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VOLTAGE STABILITY ENHANCEMENT IN DISTRIBUTION SUBSTATION USING STATIC VAR COMPENSATOR (CASE STUDY: WOLAITA SODO DISTRIBUTION SUBSTATION)

A Thesis Submitted to Faculty of Electrical and Computer Engineering of Jimma Institute of Technology

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By

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DECLARATION

I the undersigned declare that this thesis is my original work, has not been presented for a degree of otherwise in this or other universities all sources of materials for this thesis have been fully acknowledged.

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ABSTRACT

One of the major concerns of power system is the voltage instability. Voltage instability is a problem of overload or underload of a power system. The main factor causing voltage instability is the inability of the power system to meet the demand for reactive power. Static Var Compensator plays a major role in voltage stability enhancement due to its fast response and high capability. So, it is very important to study the use of static Var compensator for distribution substation voltage stability enhancement under normal operating conditions.

Data collection is carried out to study the voltage profile and reactive power compensation of Wolaita Sodo distribution substation. Wolaita Sodo distribution substation has one incoming feeder and eight outgoing feeders. There are three transformers 132/15 kV, 132/33 kV, 132/66 kV, the rating of the transformers are 20 MVA, 25 MVA, 16 MVA respectively. The 132/15 kV transformer suppling to four 15 kV outgoing feeders, the 132/33 kV transformer suppling to three 33kV outgoing feeders and the 132/66 kV transformer suppling to one 66 kV outgoing feeder. The total load of Wolaita Sodo distribution substation is 17.9 MW and 14.74 MVAR. The total connected load to the four 15 kV feeders is 13.9 MW and 10.36 MVAR.

Static Var compensator modeling and simulation studies have been carried out using ETAP software. Simulation results with and without Static Var compensator has been performed. Line Voltage stability index (L_{mn}) at various lines are calculated to identify the critical lines and weak buses. Then Static Var compensator device is introduced at the bus connected the critical lines and its effectiveness is evaluated for voltage enhancement. The size of the selected Static Var compensator is 11.544 MVAR.

After connected the Static Var compensator the voltage profile of the weakest bus is improved from 0.9489pu to 0.9925pu. The voltage profile of the other buses which connecting with the critical line also improved. Additionally the power and current flows of the distribution substation buses and lines increased, the reactive power loss decreased, the voltage deviation decreased and transformer loading decreased. Thus, based on the findings of this research, I concluded that use of static Var compensator could be a very effective FACTS device for voltage stability enhancement.

Keywords: SVC, Line voltage stability index, Voltage stability, Voltage instability, Reactive power compensation, FACTS

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List of abbreviations

AC	Alternating current
AVR	Automatic voltage regulator
B_{SVC}	Static Var compensator susceptance
B_{TCR}	Thyristor controlled reactor susceptance
CU	Copper
DC	Direct current
Dig SILENT	Digital Simulation and Electrical Network
DG	Distributed generation
D-STATCOM	Distribution Static compensator
EEU	Ethiopia electric utility
ETAP	Electrical Transient Analyzer Program
FACTS	Flexible AC Transmission Systems
FC-TCR	Fixed capacitor- thyristor controlled reactor
FVSI	Fast voltage stability index
ICS	Interconnected System
IEEE	Institute of Electrical and Electronics Engineer
IPFC	Interline Power Flow Controller
KV	kilo volt
KVA	kilo volt ampere
KVAR	kilo volt ampere reactive
L_{mn}	Line Stability Index
LTC	Load Tap Changing
LV	Low Voltage
MATLAB	Matrix Laboratory
MSC	Mechanically switched capacitor
MV	Mega volt ampere
MVAR	Megavolt ampere reactive
MW	Mega watt
OLD	One Line Diagram
P	Active Power
Pf	Power Factor

PLL	Phase locked loop
PI	Proportional integral controller
PT	Potential transformer
PSO	Particle swarm optimization
PU	Per unit
TCSR	Thyristor-Controlled Series Reactor
TRAFO	Transformer
TRAFO I	Transformer one
TRAFO II	Transformer two
TRAFO III	Transformer three
SNNP	South Nation Nationalities and Peoples
SSSC	Static Synchronous Series Compensator
SVC	Static var compensator
STATCOM	Static compensator
TCR	Thyristor-Controlled Reactor (TCR),
TSC	Thyristor Switched Capacitor (TSC)
TSC-TCR	Thyristor switched capacitor-thyristor controlled reactor
TSSC	Thyristor Switched Series Capacitor
UPFC	Unified power flow controller
V_{ref}	Reference voltage
VSI	Voltage stability index

CHAPTER ONE

INTRODUCTION

1.1. Background

Voltage stability is a problem in power systems which are heavily loaded, faulted or have a shortage in reactive power. The nature of voltage stability can be analyzed by examining the generation, transmission and consumption of reactive power.

During the last three decades, power system networks have been operated under highly stressed conditions. Environmental pressures on transmission expansion, increased electricity consumption in heavy load areas (where it is not feasible or economical to install new generating plants), new system loading patterns due to the opening up of the electricity market, etc. are the factors responsible for stressed operating conditions of power systems. It seems as though the development brought about by the increased use of electricity is raising new barriers to power system expansion. Under these stressed conditions a power system can exhibit a new type of unstable behavior characterized by slow (or sudden) voltage drops, sometimes escalating to the form of a collapse. As a consequence, voltage stability has become a major concern in power system [1].

Since the rapid development of power electronics has made it possible to design power electronic equipment of high rating for high voltage systems, the voltage stability problem resulting from transmission system may be, at least partly, improved by use of the equipment well-known as FACTS devices. A number of papers treat development status of this technology from the early years up to date. The de-regulation (restructuring) of power networks will probably imply new loading conditions and new power flow situations. Analysis of a power system with embedded FACTS devices calls for development of adequate models. Models largely depend on the type of analysis, which is generally either component or system orientated. In the component orientated analysis, individual physical elements of a FACTS-devices are concerned. On the other side, the system orientated analysis needs answers on achievements that could be possibly gained by using a FACTS-devices [2].

The SVC is now a mature technology that is widely used for power system applications for several purposes. The primary purpose is usually rapid control of voltage at weak points in the network. Worldwide, there is a steady increase in the number of installations. The IEEE-definition of an SVC is as follows: “Static VAr Compensator (SVC): A shunt-connected static VAr generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of the electrical power system (typically bus voltage).” By placing the shunt in the middle of a line and therefore dividing the line into two segments, the voltage at this point can be controlled such that it has the same value as the end line voltages. This has the advantage that the maximal power transmission is increased. If the shunt compensator is located at the end of a line in parallel to a load it is possible to regulate the voltage at this end and therefore to prevent voltage instability caused by load variations or generation or line outages [3].

1.2. Statement of the problem

In Ethiopia, the energy demand is expected to be growing much more due to population growth, social and economic developments. This increase in electric power demand makes the power system to operate close to voltage stability boundaries making it subject to the risk of voltage instability. Voltage instability leads to a low unacceptable voltage profile in a significant part of the power system. The issue of power quality is a great concern in our daily life. Since Wolaita Sodo is the zone of tewleve woredas and a preferred location for most of the industries, considerable share of the electric power supply is directed towards the woredas. Due to this fact, Wolaita Sodo substation faces distribution inefficiency, repetitive and sporadic power interruptions, and power loss and voltage instability. The people at different towns are facing problems because it is associated with their livelihood. The existing residential, commercial and industrial customers are victims of the problem.

Static VAR compensators have been widely used in power systems grid because of its fast response to system changes such as voltage and reactive power variation. The SVC takes significant part to improve the voltage profile and reactive power compensation which lead to less economic cost.

1.3. Objectives

1.3.1. General objective

The general objective of this thesis is to enhance voltage stability of Wolaita Sodo distribution substation using Static Var compensator.

1.3.2. The specific objectives

The specific objectives include: -

- To collect relevant data from Wolaita Sodo distribution substation

- ❖ To assess the voltage stability of Wolaita Sodo distribution substation system
- ❖ To improve the voltage of the weak buses to within acceptable limit
- ❖ To develop simulation model the existing Wolaita Sodo distribution substation network using ETAP software
- ❖ To compare the existing results before and after SVC connected

1.4. Scope of the study

The scope of this study is to assess the voltage instability problems of the substation and percentage of improvements gained by SVC placement to the present distribution substation system.

1.5. Significance of the study

The significant of this study are: -

- ➢ To declares the voltage instability problems to owner and customers
- ➢ To exposes the cause and effect of voltage instability in the distribution substation to customers

1.6. Methodology

The research work is started by reviewing literatures related to voltage stability enhancement. Electrical line, bus and load data is collected from the Wolaita Sodo substation and distribution systems. The collected data from different sectors have been analyzed and a model is developed based on the different recorded data to identify the voltage instability. Generally, the following methodology is followed to accomplish this research work.

- ➢ Review of literatures: Different published material based on voltage stability enhancement is reviewed.
- ➢ Data collection: transformer, line, bus and load data is gathered from the Wolaita Sodo substation and distribution systems.
- ➢ Data analysis: The collected data is analyzed.
- ➢ Modeling of the distribution substation: based on the collected data modeling of the distribution substation is performed using ETAP software.
- ➢ Simulation Results discussed.
- ➢ Conclusions and recommendations are drawn based on the simulation results.

1.7. Organization of the thesis

Chapter two: In chapter two the basic theory of voltage stability and SVC are discussed in detail. In this chapter published research result of different researches in the area of voltage stability mainly the techniques used is studied and the factors considered are also reviewed. **Chapter three:** Electrical line, bus, load and transformers data of the Wolaita Sodo distribution substation will be presented. The techniques, method and software which are used in this research also will be presented.

Chapter four: In this chapter the simulation results of voltage profile, reactive power flow and reactive power loss with and without SVC compensator will be compared. And also the simulation results of the reactive power and voltage profile of the existing distribution substation with and without SVC will be discussed.

Chapter five: The last chapter presents the different result obtained from the research work is summarized and conclusions are drawn with possible solutions methods provided. . Furthermore, recommendations are suggested for the future researchers who would like to conduct a research on the area for a voltage stability enhancement.

CHAPTER TWO

THEORETICAL BACKGROUND AND LITERATURE REVIEW

2.1. Introduction

This chapter is divided into two main parts. The first part describes the voltage stability phenomenon and the second part gives a description for a remedy method which is the shunt FACTS devices. In the first part, some terms concerning the voltage stability are defined and the aspects of the voltage stability are classified. Then the different analysis methods of the voltage stability problem are described. Finally, the proposed method of the analysis will be stated. In the second part, a brief introduction will be made about the FACTS devices in general. Then, the construction and principle of operation of the SVC is described.

2.2. Power system stability

Power system stability is the property of the system that enables it to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance. Power system stability is divided into voltage stability, frequency stability and rotor angle stability [2].

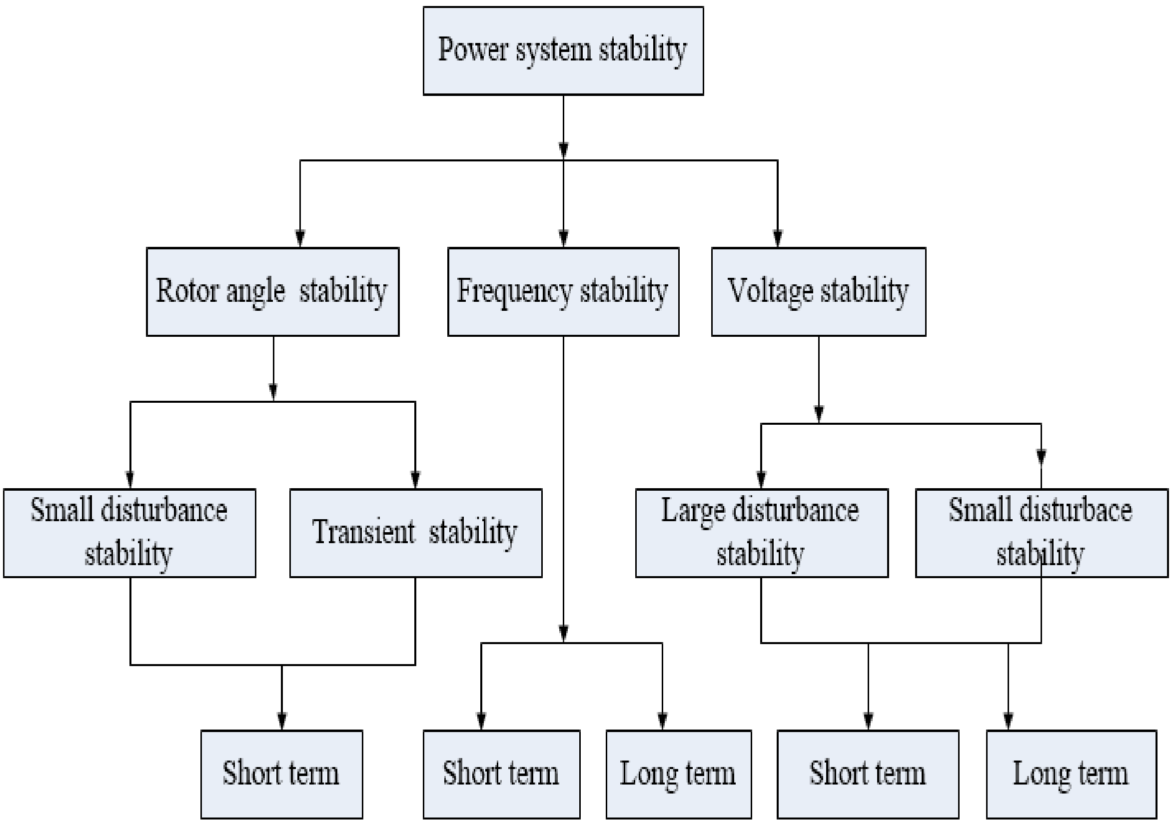


Figure 2. 1 classification of power system stability [2]

2.2.1. Rotor angle stability

Rotor Angle stability of a power system is the ability of interconnected synchronous machines of the power system network to remain in step with one another i.e. in synchronism the rotor angle stability problem involves the study of electro-mechanical oscillations. The fundamental factor of rotor angle stability is the manner in which power output of a synchronous machine varies with rotor oscillation. This could either be steady-state stability or transient state stability [3].

2.2.2. Frequency stability

Frequency stability refers to the ability of a power system to maintain steady frequency following a severe system upset resulting in a significant imbalance between generation and load. It depends on the ability of the network to maintain or restore equilibrium between system generation and load, with minimum unintentional loss of load. Generally, frequency stability problems are associated with inadequacies in equipment responses, poor coordination of control and protection equipment, or insufficient generation reserve. Frequency stability could be short-term (which ranges from a fraction of a second) or a long-term phenomenon [4].

2.3. Voltage stability

Voltage stability is the ability of a power system to maintain acceptable voltages at all the buses in the system under normal conditions and after being subjected to a disturbance. Voltage instability occurs in a power system when a disturbance causes a progressive fall or rise of voltages of buses. The main factor causing instability is the inability of the power system to meet the demand for the reactive power.

The reactive power can be supplied by generators through transmission networks or compensated directly at load buses by compensators such as shunt capacitors, FACTS devices. A disturbance such as fault or change in operating conditions, leads to increased demand for reactive power. This increase in electric power demand makes the power system to operate close to their limit conditions, which indicates that the system is operating under heavy loading conditions. Such a condition may cause voltage collapse. As a result, voltage stability becomes one of the major concerns and an appropriate remedy must be found to avoid the voltage collapse in a system [5].

Voltage stability is classifying into small and large disturbances.

2.3.1. Large disturbance voltage stability

Large-disturbance voltage stability refers to the system's ability to maintain steady voltages following large disturbances such as system faults, loss of generation, or circuit contingencies and the period of interest may extend from a few seconds to tens of minutes. Large-disturbance voltage stability can be studied using non-linear time domain simulations in the short-term time frame and load flow analysis in the long-term time frame [5].

2.3.2. Small disturbance voltage stability

Small-disturbance voltage stability refers to the system's ability to maintain steady voltages when subjected to small perturbations such as incremental changes in system load. Usually, the analysis of small-disturbances is done in steady state with the power system linearized around an operating point [6].

Voltage stability can be classified, in two ways: according to the time frame of their evolution (long-term or short-term voltage stability)

2.3.3. Short term voltage stability

Involves a fast phenomenon with a time frame in the order of fractions of a second to a few seconds. In some studies, it is also referred as transient voltage stability, but in it is recommended not to use this name to distinguish this type of stability with the transient rotor angle stability [7].

Short-term stability problems are usually related to the rapid response of voltage controllers such as generators' automatic voltage regulator (AVR) and power electronics converters like flexible AC transmission system (FACTS) or high voltage DC (HVDC) links. The analysis requires a solution of appropriate system differential equations [3].

2.3.4. Long term voltage stability

Involves slower acting equipment such as load recovery by the action of on-load tap changer or through load self-restoration and delayed corrective control actions such as shunt compensation switching or load shedding. The study period of interest may extend to several or many minutes. The modeling of long-term voltage stability requires consideration of transformer tap changers, characteristics of static loads, manual control actions of operators and automatic generation control [3].

2.3.5. Parameters affecting voltage stability

A number of factors are affecting the voltage stability of a power system. They are,

- Reactive power imbalance
- Variation in load (over load or under load)
- Changes in speed of the prime mover
- Switching heavy loads and long transmission lines
- Large changes in power angle
- Fast changes in power transfer
- Loss of synchronism and short circuit

2.4. Reactive power compensation

In power transmission, reactive power plays an important role. Real power accomplices the useful work while reactive power supports the voltage that must be controlled for system reliability. Reactive power has a profound effect on the security of power systems because it affects voltages throughout the system. Decreasing reactive power causing voltage to fall while increasing it causing voltage to rise. Voltage collapse may be occurring when the system tries to serve much more load than the voltage can support. Voltage control and reactive power management are the two aspects of a single activity that both supports reliability and facilitates commercial transactions across transmission networks. Voltage is controlled by absorbing and generating reactive power. Thus, reactive power is essential to maintain the voltage to deliver active power through transmission lines [8].

2.5. Flexible AC transmission systems

FACTS, which is the abbreviation of Flexible AC Transmission Systems, is defined as follows: “Alternating current transmission systems incorporating power electronics based and other static controllers to enhance controllability.

Since the ″other static controllers″ based FACTS devices are not widely used in current PSs, the focused only on the power electronics-based FACTS devices. The FACTS controllers are classified as follows [3]:

- ❖ Thyristor controlled based FACTS controllers such as TSC, TCR, FC-TCR, SVC, TCSC, TCPAR etc.
- ❖ VSC based FACTS controllers such as SSSC, STATCOM, UPFC, GUPFC, IPFC, GIPFC, HPFC etc.

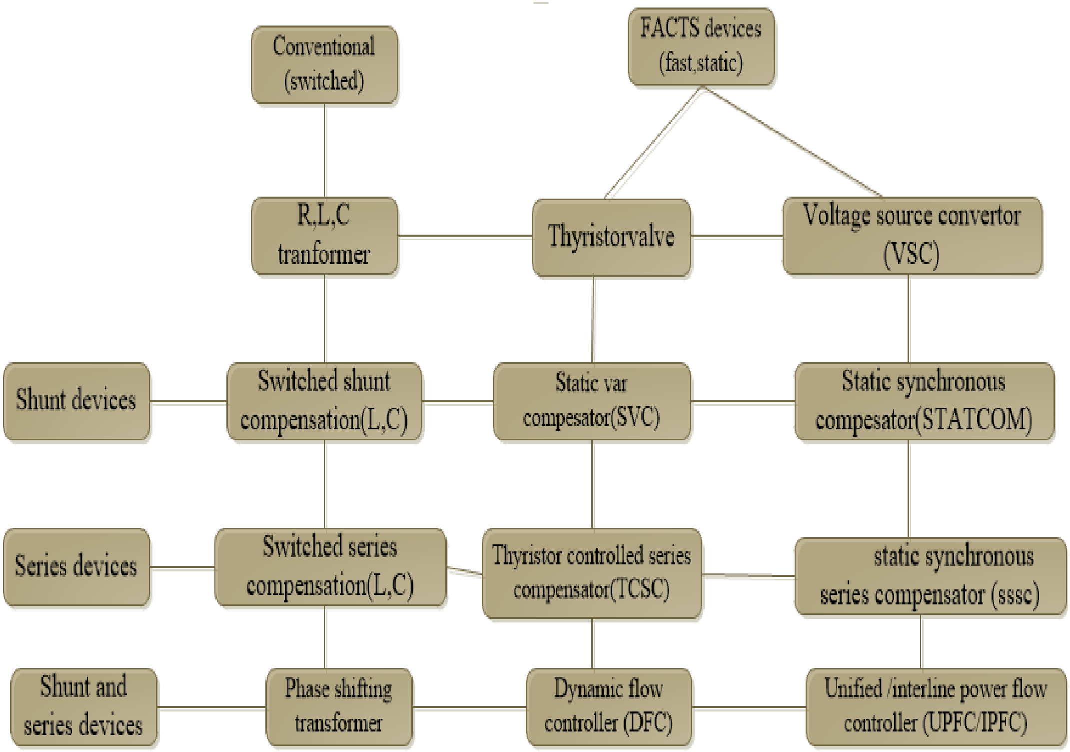


Figure 2. 2 overview of major FACTS devices [8]

In general, FACTS devices can be divided into four categories:

2.5.1. Series controllers

These types of controllers are connected in series with the transmission line. They can be of switched impedance or power electronics based variable source. TCSC, TCPAR and SSSC are among the series FACTS controllers. The basic principle of all series FACTS controllers is that they inject voltage in series with the line. In switched impedance controller, the variable impedance when multiplied with the current flow through the line represents an injected voltage in the line. The series controller injects or absorbs reactive power as long as the current injected by the controller remains in phase quadrature with the bus voltage. Any other phase relation will involve the handling of real power as well [9].

2.5.2. Shunt controllers

These types of controllers are connected in shunt with the transmission line. They can be of variable impedance, variable source or a combination of both. SVC and STATCOM are two commonly used shunt FACTS controllers. The basic principle of all shunt FACTS controllers is that they inject current into the system at the point of connection. The fundamental difference in operation principle between a SVC and a STATCOM is that STATCOM is with a converter based Var generation, functions as a shunt connected synchronous voltage source whereas SVC is with Thyristor controlled reactors and Thyristor switched capacitors, functions as a shunt connected controlled reactive admittance. The shunt controller injects or absorbs reactive power into or from the bus as long as the current injected by the controller remains in phase quadrature with the bus voltage. Any other phase relation will involve the handling of real power as well. STATCOM has the ability to exchange real power from the system if it is equipped with the energy storage element at its DC terminal [10].

2.4.5. Combined series-series controllers

These controllers address the problem of compensating a number of transmission lines at a given substation. The Interline Power Flow Controller (IPFC) is one such controller. The IPFC has a capability to directly transfer real power between the transmission lines through the common DC link together with independently controllable reactive series compensation of each individual line. This capability makes it possible to equalize both real and reactive power flow between the lines, transfer power demand from overloaded to under loaded lines, compensate against resistive line voltage drops and the corresponding reactive power demand, increase the effectiveness of the overall compensating system for dynamic disturbances [8].

2.5.4 Combined series-shunt controller

This is a combination of separate series and shunt controllers, which are controlled in a coordinated or unified manner. The Unified Power Flow Controller (UPFC) is one such controller. It can operate as a shunt and/or series compensator, a power flow controller, a voltage regulator or a phase shifter depending on its main control strategy. In this way simultaneous control on bus voltage and transmission line power flow can be realized. It can also exchange real power between a bus and a transmission line through the common DC link, provided that the shunt and series parts of the UPFC are unified [10].

2.6. Static var compensator (SVC)

SVC is considered as the first generation of shunt connected FACTS devices that have been implemented in power systems to provide fast-acting reactive power and voltage support to the power grid. By incorporating inductive and capacitive branches, SVC is able to regulate the voltage at a chosen bus by supplying or absorbing reactive power. The advantages of simplicity, low losses, low harmonics production and low cost have made SVC to be used extensively compared to other shunt FACTS devices [11]. In fact, many SVCs have been installed at power plants around the world and are considered attractive elements to enhance the performance of power systems.

A typical structure of the SVC that consists of a Thyristor-Controlled Reactor (TCR), a Thyristor Switched Capacitor (TSC) and a harmonic filter used to filter the harmonics generated by the TCR is illustrated in Fig. 2.3.

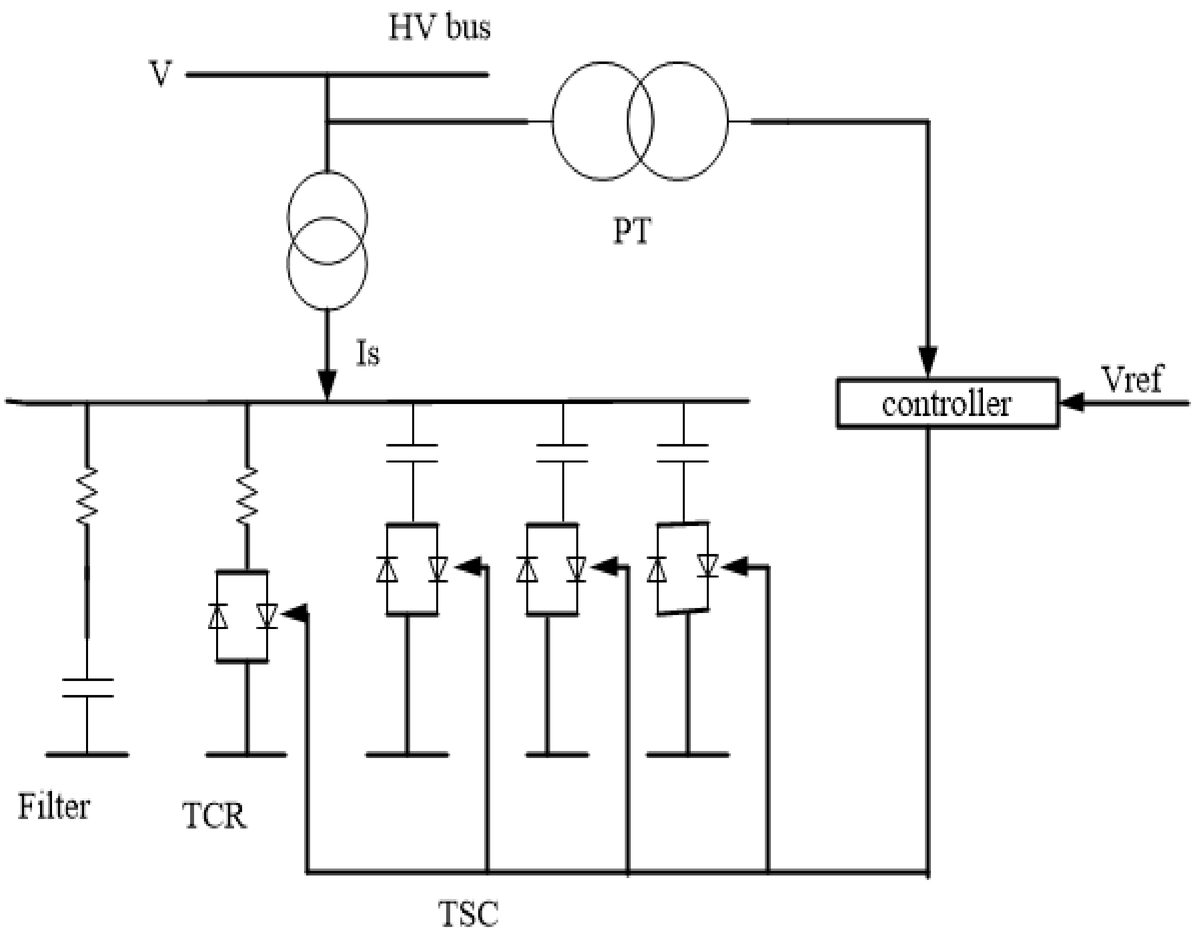


Figure 2. 3 schematic diagram of a SVC [3]

SVC is a shunt connected FACTS device whose output can be adjusted to exchange either capacitive or inductive currents to the connected system. This current is controlled to regulate specific parameters of the electrical power system (typically bus voltage).

It is a variable impedance device where the current through a reactor is controlled using back to back connected Thyristor valves. The Thyristor has been an integral part in realizing the SVC and to enable control of its reactive power flow. It is used either as a switch or as a continuously controlled valve by controlling the firing angle. Static Var compensators (SVCs) constitute a mature technology that is finding widespread usage in modern power systems for load compensation as well as transmission-line applications. In high power networks, SVCs are used for voltage control and for attaining several other objectives such as [12]:

- Increase power transfer in long lines
- Improve stability with fast acting voltage regulation
- Damp low frequency oscillations due to swing (rotor) modes
- Damp sub synchronous frequency oscillations due to torsional modes
- Control dynamic over voltages

2.7. Main components of SVCs

In general, the elements of an SVC operate on the principle of adjustable susceptance. The controlled susceptance is either a reactor or a capacitor [8].

We will discuss next the operation of the more commonly used elements: TCR, TSC.

2.7.1. Thyristor controlled reactor (TCR)

A TCR is one of the most important building blocks of Thyristor-based SVCs. Although it can be used alone, it is more often employed in conjunction with fixed or Thyristor-switched capacitors to provide rapid, continuous control of reactive power over the entire selected lagging-to-leading range.

A 3-phase, 6-pulse TCR comprises three single-phase TCRs connected in delta, as shown in Fig. 2.4. The inductor in each phase is split into two halves, as shown in Fig. 2.4, one on each side of the anti-parallel–connected Thyristor pair, to prevent the full ac voltage appearing across the Thyristor valves and damaging them if a short-circuit fault occurs across the reactor’s two end terminals. The phase and line current waveforms are also displayed in Fig. 2.4. If the 3-phase supply voltages are balanced, if the three reactor units are identical, and also if all the Thyristors are fired symmetrically with equal firing angles in each phase then the symmetric current pulses result in both positive and negative half-cycles and the generating of only odd harmonics. The percentage values of harmonic currents with respect to fundamental both in the phases and in the lines are the same [13].

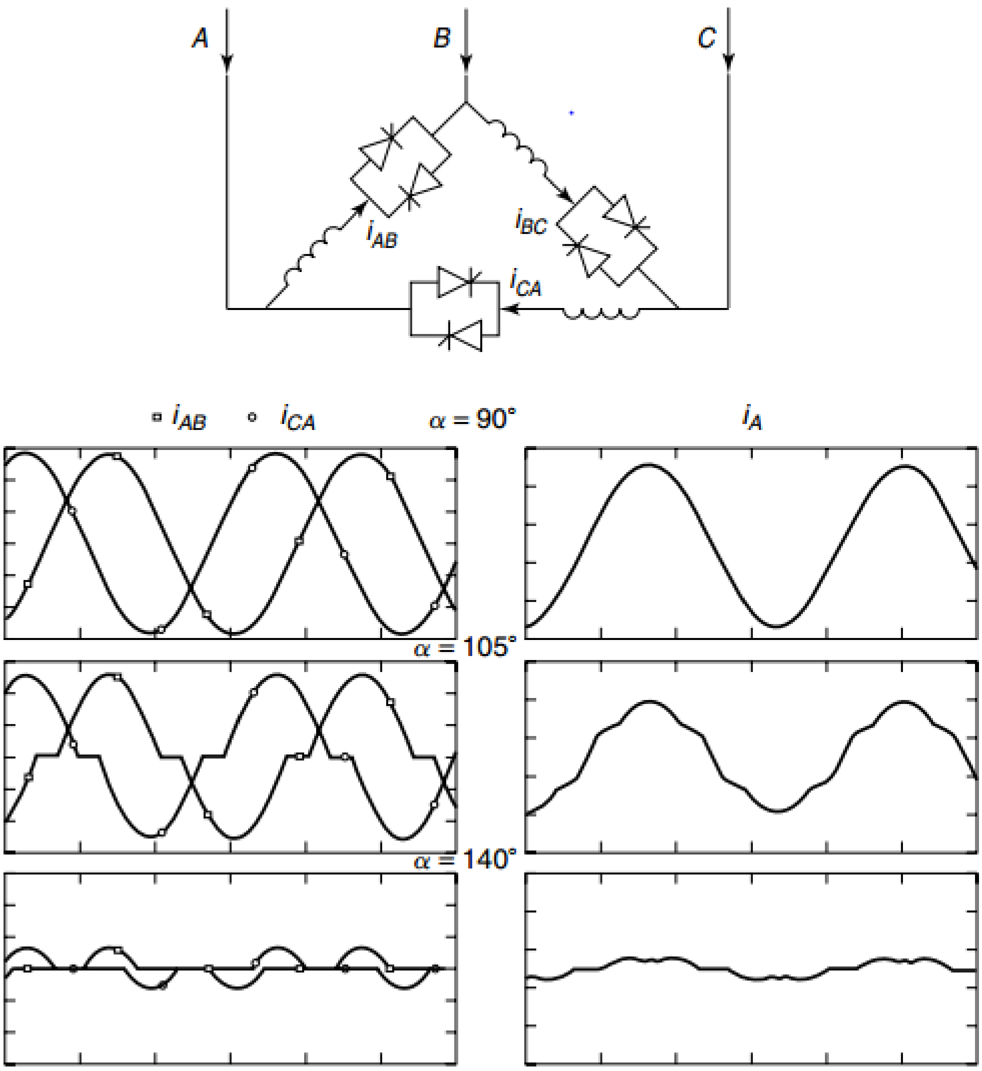


Figure 2. 4 A delta-connected TCR and its phase and line currents for different ***α*** [13]

The delta connection of the three single-phase TCRs prevents the triplen (i.e., multiples of third) harmonics from percolating into the transmission lines. The cancellation of its 3rd and multiple harmonics can be explained as follows: Let i_{ABn}, i_{BCn}, and i_{CAn} be the nth-order harmonic-phase currents in the respective delta branches, and let i_{An}, i_{Bn}, and i_{Cn} be the currents in the respective lines connected to the delta-configured TCR. Then, the 3rd harmonic currents are expressed as:

$$i_{AB3} = a_3\cos(3wt + ø_3) \quad (2.1)$$

$$i_{BC3} = a_3\cos(3wt + ø_3 - 3\frac{2\pi}{3})$$

$$= a_3\cos(3wt + ø_3 - 2\pi) \quad (2.2)$$

$$i_{CA3} = a_3\cos(3wt + \emptyset_3 - 3\frac{4\pi}{3})$$

$$= a_3 \cos\left(3wt + \emptyset_3 - \frac{4\pi}{3}\right) \quad (2.3)$$

$$\text{Thus} \quad i_{AB3} = i_{BC3} = i_{CA3} \quad (2.4)$$

All three currents are in phase and circulate in the Thyristor delta, forming a zero-sequence system. It follows that the 3rd harmonic line currents reduce to zero, as follows:

$$i_{A3} = i_{AB3} - i_{CA3} = 0 \quad (2.5)$$

$$i_{B3} = 0, i_{C3} = 0 \quad (2.6)$$

A closer analysis reveals that not only the 3rd harmonic but also all triplen harmonics get canceled out. Therefore, all harmonic components of the order 3p + 3, where p = 0,1,2,3, (3, 9, 15, 21, 27, etc.) Cannot flow in the lines during balanced operation.

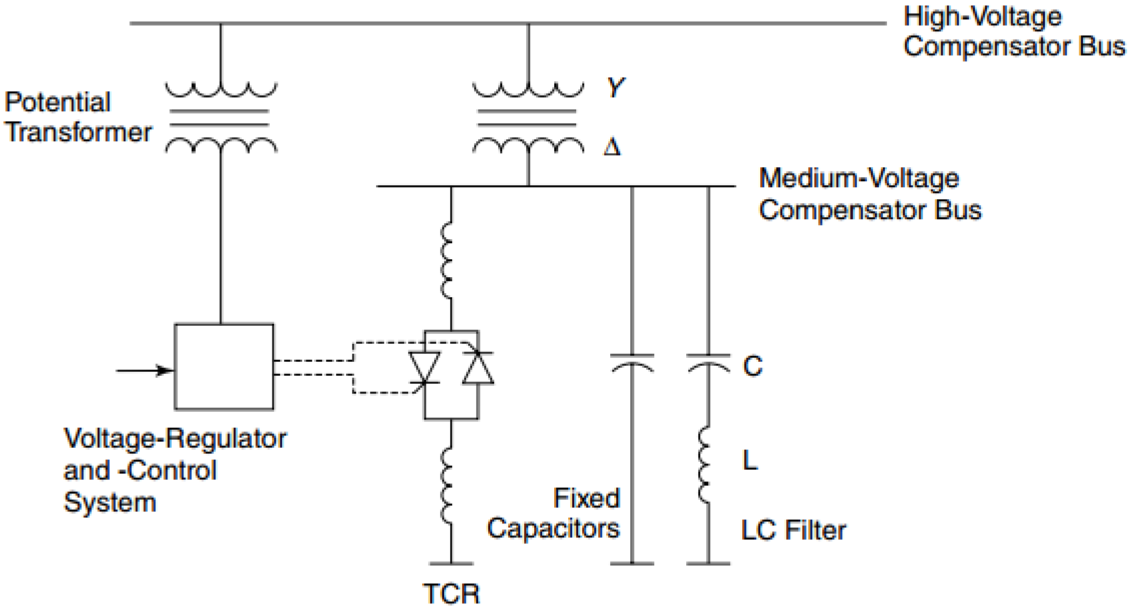


Figure 2. 5 A 1-line diagram of a TCR compensator with fixed-shunt capacitors [8]

Filters are usually provided in shunt with the TCR, which are either of series LC or LCR configuration. These filters are tuned to the dominant 5th and 7th harmonic frequencies. Sometimes, specific filters for 11th and 13th harmonics or a simple high-pass filter are also installed. The schematic diagram of a 6-pulse TCR with filters is depicted in Fig. 2.6. As it is desirable in power-system applications to have controllable capacitive reactive power, a capacitor is connected in shunt with the TCR. This capacitor may be fixed, or it may be switchable by means of mechanical or Thyristor switches.

The main advantages of the TCR are flexibility of control and ease in uprating. Different control strategies can be easily implemented, especially those involving external supplementary signals to achieve significant improvements in system performance. The voltage reference and current slope can be controlled in a simple manner. Modular in nature, a TCR SVC can have its rating extended by the addition of more TCR banks, as long as the coupling transformer rating is not exceeded. The TCR responds rapidly, typically in duration of one-and-a-half to three cycles. The actual response time is a function of measurement delays, TCR controller parameters, and system strength [8].

2.7.2. Fixed capacitor thyristor-controlled reactor (FC-TCR)

As its name indicates, the SVC of the TCR-FC type consists of a TCR, which absorbs reactive power from the ac power system to which the SVC is connected, and several FCs, which supply reactive power to the system connected to the SVC. The simplified single-wire circuit diagram of an SVC of the TCR-FC type is illustrated in Figure 2.6.

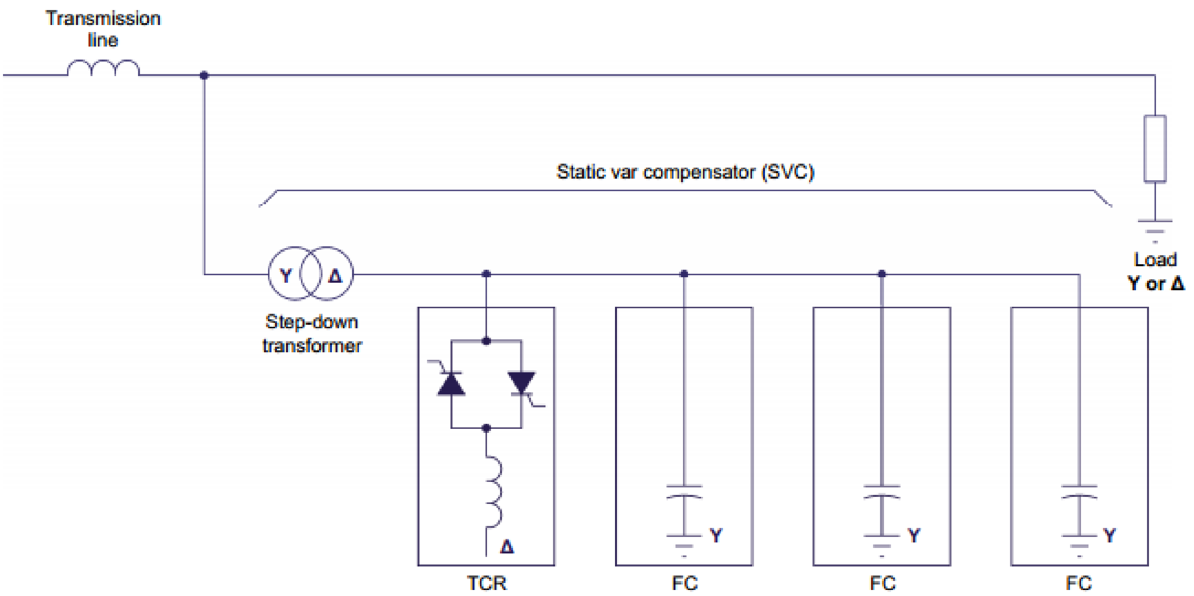


Figure 2. 6 Simplified single-wire circuit diagram of an SVC of the TCR-FC type [14]

FCs has a fixed reactance value and it supply a fixed amount of reactive power and cannot be switched in or out. The amount of reactive power absorbed by the TCR, on the other hand, can be adjusted as needed from a maximal value (TCR Firing angle= 90^0) to zero (TCR firing angle = 180^0). The main voltage, current and reactive power parameters related to one leg (phase) of an SVC of the TCR-FC type are shown on the circuit diagram in Figure 2.7. Note that to simplify the circuit diagram, only one FC is used to represent all FCs of the SVC.

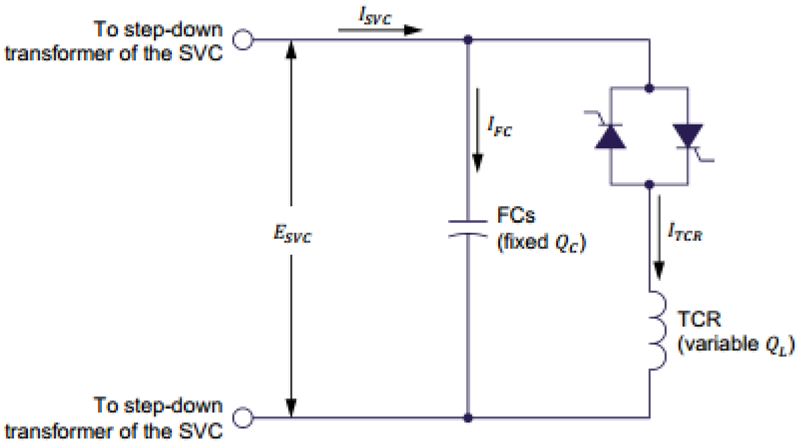


Figure 2. 7 Simplified circuit diagram of one phase of an SVC of the TCR-FC [12]

When the amount of reactive power required to compensate the voltage in the ac power system connected to an SVC of the TCR-FC type is null, the TCR firing angle is adjusted so that the reactive power absorbed by the TCR fully offsets the fixed amount of reactive power (QC) supplied by the FCs. When the SVC has to supply reactive power to compensate the voltage in the ac power system (i.e., when the system absorbs reactive power), the TCR firing angle is increased so that the amount of reactive power absorbed by the TCR decreases. The lower the reactive power which the TCR absorbs, the higher the reactive power which the SVC supplies.

When the TCR is set to the non-conducting state, the amount of reactive power supplied by the SVC is maximal. The maximal amount of reactive power which an SVC of the TCR-FC type can supply is equal to the reactive power rating (QC) of the FCs.

Conversely, when the SVC has to absorb reactive power to compensate the voltage in the ac power system (i.e., when the system supplies reactive power), the TCR must absorb enough reactive power to, firstly, fully offset the fixed amount of reactive power supplied by the FCs, and, secondly, absorb enough extra reactive power to compensate for the reactive power supplied by the ac power system connected to the SVC. The TCR provides continuously controllable reactive power only in the lagging power-factor range. To extend the dynamic controllable range to the leading power-factor domain, a fixed capacitor bank is connected in shunt with the TCR. The TCR MVA is rated larger than the fixed capacitor to compensate (cancel) the capacitive MVA and provide net inductive-reactive power should a lagging power-factor operation be desired. The reactive power exchange characteristic of an SVC of the TCR-FC type is illustrated in Figure 2.8.

The fixed-capacitor banks, usually connected in a star configuration, are split into more than one 3-phase group. Each capacitor contains a small tuning inductor that is connected in series and tunes the branch to act as a filter for a specific harmonic order. For instance, one capacitor group is tuned to the 5th harmonic and another to the 7th, whereas yet another is designed to act as a high-pass filter. At fundamental frequency, the tuning reactors slightly reduce the net MVA rating of the fixed capacitors [14].

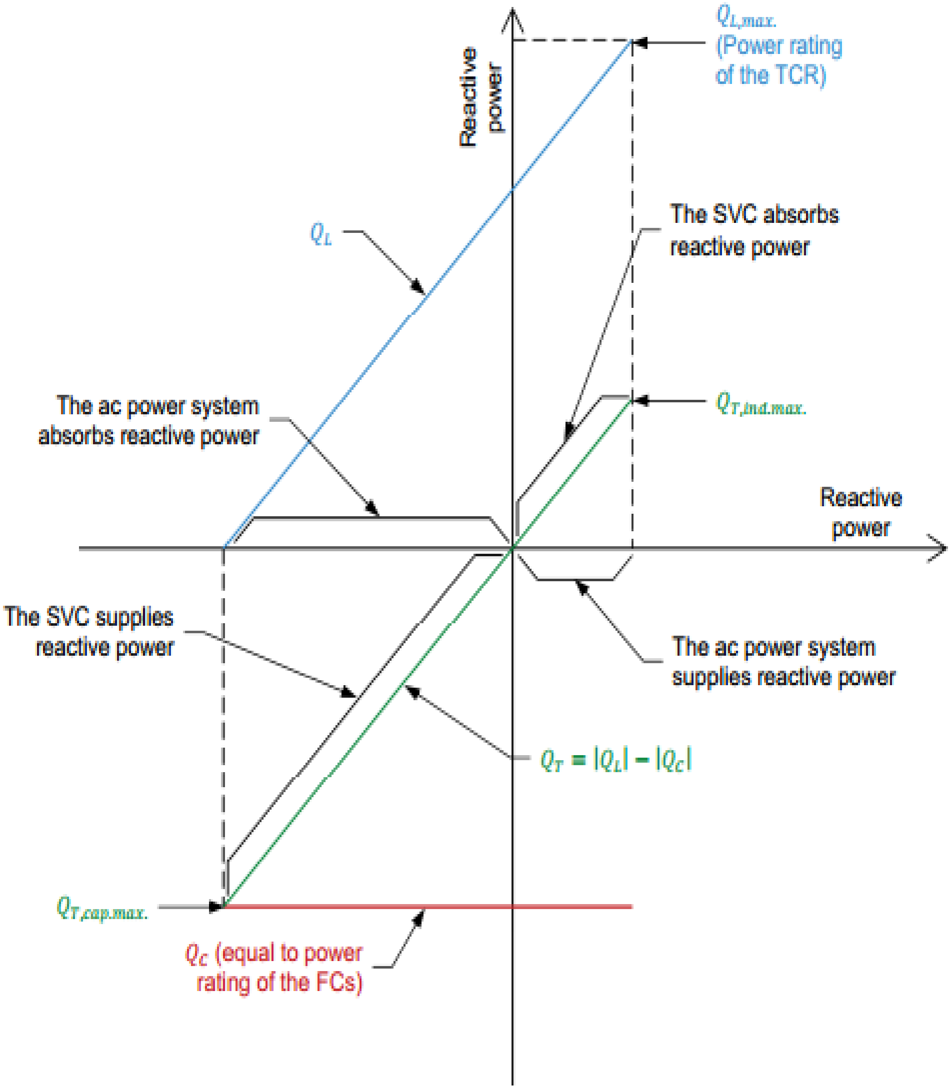


Figure 2. 8 Reactive power exchange characteristic of an SVC of the TCR-FC-type [13]

As the figure 2.8 shows, the total reactive power QT which an SVC of the TCR-FC type exchanges with the ac power system to which it is connected is equal to the variable reactive power QL absorbed by the TCR minus the fixed reactive power QC supplied by the FCs. The total reactive power QT of an SVC of the TCR-FC type thus ranges from the maximal capacitive reactive power QT, $cap.max.$, which is equal to the reactive power rating QC of the FCs, to the maximal inductive reactive power QT,., which is equal to the reactive power rating QL,max of the TCR minus the reactive power rating QC of the FCs. When the total reactive power QT in the SVC is negative, the SVC supplies reactive power. Conversely, when the total reactive power QT in the SVC is positive, the SVC absorbs reactive power. In order for an SVC of the TCR-FC type to operate properly, it is necessary for the control and monitoring components of the SVC to be implemented effectively. The two main tasks that the SVC controller must perform to meet the reactive power requirement of the ac power system connected to the SVC are summarized below:

- To determine the amount of reactive power that must be absorbed by the TCR to precisely meet the amount of reactive power needed for accurate compensation of the voltage in the ac power system connected to the SVC, taking into account the amount of reactive power supplied by the FCs.
- To control the TCR firing angle and, consequently, the rms value of the current flowing in the TCR.

The major drawback of any SVC of the TCR-FC type is that the TCR needs to have a power rating QL, max that is equal to the reactive power (QT) range of the SVC, thereby resulting in a large TCR. This is due to the fact that the TCR must absorb enough reactive power to fully offset the reactive power supplied by the FCs and still be able to absorb any additional reactive power that the ac power system connected to the SVC could supply. This generally results in significant power losses ($RI2$ losses) in the TCR because during normal operation the reactive power QL in the TCR is often comparable to, or even exceeds, the reactive power QT which the SVC exchanges with the ac power system to which it is connected (in other words, the current $ITCR$ flowing in the TCR is often comparable to, or even exceeds, the current $ISVC$ flowing between the SVC and the ac power 26 system). Furthermore, due to its large size, the TCR generates a large amount of harmonics, which means that the harmonic filters in the TCR also need to be larger to properly filter all harmonics [14].

2.7.3. Thyristor-switched capacitor (TSC)

The Thyristor switched capacitor is a shunt connected capacitor that is switched ON or OFF using Thyristor valves. Figure 2.9 shows the reactor connected in series with the capacitor is a small inductance used to limit currents. This is done to limit the effects of switching the capacitance at a non-ideal time. The switching of capacitors excites transients which may be large or small depending on the resonant frequency of the capacitors with the external system. The Thyristor firing controls are designed to minimize the switching transients. This is achieved by choosing the switching instant when the voltage across the Thyristor switch is at a minimum, ideally zero. The switching-on instant ($t1$) is chosen so that the bus voltage V is at its maximum and of the same polarity as the capacitor voltage; this ensures a transient-free switching. The switching off instant ($t2$) corresponds to a current zero.

The capacitor will then remain charged to a peak voltage, either positive or negative, ready for the next switch-on operation. The TSCs serve the purpose of supplying reactive power to the system to which the SVC is connected. TSCs also filter out to a certain extent the harmonics generated by the TCR. This is basically due to the fact that the reactance of a TSC decreases with frequency, thereby helping in attenuating harmonics. The circuit diagram of one leg (phase) of a TSC is shown in Figure 2.9.

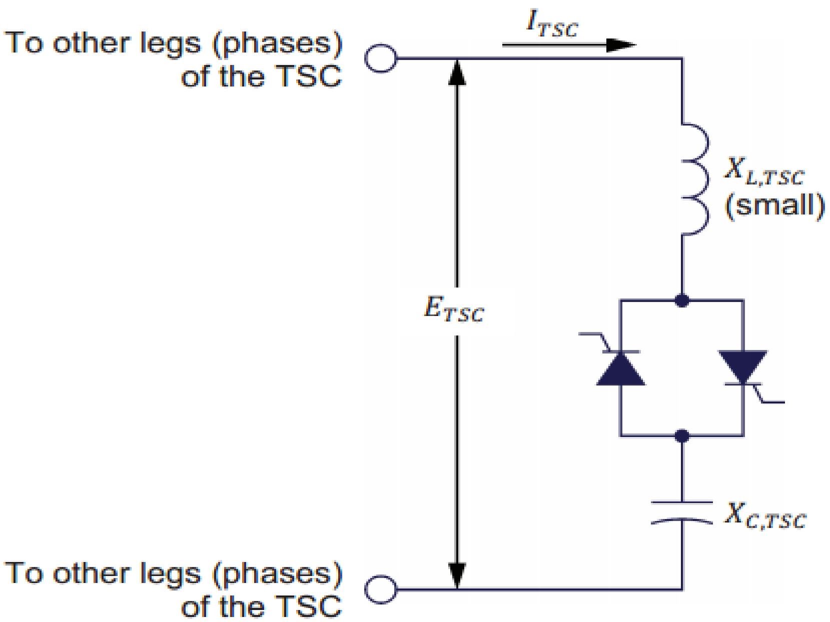
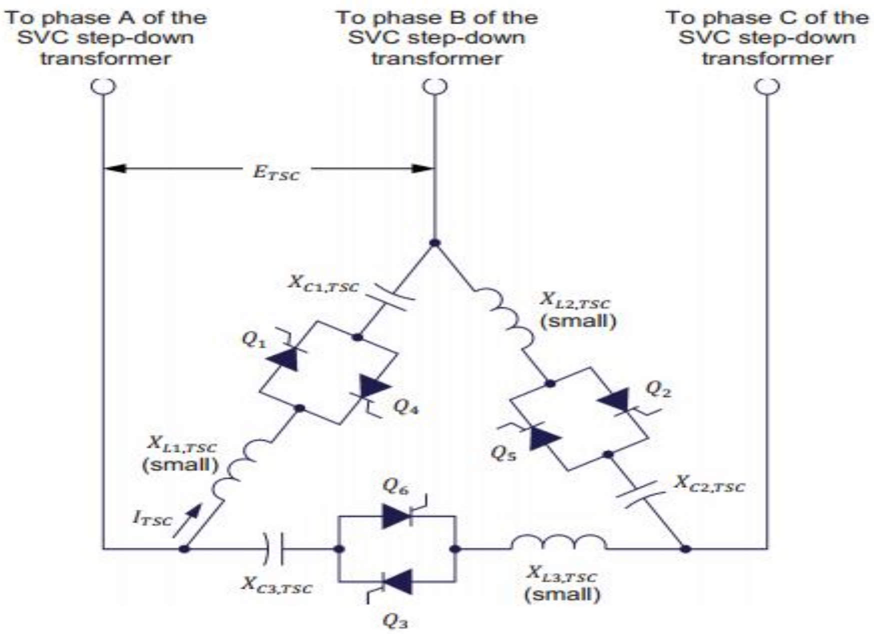


Figure 2. 9 Equivalent circuit of one phase of a TSC in an SVC [3]

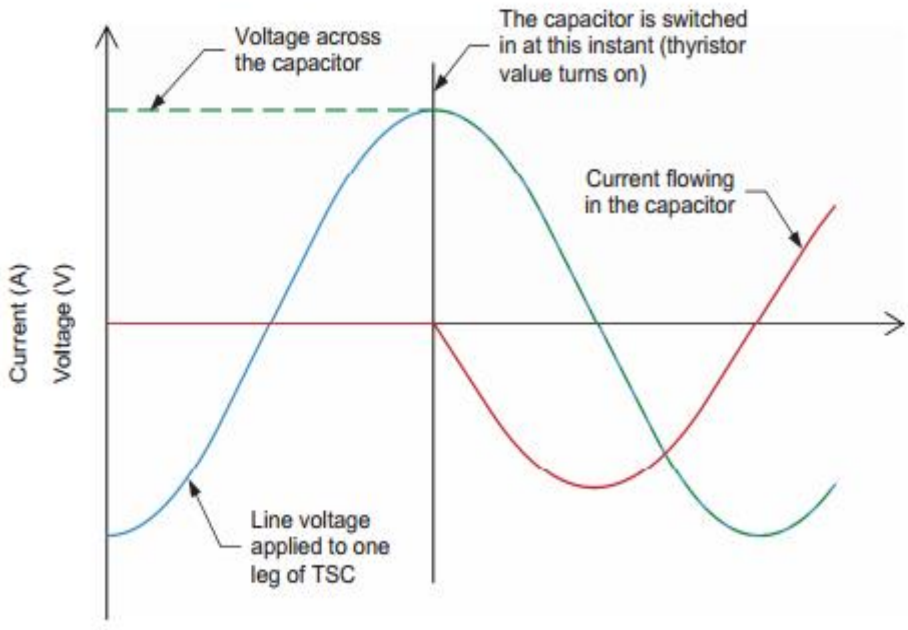
The complete diagram showing all three legs (phases) of a TSC in an SVC is illustrated in Figure 2.10. As the figure shows, TSCs are generally connected in a 6-wire, delta configuration, just as for TCRs [14].



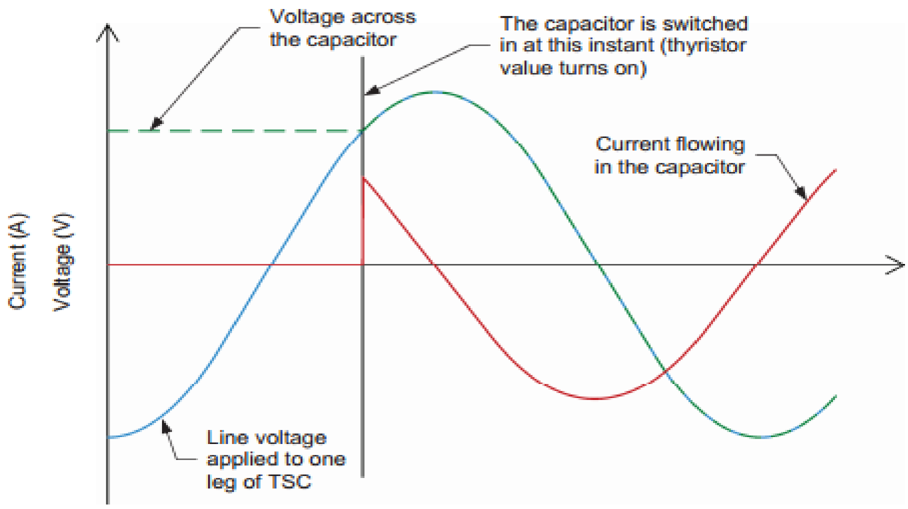
vc

Figure 2. 10 Complete diagram of the three legs (phases) of a TSC in an SVC [3]

When switching the capacitors of a TSC on, precautions must be taken in order to prevent the any excessive surge in current and ensure a transient-free switching. To achieve this, each capacitor of a TSC must be switched on at the moment when the voltage across the corresponding leg of the TSC becomes equal to the voltage across the capacitor. In other words, the capacitor must be switched in when the voltage across the Thyristor is zero. In Figure 2.11a, the capacitor is fully charged when it is switched in, while in Figure 2.11b, the capacitor is partially charged when it is switched in.



(a) The capacitor is switched in when it is fully charged



(b) The capacitor is switched in when it is partially charged

Figure 2. 11 V and I waveforms of a capacitor of TSC when it is switched on [14]

When switching off the capacitors of a TSC, the corresponding set of Thyristor are turned off by removing the firing signals from the gate of the Thyristors. Consequently, current no longer flows through the Thyristor gates and, thus, each Thyristor stops conducting as soon as the current flowing through it decreases below the holding current which is a value close to zero [14].

This means that, since the current flowing in a capacitor leads the voltage across the capacitor by 90°, current ceases to flow in the capacitor at the moment when the voltage across the capacitor is maximal. The voltage and current waveforms related to a capacitor of a TSC when it is switched out are illustrated in Figure 2.12.

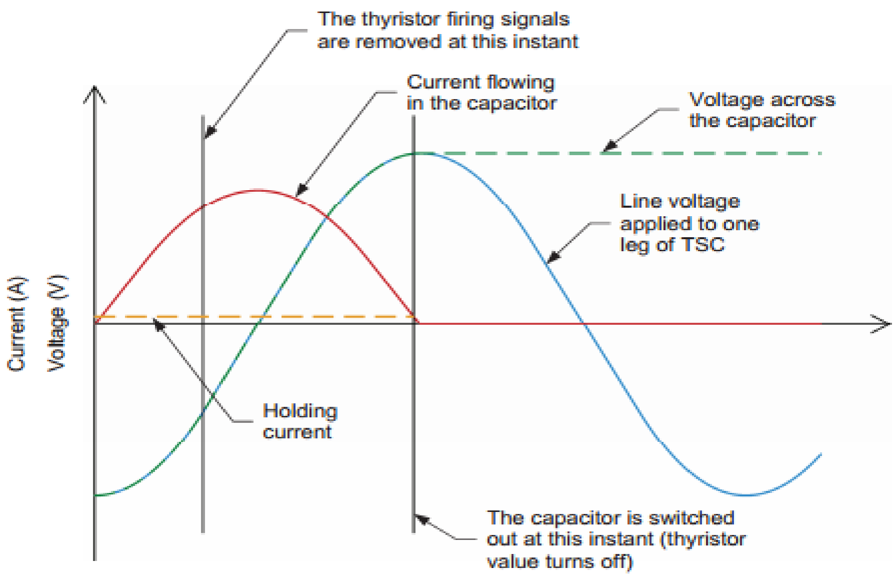


Figure 2. 12 V and I waveforms related of a capacitor of TSC when it is switched off [9]

2.7.4. Thyristor Switched Capacitor - Thyristor Controlled Reactor (TSC-TCR)

The SVC of the TCR-TSC type consists of a TCR, which absorbs reactive power from the ac power system connected to the SVC, and several TSCs, which supply reactive power to the ac power system connected to the SVC. The simplified single-wire circuit diagram of an SVC of the TCR-TSC type is illustrated in Figure 2.13. Note that, in certain cases, SVCs of the TCR-TSC type may also contain FCs, mainly for harmonic filtering purposes.

The TSCs of an SVC can only be switched in or switched out, Because of this, the amount of reactive power supplied by the TSCs can only be adjusted by steps by changing the number of TSCs that are switched in at the same time. The higher the number of TSCs that are switched in, the higher the amount of reactive power supplied by the TSCs.

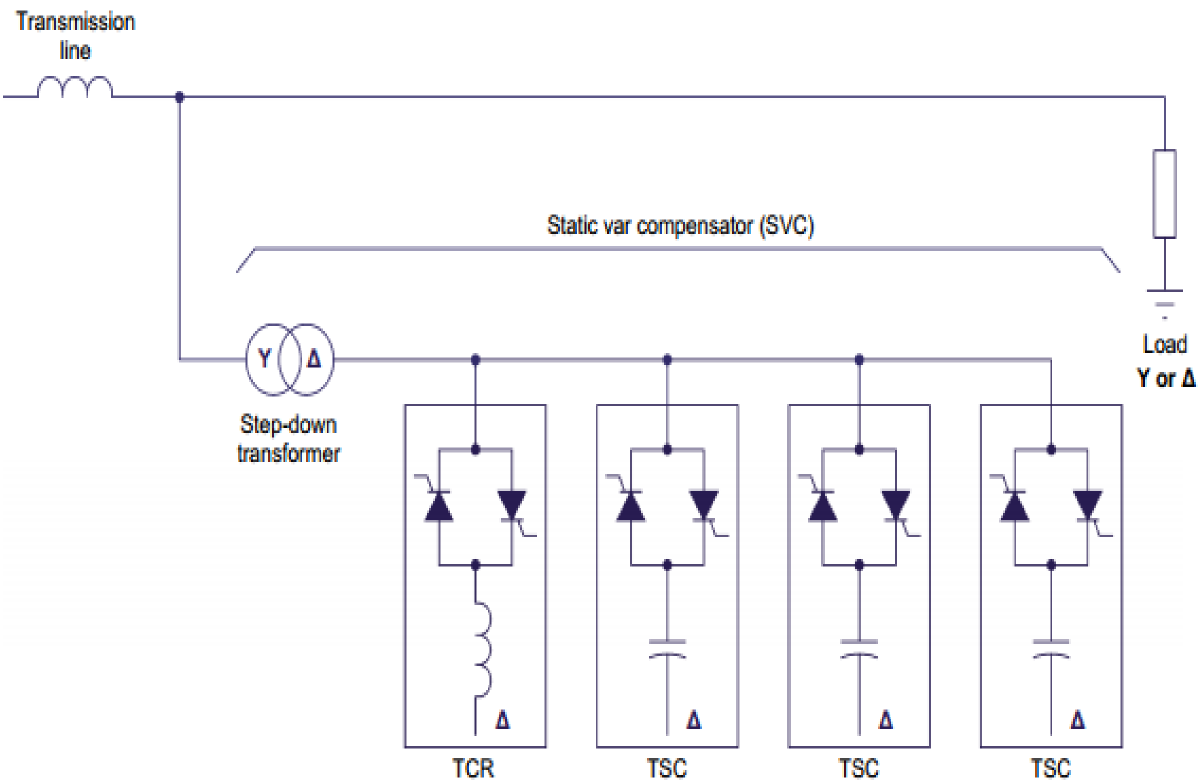


Figure 2. 13 Simplified single-wire circuit diagrams of an SVC of the TCR-TSC type [14]

The TCR, on the other hand, can be adjusted as needed from a full-conducting state (TCR firing angle = 90^0) to a non-conducting state (TCR firing angle = 180^0), thereby allowing precise and continuous adjustment of the amount of reactive power which the SVC exchanges with the ac power system to which it is connected. The main voltage, current, and reactive power parameters related to one leg (phase) of an SVC of the TCR-TSC type are shown on the circuit diagram in Figure 2.14. Note that, to simplify the circuit diagram, only one TSC is used to represent all TSCs of the SVC.

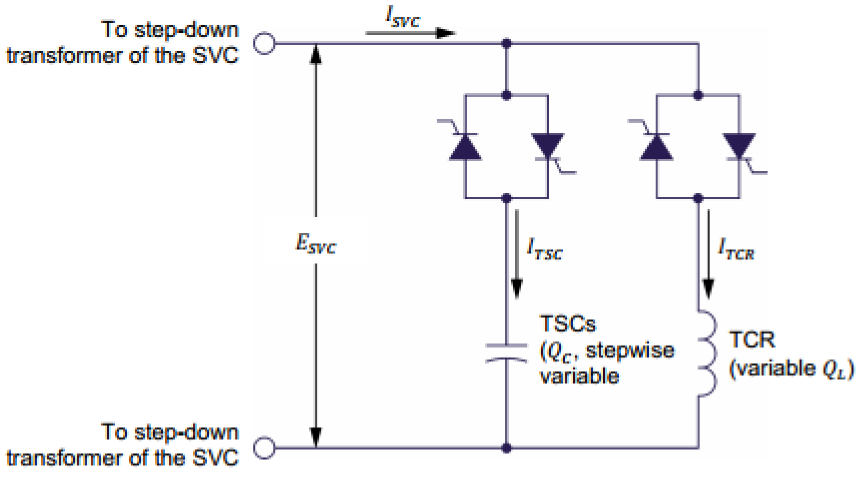


Figure 2. 14 Simplified circuit diagrams of one phase of an SVC of the TCR-TSC [12]

When the amount of reactive power required to compensate the voltage in the ac power system connected to an SVC of the TCR-TSC type is null, all TSCs are switched out and the TCR is set to the non-conducting state (TCR firing angle = 180^0). When the SVC has to supply reactive power to compensate the voltage in the ac power system, a number of TSCs are switched in so that the reactive power they supply exceeds the amount of reactive power the SVC has to supply to properly compensate the ac power system voltage. The TCR firing angle is then adjusted so that the amount of reactive power absorbed by the TCR precisely offsets the excess of reactive power supplied by the TSCs. As the amount of reactive power, the SVC has to supply to properly compensate the ac power system voltage increases or decreases, the TCR firing angle is adjusted so that the TCR absorbs just the right amount of the reactive power supplied by the TSCs.

When the amount of reactive power which the SVC has to supply to compensate the voltage in the ac power system increases and exceeds the reactive power rating of the TSCs that are currently switched in (the TCR firing angle is set to 180° in this case), another TSC must be switched in. On the other hand, when the amount of reactive power which the SVC has to supply to compensate the voltage decreases below the amount of reactive power that the SVC supplies when the TCR absorbs the maximum amount of reactive power (i.e., when the TCR firing angle is 90°), a TSC must be switched out. In both cases, the TCR firing angle is then readjusted so that the TCR absorbs just the right amount of the reactive power supplied by the TSCs to meet the reactive power requirement of the ac power system to which the SVC is connected. The maximal amount of reactive power that an SVC of the TCR-TSC type can supply is obtained when all TSCs are switched in and the TCR is set to a non-conducting state (TCR firing angle = 180^0).

Conversely, when the SVC has to absorb reactive power to properly compensate the voltage in the ac power system (i.e., when the system supplies reactive power), all TSCs in the SVC are switched out. Then, the TCR firing angle is adjusted so that the TCR absorbs all the reactive power supplied by the ac power system to which the SVC is connected. The reactive power exchange characteristic of an SVC of the TCR-TSC type is illustrated in Figure 2.15 [14].

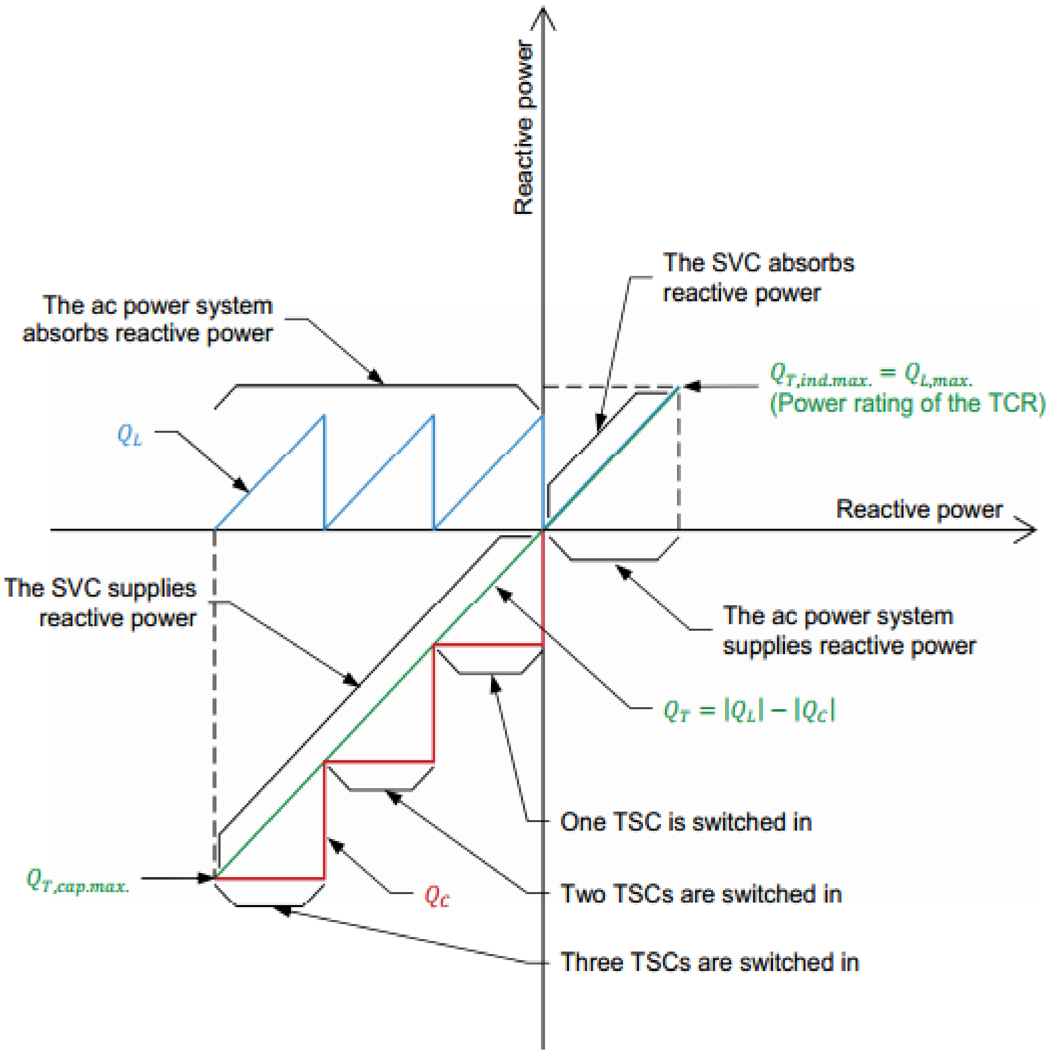


Figure 2. 15 Reactive power exchange characteristic of an SVC of the TCR-TSC-type [9]

As the figure 2.15 shows, the total reactive power QT which an SVC of the TCR-TSC type exchanges with the ac power system to which it is connected is equal to the variable reactive power QL absorbed by the TCR minus the reactive power QC (stepwise variable) supplied by the TSCs. The total reactive power QT of an SVC of the TCR-TSC type thus ranges from the maximal capacitive reactive power $QT, cap, max.$, which is equal to the total reactive power rating of the TSCs, to the maximal inductive reactive power $QT, ind, max.$, which is equal to the reactive power rating QL, max of the TCR. When the total reactive power QT in an SVC is negative, the SVC supplies reactive power. Conversely, when the total reactive power QT in an SVC is positive, the SVC absorbs reactive power.

In order for an SVC of the TCR-TSC type to operate properly, it is necessary for the control and monitoring components of the SVC to be implemented effectively. The four main tasks that the controller must perform to meet the reactive power requirement of the ac power system connected to the SVC are summarized below:

To determine the number of TSCs required and the amount of reactive power that the TCR must absorb to precisely meet the reactive power requirement of the ac power system to which the SVC is connected.

- To switch TSCs in and out so as to match the required number of TSCs.
- To control the TCR firing angle (and, consequently, the rms value of the current flowing in the TCR) so that the amount of reactive power absorbed by the TCR.
- To properly coordinate the TSC switching control and TCR firing angle control so as to ensure transient-free operation (i.e., so as to minimize voltage transients in the ac power system to which the SVC is connected).

The primary advantage of SVCs of the TCR-TSC type over SVCs of the TCR-FC type is the smaller size of the TCR. This is due to the fact that the TCR in an SVC of the TCR-TSC type only needs to have a power rating that is slightly higher than that of any of the TSCs in order to provide a certain flexibility when switching TSCs in and out. The TCR in an SVC of the TCR-FC type, on the other hand, needs to be able to fully offset the reactive power QC supplied by all TSCs, as well as being able to absorb any extra amount of reactive power which the system to which the SVC is connected could supply.

Due to its much smaller size, the TCR in SVCs of the TCR-TSC type is less costly and more efficient (i.e., it has less power losses) than the larger TCR in SVCs of the TCR-FC type. The smaller size of the TCR in SVCs of the TCR-TSC type also decreases the amount of harmonics generated by the TCR which, in turn, means that the harmonic filters in the SVC can be reduced in size.

2.8. SVC control systems

The SVC Controller System Consists of Voltage Measurement System, Voltage regulator, Distribution unit and Synchronizing Pulse generator as shown in Figure 2.16.

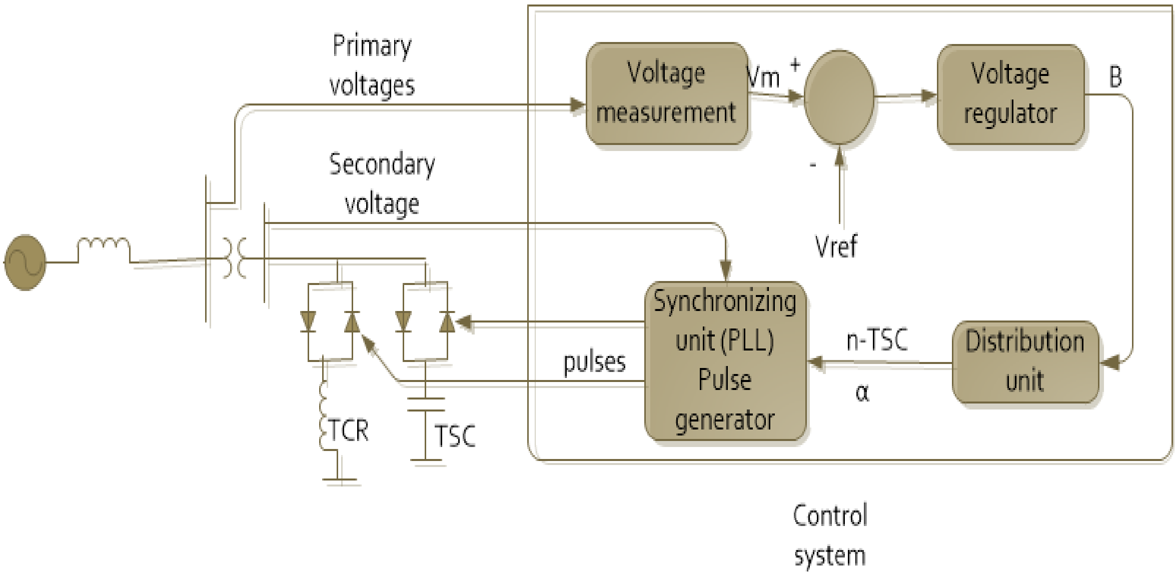


Figure 2. 16 SVC with control system [16]

- Voltage measurement system is used to measures the positive sequence of system voltage and it provide the necessary inputs to the SVC controller for performing its control operations.
- Voltage regulator model, shown in Fig. 2.17, is used to compare the measured voltage V_m and reference voltage V_{ref} thereby obtain voltage error to determine the SVC susceptance B needed to keep the system voltage constant. It uses a PI regulator to regulate voltage at the reference voltage. The SVC voltage regulator processes the measured system variables and generates an output signal that is proportional to the desired reactive-power compensation.
- Distribution unit is used to determine TSCs that must be switched in and out, and it compute the firing angle (α) of the Thyristor Control Reactors. it uses the susceptance B_{svc} computed by the voltage regulator system to compute the Thyristor Controller Reactor firing angle (α) and switching of the Thyristor Switched Capacitor (TSCs).
- Synchronizing unit pulse generator using a phase locked loop (PLL) with the secondary voltage synchronized and generate appropriate pulse to the Thyristor. The purpose of the synchronizing system is to generate reference pulses in synchronism with the fundamental component of system voltage [16].

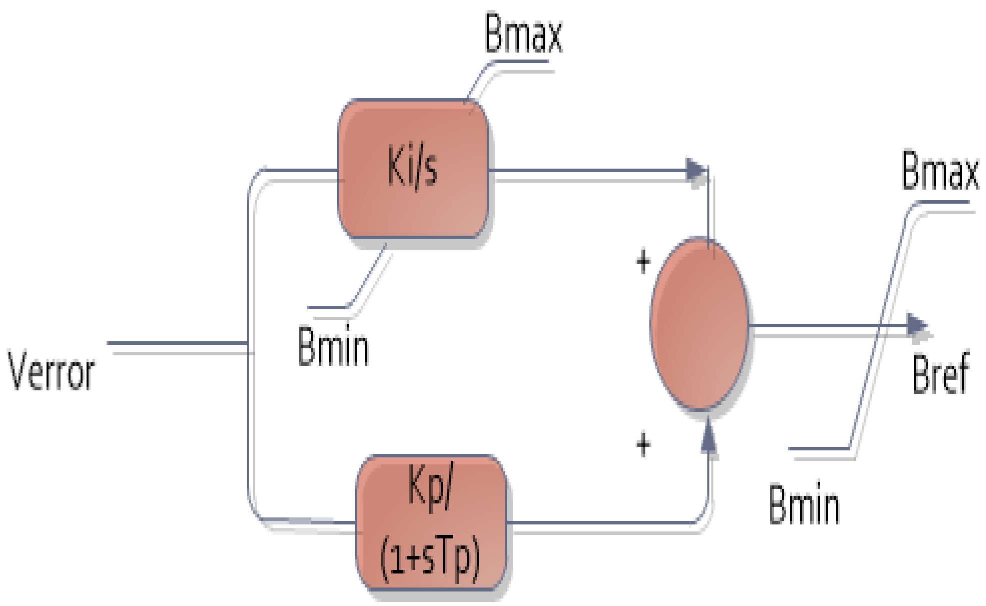


Figure 2. 17 Voltage regulator Model of SVC [16]

2.9. SVC voltage control characteristics

Static var compensators (SVCs) are used primarily in power systems for voltage control as either an end in itself or a means of achieving other objectives, such as system stabilization. The performance of SVC voltage control is critically dependent on several factors, including the influence of network resonances, transformer saturation, geomagnetic effects, and voltage distortion. When SVCs are applied in series-compensated networks, a different kind of resonance between series capacitors and shunt inductors becomes decisive in the selection of control parameters and filters used in measurement circuits [13].

V-I characteristics of the SVC

The SVC can be operated in two different modes: In voltage regulation mode and in Var control mode (the SVC susceptance is kept constant). When the SVC is operated in voltage regulation mode, the SVC susceptance B stays within the maximum and minimum susceptance values imposed by the total reactive power of capacitor banks $B_{c\,max}$ and reactor banks $B_{l\,min}$ the voltage is regulated at the reference voltage V_{ref} as shown in figure 2.18. The V-I characteristic of the SVC indicates that regulation with a given slope around the nominal voltage can be achieved in the normal operating range defined by the maximum capacitive and inductive currents of the SVC. In the active control range, current/susceptance and reactive power is varied to regulate voltage according to a slope (droop) characteristic. The slope (X_S) value depends on the desired sharing of reactive power production between various sources, and other needs of the system.

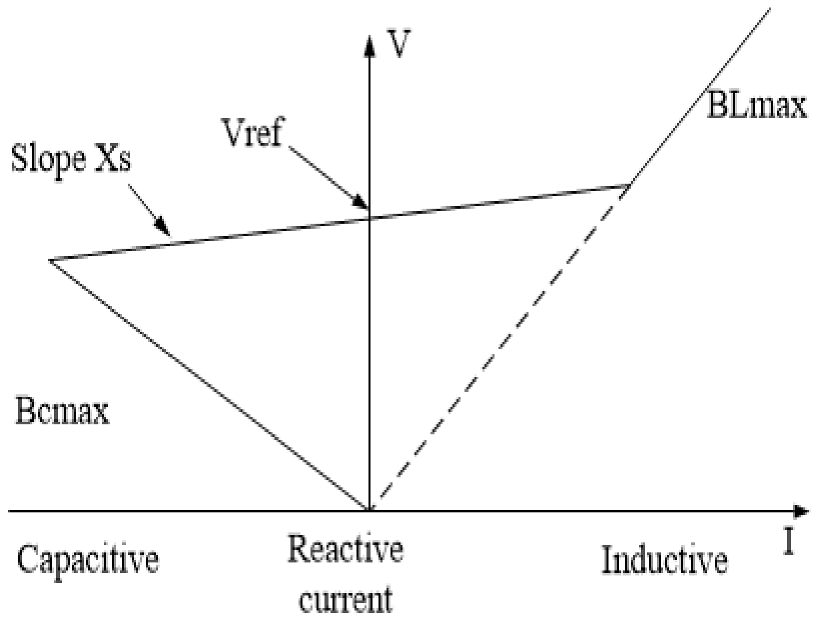


Figure 2. 18 the V-I Characteristic Curve of SVC [13]

In Voltage regulation mode, The Voltage control action of the SVC in the linear voltage regulation range ($-B_{C\,max} < B < B_{L\,max}$) is described:

$$V_{SVC} = V_{ref} + X_S I_{SVC} \quad (2.7)$$

where V_{SVC}= SVC positive sequence Voltage

V_{ref}= Reference voltage at the terminals of the SVC during the floating condition.

When the SVC is neither absorbing nor generating any reactive power.

X_S= Slope or Current Droop is defined as the ratio of voltage-magnitude change to current-magnitude change over the linear-controlled range of the compensator.

I_{SVC}= SVC reactive current (I>0 indicated an inductive current)

In the Var control mode, the SVC is operating as a fixed susceptance device. It absorbs or injects a fixed amount of reactive power into the system. The following equations govern the var control mode:

$V = \frac{I}{B_{L\,max}}$ when SVC is full inductive (B = $B_{L\,max}$)

$B_{L\,max}$= Maximum inductive susceptance

$V = -\frac{I}{B_{C\,max}}$ when SVC is fully capacitive ($B = B_{C\,max}$)

$B_{C\,max}$ = Maximum capacitive susceptance

V: Positive sequence voltage (pu)

I: Reactive current

X_S : Slope or droop reactance

V-I characteristic represents steady-state and dynamic characteristics of Static Var Compensators describe the variation of SVC bus voltage with SVC current or reactive power. The two alternative representations of these characteristics are shown in Fig. 2.18 [13].

Voltage Control by the SVC

The voltage-control action of the SVC can be explained through a simplified block representation of the SVC and power system, as shown in Fig.2.19. The power system is modeled as an equivalent voltage source, VS, behind an equivalent system impedance, XS, as viewed from the SVC terminals. The system impedance XS indeed corresponds to the short-circuit MVA at the SVC bus and is obtained as:

$$X_s = \frac{V_b^2}{S_c} * MVA_b \qquad in\ pu \tag{2.8}$$

Where S_c= the 3-phase short circuit MVA at the SVC bus

V_b= the base line-to-line voltage

MVA_b= the base MVA of the system

If the SVC draws a reactive current I_{svc}, then in the absence of the SVC voltage regulator, the SVC bus voltage is given by

$$V_s = V_{svc} + I_{svc}X_s \tag{2.9}$$

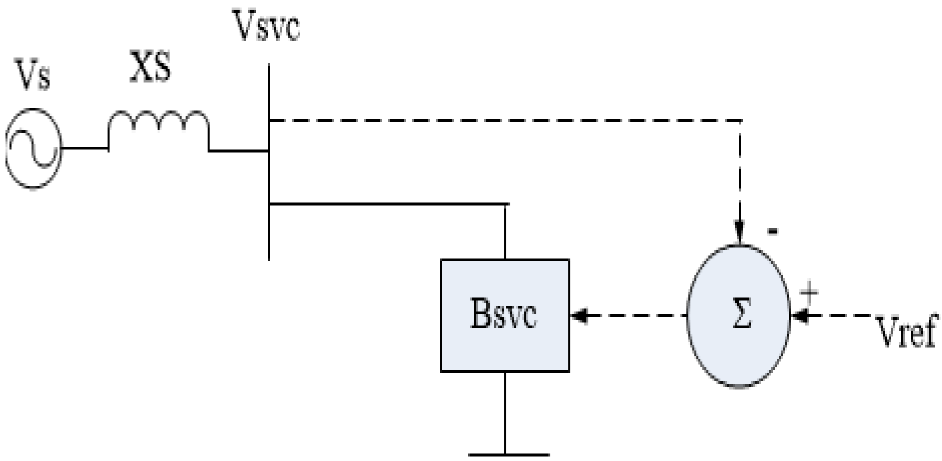


Figure 2. 19 block diagram of the power system and SVC control system [13]

The SVC current thus results in a voltage drop of $I_{svc}X_s$ in phase with the system voltage V_s. The SVC bus voltage decreases with the inductive SVC current and increases with the capacitive current. An implication of Eq. (2.8) is that the SVC is more effective in controlling voltage in weak ac systems (high X_s) and less effective in strong ac systems (low X_s). The dynamic characteristic of the SVC depicted in Fig. 2.19 describes the reactive-power compensation provided by the SVC in response to a variation in SVC terminal voltage. The voltage-control action in the linear range is described as [13]:

$$V_{svc} = V_{ref} + X_s I_{svc} \quad (2.10)$$

Where I_{svc} is positive if inductive, negative if capacitive.

2.10. Modelling of SVC

In order to improve voltage profile and the impact of SVC on power systems, appropriate SVC model is very important. In this section, SVC and its mathematical model will be introduced. SVC is built up with reactors and capacitors, controlled by Thyristor valves which are in parallel with a fixed capacitor bank [17]. It is connected in shunt with the transmission line through a shunt transformer and thus, represented in Figure 2.19.

Figure 2.20 shows the equivalent circuit at which SVC is modeled.

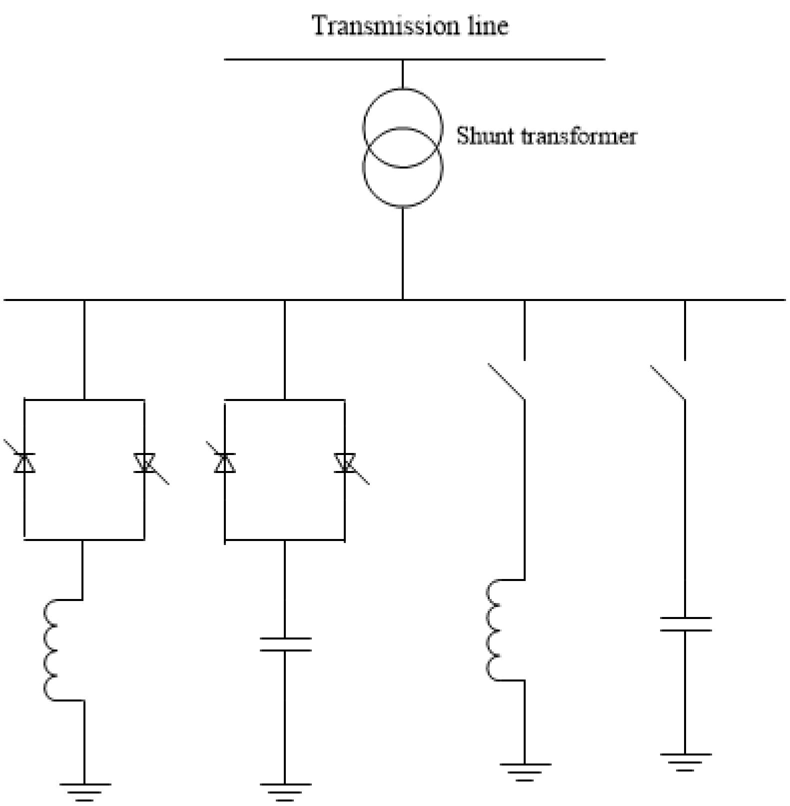


Figure 2. 20 Functional diagram of SVC **[12]**

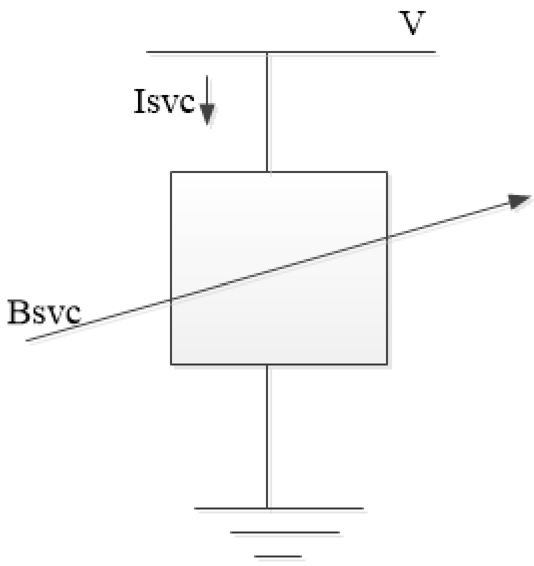


Figure 2. 21 Equivalent circuit of SVC [17]

The model considers SVC as shunt-connected variable susceptance, B_{SVC} which is adapted automatically to achieve the voltage control. The equivalent susceptance, Beq is determined by the firing angle α of the Thyristors that is defined as the delay angle measured from the peak of the capacitor voltage to the firing instant. The fundamental frequency equivalent neglecting harmonics of the current results in:

If the real power consumed by the SVC is assumed to be zero, then

$$Psvc = 0 \qquad (2.11)$$

$$Qsvc = -V^2 Bsvc \qquad (2.12)$$

V=the bus voltage magnitude

As the reactive power demand at the bus varies, the susceptance is varied subject to the limits. However, the reactive power is a function of the square of the bus voltage. Hence the reactive power generated decreases as the voltage decreases. The SVC can both absorb as well as supply reactive power at the bus it is connected to by control of the firing angle of the Thyristor elements. By controlling the firing angle α of the Thyristors (i.e., the angle with respect to the zero crossing of the phase voltage), the device is able to control the bus voltage magnitude. Changes in α results in changes on the current and hence, the amount of reactive power consumed by the inductor. When α = 90°, the inductor is fully activated but is deactivated when α = 180°. Actually, the basic control strategy is typically to keep the transmission bus voltage within certain narrow limits defined by a controller droop and the firing angle α limits (90° < α > 180°) [17].

2.11. Application of static Var compensator

The major application of SVC is for rapid voltage regulation and control of dynamic (temporary) over voltages caused by load throw off, faults or other transient disturbances. The dynamic reactive control at the load bus increases power transfer and can solve the problem of voltage instability (collapse) caused by contingency conditions. It is to be noted that steady state voltage regulation can be achieved by mechanically switched capacitors and reactors (MSC and MSR). However, fast voltage regulation is required to prevent instability under transient conditions. Thus, generally, a SVC is operated with minimum reactive power output under normal conditions. This is achieved by the Susceptance Regulator described earlier which ensures that full dynamic range is available for control under contingency conditions. Static Var compensators (SVCs) constitute a mature technology that is finding widespread usage in modern power systems for load compensation as well as transmission-line applications. [8].

2.12. Literatures

Yared tafesse [9], proposed studies on voltage control of distribution substations using static var compensators. His studies voltage control of Kality II 15 kV distribution substation using Static Var Compensators (SVCs) is investigated. His SVCs modeling and simulation studies have been carried out using DIgSILENT software. His results indicated that the maximum voltage drop of 0.06pu (6%) occurs without use of SVC whereas the voltage profile is improved from 0.94pu to 0.97pu with the implementation of the proposed SVC. To identify the weak buses he has not used any technique.

B.RAJEEV and N.MADHU [18], used Fast voltage stability index to identify the critical lines. FVSI at various lines are calculated to identify the critical lines. Static var compensator devices are introduced at the buses connecting the critical lines and its effectiveness is evaluated for voltage enhancement. In this paper low Effectiveness of fast voltage stability index is they have not considered.

M. Biswas et al. [20], this paper presented the potential applications of FACTS controllers, such as the static VAR compensator. In this paper he is discussed the static VAR compensators are being increasingly applied in electric transmission systems economically to improve the post-disturbance recovery voltages that can cause to system instability. A SVC performs such system improvements and advantages by controlling shunt reactive power sources, both capacitive and inductive, with high-tech power electronic switching devices. In this paper the detailed how such size of SVC is selected are not well addressed.

J. Eminzang et al. [21], this paper presents Using static var compensator to enhance Voltage Stability of the PS. Comparison had therefore been made between the use of SVC and Fixed Compensator. Line and generator contingencies as well as small signal disturbances analysis had been carried out. Voltage stability is enhanced with the installation of SVC as well as reduction in voltage oscillation during transient. They have not used any technique to identify the critical lines.

Shraddha Udgir [22], studied Line Outages Contingency. The first case considered for placement of SVC is the line outage which provides highest value of VPI and hence is the most severe contingency. The impact of SVC at selected optimal placement is evaluated and compared for varying load condition of the power system. In this studies the accuracy, simplest and easy technique for placement of SVC is not considered.

G. Kour et al. [23], evaluated the potential applications of SVC as one of the FACTS controllers, using power electronic switching devices in the fields of power transmission systems with increasing the voltage and power flow in distribution substations. Load flow analysis of 33/11 kV distribution substation is performed to calculate the various values of voltage and power flow at each bus. Low rated SVC is installed at load ends. The objective of the study is improvement in voltage at various buses and the enhancement in power flows with reduction in branch losses. In his studies the effect of connected SVC at load end is increasing loading of buses and transformers not considered.

C. L. Su [24]**,** suggested a reasonable analysis of voltage control plans in distribution networks with DGs. He discussed numerous voltage control plans that unified existing voltage control devices and reactive power compensators with various degrees of integration. His results indicated that the synchronized control approach integrating distribution and generation plants was the most in influence among the planned control strategies and can offer an effective way to achieve network voltage against DG penetration. DG requires huge space for construction comparing to SVC.

R. Sirjani et al. [25**],** published a paper on optimal location and sizing of Static Var Compensators in power systems using Improved Harmony Search Algorithm. This paper presents the application of the improved harmony search algorithm for determining the weak bus to enhance the voltage profile and reduce power system losses. A multi-criterion objective function comprising of both operational objectives and investment costs is considered. The simplest and easy technique for identified weak bus is not considered.

M. Vinod and K. Shende1 [26], discussed on optimal placement and Sizing of Static Var Compensator (SVC) by PSO Technique for Power Loss Minimization. The facts device performance is depending upon its location and parameter setting. In this paper the optimal location and optimal sizing of SVC is studied on the basis of PSO technique to minimize network losses using PSO have been presented. They have not investigated SVC for voltage profile improvement.

Mark Ndubuka Nwohu [27], presented a Voltage Stability enhancement using Static Var Compensator in Power Systems. He investigates the effects of Static Var Compensator on voltage stability of a power system. The functional structure for SVC built with a Thyristor Controlled Reactor (TCR) and its model are described. The model is based on representing the controller as variable impedance that changes with the firing angle of the TCR. (PSCAD/EMTDC) is used to carry out simulations of the system under study and detailed results are shown to access the performance of SVC on the voltage stability of the system. In this he implemented for absorbing reactive power but he has not studied for shortage of reactive power it required a reactive power supplier.

CHAPTER THREE

PROPOSED RESEARCH METHODOLOGY AND APPROACHES

3.1. Introduction

This chapter describes how the research was conducted and which type of techniques and materials are directly or indirectly incorporating for this research, such as brief discussion of the study area, where the data are obtained, data collection method. The study area of this research is in Wolaita Sodo town at the Wolaita Sodo distribution substation system. Wolaita Sodo town is the capital city and administrative center of Wolaita zone of the South Nation Nationalities and Peoples (SNNP's) region. It is found 329 km away from Addis Ababa the capital city of Ethiopia. The town under study is located 6051′36″N latitude and 37045′51″ E longitude with an average altitude of 2,028 meters above sea level.

3.2. Data Collection and Analysis

Reactive power compensation and bus voltage analysis needs line data, bus data, transformer rating and loads connected. These data are analyzed to identify the current reactive power and bus voltage status of the distribution substation and to distinguish the main problems.

Figure 3. 1 Wolaita Sodo distribution substation 132/15 kV transformer

3.2.1. Case study and basic data

In this sub topic only the collected data from Wolaita Sodo distribution substation is considered. These data are analyzed to identify the current voltage status and the main problems of the distribution substation system.

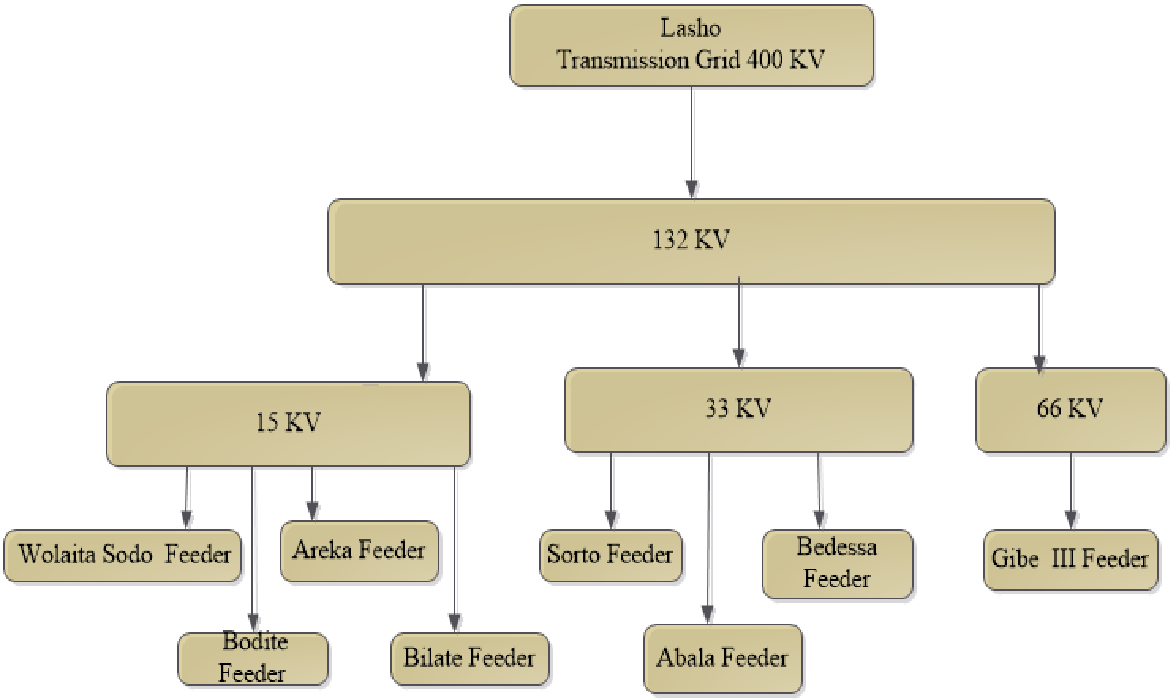


Figure 3. 2 Voltage Compositions of Transmission and Distribution Systems

Wolaita Sodo distribution substation has one incoming feeder and 8 outgoing feeders. The incoming feeder is 132 kv supplied from main grid that is interconnected system (ICS) from Lasho transmission grid 400kv. The outgoing feeders are one 66kv, three 33kV and four 15kV. The 8 outgoing feeders in the substation namely, 66kv Gibe III feeder, 15kv Wolaita Sodo feeder, 15kv Bodite feeder, 15 kv Areka feeder, 15 kv Bilate feeder, 33kv Abala feeder, 33kv Bedessa feeder, 33KV Sorto feeder. The step-down transformer 132/15kv is rated 20 MVA.

The grid is connected to the bus bar through the 132/66 kV, 132/33 kV and 132/15 kV transformers stations. The 132/66 kV transformer feeds a power to Gibe III. The 132/33KV transformer feeds a power to Abala, Bedessa, and Serto feeders and 132/15 KV transformer feeds a power to Wolaita Sodo, Areka, Bilate, Bodite feeders. And the 66kv, 33kv, 15 KV voltage value is stepped down to 400V in three phases or 0.4 kV systems are considered a load connected point.

The 66kv, 33kv, 15 kV network is operated as radials and the total capacity of 132/66 kv, 132/33 kv, 132/15 kV transformers are 16 MVA, 25MVA, 20 MVA respectively. The total load of Wolaita Sodo distribution substation is 17.9 MW and 14.74 MVAR. The total load of the four 15 kV feeders is 13.9MW and 10.36 MVAR.

The existing peak load of the distribution substation is described in table 3.1. It consists peak and minimum load of three months each feeder.

Table 3.1 Peak and minimum load of three months of each feeder

Feeder Name	Peak load						Minimum load					
	P (MW)	Current(A)			Date	Time	P (MW)	Current(A)			Date	Time
		R	S	T				R	S	T		
Wolaita Sodo	8.4	336	336	336	18/06/18	19:00	2.4	97	97	97	01/07/18	24:00
Bodite	3.5	140	140	140	07/06/18	20:00	0.7	27	27	27	01/07/18	24:00
Areka	1.5	60	60	60	19/07/18	10:00	0.3	15	15	15	02/05/18	24:00
Blate	0.5	23	23	23	08/07/18	21:00	0.03	2	2	2	01/07/18	24:00
Serto	1.5	63	63	63	14/07/18	23:00	0.4	8	8	8	01/07/18	09:00
Abala	1.9	75	75	75	16/06/18	19:00	0.4	18	18	18	01/07/18	09:00
Bedessa	1.3	53	53	53	28/05/18	19:00	0.2	5	5	5	24/06/18	21:00
Gibe III	1.2	47	47	47	10/05/18	16:00	0.09	3	3	3	27/05/18	08:00

The recorded data of the minimum, average and peak load for real power and current of each feeder is shown in figures 3.3 and 3.4. Additionally, the comparison the average load, peak load and minimum load for real power P (MW) and current I(A) of each feeder and the system is shown in following figure 3.3 and 3.4 respectively.

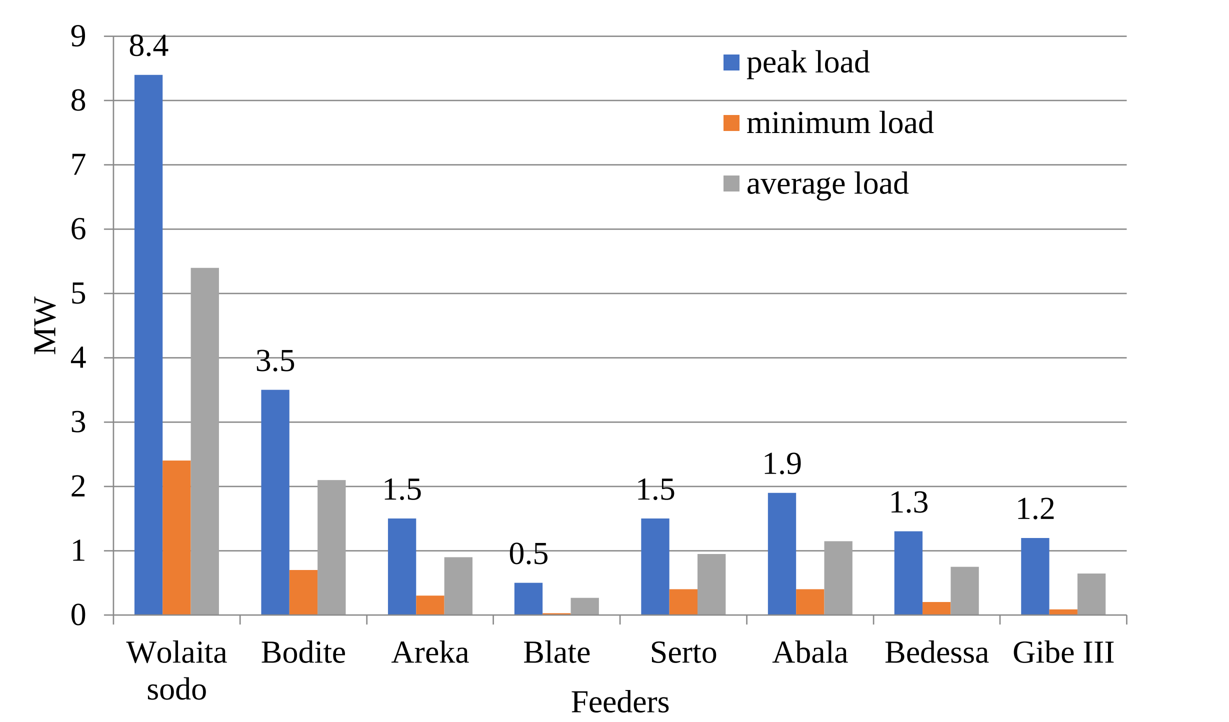


Figure 3. 3 The Minimum, Average and Peak Load Data P (MW) of each feeder

Figure 3.3 shows Wolaita Sodo feeder has highest peak load 8.4 MW comparing to other feeders and Blate feeder has lowest peak load 0.5 MW. Due to Wolaita Sodo feeder has highest peak load it more affect to the distribution substation system buses, lines, transformers status.

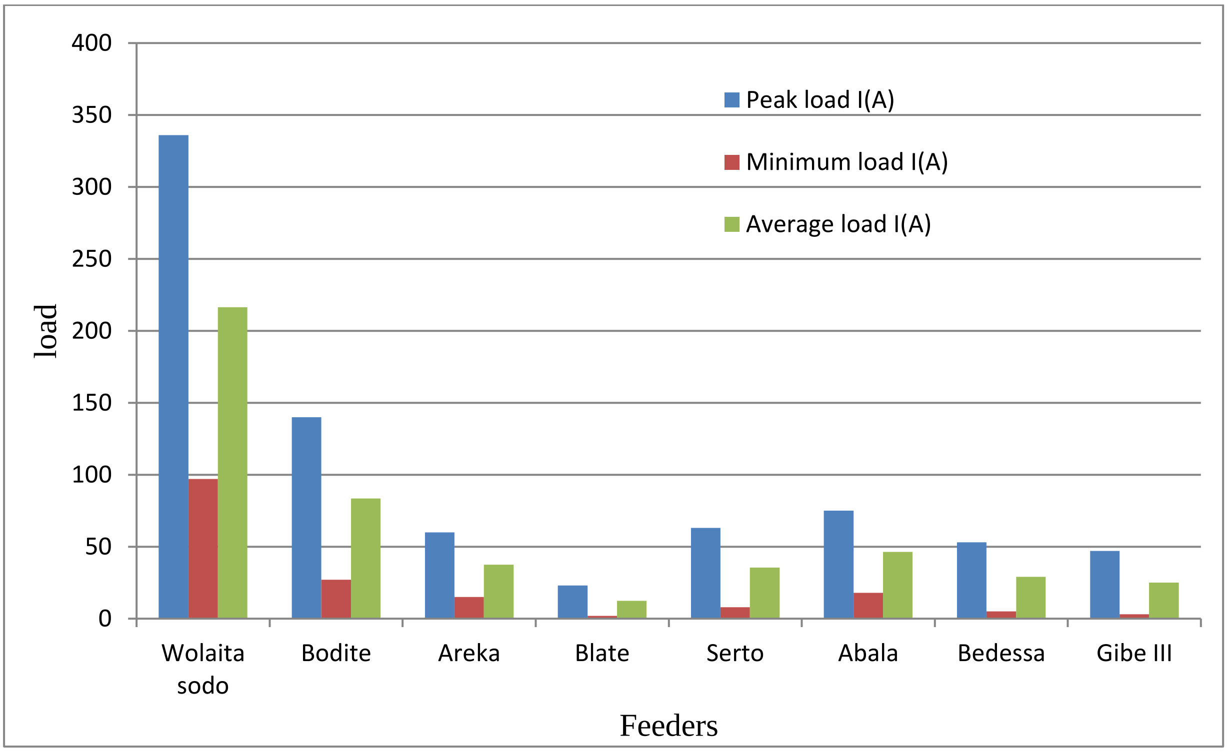


Figure 3. 4 The Minimum, Average and Peak Load Data I (A) of each feeder

Table 3.2 Overview of the case study distribution substation Transformers

Transformer name	Ratings of the transformers Wolaita Sodo distribution substation (MVA)	Transformer Voltage level (kV)	Type of Conductor	Conductor Size
Trafo I	20	132/15	CU	120 mm^2
Trafo II	25	132/33	CU	120 mm^2
Trafo III	16	132/66	CU	120 mm^2

Wolaita Sodo distribution substation has three transformers trafo I, trafo II, trafo III, the rating of the transformers are 20MVA, 25MVA, and 16MVA respectively. The type of conductor that used in the substation is copper. The transformers are stepped down transformers.

3.3. General software

ETAP (Electrical Transient Analyzer Program) software is used for modeling and simulation of the distribution substation.

3.3.1. ETAP (Electrical Transient Analyzer Program)

ETAP is widely used commercial software that is used for design, simulation, and operation, control, of transmission, distribution and industrial power systems.

3.4. Voltage stability index

There are varieties of tools for assessing whether a system is voltage stable or not and how close the system is to instability. These tools are called voltage stability indices. These indices help the system planner and operators to know the condition of voltage stability in a power system. They indicate how close the system is to voltage collapse or instable. The indices should be simple, easy to implement and computationally inexpensive. The indices expose the critical bus of a power system and the stability condition of each line connected between two buses in an interconnected network. In general, the analysis of the voltage stability problem of a given power system network should [29].

- ❖ Determine the system’s proximity to collapse.
- ❖ Establish when the voltage instability could occur.
- ❖ Identify the weak buses in the areas involved.

3.4.1. Line Stability Index ($\mathbf{L_{mn}}$)

Line stability index (L_{mn}) is derived based on power transmission line concept in a single line. Line stability index to evaluate the stability of the line between two buses in an inter-connected system reduced to a single-line network as shown in Figure 3.5 [30].

Consider the one-line diagram of a two-bus power system model shown in figure 3.5. All parameters and variables are in per unit.

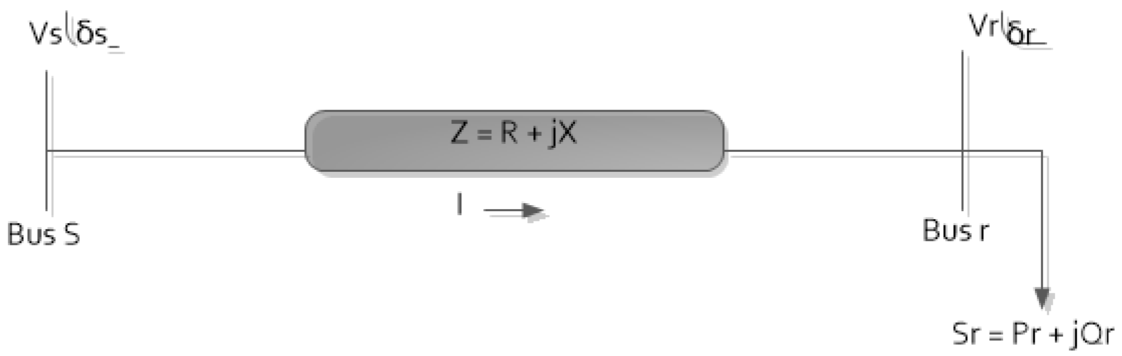


Figure 3. 5 One-line diagram of a two-bus power system model [30]

In Figure 3.5, bus‘s’ is the sending-end bus and is chosen to be the reference bus while bus ‘r’ is the receiving-end bus. The variables and parameters are defined as follows:

- Sr is the apparent power at the receiving bus ‘r’.
- Pr is the real power at the receiving bus ‘r’
- Vs, Vr are respectively the sending-end voltage and the receiving-end voltage.
- Qr is the reactive power at the receiving bus ‘r’.
- δs, δr are respectively the voltage angles of the sending-end and the receiving end buses.
- δ is the difference between δs and δr

$$\Theta = tan^{-1}\frac{X}{R} \quad (3.1)$$

$$\bar{Z} = R + jX \quad (3.2)$$

Θ, is the transmission line angle

Z, is transmission line impedance

where

- ✓ R is the line resistance
- ✓ X is the line reactance

Using the concept of power flow in the line and analyzing the one-model representation, the power flow at the receiving end of the power system network shown in Figure 3.5 is expressed as

$$S_r = P_r + jQ_r \quad (3.3)$$

The complex power S, real power, P and reactive power, Q is as shown in the power triangle in Figure 3.6.

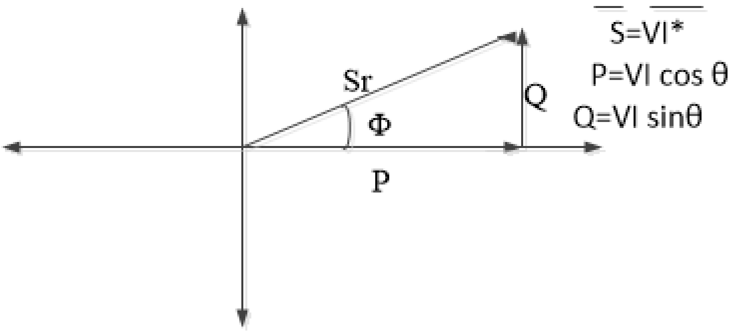


Figure 3. 6 the power triangle

$$S_r = V_r I_r^* \quad (3.4)$$

Where

$$\bar{I}_r = \frac{\bar{V}}{\bar{Z}} = \frac{V_S \angle\delta s - V_r \angle\delta r}{Z\angle\theta} \quad (3.5)$$

With

$$\tan\theta = \frac{X}{R} \quad (3.6)$$

$$S_r = \frac{|V_S||V_r|}{|Z|} < (\theta + \delta_r - \delta_s) - \frac{V_r^2}{|Z|} < \theta \quad (3.7)$$

The phasor diagram for the two-bus transmission system of figure 3.5 with the I as the reference phasor.

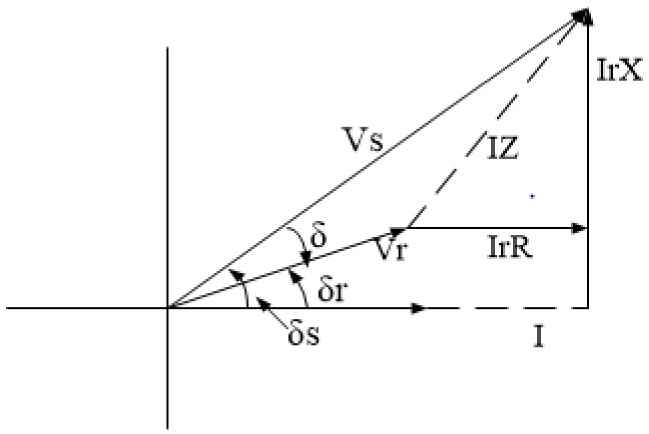


Figure 3. 7 the phasor diagram for the two-bus transmission system of figure 3.5 [30]

Expressing in terms of its real and imaginary parts, then (3.5) equation becomes

$$S_r = \frac{|V_s||V_r|}{|z|}\cos(\theta + \delta_r - \delta_s) + j\frac{|V_s||V_r|}{|z|}\sin(\theta + \delta_r - \delta_s) - \frac{|V_r^2|}{|z|}\cos\theta + j\frac{|V_r^2|}{|z|}\sin\theta \quad (3.8)$$

Rearranging equation (3.8) gives

$$S_r = \frac{|V_s||V_r|}{|z|}\cos(\theta + \delta_r - \delta_s) - \frac{|V_r^2|}{|z|}\cos\theta + j(\frac{|V_s||V_r|}{|z|}\sin(\theta + \delta_r - \delta_s) - \frac{|V_r^2|}{|z|}\sin\theta) \quad (3.9)$$

But

$$S_r = P_r + jQ_r \quad (3.10)$$

Then equating real and imaginary parts on both sides, gives

$$P_r = \frac{|V_s||V_r|}{|z|}\cos(\theta - \delta_s + \delta_r) - \frac{|V_r^2|}{|z|}\cos\theta \quad (3.11)$$

$$Q_r = \frac{|V_s||V_r|}{|z|}\sin(\theta - \delta_s + \delta_r) - \frac{|V_r^2|}{|z|}\sin\theta \quad 3.12$$

Substituting $\delta = \delta_r - \delta_s$ and finding a quadratic equation in terms of in (3.12) gives

$$\frac{|V_r^2|}{|z|}\sin\theta - \frac{|V_r||V_s|}{|z|}\sin(\theta - \delta) + Q_r = 0 \quad (3.13)$$

Therefore, the voltage quadratic equation is given as

$$\frac{\sin\theta}{|z|}V_r^2 - |V_r|\frac{|V_s|\sin(\theta-\delta)}{|z|} + Q_r = 0 \quad (3.14)$$

Equation (3.14) is a quadratic equation

Therefore, solving for V_r gives

$$V_r = \frac{\frac{|V_s|\sin(\theta-\delta)}{|z|} \pm \sqrt{(\frac{(|V_s|\sin(\theta-\delta))^2}{|Z|}) - 4\frac{\sin\theta}{|z|}Q_r}}{2\frac{\sin\theta}{|z|}} \quad (3.15)$$

For stability, the discriminant of equation (3.15) should be greater than or equal to zero i.e.

$$\frac{|V_S|^2\sin^2(\theta-\delta)}{|Z|^2} - 4\frac{\sin\theta}{|Z|}Q_r \geq 0 \quad (3.16)$$

Multiplying both sides with |E|D, we have

$$|V_S|^2\sin^2(\Theta - \delta) - 4|Z|sin\Theta Q_r \geq 0 \quad (3.17)$$

But the reactance, X from the relevance impedance triangle is given as

$$X = |Z| \sin \Theta \quad (3.18)$$

Substituting X into equation (3.17), then

$$|V_S|^2\sin^2(\Theta - \delta) - 4XQ_r \geq 0 \quad (3.19)$$

Dividing both sides by $|V_S|^2\sin^2(\Theta - \delta)$, then equation (3.19) becomes

$$1 - \frac{4XQ_r}{|V_S|^2\sin^2(\Theta-\delta)} \geq 0 \quad (3.20)$$

Therefore, the voltage stability index, (Lmn) is obtained as:

$$L_{mn} = \frac{4XQ_r}{|V_S|^2\sin^2(\Theta-\delta)} \quad (3.21)$$

The power flow through a transmission line for a two-bus system is used and the discriminant of the voltage quadratic equation is set to be greater than or equal to 0 (zero). If the discriminant is less than 0 (zero), the roots will be imaginary suggesting that there is instability in the system [10].

The line index is also directly related to the reactive power and indirectly related to the active power through the voltage phase angle δ. A line in the system is said to be close to instability when the L_{mn} is close to one (1) [12].

The L_{mn} values in table 3.3 are calculated by using the L_{mn} formula in equation 3.21 and the data from appendix

Table 3.3 The VSI of lines and reactive power load connected to the lines

Line	From bus	To bus	L_{mn}	Q- Load
2	2	3	0.71479	6.29
3	2	4	0.29865	2.62
4	2	5	0.11293	1.1
5	2	6	0.04233	0.37
6	1	7	0.29530	
7	7	8	0.12926	1.41
8	7	9	0.10098	1.1
9	7	10	0.01377	0.97
10	1	11	0.14647	
11	11	12	0.1637	0.9

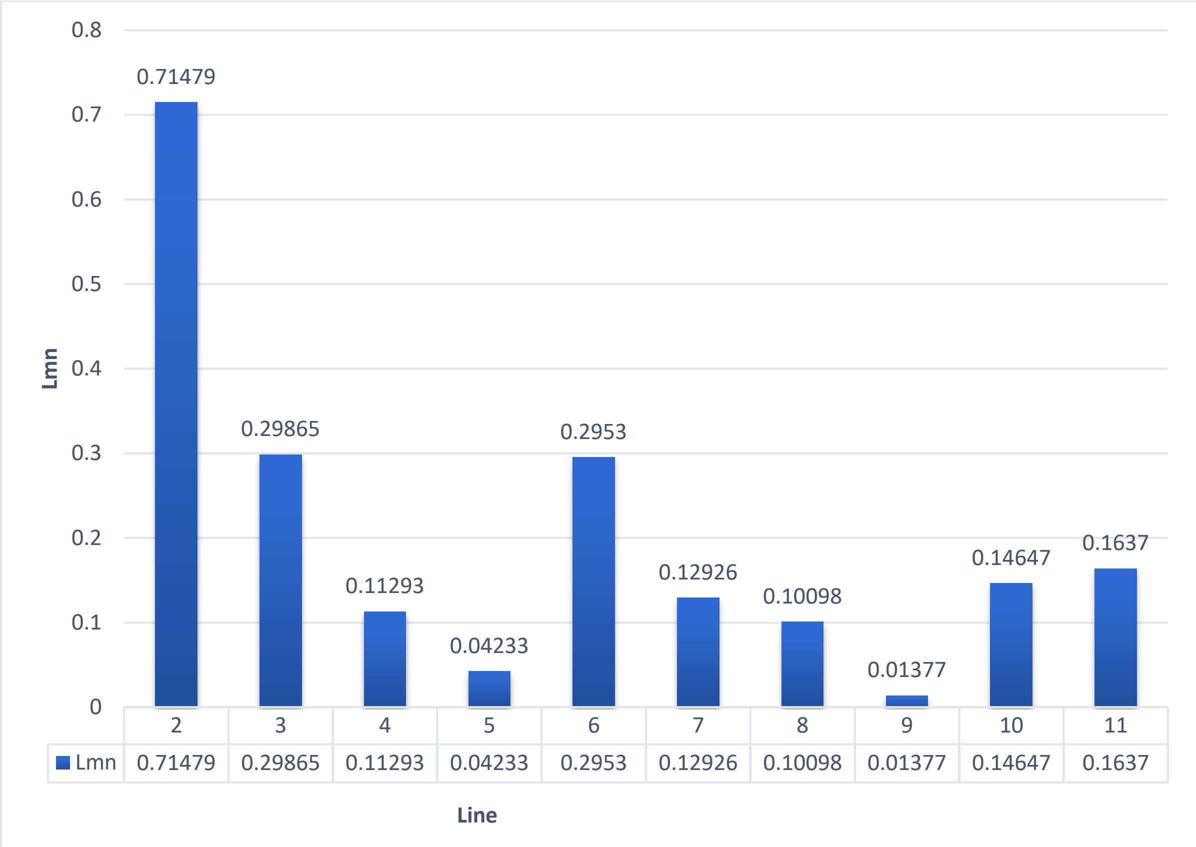


Figure 3. 8 line stability index of Wolaita Sodo distribution substation lines

The line stability index of the line 2 from bus 2 to bus 3 is 0.71479. Bus 3 is found to be the weakest load bus in the system with the maximum permissible reactive power load of 6.29 MVAR and the critical voltage is 0.9489 p.u. This means that any increase in the reactive power load will probably lead to voltage collapse. Bus 3 is then the optimal location for a possible compensating device.

The weakest line here is the line from bus 2 to bus 3. It can be seen that the line connected to individual load bus with the lowest stability index value is the most stable line while the line with the highest stability index value is the critical lines with respect to that particular load bus as shown in Tables 3.3 and 3.8. Line 9 from bus 7 to 10 is the most stable line having the lowest line stability index 0.01377.

3.5. Voltage Constraints

Voltage constraints helps for the prediction of voltage collapse in power system networks. It used for identifying the weakest bus in the network, the critical and most vulnerable bus. This will consequently guide the operator to take quick action to avert the voltage collapse when a particular bus is being overloaded and where to place compensation devices will be so revealed.

The voltage magnitude of each bus should be kept within operating limits, as follows:

$$0.95 p.u \leq Vi \leq 1.05 \text{ p.u} \qquad (3.22)$$

3.6. SVC rating and formulation

An SVC cannot assure perfect voltage stabilization and perfect reactive power compensation at the same time. The requirement for highest power quality precedes the need for perfect reactive power compensation. For optimum voltage stabilization, the variable reactive power output of the SVC hence needs to compensate not only the reactive power of the load, but also correct the voltage variations: Equation (3.2) defines the required minimum rating of the SVC [9].

$$Q_{SVC} = Q_{load} + \frac{(P_{load})^2}{2S_{sc}} + KP_{load} \qquad (3.23)$$

with K = $\frac{R}{X}$ (the resistance ratio of the impedance)

Where Q_{load} *and* P_{load} the reactive and active power of load are respectively S_{sc} is short circuit MVA

$$\text{Short circuit MVA} = \frac{100S}{X\%} \qquad (3.24)$$

$$\text{Short circuit current } I_{KA} = \frac{MVA}{KV\sqrt{3}} \qquad (3.25)$$

Where

S = Transformer rating in MVA

X% = internal reactance of transformer in %

I_{KA} = short circuit current in KA

KV = Transformer secondary voltage in KV

Normally, the % reactance value of the transformer can be obtained from the nameplate, or if not, from the transformer data sheets. The rating of transformer I is 20 MVA and the % reactance of transformer are 8.987%.

Based on the equation 3.24 the short-circuit MVA becomes:

<u>Trafo I</u>

Short circuit MVA = $\frac{100S}{X\%}$ = 100 $\frac{20}{8.987\%}$ = 222.717 MVA

From equation (3.23) the SVC rating becomes

$$P_{load} = 13.9 \ MW$$

$$Q_{load} = 10.36\ MVAR$$

$$Q_{SVC} = 10.36 + \frac{(13.9)^2}{2 * 222.717} + 0.054 * 13.9 = \ 11.544\ MVAR$$

3.7. SVC rating cost

Although FACTS controllers can offer high-speed control for enhancing electric power system, one significant disadvantage of power electronic based controllers is more expense per unit of rating than that of similar conventional equipment. The total cost also depends on the size of fixed and controlled portion of the FACTS controllers. Table 3.4 shows an idea at the expense of the various controllers. The FACTS equipment cost represents only half of the total FACTS project cost [9]. Other expenses like civil works, installation, commissioning, insurance, engineering and project management constitute the other half of the FACTS project cost**.**

Table 3.4 expenses comparison of different FACTS controllers [9]

FACTS CONTROLLERS	Expense (US $)
DSTATCOM	43$ per one KVAR
Static var compensator	26$ per one KVAR
TCSC	47$ per one KVAR controlled portions
UPFC	37$ per one KVAR through power

Table 3.5 modeled SVC rating cost

	Total Rating [MVAR]	Cost per KVAR	Total cost $
SVC	11.544	$26	300144.00

CHAPTER FOUR

SIMULATION RESULTS AND DISCUSSION

4.1. Introduction

This chapter is given simulation results for comparison of voltage profile, Reactive power compensation and reactive power loss with and without SVC compensator using ETAB software. This also discusses the simulation results of the reactive power and voltage profile of the existing distribution substation system with and without SVC. The compensation of SVC technology, analysis using ETAP software and the enhancement using SVC are presented in detail.

4.2. ETAB simulation circuit

The substation system modeled with ETAB software is shown in Figure 4.1. There is incoming 132 kV main bus that is connected to three substation transformer (trafo I 132/15kv, Trafo II 132/33kV and Trafo III 132/66kv) which is 132/15 kV transformer suppled to four 15 kV feeders. Though the 15 kV feeders the power supply by 20 MVA transformers. The 33kv bus supplied to 3 feeders and the 66kv bus supplied to one feeder.

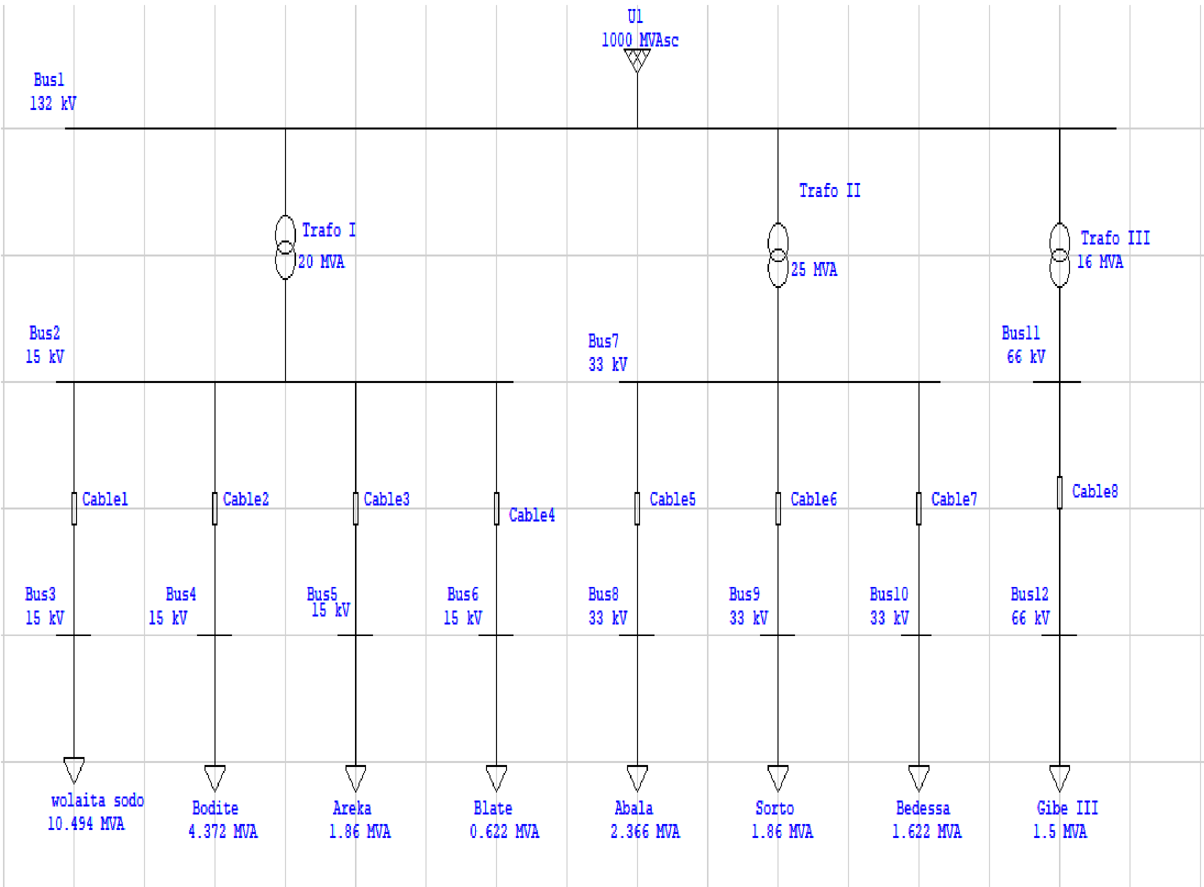


Figure 4. 1 Wolaita Sodo distribution substation modeling

4.3 Simulation result for peak load condition without SVC

Power flow has been carried out by ETAB software during peak load condition.

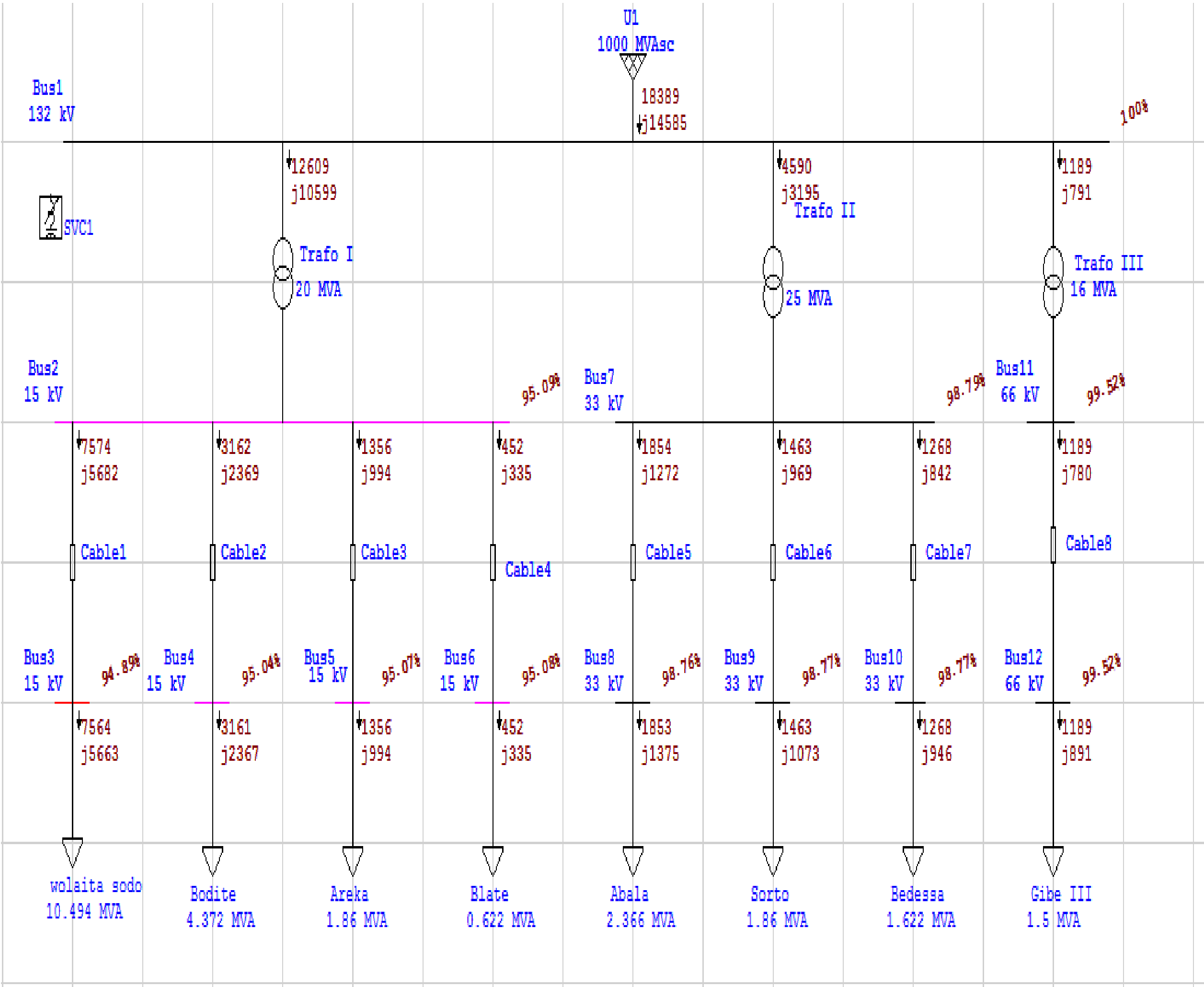


Figure 4. 2 base case voltage profile of the distribution substation

Figure 4.3 shows without SVC voltage profile the Wolaita Sodo distribution substation buses. By feeding line data, bus data, and load data to the existing distribution substation gives the result in figure 4.3.

The instability considered is the variation of the reactive power load. This is carried out to determine the maximum load ability and critical line by varying the reactive demand (Q MVAR) on the load buses until the value of the voltage stability index approaches 1 or the power flow fails to converge. From the simulation result of figure 4.3 observed that bus 3 has a voltage profile of 94.89%. This is the only bus its voltage falls short of the ±5% tolerance margin of the voltage criterion. This low voltage is an indication that the bus has voltage instability. This is the bus that requires compensation devices, and mitigating against voltage collapse or instability. From figure 4.3, the maximum load-ability of each load bus, the most critical line and most stable line with respect to a particular load bus are identified.

The critical line is line 2 from bus 2 to bus 3 having 0.71479 the maximum line stability index. Line 9 from bus 7 to 10 is the most stable line having the lowest line stability index 0.01377.

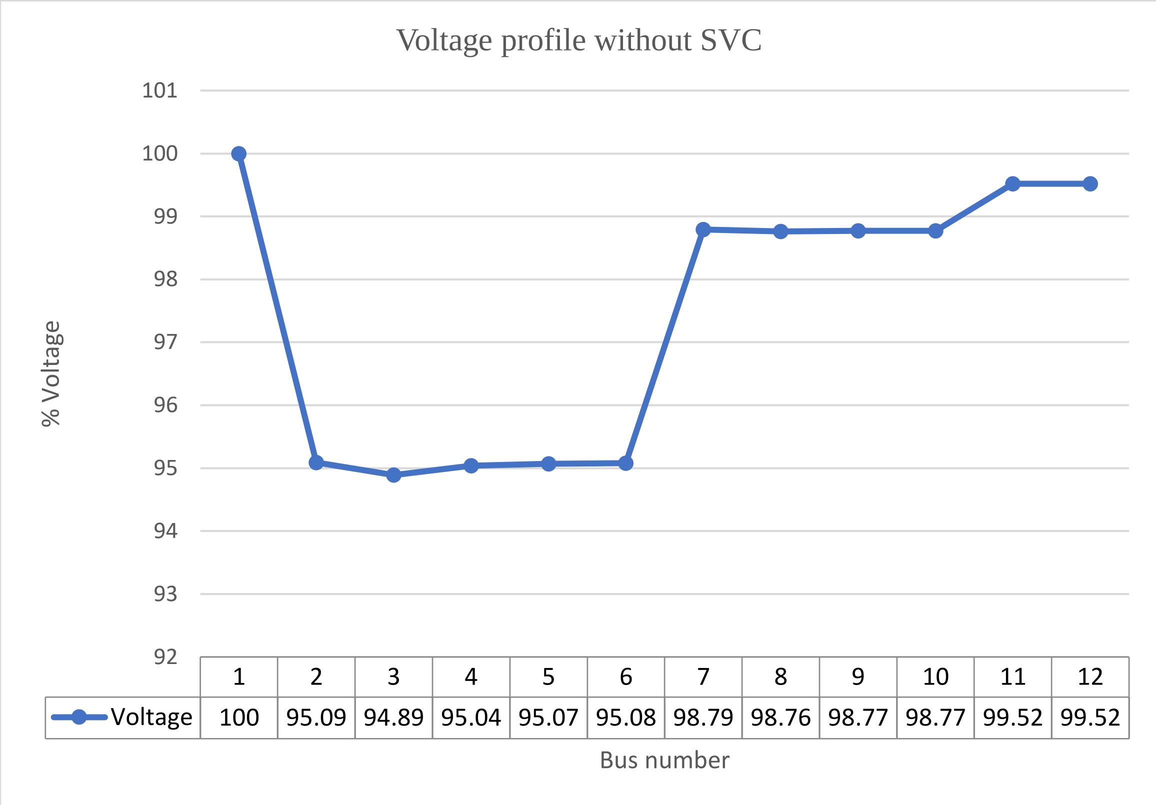


Figure 4. 3 Voltage profile of distribution substation buses without SVC

4.4. Simulation result for peak load condition after SVC coonected at bus-11

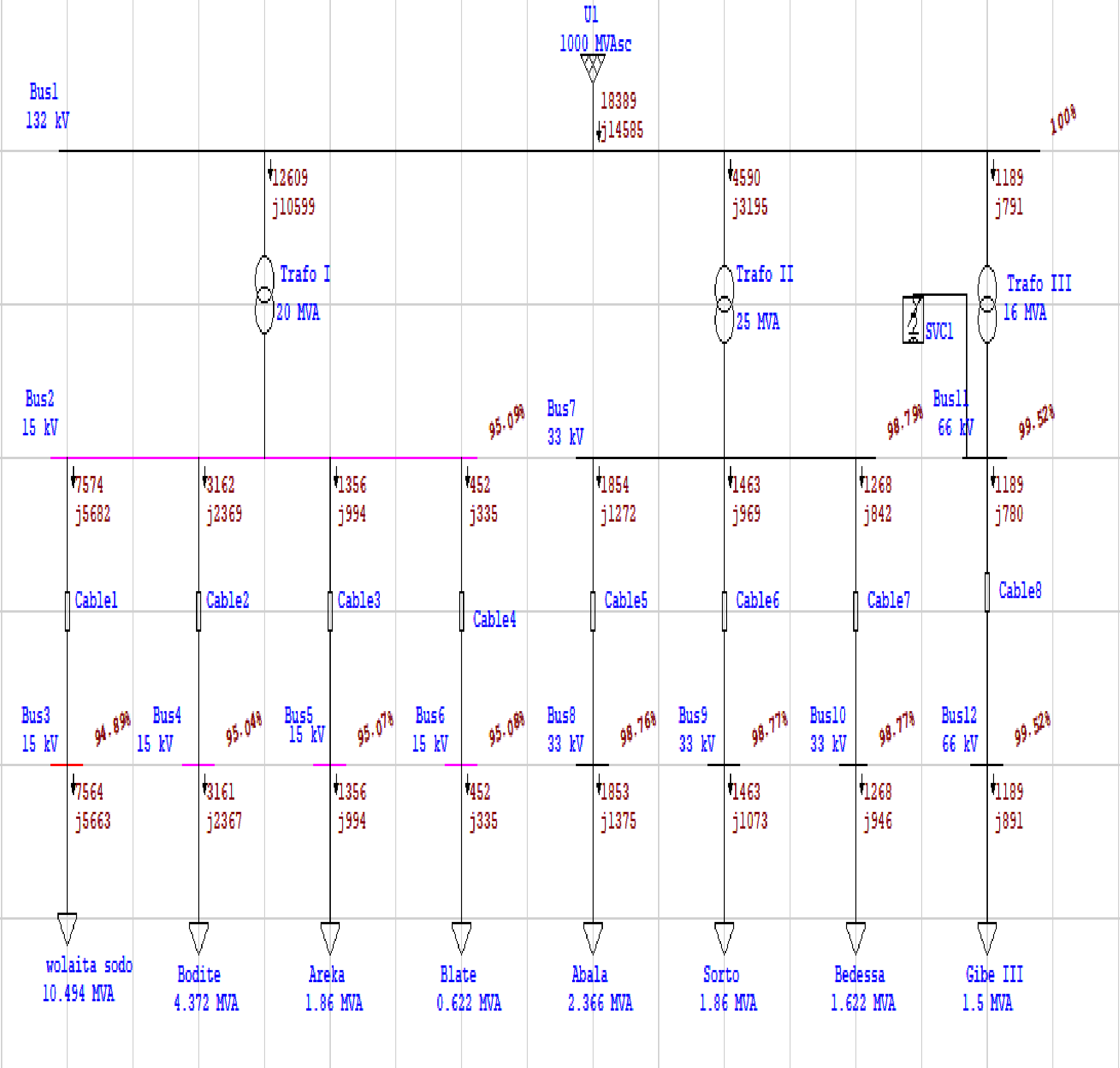


Figure 4. 4 Wolaita Sodo distribution substation after SVC connected at bus 11

By connecting 11.544 MVAR SVC to bus-11, the result in figure 4.5 which is voltage profile of the weak buses 3, 4, 5 not improved as we required. So the voltage at all buses is not improved. Because the SVC is not feed to the buses having the low voltage level. The negative impact of connecting of SVC to 66 KV feeder of bus-11 is not improved the voltage profile due to the improper connecting of SVC. The result of connecting SVC at 66KV feeder of bus-11 is shown in figure 4.5. The SVC should be connected at the critical bus having highest voltage stability index.

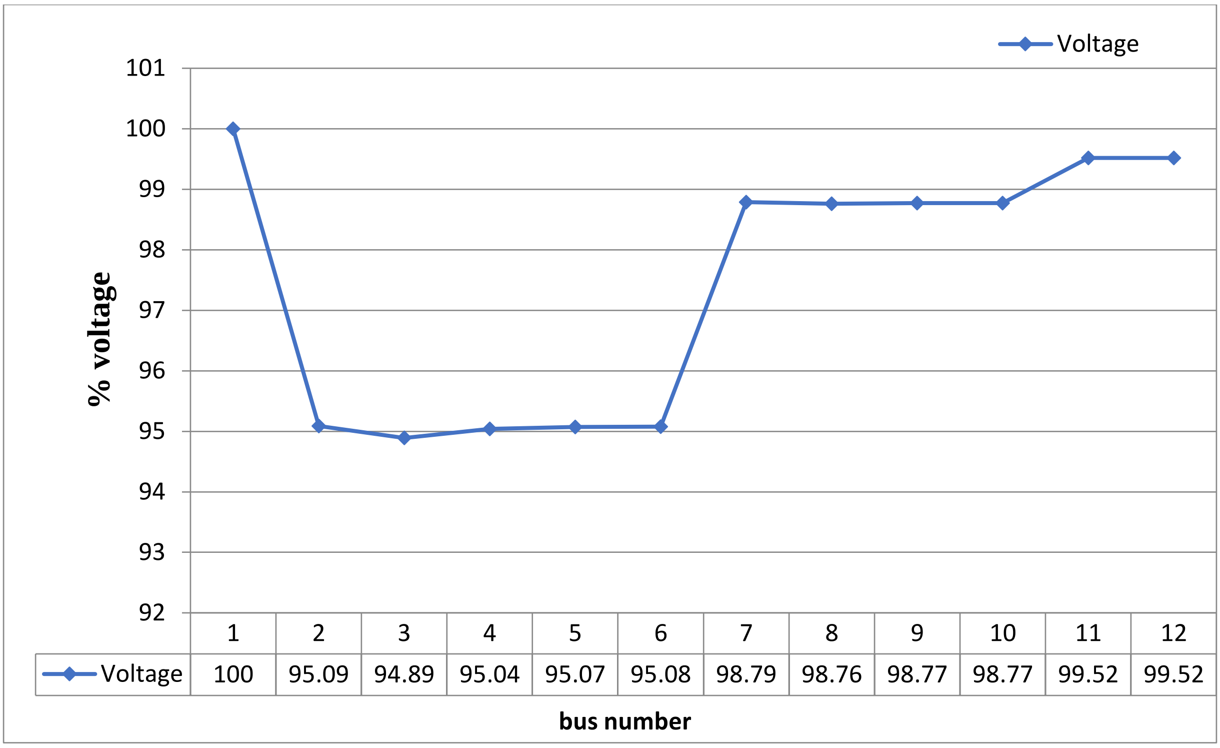


Figure 4. 5 Voltage profile of distribution substation buses with SVC at bus 11

4.5 Simulation result for peak load condition after SVC conncted at bus-7

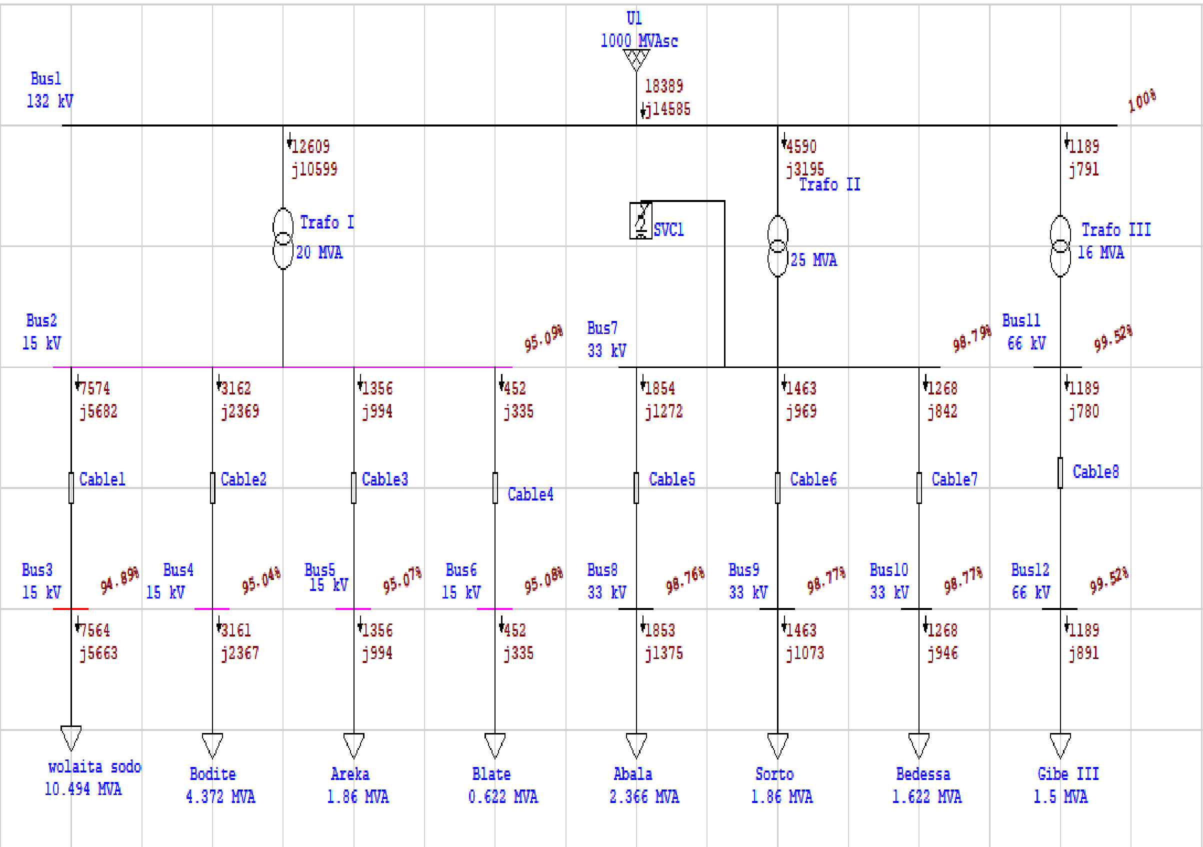


Figure 4. 6 Wolaita Sodo distribution substation after SVC connected at bus 7

Now similar to the above case 11.544 MVAR SVC is connected to bus-7 of 33KV and the simulation is conducted. The output of the simulation shows that the voltage profile of the weak buses 3, 4, 5 are not improved. The SVC is not connected optimally. The simulation result shown below in figure below.

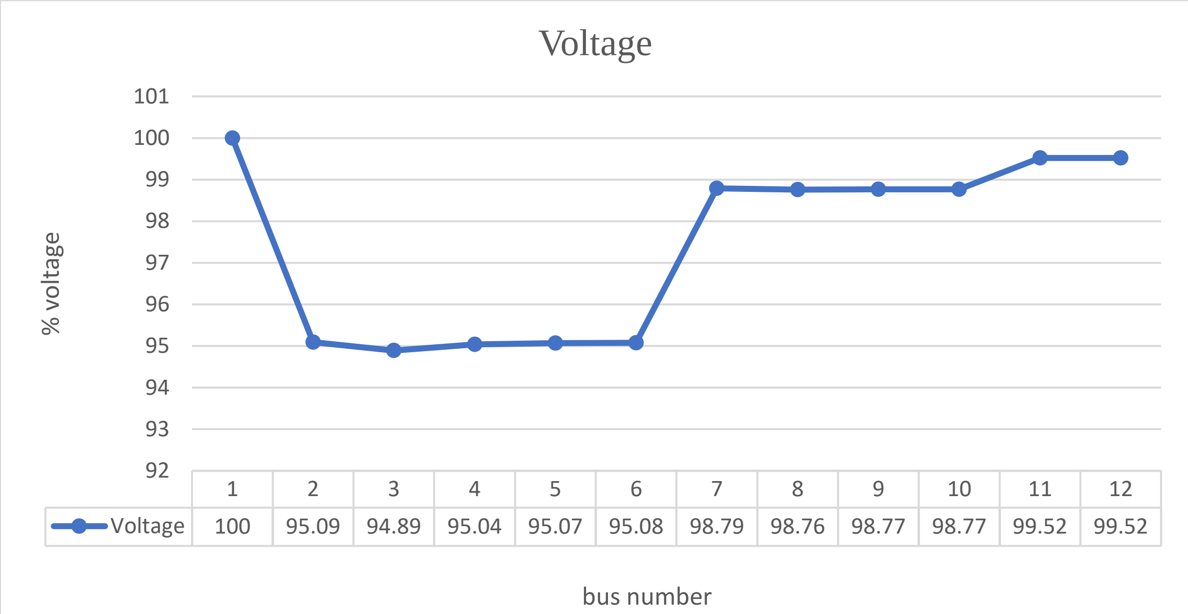


Figure 4. 7 Voltage profile of distribution substation buses with SVC at bus 7

4.6 Simulation result after SVC connected at bus-1

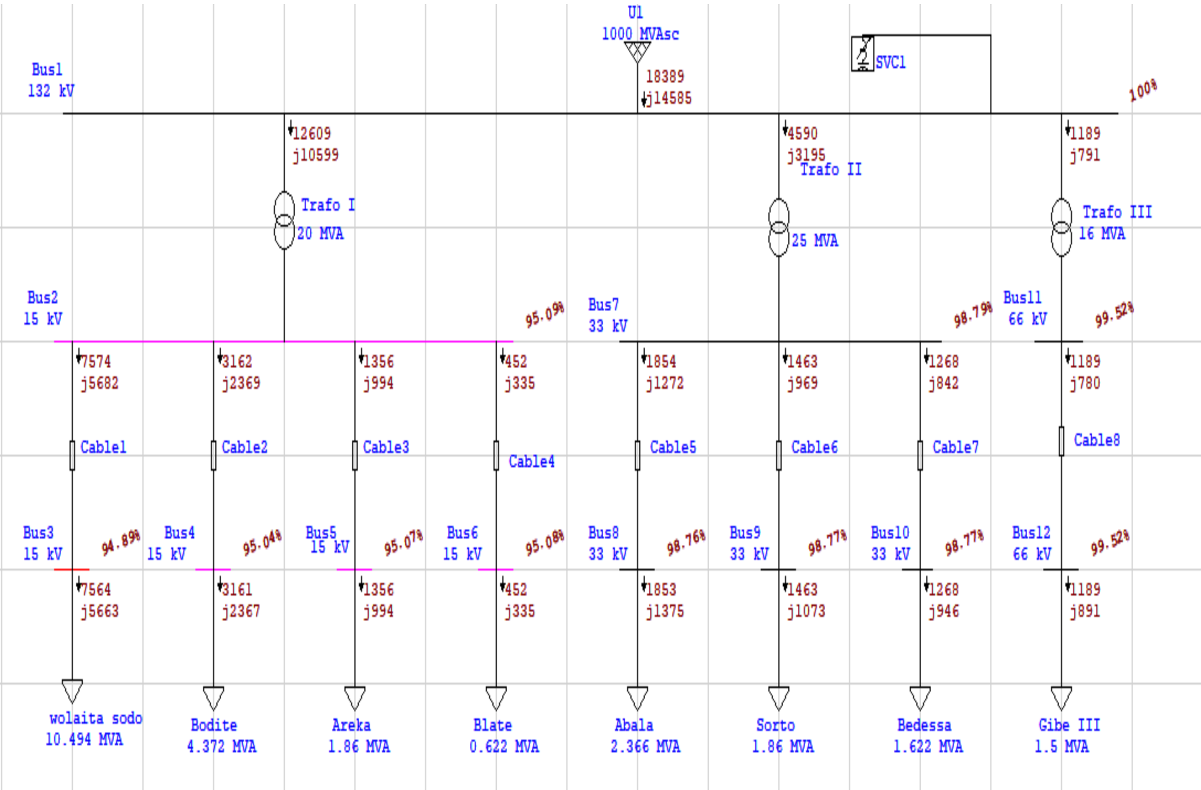
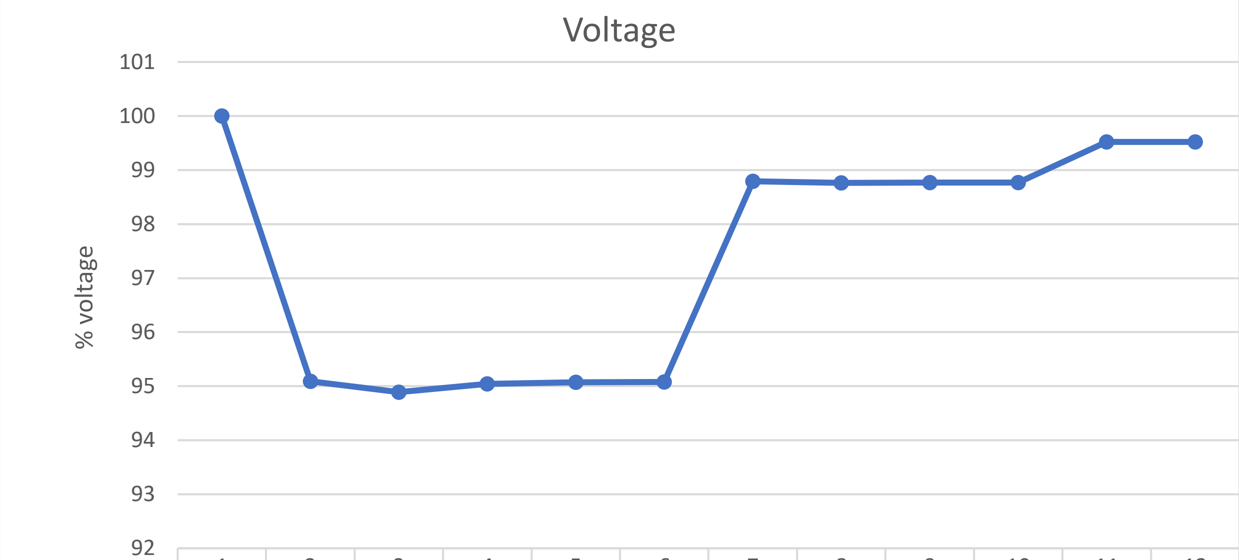


Figure 4. 8 Wolaita Sodo distribution substation after SVC connected at bus 7

By connecting 11.544 MVAR SVC to bus-1, the voltage profile of the weak buses 3, 4, 5 are not improved. So the voltage at all buses is not improved. Because the SVC is not feed to the buses having the low voltage level. The negative impact of connecting of SVC to 132 KV bus-1 is not improved the voltage profile due to the improper connecting of SVC. The result of connecting SVC at 132KV of bus-1 is shown in figure below.



	1	2	3	4	5	6	7	8	9	10	11	12
Voltage	100	95.09	94.89	95.04	95.07	95.08	98.79	98.76	98.77	98.77	99.52	99.52

Figure 4. 9 Voltage profile of distribution substation buses with SVC at bus 1

4.7. Simulation result after SVC connected at bus-2

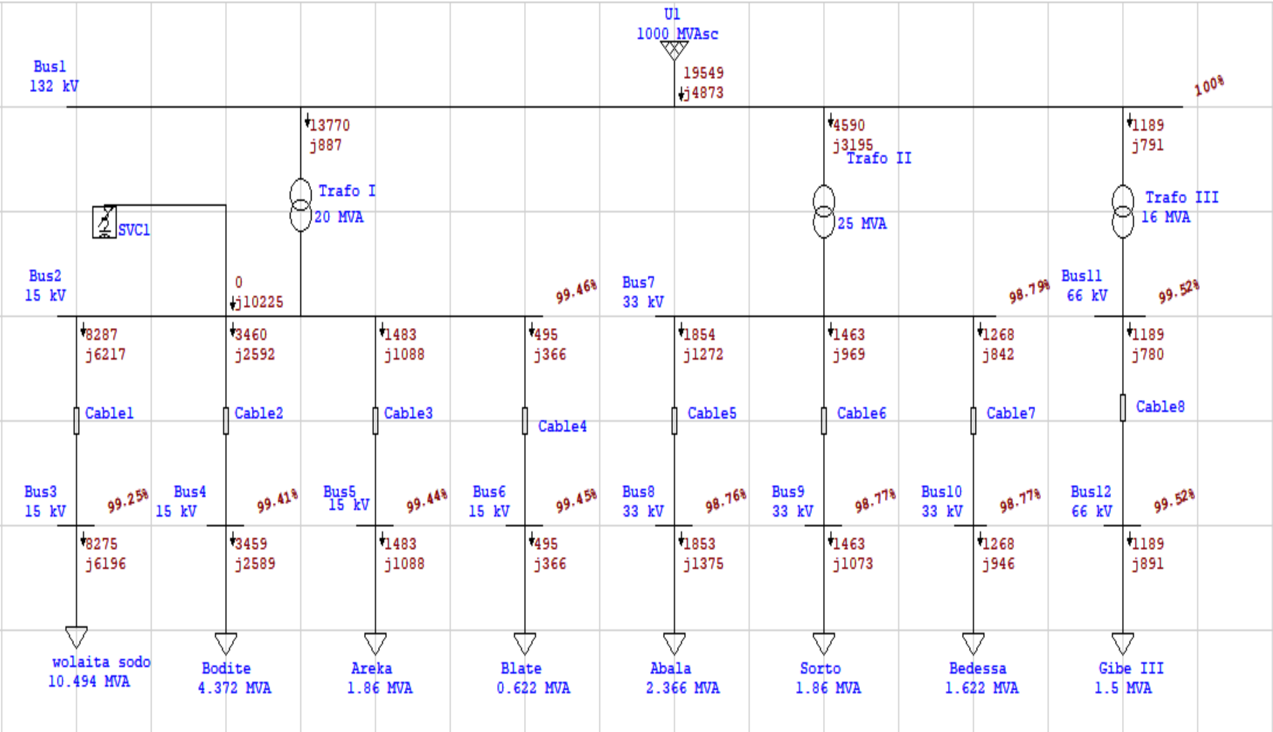


Figure 4. 10 Wolaita Sodo distribution substation after SVC connected at bus 2

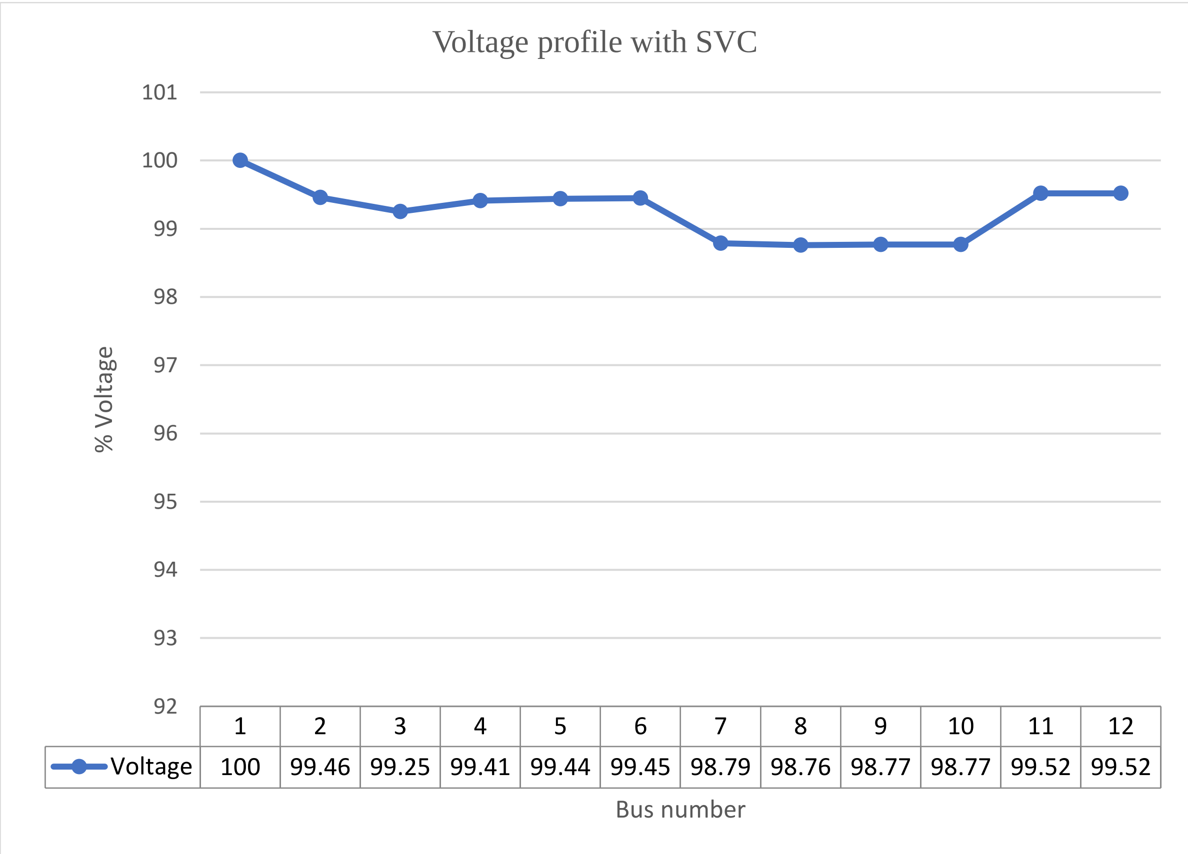


Figure 4. 11 Voltage profile of distribution substation buses with SVC at bus 2

Figure 4.11 shows the voltage profile of buses the Wolaita Sodo distribution substation buses with SVC at 15kv bus2. The voltage profile of the buses connected to the critical line are bus2, bus3, bus4, bus5, bus6 is improved. The voltage profile of the weakest bus 3 is improved from 94.89% to 99.25% after SVC connected at bus2 and the 15kv buses are improved its voltage profile.

Because the SVC is feed to the buses having the low voltage level. The connecting of SVC to 15 KV feeder of bus-2 is improved the voltage profile due to the proper connecting of SVC. Therefore I concluded that connecting SVC at 15kv bus is the optimal placement.

4.8. Simulation results comparison for peak load condition without and with SVC

The figures 4.11 and figure 4.3 shows the voltage profile of the Wolaita Sodo distribution substation buses with and without SVC. The results of voltage profile of the buses without SVC gives, the Wolaita Sodo feeder 15kv bus3 is less than critical limits 95%, the other 15kv buses approaches to the critical limits 95%, so the 15kv buses shows having weak voltage profile.

After connected SVC at 15kv bus2 with rating of 11.544 Mvar, the 15Kv buses improved the voltage profile. The voltage profile of the Wolaita Sodo distribution substation system is enhanced.

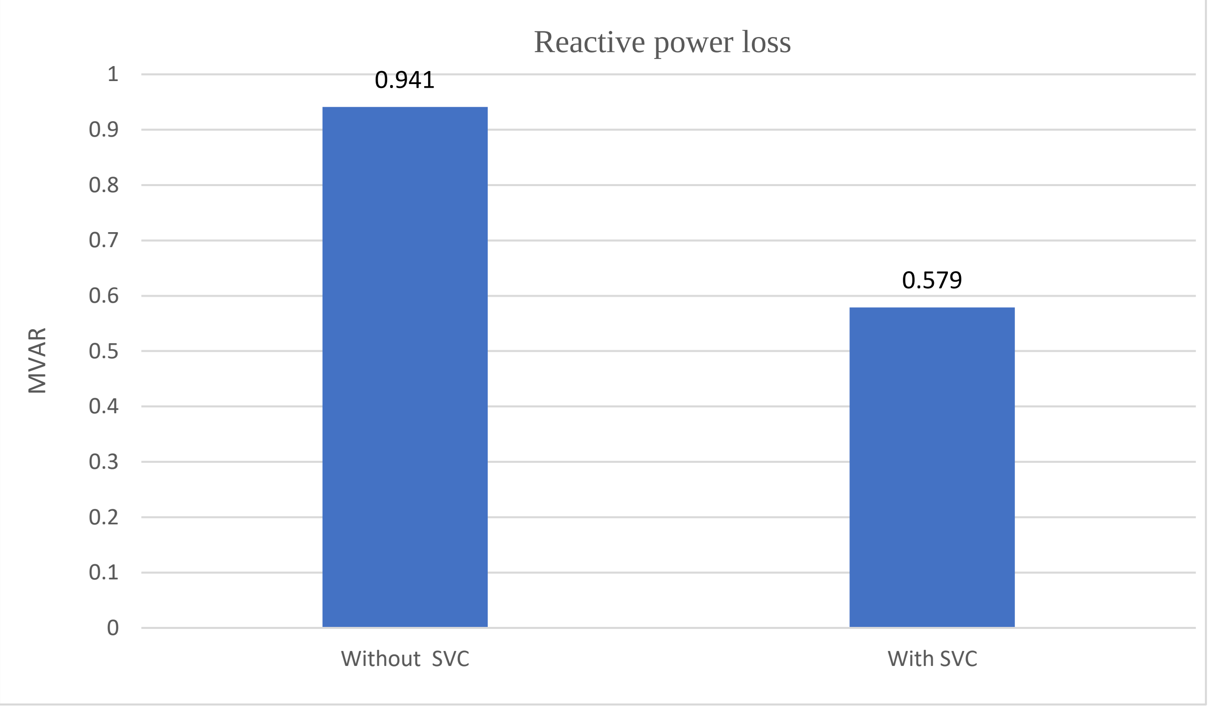


Figure 4. 12 Reactive power losses of the Wolaita Sodo distribution substation

The reactive power loss of Wolaita Sodo distribution substation before SVC connected at the substation is 0.941. After SVC connected at the substation the reactive power loss decreased from 0.941 Mvar to 0.579 Mvar.

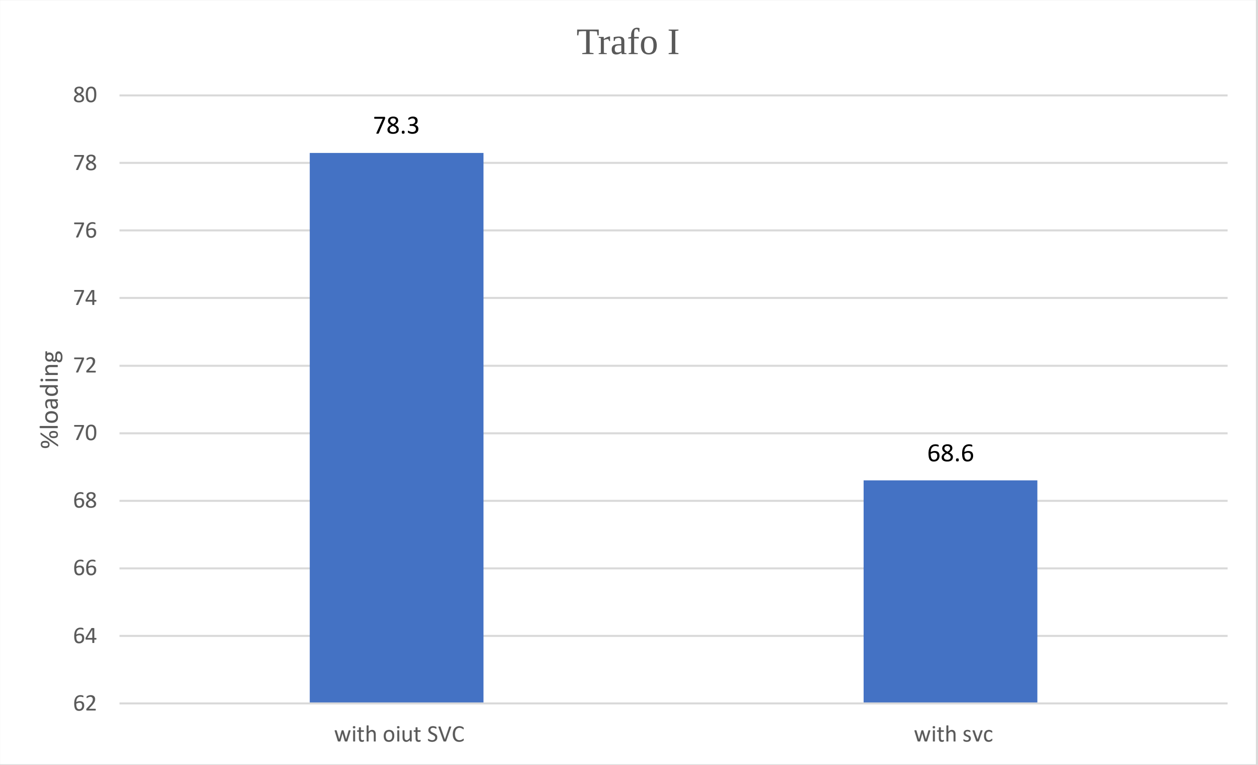


Figure 4. 13 Loading of trafo I without and with SVC

Power transformer is very important in electric power system due to its function to raise or lower the voltage according to its designation. On the power side, the power transformer serves to raise voltage to be transmitted to the transmission line. On the transmission side, the power transformer serves to distribute the voltage between the main substations or down to the distribution voltage. On the distribution side, the stresses are channeled to large customers or lowered to serve small and medium customers. As the power transformer is so importance, it is necessary to protect against disturbance, as well as routine and periodic maintenance, so that the power transformer can operate in accordance with the planned time. Some factors that affect the duration of the power transformer is the ambient temperature, transformer oil temperature, and the pattern of load.

Distribution transformer used to distribute power to customers. A proper election of distribution transformer capacity is highly decided by the supplied load; therefore, it can support the continuity of service, reliability, and transformer lifetime. Distribution transformer reach maximum efficiency when it is loaded until 80 percent of its capacity.

When the load is too high, it is required to change the transformer or insert compensator device.

Figure 4.13 shows the loading of trafo I is 78.3% befor SVC connected at the substation. After SVC connected at the substation the trafo I loading is decreased to 68.6%.

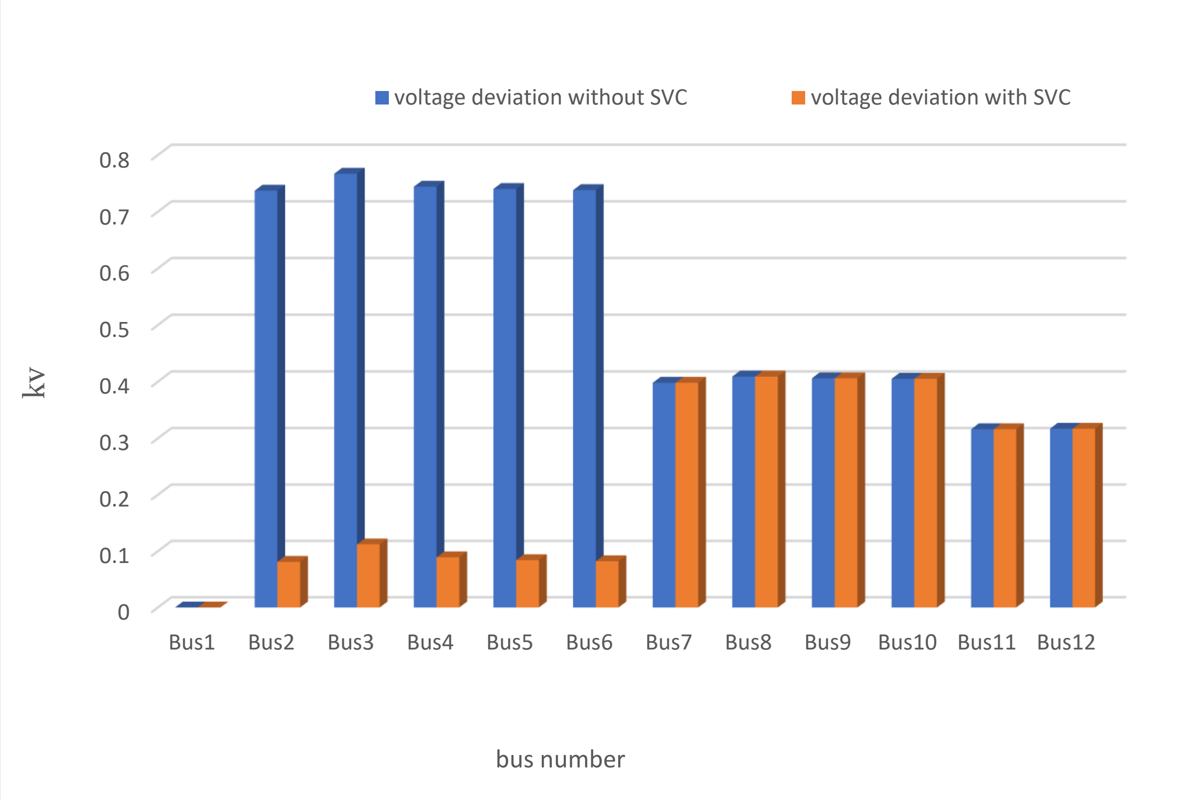


Figure 4. 14 voltage deviation of substation buses

The voltage variations may occur in distribution systems because of many different reasons. Line impedances cause a significant drop in voltage. Moreover, when the available reactive generation cannot meet the growing demand for reactive power at customer's sides, a voltage drop may occur in the system. Also, for long radial feeders, which are very common in rural areas, the transmission of reactive power may not be possible and therefore voltage drop will also be increased at the customer's connection points of loads.

Voltage deviation can be defined as the difference between the nominal voltage and the actual voltage. The smaller the deviation of bus voltage from the nominal voltage, the better the voltage condition of the system. Here the goal is to increase voltage profile by reducing the voltage deviation. The SVC inclusion into the system can improve voltage profile of the system and reduce the voltage deviation. After connected SVC at bus 2, the voltage deviation of the weak buses (bus 2, bus 3, bus 4, bus 5, and bus 6) is minimized. Figure 4.14 shows the voltage deviation decreased, bus 2 from 0.737 to 0.081, bus 3 from 0.767 to 0.112, bus 4 from 0.844 to 0.089, bus 5 from 0.74 to 0.84 and bus 6 from 0.738 to 0.082.

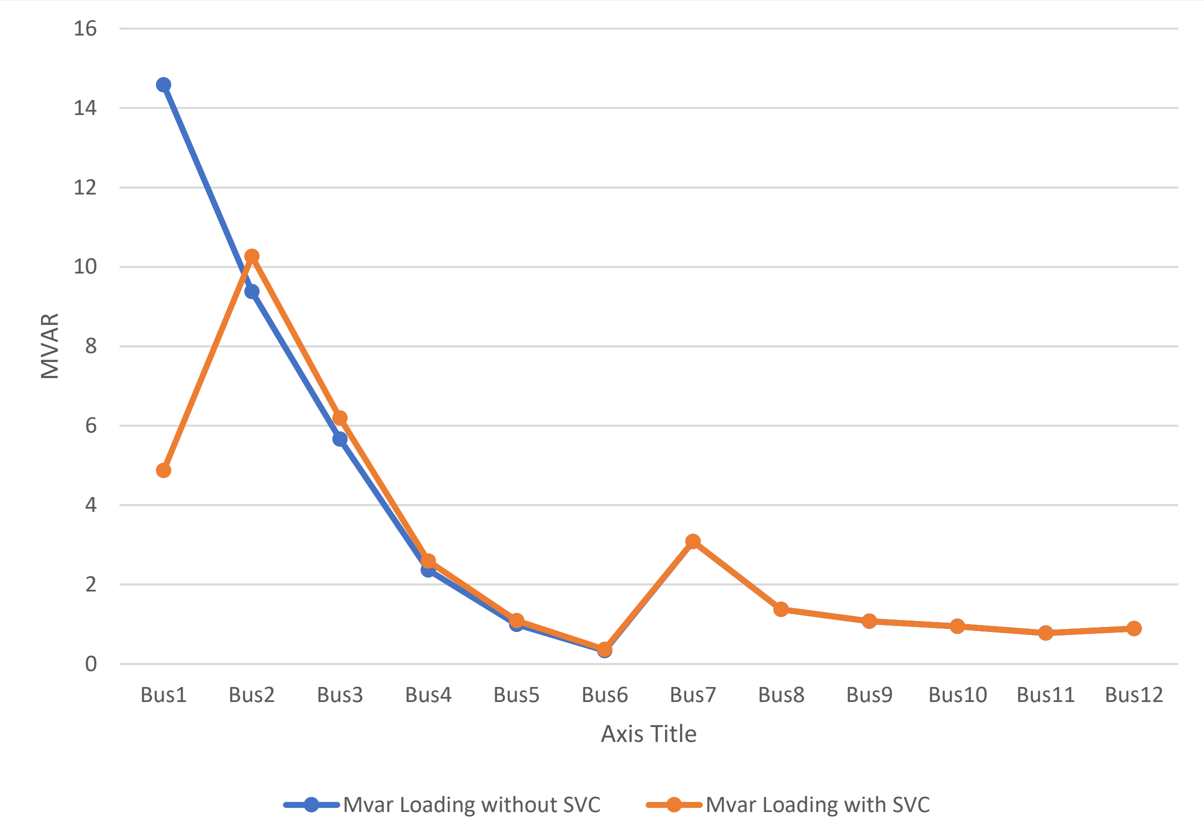


Figure 4. 15 Reactive power flow of buses

Due to heavy demand of power, distribution networks are always in stress which results in reduced voltage across the load and effect on the performance. It is necessary to improve the performance of power system to received quality power at the consumer end. Reactive power compensation is the main measure to keep power network running with high voltage stability, high power quality and minimum system loss. Reactive power flows can give rise to substantial voltage changes across the system, which means that it is necessary to maintain reactive power balances between sources of generation and points of demand. Some of devices available for reactive power compensation and control. Static VAr controller is one of the compensators used to maintain reactive power. Voltage is controlled by absorbing and generating reactive power. Thus, reactive power is essential to maintain the voltage to deliver active power through transmission lines. After SVC connected at the critical bus, the reactive power flow of the 15 kV buses (bus 2, bus 3, bus 4, bus5, bus6) is increased. The reactive power flow from generation system to Wolaita Sodo substation is decreased due to reactive power supplier SVC device is connected at the distribution substation 15 kv bus.

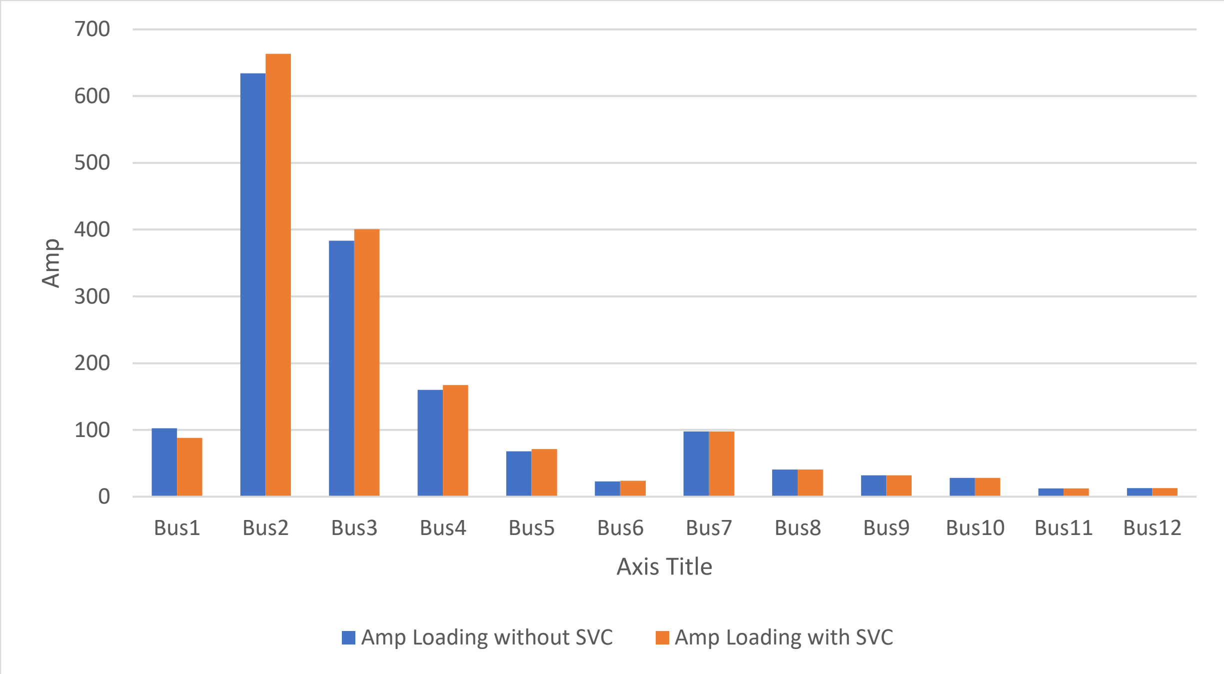


Figure 4. 16 current flow of buses

The current flow of the weak buses of the distribution substation (bus 2, bus 3, bus 4, bus and bus 6) after SVC connected is increased. The current flow of the buses of 33kV and 66 kV after SVC connected not increased. Because SVC is connected at 15kV bus. Therefore, SVC plays a major role to increase the current flow in distribution substation buses.

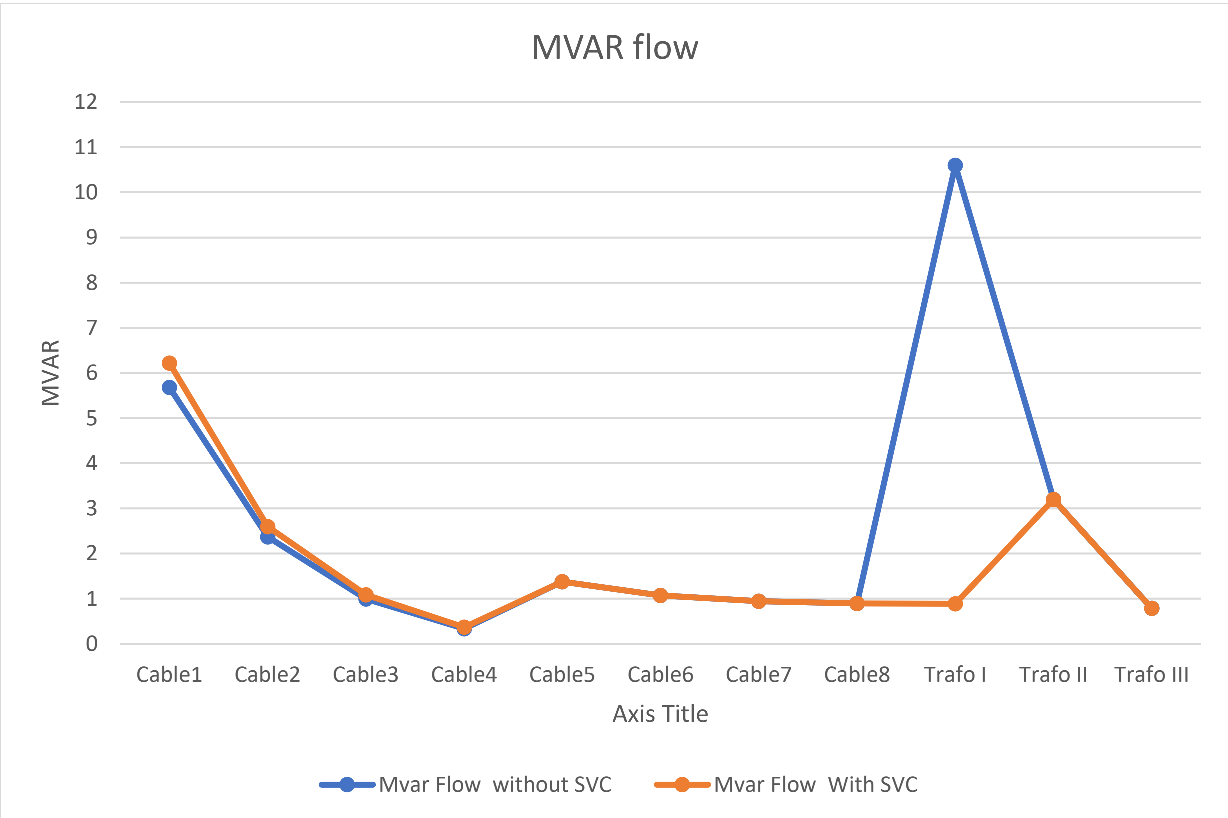


Figure 4. 17 Reactive power flow of branch

The reactive power flow of the cables (cable 1, cable 2, cable 3, cable 4,) is increased after SVC conncted at wolaita sodo distribution substation. Cable 1 is connected from bus 2 to bus 3, cable 2 is connected from bus 2 to bus 4, cable 3 is connected from bus 2 to bus 5, and cable 4 is conncted from bus 2 to bus 6. The reactive power flow of the 33kV and 66kV cables (cable 5, cable 6, cable 7, cable 8) is not incresead due to the SVC is connected at 15 kV bus. Trafo I is supplied power to 15 kV feeders. The 15kV fedeers are heavily loaded fedeers. After SVC conncted at the 15 kV bus of the distribution substation, the reactive power flow in trafo I is decreased. Therefore, the reactive power flow of the substation branches after SVC connected is increased.

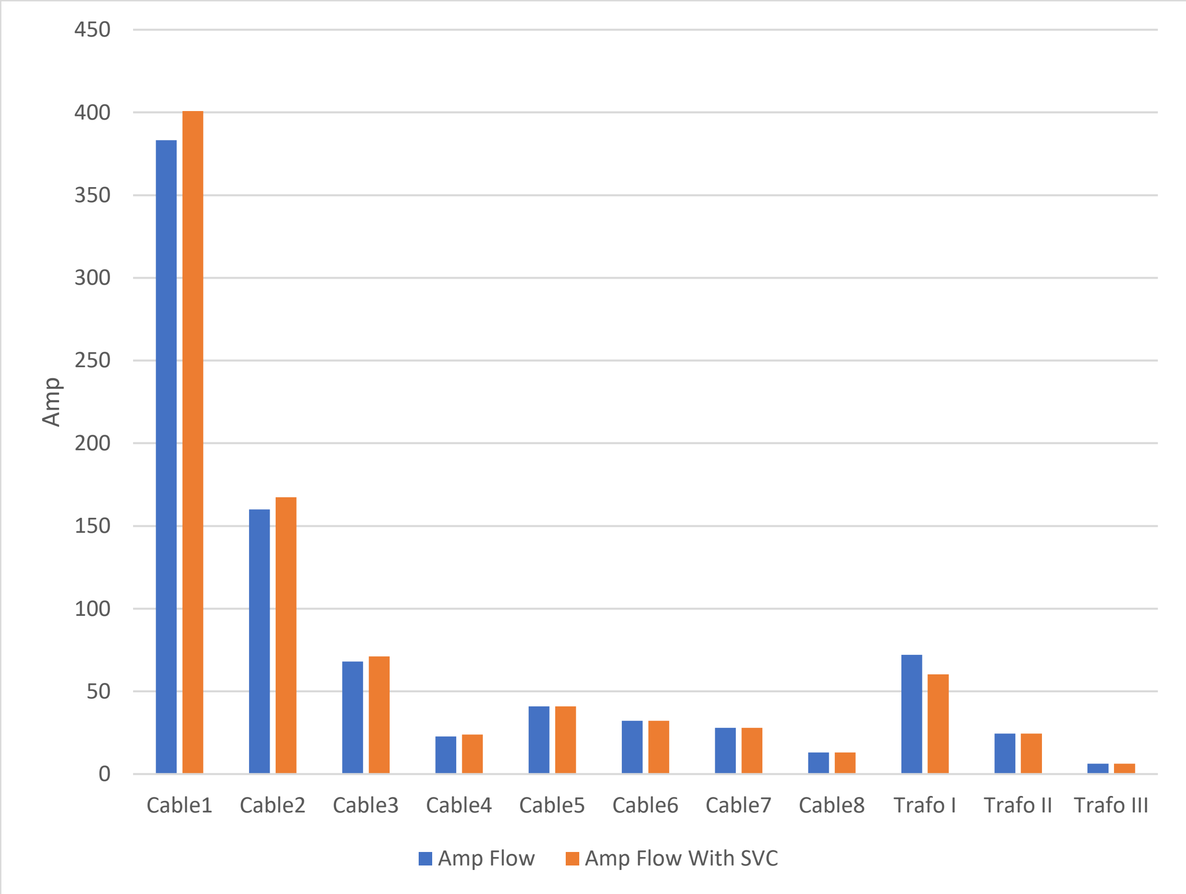


Figure 4. 18 Current flow of branches

The current flow of the cables (cable 1, cable 2, cable 3, and cable 4) is increased after SVC connected at Wolaita Sodo distribution substation. The current flow of 33kV and 66 kV cables (cable 5, cable 7, cable 8 and cable 8) not increased because SVC is connected at 15 kV bus. The current flow in Trafo I is decreased. Therefore, the current flow of the substation branches after SVC connected is increased.

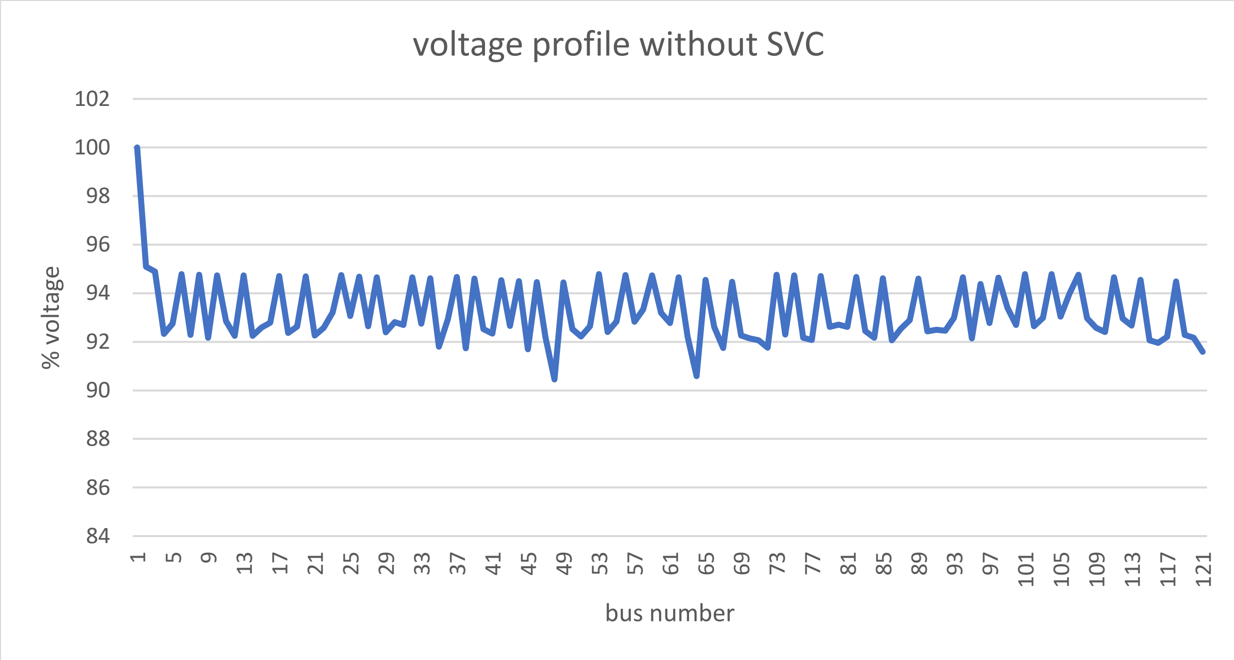


Figure 4. 19 Voltage profile of Wolaita Sodo feeder without SVC

Figure 4.19 shows the voltage profile of Wolaita Sodo feeder buses before SVC connected at Wolaita Sodo distribution substation. The Wolaita Sodo feeder 15 kV bus is weakest bus compared with the other feeders' bus. It is observed that the voltage profiles of Wolaita Sodo feeder buses have the voltage magnitudes of less than the critical limits 95%. These buses are considered to have violated the ±5% tolerance margin of voltage criterion. This low voltage is an indication that the network is susceptible to possible voltage instability.

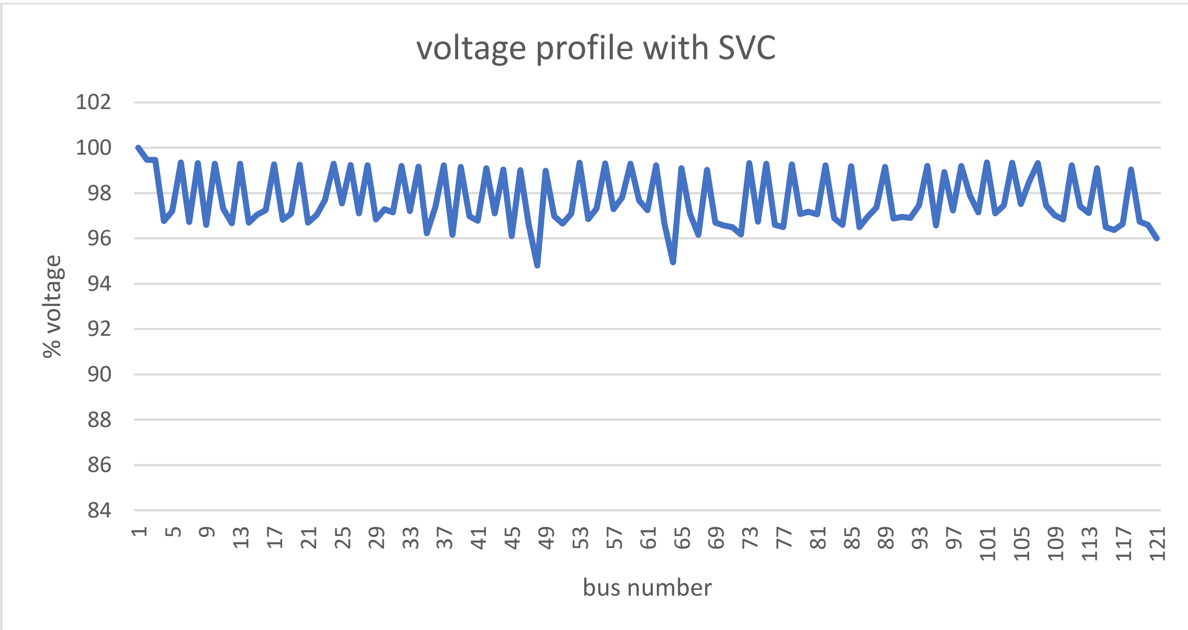


Figure 4. 20 Voltage profile of Wolaita Sodo feeder buses with SVC

Figure 4.20 shows the voltage profile of Wolaita Sodo feeder buses after SVC connected at Wolaita Sodo distribution substation. The Wolaita Sodo feeder 15 kV bus is weakest bus compared with the other feeders' bus. Therefore it is important to show how much improved the voltage profile of the feeder having weakest bus voltage profile. After connected SVC at the 15 kV Wolaita Sodo distribution substation bus, the Wolaita Sodo feeder buses improved the voltage profile to greater than 95%. The voltage magnitudes in all buses are within acceptable limit ± 0.05 pu.

CHAPTER FIVE

CONCLUSION, RECOMMENDATION AND FUTURE WORK

5.1. Conclusions

In this thesis the voltage stability improvement in distribution substation system has been achieved by using static Var compensator. Voltage stability index is used to identify the critical lines and weak buses. The modeling of Wolaita Sodo distribution substation is done in this thesis by using ETAP software. SVC is connected at 15 kV bus of Wolaita Sodo distribution substation. The results show that after SVC connected the weak buses voltage profile of Wolaita Sodo distribution substation that recovered to within acceptable limit between 0.95pu and 1.05pu. Additionally observed that adding static Var compensator at weakest bus in the network is significantly help to improve voltage and the distribution substation network operated within the allowable voltage range. As a further matter, I concluded that use of static Var compensator could be a very effective FACTS device for voltage stability enhancement

5.2. Recommendations

The electrical energy consumption of Ethiopia is increasing rapidly due to the country is on the way of growth and transformation. The existing distribution substation of EEU will be incapable to handle the increasing demand efficiently. Thus, EEU, the sole utility company of the country, should have to implement power electronics based equipment's in order to improve voltage stability.

Based on the findings of this thesis, I recommended to EEU, static Var compensator controller use for reactive power compensation in the Wolaita Sodo distribution substation system. It is further recommended that SVC add at the weakest buses in the network to significantly improve the voltage stability of distribution substation system and operate the network within the allowable voltage limits.

5.3. Suggestions for future work

Some of the issues related to future works are listed as follows:

- ❖ Performing the simulations studies using different software's such as MATLAB and DIGSILENT to test the effectiveness of the proposed method of voltage stability enhancement as well as to compare the simulation results.

- Investigating the use of different types of FACTS devices such as D-STATCOM for voltage stability enhancement of distribution substation systems.
- Further investigate automation of the load interruption algorithm for voltage control of distribution substations.

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Appendix

Table A1: Line and load Data of the Woliata Sodo distribution substation

Bus number	From bus	To bus	R(pu)	X(pu)	Q (MVAR)
1	1	2	0.0678	0.2345	0
2	2	3	0.094	0.1752	6.29
3	2	4	0.092	0.1750	2.62
4	2	5	0.90	0.1748	1.1
5	2	6	0.92	0.1752	0.37
6	1	7	0.04356	0.3467	0
7	7	8	0.098	0.15	1.41
8	7	9	0.096	0.14	1.1
9	7	10	0.098	0.15	0.97
10	1	11	0.00483	0.08987	0
11	11	12	0.98	0.15	0.9

Table A2: line, transformer rating and load data of Wolaita Sodo feeder

Line number	From bus	To bus	KVA	R(pu)	X(pu)	Real power (MW)	Reactive power (MVAR)
1	1	2		0.08987	0.00483	0	0
2	2	3		0.092	0.1752	0	0
3	3	4	315	0.06278	0.02564	0.128	0.094
3	3	5	315	0.07678	0.02429	0.106	0.079
4	3	6		0.21465	0.12873	0	0
5	6	7	200	0.06927	0.04174	0.088	0.056
6	6	8		0.53932	0.32343	0	0
7	8	9	315	1.86971	1.12127	0.123	0.098
8	8	10		0.17895	0.10732	0	0
9	10	11	315	0.65921	0.19443	0.101	0.067
10	10	12	315	0.02159	0.01295	0.121	0.093
11	6	13		0.29696	0.17809	0	0

12	13	14	630	2.80480	1.68204	0.259	0.191
13	13	15	200	0.15018	0.09006	0.069	0.049
14	13	16	200	0.97915	0.38630	0.066	0.044
15	13	17		0.22056	0.23180	0	0
16	17	18	100	0.06078	0.03645	0.036	0.026
17	17	19	315	0.25766	0.27079	0.103	0.076
18	17	20		0.22250	0.07040	0	0
19	20	21	100	0.84981	0.89311	0.039	0.026
20	20	22	315	0.05480	0.01734	0.103	0.078
21	20	23	100	0.07519	0.07902	0.023	0.016
22	3	24		0.25701	0.15413	0	0
23	24	25	50	0.06387	0.03830	0.013	0.009
24	24	26		0.24606	0.14756	0	0
25	26	27	315	0.12237	0.12861	0.108	0.072
26	26	28		0.71225	0.20808	0	0
27	28	29	200	0.15795	0.16600	0.075	0.052
28	28	30	315	0.01259	0.00398	0.2805	0.2303
29	28	31	200	0.21883	0.22998	0.09	0.068
30	26	32		0.16869	0.10116	0	0
31	32	33	315	0.39228	0.41228	0.102	0.068
32	32	34		0.22831	0.13692	0	0
33	34	35	630	0.65905	0.16942	0.292	0.219
34	34	36	50	0.02533	0.06257	0.013	0.009
35	24	37		0.71225	0.20808	0	0
36	37	38	315	0.02078	0.06422	0.145	0.108
37	37	39		0.71225	0.20808	0	0
38	39	40	100	0.18581	0.11143	0.033	0.022
39	39	41	315	0.02075	0.06422	0.118	0.081
40	39	42		0.71225	0.20808	0	0
41	42	43	315	0.0278	0.06422	0.091	0.07
42	42	44		0.71222	0.20800	0	0
43	44	45	315	0.02077	0.06422	0.0910	0.0700

44	44	46		0.70878	0.2432	0	0
45	46	47	315	0.02078	0.06422	0.118	0.082
46	46	48	100	0.02533	0.06257	0.068	0.043
47	46	49		0.71225	0.20808	0	0
48	49	50	315	0.02078	0.06422	0.091	0.072
49	49	51	100	0.02533	0.06253	0.036	0.029
50	49	52	315	0.13467	0.08076	0.091	0.066
51	2	53		0.3767	0.1911	0	0
52	53	54	630	0.01653	0.06545	0.233	0.118
53	53	55	315	0.0278	0.06422	0.102	0.069
54	53	56		0.7122	0.20800	0.2804	0.2203
55	56	57	315	0.09592	0.10081	0	0
56	56	58	315	0.26457	0.15866	0.0312	0.0234
57	56	59		0.02078	0.06422	0.091	0.072
58	56	59		0.06404	0.06731	0	0
59	59	60	315	0.00452	0.00475	0.094	0.068
60	59	61		0.34099	0.35837	0	0
61	61	62	315	0.14632	0.08775	0.032	0.024
62	35	63	200	0.22754	0.13646	0.0496	0.0372
63	50	64		0.21520	0.12905	0.0312	0.0234
64	64	65	315	0.07196	0.04316	0.0312	0.0234
65	64	66	315	0.12696	0.07614	0.204	0.160
66	45	67		0.05141	0.05404	0	0
67	67	68	630	0.04967	0.02978	0.220416	0.18031
68	67	69	100	0.02584	0.01549	0.0656	0.0492
69	45	70	315	0.12732	0.13381	0.1023	0.07876
70	64	71	315	0.15281	0.16059	0.1096	0.0822
71	51	72		0.10654	0.11196	0	0
72	72	73	315	0.39817	0.41845	0.0608	0.0456
73	28	74	315	0.14232	0.14957	0.0648	0.0486
74	67	75		0.20472	0.21515	0	0
75	75	76	200	0.42873	0.45057	0.104	0.078

76	75	77		0.12257	0.12882	0	0
77	77	78	315	0.29114	0.30597	0.04	0.03
78	77	79		0.10118	0.10634	0.0656	0.0492
79	79	80	315	0.06491	0.06821	0.0608	0.0456
80	79	81	315	0.16597	0.17443	0.0536	0.0402
81	79	82		0.12340	0.12969	0	0
82	82	83	315	0.10536	0.06318	0.0616	0.0462
83	82	84		0.34231	0.35975	0	0
84	84	85	150	0.40154	0.12705	0.0928	0.0696
85	84	86		0.11708	0.07021	0	0
86	86	87	315	0.07404	0.04440	0.1228	0.0846
87	86	88		0.11117	0.03517	0	0
88	88	89	315	0.08377	0.02650	0.072	0.054
89	86	90	50	0.40295	0.12750	0.1944	0.1458
90	88	91		0.16413	0.09843	0	0
91	91	92	200	0.02831	0.01697	0.2192	0.1644
92	91	93	50	0.17621	0.18519	0.1792	0.1344
93	91	94		0.04936	0.05187	0	0
94	94	95	100	0.00355	0.00213	0.0704	0.0528
95	94	96		0.09913	0.10418	0	0
96	96	97	50	0.02607	0.01563	0.0312	0.0234
97	96	98	315	0.07840	0.08239	0.0424	0.0318
98	20	99		0.01341	0.01409	0	0
99	99	100	315	0.00894	0.00537	0.32	0.24
100	99	101	200	0.02237	0.0134	0.0528	0.0396
101	20	102	630	0.05586	0.30351	0.2032	0.1024
102	9	103	50	0.06108	0.03663	0.0408	0.0306
103	99	104		0.04409	0.04634	0	0
104	104	105	315	0.06550	0.62680	0.12328	0.08246
105	104	106	315	0.03989	0.04193	0.4152	0.3114
106	104	107	315	0.00003	0.00290	0.312	0.234
107	104	108		0.05183	0.05447	0	0

108	108	109	315	0.03162	0.01897	0.0448	0.0306
109	108	110		0.02550	0.00351	0	0
110	108	111	315	0.02607	0.04634	0.077	0.0502
111	111	112	50	0.03989	0.01563	0.072	0.054
112	111	113		0.07840	0.02680	0	0
113	113	114	200	0.03989	0.00351	0.0408	0.0306
114	113	115		0.02550	0.04634	0	0
116	113	116	100	0.02607	0.01563	0.0406	0.0304
117	116	117		0.03989	0.02680	0	0
118	117	118	100	0.02550	0.05447	0.4164	0.3146
119	117	119	100	0.02607	0.01563	0.0328	0.0246
120	119	120		0.03989	0.04634	0	0
121	119	121	200	0.07840	0.00351	0.0786	0.0764