer or auxiliary losses. The losses are shown to extend steadily [23], [34], [40]. The source is linked to the thyristor-controlled reactor (TCR) branch via a power line with a fixed capacitor and concurrent loads-1 and load-2. Load-1 is fixed, while load-2 is powered up by a breaker after a predetermined period to affect the system voltage and Q.

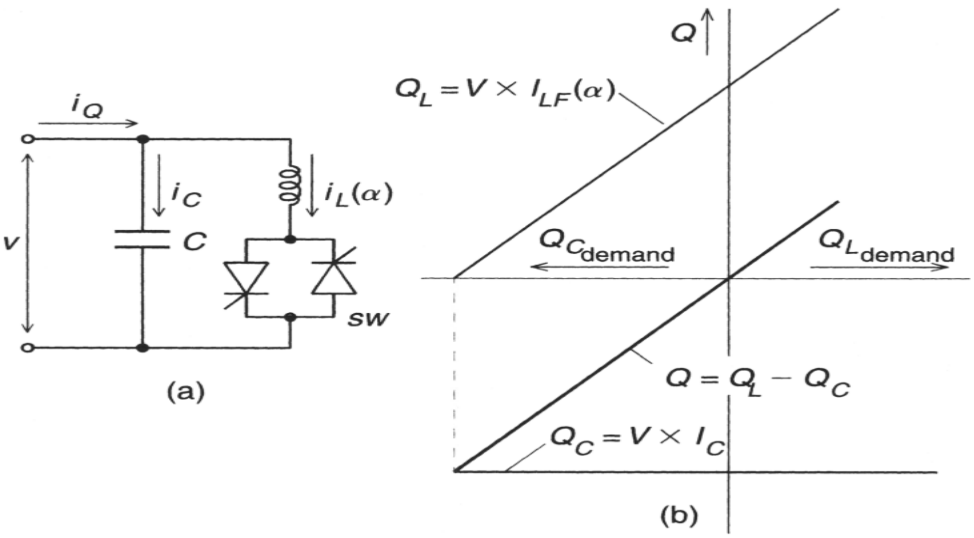

Fig. 2.9: (a) Basic FC-TCR type static VAR generator and (b) its VAR demand output characteristic.

A. Pekdemir and A.B Yildiz (2018) made analysis on the TCR conduction, and which is primarily comprised of I^2R losses in the reactor and thyristor conduction losses. An evaluation of losses for this equipment is dependent upon the anticipated steady-state operating point or range in a particular application. Utility specifications indicate no unanimous convention in this regard. However, it can be observed that if a particular application requires the SVS to operate well into the capacitive region most of the time, then the losses associated with this approach will be relatively acceptable that the SVS of the time, in providing approaches. If, on the other hand, the system requires operating with the reactor substantially on most then the equipment losses could become a factor and an incentive to examine alternative SVS. At some operating points, a major portion of these losses is associated with TCR current that serves to compensate for the SVS capacitors. This loss occurs when no reactive power (capacitive or inductive) is required of the SVS. There the reactor conduction serves no purpose other than to compensate for the current of the SVS capacitor branches. Reactor conduction and losses could be reduced if the capacitors could be switched off. The primary benefit of the TSC-TCR over the FC-TCR is the availability of various operations with minimum losses. When the VAR output is set to "0," the lowest losses are obtained. As the capacitive output rises, an increasing number of TSC banks are energized with the TCR that consumes the excess capacitive reactive power. As a result, with each switched-in TSC bank, the losses escalated by a predetermined amount. In addition to this constant loss, TCR losses range from maximum to "0" between consecutive switching of TSC banks. All capacitor banks are switched off at or near "0" reactive power output, and the TCR current is "0" or negligibly low. As a result, the losses are "0" or nearly "0." The losses vary, but they are typically proportionate to the inductive or capacitive output. This configuration is helpful when dynamic compensation is necessary but no relatively high supply is required (R. Mohan et al., 2002).

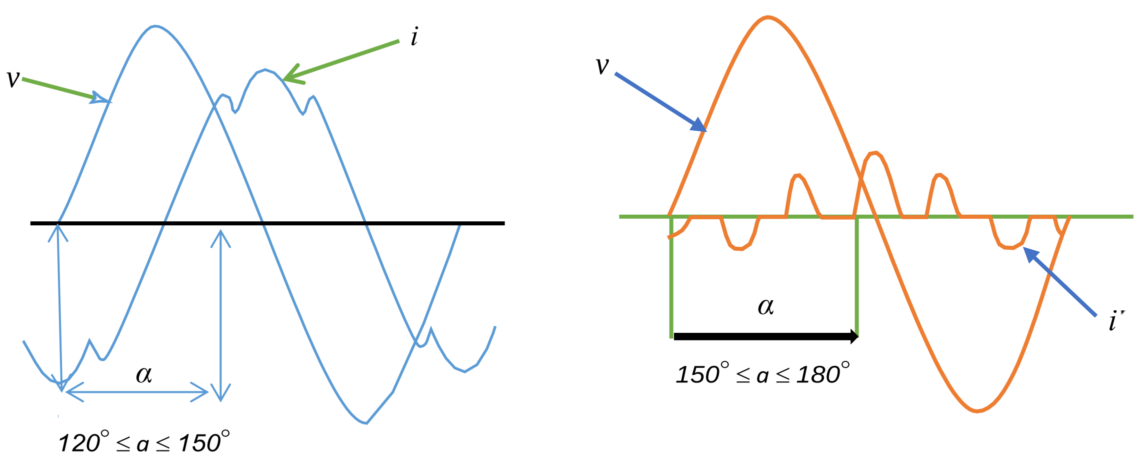

Fig. 2.10: a) configuration b) voltage and currents for two values of α.

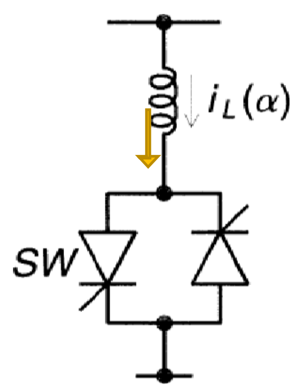

Fig. 2.11: $I_L(\alpha)$ switching during two half cycles.

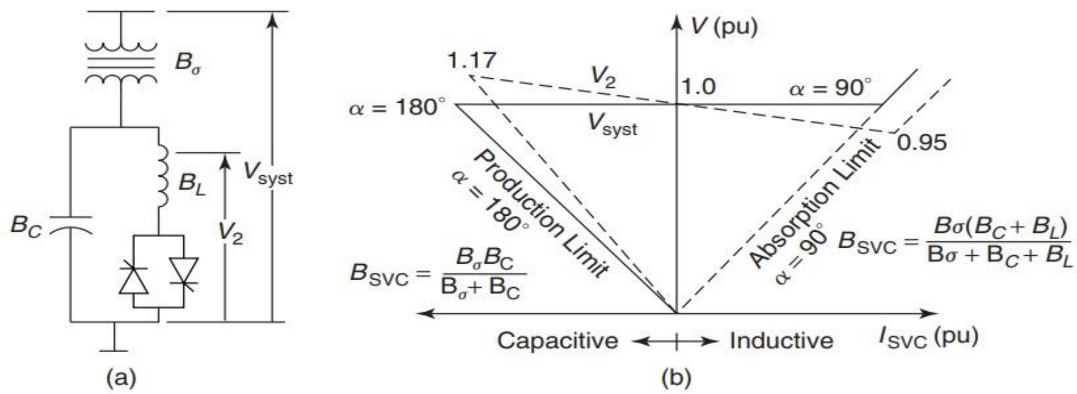

Fig. 2.12: An FC-TCR with a step-down transformer and its V-I characteristics.

(J. Gutierrez et al., 2002) suggests that the first step in implementing FC-TCR modeling and simulation in the system is to size the capacitor and inductor. There is no need to activate SVC under normal loading conditions. The initial firing angle must be such that the condition that SVC exchanges no power with the AC system or load system is zero. As a result, we can state that the SVC branch's effective reactance or reactive power varies with the firing angle. The current and reactive power rise, while the power factor of the system decreases. This means that transmission line losses increase, resulting in a lower receiving end voltage than the sending end voltage, and the line conductor gets heated, reducing line capability. To compensate for the capacitive MVA and supply net inductive-reactive power if a lagging power factor operation is desired, the TCR MVA is rated greater than the fixed capacitor. The fixed capacitor bank is often connected in a star arrangement and divided into many three-phase groups. Each capacitor has a small tuning inductor linked in series that adjusts the branch to function as a filter for a given harmonic value. For example, one capacitor set is tuned to the 5th harmonic, another to the 7th harmonic, yet still performs like a high pass filter. The tuning reactors reduce the net MVA capacity of the fixed capacitors significantly at a fundamental frequency. To minimize the capacitive output, the reactor current is maximized by reducing the delay angle. The capacitive and inductive currents become equal at zero VAR output, and therefore both VARs are canceled entirely. As the angle decreases further, the inductive current exceeds the capacitive current, resulting in net inductive output. Controlling reactive power flows in HVAC networks is critical for reducing system losses and maintaining acceptable voltage profiles. Because the needed response speed is typically so low, employing one or more static VAR systems for that purpose alone may be less cost-effective than using switched shunt capacitors and/or reactors. If SVS (Static VAR Systems) is used for dynamic voltage control in key locations on the HVAC networks, they can also be programmed to offer some constant voltage and/or VAR flowing control. In such circumstances, caution should be exercised to ensure that a significant portion of the overall SVS rating is retained in reserve for the dynamic voltage tasks that functions are installed to supply.

The Concept of Transient-Free Switching: (Filipovic Grcic B. et al., 2021) suggest that the Thyristors allow power to flow when the current in a single capacitor achieves a natural zero-crossing. The system abruptly terminates with an untriggered trapped charge and no further VARs are sent to the supply. Due to the capacitor charge, the voltage between the thyristors varies between zero and double the peak phase voltage. Only when the voltage across the thyristors is zero can they be activated again with perturbations. This corresponds to the peak voltage level on the system side, assuming no trapped charge drain-off on the de-energized capacitor. So, the concept of transient-free switching just described applies in the highly idealized case where there is no inductance in series with the capacitors. In practice, there are capacitors. It is always inductance that exists in the form of a series with of the normal inductances of busbars and interconnections. In addition, it is almost always necessary to add a small inductance in series with every switched capacitor in the TSC to limit the rate of change of current (di/dt) in the thyristors, especially when parallel capacitors may discharge through them. The series inductors automatically tune each capacitor leg to some resonant frequency, and this must be very carefully chosen to avoid interference with system resonances. A more thorough analysis of the switching process in the presence of inductance shows that conditions do exist under which transient-free switching can be obtained. But it will be rare for them to be precisely satisfied. In general, the capacitor switching does excite transients which may be larger or smaller, depending on the resonant frequency of the capacitors with the external system. A switching control system capable of minimizing the switching transients under all conditions can become complicated. The design difficulties are increased by the wide variation which is usually specified for the driving-point impedance of the power system at the point of connection of the TSC. Underbalanced conditions, the line with α=180° (full conduction) corresponds to the normal reactance of the linear reactors, and by appropriate control of the thyristor firing angles, any characteristic above this can be obtained. is typical. It can be said that the voltage/current characteristics are programmable via power electronic controls. Under fundamental-frequency overvoltage conditions, the best that the TCR can do to limit the voltage is to act as a plain linear reactor (with full conduction). Based on the MVA rating of the reactor, the voltage/current slope may be insufficient to appreciably limit the overvoltage unless the power system is relatively weak. The flat-slope range can be extended out to higher values of overcurrent by adopting the use of smaller conduction angles at normal currents, with a corresponding increase in the average harmonic content of the current. By adding an unswitched or fixed (FC) capacitor bank in parallel, the TCR voltage control characteristic is biased into the capacitive or reactive power production region. With the rapid fractional cycle control response of the TCR, the TCR-FC configuration yields extremely high-speed adjustability of reactive power. This, together with its basic simplicity, are the TCR-FC configuration's main advantages. Two disadvantages to the TCR-FC are the TCR must be rated to absorb all the FC reactive power plus any additional reactive power required by the system to hold down the controlled voltage. Most of the losses associated with the TCR are caused by the forward voltage drop across the thyristors during its partly phased-on steady-state operation.

2.6 FC- TCR Controller

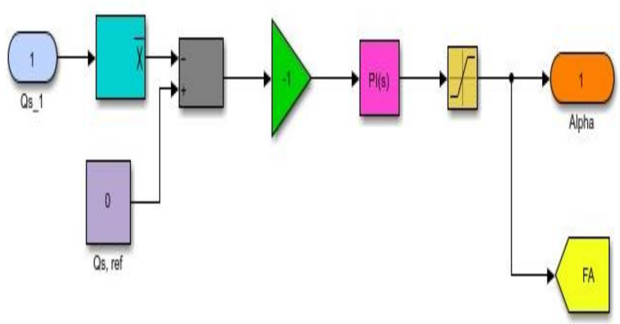

Fig. 2.13: FC-TCR firing angle and reactive power controller.

2.7 Reactive Power Control in Electrical Power Transmission Systems

(K. Chaurasiya et al., 2018) put forward for consideration on the creation of the transmission networks that operate at intervals of desired voltage limits, reactive power generation has to be limited within a given operating range which will be related to the voltage that is supplied to the system in many ways by constructing models and assessing their applications. A thorough grasp of reactive power in alternating current systems is important. When powered on, the alternating current power networks and the devices linked to the power system generate time-varying electrical fields connected to the applied voltage, as well as magnetic fields dependent on current flow. Except for energy loss in resistive components, these fields store energy that is discharged once they collapse. All energy-coupling systems, as well as transformers and energy-conversion devices (e.g., motors and generators), work based on their ability to store and transfer power. A TCR is one of the most important components of thyristor-based SVCs. It can be used alone, but it is more commonly employed in conjunction with mounted or thyristor-switched capacitors to enable quick, continuous control of reactive power across the entire specified lagging-to-leading range. The anti-parallel linked thyristor pair operates as a bidirectional switch, with thyristor valve T1 conducting in positive half-cycles of the supply voltage & thyristor valve T2 conducting in negative half-cycles. The thyristor's firing angle is determined by the zero-crossing of the voltage throughout its terminals. The TCR firing angle has a controllable range of 90^0 to 180^0.

Voltage–Current Operational Characteristic: (Lomi, Abraham et al., 2018) have shown the SVC current has an operation on the system voltage for various firing angles. This characteristic clearly illustrates the bounds of the operational range, and it should include the steady-state characteristics of the assorted attainable controls. It is the usual manner within which the system engineering will be better under investigation of the steady-state performance of the SVC.

2.8 SVC Rating Selection and Features

M.S. Ali Nasir, and S.A. Jumaat (2020) focused on the basic studies for the selection of SVS ratings of the following features, and parameters of an SVS should be determined from planning studies. The net capacitive and inductive ratings required for controlling the voltage in the steady-state should be determined with power flow studies. The influence of load tap changing transformers automatically switched and manually operated capacitors and reactors in the vicinity of the planned SVS should be considered since some economies in SVS rating may result. Models of SVS suitable for use in load flow studies are described. Also, the additional capacitive and inductive SVS range required for large, but momentary excursions due to faults, line tripping, and load rejection should be identified. The steady-state operating points from the

SVS may be called upon to deliver the short-time duty should be considered carefully. Simulations using digital stability will be required for these studies. Suitable SVS models for those studies are described. Possible economies in inductive SVS ratings should be sought through capacitor banks' consideration of auxiliary switches to extend the SVS voltage control range. For stabilization or for minimizing voltage dips following faults, capacitors switched online quickly after the fault can be quite effective. Further costs in SVS inductive rating may be realized if the system disturbances at cause overvoltage conditions are infrequent and a short-time overload rating can be specified in terms of inductive MVAR or current and a maximum accumulated time for each event. In the third, based on the steady-state and dynamic performance studies in the equipment voltage ratings, steady-state and short-term should be identified. Operational features of the SVS should be determined whether voltage setpoint and droop (slope) should be adjustable and whether those adjustments must be made via supervisory control. An SVS can be automatic if the remote system operation has the capability of starting, stopping, and adjusting its operating point from a centralized dispatch center. The startup sequence must be chosen because an SVS may cause a noticeable voltage disturbance when it is online particularly since the system is likely to be in a low voltage state when the SVS is energized. Even under the worst of prestart system conditions, acceptable startup sequences are all achievable and the SVS startup sequence can be automated to occur in about one second. The tools required to perform the studies mentioned above are the conventional digital power flow program and digital stability program. A PLL consistently supplies reference phase angle (θ) and so permits decoupled control of active and reactive power that is shifted by that angle. It is critical to note that the maximum values of input and output signals, as well as the limits employed in controllers, are all expressed in per-unit values. As a result, the measurement unit for proper synchronization of the thyristor gate pulses is the fundamental component of the SVC control systems.

2.9 Related Works

(M. Maheshkumar, 2016) recommends that the power quality disturbances are interruptions of low or significant voltages and transients. The buses are the points of the common coupling and also the weak ones. The effective inductance of the TCR compensator will be varied by dynamic the firing angle of the thyristors. If the thyristors are specifically at the voltage peak of the supply, then they're going to conduct perfectly. The TCR current is reactive with a 90^0 lag phase compensated capacitor. The paper suggests that less reactive power during a system causes voltage instability and conjointly it affects the loadability wherever it happens by injecting reactive power to neutralize the consequences on the generator-load reactive power equation that maintains the equilibria of the system.

(Jahnavi Lakkireddy, 2014) suggests that, PSAT software was utilized in the study to analyze the system. The TSC is turned on in its techniques by connecting two thyristor switches at an instant of a cycle when the voltage across the valve is least and positive, resulting in low switch transients. TSC generates no harmonics during a steady-state. When a TSC is turned off, the gate pulses are stopped, and the thyristors are turned off when the current through them falls below the holding currents. It should be noted that multiple pairs of thyristors are connected in series because a thyristor's voltage rating is insufficient for the voltage level required to control the speed of change of current throughout a TSC. However, it's necessary to design a small reactor in series with the capacitor.

(Divyam A. Saxena et al., 2020) suggests that the increment of reactive power consumption from the supply, therefore carrying a voltage loss and a power flow becomes lagging. Inserting the TSC-TCR hybrid model into the system compensates for the reactive power and maintains the voltage level. The model is the most versatile among all SVC configurations and cost-effective.

(Patil and Lalit. 2020) has taken into account the amplitude of inductive current required to cancel the excess of the TSC branches that vary the current in the TCR by firing delay angle control and the number of TSC branches required to switch into pertinent and specified conducting output current with a positive surplus. To activate the TCR, a variable current is passed through the reactor, varying the susceptance, and adjusting the high voltage shunt capacitors. When the voltage throughout the thyristor valve drops to zero or when the voltage across the thyristor valve is at its smallest, the specific firing pulse generation for the thyristors inside the TSC valve is comparable to that used during TCR, with the exception that a continuous gate is attained if every once in a while provided to maintain the consistency in absorption whenever the current is transmitted through one thyristor string carrying a current of polarity such positive to the opposite string carrying a current of polarity such negative. The

TSC-TCR model is intended and assessed to achieve voltage output by providing variable reactive power to the load.

(Komen, V. Blasina et al., 2012) has shown the reactive power and voltage interconnection when +Q is required to boost the voltage stability margin. It defines the TSC-TCR configuration connected to the system to study the loadability within the transmission system when there's a load variation in the load voltage which is directly proportional to one another. The research suggests that reactive power analysis maintains the power flow and gives a unity power factor to the system.

The journal paper mentioned the environmental impacts of FACTS devices within the transmission network. Particularly for the contribution to increasing the system's reliability, and loading capacity of the lines, as well as additionally minimizing the power losses for the directed change of the voltage profile. The paper ensures that uncontrolled real and reactive powers cause AC power supply problems. So, controlling reactive power mainly improves the system's power transfer capacity by exploiting static volt-ampere compensators (P. Boheme, 2006).

(JinBo Che, and WenYu Hu, 2021) demonstrated that the TSC-TCR model is most effective and it senses the line voltage and retains it stable by adding capacitance or inductance in the system network this type of static volt-ampere compensator has excellent voltage to regulate capabilities. Reactive power compensation is employed to scale back transmission losses, maintain power transfer capability, and maintain the supply voltage level at the load side. However, this thesis can increment the outcome by increasing the recommended scope to a high level of effectiveness such as using other shunt controllers like FC-TCR and making comparisons with the simulated values.

This combined TSC-TCR configuration provides the lagging and leading power factor quickly and independently with voltage values. The number of thyristors switched capacitors and one thyristor-controlled reactor to be used is set consistent with the reactive power demand of the system. Realization with TCR and switched capacitors phase control with the TCR inherently gives a nonstop variation of reactive current, whereas integral-cycle control with switched capacitors gives stepped or discontinuous control. The biasing principle makes it attainable to get continuous control over a wide range of lagging and leading currents, by combining an integral-cycle controlled susceptance with a phase-controlled one. This might be through with all TCR and a comparatively small number of thyristor-switched electrical condenser banks, the supposed TSC-TCR topology (M. Hedayati, 2004).

The research journal recommends the close investigation of HVAC system needs often reveals that the timing preciseness of thyristors isn't necessary with the capacitors during this configuration, as a result of the speed of response and continuous control designed into the TCR are adequate. In principle, the reactive power of the SVS is often modified between any two points in its entire range within one cycle or less. For special applications like arc-furnace flicker compensation, this fast response of 3-50 can be applied. The suggested approach under the study implies that the TSC-TCR hybrid configuration is applied. However, the configuration can be tested on medium voltage with other scenarios to implement the reactive power compensation and voltage stability techniques by using appropriate controllers. (Komen, V. Blasina et al., 2012).

The research paper recommends the use of the FC-TCR combination for the power factor correction under dynamic load variations. Thus from the findings, it concludes that the SVC can determine the voltage stability of the power system is achieved, as is the system's dynamic performance. Based on a thyristor-controlled reactor and a fixed capacitor, the variation of reactive power compensation is examined. The simulation results indicate that reactive power compensation is managed to accomplish with FC-TCR. This thesis can fill the gap in the research by adding the closed-loop system for the feedback signal to control the thyristor that is going to be switched in or out accordingly under the medium-voltage transmission substation system to stabilize the voltage (J. Guitierrez et al., 2002).

Reactive power variation with firing angle variation is studied, according to a journal on FC-TCR SVC. The FC-TCR circuit model is obtained, and it is then used for simulation with MATLAB Simulink. As per the analytical model, the reactive power variation is monitored by the FC TCR system. The reactive power drawn by the load will also rise with FC-TCR. However, the research has a gap in the closed-loop control system in that the firing signal generator has no control of the thyristor valves. Hence, this thesis can fill this situation by adding a closed-loop operation of FC-TCR SVC into the system and compensating for the required amount of reactive power under dynamic load variation (Y. Beck et al., 2016).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Flow Chart for the Research Methodology

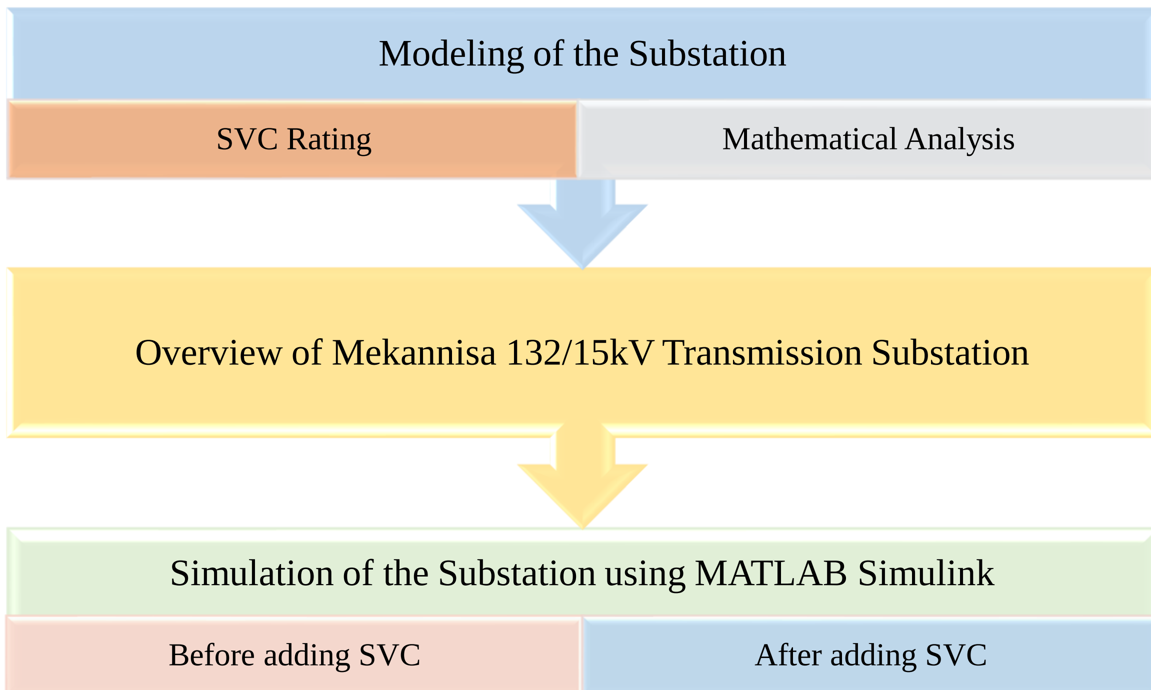

Fig. 3.1: Flow chart diagram for the research methodology.

The data gathering and organization techniques positively contribute to the fulfillment of the thesis. The substation staff provided the necessary documents that the requested data is analyzed for better achievement and for computing the system using shunt compensation techniques. The analysis part of the thesis needs a critical point of view for data collection and organization especially for calculating and analyzing the system components which further assist the modeling and simulation part of the work. The analysis has been done by applying the load flow mechanism of the load buses including two power transformers rated at 50 MVA and 20 MVA (132/15 kV). As well as there are incoming and outgoing line feeders which carry a high voltage from three substations namely Sebeta/Geffersa, Kality-I, and Gofa. By the use of the single line diagram, the transmission substation system could be analyzed by implementing the shunt controlling techniques and taking a comparative consideration before and after adding SVCs.

3.2 Mathematical Analysis (Modeling of the System)

Static VAR Compensator Rating Calculations

Short- circuit MVA = $\frac{100S}{X\%}$ (3.1)

Short-circuit Current = $\frac{MVA}{kV\sqrt{3}}$ (3.2)

$Q_{SVC} = Q_L + \frac{{P_L}^2}{2S_{Sc}} + KP_L, \; K = \frac{R}{X}$ (3.3)

K = the resistance – reactance ratio of the impedance at 10.46% of the trafo-I and 10.12% of the trafo-II at 50 MVA and 20 MVA power ratings respectively.

Trafo-I: 50 MVA, % Z = 10.46%

Short- circuit MVA = $\frac{100 * 50\ MVA}{10.46\%}$ = 478.01 MVA

Short-circuit Current = $\frac{50\ MVA}{15\ kV\sqrt{3}}$ = 1.924 kA

$Q_{SVC} = 9.9 + \frac{(38.1)^2}{2\ x\ 478.01} + 0.9*38.1 = 45.708$ MVAR

Where Q_L = Reactive power of the load

P_L = Real power of the load

S_{SC} = Short circuit MVA

Table. 3.1: Data from the substation (The one-month peak load on May 2021).

Trafo-I	MW = 38.1	MVAR = 9.9	P.F = 0.959
Trafo-II	MW = 6.4	MVAR = 1.6	P.F = 0.943

The Q_{SVC} is controlled by firing delay angle α

$Q_{SVC} = \frac{V2}{Xc} - V^2 * B_{SVC}(\alpha) X_L$ (3.4)

$B_{SVC} = \frac{2\pi - \alpha + \sin 2\alpha}{\pi X_L}$

$\frac{V^2}{X_C} - \frac{V^2}{X_L} \leq Q_{SVC} \leq \frac{V^2}{X_C}$

$Q_{SVC} = V^2 * B_{SVC}$ (3.5)

$B_{SVC} = \frac{Q_{SVC}}{V^2} = \frac{45.708 \text{ MVAR}}{(\frac{15\ kV}{\sqrt{3}})^2} = 0.609$ S

Consequently, $I_{SVC} = B_{SVC} * V = 0.609 * (\frac{15\ kV}{\sqrt{3}}) = 5274.094$ Amps = 5.274 kA

The TCR can draw maximum reactive power at peak load per phase:

$S^2 = P^2 + Q^2$, where $Q^2 = S^2 - P^2$

$Q = \sqrt{50^2 - 38.1^2} = 32.378$ MVAR

Then, the system needs 0.539 MVAR to compensate for this value of a 5% increase in the load reactive power. One Unit TSC is switched on, it will compensate 32.378 MVAR per phase to the system.

$Q_{TSC} = \Delta Q_{Ph} + Q_{TCR}$ (3.6)

The AC bus voltage to its nominal value for 5% change

$\Delta Q = 5\% * Q = 0.05 * 32.378$ MVAR = 1.6189 MVAR

$\Delta Q_{Ph} = n * Q_{TSC} - Q_{TCR}$, n= no of capacitor banks (3.7)

$0.539 = n * 32.378 - Q_{TCR,}$ let take n=1

$0.539 = 1 * 32.378 - Q_{TCR}$

$Q_{TCR} = 32.378 - 0.539$

$Q_{TCR} = 31.838$ MVAR

$Q_{TCR} = \frac{V^2}{X_{Leff}}$, $X_{Leff} = 2\pi fL$

$L_{eff} = \frac{V^2}{2\pi f\ Q_{TCR}}$ (3.8)

$L_{eff} = \frac{(\frac{15\ kV}{\sqrt{3}})^2}{2 * 3.14 * 50 * 31.838 * 10^6}$

$L_{eff} = 0.007502$H = 7.502 mH

Trafo-II: 20 MVA, % Z = 10.12%

Short- circuit MVA = $\frac{100 * 20\ MVA}{10.12\%}$ = 197.63 MVA

Short-circuit Current = $\frac{20\ MVA}{15\ kV\sqrt{3}}$ = 0.769 kA

Q_{SVC} = 1.6 + $\frac{(6.4)^2}{2 * 197.63}$ + 0.86 * 6.4 = 7.207 MVAR

$B_{SVC} = \frac{Q_{SVC}}{V^2} = \frac{7.207\ \text{MVAR}}{(\frac{15\ kV}{\sqrt{3}})^2}$ = 0.09609 S

Consequently, $I_{SVC} = B_{SVC} * V$ = 0.09609 * $(\frac{15\ kV}{\sqrt{3}})$ = 832.217 Amps = 0.8322 kA

$S^2 = P^2 + Q^2$, where $Q^2 = S^2 - P^2$

Q = $\sqrt{20^2 - 6.4^2}$= 18.948 MVAR

$Q_{TSC} = \Delta Q_{ph} + Q_{TCR}$

ΔQ = 5% * Q = 0.05 * 18.948 MVAR = 0.947 MVAR

$\Delta Q_{ph} = n * Q_{TSC} - Q_{TCR}$, n= no of capacitor banks

$\Delta Q_{Ph} = \frac{\Delta Q}{3} = \frac{0.947}{3}$ = 0.315 MVAR

TCR Rating:

0.315 = n * 32.378 - Q_{TCR} , let take n=1

0.315 = 1 * 32.378 - Q_{TCR}

Q_{TCR} = 18.948 – 0.315

Q_{TCR} = 18.632 MVAR

$Q_{TSC} = \Delta Q_{Ph} + Q_{TCR}$ = 0.315 MVAR + 18.632 MVAR = 18.948 MVAR

$Q_{TCR} = \frac{V^2}{X_{Leff}}$, $X_{Leff} = 2\pi fL$

$L_{eff} = \frac{V^2}{2\pi f\ Q_{TCR}} = \frac{(\frac{15\ kV}{\sqrt{3}})^2}{2 * 3.14 * 50 * 18.632 * 10^6}$

L_{eff} = 0.01282 H = 12.8202 mH

System gain = K

For SVC 1 ➔ $K_{1,max} = \frac{Q_{SVC1}}{S_{cmin}} = \frac{45.708 MVAR}{478.01\ MVA}$ = 0.0956 p.u

For SVC 2 ➔ $K_{2,max} = \frac{Q_{SVC2}}{S_{cmin}} = \frac{7.209MVAR}{197.63\ MVA}$ = 0.0364 p.u

$$L_{eff} = \frac{\pi}{2(\pi-\alpha) + sin2\alpha} * L \quad (3.9)$$

$2(\pi-\alpha) + \sin 2\alpha = \frac{\pi L}{L_{eff}} = \pi * \frac{0.00737}{0.007502} = \pi * 0.982$

$2(\pi-\alpha) + \sin 2\alpha - 0.982\pi = 0$

Using mathematical method,

$2\pi - 2\alpha + \sin 2\alpha = 0.982\pi$

$2\pi - 0.982\pi = -2\alpha + \sin 2\alpha$

$1.018\pi = \sin 2\alpha - 2\alpha$

$\alpha = 1.58493443\text{rad} * \frac{180}{\pi} = 90.811$, where "α" is the firing angle at which the TCR operates.

The firing angle "α" of TCR must be in the range of "90 < α < 180" to get a continuous or controllable current waveform.

Capacitance and susceptance (inductive and capacitive) values calculation for both SVC types have to be accurate for reactive power absorption and generation and also mathematical approach of the proportional gain for the voltage regulator in the SVC controller has to be calculated for both static var compensators.

Hence, the following aspects are done to ensure the proper amount for both SVCs.

For SVC 1:

$$X_C = \frac{V^2}{Q_{TSC}} = \frac{(15kV)^2}{32.378MVAR} \quad (3.10)$$

$X_C = 6.949\Omega$

$$X_C = \frac{1}{2\pi fC} \quad (3.11)$$

$C = \frac{1}{2\pi f X_C} = \frac{1}{2{,}183.093}$

C = 0.000458 F = 458 μF

For SVC 2:

$X_C = \frac{V^2}{Q_{TSC}} = \frac{(15kV)^2}{18.948MVAR} = 11.875\Omega$

$X_C = \frac{1}{2\pi f C}$

$C = \frac{1}{2\pi f X_C}$

$C = \frac{1}{3{,}728.75}$

C = 0.000268 F = 268 μF

For SVC 1 → $B_C = \omega C = 2\pi fC = 2\pi * 50 * 458\text{x}10^{-6} = 0.144$

For SVC 2 → $B_C = \omega C = 2\pi fC = 2\pi * 50 * 268\text{x}10^{-6} = 0.084$

$B_L = \frac{1}{2\pi fL} = \frac{1}{2\pi * 50 * 0.007502} = 0.424$, for SVC 1

$B_L = \frac{1}{2\pi fL} = \frac{1}{2\pi * 50 * 0.01282} = 0.248$, for SVC 2

$K_{P1} = -\frac{1}{2(K_{SL} + K_{1,max})} = -\frac{1}{2(0.03+0.0956)} = -3.98$

$K_{P2} = -\frac{1}{2(K_{SL} + K_{2,max})} = -\frac{1}{2(0.03+0.0364)} = -7.53$

Note that the capacitance and susceptance values for both controllers can be applied to stabilize the system according to the outputs that will be changed. This indicates that the susceptance values are considered when the controllers use the voltage regulation principle. Each inductive and capacitive values for both susceptances are the key roles to govern the performance under the hybrid configuration of the shunt controllers. For FC-TCR combination the capacitors are switched without the influence of the thyristor valves. However, in the TSC-TCR they are controlled by the gates of the back-to-back thyristors.

Mathematical analysis of the TCR: reactor current in the positive half cycle is

$$i_L(\omega t) = \frac{V_m}{\omega L}\left[\sin(\omega t) - \sin(\alpha)\right], \quad \alpha \le \omega t \le \pi - \alpha. \tag{3.12}$$

The fundamental component of using Fourier series expansion [FSE]:

$$i_L(\omega t) = \sum_{i=1}^{\infty} a_n Cos\, n(\omega t) + b_n Sin\, n(\omega t) \tag{3.13}$$

$$i_{L1}(\omega t) = \sum_{i=1}^{\infty} a_1 Cos\ (\omega t) + \ b_1 Sin\ (\omega t) \quad (3.14)$$

At a_1 =0, odd symmetry or quarter-wave symmetry exists.

$$b_1 = \frac{2}{\pi}\int_{\alpha}^{\pi-\alpha} i(\omega t) + Sin\ (\omega t) d\omega t \quad (3.15)$$

then, $b_1 = \frac{2}{\pi}\int_{\alpha}^{\pi-\alpha} \frac{V_m}{\omega L}[sin(\omega t) - Sin\ (\alpha)] \sin\ (\omega t) d\omega t$

$b_1 = \frac{2}{\pi}\ \frac{V_m}{\omega L}\int_{\alpha}^{\pi-\alpha}[sin(\omega t)^2 - Sin\ (\alpha)] \sin\ (\omega t) d\omega t$

After simplification, $b_1 = \frac{2}{\pi}\ \frac{V_m}{\omega L}\ [\ \frac{\pi-2\alpha}{2} - \frac{1}{2} Sin\ (2\alpha)]$ (3.16)

$$i_L(\omega t) = \frac{2}{\pi}\ \frac{V_m}{\omega L}\ [\ \frac{\pi-2\alpha}{2} - \frac{1}{2} Sin\ (2\alpha)] \sin \omega t \quad (3.17)$$

Peak current, $I_{L1P}(\alpha) = \frac{V_m}{\omega L}\ [\ 1 - \frac{2\alpha}{\pi} - \frac{1}{\pi} Sin\ (2\alpha)]$ (3.18)

$$I_{L1\,P}(\alpha) = V_m B_L \quad (3.19)$$

$B_L = B_{Lmax}\ [\ 1- \frac{2\alpha}{\pi} - \frac{1}{\pi} Sin\ (2\alpha)]$, $B_{Lmax} = \frac{1}{\omega L}$ (3.20)

Now the expression of susceptance in conduction angle δ, where $\alpha = \frac{\pi-\delta}{2}$

$$B_L = B_{Lmax}\ [\ \frac{\delta}{\pi} - \frac{sin\delta}{\pi}] \quad (3.21)$$

$$i_{TCR}(t) = \frac{1}{l}\int_{\infty}^{\omega t} V_{TCR}(t)\ dt = \frac{V_{TCR}}{\omega L}\ (\sin \omega t - \sin \alpha) \quad (3.22)$$

$$i_{TCR}(\alpha) = \frac{V_{TCR}}{\omega L}(\ \frac{2\alpha}{\pi} - \frac{1}{\pi} \sin(2\alpha)) \quad (3.23)$$

$$B_{TCR}(\alpha) = \frac{1}{X_L}\ (\ \frac{\sigma - sin\sigma}{\pi}\ ) \quad (3.24)$$

$\alpha = \pi - \frac{\sigma}{2}$, where σ is the conduction angle $\sigma = 2(\ \pi - \alpha)$ (3.25)

$$i_{TCR}(\alpha) = \frac{V_{TCR}}{XL}\ (\ \frac{\sigma - sin\sigma}{\pi}\ ) \quad (3.26)$$

$$1- X_L\ B(\alpha) = \alpha + \frac{\sin(\alpha\pi)}{\pi} \quad (3.27)$$

3.3 Overview of the Mekannisa 132/15 kV Transmission Substation

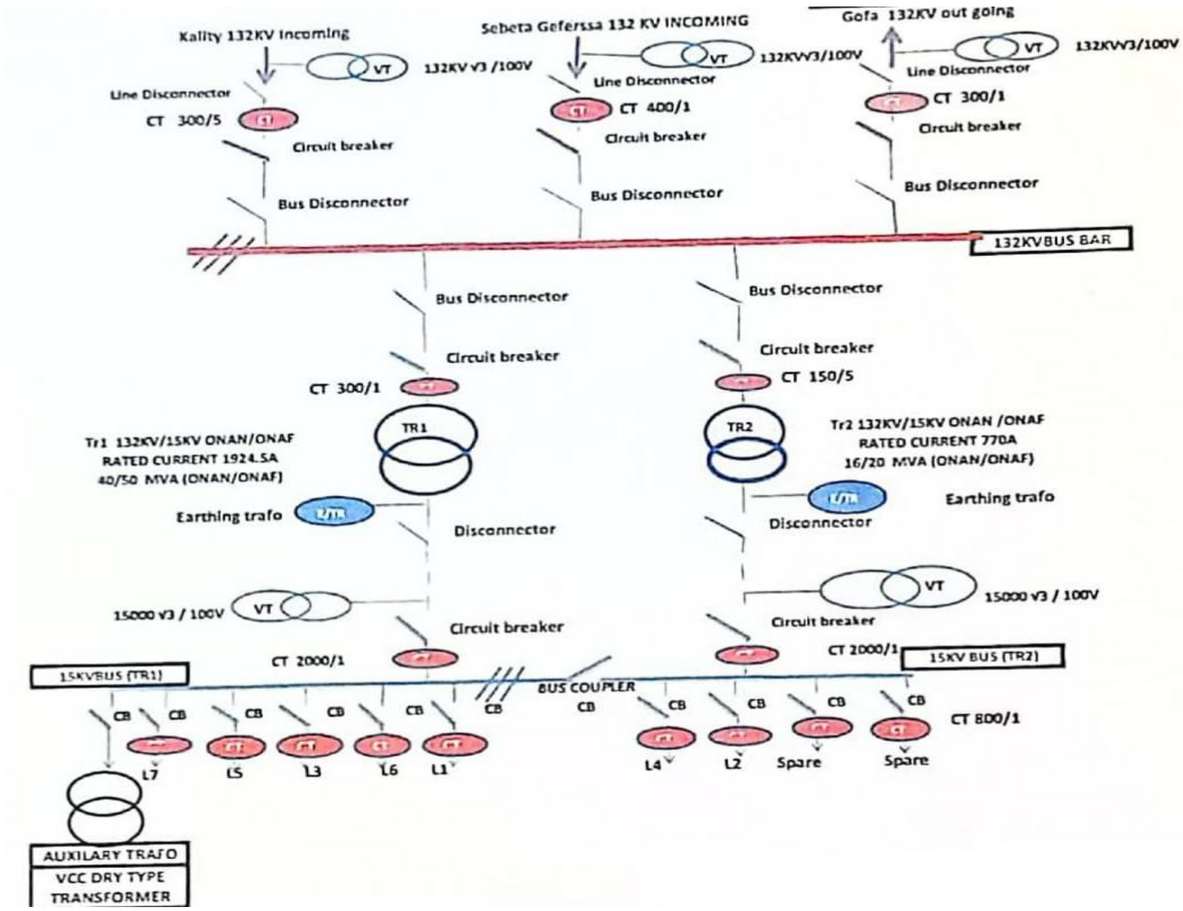

Fig. 3.2: One-line diagram of Mekannisa substation.

As seen in Fig. 3.2, there are two incoming 132 kV transmission lines from Kality-I and Sebeta/Geffersa substation to supply for Gofa substation. The incoming 132 kV is stepped down by two transformers, and distributed by seven 15 kV feeders. The line feeders are fed by two 132/15 kV, 50 MVA step down transformer (trafo-I), and 20 MVA transformer (trafo-II). The substation consists of 7 outgoing feeders which imply transformer 1 (trafo-I) supplies power for 5 feeders such that feeder 1, feeder 3, feeder 5, feeder 6, and feeder 7. Transformer two (trafo-II) supplies power for feeder 2, and feeder 4. Consequently, two other feeders are used as spares. The bus coupler is used for 15 kV bus for maintenance purposes. There are current transformers, circuit breakers, line disconnectors as well as bus disconnectors/ isolators, wave traps, and potential transformers with their ratings.

3.4 Data Organization of the Substation

Table. 3.2: Three months of data for May, June, and July months from the substation.

No.	Bay/Line	Peak load Power (MW)	Peak load Current(A) R	S	T	Date	Time	Minimum load Power (MW)	Minimum load Current(A) R	S	T	Date	Time
1	LINE 1	5.8	278	278	278	May 06/21	19:00	0.46	22	22	22	May 06/21	17:00
2	LINE 2	0.46	22	22	22	May 03/21	20:00	0.45	22	22	22	May 16/21	15:00
3	LINE 3	9.7	466	466	466	May 01/21	18:00	2.40	113	113	113	May 08/21	4:00
4	LINE 4	4.7	226	226	226	May 06/21	19:00	0.7	32	32	32	May 01/21	0:00
5	LINE 5	8.6	414	414	414	May 25/21	11:00	1.6	75	75	75	May 02/21	17:00
6	LINE 6	6.7	325	325	325	May 26/21	20:00	1.3	64	64	64	May 04/21	0:00
7	LINE 7	3.6	175	175	175	May 07/21	18:00	0.7	32	32	32	May 08/21	4:00

Bay/Line	Peak load Power (MW)	Peak load Current(A) R	S	T	Date	Time	Minimum load Power (MW)	Minimum load Current(A) R	S	T	Date	Time
LINE 1	10.90	523	523	523	June 04/21	16:00	0.46	22	22	22	June 9/21	9:00
LINE 2	0.66	32	32	32	June 24/21	11:00	0.45	22	22	22	June 1/21	9:00
LINE 3	9.76	470	470	470	June 20/21	12:00	2.10	101	101	101	June 21/21	23:00
LINE 4	4.6	225	225	225	June 22/21	18:00	0.81	39	39	39	June 3/21	1:00
LINE 5	8.3	450	450	450	June 23/21	11:00	0.66	32	32	32	June 20/21	17:00
LINE 6	7.7	372	372	372	June 06/21	13:00	0.93	45	45	45	June 21/21	23:00
LINE 7	3.5	169	169	169	June 16/21	19:00	0.66	32	32	32	June 6/21	1:00

Bay/Line	Peak load Power (MW)	Peak load Current(A) R	S	T	Date	Time	Minimum load Power (MW)	Minimum load Current(A) R	S	T	Date	Time
LINE 1	5.80	281	281	281	July 07/21	21:00	0.46	22	22	22	July 15/21	12:00
LINE 2	0.66	32	32	32	July 07/21	0:00	0.45	22	22	22	July 02/21	9:00
LINE 3	11.38	548	548	548	July 28/21	19:00	2.10	101	101	101	July 10/21	0:00
LINE 4	4.67	225	225	225	July 13/21	20:00	0.81	39	39	39	July 04/21	0:00
LINE 5	10.1	486	486	486	July 03/21	10:00	2.1	101	101	101	July 21/21	20:00
LINE 6	7.95	383	383	383	July 21/21	21:00	1.33	64	64	64	July 04/21	1:00
LINE 7	3.86	186	186	186	July 16/21	20:00	0.46	22	22	22	July 23/21	8:00

Table. 3.3: Feeder fault statistics for the three months of the substation.

NO.	**LINE**	**REASON OF INTERRUPTION**	**DURATION OF HOURS**	**LOAD BEFORE INTERRUPTION (KW)**	**LOSS OF PRODUCTION (KWH)**
1	LINE 1	EARTH FAULT	0.67	3510	2351.7
2	LINE 3	SHORT CIRCUIT	0.67	8866	5940.22
3	LINE 5	EARTH FAULT	0.05	9828	491.4
4	LINE 5	EARTH FAULT	0.07	9828	687.96
5	LINE 4	EARTH FAULT	0.5	4420	2210
6	LINE 5	SHORT CIRCUIT	0.25	10580	2645
7	LINE 4	EARTH FAULT	0.33	4990	1646.7
8	LINE 5	UNBALANCED LOAD	0.75	11020	8265
9	LINE 4	EARTH FAULT	0.75	5720	4290

NO.	*LINE*	*REASON OF INTERRUPTION*	DURATION OF HOURS	*LOAD BEFORE INTERRUPTION*	*LOSS OF PRODUCTION*
				KW	KWH
1	LINE 4	EARTH FAULT	0.083	3900	323.7
2	LINE 1	SHORT CIRCUIT	2.217	3770	8358.09
3	LINE 4	EARTH FAULT	0.083	3380	280.54
4	LINE 5	EARTH FAULT	0.1	8918	891.8
5	LINE 4	EARTH FAULT	0.083	3777	313.491
6	LINE 2	SHORT CIRCUIT	4	8684	34736
7	LINE 4	EARTH FAULT	0.083	4940	410.02
8	LINE 2	UNBALANCED LOAD	0.17	4940	839.8
9	LINE 4	EARTH FAULT	0.083	3900	323.7
10	LINE 1	EARTH FAULT	0.083	9520	790.16
11	LINE 3	SHORT CIRCUIT	0.75	7490	5617.5

NO.	**LINE**	**REASON OF INTERRUPTION**	DURATION OF HOURS	**LOAD BEFORE** INTERRUPTION KW	**LOSS OF** PRODUCTION KWH
1	LINE 1	EARTH FAULT	0.75	4680	3510
2	LINE 2	SHORT CIRCUIT	1	3328	3328
3	LINE 2	EARTH FAULT	0.3	4706	1411.8
4	LINE 6	EARTH FAULT	0.68	2394	1627.92
5	LINE 4	EARTH FAULT	0.5	4420	2210
6	LINE 5	SHORT CIRCUIT	0.25	10580	2645
7	LINE 4	EARTH FAULT	0.33	4990	1646.7
8	LINE 5	UNBALANCED LOAD	0.75	11020	8265
9	LINE 4	EARTH FAULT	0.75	5720	4290

3.5 Cost of SVC Ratings

The thyristor-based is the most important FACTS device and is anticipated to grow at an average of 3.9% throughout time. However, the cost due to the size of MVAR might be higher as the increasing need for these types of FACTS controllers widely utilized for stabilizing the system with the increasing market growth within the international market throughout the world. The overall cost is also affected by the size of fixed and controlled parts of the FACTS components. The price of FACTS devices is only half of the entire cost of the FACTS project. The other fifty percent of the FACTS cost of the project is comprised of building services, installation, operational phase, insurance, technology, and project planning.

Table 3.4 Cost of the designed SVCs (Komen, V. Blasina et al., 2012).

Quantity	Rating in MVAR	Cost of SVC in USD per kVAR	Total Amount
SVC 1	45.708	$35	$1,599,000
SVC 2	7.207	$35	$252,000
Total	52.915	$35	$1,859,000

The capital costs by production of the kVAR, the level of operational costs of each device that might participate in voltage, and the reactive power regulation in the electric power system are all taken into account in the cost requirement. The assessment of production costs or reactive power usage in the power network is quite technical, and a variety of parameters must be considered. The other services required for the system's consistent and steady operation (primary and secondary regulation of voltage and reactive power, cold and spinning reserve, and similar) exacerbate the issue further. The concern is billing these additional services to the system's single units. The SVC devices' widespread use is due to their inexpensive running costs and great operational dependability. The SVC compensator could accomplish the following tasks in the electrical power system networks. These are voltage regulation and reactive power adjustments, more harmonics in the system should be controlled, mismatches in the system are adjusted, improved system reliability and transmission efficiency. When determining the price of efficient energy management and consumption (capital and operating costs), grid compensating devices such as synchronous compensators and capacitors are considered (Komen, V. Blasina et al., 2012).

3.6 Simulink Models for the 132/15 kV Substation With and Without the Static VAR Compensator

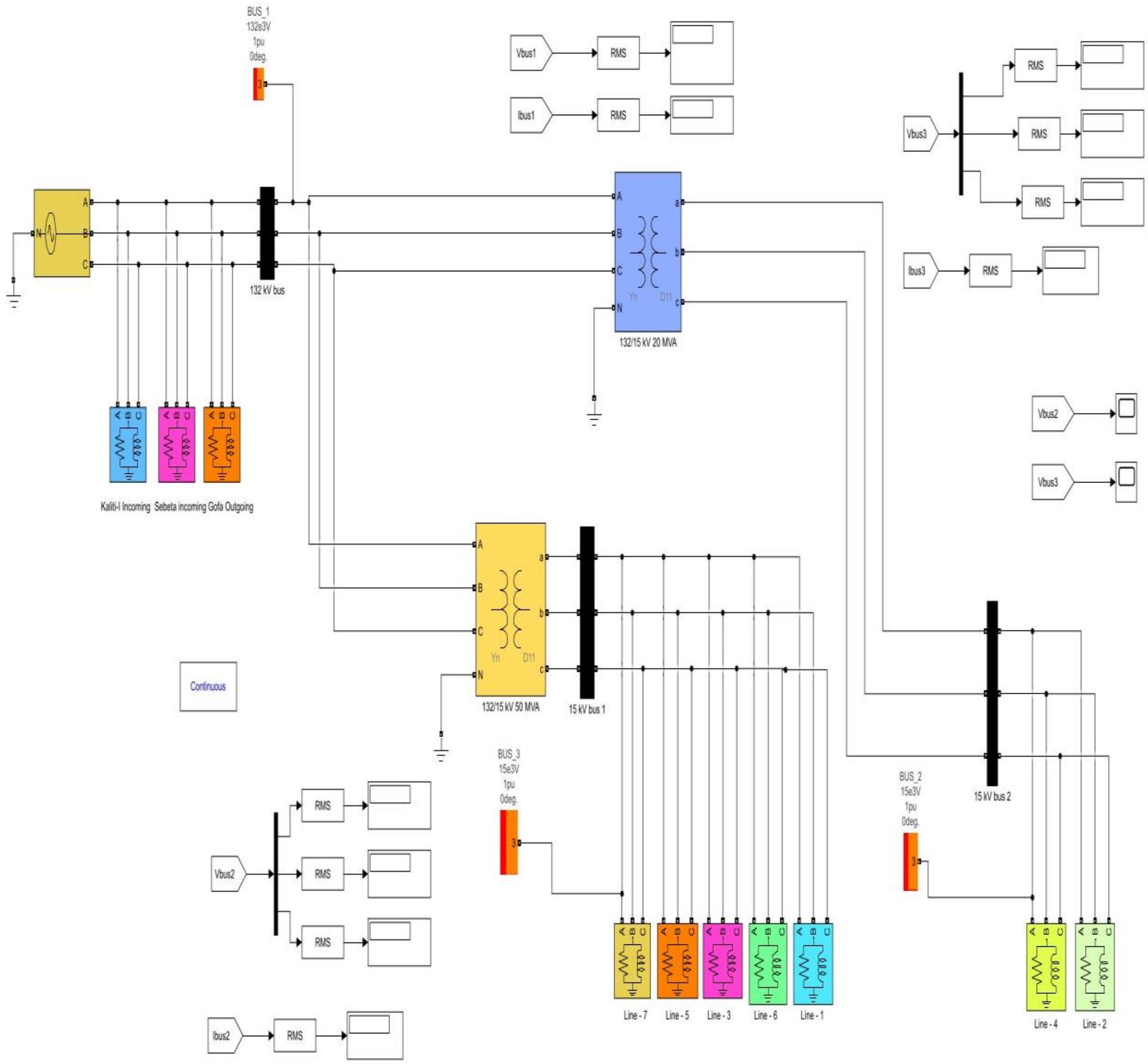

Fig. 3.3: Simulink modeling before adding SVC.

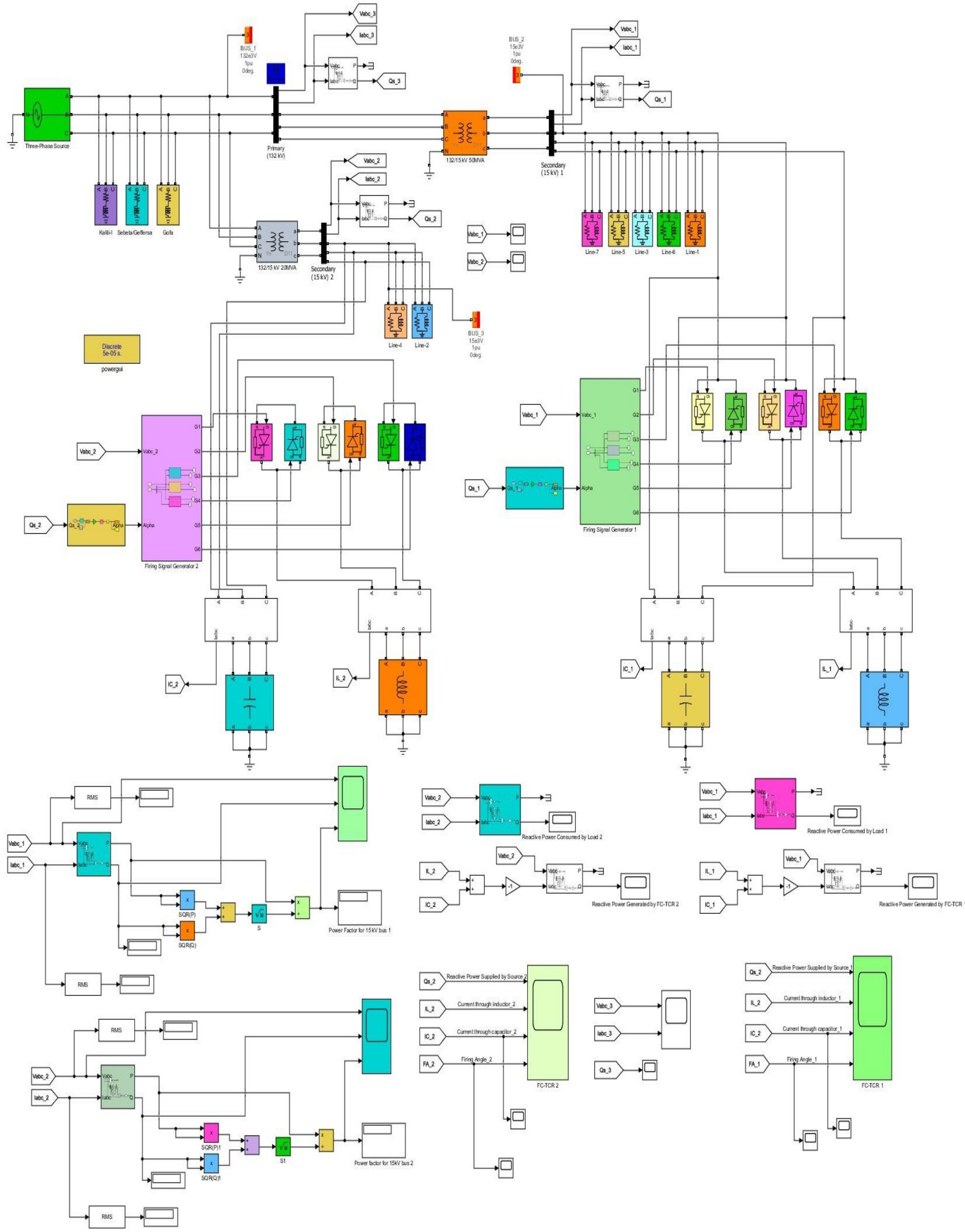

Fig. 3.4: Simulink modeling after adding FC-TCR SVC.

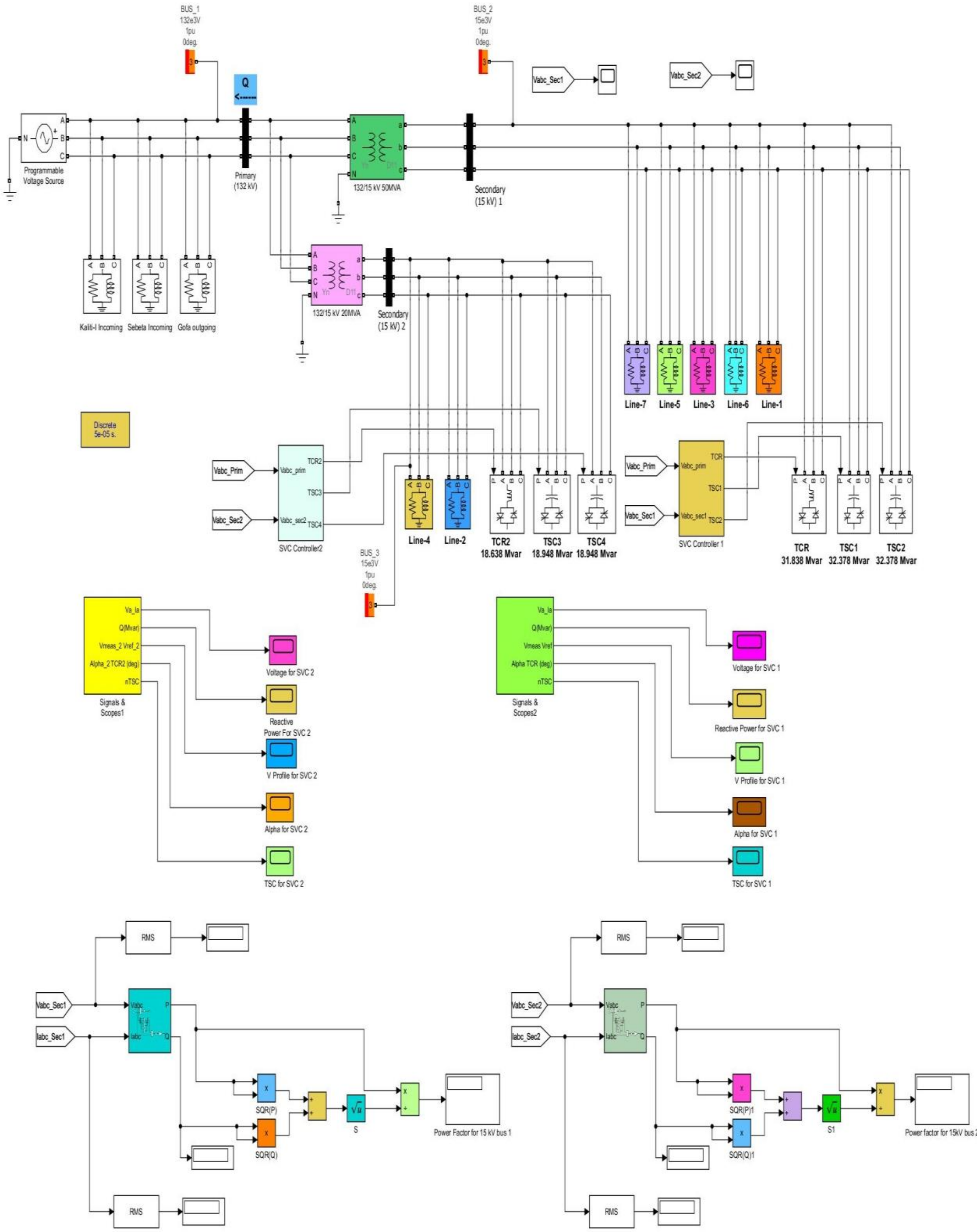

Fig. 3.5: Simulink modeling after adding TSC-TCR SVC.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Voltage Profile in p.u Values Without SVC

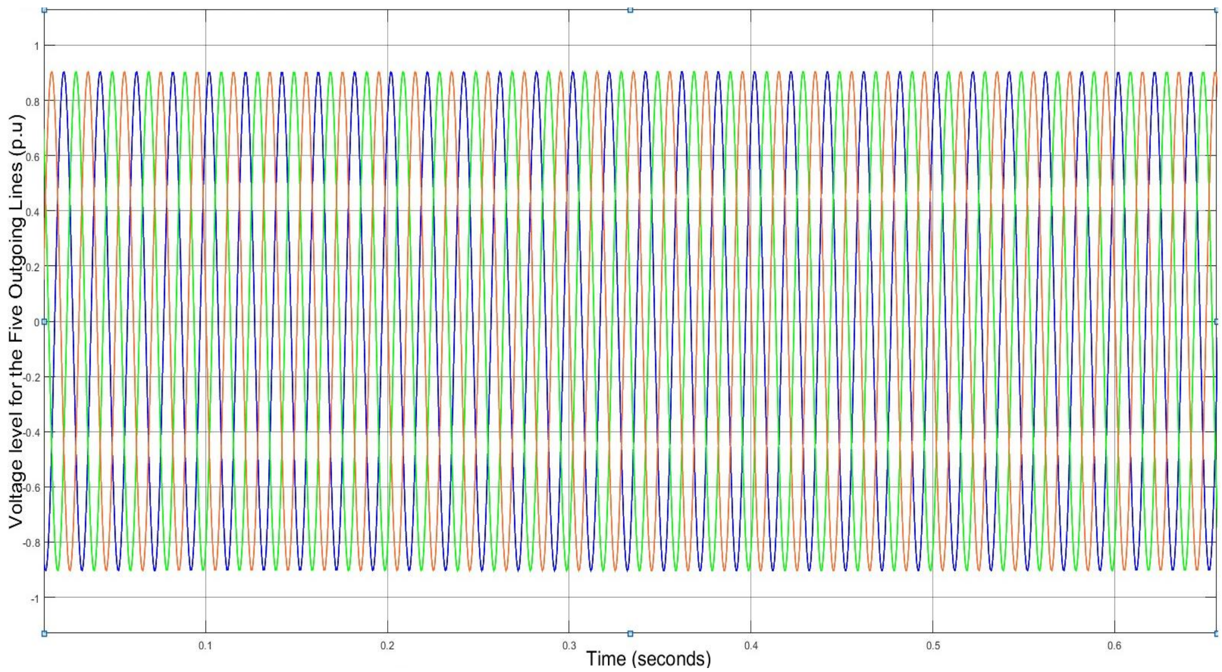

Fig. 4.1: Voltage levels for the five outgoing lines in p.u without SVC.

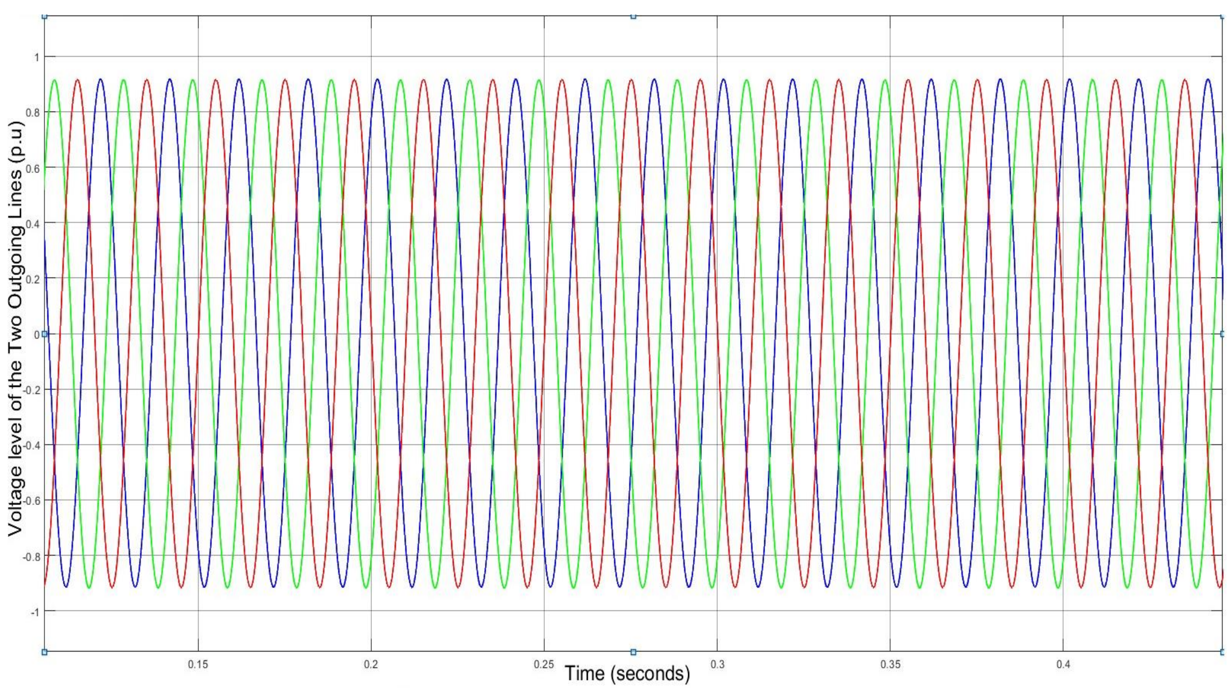

Fig. 4.2: Voltage levels for the two outgoing lines without SVC.

The voltage levels from the above two figures namely fig. 4.1 and fig. 4.2 without the applied effect of the SVCs into buses that carry the outgoing feeders shows that the specified voltage profile without the SVC is 0.9494 p.u. and 0.9615 p.u respectively.

Table. 4.1: Voltage levels for the seven outgoing lines from two buses.

Model: yibbabieSimulationwithoutSVC_R2(Update The load flow converged! The table shows the load flow solution. Click Apply to update the model with this solution. Compute Apply Add bus blo

	Block name	Block type	Bus type	Bus ID	Vbase (kV)	Vref (pu)	Vangle (deg)	P (MW)	Q (Mvar)	Qmin (Mvar)	Qmax (Mvar)	V_LF (pu)	Vangle_LF (deg)
1	Gofa Outgoing	RLC load	Z	BUS_1	132.0000	1.0500	0	38.0000	11.0000	-Inf	Inf	1.0500	0
2	Kaliti-I Incoming	RLC load	Z	BUS_1	132.0000	1.0500	0	54.0000	14.0000	-Inf	Inf	1.0500	0
3	Sebeta Incoming	RLC load	Z	BUS_1	132.0000	1.0500	0	46.0000	19.0000	-Inf	Inf	1.0500	0
4	Three-Phase Source	Vsrc	swing	BUS_1	132.0000	1.0500	0	54.0000	14.0000	-Inf	Inf	1.0500	0
5	Line - 2	RLC load	Z	BUS_2	15.0000	1.0500	0	0.4600	7.0247	-Inf	Inf	0.9615	27.9433
6	Line - 4	RLC load	Z	BUS_2	15.0000	1.0500	0	4.7000	4.2500	-Inf	Inf	0.9615	27.9433
7	Line - 1	RLC load	Z	BUS_3	15.0000	1.0500	0	5.8000	5.5200	-Inf	Inf	0.9494	24.4063
8	Line - 3	RLC load	Z	BUS_3	15.0000	1.0500	0	9.7000	10.1800	-Inf	Inf	0.9494	24.4063
9	Line - 5	RLC load	Z	BUS_3	15.0000	1.0500	0	8.6000	12.9000	-Inf	Inf	0.9494	24.4063
10	Line - 6	RLC load	Z	BUS_3	15.0000	1.0500	0	6.7000	0.1200	-Inf	Inf	0.9494	24.4063
11	Line - 7	RLC load	Z	BUS_3	15.0000	1.0500	0	3.6000	1.8537	-Inf	Inf	0.9494	24.4063

4.2 Static VAR Compensator Contribution Under Peak Load Conditions

Case-I: After Adding FC-TCR Static VAR Compensator

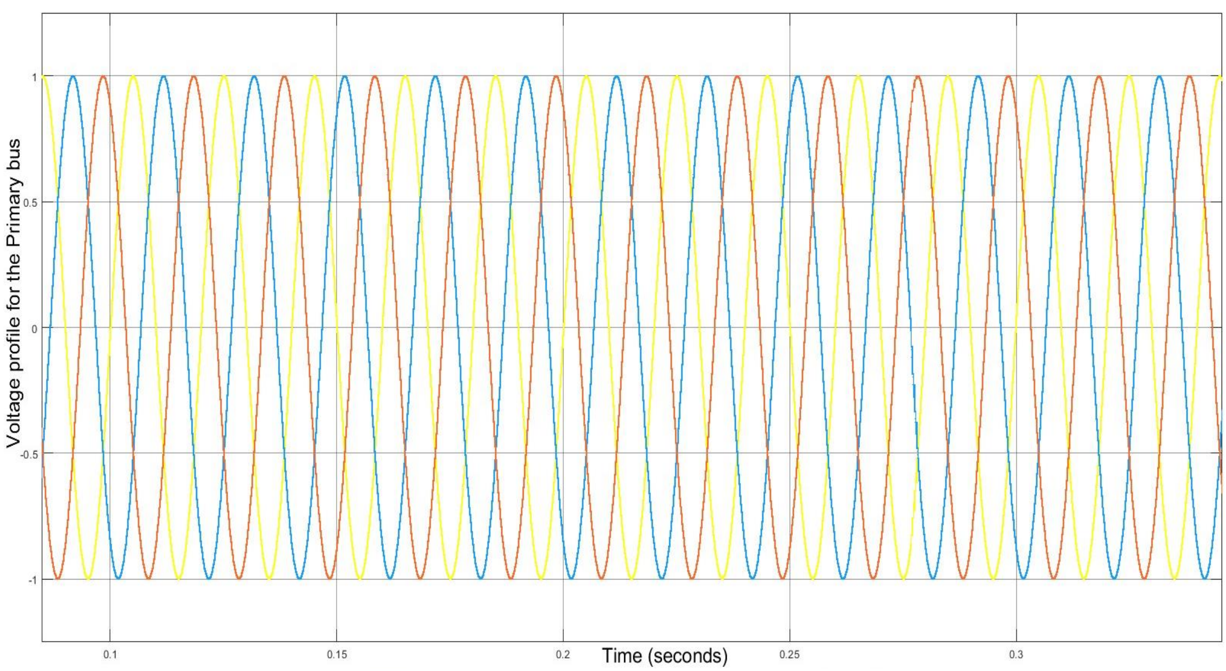

Fig. 4.3: Voltage profile for the 132 kV bus (p.u).

The voltage profile for the 132 kV bus which includes the 2 incoming lines and one outgoing line is 1.0 p.u.

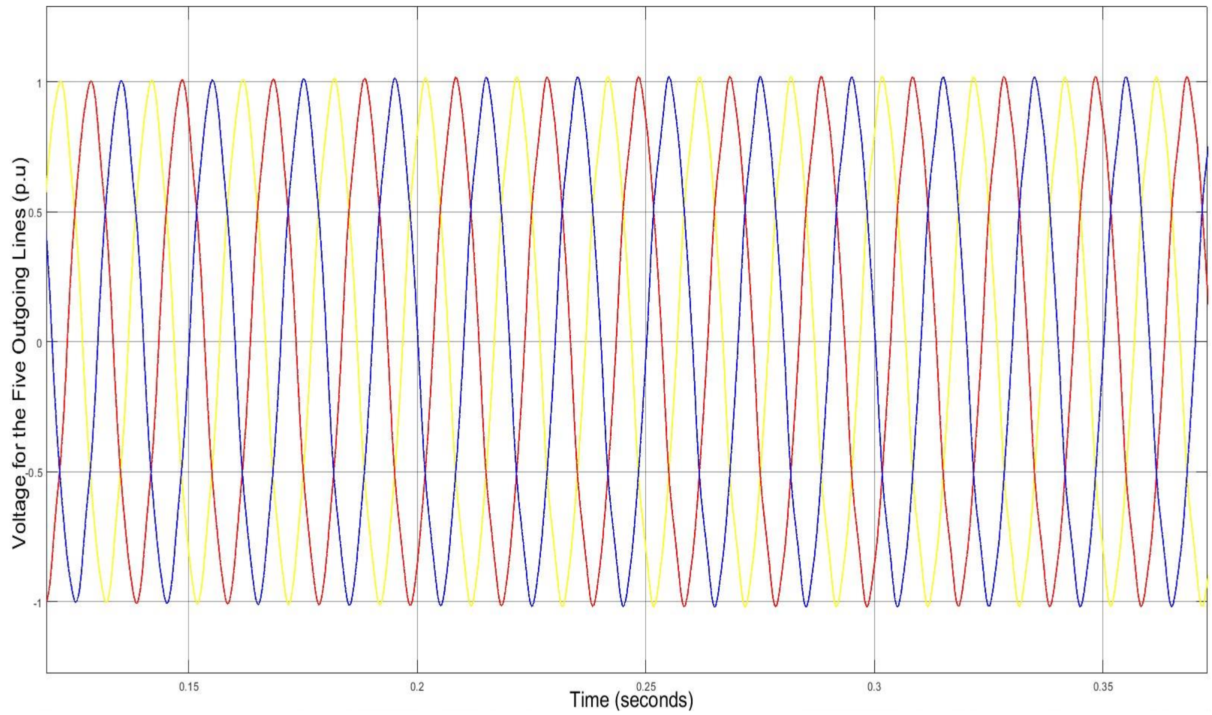

Fig. 4.4: Voltage profile in p.u for the five outgoing lines.

The voltage level of the above figure after adding FC-TCR into the bus which carries five outgoing lines shows that the SVC supports the voltage level with an increase of 104.26 % of the voltage level without the SVC. i.e.the desirable voltage was 0.9494 p.u. and thus increased to 0.9899 p.u.

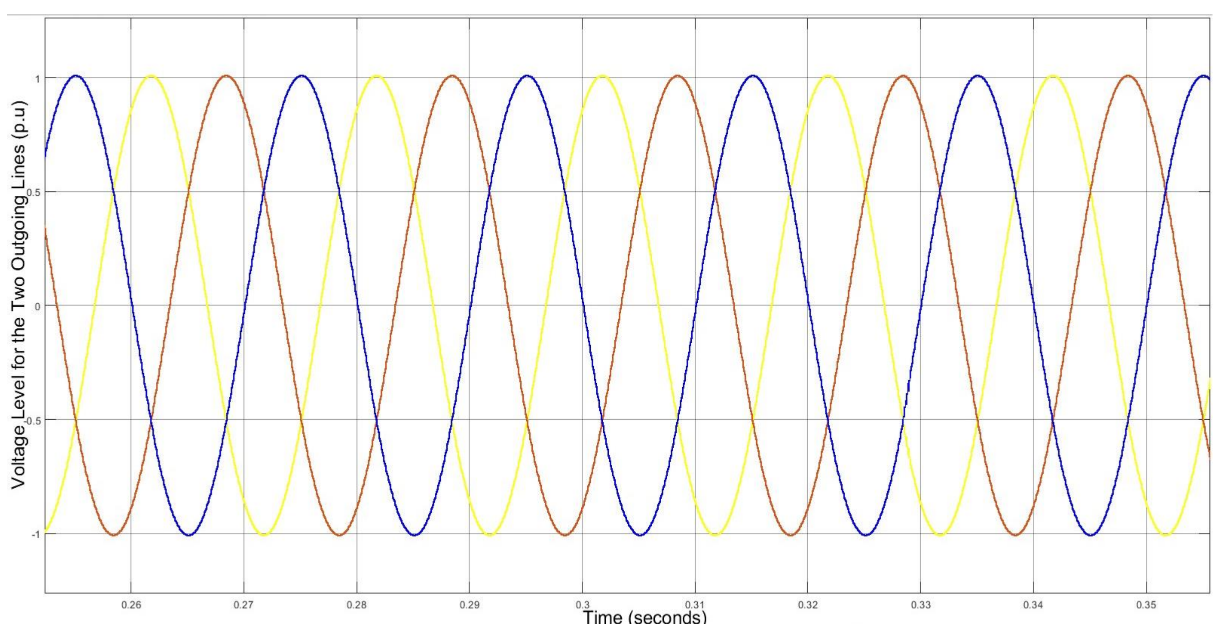

Fig. 4.5: Voltage profile in p.u. for the two outgoing lines.

The voltage levels from the above figure after adding FC-TCR into the buses shows that the SVC supports the voltage level with an increase of 105.15 % of the voltage level without the SVC. i.e.the desirable voltage was 0.9615 p.u. and thus increased to 1.0111 p.u.

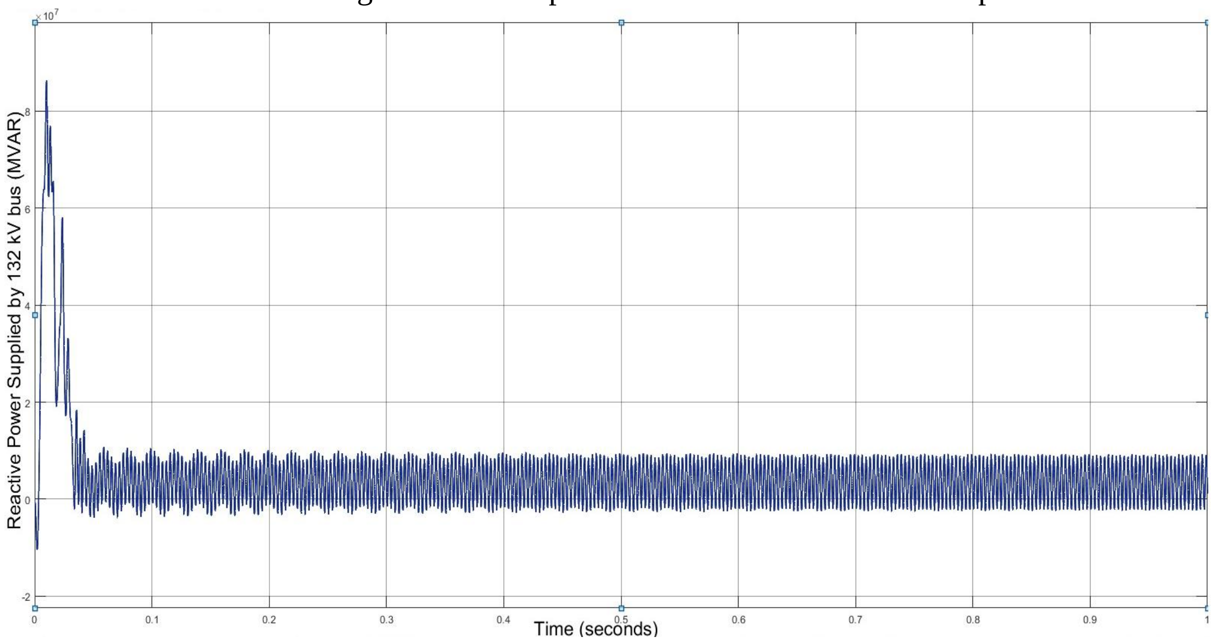

Fig. 4.6: Reactive power supplied by 132 kV bus from two incoming and one outgoing line.

The figure shows that the supplied reactive power is in the given range for the power transfer.

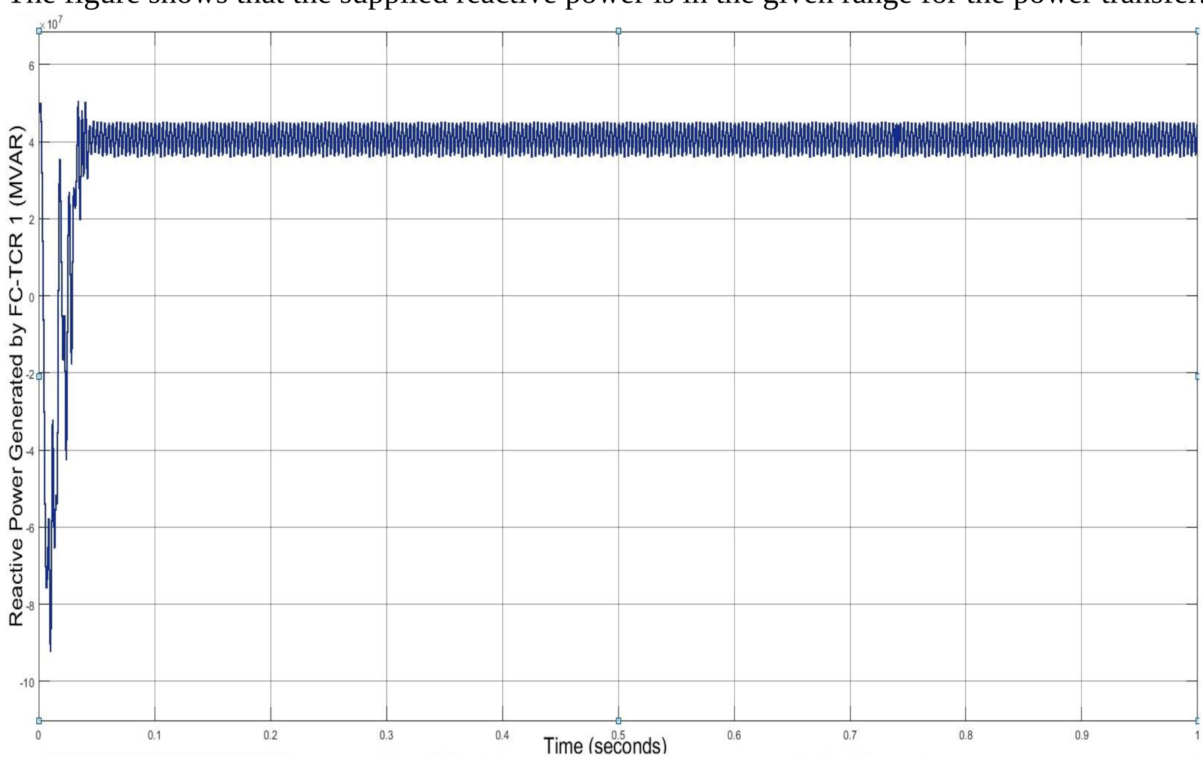

Fig. 4.7: Reactive power generated by FC-TCR on the load bus 1.

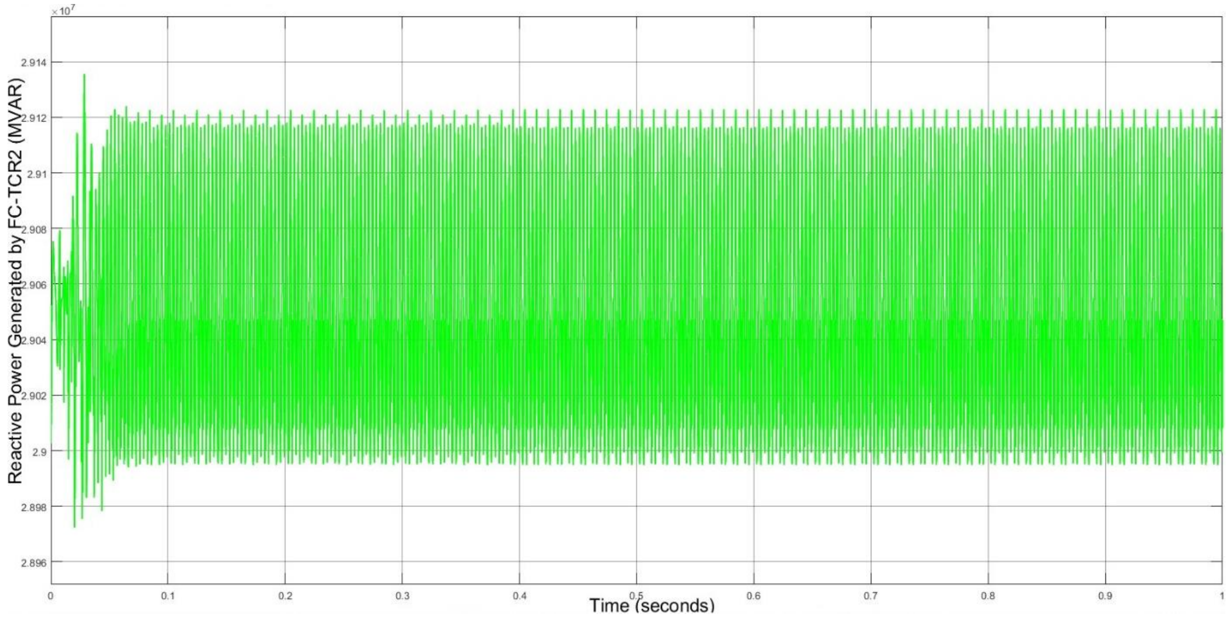

Fig. 4.8: Reactive power generated by FC-TCR at two outgoing feeders.

The above two figures show that the reactive powers generated by the capacitors are 29.08 MVAR and 43.48 MVAR to support the volage by compensating the reactive power as well.

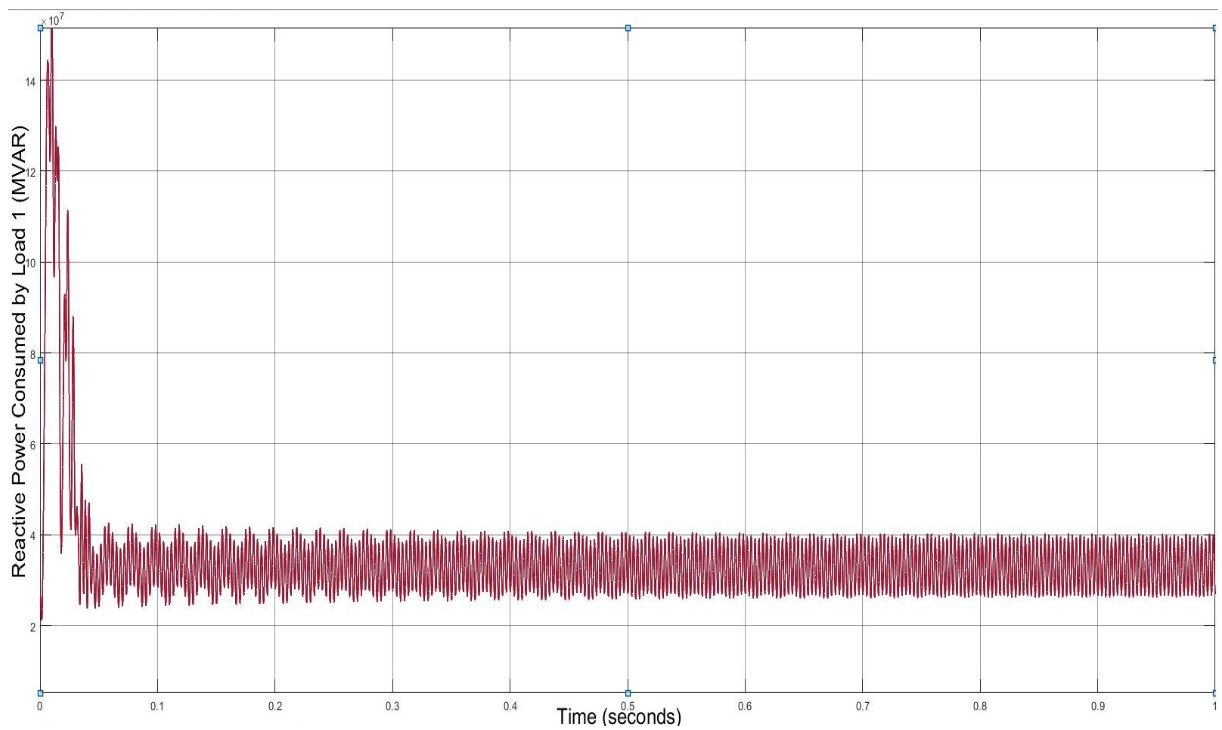

Fig. 4.9: Reactive power consumed by load buses by FC-TCR 1 SVC.

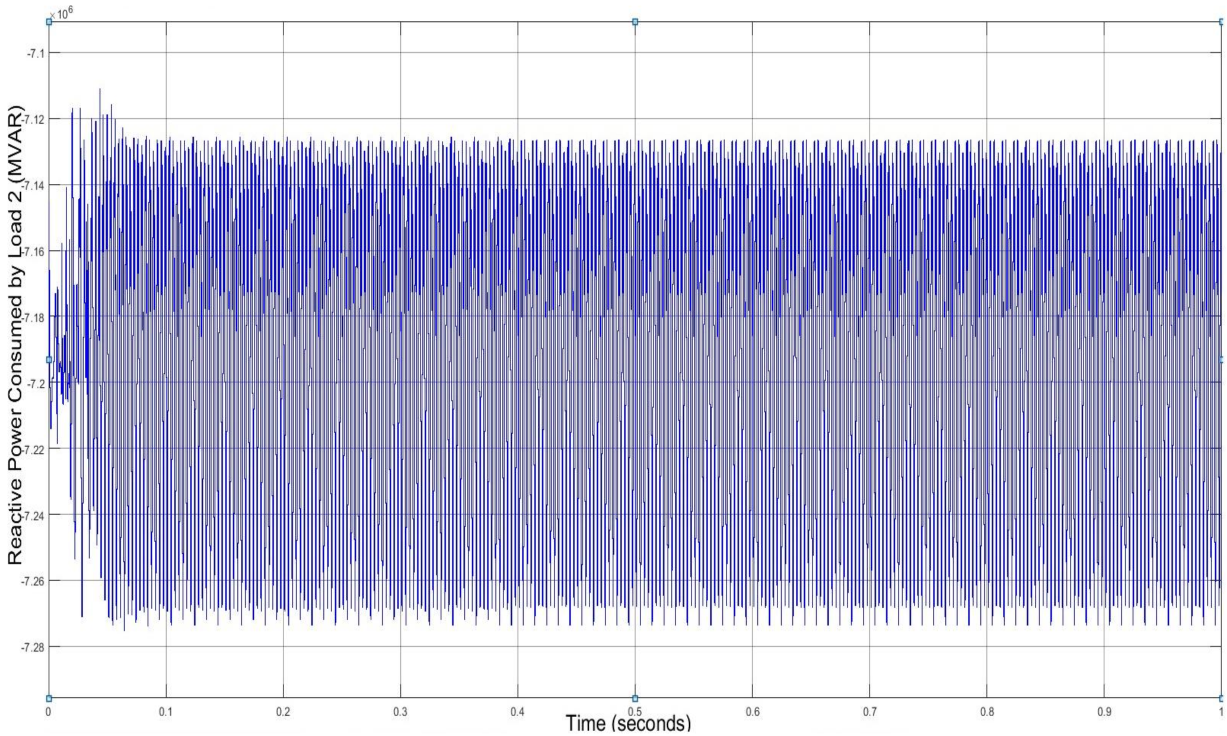

Fig. 4.10: Reactive power consumed by load buses by FC-TCR 2 SVC.

Reactive power which is absorbed by the load bus is 7.2 MVAR (inductive) which is used to compensate and support the desirable voltage as well.

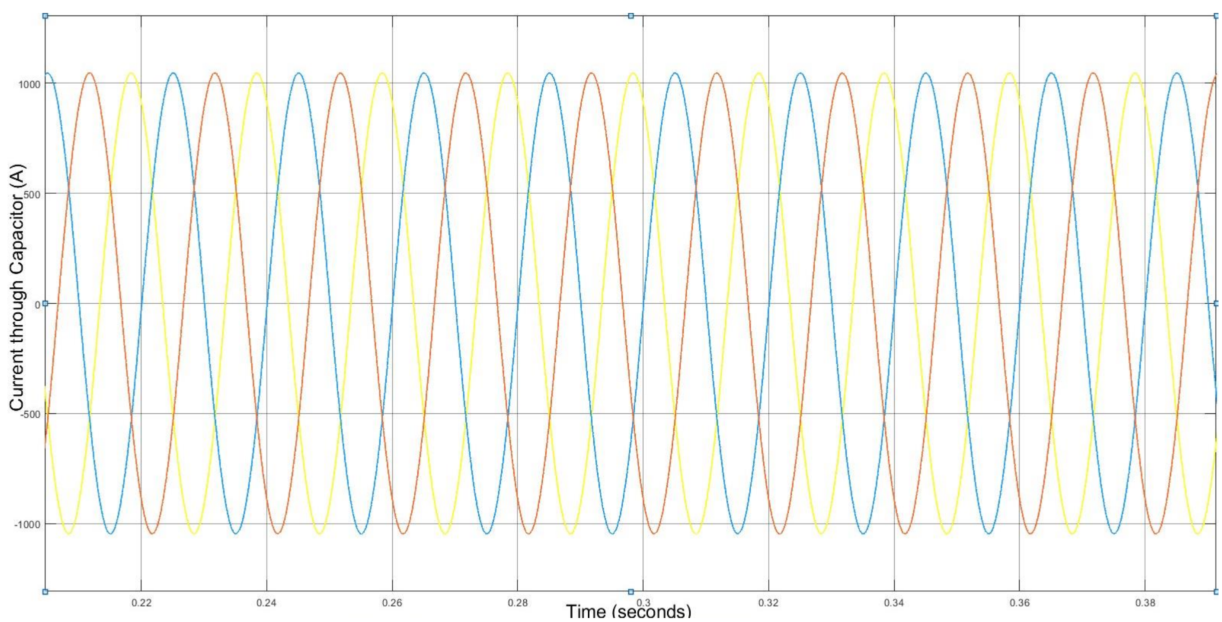

Fig. 4.11: Current through the capacitor.

The above figure shows the current through the capacitor which is directly dependent on the voltage across the capacitor that causes charge to accumulate that going to be discharged to generate the reactive power when necessary.

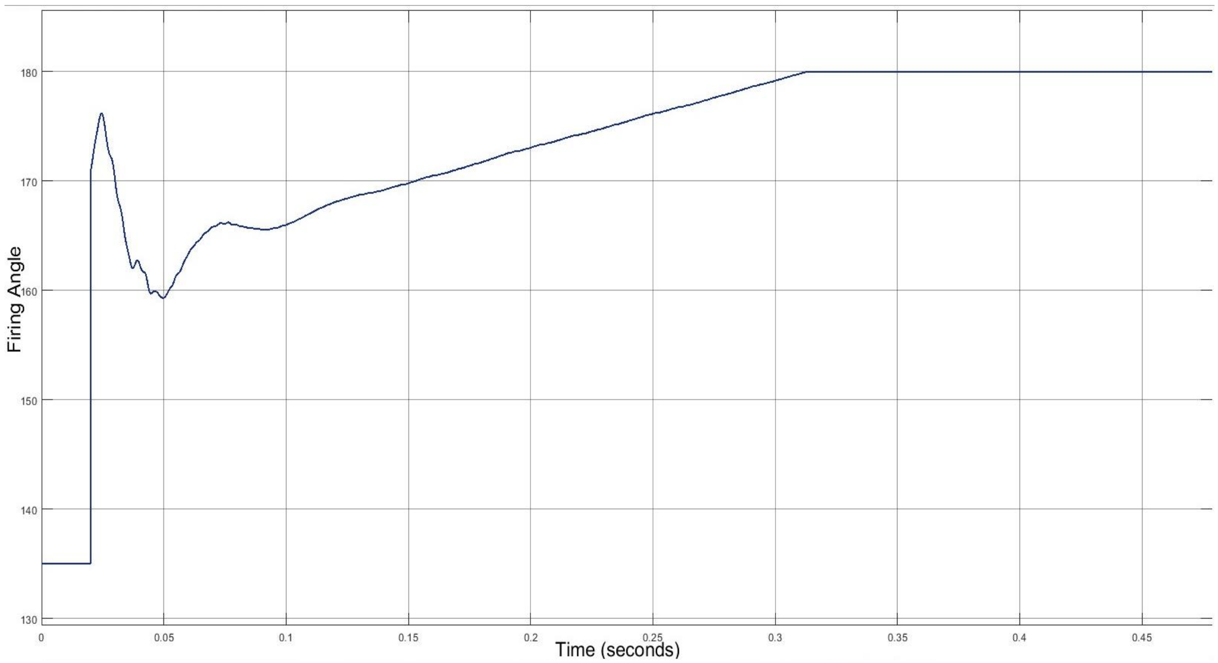

Fig. 4.12: Firing angle of the TCR.

The firing angle is triggered to control the switching in and out of the thyristor valves in the TCR.

Table. 4.2: Voltage levels in p.u of the load buses.

Model: YibbabieSimulationwithSVCFCTCR | Update | The load flow converged! The table shows the load flow solution. Click Apply to update the model with this solution. | Compute | Apply | Add bus blocks

	Block name	Block type	Bus type	Bus ID	Vbase (kV)	Vref (pu)	Vangle (deg)	P (MW)	Q (Mvar)	Qmin (Mvar)	Qmax (Mvar)	V_LF (pu)	Vangle_LF (deg)
1	Gofa	RLC load	Z	BUS_1	132.0000	1.0000	0	38.0000	11.0000	-Inf	Inf	1.0000	0
2	Kaliti-I Incoming 54 MW	RLC load	Z	BUS_1	132.0000	1.0000	0	54.0000	14.0000	-Inf	Inf	1.0000	0
3	Sebeta// Geffersa	RLC load	Z	BUS_1	132.0000	1.0000	0	46.0000	19.0000	-Inf	Inf	1.0000	0
4	Three-Phase Source	Vsrc	swing	BUS_1	132.0000	1.0000	0	0.0100	0	-Inf	Inf	1.0000	0
5	Line - 1	RLC load	Z	BUS_2	15.0000	1.0500	0	5.8000	5.5204	-Inf	Inf	0.9899	28.7180
6	Line - 3	RLC load	Z	BUS_2	15.0000	1.0500	0	9.7000	10.1833	-Inf	Inf	0.9899	28.7180
7	Line - 5	RLC load	Z	BUS_2	15.0000	1.0500	0	8.6000	12.9428	-Inf	Inf	0.9899	28.7180
8	Line - 6	RLC load	Z	BUS_2	15.0000	1.0500	0	6.7000	0.1214	-Inf	Inf	0.9899	28.7180
9	Line - 7	RLC load	Z	BUS_2	15.0000	1.0500	0	3.6000	1.8537	-Inf	Inf	0.9899	28.7180
10	Line - 2	RLC load	Z	BUS_3	15.0000	1.0500	0	0.4600	7.0247	-Inf	Inf	1.0111	29.0452
11	Line - 4	RLC load	Z	BUS_3	15.0000	1.0500	0	4.7000	4.2500	-Inf	Inf	1.0111	29.0452

The voltage levels for the outgoing lines namely feeder-1, feeder-3, feeder-5, feeder-6, feeder-7, feeder-2, and feeder-4 are increased because of the reactive power that was compensated by injecting and consuming the required amount into and from the load as well as the power network on the 15 kV power transmission buses.

Case-II: After Adding TSC-TCR Static Var Compensator

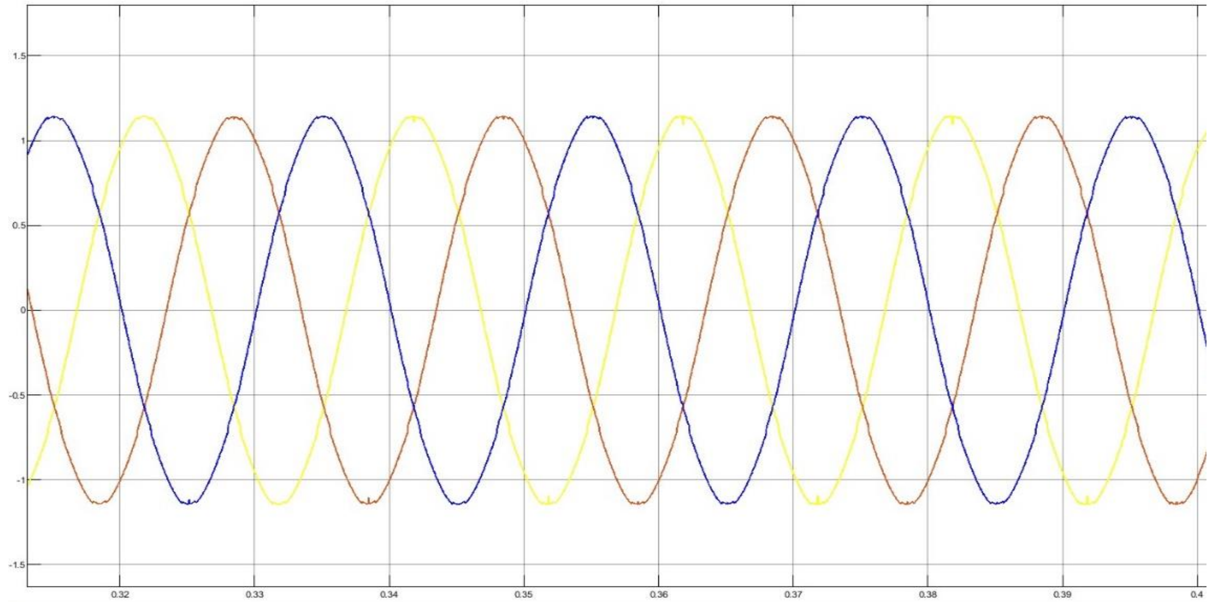

Fig. 4.13: Voltage levels in p.u. for the two outgoing lines.

The voltage levels from the above figure after adding TSC-TCR into the buses shows that the SVC supports the voltage level with an increase of 106.08 % of the voltage level without the SVC. i.e.the desirable voltage was 0.9494 p.u. and thus increased to 1.014 p.u.

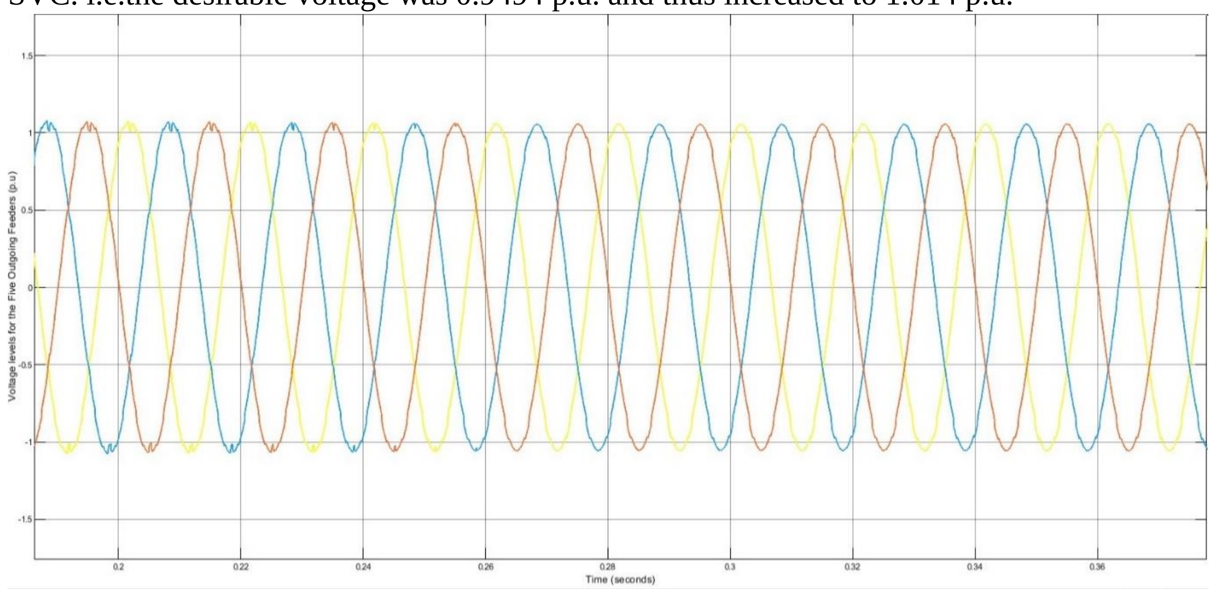

Fig. 4.14: Voltage levels in p.u for the five outgoing lines.

The voltage levels from the above figure after adding TSC-TCR into the buses show that the SVC supports the voltage level with an increase of 106.39 % of the voltage level without the SVC. i.e.the desirable voltage was 0.9615 p.u. and thus increased to 1.023 p.u.

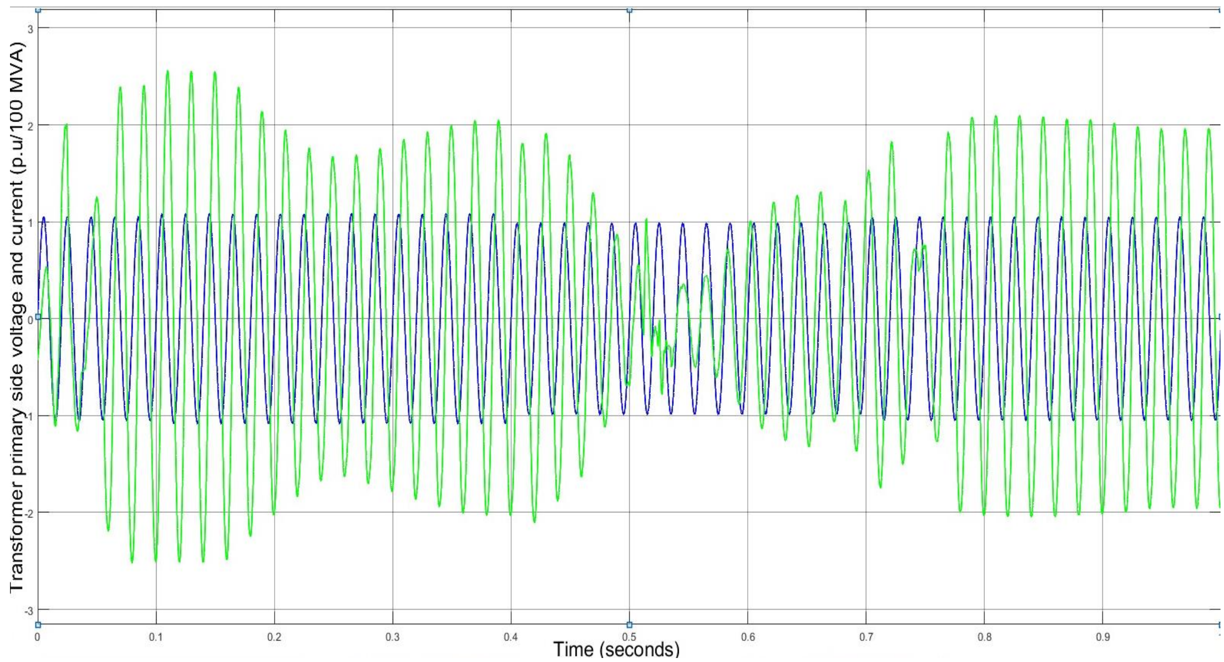

Fig. 4.15: Transformer primary side voltage and current (V_a and I_a) waveform in p.u.

The voltage and current values in per unit for the positive sequence in the primary side of the transformers.

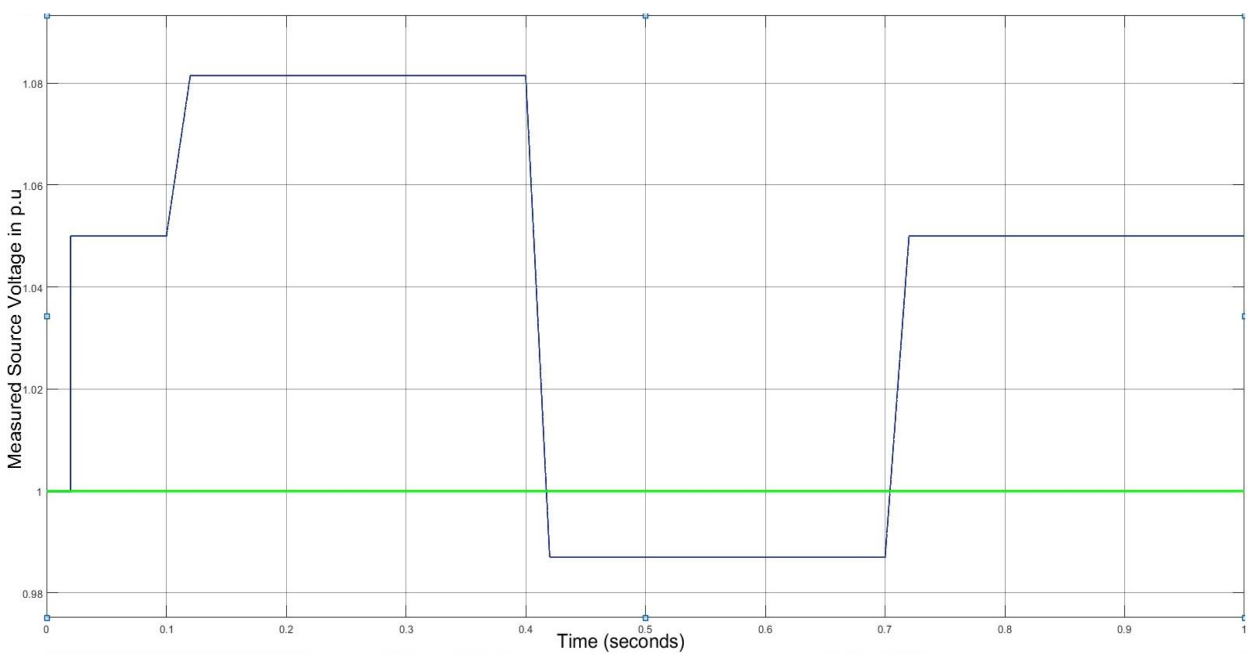

Fig. 4.16: Measured source voltage profile after adding TSC-TCR SVC.

The above figure shows that the measured value of the voltage gives a value of 1.081 p.u depending on the generation and absorption of reactive power by TSC and TCR shunt compensation respectively.

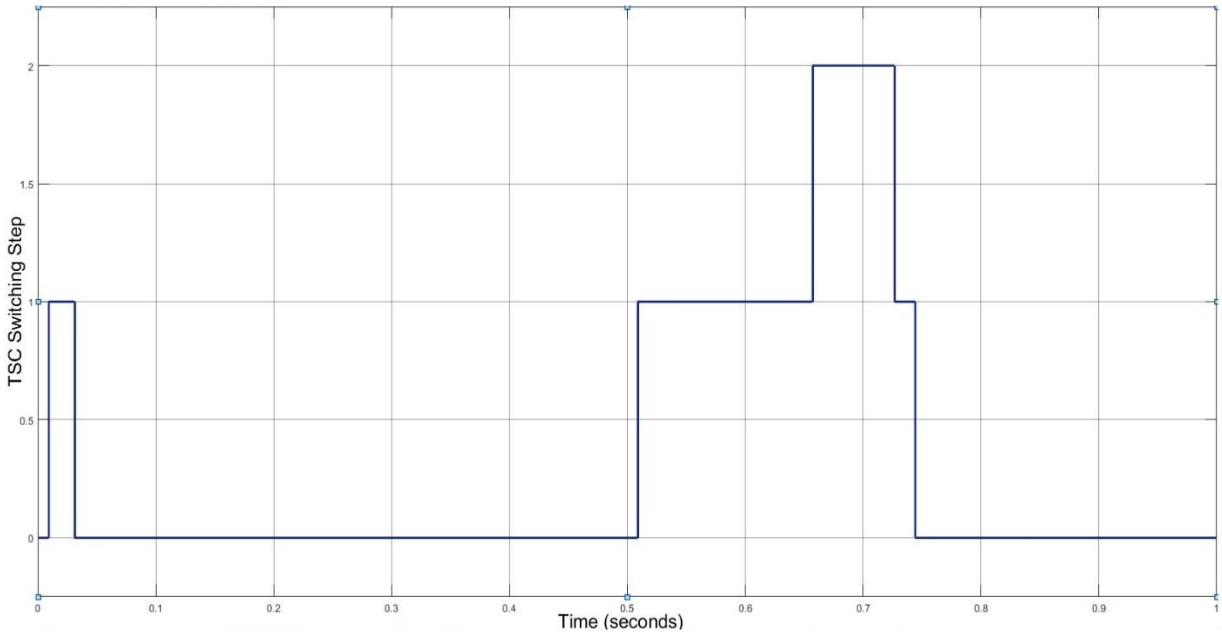

Fig. 4.17: TSC switching step.

The TSC switching two steps varied in discretely to generate a reactive power under its rating which contributes to the compensation. This helps the voltage to be measured and gives a high value when the TSC generates a reactive power.

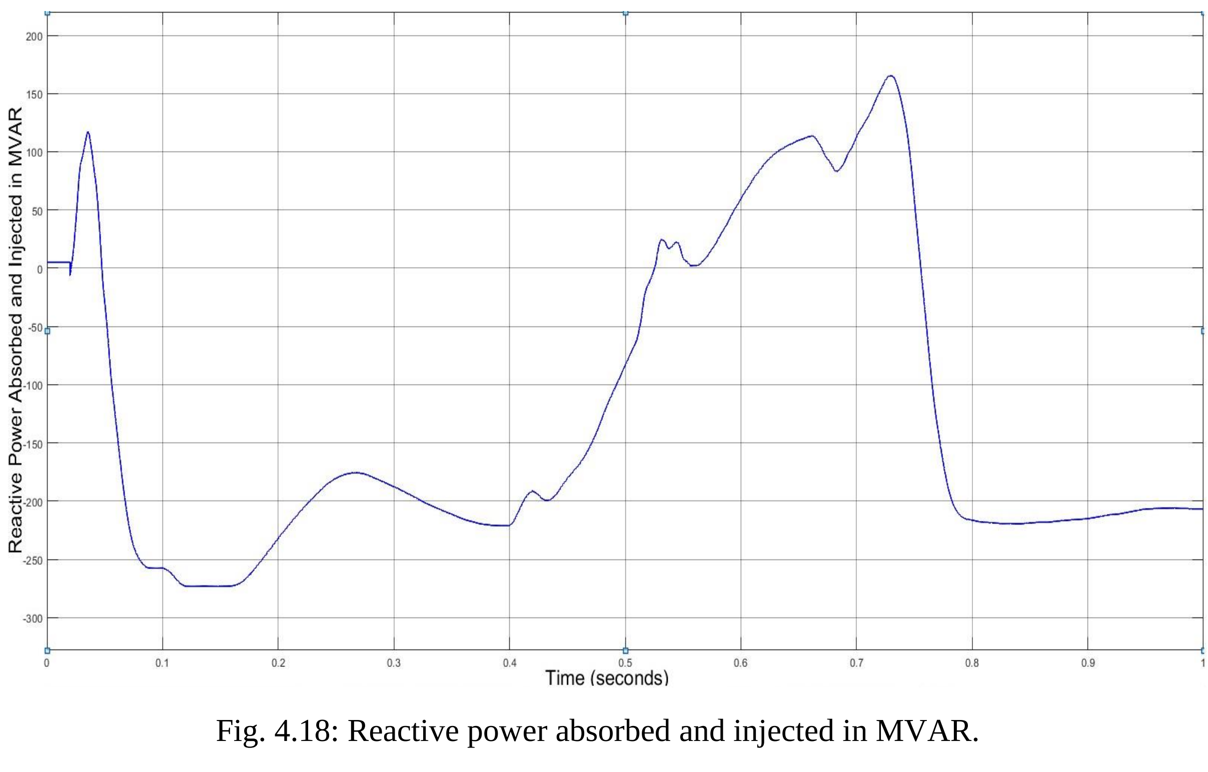

Fig. 4.18: Reactive power absorbed and injected in MVAR.

The figure explains that the reactive power generated and absorbed in MVAR with the time to retain the voltage at stability and increases the amount of it by compensation of adding the TSC-TCR hybrid configuration.

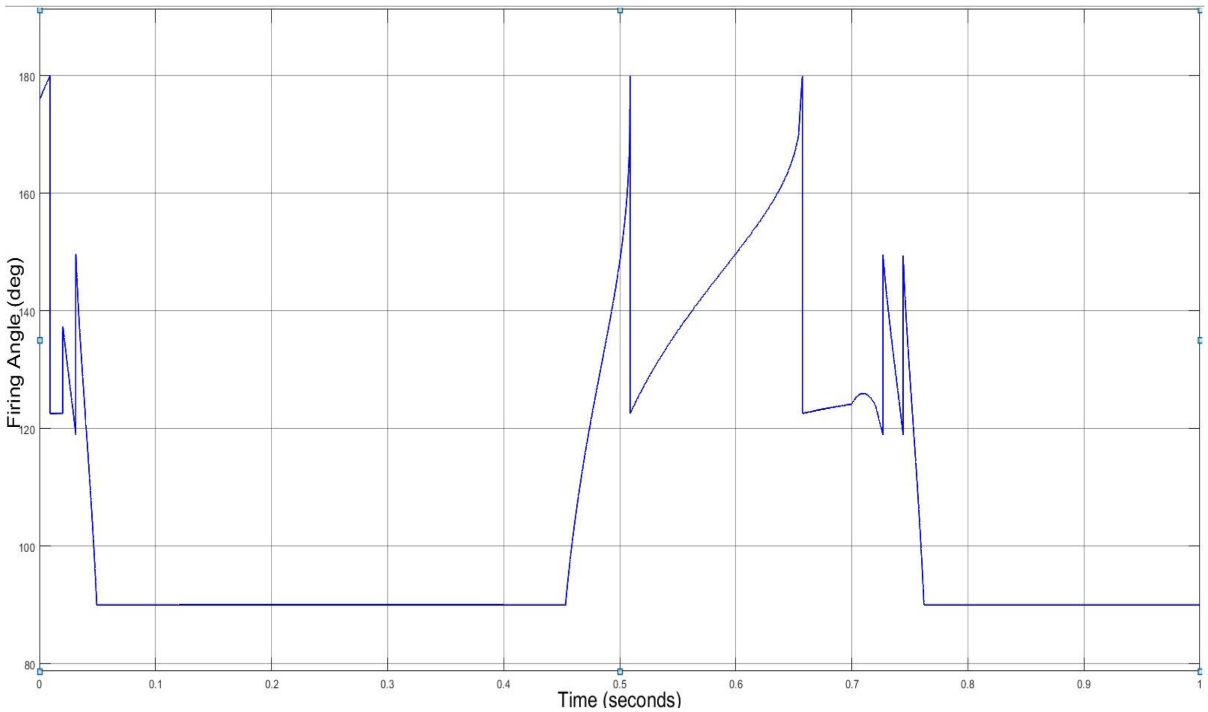

Fig. 4.19: Firing angle triggered by the two SVCs.

The firing angle is triggered to control the switching in and out of the thyristor valves in the TCR that gives from a zero conduction state to a full conduction state. ($90^0 \leq \alpha \leq 180^0$).

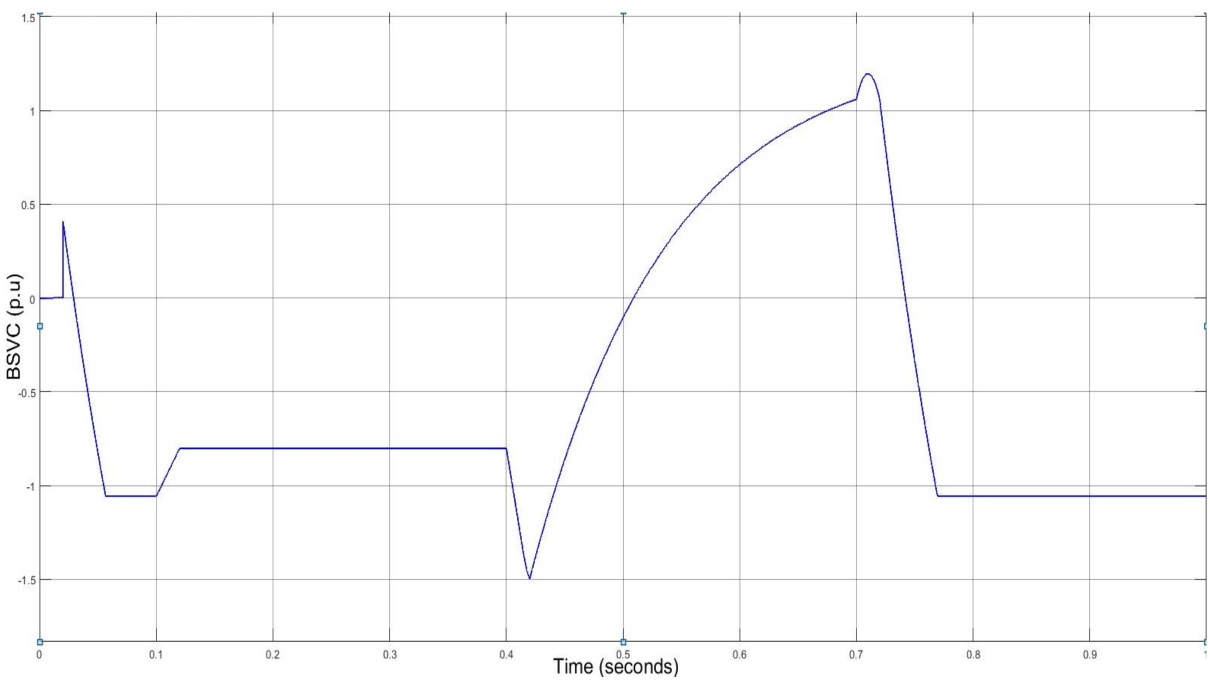

Fig. 4.20: B_{SVC} (p.u/100 MVA).

Table. 4.3: Voltage levels in p.u for the seven outgoing lines after TSC-TCR SVC.

Model: YibbabieSimulationwithSVCTSCTC Update The load flow converged! The table shows the load flow solution. Click Apply to update the model with this solution. Compute Apply Add bus blocks Re

	Block name	Block type	Bus type	Bus ID	Vbase (kV)	Vref (pu)	Vangle (deg)	P (MW)	Q (Mvar)	Qmin (Mvar)	Qmax (Mvar)	V_LF (pu)	Vangle_LF (deg)
1	Gofa Outgoing	RLC load	Z	BUS_1	132.0000	1.0500	0	38.0000	11.0000	-Inf	Inf	1.0500	0
2	Kaliti-I Incoming	RLC load	Z	BUS_1	132.0000	1.0500	0	54.0000	14.0000	-Inf	Inf	1.0500	0
3	Sebeta Incoming	RLC load	Z	BUS_1	132.0000	1.0500	0	46.0000	19.0000	-Inf	Inf	1.0500	0
4	Programmable Voltage Source	Vprog	swing	BUS_1	132.0000	1.0500	0	0	0	-Inf	Inf	1.0500	0
5	Line - 1	RLC load	Z	BUS_2	15.0000	1.0500	0	5.8000	5.5200	-Inf	Inf	1.0140	29.0141
6	Line - 3	RLC load	Z	BUS_2	15.0000	1.0500	0	9.7000	10.1800	-Inf	Inf	1.0140	29.0141
7	Line - 5	RLC load	Z	BUS_2	15.0000	1.0500	0	8.6000	12.9000	-Inf	Inf	1.0140	29.0141
8	Line - 6	RLC load	Z	BUS_2	15.0000	1.0500	0	6.7000	0.1200	-Inf	Inf	1.0140	29.0141
9	Line - 7	RLC load	Z	BUS_2	15.0000	1.0500	0	3.6000	1.8537	-Inf	Inf	1.0140	29.0141
10	Line - 2	RLC load	Z	BUS_3	15.0000	1.0500	0	0.4600	7.0247	-Inf	Inf	1.0230	29.9182
11	Line - 4	RLC load	Z	BUS_3	15.0000	1.0500	0	4.7000	4.2500	-Inf	Inf	1.0230	29.9182

4.3 Discussions

After inserting the FC-TCR SVC into the buses, the voltage level for the two outgoing feeders such that line-2 and line-4, the value is changed from 0.949 p.u to 0.989 p.u. Similarly, the voltage level for the five outgoing feeders changed from 0.9615 p.u to 1.011 p.u. Whereas TSC-TCR improves the voltage level from 0.9494 p.u to 1.014 p.u at bus-1 and from 0.9615 p.u to 1.023 p.u at load bus-2. Under FC-TCR, the reactive power supplied by 132 kV at t=0.009705 sec which is 92 MVAR is reduced suddenly to 5.961MVAR when the time exceeds 0.56s. Reactive power generated by FC-TCR 1 at t= 0.038 second becomes 43.48 MVAR. As the time exceeds t=0.044 seconds, it increases to 44.02 MVAR, and also at the time exceeds 0.059 sec, it is then decreased to 41.13 MVAR that is generated by the load. Similarly, for SVC 2, 29.08 MVAR is generated by the capacitor at t=0.029 sec, and -7.271 MVAR is consumed by the load. Under heavy load conditions, when positive VARs are needed, capacitor banks are employed; while under light load conditions, when negative VARs are needed, inductor banks are switched on. At t=0.035 sec, the source voltage is suddenly raised to 1.051 p.u by which TSC generates a required amount of MVAR. At t=0.437 sec, it is fallen to 0.9871 p.u as the TCR absorbs 201.3 MVAR from the system. At t=0.533 sec, the voltage level becomes 1.081p.u when the TSC generates 31.87 MVAR. In this case scenario, the TSC switching leveled up by one discrete step, and keeps this level by generating +166.4 MVAR by two steps of switching. The TSC also contributed to the generation of 26.51 MVAR at t= 0.545 sec and 84.83 MVAR at the time of 0.685 sec as well to keep the voltage level to maximum. The static var compensator interrelates with t=0.022s by generating 8.256 MVAR at the firing angle $\alpha=134.2^0$. At t=0.659s, TSC generates 115.5 MVAR at a firing angle α of 122.6^0. This enables the switching step by two. The TCR firing angle changes suddenly from 180^0 (no conduction) to 90^0 (full conduction). So, when the angle becomes 90^0, TCR absorbs inductive -86.47 MVAR. Then, the capacitors are switched off by the thyristor valves when the voltage retains 1.051 p.u at the time of t= 0.793 sec. At this time, the TCR absorbs the reactive power corresponding to the firing angle by 213.3 MVAR (inductive) from the system bus.

Table. 4.4: Voltage level comparison between the SVCs.

Comparison of voltage levels			
	Without SVC	With FC-TCR SVC	With TSC-TCR SVC
Line -1	0.9494	0.989	1.014
Line-2	0.961	1.0111	1.02
Line-3	0.949	0.9899	1.014
Line-4	0.9615	1.011	1.023
Line-5	0.949	0.989	1.02
Line-6	0.9494	1.011	1.023
Line-7	0.949	1.011	1.01

Table. 4.5: Power factor comparison between SVCs.

Comparison of Power factor		
Without SVC	With FC-TCR SVC	With TSC-TCR SVC
0.9398	0.962	0.9796
0.9786	0.9972	0.9985

Table 4.6: Reactive Power Compensation.

Before Compensation		After Compensation	
		FC-TCR	TSC-TCR
	Q (MVAR)	Q (MVAR) – Ind.	Q (MVAR)- Cap.
Line -1	0.545	0.115	0.154
Line -2	0.531	0.157	0.323
Line-3	1.005	0.204	0.284
Line-4	0.321	0.095	0.195
Line-5	1.273	0.26	0.359
Line-6	0.012	0.038	0.003
Line-7	0.183	0.002	0.051

Therefore, the discussion part of the research presents the contribution of the static VAR compensators to the power transmission substation system. In this regard, TSC-TCR is better when compared to FC-TCR in the compensation of the reactive power and maximizes the voltage level within the acceptable range. This compensation of reactive power gives support to the stability of the substation and provides the active power transfer capability of the outgoing lines which feed the inductive loads. Hence, the hybrid shunt controlling techniques of FACTS devices have their impact on the control of reactive power in the power system network. The voltage is increased as the reactive power is compensated by injection and absorption methods of the thyristor-based static VAR compensators.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This case study research discusses well the utilization of various hybrid SVC configurations corresponding to FC-TCR as well as TSC-TCR for reactive power compensation, and voltage control techniques by the numerous applications of the exploiting SVCs which are investigated and implemented on Mekannisa 132/15 kV transmission substation to check their effectiveness in voltage control and reactive power compensation. The results show that the number of load buses with the desirable voltage profile remained in the tolerable range and also the power factor is properly improved after adding the above SVC types to the buses. It's more essential that the adding of SVCs at the weakest bus within the power transmission network can considerably facilitate to boost of the voltage and could also be operated within the specified limit of operation. Moreover, it's additionally important that the utilization of SVCs might be a real efficient FACTS device for voltage control and to boost the power transfer across the full point of interconnection that supports the voltage level of the power network within the acceptable range over the reference voltage level, which has a crucial effect on enhancing the voltage stability of the transmission network.

5.2 Recommendations

According to the research study, it's recommended that SVC shunt controllers could also be used for the improvement of power quality under harmonic distortion within the Mekannisa 132/15 kV transmission substation. It's additionally recommended that SVCs may be supplementary at the poor buses with dynamic load variations to considerably improve the voltage levels of the outgoing feeders and also the injection as well as absorption of the reactive power which can be interrelated to control the voltage within the specified amount and operates in the power system network that possibly supports the voltage profile.

5.3 Suggestions for Future Work

The following works are highly suggested to supplement the study presented in this thesis.

- In the future, a study on the SVC location (placement) using the particle swarm optimization technique can be applied to the analyzed system.
- To verify the effectiveness of the suggested approach for reactive power compensation and voltage regulation by comparing the simulation results with various scenarios can be performed using different software such as DigSILENT Power Factory and PSCAD.
- This thesis has addressed the scope of applications of static VAR compensator devices on the transmission substation system. Hence, in the future examining the use of various types of FACTS controllers, such as Static Synchronous Compensator (STATCOM) for reactive power compensation and voltage stability can be studied.
- Further study on the investigation of control-based power quality improvement appropriate techniques such as Dynamic Voltage Restorer (DVR) under harmonic distortion can be implemented.

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APPENDIX I

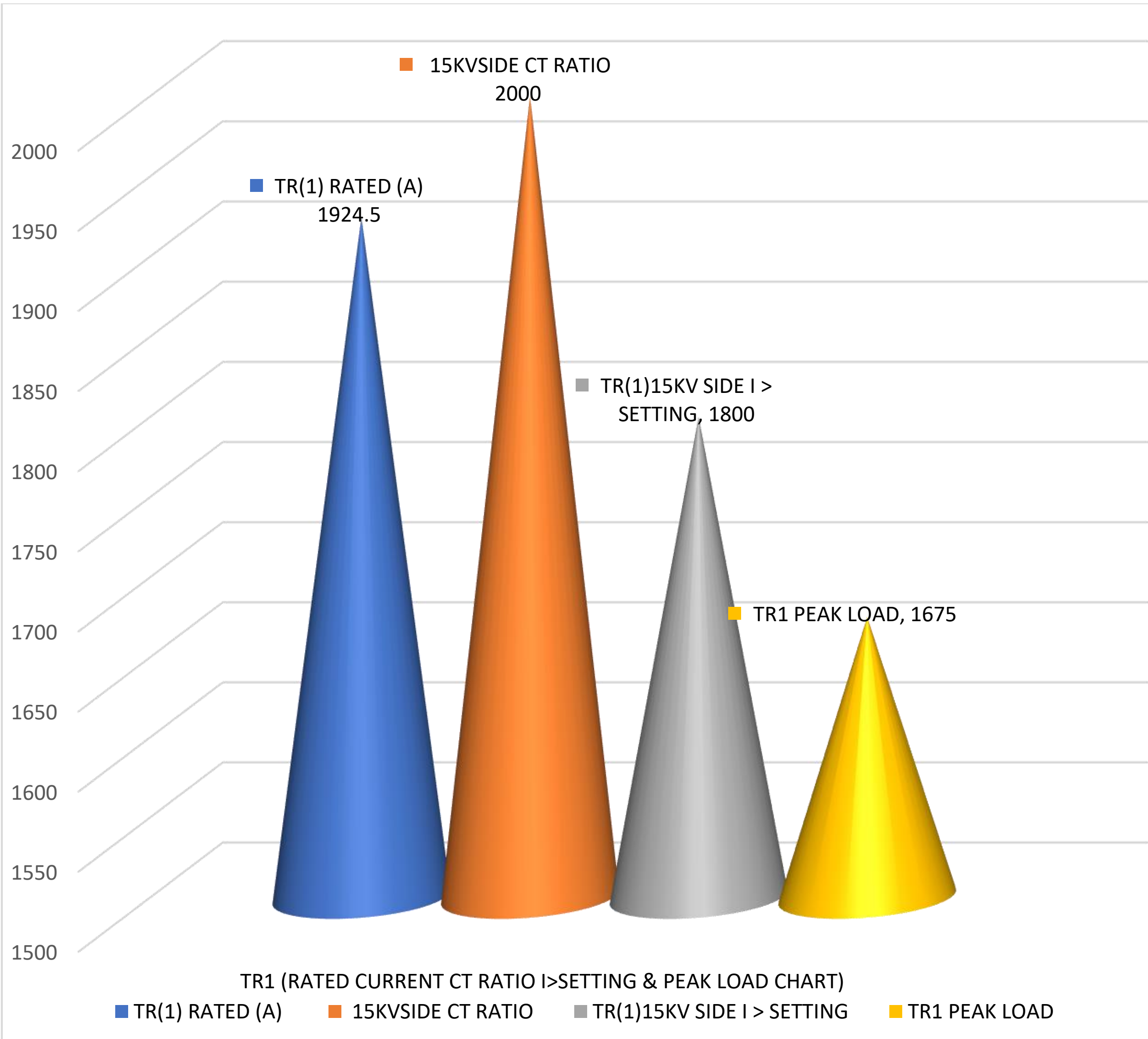

Fig. A-I.1: Trafo-I 15 kV outgoing line peak load chart.

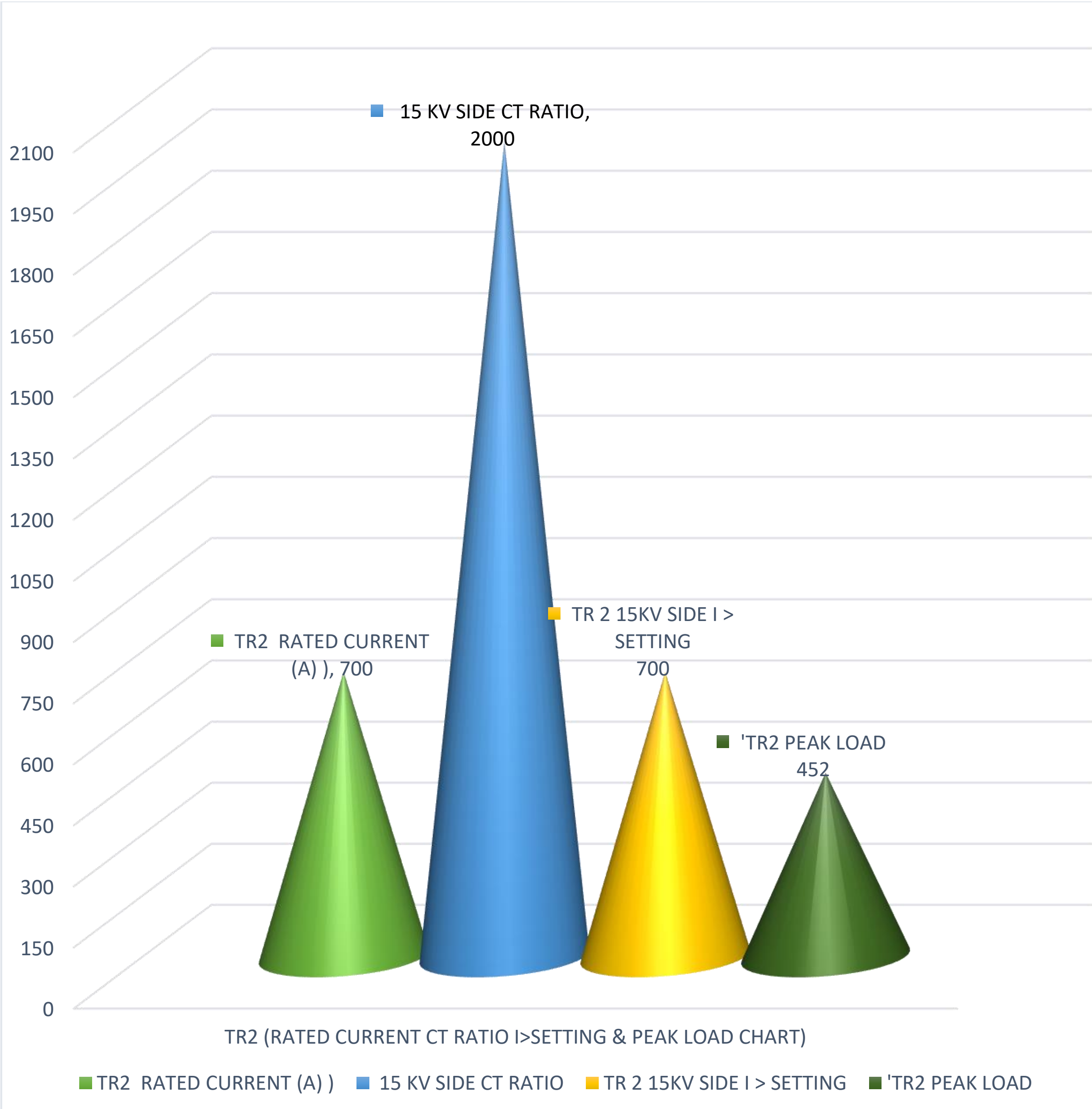

Fig. A-I.2: Trafo-II 15 kV outgoing line peak load chart.

APPENDIX II

	132 KV SEBETA GEFERSA LINE								132KV KALITI LINE								132KV GOFA LINE			
	LINE CUR			BUS VOLTAGE					LINE CUR			BUS VOLTAGE								
	A			KV			POWER		A			KV			POWER		CUR	POWER		VOLT
HOUR	R	S	T	RS	ST	TR	MW	Mvar	R	S	T	RS	ST	TR	MW	Mvar	A	MW	Mvar	KV
1:00	97	97	97	132	132	132	12	18	142	142	142	132	132	132	11	26	41	8	3	132
2:00	97	97	97	132	132	132	12	18	142	142	142	132	132	132	11	26	41	8	3	132
3:00	97	97	97	132	132	132	12	18	142	142	142	132	132	132	11	26	41	8	3	132
4:00	97	97	97	132	132	132	12	18	142	142	142	132	132	132	11	26	41	8	3	132
5:00	97	97	97	132	132	132	12	18	142	142	142	132	132	132	11	26	41	8	3	132
6:00	118	118	118	131	131	131	21	16	142	142	142	131	131	131	15	24	74	16	3	131
7:00	129	129	129	129	129	129	26	13	167	167	167	129	129	129	24	23	114	25	5	129
8:00	128	128	128	130	130	130	26	12	178	178	178	130	130	130	25	25	117	25	6	130
9:00	159	159	159	129	129	129	34	8	177	177	177	129	129	129	25	25	134	28	8	129
10:00	159	159	159	129	129	129	34	8	177	177	177	129	129	129	25	25	134	28	8	129
11:00	175	175	175	128	128	128	37	8	196	196	196	128	128	128	27	28	143	30	9	128
12:00	175	175	175	128	128	128	37	11	219	219	219	128	128	128	30	11	147	31	9	128
13:00	152	152	152	130	130	130	31	12	184	184	184	130	130	130	22	30	110	23	8	130
14:00	164	164	164	129	129	129	34	12	190	190	190	129	129	129	23	29	115	24	8	129
15:00	164	164	164	129	129	129	34	12	190	190	190	129	129	129	23	29	115	24	8	129
16:00	161	161	161	131	131	131	32	16	136	136	136	131	131	131	10	26	55	12	2	131
17:00	161	161	161	131	131	131	32	16	136	136	136	131	131	131	10	26	55	12	2	131
18:00	200	200	200	131	131	131	42	15	140	140	140	131	131	131	12	25	97	21	4	131
19:00	200	200	200	131	131	131	42	15	140	140	140	131	131	131	12	25	97	21	4	131
20:00	200	200	200	131	131	131	42	15	140	140	140	131	131	131	12	25	97	21	4	131
21:00	167	167	167	130	130	130	34	13	143	143	143	130	130	130	15	24	117	25	5	130
22:00	113	113	113	131	131	131	19	16	124	124	124	131	131	131	9	23	62	13	3	131
23:00	113	113	113	131	131	131	19	16	124	124	124	131	131	131	9	23	62	13	3	131
0:00	91	91	91	132	132	132	12	16	115	115	115	132	132	132	7	22	42	9	3	132

Table A-II:1. Hourly data.

INSPECTION LIST					
	TIME			TIME	
PARTICULAR	10:00	17:00	PARTICULAR	10:00	17:00
132 kV C.B SF6 PRESSURE TRANSFORMER 2	6	0.6	EARTHING TRANSFORMER 1 OIL LEVEL	OK	OK
132 kV C.B SF6 PRESSURE TRANSFORMER 1	6	0.6	EARTHING TRANSFORMER 2 OIL LEVEL	OK	OK
132 kV C.B SF6 PRESSURE KALITI - I	6	0.6	TRANSFORMER 2 OIL LEVEL	OK	OK
LIGHTNING ARRESTOR COUNTER KALITI	28	28	TRANSFORMER 2 OIL TEMPRATURE	40	30
LIGHTNING ARRESTOR COUNTER TRAFO 1	26	26	TRANSFORMER 2 SELICAGEL	OK	OK
LIGHTNING ARRESTOR COUNTER TRAFO 2	26	26	TRANSFORMER 2 TAP POSITION		
LIGHTNING ARRESTOR COUNTER SEB/GEFFERSA	26	26	LIGHTNING ARRESTOR COUNTER GOFA LINE	3	3
SF6 GAS PRESSURE SEBETA/GEFFERSA	0.61	0.6	SF6 GAS PRESSURE READING GOFA LINE	0.64	0.62
TRANSFORMER 2 TAP CHANGER COUNTER			BATTERY TOTAL TERMINAL VOLTAGE	134.4	134
TRANSFORMER 1 TAP CHANGER COUNTER	23522	23528	BATTERY TOTAL VOLTAGE	134.4	134
TRANSFORMER 1 TAP POSITION	14	13	ROOM TEMPERATURE	22	20
TRANSFORMER 1 OIL TEMPRATURE	48	41	BATTERY SP GRAVITY		
TRANSFORMER 1 WINDING TEMPERATURE	54/58	40/46	TRANSFORMER 2 WINDING TEMPERATURE	42	30

		E.E.P.C							DAY	WEDNESDAY			DATE		07/07/2021				YEAR	2021								
		SUBSTATION																										
DAY LOG SHEET & INSPECTION LIST																												
15KV TRAFO FEEDER A				15KV TRAFO FEEDER B				BUS BAR VOLTAGE (KV)																		15KV		
CURRENT				CURRENT				15KV						15KV OUTGOING		15KV OUTGOING		15KV OUTGOING		15KV OUTGOING		15KV OUTGOING		15KV OUTGOING		OUTGOING		
A			POWER	A			POWER							H/MARIAM		LAFTO		LEBU		MEKANISSA		SEBETA		C.G.C		Water Supply		Frequency
R	S	T	MW	R	S	T	MW	RS	ST	TR	RO	SO	TO	A	MW	A	MW	A	MW	A	MW	A	MW	A	MW	A	MW	
606	606	606	12.5806				0	15	15	15	8.7	8.7	8.7	64	1.32864		0	123	2.55348	39	0.80964	231	4.79556	150	3.114	39	0.80964	49.8
606	606	606	12.5806				0	15	15	15	8.7	8.7	8.7	64	1.32864		0	123	2.55348	39	0.80964	231	4.79556	150	3.114	39	0.80964	49.8
606	606	606	12.5806				0	15	15	15	8.7	8.7	8.7	64	1.32864		0	123	2.55348	39	0.80964	231	4.79556	150	3.114	39	0.80964	49.8
606	606	606	12.5806				0	15	15	15	8.7	8.7	8.7	64	1.32864		0	123	2.55348	39	0.80964	231	4.79556	150	3.114	39	0.80964	49.8
606	606	606	12.5806				0	15	15	15	8.7	8.7	8.7		0		0	123	2.55348	39	0.80964	231	4.79556	150	3.114	39	0.80964	49.8
741	741	741	15.3832	113	113	113	2.34588	15	15	15	8.7	8.7	8.7		0		0	219	4.54644	113	2.34588	262	5.43912	193	4.00668	71	1.47396	50.03
926	926	926	19.2238	159	159	159	3.30084	15	15	15	8.7	8.7	8.7		0		0	302	6.26952	155	3.2178	269	5.58444	245	5.0862	115	2.3874	49.9
989	989	989	20.5316	169	169	169	3.50844	15	15	15	8.7	8.7	8.7		0	0	0	315	6.5394	166	3.44616	261	5.41836	277	5.75052	177	3.67452	50.02
1095	1095	1095	22.7322	195	195	195	4.0482	15	15	15	8.7	8.7	8.7	32	0.66432	22	0.45672	362	7.51512	178	3.69528	295	6.1242	285	5.9166	110	2.2836	50.1
1095	1095	1095	22.7322	195	195	195	4.0482	15	15	15	8.7	8.7	8.7	32	0.66432	22	0.45672	362	7.51512	178	3.69528	295	6.1242	285	5.9166	110	2.2836	50.1
1288	1288	1288	26.7389	195	195	195	4.0482	15	15	15	8.7	8.7	8.7	207	4.29732	22	0.45672	372	7.72272	176	3.65376	301	6.24876	299	6.20724	125	2.595	49.96
1397	1397	1397	29.0017	195	195	195	4.0482	15	15	15	8.7	8.7	8.7	224	4.65024	22	0.45672	388	8.05488	181	3.75756	376	7.80576	284	5.89584	133	2.76108	50.05
1160	1160	1160	24.0816	169	169	169	3.50844	15	15	15	8.7	8.7	8.7	190	3.9444	22	0.45672	286	5.93736	145	3.0102	337	6.99612	251	5.21076	93	1.93068	50.05
1206	1206	1206	25.0366	178	178	178	3.69528	15	15	15	8.7	8.7	8.7	189	3.92364	22	0.45672	317	6.58092	158	3.28008	357	7.41132	249	5.16924	95	1.9722	50.04
1206	1206	1206	25.0366	178	178	178	3.69528	15	15	15	8.7	8.7	8.7	189	3.92364	22	0.45672	317	6.58092	158	3.28008	357	7.41132	249	5.16924	95	1.9722	50.04
1325	1325	1325	27.507	178	178	178	3.69528	15	15	15	8.7	8.7	8.7	202	4.19352	0	0	374	7.76424	158	3.28008	317	6.58092	281	5.83356	121	2.51196	50.22
1325	1325	1325	27.507	178	178	178	3.69528	15	15	15	8.7	8.7	8.7	202	4.19352	0	0	374	7.76424	158	3.28008	317	6.58092	281	5.83356	121	2.51196	50.22
1145	1145	1145	23.7702	187	187	187	3.88212	15	15	15	8.7	8.7	8.7	230	4.7748	0	0	422	8.76072	181	3.75756	375	7.785		0	139	2.88564	50.03
1145	1145	1145	23.7702	187	187	187	3.88212	15	15	15	8.7	8.7	8.7	230	4.7748	0	0	422	8.76072	181	3.75756	375	7.785		0	139	2.88564	50.03
1145	1145	1145	23.7702	187	187	187	3.88212	15	15	15	8.7	8.7	8.7	230	4.7748	0	0	422	8.76072	181	3.75756	375	7.785		0	139	2.88564	50.03
889	889	889	18.4556	138	138	138	2.86488	15	15	15	8.7	8.7	8.7	281	5.83356	0	0		0	139	2.88564	304	6.31104	295	6.1242	106	2.20056	50.11
582	582	582	12.0823	79	79	79	1.64004	15	15	15	8.7	8.7	8.7	98	2.03448	0	0		0	78	1.61928	229	4.75404	201	4.17276	55	1.1418	50.01
582	582	582	12.0823	79	79	79	1.64004	15	15	15	8.7	8.7	8.7	98	2.03448	0	0		0	78	1.61928	229	4.75404	201	4.17276	55	1.1418	50.01
403	403	403	8.36628	56	56	56	1.16256	15	15	15	8.7	8.7	8.7	64	1.32864	0	0		0	55	1.1418	212	4.40112	117	2.42892	39	0.80964	49.87

Table A-II:2. Day log sheet.

Fig. A-II: Picture of the Mekannisa Substation.