ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING

STUDIES ON VOLTAGE CONTROL OF DISTRIBUTION SUBSTATIONS USING STATIC VAR COMPENSATORS

(CASE STUDY: ADDIS ABABA KALITY II 132/15 kV SUBSTATION)

A thesis submitted to Addis Ababa Institute of Technology, School of Graduate Studies, Addis Ababa University

In partial fulfillment of the requirement for the Degree of Master of Science in Electrical Engineering

BY

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APPROVAL BY BOARD OF EXAMINERS

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Declaration

I, Yared Tafesse, declare that this MSc thesis is my original work and has not been presented for the fulfillment of a degree in this or any other university, and all sources and materials used for the thesis have been acknowledged.

Signature: __________________ Date: ______________________

Acknowledgments

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I would also like to express my ultimate gratitude to my family, especially my mam for their endless prays and their outstanding support.

Finally, I praise and glorify the name of GOD, the Almighty, the Creator who creates all these nice people and these pleasant opportunities.

Abstract

Voltage control of power distribution systems is very important to ensure quality power supply to the customers. The potential applications of flexible AC transmission system (FACTS) devices, such as the Static Var Compensators (SVCs) play a major role in voltage regulation due to its fast response and high capability. Thus, it becomes necessary to study the use of SVCs for distribution system voltage control under normal operating conditions. In this thesis, voltage control of Kality II 15 kV distribution substation using Static Var Compensators (SVCs) is investigated.

Data collection and analysis is carried out to study the voltage profile and control of Kality II substation. SVCs modeling and simulation studies have been carried out using DIgSILENT software. Simulation studies with and without SVCs has been performed for different scenarios of SVCs Configurations, such as FC-TCR (Fixed Capacitor-Thyristor Controlled Reactor) and TCR-TSC (Thyristor Controlled Reactor - Thyristor Switched Capacitor), to analyze its effect on voltage profile.

The simulation results reveal 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. Thus, based on the findings of this research, it is concluded that SVCs may be implemented for improvement of voltage profile of distribution substations.

Keywords: SVCs, Voltage control, FACTS, FC-TCR , TCR-TSC, Reactive power compensation

Table of Contents

List of Figures

List of Tables

List of Abbreviation and Terminologies

AC	Alterative Current
AVR	Automatic Voltage Regulator
B_{SVC}	Static Var Compensator susceptance
B_{TCR}	Thyristor Controlled Reactorsusceptance
CMS	Customers’ Management System
CSC	Customer Service Centre
DC	Direct Current
EEA	Ethiopia Electricity Agency
EEP	Ethiopian Electric Power
EEPCO	Ethiopian Electric Power Corporation
EEU	Ethiopian Electricity Utility
FACTS	Flexible AC Transmission Systems
FC-TCR	Fixed Capacitor-Thyristor Controlled Reactor
GUPFC	Generalized Unified Power Flow Controller
GIPFC	Generalized Interline Power-Flow Controller
HPFC	Hybrid Power Flow Controller
IPFC	Interline Power Flow Controller
MVA	Mega-Volt-Ampere
MVAR	Megavolt Ampere Reactive
P.F	Power Factor
PI	Proportional–Integral Controller
SVC	Static Var Compensator
SSSC	Static Synchronous Series Compensator

SSG	Static Synchronous Generator
STATCOM	Static Synchronous Compensator
TCPST	Thyristor-Controlled Phase Shifting Transformer
TCR	Thyristor Controlled Reactor
TCSC	Thyristor-switched series capacitor
TCPAR	Thyristor Controlled Phase Angle Regulators
TSC	Thyristor Switched Capacitor
TSC-TCR	Thyristor Switched Capacitor - Thyristor Controlled Reactor
UPFC	Unified Power-flow Controller
VSI	Voltage Source Inverters
V_{ref}	Reference Voltage
X	Reactance in ohm
Xs	Slope or droop reactance

Chapter One

Introduction

1.1 Background

The electricity losses through transmission and distribution in Ethiopia are around 20%, which is much higher than the international average of 12-13%. Most of the loss happens during distribution from the national grid to end users.

The Ethiopian Electric Power Corporation (EEPCO), founded in 1956, is the state-owned utility in charge of electric power generation, transmission, distribution, sales service in the country and maintenance of the national grid. The company has been undergoing various continued transformations, such as via Customers' Management System (CMS), decentralization of Accounting and Billing system from once highly centralized down to the regional distribution offices, districts, and customer service centers (CSCs), and Prepayment (Metering) System, in an effort to realize its long term strategic vision of "becoming a center of excellence in providing quality electric service to everyone's doorstep and being competitive in energy export."

(http://www.reegle.info/policy-and-regulatory-overviews/ET)

In Ethiopia, the electricity law (Electricity Proclamation No.86) was amended in 1997. As the result, power utility was privatized as Ethiopia Electric Power Corporation (hereinafter called "EEPCo") and the power generation sector was liberalized. In addition, Ethiopia Electricity Agency (hereinafter called "EEA") was established as regulatory authority of electric power business. EEA is conducting regulation relevant to business license, investment license and grid access. Afterwards EEPCo was divided into two organizations in December 2013, i.e. Ethiopian Electric Power (hereinafter called "EEP") which is responsible for power generation and transmission, and Ethiopian Electricity Utility (hereinafter called "EEU") which is responsible for distribution.

1.2 Problem Statement

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 protection scheme of the SVCs takes significant part when installing SVCs to appropriate locations to improve the voltage profile and reactive power compensation. This thesis addresses the problems of voltage control of distribution substations using stat var compensators (SVCs) and investigates methods for improving voltage profile of Kality II 132/15 kV distribution substation.

1.3 Objectives of the Thesis

General Objective:

The general objective of this thesis is to carry out studies on voltage control of distribution substations using static var compensators (SVCs).

The Specific Objectives:

The specific objectives include the following:

- To collect relevant data from Ethiopian electric utility, Ethiopian electric power and load demand of Kality II 132/15 kV distribution substation
- To analyze the relevant data and identify the voltage related problems of Kality II distribution substation
- To study voltage control mechanisms and investigate methods for improving voltage profile using Static Var Compensators
- To develop simulation model the existing Kality II distribution network using DIgSILENT (Power Factory 15) software
- To carry out simulation studies and evaluate the network performance for different SVCs configurations for voltage control
- To analyze and compare the voltage profile of Kality II 132/15 kV distribution substation with and without SVCs & To draw relevant conclusions and suggest recommendations based on the finding of this research.

1.4 Methodology

Before visiting the substation, I started by reviewing published literature from international electrical engineering groups such as the Institute of Electrical and Electronics Engineers (IEEE), were reviewed with important relevant subjects related to voltage control, and static var compensators briefly discussed and identified.

History and current important data of the existing network have been collected from Ethiopian electric power and Ethiopian electric utility. Interview with engineers of substation and distribution network have been considered.

Analyzed the collected data and then model the system in DIgSILENT (Power Factory 15) distribution software and simulate with and without SVC to achieve the objectives.

1.5 Scope and Limitations of the Thesis

This thesis work is limited by the following factors:

- This work only addresses technical aspects of possible solutions for keeping the voltage profile within the allowed voltage limit.
- The reactive power control model for SVC is considered as an ideal, and thus losses are not taken into consideration.

1.6 Thesis Layout

The organization of the thesis has been made in such a way that the reader finds an introduction, literature review of different methods for improving voltage deviation, results of the simulations of different methods, conclusion and future work. The layout of the thesis is as follows:

Chapter one gives an introduction background, statement of the problem, objectives of the study, methodology followed in the thesis work and finally it provides the thesis layout.

Chapter two presents literature review on voltage control, gives some background and explanation of static Var compensator (SVC) in detail and discusses different type of configuration.

Chapter three contains data collection, Modeling and Control aspects of Kality II Substation in more detail starting from site description.

Chapter four presents simulation studies using DIgSILENT software and analysis of the results.

Chapter five includes the conclusions, recommendations and suggestions for future work to further investigate the research work carried out in this thesis.

Chapter Two

Literature Review on Voltage Control Using Static Var Compensators

2.1 Introduction

For the past two decades, Flexible AC Transmission Systems (FACTS) devices have been implemented in the power systems to enhance their capacity, stability, security and power quality. Since FACTS devices are designed based on advanced power electronics technology, they are capable of providing control action at high speed [3].

Several types of FACTS devices have been developed for application in power systems [5]. The function of these devices is primarily to control the power flow through the transmission lines and regulate the voltage level where they are installed. FACTS devices can generally be classified as below [4]:

- shunt connected controllers such as static Var compensator (SVC) and static synchronous compensator (STATCOM)
- series connected controllers such as static synchronous series compensator (SSSC), series capacitive reactance compensator (SCRC), Thyristor-switched series capacitor (TCSC), and Thyristor-controlled series reactor (TCSR)
- a combination of shunt and series connected controllers such as unified power flow controller (UPFC), Thyristor-controlled phase shifting transformer (TCPST).

The Flexible AC Transmission System (FACTS) is a concept that involves the application of high power electronic controllers in AC transmission networks which enable fast and reliable control of power flows and voltages. FACTS controllers have a significant impact on damping power system oscillations and compensating dynamic reactive power.

Since the ″other static controllers″ based FACTS devices are not widely used in current Power systems, the focused only on the power electronics based FACTS devices. The FACTS controllers are classified as follows:

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

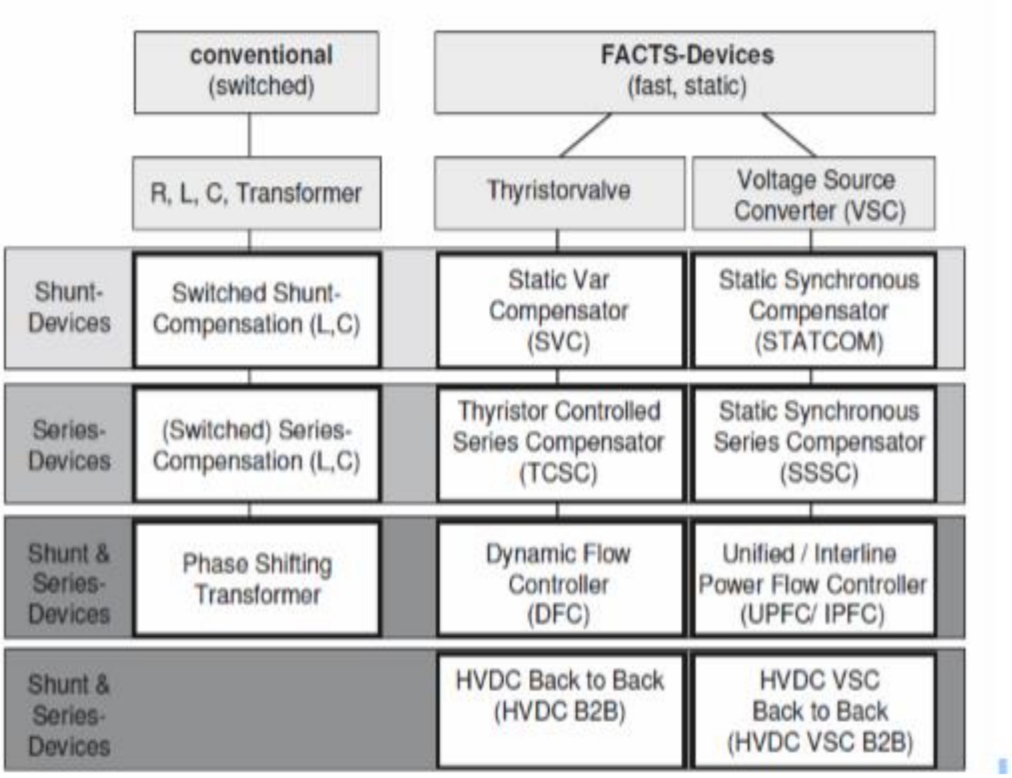


Figure 2.1 overview of major FACTS-Devices

2.2 FACTS Classification

FACTS can be divided into four categories as follows:

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.

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.

Combined series-series controller

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. [9]

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 is the most versatile and powerful device among the FACTS device family. 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. [1]

2.3 Static Var Compensators (SVCs)

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 [6]. 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 [7].

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. 2.2 [8].

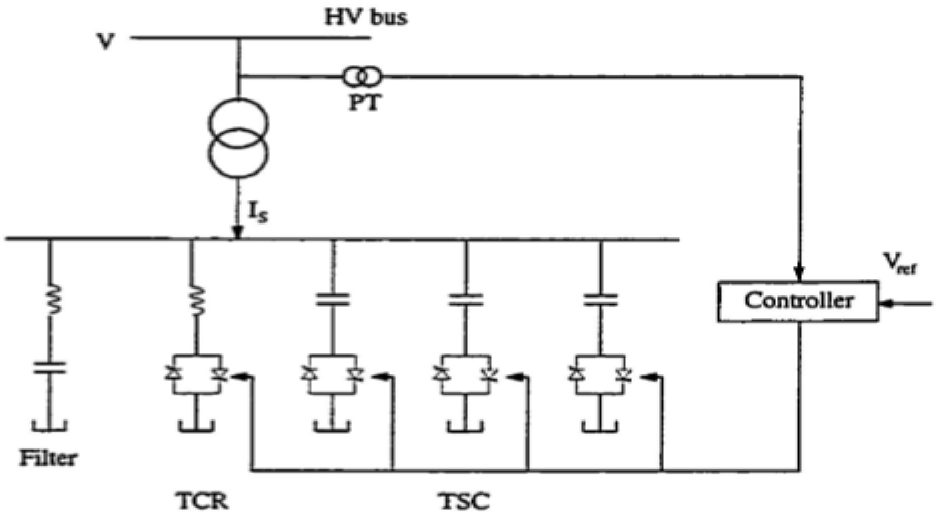


Figure 2. 1 Schematic diagram of a SVC

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) [11].

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 [10]. It should be noted that the SVC current will contain some harmonic content, something that needs attention in the design process. 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 [6].

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:

- Increase power transfer in long lines [12,13]
- Improve stability with fast acting voltage regulation [14,15]
- Damp low frequency oscillations due to swing (rotor) modes [16]
- Damp sub synchronous frequency oscillations due to torsional modes [17]
- Control dynamic over voltages [18,19]

2.4 Main Components of SVCs

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. 2.3. 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. 2.3. 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. [2]

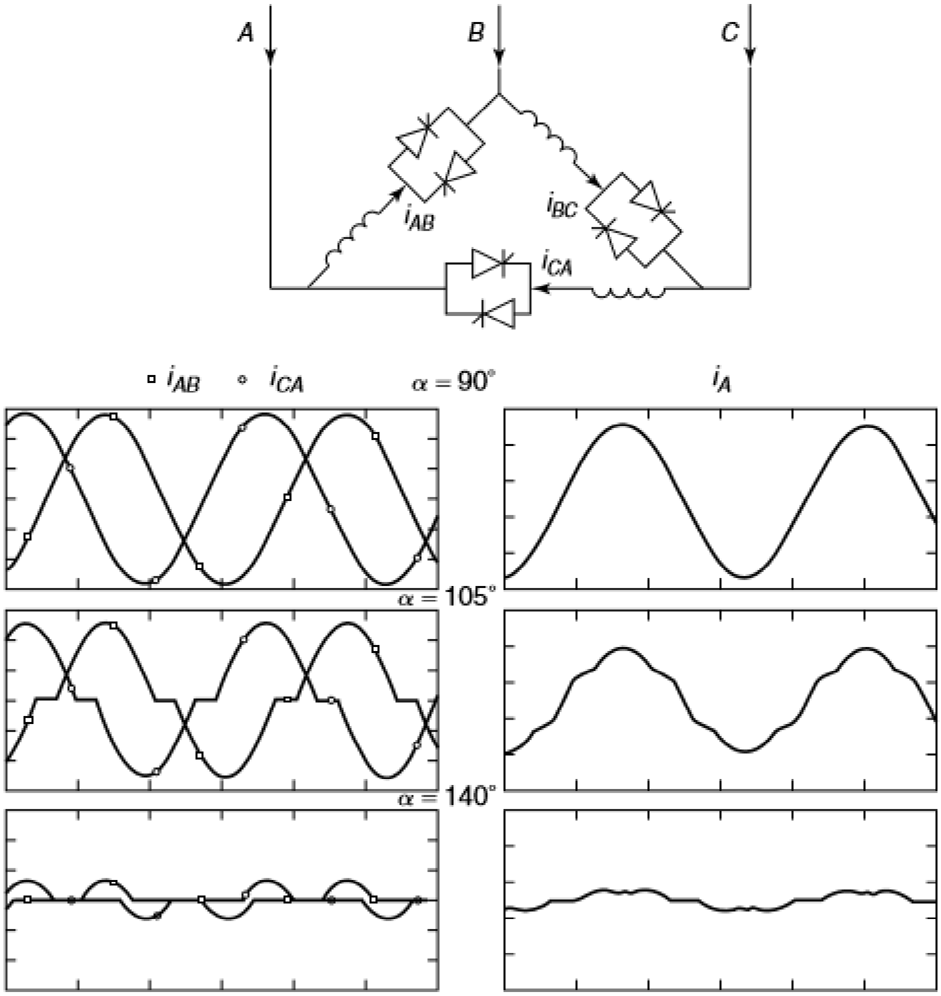


Figure 2. 2 A delta-connected TCR and its phase and line currents for different α

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

$$i_{AB3} = a_3 \cos(3wt + \emptyset_3)$$

$$i_{BC3} = a_3 \cos(3wt + \emptyset_3 - 3\frac{2\pi}{3})$$

$$= a_3\cos(3wt + \emptyset_3 - 2\pi)$$

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

$$= a_3\cos(3wt + \emptyset_3 - 4\pi$$

Thus $$i_{AB3} = i_{BC3} = i_{CA3} \quad (2.1)$$

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:

$$i_{A3} = i_{AB3} - i_{CA3} = 0 \quad (2.2)$$

Likewise $$i_{B3} = 0\,,\; i_{C3} = 0 \quad (2.3)$$

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 $p = 0,1,2,3, \ldots.$ (3, 9, 15, 21, 27, etc.) cannot flow in the lines during balanced operation. [2]

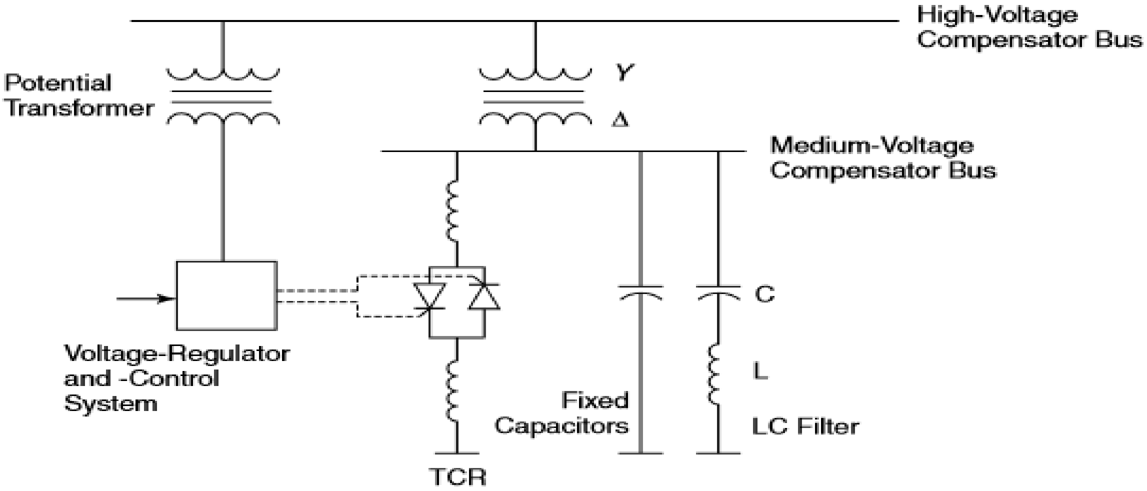


Figure 2. 3 A 1-line diagram of a TCR compensator with fixed-shunt capacitors

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. 2.4. 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.

TCR Operating Characteristics Without Voltage Control

The simplest SVC configuration consists of a TCR connected to the power system as shown in Fig. 2.5. In the analysis of compensator performance, the fundamental frequency behavior is generally considered. In practice, harmonics are filtered and reduced to very low values. The approach shown in Fig. 2.5 is very convenient for the performance analysis the whole TCR branch is replaced by an equivalent continuously variable reactor. The sinusoidal current flowing in this reactor is equal to the fundamental component of the non-sinusoidal current flowing in the TCR. Note that B_{TCR} is the variable susceptance in the foregoing equivalent of the TCR. The overall compensator susceptance B_{SVC} can be defined with the following equation:

$$I_{SVC} = VjB_{SVC} \tag{2.4}$$

In the simple case of a TCR, the compensator susceptance is

$$B_{SVC} = B_{TCR} \tag{2.5}$$

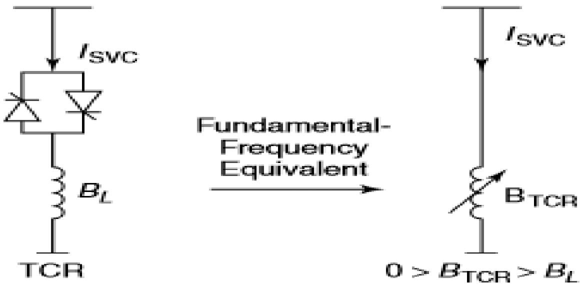


Figure 2. 4 A simple SVC circuit using a TCR

Voltage–Current Characteristic or Operating Characteristic shows the SVC current as a function of the system voltage for different firing angles, as depicted in Fig. 2.6(a). This V-I characteristic is given in a very general sense. No control system is assumed to vary the firing angle, and any operating point within the two limits is possible depending on the system voltage and the setting of the firing angle. This characteristic clearly illustrates the limits of the operating range, and it may include the steady-state characteristics of the various possible controls. This characteristic is the usual way in which the system engineers prefer to look at the compensator, because the characteristic shows the steady-state performance of the SVC plant.[2]

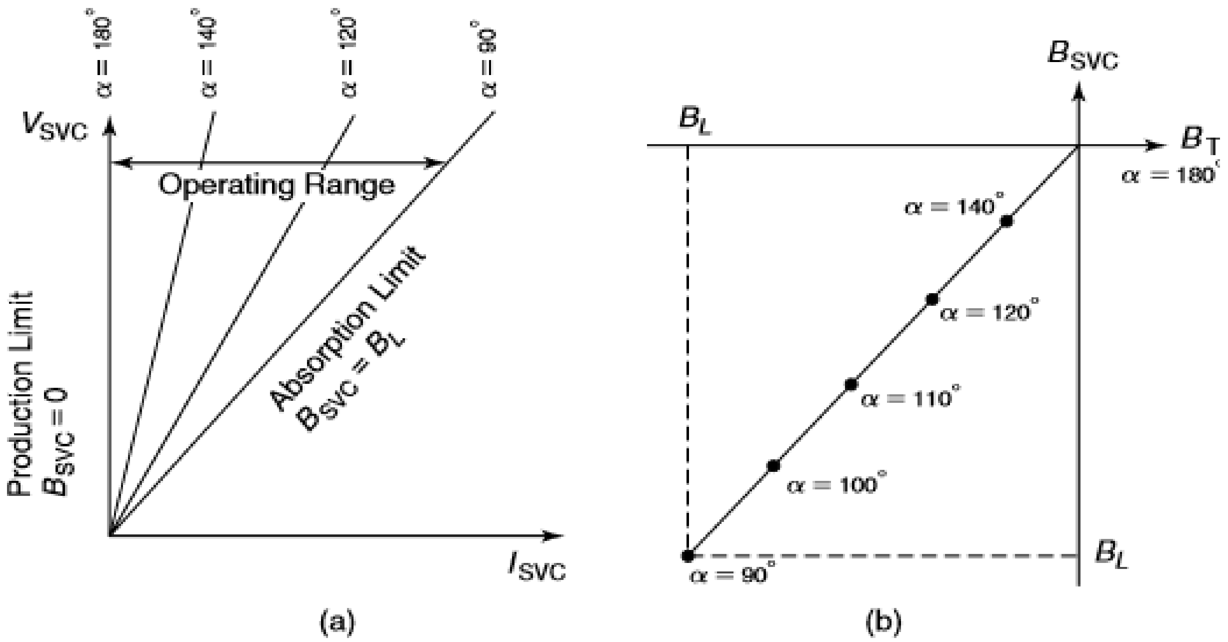


Figure 2. 5 Different characteristics of an SVC: (a) the voltage–current characteristic and (b) the SVC TCR susceptance characteristic

SVC TCR Susceptance Characteristics illustrate the change of the total SVC susceptance when the TCR susceptance is varied, as shown in Fig. 2.6(b). The susceptance characteristic for this case is very simple because $B_{SVC} = B_{TCR}$. Note that the TCR susceptance is negative, indicating that the TCR is an absorbing reactive component. These characteristics are of most interest to control-system analysis. The controls affect the TCR firing angle, whereas the total susceptance B_{SVC} influences the power system.

TCR Operating Characteristics with Voltage Control

The operating range of Fig. 2.6(a) can be reduced to a single characteristic of operating points if the effect of the voltage control is incorporated. Let us assume that the compensator is equipped with the voltage control shown in Fig. 2.7(a). The system voltage is measured, and the feedback system varies B_{TCR} to maintain V_{ref} on the system. This control action is represented in the operating characteristic in Figure 2.7(b) by the horizontal branch marked as control range. This characteristic shows the hard-voltage control of the compensator, which stabilizes the system voltage exactly to the set point V_{ref}.

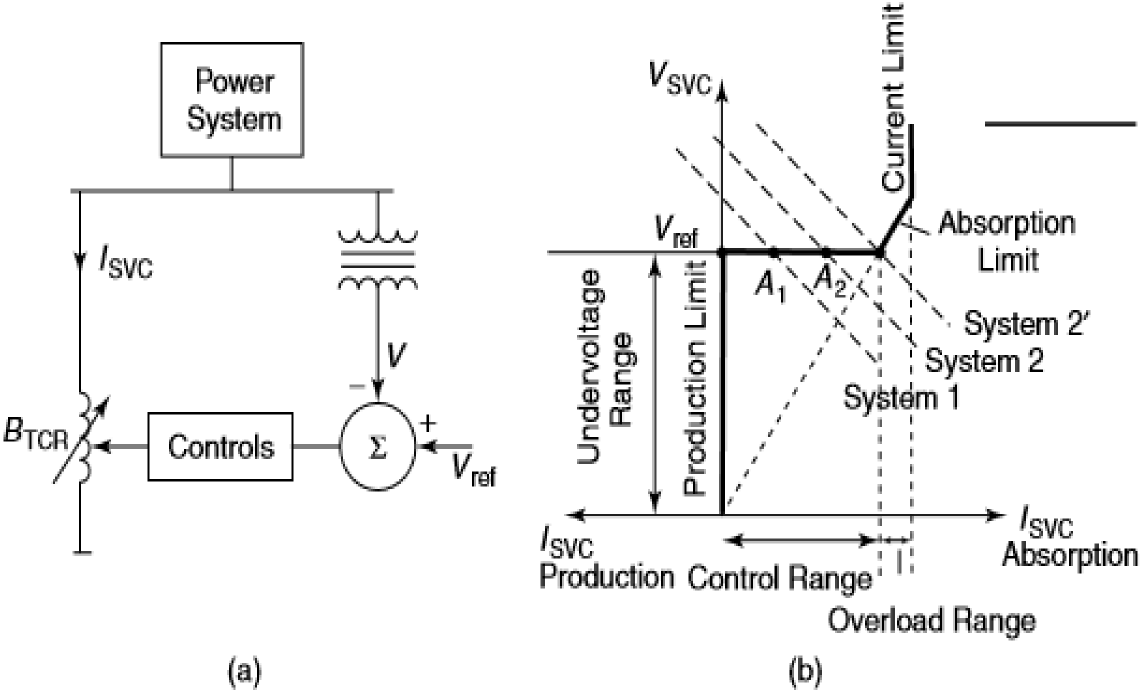


Figure 2. 6 The operating characteristics of a TCR with voltage control (a) an SVC control system and (b) the V-I characteristic

Two system characteristics-system 1 and system 2 are illustrate the decline in system node voltage when the node is loaded inductively and reactive power is absorbed.

The corresponding operating points for the two system conditions are A_1 and A_2. If the system voltage of system 2 rises, a new characteristic-system 2′ results. Operating point A then moves to the right and reaches the absorption limit of the compensator. Any further increase in system voltage cannot be compensated for by the control system, because the TCR reactor is already fully conducting. The operating point A_2 will, therefore, move upward on the characteristic, corresponding to the fully on reactor connected to the system $(\alpha = 90^{\circ})$. The compensator then operates in the overload range, beyond which a current limit is imposed by the firing control to prevent damage to the Thyristor valve from an overcurrent. At the left-hand side, the compensator will reach the production limit if the system voltage drops excessively; the operating point will then lie on the characteristic of the under voltage range.

Thyristor-Switched Capacitor (TSC)

The Thyristor switched capacitor is a shunt connected capacitor that is switched ON or OFF using Thyristor valves [9]. Figure 2.8 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 [4]. 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 $(t_1)$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 (t_2) 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 2.8.

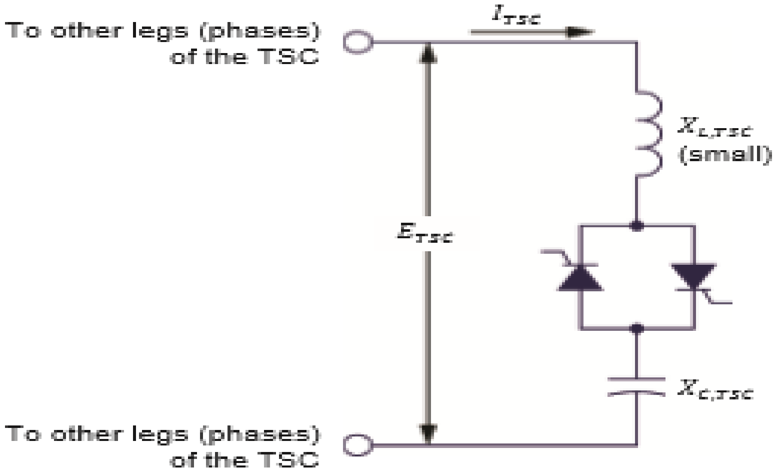


Figure 2. 7 Equivalent circuit of one phase of a Thyristor-switched capacitor (TSC) in an SVC

The complete diagram showing all three legs (phases) of a TSC in an SVC is illustrated in Figure 2.9 As the figure shows, TSCs are generally connected in a 6-wire, delta configuration, just as for TCRs.

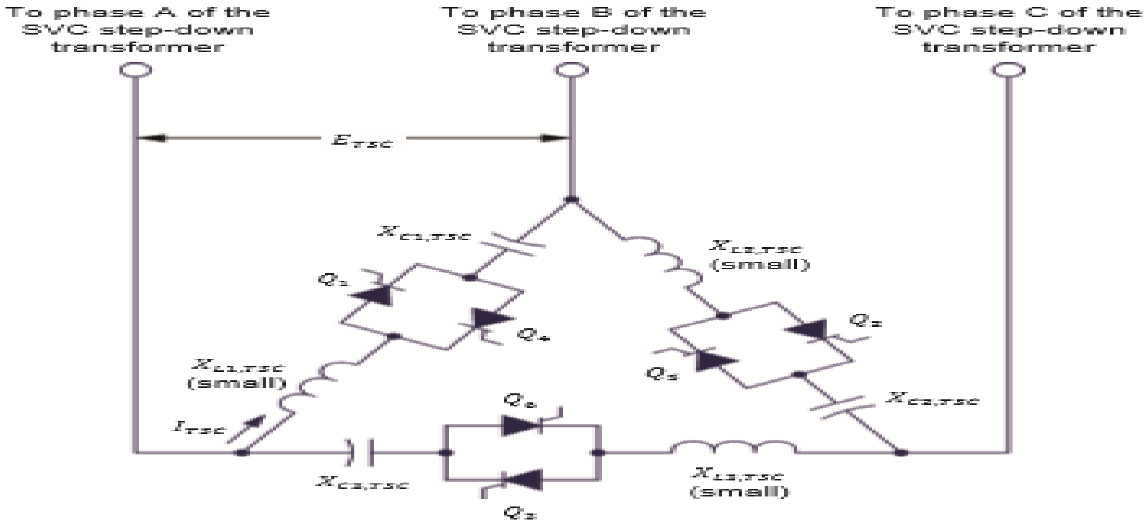
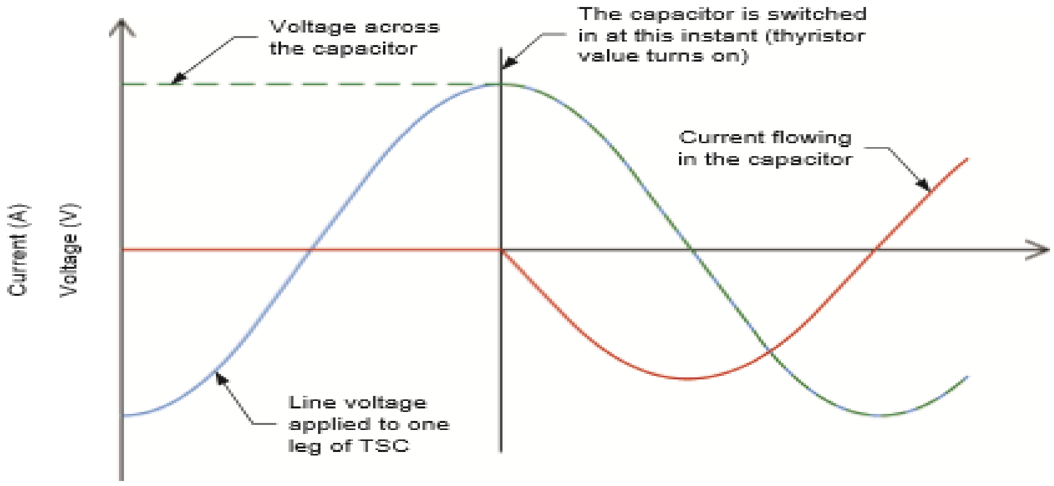


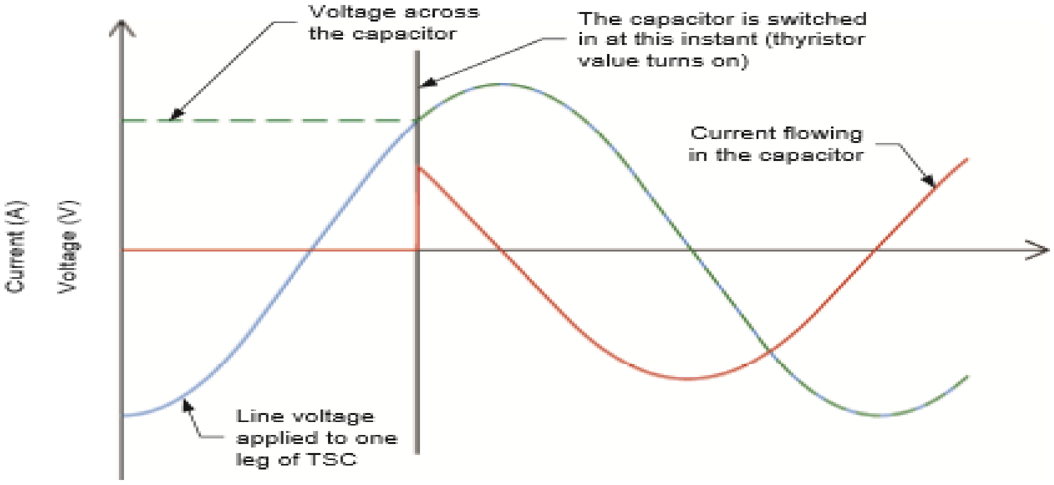
Figure 2. 8 Complete diagram of the three legs (phases) of a Thyristor-switched capacitor (TSC) in an SVC

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 2.10a, the capacitor is fully charged when it is switched in, while in Figure 2.10b, 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. 9 Voltage and current waveforms of a capacitor of TSC when it is switched on

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.

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 2.11

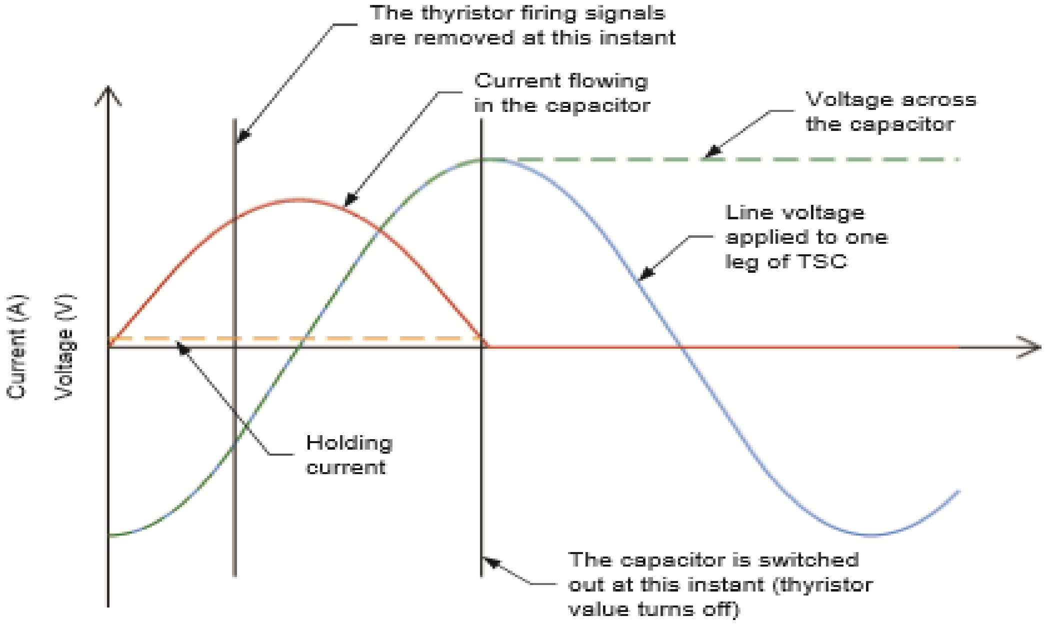


Figure 2. 10 Voltage and current waveforms related of a capacitor of TSC when it is switched off

Switching A Capacitor to A Voltage Source

The circuit shown in Fig. 2.12 consists of a capacitor in series with a bidirectional Thyristor switch. It is supplied from an ideal ac voltage source with neither resistance nor reactance present in the circuit. The analysis of the current transients after closing the switch brings two cases: [2]

- The capacitor voltage is not equal to the supply voltage when the Thyristors are fired. Immediately after closing the switch, a current of infinite magnitude flows and charges the capacitor to the supply voltage in an infinitely short time. The switch realized by Thyristors cannot withstand this stress and would fail.
- The capacitor voltage is equal to the supply voltage when the Thyristors are fired, as illustrated in Fig. 2.12(b). The analysis shows that the current will jump immediately to the value of the steady-state current. The SteadyState condition is reached in an infinitely short time. Although the magnitude of the current does not exceed the steady-state values, the

Thyristors have an upper limit of di / dt values that they can withstand during thefiring process. Here, di / dt is infinite, and the Thyristor switch will again fail. It can therefore be concluded that this simple circuit of a TSC branch is not suitable.

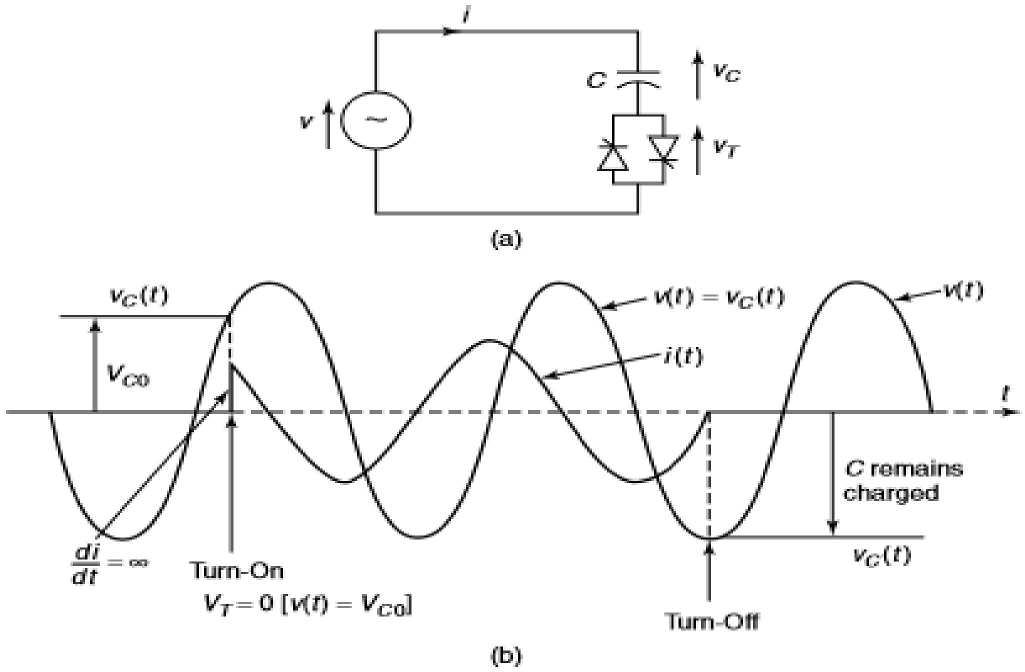


Figure 2. 11 Switching of a capacitor at a voltage source (a) a circuit diagram (b) the current and voltage waveforms

Switching A Series Connection of a Capacitor and Reactor

To overcome the problems discussed in the preceding list, a small damping reactor is added in series with the capacitor, as depicted in Fig. 2.13. Let the source voltage be

$$V(t) = Vsinw_o t \tag{2.6}$$

where w_0 is the system nominal frequency. The analysis of the current after closing the Thyristor switch at $t = 0$ leads to the following result.[2]

$$i(t) = Icos(w_0 t + \alpha) - nB_c \left(V_{co} - \frac{n^2}{n^2-1} V \sin\alpha\right) \sin w_n t - I \cos\alpha \cos w_n t \tag{2.7}$$

where α is the Thyristor firing angle, w_n is the TSC natural frequency, V_{co} is the voltage across the capacitor at t = 0.

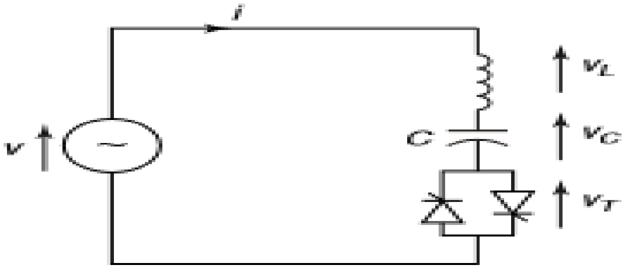


Figure 2. 12 A TSC with a series reactor

where the natural frequency is

$$w_n = nw_0 = 1/\sqrt{LC} \tag{2.8}$$

The current amplitude I is determined by

$$I = V\frac{B_c B_l}{B_c + B_l} \tag{2.9}$$

where B_C is the capacitor susceptance and B_L is the reactor susceptance and n is given by:

$$n = \frac{1}{\sqrt{w_0^2 LC}} = \sqrt{\frac{X_C}{X_L}} \tag{2.10}$$

We can alternatively express the magnitude of the TSC current (2.9), as [4, 2]

$$I = V\frac{B_C B_L}{B_C + B_L} = VB_C\frac{n^2}{n^2 - 1} \tag{2.11}$$

If we consider the steady-state case without a series connected reactor and note that the magnitude of the TSC current is determined by:

$$I = VB_C \tag{2.12}$$

A magnification in current by a factor of $n^2/(n^2 - 1)$ is seen as compared to the case without reactor. As n is determined by X_L and X_C, shown in (2.10), the LC circuit have to be carefully designed to avoid resonance. This is normally done by keeping the inductor reactance X_L at 6% of X_C [11]. The same magnification factor is also inherent in the magnitude of the capacitor voltage.

$$V_C = IX_C = V\frac{n^2}{n^2 - 1} \tag{2.13}$$

It is interesting to study this magnification as a function of the tuning of the TSC branch. For LC circuits tuned to resonance frequencies of three times the supply frequency and higher, the magnification factor is close to 1.0; for tuning below $3w_0$, the magnification factor increases very rapidly. For practical schemes, therefore, n should be chosen higher than 3 (typically, between the 4th and 5th harmonic).

TSC Switching Operation

The Terms Involving Natural Resonance Frequency, w_n These terms constitute the oscillatory transients. it is seen that the following two conditions need to be fulfilled simultaneously to avoid the transients [2,4]:

$$\cos\alpha = 0 \;\Rightarrow\; \sin\alpha = \pm 1 \tag{2.14}$$

$$V_{CO} = \pm V\frac{n^2}{n^2-1} = IX_C \tag{2.15}$$

The first condition, Eq. (2.14), expresses that to avoid transients, the switch must be closed either at the positive or the negative peak of the supply-voltage sine wave. The second condition, Eq. (2.15), shows that the capacitor must be charged to a predetermined value. In practice, there are many problems in the realization of a firing strategy that avoids the transients, including the following:

- At places where SVCs are installed, usually the voltages are not purely sinusoidal and constant, which makes the decision of when to switch on less predictive than the ideal condition. A certain amount of transients is to be expected, even with very precise firing strategies
- Keeping the capacitor charged at $V\frac{n^2}{n^2-1}$ asks for extra charging equipment. It is easier to keep a capacitor charged at V, but then a certain amount of transients will occur anyway, for the supply voltage V, line inductance X, and, consequently, n can change randomly during system operation.

it is very hard to achieve switches that are completely transient free and the objective and the actual firing strategies are instead focused on minimizing the oscillatory transients. This is done by switching the TSC when the capacitor voltage is equal to the grid voltage, if $V_{CO} < V$, or at the peak of the grid voltage when the Thyristor valve voltage is at a minimum, if $V_{CO} \geq V$ [4]. Note that V is the peak value of the grid voltage. Thyristor switches can only be turned off at zero current [10], which entails leaving a voltage across the capacitor equal to its peak value:

$$V_{CO} = V \frac{n^2}{n^2-1} \tag{2.16}$$

This leads to an increased voltage stress of the Thyristor valve as the voltage across it will vary between zero and the peak-to-peak voltage of the supply.

The TSC Configuration

A basic single-phase TSC consists of an anti-parallel–connected Thyristor-valve pair that acts as a bidirectional switch in series with a capacitor and a current limiting small reactor. The Thyristor switch allows the conduction for integral number of half-cycles. The capacitor is not phase controlled, as is a TCR. The Thyristor valves are turned on at an instant when minimum voltage is sensed across the valves to minimize the switching transients. Barring these initial transients, the TSC current is sinusoidal and free from harmonics, thus obviating the need for any filters.

The small-series inductor is installed to limit current transients during overvoltage conditions and planned switching operations, as well as when switching at incorrect instants or at the inappropriate voltage polarity. The inductor magnitude is chosen to give a natural resonant frequency of four to five times the system nominal frequency, which ensures that the inductance neither creates a harmonic-resonant circuit with the network nor hampers the TSC control system. Another function of this series inductor is to act in combination with the capacitor as a filter for harmonics generated by the associated TCR. In some cases, discharge circuits are provided with the capacitors to rapidly dissipate the remnant charge on the capacitor after a switch-off. A practical TSC compensator involves n 3-phase TSC banks of equal rating connected in shunt. The overall TSC susceptance at any given instant is the sum of conducting TSC. In some cases, the ratings of different constituent TSC steps may be chosen based on a binary system. In this scheme, $n-1$ capacitors are rated for susceptance B and one capacitor is rated for susceptance $\frac{B}{2}$. Thus the total number of possible TSC steps get extended to 2n. [2]

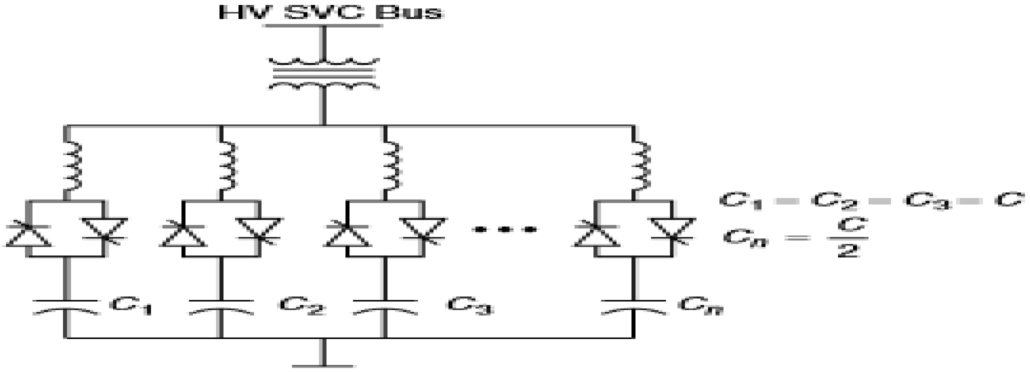


Figure 2. 13 A general TSC scheme

The TSC provides a fast response typically between one-half to one cycle. However, this response time may be extended because of any delays in the measurement and control systems. The TSCs provide virtually unlimited switching operations.

2.5 Configurations of SVCs

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 2.15.

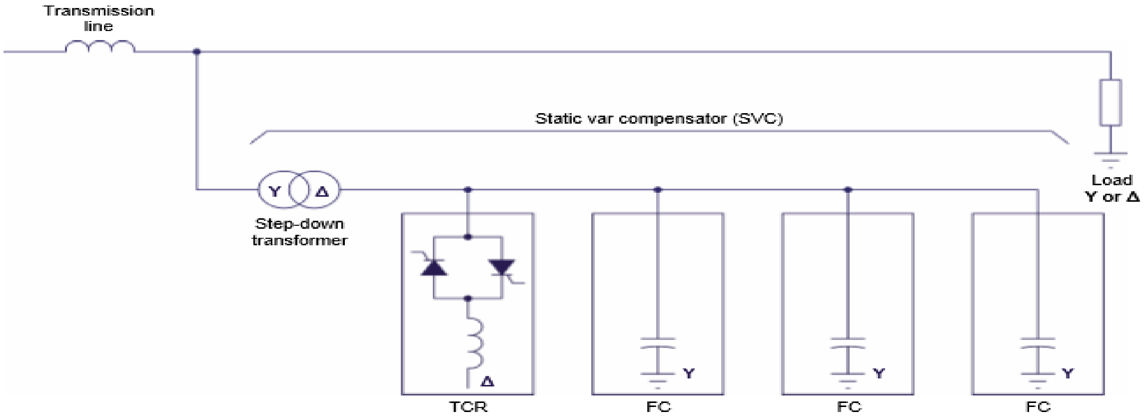


Figure 2. 15 Simplified single-wire circuit diagram of an SVC of the TCR-FC type

FCs have 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 2.16. Note that to simplify the circuit diagram, only one FC is used to represent all FCs of the SVC.

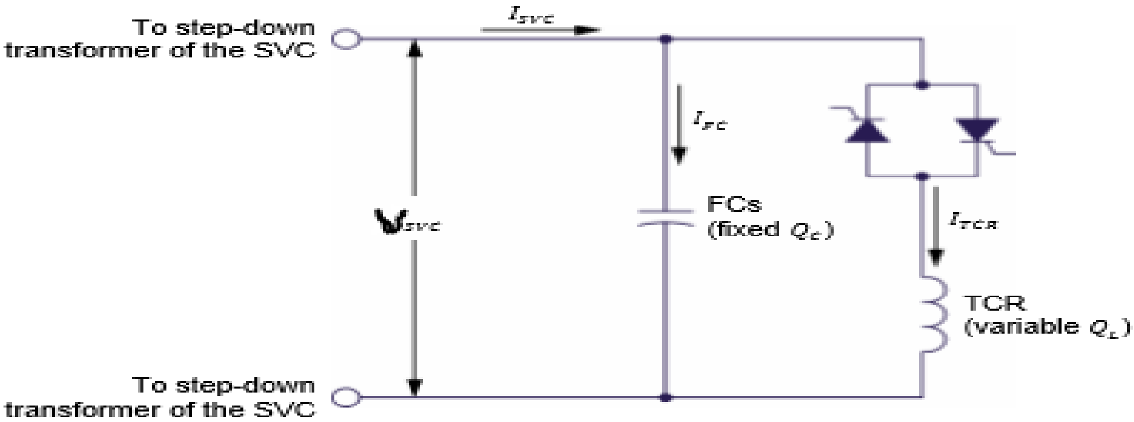


Figure 2. 16 Simplified circuit diagram of one leg (phase) of an SVC of the TCR-FC-type

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 (Q_C) 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 (Q_C) 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 2.17.

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.

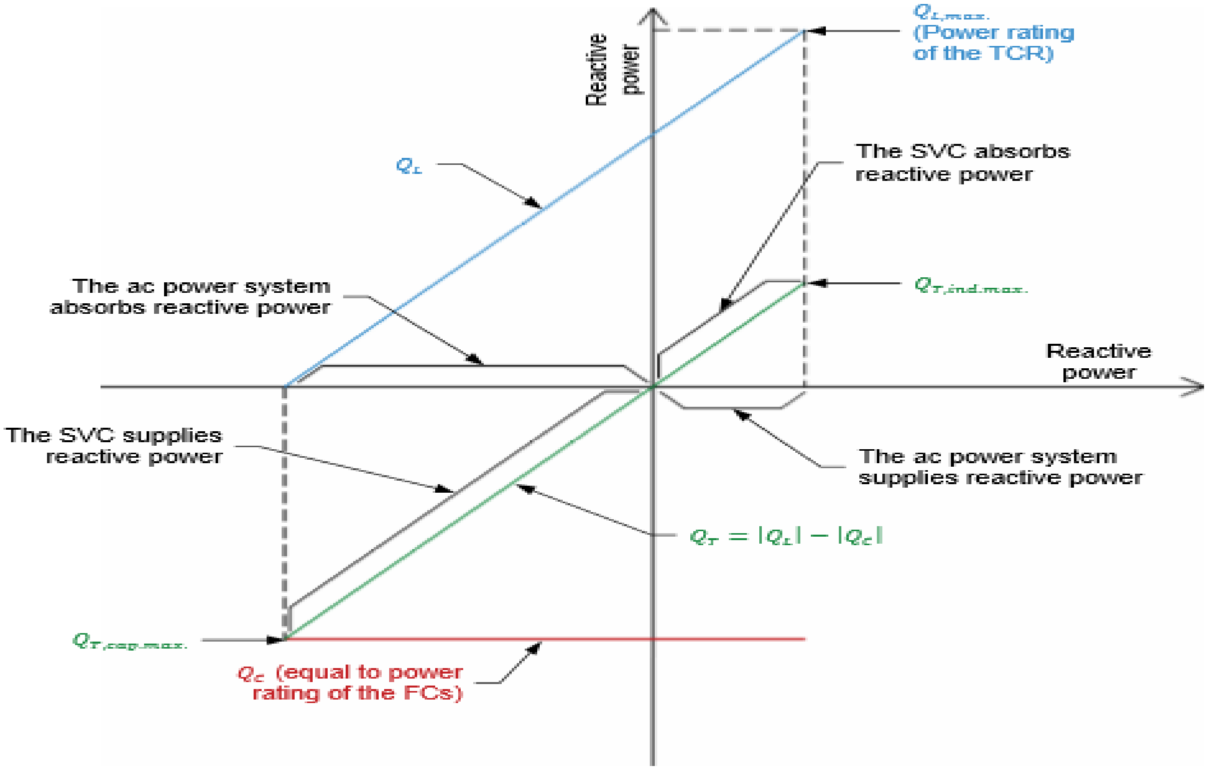


Figure 2. 17 Reactive power exchange characteristic of an SVC of the TCR-FC-type

As the figure 2.17 shows, the total reactive power Q_T 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 Q_L absorbed by the TCR minus the fixed reactive power Q_C supplied by the FCs.

The total reactive power Q_T of an SVC of the TCR-FC type thus ranges from the maximal capacitive reactive power $Q_{T,cap.max.}$, which is equal to the reactive power rating Q_C of the FCs, to the maximal inductive reactive power $Q_{T,ind.max.}$, which is equal to the reactive power rating $Q_{L,max.}$ of the TCR minus the reactive power rating Q_C of the FCs. When the total reactive power Q_T in the SVC is negative, the SVC supplies reactive power. Conversely, when the total reactive power Q_T 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 $Q_{L,max.}$ that is equal to the reactive power (Q_T) 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 (RI^2 losses) in the TCR because during normal operation the reactive power Q_L in the TCR is often comparable to, or even exceeds, the reactive power Q_T which the SVC exchanges with the ac power system to which it is connected (in other words, the current I_{TCR} flowing in the TCR is often comparable to, or even exceeds, the current I_{SVC} flowing between the SVC and the ac power 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.

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 2.18. 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.

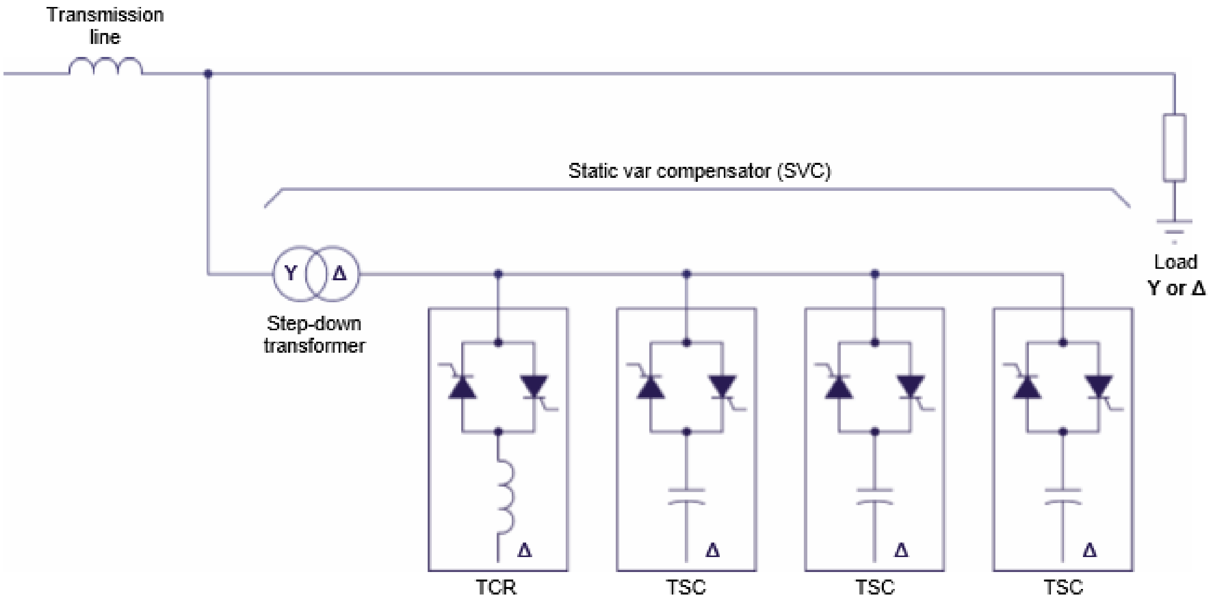


Figure 2. 18 Simplified single-wire circuit diagram of an SVC of the TCR-TSC type

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 2.19. Note that, to simplify the circuit diagram, only one TSC is used to represent all TSCs of the SVC.

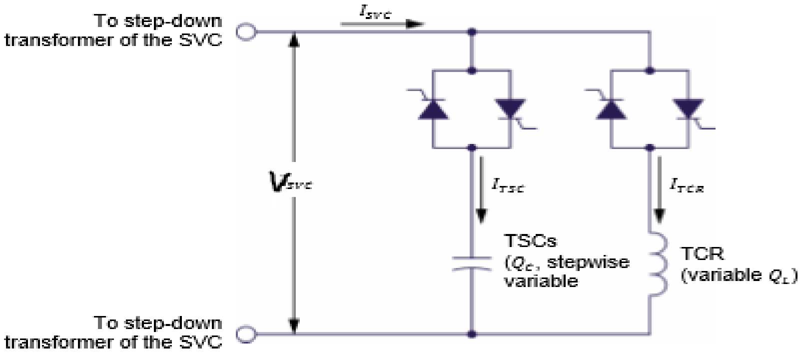


Figure 2. 19 Simplified circuit diagram of one leg (phase) of an SVC of the TCR-TSC type

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 2.20.

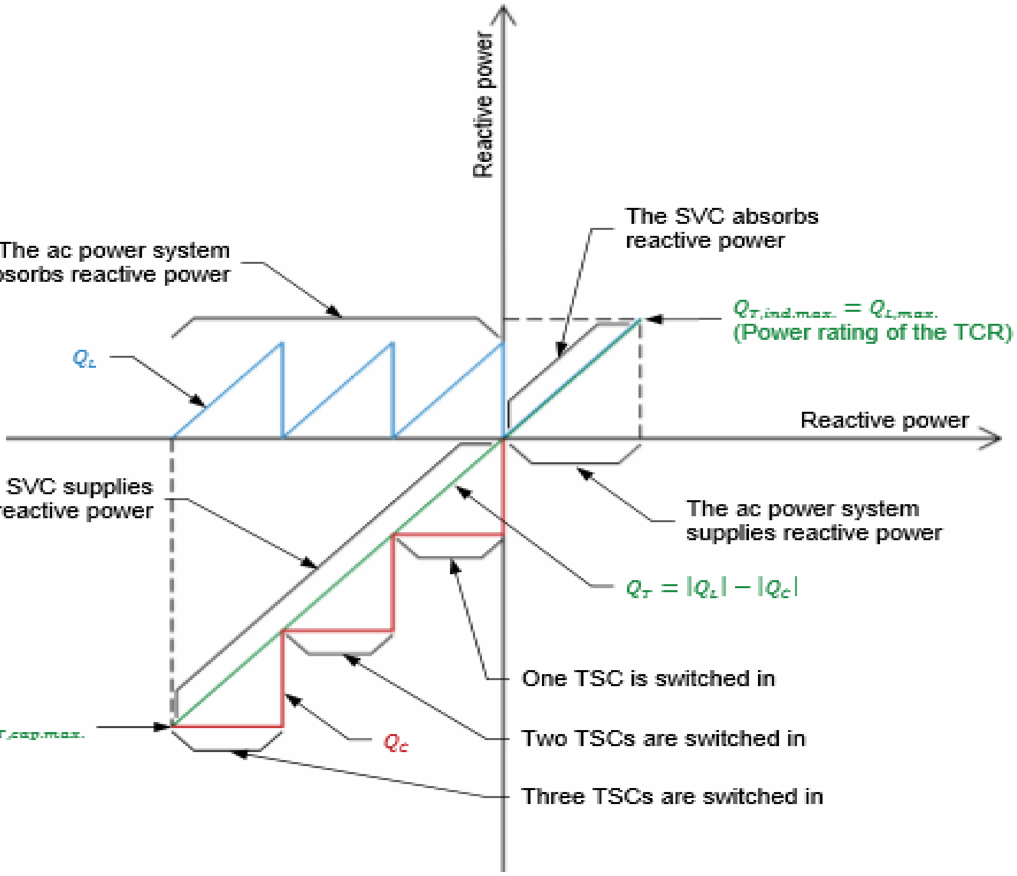


Figure 2. 20 Reactive power exchange characteristic of an SVC of the TCR-TSC-type

As the figure 2.20 shows, the total reactive power Q_T 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 Q_L absorbed by the TCR minus the reactive power Q_C (stepwise variable) supplied by the TSCs. The total reactive power Q_T of an SVC of the TCR-TSC type thus ranges from the maximal capacitive reactive power $Q_{T,cap,max.}$, which is equal to the total reactive power rating of the TSCs, to the maximal inductive reactive power $Q_{T,ind,max.}$, which is equal to the reactive power rating $Q_{L,max.}$ Of the TCR. When the total reactive power Q_T in an SVC is negative, the SVC supplies reactive power. Conversely, when the total reactive power Q_T 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 Q_C 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.

Mechanically Switched Capacitor –Thyristor Controlled Reactors (MSC–TCR)

In certain applications, especially those involving few capacitor switchings, an MSC–TCR has been shown to offer acceptable performance at much lower compensating system costs than a TSC–TCR. The different MSC–TCR circuit configurations are shown in Fig. 2.21. The mechanically switched capacitor can be located at the high-voltage bus; however, in such a case, fixed-harmonic filters must be installed in shunt with the TCR on the transformer secondary to reduce the harmonic loading of the transformer.

One advantage of the MSC–TCR scheme lies in its lower capital cost from the elimination of the Thyristor switches in the capacitor branches; another advantage, in the reduced operating costs in terms of losses. The disadvantage of the MSC–TCR is a slower speed of response. The mechanical switches can close in two cycles and open in about eight, compared to one-half to one cycle with Thyristor switches. Some studies show that to compensate for the slower speed and to achieve a level of transient stability similar to a Thyristor switched capacitor–Thyristor-controlled reactor (TSC–TCR), a 25% higher–rated MSC–TCR SVC may be needed. [2]

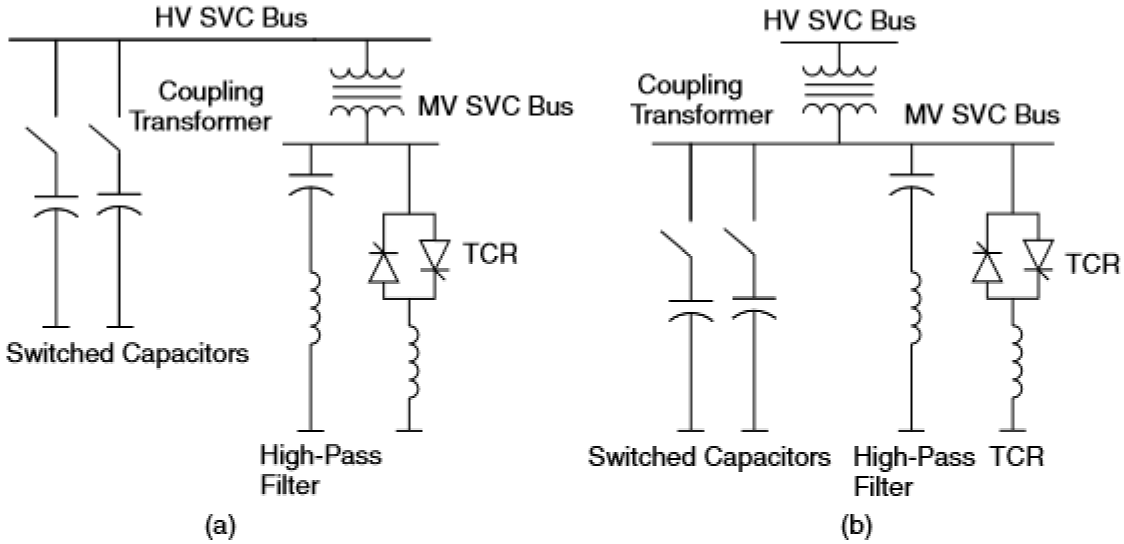


Figure 2. 21 Different configurations of an MSC–TCR compensator

Another problem with the MSC–TCR relates to the trapped charge that is invariably left on the capacitor following DE energization. The residual charge on the capacitors is usually dissipated in about five minutes through discharge resistors built into the capacitor units. If the capacitor is switched on within five minutes after DE energization, the trapped charge may lead to increased switching transients. The MSCs can be switched in only when the capacitors are discharged. One solution [20] to the problem of trapped charges is to connect a small magnetic transformer, such as a potential transformer, in parallel with each phase of the capacitor bank. Doing so aids in dissipating the trapped charge within 0.15 s.

The TCR in an MSC–TCR is designed to have a lower inductance as compared to a TCR in a TSC–TCR SVC of similar rating. This design is to permit the increase of its overload capacity to transiently balance the capacitive-reactive power output. A lower inductance TCR produces an increased level of harmonics and thus needs a more elaborate filtering than a TSC–TCR.

The mechanical switches also possess a finite life, typically 2000–5000 operations, compared to the infinite switching life of Thyristors. The MSCs are usually switched two to four times a day; they are connected during heavy-load conditions and removed under light-load conditions. An MSC–TCR may not be very suitable for voltage-control applications in a system experiencing frequent disturbances; nevertheless, a study [20] has shown that MSC–TCRs provide performance comparable to a TSC–TCR in damping-power swings between two areas and also in alleviating severe voltage depression from system faults, all at a much lower installed capital cost than an equivalent TSC–TCR. Losses with mechanically switched capacitors are fairly low; they lie in the range of 0.02–0.05%. Because capacitors are very sensitive to over voltages and over currents, appropriate protection strategies need to be employed.

2.6 Comparison of SVCs Having Different Configurations

The real-power losses are an important factor during the selection of a specific SVC configuration. Because these losses are constantly present, the capitalized cost of these losses keep accruing to significantly high levels. A comparison of losses of three main SVC configurations, namely, FC–TCR, TSC–TCR, and MSC–TCR, is presented in Fig. 2.22. In each of these cases, the losses are expressed as the percent of rated MVA of SVC. The following losses are contributed by different components [2]:

- Small, resistive losses are in the permanently connected filter branches in the TSC–TCR and MSC–TCR.
- Losses in the main capacitors in all three SVCs.

- Valve-conduction losses and switching losses in the Thyristor power circuit.
- Resistive losses in the inductor of the TCR, which increases substantially with the TCR current.

Maximum losses occur with FC–TCR in the floating state, that is, when the SVC is not exchanging any reactive power with the power system. This condition is a prime disadvantage with this type of SVC, as for an extended period of time, the SVC largely remains in the floating state with its reactive power margins in standby to meet any system exigency.

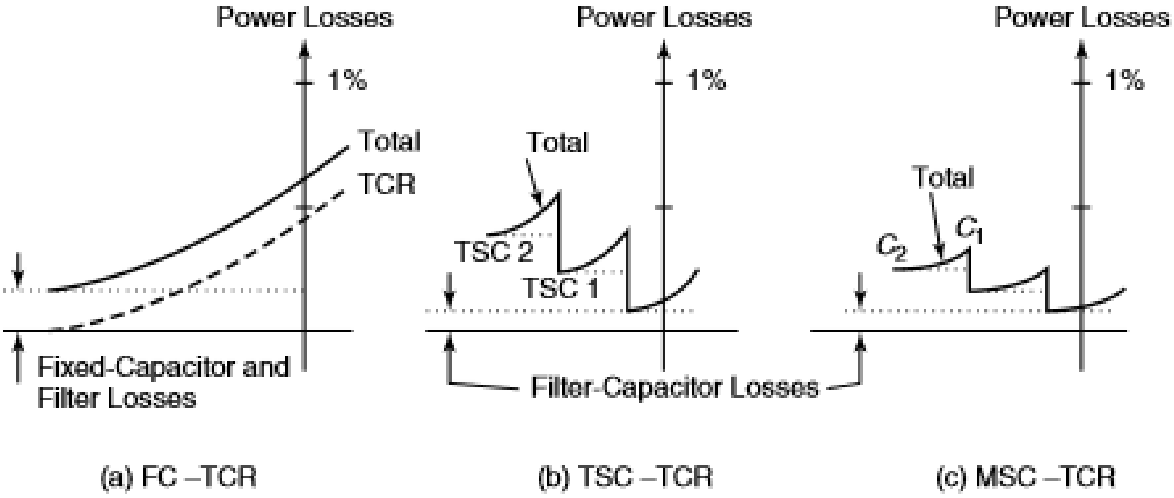


Figure 2. 22 A comparison of losses for different SVC configurations

The TSC–TCR losses are the least in the floating state, just as with MSC–TCR. However, these losses increase as more TSCs are switched into service. The TCR losses in a TSC–TCR are lower because of the smaller reactor rating. This SVC generates higher losses only for short duration when it is involved in system stabilization in case of a contingency.

The MSC–TCR losses show a similar trend as those of the TSC–TCR, but they have a much lower magnitude in comparison, for the losses associated with Thyristor valves are absent. Losses in each of the three SVCs are dependent on the operating point, so the preference of one SVC configuration over another must be based on the operating point at which the SVC will generally reside for most of the time in a given application.

2.7 SVC Controllers

Open Loop and Closed Loop Control

Open-loop control is a process taking place in a system where by one or more variables in the form of input variables exert influence on other variables in the form of output variables by reason of the laws which characterize the system. The distinguishing feature of open-loop control is the open nature of its action, that is, the output variable does not have any influence on the input variable.

Closed-loop control as a process where the controlled variable is continuously monitored and compared with the reference variable. Depending on the result of this comparison, the input variable for the system is influenced to adjust the output variable to the desired value despite any disturbing influences. This feedback results in a closed-loop action. The aim of any closed-loop control is to maintain a variable at a desired value or on a desired-value curve. The variable to be controlled is known as the controlled variable.

Automatic closed-loop control can only take place if the machine or system offers a possibility for influencing the controlled variable. The variable which can be changed to influence the controlled variable is called the manipulated variable. if the disturbances occur in any controlled system, Indeed, disturbances are often the reason why a closed-loop control is required. The controlled system is the part of a controlled machine or plant in which the controlled variable is to be maintained at the value of the reference variable. The controlled system can be represented as a system with the controlled variable as the output variable and the manipulated variable as the input variable.

The reference variable is also known as the set point. It represents the desired value of the controlled variable. The reference variable can be constant or may vary with time. The instantaneous real value of the controlled variable is called the actual value.

Controlled System

The controlled system is the part of a machine or plant in which the controlled variable is to be maintained at the desired value and in which manipulated variables compensate for disturbance variables. Input variables to the controlled system include not only the manipulated variable, but also disturbance variables.

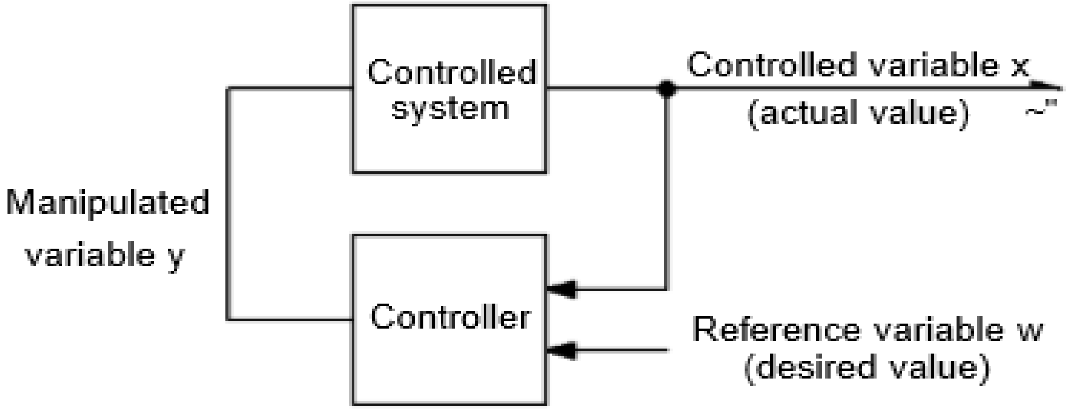


Figure 2. 23 block diagram of a closed loop control

The dynamic response of a system (also called time response) is an important aspect. It is the time characteristic of the output variable (controlled variable) for changes in the input variable. Particularly important is behavior when the manipulated variable is changed. The response of a system to a sudden change of the input variable is called the step response. Every system can be characterized by its step response. The step response also allows a system to be described with mathematical formulas. Another characteristic of a system is its behavior in equilibrium, the static behavior. Static behavior of a system is reached when none of the variables change with time. Equilibrium is reached when the system has settled.

The controller is the device in a closed-loop control that compares the measured value (actual value) with the desired value, and then calculates and outputs the manipulated variable. The controller has the task of holding the controlled variable as near as possible to the reference variable. The controller constantly compares the value of the controlled variable with the value of the reference variable. From this comparison and the control response, the controller determines and changes the value of the manipulating variable. Control response is the way in which the controller derives the manipulated variable from the system deviation. There are two broad categories: continuous-action controllers and non-continuous-action controllers.

The manipulated variable of the continuous action controller changes continuously dependent on the system deviation. Controllers of this type give the value of the system deviation as a direct actuating signal to the manipulating element. The manipulated variable of a non-continuous-action controller can only be changed in set steps.

Time response of a controller, every controlled system has its own time response. This time response depends on the design of the machine or system and cannot be influenced by the control engineer. The time response of the controlled system must be established through experiment or theoretical analysis. The controller is also a system and has its own time response. This time response is specified by the control engineer in order to achieve good control performance.

The time response of a continuous-action controller is determined by three components:

- Proportional component (P component)
- Integral component (I component)
- Differential component (D component)

In the proportional controller, the manipulated variable output is proportional to the system deviation. If the system deviation is large, the value of the manipulated variable is large. If the system deviation is small, the value of the manipulated variable is small. As the manipulated variable is proportional to the system deviation, the manipulated variable is only present if there is a system deviation. For this reason, a proportional controller alone cannot achieve a system deviation of zero. In this case no manipulated variable will be present and there would therefore be no control.

An integral-action controller adds the system deviation over time, that is it is integrated. For example, if a system deviation is constantly present, the value of the manipulated variable continues to increase as it is dependent on summation over time. However, as the value of the manipulated variable continues to increase, the system deviation decreases. This process continues until the system deviation is zero. Integral-action controllers or integral components in controllers are therefor used to avoid permanent system deviation.

The differential component evaluates the speed of change of the system deviation. This is also called differentiation of the system deviation. If the system deviation is changing fast, the manipulated variable is large. If the system deviation is small, the value of manipulated variable is small. A controller with D component alone does not make any sense, as a manipulated variable would only be present during change in the system deviation. A controller can consist of a single component, for example a P controller or an I controller. A controller can also be a combination of several components - the most common form of continuous-action controller is the PID controller.

The PI controller combines the behavior of the I controller and P controller. This allows the advantages of both controller types to be combined: fast reaction and compensation of remaining system deviation. For this reason, the PI controller can be used for a large number of controlled systems. In addition to proportional gain, the PI controller has a further characteristic value that indicates the behavior of the I component: the reset time (integral-action time). The reset time is a measure for how fast the controller resets the manipulated variable (in addition to the manipulated variable generated by the P component) to compensate for a remaining system deviation. In other words: the reset time is the period by which the PI controller is faster than the pure I controller. The reset time is a function of proportional gain K_P as the rate of change of the manipulated variable is faster for a greater gain. In the case of a long reset time, the effect of the integral component is small as the summation of the system deviation is slow. The effect of the integral component is large if the reset time is short. The effectiveness of the PI controller increases with increase in gain K_P and increase in the I-component (i.e., decrease in reset time).

The PD controller consists of a combination of proportional action and differential action. The differential action describes the rate of change of the system deviation. The greater this rate of change - that is the size of the system deviation over a certain period - the greater the differential component. In addition to the control response of the pure P controller, large system deviations are met with very short but large responses. This is expressed by the derivative-action time (rate time). The derivative-action time Td is a measure for how much faster a PD controller compensates a change in the controlled variable than a pure P controller. A jump in the manipulated variable compensates a large part of the system deviation before a pure P controller would have reached this value. The P component therefore appears to respond earlier by a period equal to the rate time. Two disadvantages result in the PD controller seldom being used. Firstly, it cannot completely compensate remaining system deviations. Secondly, a slightly excessive D component leads quickly to instability of the control loop.

PID controller, in addition to the properties of the PI controller, the PID controller is complemented by the D component. This takes the rate of change of the system deviation into account. If the system deviation is large, the D component ensures a momentary extremely high change in the manipulated variable. While the influence of the D component falls of immediately, the influence of the I component increases slowly. If the change in system deviation is slight, the behavior of the D component is negligible. This behavior has the advantage of faster response and quicker compensation of system deviation in the event of changes or disturbance variables. The disadvantage is that the control loop is much more prone to oscillation and that setting is therefore more difficult.

SVC Control Functions:

The main control functions of the SVC consist:

- PLL (Phase locked loop) – synchronization to the voltage
- Reactive power reference controller
- Voltage controller
- Susceptance controller
- TCR current limiter

The main input variables to the control of the SVC are the reference voltage with the droop settings for voltage control and reference reactive power for reactive power control.

The reactive power reference controller is based on the PI controller which compares the output reactive power of the SVC at the primary side of the step-up transformer with the reference reactive power of the SVC. The output variable of the controller is the reference susceptance used with the susceptance controller.

The voltage reference controller is with the PI controller, the input to the PI is the error between the measured RMS filtered value of the voltage and the reference voltage at the primary side of the step-up transformer, at high voltage side.

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 2.24.

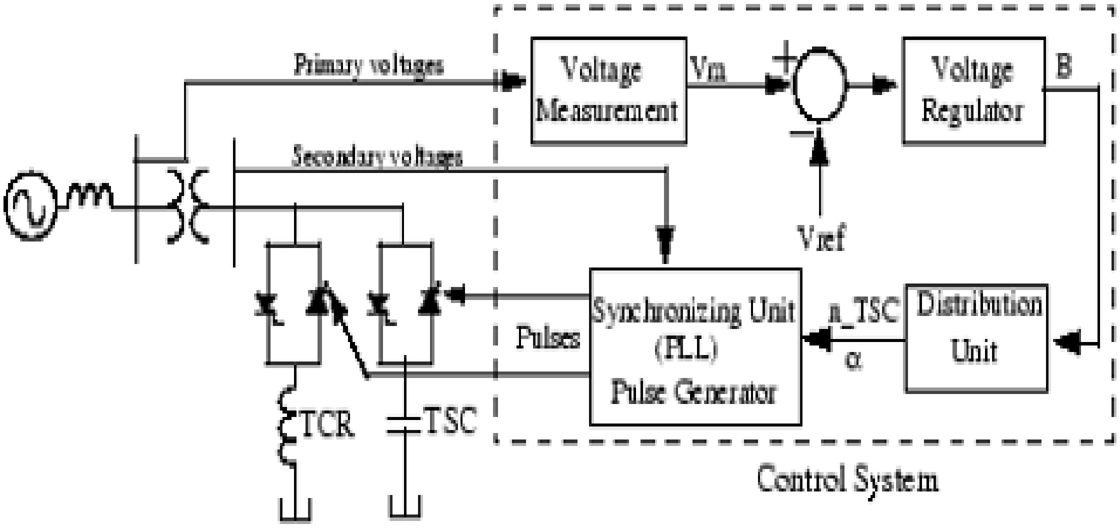


Figure 2. 24 SVC with control system

- 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. 2.25, 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.

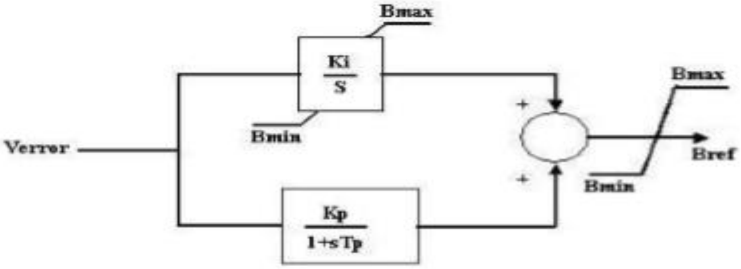


Figure 2. 25 Voltage regulator Model of SVC

Susceptance Regulator (SR)

The SVC requires a substantial reactive-power reserve capacity to improve system stability. In the event of a disturbance, the fast-voltage regulator control uses a significant part of the reactive-power range of the SVC to maintain a prespecified terminal voltage. If the SVC continues to be in this state, not enough reactive-power capacity may be available for it to respond effectively to a subsequent disturbance. A slow susceptance (or var) regulator is provided in the control system that changes the voltage reference to return the SVC to a preset value of reactive-power output, which is usually quite small. Other neighboring compensating devices, such as mechanically switched capacitors or inductors, can then be employed to take up the required steady-state reactive-power loading.

A typical Susceptance Regulator is shown in Fig.2.26. Here the output of the voltage regulator, B_{ref} SV C and a set reference B_{set} SV C are compared. If the error exceeds a threshold, it activates an integrator after an adjustable time delay (of the order of several seconds). The integrator output is hard limited by a non-wind up limiter and modifies the voltage reference. [4]

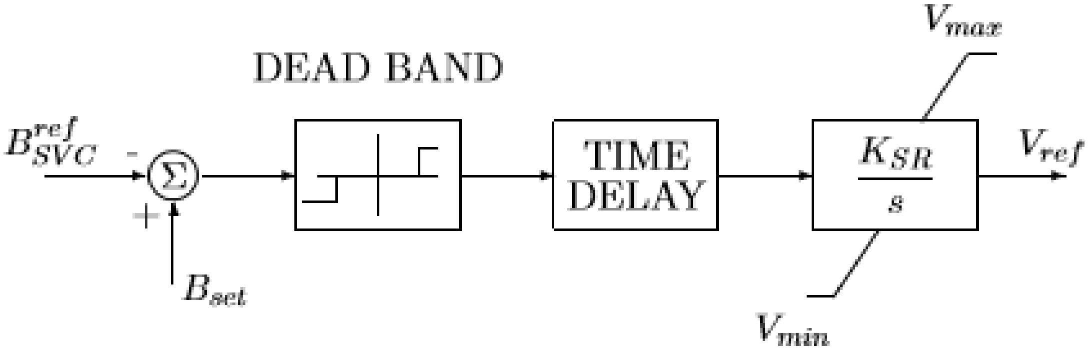


Figure 2. 26 Susceptance Regulator

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 [21]. 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.

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 $B_{l\,max}$, the voltage is regulated at the reference voltage V_{ref} as shown in figure 2.27. 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.

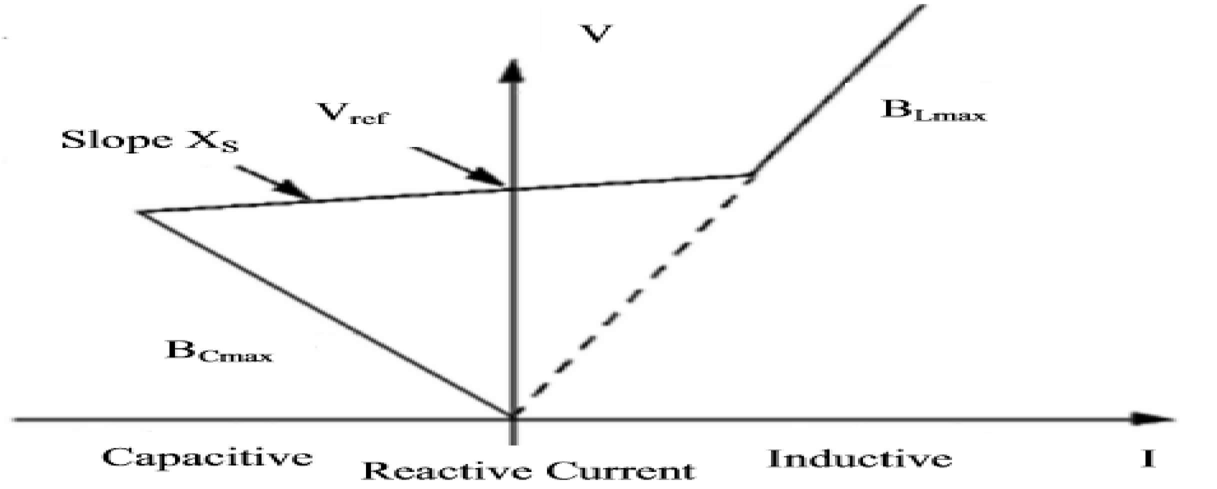


Figure 2. 27 The V-I Characteristic Curve of SVC

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:

$$V_{SVC} = V_{ref} + X_s I_{SVC} \tag{2.17}$$

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:

$$V = \frac{I}{B_{l\,max}} \quad \text{when } SVC\ is\ full\ inductive\ \ (B = B_{l\,max}) \tag{2.18}$$

Where $B_{l\,max}$ = Maximum inductive susceptance

$$V = -\frac{I}{B_{C\,max}} \quad \text{when SVC is fully capacitive } (B = B_{C\,max}) \tag{2.19}$$

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

V: Positive sequence voltage (pu)

I: Reactive current

X_S : Slope or droop reactance

The 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. 2.28.

Dynamic Characteristics

SVCs are mainly used for voltage regulation at a specified bus, the controller can however also be tuned to dampen electromechanical oscillations. Voltage reference (V_{ref}) is the voltage at the terminals of the Static Var Compensator during the floating condition, it means the state of SVC cannot generate or absorb any reactive power. The reference voltage can be varied between the maximum and minimum limits ($V_{ref,max}$ and $V_{ref\ min}$) by the SVC control system. The typical values of $V_{ref\ max}$ and $V_{ref\ min}$ are 1.05 pu and 0.95 pu, respectively.

Linear Range of SVC Control is the control range over which SVC terminal voltage varies linearly with SVC current or reactive power and it is varied over its entire capacitive to inductive range. The slope or Current droop of the V-I characteristic is defined as the ratio of voltage-magnitude change to current-magnitude change over the linear-controlled range of the compensator. Thus slope X_S is given by $X_S = \frac{\Delta V}{\Delta I}$

Where ΔV = the change in voltage magnitude (V)

ΔI = the change in current magnitude (I)

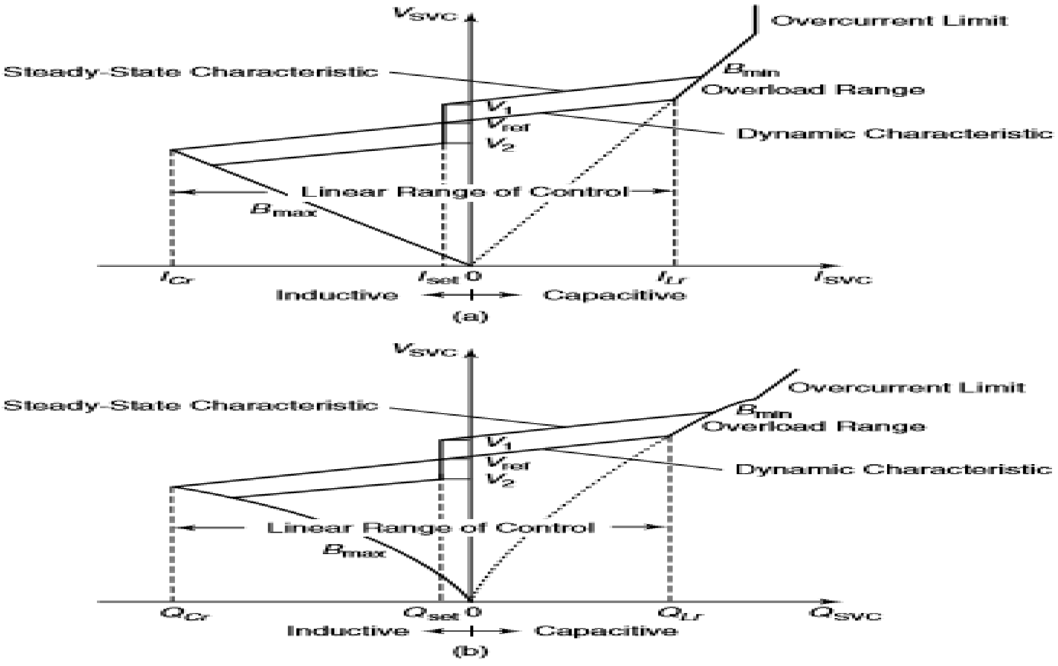


Figure 2. 28 (a) The voltage–current characteristic of the SVC and (b) the voltage– reactive-power characteristic of the SVC.

The slope can be defined alternatively as the voltage change in percent of the rated voltage measured at the larger of the two-maximum inductive or maximum capacitive reactive-power outputs, as the larger output usually corresponds to the base reactive power of the SVC.

Overload Range, When the SVC traverses outside the linear-controllable range on the inductive side, the SVC enters the overload zone, where it behaves like a fixed inductor.

Overcurrent Limit, to prevent the Thyristor valves from being subjected to excessive thermal stresses, the maximum inductive current in the overload range is constrained to a constant value by an additional control action.

The SVC is operating in voltage regulation mode; its response speed to a change of system voltage depends on the voltage regulator gains (proportional gains K_p and integral gain K_i), the droop reactance X_S, and the system strength (short circuit level). For an integral type voltage regulator ($K_P = 0$), if the voltage measurement time constant T_m and the average time delay T_d due to valve firing are neglected, the closed loop system consisting of the SVC and the power system can be approximated by a first-order system having the following closed-loop time constant:

$$T_c = \frac{1}{K_i(X_S+X_n)} \tag{2.20}$$

Where $T_C =$ Closed loop time constant

$K_i =$ Proportional gain of the voltage regulator

$X_S =$ slop reactance

$X_n =$ Equivalent power system reactance

Steady-State Characteristic

The steady-state V-I characteristic of the SVC is very similar to the dynamic V-I characteristic except for a dead band in voltage, as depicted in Figs. 2.28 (a) and (b). [2] In the absence of this dead band, in the steady state the SVC will tend to drift toward its reactive-power limits to provide voltage regulation. It is not desirable to leave the SVC with very little reactive-power margin for future voltage control or stabilization excursions in the event of a system disturbance. To prevent this drift, a dead band about V_{ref} holds the I_{SVC} at or near zero value, depending on the location of the dead band. Thus the reactive power is kept constant at a set point, typically equal to the MVA output of the filters. This output is quite small; hence the total operating losses are minimized [22], [23].

A slow susceptance regulator is employed to implement the voltage dead band, which has a time constant of several minutes. Hence the susceptance regulator is rendered virtually ineffective during fast transient phenomena, and it does not interfere with the operation of the voltage controller.

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.2.29. The power system is modeled as an equivalent voltage source, V_S, behind an equivalent system impedance, X_S, as viewed from the SVC terminals. The system impedance X_S indeed corresponds to the short-circuit MVA at the SVC bus and is obtained as[2]:

$$X_S = \frac{V_b^2}{S_C} * MVA_b \quad in\ pu \tag{2.21}$$

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

$$V_S = V_{SVC} + I_{SVC}X_S \tag{2.22}$$

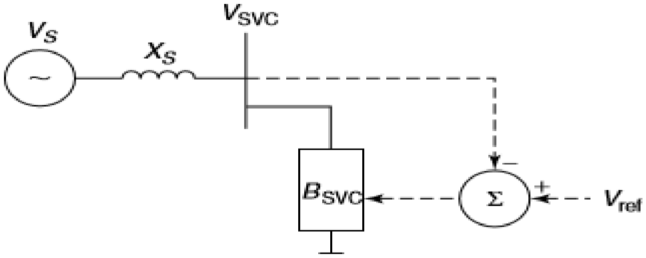


Figure 2. 29 block diagram of the power system and SVC control system

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. (2.22) 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. 2.28 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:

$$V_{SVC} = V_{ref} + X_s I_{SVC} \tag{2.23}$$

Where I_{SVC} is positive if inductive, negative if capacitive

2.10 Voltage Regulator Design

The SVC voltage regulator processes the measured system variables and generates an output signal that is proportional to the desired reactive-power compensation. Different control variables and transfer functions of the voltage regulator are used, depending on the specific SVC application. The measured control variables are compared with a reference signal, usually V_{ref}, and an error signal is input to the controller transfer function. The output of the controller is a per-unit susceptance signal B_{ref}, which is generated to reduce the error signal to zero in the steady state. The susceptance signal is subsequently transmitted to the gate pulse–generation circuit. The principle of design of the SVC voltage regulator is expressed in the two alternative ways of modeling exist: the gain–time-constant form and the integrator–current-droop form.

In the gain–time-constant representation, the voltage regulator is expressed by the following transfer function:

$$G_R(s) = \frac{K_R}{1+sT_C} \tag{2.24}$$

Where $K_R =$ the static gain $= 1/X_S(pu)$

$X_S =$ the current droop (pu)

$T_C =$ the regulator time constant (s)

The closed-loop control system in Fig. 2.30(b) can be simplified to the gain–time-constant form of the controller depicted in Fig. 2.30(c). The gain K_R is termed the static gain, which is defined as the inverse of the current droop and the term transient gain, K_T, which is representative of the dynamic nature of the voltage regulator, is defined as

$$K_T = \frac{K_R}{T_C} \tag{2.25}$$

Alternative implementations of current droop (slope) in the voltage-regulator model are illustrated in Fig. 2.30; the current droop-feedback arrangement is depicted in Fig. 2.30(a). The SVC current is explicitly measured and multiplied by a factor X_S representing current droop before feeding as a signal V_{SL} to the summing junction. The sign of V_{SL} is such that it corresponds to an increase of reference voltage for inductive SVC currents and a decrease of the reference voltage for capacitive SVC currents. Simple integral control finds most common usage in voltage controllers. R_R is termed the response rate, which is indicative of the time taken by an SVC to move across its entire reactive-power range, that is, from a fully capacitive to a fully inductive state, in response to a large (1-pu) voltage error.

In the integrator–current-droop model, the voltage regulator is described as an integrator $G_R'(s)$, with the following current feedback loop:

$$G_R'(s) = \frac{1}{sR_R} \tag{2.26}$$

Where $R_R =$ the response rate (ms/pu)

The regulator time constant, T_C, and the response rate, R_R, are related as

$$T_C = \frac{R_R}{X_s} \tag{2.27}$$

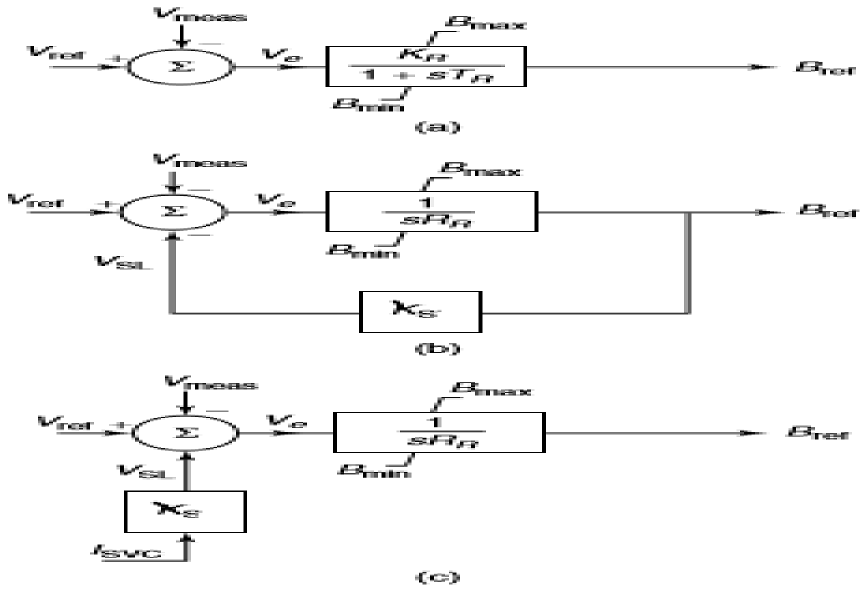


Figure 2. 30 Alternate voltage-regulator forms: (a) a gain–time constant (b) an integrator with susceptance-droop feedback (c) an integrator with current-droop feedback

In most stability studies, the Thyristor phase control G_Y, the Thyristor dead time, T_d, and the Thyristor firing delay time, T_Y, are together represented by the following transfer function [4], [22], [23], [24]:

$$G_Y(s) = \frac{e^{-sT_d}}{1+sT_Y} \tag{2.28}$$

Where $T_d =$ the Thyristor dead time (=one-twelfth cycle time)

$T_Y =$ the Thyristor firing-delay time caused by the sequential switching of Thyristors (≅ one-quarter cycle time)

A PI controller that gives the fastest stable response for the weakest system configuration having gain $K_{N\,max}$ is determined [24] as

$$G_R(s) = K_P(1+\frac{1}{sT_Y})=-\frac{1}{2(X_S+K_{N\,max})}(1+\frac{1}{sT_Y}) \tag{2.29}$$

$$K_{N\,max} = \frac{\Delta V_{SVC}}{B_{SVC}} = \frac{Q_{SVC}}{S_{C\,min}} \tag{2.30}$$

Where $S_C =$ the short-circuit power

2.11 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. It is connected in shunt with the transmission line through a shunt transformer and thus, represented in Figure 2.31 [25]. Figure 2.32 shows the equivalent circuit at which SVC is modeled [26, 27].

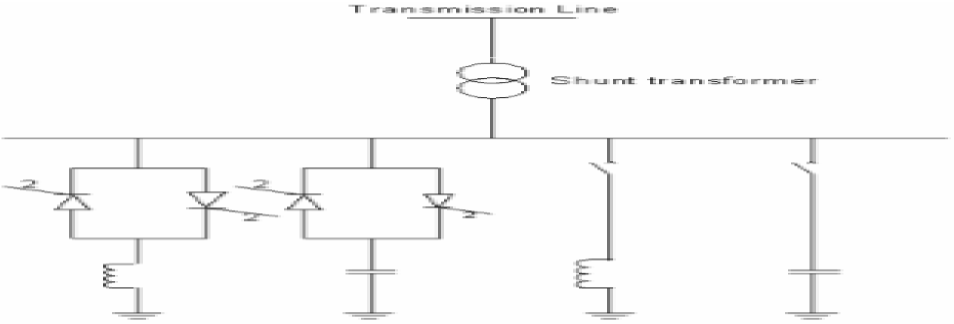


Figure 2. 31 Functional diagram of SVC

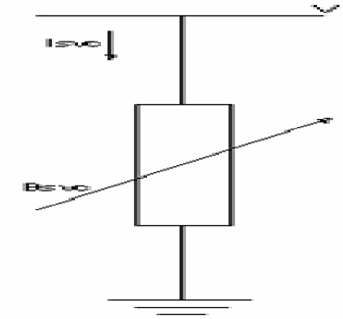


Figure 2. 32 Equivalent circuit of SVC

The model considers SVC as shunt-connected variable susceptance, B_{SVC} which is adapted automatically to achieve the voltage control. The equivalent susceptance, B_{eq} 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 [4]:

$$B_{eq} = B_L(\alpha) + B_C \tag{2.31}$$

where $B_L(\alpha) = -\frac{1}{wL}\left(1 - \frac{2\alpha}{\pi} - \frac{\sin(2\alpha)}{\pi}\right), \ B_C = wC \ and \ 0^0 \leq \alpha \leq 90^0$

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

$$P_{SVC} = 0$$

$$Q_{SVC} = -V^2 B_{SVC} \tag{2.32}$$

where 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°).

2.12 Applications of SVCs

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.

Chapter Three

Modeling and Control of Kality II Distribution Substation

3.1 Introduction

Transmission network supplying power to Addis Ababa Capital city consists of 400kV, 230kV, 132kV and 45kV. Distribution network consists of 33 kV and15kV middle voltage distribution line by step down transformer rated at 132/33kV, 132/15kV and 45/15kV.

Electricity of low voltage customers are supplied by 400V or 220V with frequency of 50 Hz using 3-phase 4-wire distribution line.

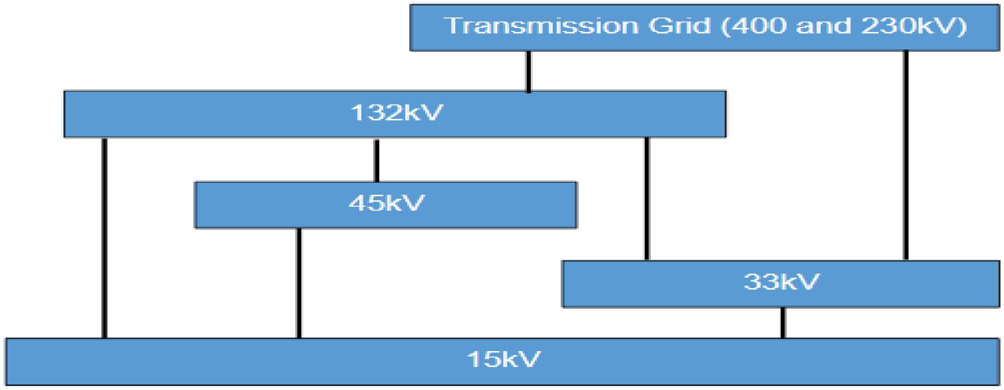


Figure 3. 1 Voltage Composition of Transmission and Distribution System

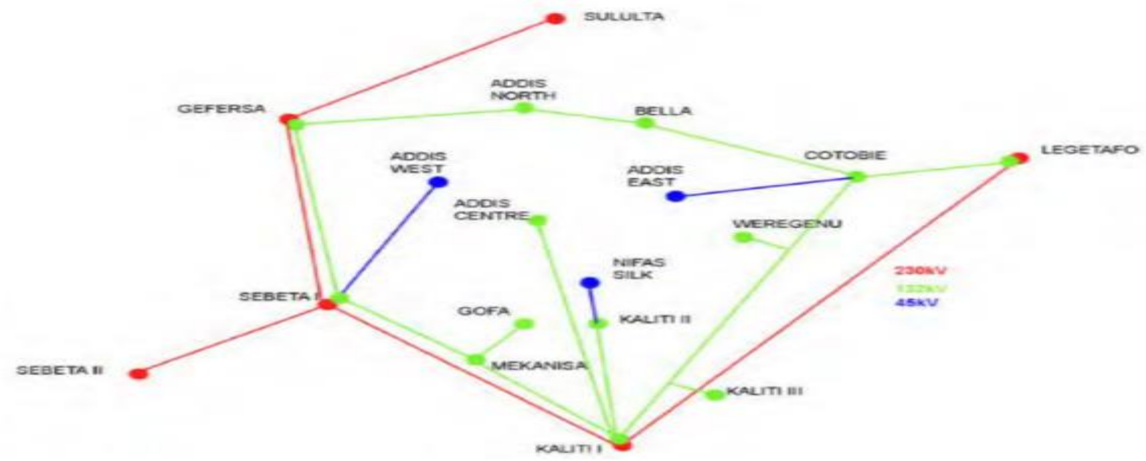


Figure 3. 2 Outline of Transmission Network in Addis Ababa

3.2 Kality II Substation Overview

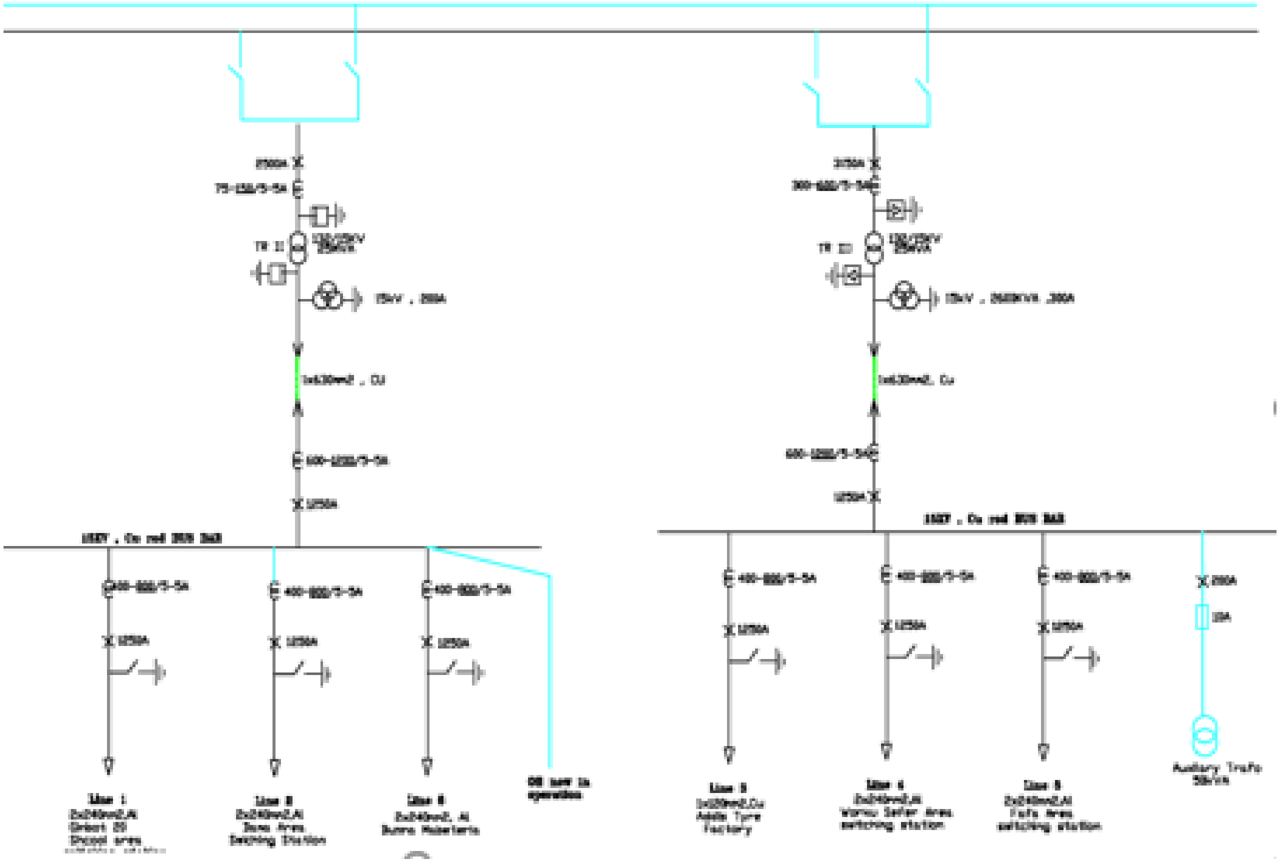


Figure 3. 3 One-Line Diagram of Kality II Substation

As illustrated in Fig. 3-3, There are Two incoming 132kv transmission lines from kality I to supply for kality II substation and Nifas silik substation is supplied by double underground cable from Kality-II substation. The incoming 132kv is stepped down and distributed by 15kv feeders. The study area is served by two 132/15 kV,25MVA step down transformer (trafo II and Trafo III) and the Substation consists of 5 outgoing feeders. Transformer two (trafo II) power supplies for feeder 1, feeder 2 and feeder 6 but currently feeder 1 not functional due to feeder damage before a year. Transformer three (trafo III) power supplies for feeder 3, feeder 4 and feeder 5 and its nominal voltage of the five feeders is 15 kV.

3.3 Data Collection and Analysis

Load Profile

The existing monthly peak load of the substation is described in table 3.1. it consists three months' peak load of each feeder.

Table 3. 1 Three months' peak load per feeder

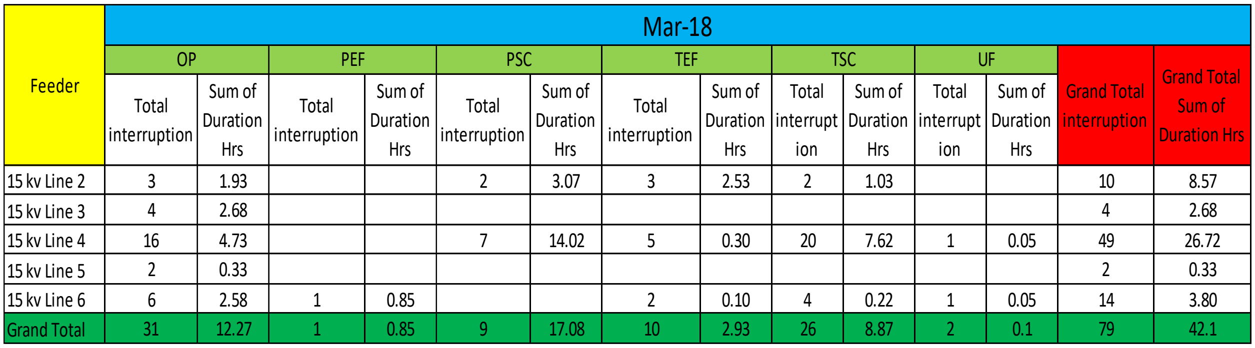
May-18	PEAK LOAD						MINIMUM LOAD					
	Power	CURRENT(A)				Time	Power	CURRENT(A)				Time
BAY/LINE	(MW)	R	S	T	Date	(HR)	(MW)	R	S	T	Date	(HR)
Line-2	11	462	462	462	5/1/2018	13:00	2.3	100	100	100	5/27/2018	1:00
Line-3	3.3	133	133	133	1/31/1900	17:00	0.2	8	8	8	5/13/2018	3:00
Line-4	9.4	397	397	397	5/1/2018	19:00	1.8	79	79	79	5/13/2018	3:00
Line-5	2.07	87	87	87	5/22/2018	20:00	0.7	30	30	30	5/13/2018	3:00
Line-6	7.95	334	334	334	5/19/2018	19:00	1.9	81	81	81	5/27/2018	3:00

Apr-18	PEAK LOAD						MINIMUM LOAD					
	Power	CURRENT(A)				Time	Power	CURRENT(A)				Time
BAY/LINE	(MW)	R	S	T	Date	(HR)	(MW)	R	S	T	Date	(HR)
Line-2	11.7	495	495	495	7/4/2018	9:00	2.19	92	92	92	9/4/2018	3:00
Line-3	3.5	145	145	145	26/04/18	10:00	0.24	10	10	10	11/4/2018	3:00
Line-4	8.9	374	374	374	7/4/2018	10:00	1.88	73	73	73	25/04/18	2:00
Line-5	1.9	80	80	80	7/4/2018	11:00	0.33	14	14	14	28/04/18	1:00
Line-6	7.9	334	334	334	7/4/2018	8:00	1.8	75	75	75	30/04/18	2:00

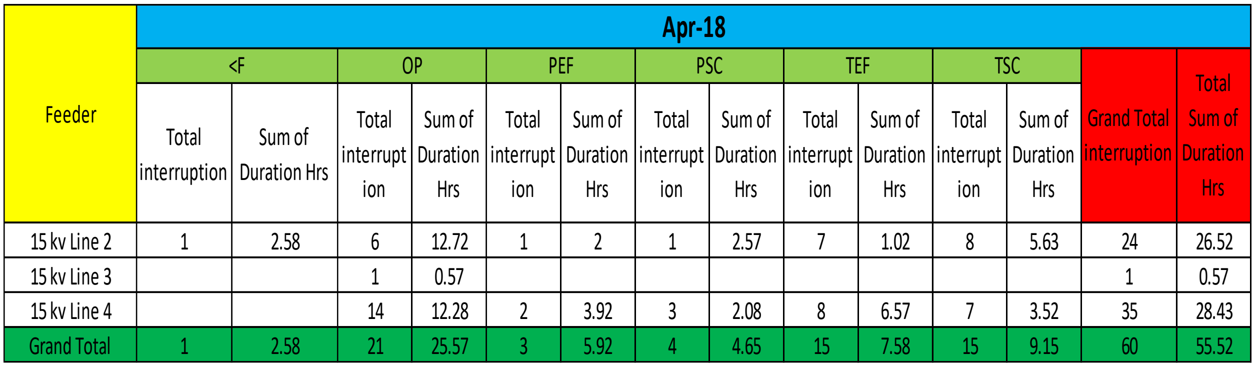
Mar-18	PEAK LOAD						MINIMUM LOAD					
	Power	CURRENT(A)				Time	Power	CURRENT(A)				Time
BAY/LINE	(MW)	R	S	T	Date	(HR)	(MW)	R	S	T	Date	(HR)
Line-2	11.9	470	470	470	3/13/2018	19:00	2.7	116	116	116	3/14/2018	3:00
Line-3	3.2	135	135	135	3/16/2018	17:00	0.5	22	22	22	3/18/2018	2:00
Line-4	8.6	361	361	361	3/8/2018	19:00	1.6	68	68	68	3/9/2018	3:00
Line-5	1.7	70	70	70	3/6/2018	11:00	0.6	28	28	28	3/23/2018	3:00
Line-6	7.9	320	320	320	3/7/2018	11:00	2.1	90	90	9	3/16/2018	3:00

Fault Statistics

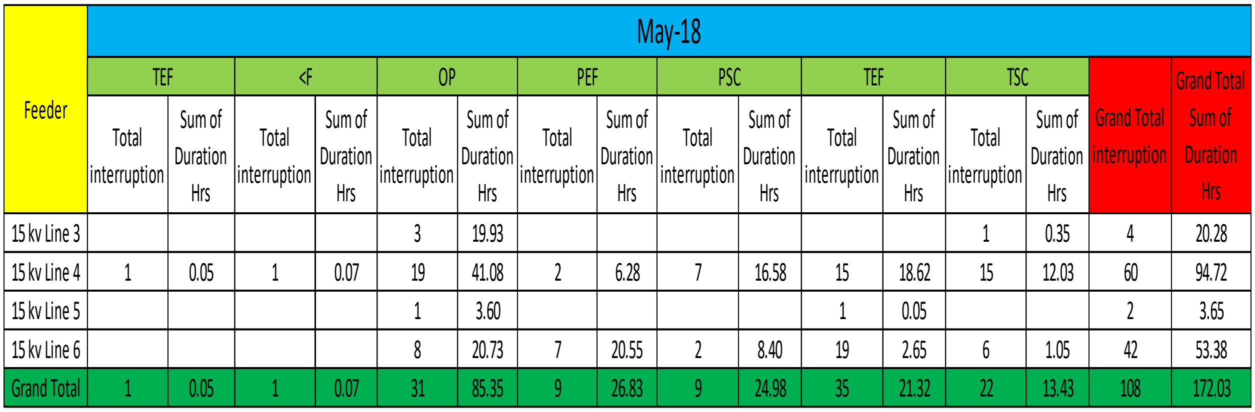
Table 3.2 Feeder Fault Recorded Per Months



Feeder	Mar-18													
	OP		PEF		PSC		TEF		TSC		UF		Grand Total interruption	Grand Total Sum of Duration Hrs
	Total interruption	Sum of Duration Hrs	Total interruption	Sum of Duration Hrs	Total interruption	Sum of Duration Hrs	Total interruption	Sum of Duration Hrs	Total interruption	Sum of Duration Hrs	Total interruption	Sum of Duration Hrs		
15 kv Line 2	3	1.93			2	3.07	3	2.53	2	1.03			10	8.57
15 kv Line 3	4	2.68											4	2.68
15 kv Line 4	16	4.73			7	14.02	5	0.30	20	7.62	1	0.05	49	26.72
15 kv Line 5	2	0.33											2	0.33
15 kv Line 6	6	2.58	1	0.85			2	0.10	4	0.22	1	0.05	14	3.80
Grand Total	31	12.27	1	0.85	9	17.08	10	2.93	26	8.87	2	0.1	79	42.1



Feeder	Apr-18													
	<F		OP		PEF		PSC		TEF		TSC		Grand Total interruption	Total Sum of Duration Hrs
	Total interruption	Sum of Duration Hrs	Total interruption	Sum of Duration Hrs	Total interruption	Sum of Duration Hrs	Total interruption	Sum of Duration Hrs	Total interruption	Sum of Duration Hrs	Total interruption	Sum of Duration Hrs		
15 kv Line 2	1	2.58	6	12.72	1	2	1	2.57	7	1.02	8	5.63	24	26.52
15 kv Line 3			1	0.57									1	0.57
15 kv Line 4			14	12.28	2	3.92	3	2.08	8	6.57	7	3.52	35	28.43
Grand Total	1	2.58	21	25.57	3	5.92	4	4.65	15	7.58	15	9.15	60	55.52



Feeder	May-18															
	TEF		<F		OP		PEF		PSC		TEF		TSC		Grand Total interruption	Grand Total Sum of Duration Hrs
	Total interruption	Sum of Duration Hrs	Total interruption	Sum of Duration Hrs	Total interruption	Sum of Duration Hrs	Total interruption	Sum of Duration Hrs	Total interruption	Sum of Duration Hrs	Total interruption	Sum of Duration Hrs	Total interruption	Sum of Duration Hrs		
15 kv Line 3					3	19.93							1	0.35	4	20.28
15 kv Line 4	1	0.05	1	0.07	19	41.08	2	6.28	7	16.58	15	18.62	15	12.03	60	94.72
15 kv Line 5					1	3.60					1	0.05			2	3.65
15 kv Line 6					8	20.73	7	20.55	2	8.40	19	2.65	6	1.05	42	53.38
Grand Total	1	0.05	1	0.07	31	85.35	9	26.83	9	24.98	35	21.32	22	13.43	108	172.03

Legend

- ➢ TSC - Transient Short Circuit
- ➢ TEF - Transient Earth Fault
- ➢ <F - Under Frequency
- ➢ OP - Operational
- ➢ PSC - persistence Short circuit
- ➢ PEF - Persistence Earth Fault
- ➢ BO - black out
- ➢ O/C - over current

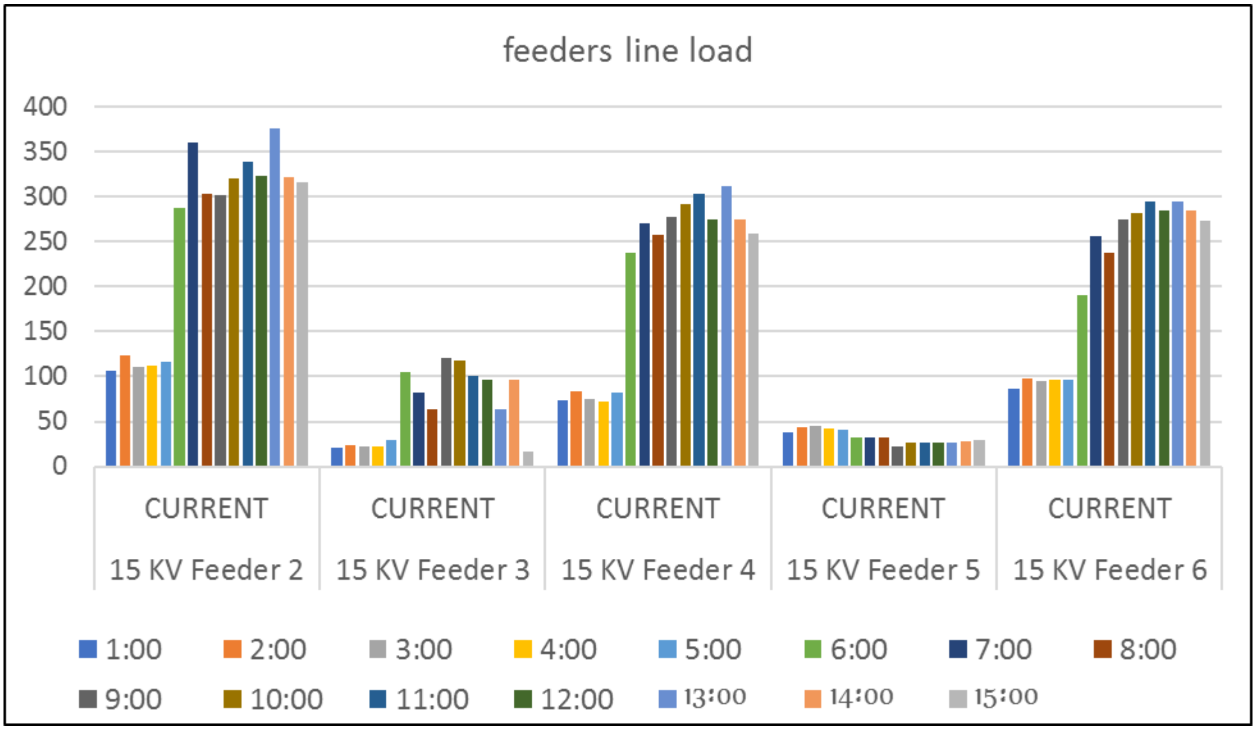


Figure 3. 4 Feeders Load Current Per Hour

Table 3. 3 Substation Relay setting

Substation	**KALITTI -II**				
Voltage Level	132/15 kV				
Transformer Capacity	2x25 MVA [50 MVA]				
Transformer Capacity in MW	**45**	**MW**			
The average cosα considered for the calculation is	**0.9**	**1MW**	**=**	**42.77**	**A**

Trafo-II Out going Feeders	Cable				CT ratio			Relay Setting			Peak Load	
	C.S.A (mm2)	Type	C.C.C (A)	MW	Ratio	A	MW	Setting	A	MW	A	MW
Line-1	2x240	AL	834	19.5	400-800/5/5	800	18.7	0.5XIn	400	9.4	-	-
Line-2	2x240	"	834	19.5	"	800	18.7	0.7XIn	560	13.1	398	10.1
Line-6	2x240	"	834	19.5	"	800	18.7	0.5XIn	400	9.4	256	8.6
Total									**1360**	**31.8**	654	18.7
Trafo-II Out going Feeders	Cable				CT ratio			Relay Setting			Peak Load	
	C.S.A (mm2)	Type	C.C.C (A)	MW	Ratio	A	MW	Setting	A	MW	A	MW
Line-3	1x120	CU	367	8.6	400-800/5/5	800	18.7	0.4XIn	320	7.5	140	3.5
Line-4	1x240	AL	834	19.5	"	800	18.7	0.5XIn	400	9.4	-	-
Line-5	2x240	"	834	19.5	"	800	18.7	0.5XIn	400	9.4	406	10.1
Total									**1120**	**26.2**	546	13.6
Incoming Feeder -II	1x630	CU	780	18.2	600-1200/5/5	1200	28.1	0.8XIn	1080	25.3	701	17.6
Incoming Feeder -III	1x630	"	780	18.2	"	1200	28.1	0.8XIn	1080	25.3	424	15.8
Total									2160	50.5	1125	11.0

3.4 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 [28]: Equation (3.1) defines the required minimum rating of the SVC.

$$Q_{SVC} = Q_{load} + \frac{P_{load}^2}{2S_{SC}} + KP_{load} \tag{3.1}$$

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

Where Q_{load} and P_{load} are the reactive and active power of load respectively

S_{SC} is short circuit MVA

Accurate fault current calculations are normally carried out using an analysis method called "Symmetrical Components." This method involves the use of higher mathematics and is based on the principal that any unbalanced set of vectors can be represented by a set of 3 balanced systems, namely; positive, negative and zero sequence vectors. However, for practical purposes, it is possible to attain a good approximation of three phase short circuit currents using some very simplified methods, which are discussed below. The short circuit current close to the transformer and at the secondary side of the transformer can be quickly calculated, using the following formula:

$$short - circuit\ MVA = \frac{100S}{X\%} \tag{3.2}$$

$$short - circuit\ current\ I_{KA} = \frac{MVA}{KV\sqrt{3}} \tag{3.3}$$

Where P = 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 II and transformer III are identical, it is 25 MVA and the % reactance of transformer are 10.22% and 8.67% respectively.

Based on the equation 3.2 the short-circuit MVA becomes:

Transformer II

Short-circuit MVA=$100 * \frac{25MVA}{10.22\%} = 244.62MVA$

From equation (3.1) and figure 3.5 input data the SVC rating becomes

$$Q_{SVC} = 3.25 + \frac{14.48^2}{2*244.62} + 0.833 * 14.48 = 15.74\ MVAR$$

We can calculate the susceptance of SVC by equation 2.34

$$Q_{SVC} = V^2 * B_{SVC}$$

$$B_{SVC} = \frac{Q_{SVC}}{V^2} = \frac{15.74MVAR}{(\frac{15KV}{\sqrt{3}})^2} = 0.2095$$

$$I_{SVC} = B_{SVC} * V = 0.2095 * \frac{15kv}{\sqrt{3}} = 1.816KA$$

Where I_{SVC} is positive if inductive and I_{SVC} is negative if capacitive.

The SVC equivalent reactance is

$$X_{SVC} = -\frac{1}{B_{SVC}} = 33.89$$

A static Var compensator (SVC) is defined as a device whose output is adjusted to exchange capacitive or inductive current in order to maintain or control specific parameters of the electrical power system. The reactive power Q_{svc} injected by the SVC is controlled by firing delay angle α accorging to the following equation:

$$Q_{SVC} = \frac{V^2}{X_C} - V^2 B_{SVC}(\alpha) \qquad (3.4)$$

Where V voltage at SVC connection point is the voltage being controlled, X_L total inductance,

X_C capacitive reactance. According to the Fourier analysis, the variable susceptance, B_{SVC} can be expressed as :

$$B_{SVC} = \frac{2\pi - \alpha + sin2\alpha}{\pi X_L} \tag{3.5}$$

Maximum inductive and capacitive injected power Q_{SVC} is defined by the reactances X_L and X_C :

$$\frac{V^2}{X_C} - \frac{V^2}{X_L} \le Q_{SVC} \le \frac{V^2}{X_C} \tag{3.6}$$

The TCR can draw maximum of reactive power at peak load:

$$S^2 = P^2 + Q^2 \tag{3.7}$$

$$Q = \sqrt{S^2 - P^2} = \sqrt{25^2 - 14.48^2} = 20.38MVar$$

One unit of TSC is switched on, it will compensate 20.38MVar per phase

$$Q_{TSC} = \Delta Q_{ph} + Q_{TCR} \tag{3.8}$$

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

$$\Delta Q = 0.05 * Q = 0.05 * 20.38MVar = 1.019MVar$$

$$\Delta Q_{ph} = \frac{\Delta Q}{3} = \frac{1.019}{3} = 0.3397$$

$$\Delta Q_{ph} = n * Q_{TSC} - Q_{TCR} \tag{3.9}$$

Where n is the number of capacitor

$$0.3397 = (1 * 20.38) - Q_{TCR}$$

$$Q_{TCR} = 20.04MVar$$

$$Q_{TCR} = \frac{V^2}{X_{Leff}} \tag{3.10}$$

Where X_{Leff} is inductive effective reactance,

$$X_{Leff} = 2\pi f L \tag{3.11}$$

Substitute equation 3.11 to equation 3.10

$$L_{eff} = \frac{V^2}{2*\pi*f*Q_{TCR}} = \frac{(15KV/\sqrt{3})^2}{2*50*3.14*20.04MVar} = 0.01195H$$

Transformer III

Short-circuit MVA=100 $* \frac{25MVA}{8.67\%} = 288.35MVA$

$$Q_{SVC} = 3.15 + \frac{10.17^2}{2*288.35} + (0.833 * 10.17) = 11.8MVAR$$

$$B_{SVC} = \frac{Q_{SVC}}{V^2} = \frac{11.8MVAR}{\left(\frac{15KV}{\sqrt{3}}\right)^2} = 0.15696$$

$$I_{SVC} = B_{SVC} * V = 0.15696 * \frac{15kv}{\sqrt{3}} = 1.36KA$$

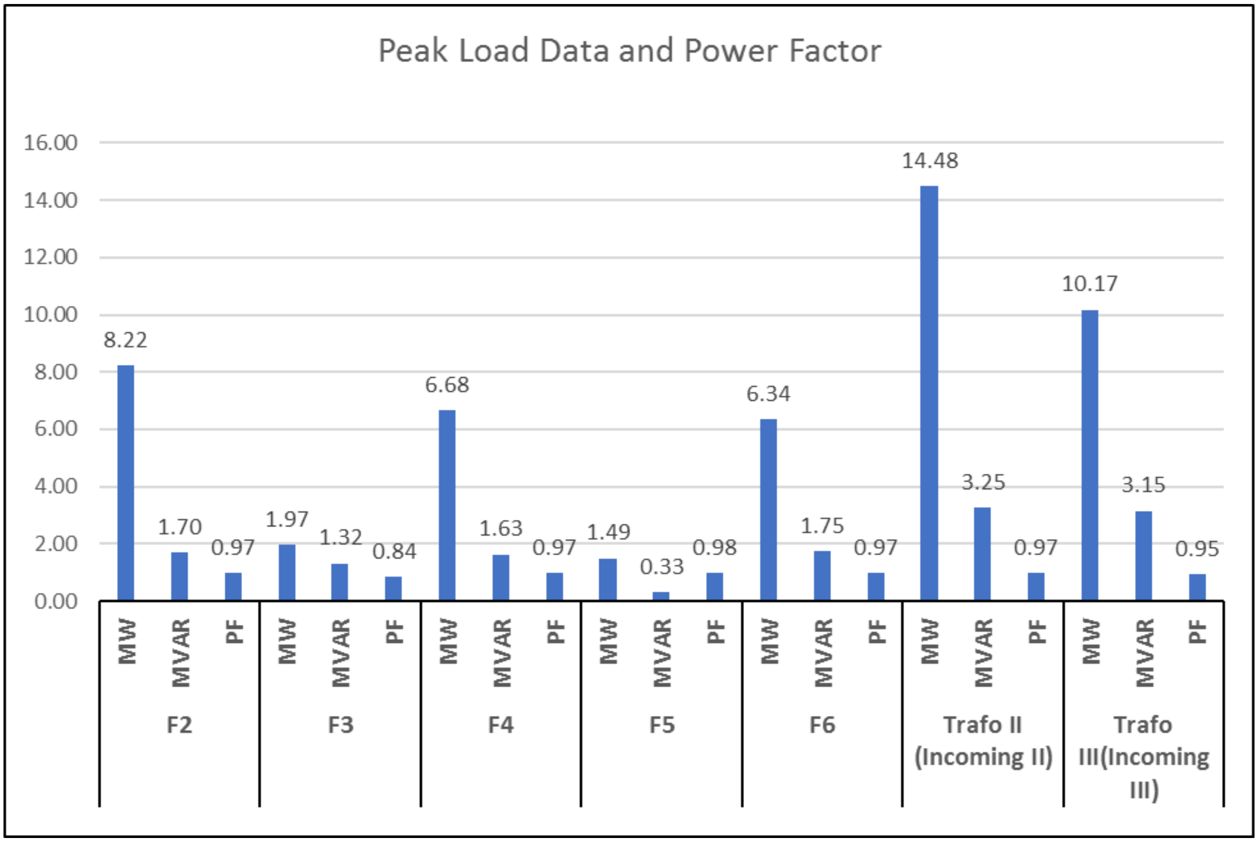


Figure 3. 5 one-month peak load

By equation 3.7 and 3.8 the maximum reactive power draws the TCR

$$\boldsymbol{Q = \sqrt{S^2 - P^2} = \sqrt{25^2 - 10.17^2} = 22.84MVar}$$

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

$$\boldsymbol{\Delta Q = 0.05 * Q = 0.05 * 22.84MVar = 1.142MVar}$$

$$\boldsymbol{\Delta Q_{ph} = \frac{\Delta Q}{3} = \frac{1.142}{3} = 0.3807\mathrm{MVar}}$$

Applying equation 3.9 to get TCR rating

$$\boldsymbol{0.3807 = (1 * 22.84) - Q_{TCR}}$$

$$\boldsymbol{Q_{TCR} = 22.46MVar}$$

$$L_{eff} = \frac{V^2}{2 * \pi * f * Q_{TCR}} = \frac{(15KV/\sqrt{3})^2}{2 * 50 * 3.14 * 22.46MVar} = 0.0106598H$$

System gain calculated by equation 2.30 for SVC 1 and SVC 2 respectively

$$K_{1\,max} = \frac{Q_{SVC1}}{S_{C\,min}} = \frac{15.74}{244.62} = 0.0643$$

$$K_{2\,max} = \frac{Q_{SVC1}}{S_{C\,min}} = \frac{11.78}{288.35} = 0.0643$$

3.5 Cost of SVC Rating

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 confer an idea at the expense of the various controller. The FACTS equipment cost represents only half of the total FACTS project cost. Other expenses like civil works, installation, commissioning, insurance, engineering and project management constitute the other half of the FACTS project cost [http://www.eco-energy.com/learnmoreEC.asp.].

Table 3.4: Expenses comparison of different FACTS controllers [29]

FACTS Controllers	**Expense (US $)**
DSTATCOM	34$ per one KVAR
Static Var Compensator	26$ per one KVAR
TCSC	47$ per one KVAR Controlled portions
UPFC	37$ per one KVAR through power

Based on table 3.4 the SVC rating cost calculated in table 3.5

Table 3.5: modeled SVC rating cost

	Rating [Mvar]	Cost per KVAR	Total cost $
SVC 1	15.74	$26	409240
SVC 2	11.8	$26	306800

3.6 DIgSILENT Power Factory Derived Model

The calculation program PowerFactory, as written by DIgSILENT, is a computer aided engineering tool for the analysis of transmission, distribution, and industrial electrical power systems. It has been designed as an advanced integrated and interactive software package dedicated to electrical power system and control analysis in order to achieve the main objectives of planning and operation optimization.

“DIgSILENT " is an acronym for “**DIg**ital **SI**mu**L**ation of **E**lectrical **N**e**T**works". DIgSILENT Version 7 was the world’s first power system analysis software with an integrated graphical single-line interface. That interactive single-line diagram included drawing functions, editing capabilities and all relevant static and dynamic calculation features.

PowerFactory was designed and developed by qualified engineers and programmers with many years of experience in both electrical power system analysis and programming fields. The accuracy and validity of results obtained with PowerFactory has been confirmed in a large number of implementations, by organizations involved in planning and operation of power systems throughout the world.

DIgSILENT has set standards and trends in power system modelling, analysis and simulation for more than 25 years. The proven advantages of the PowerFactory software are its overall functional integration, its applicability to the modelling of generation, transmission, distribution and industrial grids, and the analysis of these grids' interactions.

3.6.1 SVC Composite Model using DIgSILENT

A composite model element can be created in DIgSILENT PowerFactory. A composite frame is the essential for the definitions required for creating as specific function or operation for an electrical element. The reason why one would want to create a composite model including specific controllers are for specific applications where studies are required for voltage control analysis specifically. Thus, in order to model an entire system correctly to ascertain the response the specific elements are producing, one needs to create composite frames that consist of a specific composite model that then shows the list of slots in the composite frame making up the specific element. Particular controllers or models can be assigned to a slot which inherently makes up a standard composite model.

DIgSILENT PowerFactory has specific standard composite models which are available for:

- The synchronous motor and generator
- The asynchronous motor and generator
- The SVC system

When a composite frame has been created for a specific application together with all the specific models and interfaces making up that particular frame then there is now no longer any connection between the original elements and the new elements of the composite model or frame. Therefore, one can change the controller settings within the SVC without changing the network or part of the network that the SVC is attempting to control.

Figure 3.6 shows the Composite frame that is used in DIgSILENT PowerFactory and was created specifically for the research carried out in this project in order to replicate the controller configuration at site for the SVC. Figure 3.6 indicates four models within the frame that manipulates the SVC in such a way that it knows when and how to correct the 15kV busbar voltage at Kality II Substation. One can see that one of the models within the frame consists of the SVS-Controller which makes up the entire controller model as discussed in the previous section.

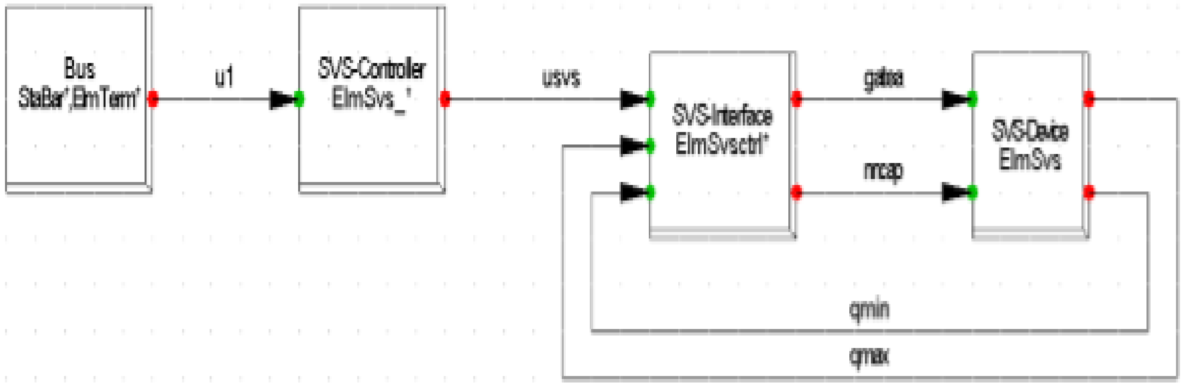
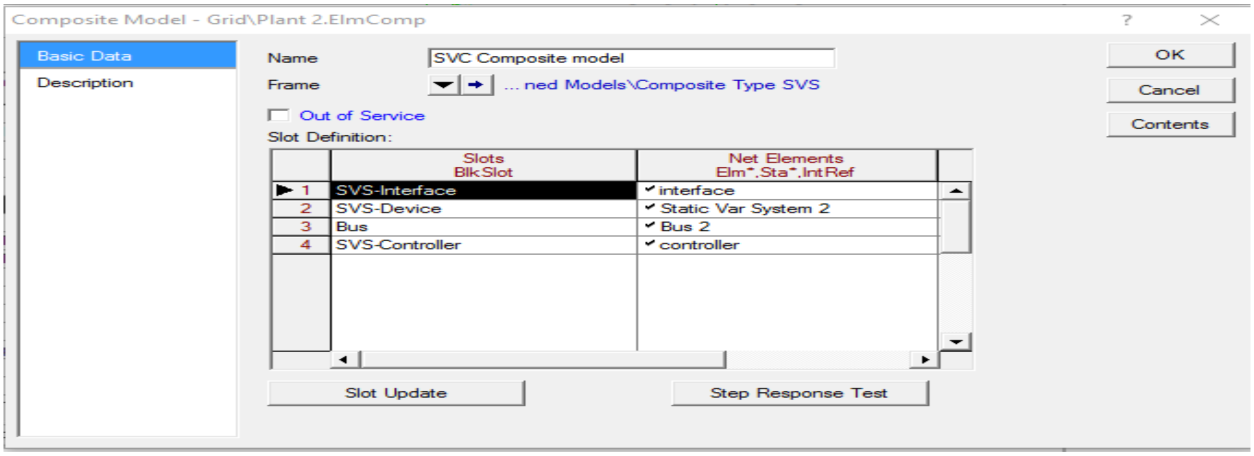


Figure 3. 6 SVC composite frame in DIgSILENT

To ensure that the settings are correctly applied within the software each model within the composite frame needs to be verified to ensure that it is in fact doing the job required to complete the overall model. Thus, as seen in Figure 3.7 each slot for the four devices are updated accordingly (linked) to the appropriate device or section within the frame. Therefore, the bus needs to know that it is controlling the 15kV busbar at Kality II Substation. The SVS-Controller is linked to the controller that was created in depth previously and saved on DIgSILENT's database. The actual SVS-device element is linked to the actual Thyristor controlled reactor/capacitor bank and not to another unknown element. Figure 3.7 indicates all the slots together with the step response test that can be performed before implementation.



Name: SVC Composite model

Frame: ... ned Models\Composite Type SVS

☐ Out of Service

Slot Definition:

	Slots Blk Slot	Net Elements Elm*,Sta*,IntRef
1	SVS-Interface	✓ interface
2	SVS-Device	✓ Static Var System 2
3	Bus	✓ Bus 2
4	SVS-Controller	✓ controller

Figure 3. 7 SVC Controller composite model using DIgSILENT

3.6.2 SVC Controller Model

The controller for the SVC is specific to the design aspect of the SVC used and how it is integrated into the power systems grid. Therefore, as discussed in depth in the previous chapters, the SVC located at Kality II substation has a fixed capacitor bank with a Thyristor controlled reactor. The purpose of the SVC is purely to stabilize the 15kV busbar voltage during voltage depression and surge stages. Therefore, the controller is simulated using DIgSILENT specifically with block definitions that allow for certain parameter input quantities that replicate the real life installation.

Figure 3.8 shows the internal program logic relating to the decision process that the SVC undergoes when deciding how to control the 15kV busbar voltage relating to the set-point the user has inputted via the usetp value which is the set-point voltage in pu desirable by the relevant operator/controller. The scalar quantities such as V_{max} and V_{min} are used to set the range that the SVC is allowed to adjust the busbar voltage and of course is dependent on the limit of the size of the capacitors and reactors making up the SVC. At the end of the process of decision making within the controller a value is passed on to the next stage, y_{svs}, with in the composite model in order to allow the SVC to react accordingly such that the Thyristors firing angles are turned on or off relating to the amount of reactive power that is required to be absorbed within the system in order to compensate for voltage surges that might be occurring on the relevant 15kv busbar. Similarly, the decision process might call for the Thyristors to be completely turned off such that the capacitor bank can be switched in therefore allowing for MVAr's to be "shunted" onto the 15kV busbar in order to compensate for voltage depression that might be occurring.

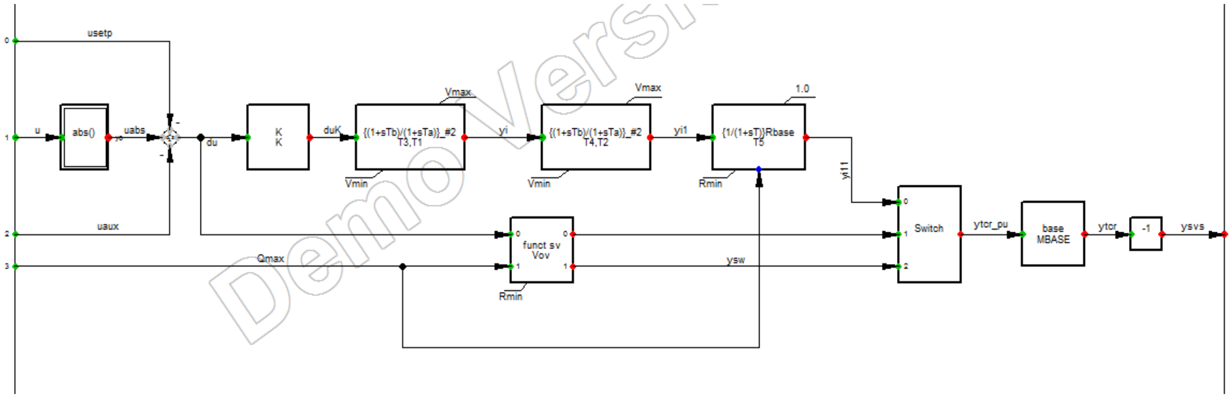


Figure 3. 8 SVC Controller simulation using DIgSILENT

Chapter Four

Simulation Studies and Analysis of Results

4.1 Introduction

This chapter is given simulation results for comparison of voltage regulation, Reactive power compensation and power loss with and without SVC compensator.

The SVC model within DIgSILENT uses an approach that is rather different and more intricate than the other relevant components making up the derived network model. The composite model is defined with a fixed capacitor bank in parallel with it. The SVCs in use today are variable impedance type made of Thyristor Controlled Reactor (TCR) in parallel with either fixed capacitor (FC) or Thyristor Switched Capacitor (TSC).

A case study of the system simulation using DIgSILENT Power Factory software model is presented. The simulation is carried out to study the response of the system for both configurations of FC-TCR and TCR-TSC.

4.2 DIgSILENT Simulation Circuit

The substation system modeled with DIgSILENT software is shown in Figure 4.1. There is incoming 132 kV main bus bar that connected to two substation transformer (trafo II and Trafo III) which is connected to 132/15 kV transformer through five 15 kV feeders. Though the 15 kV feeder the power supply by two 25 MVA transformer, transformer II is supply to feeder 2 and feeder 6 and Transformer 3 supply to feeder 3, feeder 4 and feeder 5.

Line diagram of substation shown in figure 3.3, with the data related to voltage, power, length of distribution feeder, transformer on each feeders, reactance and resistances of distribution line and all measurement received from EEU and EEP is considered for computer simulation. Power flow has been carried out by DIgSILENT Power Factory software during peak load condition.

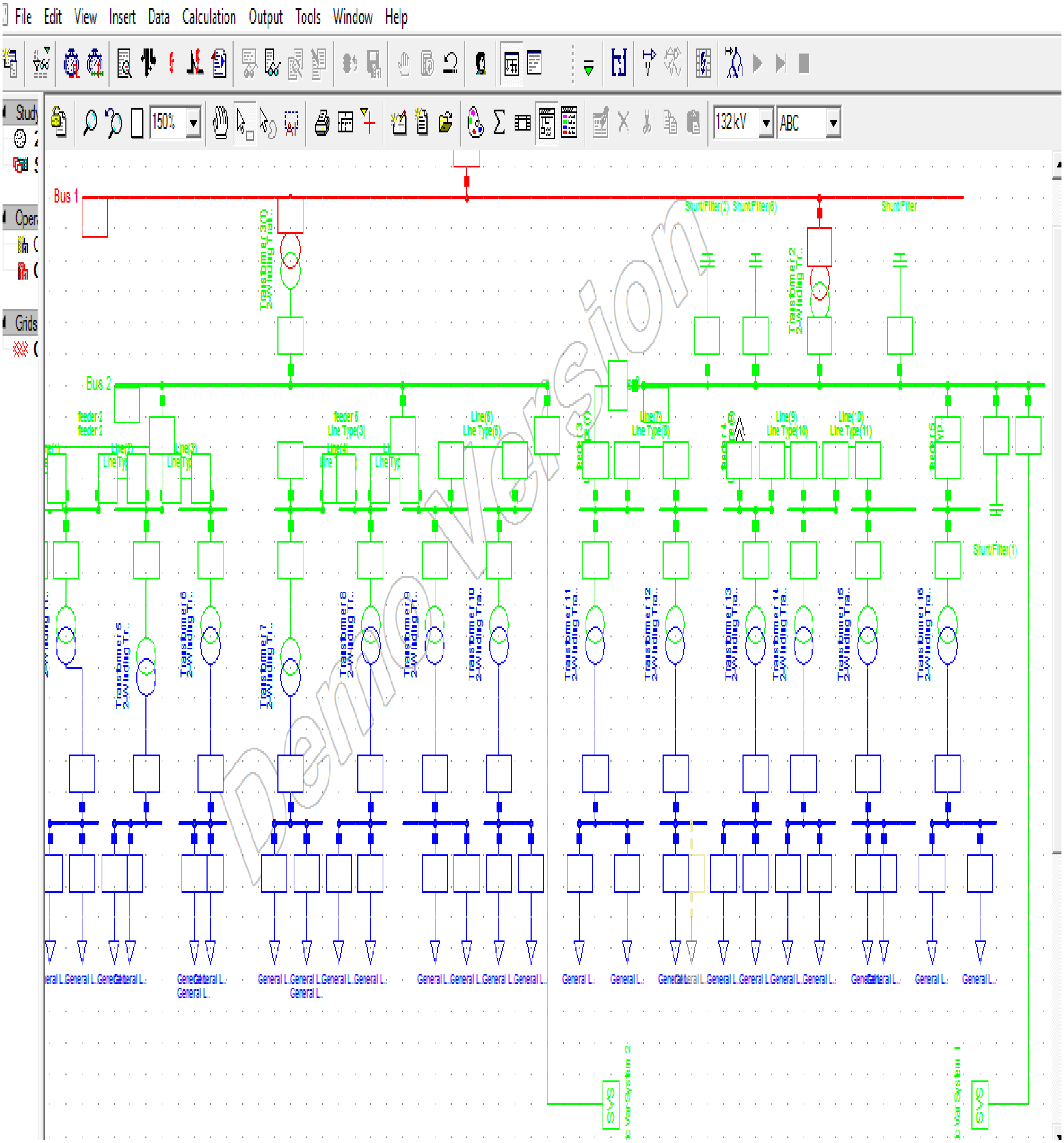
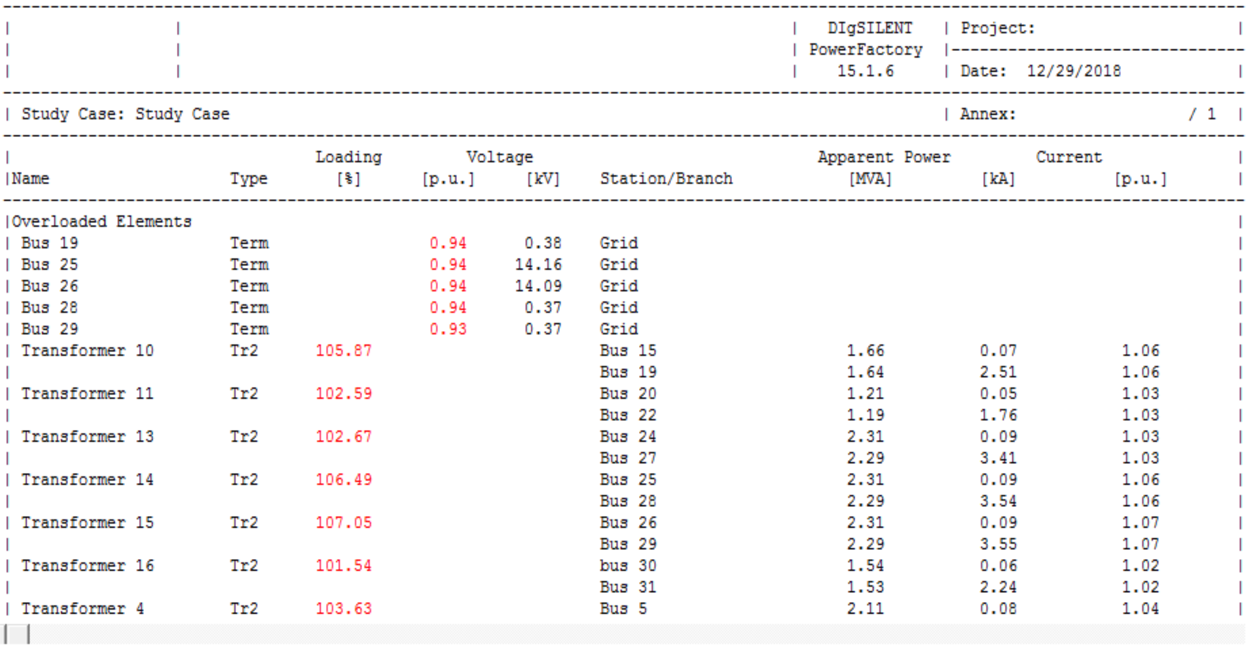


Figure 4. 1 SVC simulated circuit of Kality II Substation

4.3 Simulation Results for Peak Load Condition-NO SVC



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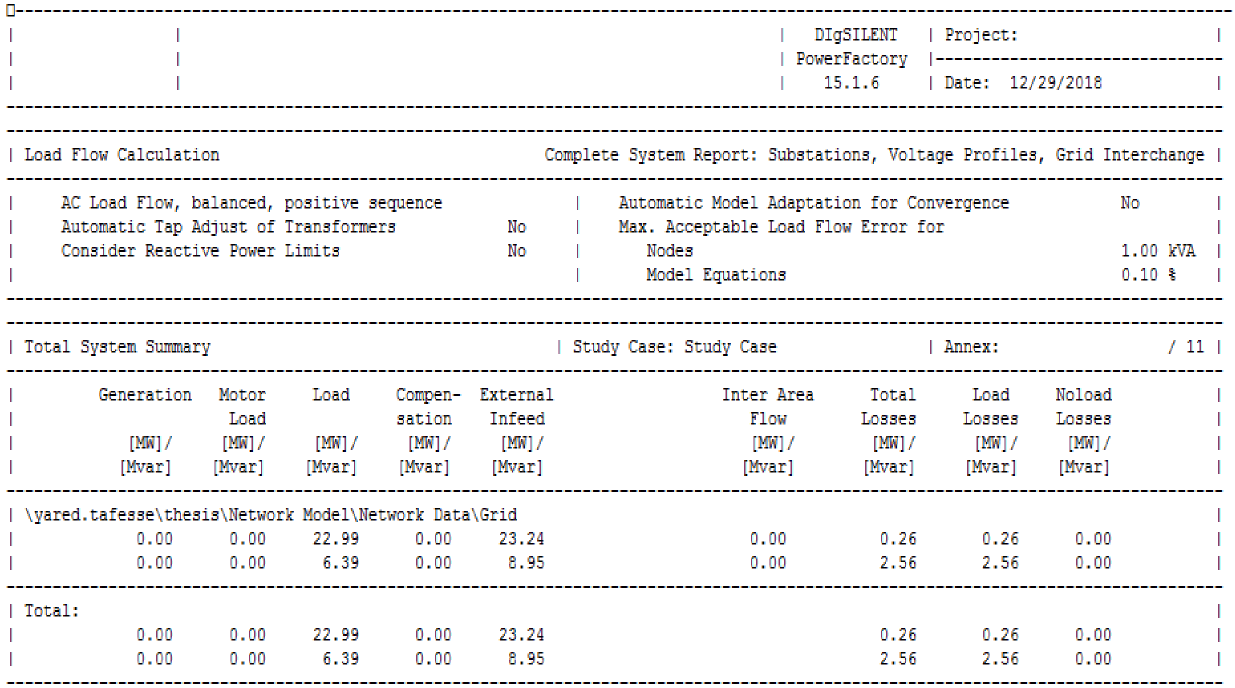
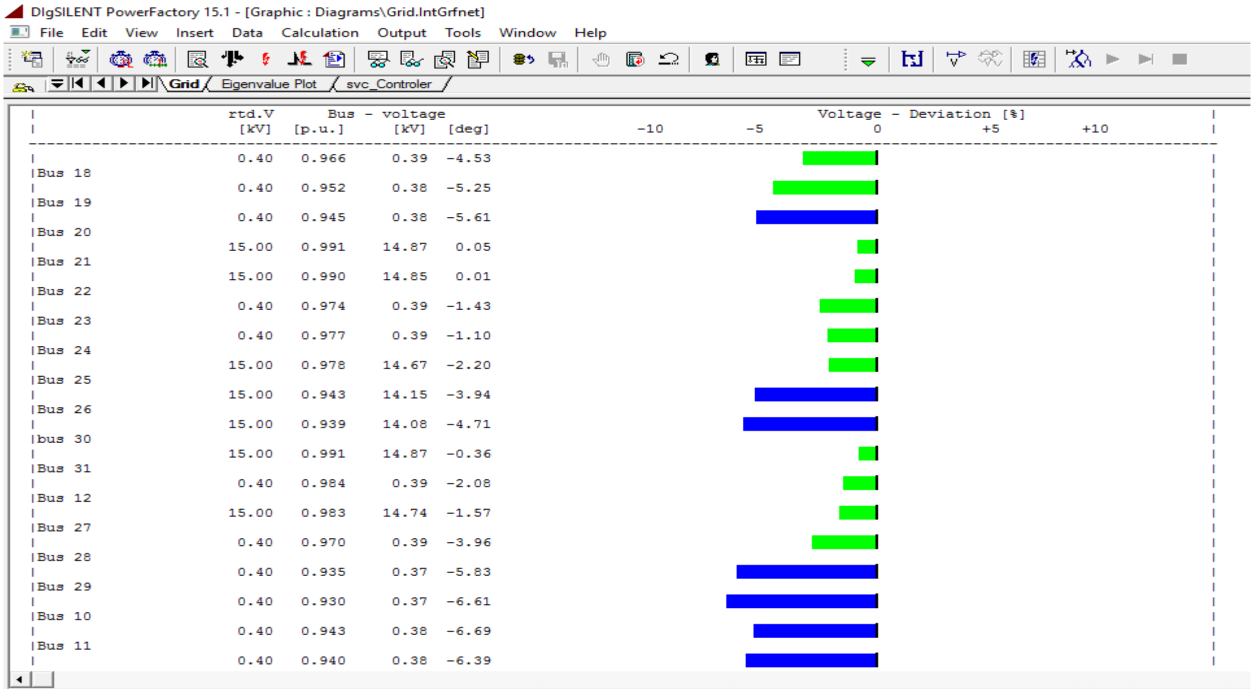
------------------------------------------------------------------------------------------------------------------
|               |                                                      |  DIgSILENT   | Project:                   |
|               |                                                      | PowerFactory |-------------------------------
|               |                                                      |    15.1.6    | Date:  12/29/2018          |
------------------------------------------------------------------------------------------------------------------
| Study Case: Study Case                                                              | Annex:               / 1  |
------------------------------------------------------------------------------------------------------------------
|                             Loading       Voltage                         Apparent Power        Current         |
|Name                  Type     [%]     [p.u.]    [kV]   Station/Branch        [MVA]        [kA]        [p.u.]     |
------------------------------------------------------------------------------------------------------------------
|Overloaded Elements                                                                                              |
| Bus 19               Term              0.94     0.38   Grid                                                     |
| Bus 25               Term              0.94    14.16   Grid                                                     |
| Bus 26               Term              0.94    14.09   Grid                                                     |
| Bus 28               Term              0.94     0.37   Grid                                                     |
| Bus 29               Term              0.93     0.37   Grid                                                     |
| Transformer 10       Tr2     105.87                    Bus 15                 1.66        0.07        1.06      |
|                                                        Bus 19                 1.64        2.51        1.06      |
| Transformer 11       Tr2     102.59                    Bus 20                 1.21        0.05        1.03      |
|                                                        Bus 22                 1.19        1.76        1.03      |
| Transformer 13       Tr2     102.67                    Bus 24                 2.31        0.09        1.03      |
|                                                        Bus 27                 2.29        3.41        1.03      |
| Transformer 14       Tr2     106.49                    Bus 25                 2.31        0.09        1.06      |
|                                                        Bus 28                 2.29        3.54        1.06      |
| Transformer 15       Tr2     107.05                    Bus 26                 2.31        0.09        1.07      |
|                                                        Bus 29                 2.29        3.55        1.07      |
| Transformer 16       Tr2     101.54                    bus 30                 1.54        0.06        1.02      |
|                                                        Bus 31                 1.53        2.24        1.02      |
| Transformer 4        Tr2     103.63                    Bus 5                  2.11        0.08        1.04      |
```

Figure 4. 2 Simulation Output of Transformer Loading and Poor Buses Without SVC



```
-----------------------------------------------------------------------------------------------------------------
|               |                                                      |  DIgSILENT   | Project:                |
|               |                                                      | PowerFactory |--------------------------------
|               |                                                      |    15.1.6    | Date:  12/29/2018       |
-----------------------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------------------
| Load Flow Calculation                              Complete System Report: Substations, Voltage Profiles, Grid Interchange |
-----------------------------------------------------------------------------------------------------------------
|    AC Load Flow, balanced, positive sequence           |   Automatic Model Adaptation for Convergence       No    |
|    Automatic Tap Adjust of Transformers          No    |   Max. Acceptable Load Flow Error for                    |
|    Consider Reactive Power Limits                No    |     Nodes                                      1.00 kVA  |
|                                                        |     Model Equations                            0.10 %    |
-----------------------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------------------
| Total System Summary                                   | Study Case: Study Case            | Annex:          / 11 |
-----------------------------------------------------------------------------------------------------------------
|        Generation    Motor     Load    Compen-   External           Inter Area    Total     Load    Noload       |
|                       Load              sation    Infeed               Flow       Losses    Losses   Losses       |
|            [MW]/     [MW]/     [MW]/    [MW]/     [MW]/               [MW]/      [MW]/     [MW]/    [MW]/        |
|           [Mvar]    [Mvar]    [Mvar]   [Mvar]    [Mvar]              [Mvar]     [Mvar]    [Mvar]   [Mvar]        |
-----------------------------------------------------------------------------------------------------------------
| \yared.tafesse\thesis\Network Model\Network Data\Grid                                                            |
|             0.00      0.00     22.99     0.00     23.24                0.00       0.26      0.26     0.00        |
|             0.00      0.00      6.39     0.00      8.95                0.00       2.56      2.56     0.00        |
-----------------------------------------------------------------------------------------------------------------
| Total:                                                                                                           |
|             0.00      0.00     22.99     0.00     23.24                           0.26      0.26     0.00        |
|             0.00      0.00      6.39     0.00      8.95                           2.56      2.56     0.00        |
-----------------------------------------------------------------------------------------------------------------
```

Figure 4. 3 Simulation Output of Total Power Loss Without SVC

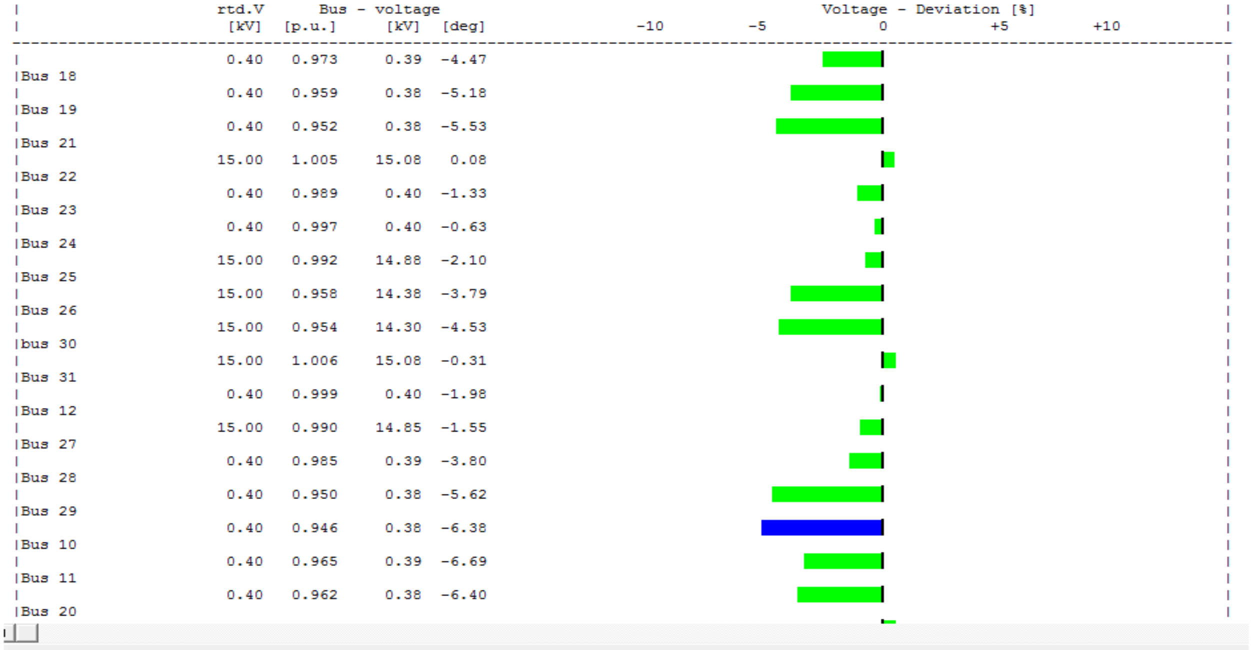


```
|                          rtd.V       Bus - voltage                              Voltage - Deviation [%]
|                          [kV]  [p.u.]      [kV]  [deg]        -10        -5          0         +5        +10
--------------------------------------------------------------------------------------------------------------
|                           0.40  0.966      0.39  -4.53
|Bus 18
|                           0.40  0.952      0.38  -5.25
|Bus 19
|                           0.40  0.945      0.38  -5.61
|Bus 20
|                          15.00  0.991     14.87   0.05
|Bus 21
|                          15.00  0.990     14.85   0.01
|Bus 22
|                           0.40  0.974      0.39  -1.43
|Bus 23
|                           0.40  0.977      0.39  -1.10
|Bus 24
|                          15.00  0.978     14.67  -2.20
|Bus 25
|                          15.00  0.943     14.15  -3.94
|Bus 26
|                          15.00  0.939     14.08  -4.71
|bus 30
|                          15.00  0.991     14.87  -0.36
|Bus 31
|                           0.40  0.984      0.39  -2.08
|Bus 12
|                          15.00  0.983     14.74  -1.57
|Bus 27
|                           0.40  0.970      0.39  -3.96
|Bus 28
|                           0.40  0.935      0.37  -5.83
|Bus 29
|                           0.40  0.930      0.37  -6.61
|Bus 10
|                           0.40  0.943      0.38  -6.69
|Bus 11
|                           0.40  0.940      0.38  -6.39
```

Figure 4. 4 Simulation Output of voltage deviation Without SVC

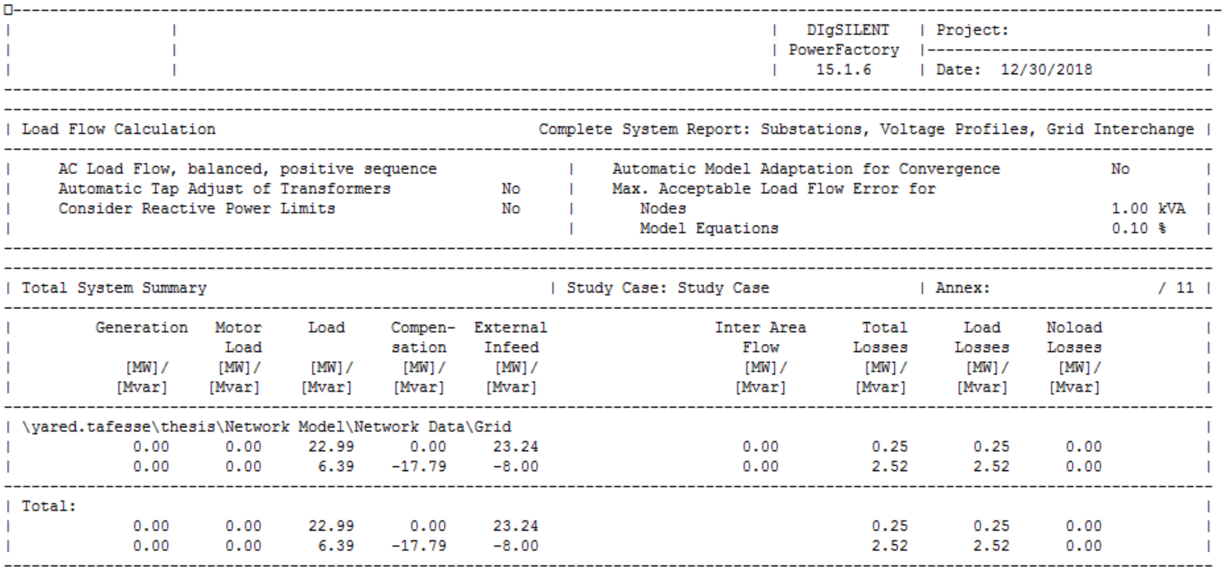
4.4 Results for Peak Load Conditions with SVC

Case 1: FC – TCR Configuration simulation out put



```
|                          rtd.V       Bus - voltage                              Voltage - Deviation [%]
|                          [kV]  [p.u.]      [kV]  [deg]        -10        -5          0         +5        +10
--------------------------------------------------------------------------------------------------------------
|                           0.40  0.973      0.39  -4.47
|Bus 18
|                           0.40  0.959      0.38  -5.18
|Bus 19
|                           0.40  0.952      0.38  -5.53
|Bus 21
|                          15.00  1.005     15.08   0.08
|Bus 22
|                           0.40  0.989      0.40  -1.33
|Bus 23
|                           0.40  0.997      0.40  -0.63
|Bus 24
|                          15.00  0.992     14.88  -2.10
|Bus 25
|                          15.00  0.958     14.38  -3.79
|Bus 26
|                          15.00  0.954     14.30  -4.53
|bus 30
|                          15.00  1.006     15.08  -0.31
|Bus 31
|                           0.40  0.999      0.40  -1.98
|Bus 12
|                          15.00  0.990     14.85  -1.55
|Bus 27
|                           0.40  0.985      0.39  -3.80
|Bus 28
|                           0.40  0.950      0.38  -5.62
|Bus 29
|                           0.40  0.946      0.38  -6.38
|Bus 10
|                           0.40  0.965      0.39  -6.69
|Bus 11
|                           0.40  0.962      0.38  -6.40
|Bus 20
```

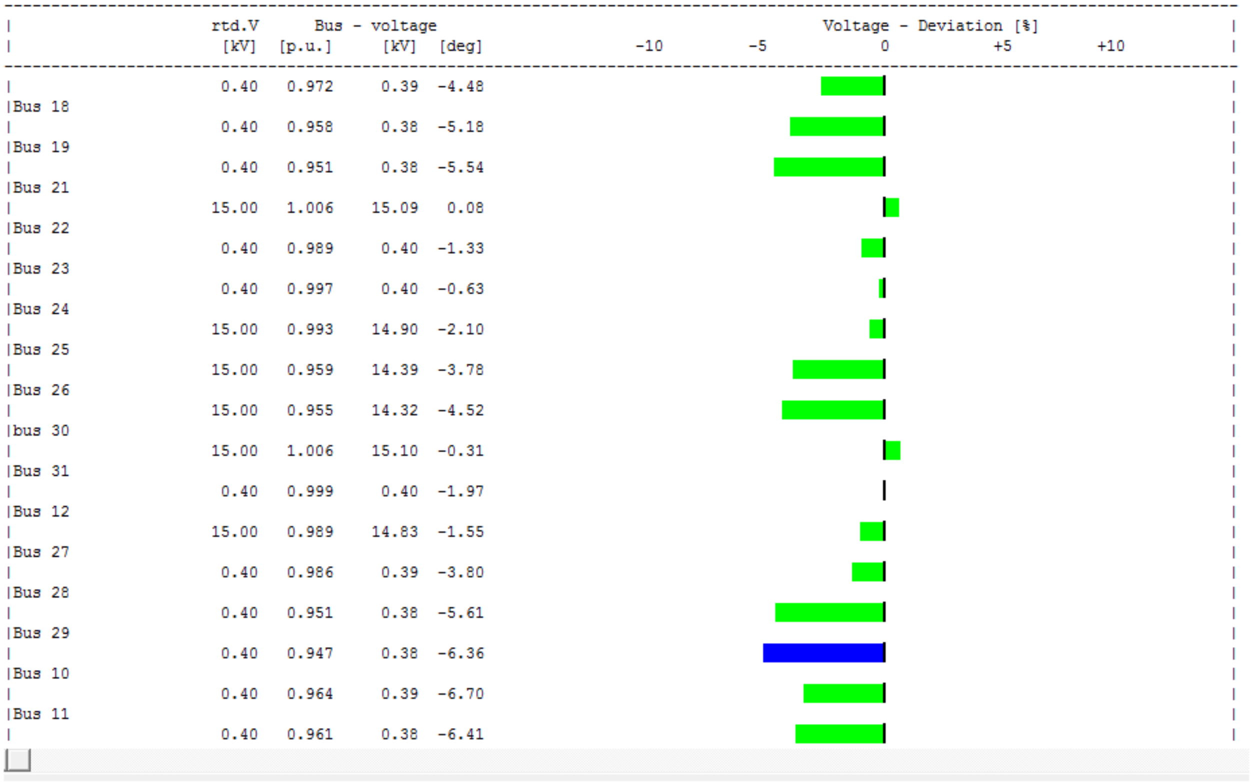
Figure 4. 5 Simulation Output of voltage profile FC-TCR Configuration



```
--------------------------------------------------------------------------------------------------------------------------
|              |                                                           |  DIgSILENT  | Project:                       |
|              |                                                           | PowerFactory |-------------------------------
|              |                                                           |   15.1.6    | Date:  12/30/2018               |
--------------------------------------------------------------------------------------------------------------------------
--------------------------------------------------------------------------------------------------------------------------
| Load Flow Calculation                                Complete System Report: Substations, Voltage Profiles, Grid Interchange |
--------------------------------------------------------------------------------------------------------------------------
|     AC Load Flow, balanced, positive sequence              |  Automatic Model Adaptation for Convergence          No      |
|     Automatic Tap Adjust of Transformers          No       |  Max. Acceptable Load Flow Error for                          |
|     Consider Reactive Power Limits                No       |     Nodes                                            1.00 kVA |
|                                                            |     Model Equations                                  0.10 %   |
--------------------------------------------------------------------------------------------------------------------------
--------------------------------------------------------------------------------------------------------------------------
| Total System Summary                                 | Study Case: Study Case               | Annex:               / 11 |
--------------------------------------------------------------------------------------------------------------------------
|         Generation   Motor      Load      Compen-   External                Inter Area     Total      Load     Noload      |
|                      Load                  sation    Infeed                     Flow       Losses     Losses   Losses      |
|            [MW]/     [MW]/      [MW]/      [MW]/     [MW]/                     [MW]/       [MW]/      [MW]/    [MW]/       |
|           [Mvar]    [Mvar]     [Mvar]     [Mvar]    [Mvar]                    [Mvar]      [Mvar]     [Mvar]   [Mvar]       |
--------------------------------------------------------------------------------------------------------------------------
| \yared.tafesse\thesis\Network Model\Network Data\Grid                                                                     |
|             0.00      0.00      22.99       0.00     23.24                      0.00         0.25       0.25     0.00      |
|             0.00      0.00       6.39     -17.79     -8.00                      0.00         2.52       2.52     0.00      |
--------------------------------------------------------------------------------------------------------------------------
| Total:                                                                                                                    |
|             0.00      0.00      22.99       0.00     23.24                                   0.25       0.25     0.00      |
|             0.00      0.00       6.39     -17.79     -8.00                                   2.52       2.52     0.00      |
--------------------------------------------------------------------------------------------------------------------------
```

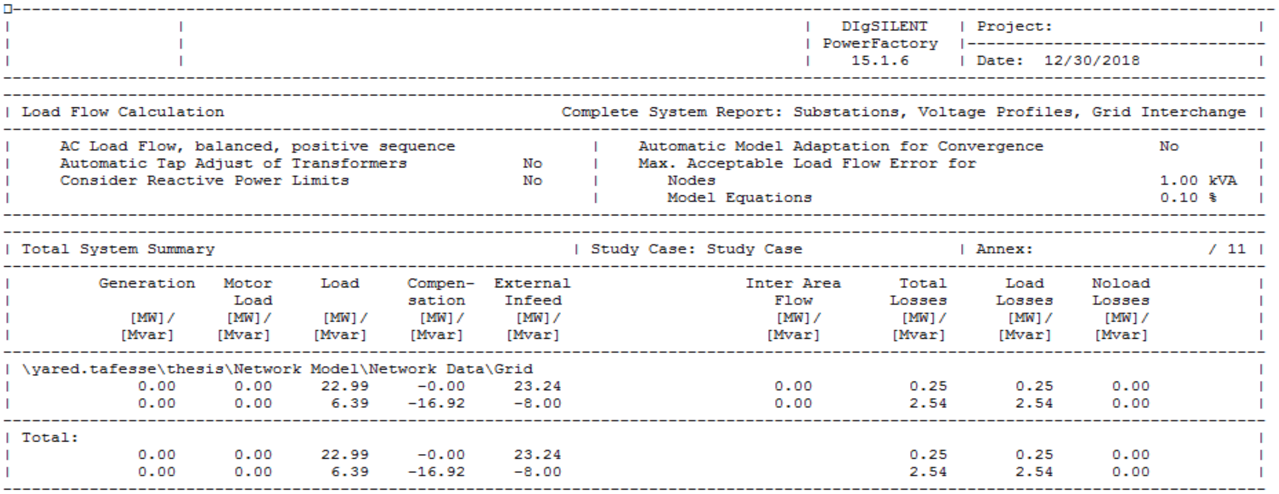
Figure 4. 6 Simulation Output of Reactive power compensation FC-TCR Configuration

Case 2: TSC – TCR Configuration simulation out put



```
--------------------------------------------------------------------------------------------------------------------------
|                      rtd.V      Bus - voltage                                  Voltage - Deviation [%]                  |
|                      [kV]   [p.u.]     [kV]   [deg]               -10          -5          0          +5         +10      |
--------------------------------------------------------------------------------------------------------------------------
|                       0.40   0.972     0.39  -4.48                                                                      |
|Bus 18                                                                                                                   |
|                       0.40   0.958     0.38  -5.18                                                                      |
|Bus 19                                                                                                                   |
|                       0.40   0.951     0.38  -5.54                                                                      |
|Bus 21                                                                                                                   |
|                      15.00   1.006    15.09   0.08                                                                      |
|Bus 22                                                                                                                   |
|                       0.40   0.989     0.40  -1.33                                                                      |
|Bus 23                                                                                                                   |
|                       0.40   0.997     0.40  -0.63                                                                      |
|Bus 24                                                                                                                   |
|                      15.00   0.993    14.90  -2.10                                                                      |
|Bus 25                                                                                                                   |
|                      15.00   0.959    14.39  -3.78                                                                      |
|Bus 26                                                                                                                   |
|                      15.00   0.955    14.32  -4.52                                                                      |
|bus 30                                                                                                                   |
|                      15.00   1.006    15.10  -0.31                                                                      |
|Bus 31                                                                                                                   |
|                       0.40   0.999     0.40  -1.97                                                                      |
|Bus 12                                                                                                                   |
|                      15.00   0.989    14.83  -1.55                                                                      |
|Bus 27                                                                                                                   |
|                       0.40   0.986     0.39  -3.80                                                                      |
|Bus 28                                                                                                                   |
|                       0.40   0.951     0.38  -5.61                                                                      |
|Bus 29                                                                                                                   |
|                       0.40   0.947     0.38  -6.36                                                                      |
|Bus 10                                                                                                                   |
|                       0.40   0.964     0.39  -6.70                                                                      |
|Bus 11                                                                                                                   |
|                       0.40   0.961     0.38  -6.41                                                                      |
```

Figure 4. 7 Simulation Output of voltage profile TSC-TCR Configuration



```
□-----------------------------------------------------------------------------------------------------------------------------------
|                 |                                                                |   DIgSILENT   | Project:                     |
|                 |                                                                | PowerFactory  |------------------------------
|                 |                                                                |    15.1.6     | Date:  12/30/2018            |
-----------------------------------------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------------------------------------
| Load Flow Calculation                                    Complete System Report: Substations, Voltage Profiles, Grid Interchange |
-----------------------------------------------------------------------------------------------------------------------------------
|     AC Load Flow, balanced, positive sequence                 |    Automatic Model Adaptation for Convergence            No       |
|     Automatic Tap Adjust of Transformers           No         |    Max. Acceptable Load Flow Error for                            |
|     Consider Reactive Power Limits                 No         |       Nodes                                              1.00 kVA |
|                                                               |       Model Equations                                    0.10 %   |
-----------------------------------------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------------------------------------
| Total System Summary                                     | Study Case: Study Case                    | Annex:                 / 11 |
-----------------------------------------------------------------------------------------------------------------------------------
|         Generation    Motor      Load      Compen-   External                           Inter Area      Total      Load      Noload          |
|                       Load                 sation    Infeed                                Flow         Losses     Losses    Losses          |
|              [MW]/     [MW]/      [MW]/     [MW]/      [MW]/                             [MW]/         [MW]/      [MW]/     [MW]/          |
|             [Mvar]    [Mvar]     [Mvar]    [Mvar]     [Mvar]                            [Mvar]        [Mvar]     [Mvar]    [Mvar]          |
-----------------------------------------------------------------------------------------------------------------------------------
| \yared.tafesse\thesis\Network Model\Network Data\Grid                                                                           |
|               0.00      0.00      22.99     -0.00      23.24                             0.00          0.25       0.25      0.00           |
|               0.00      0.00       6.39    -16.92      -8.00                             0.00          2.54       2.54      0.00           |
-----------------------------------------------------------------------------------------------------------------------------------
| Total:                                                                                                                          |
|               0.00      0.00      22.99     -0.00      23.24                                           0.25       0.25      0.00           |
|               0.00      0.00       6.39    -16.92      -8.00                                           2.54       2.54      0.00           |
-----------------------------------------------------------------------------------------------------------------------------------
```

Figure 4. 8 Simulation Output of Reactive power compensation TSC-TCR Configuration

4.5 Simulation Results comparison

Table 4. 1 Voltage profile comparison with SVC simulation

Bus	Voltage [p.u]		
	Without SVC	with SVC	
		FC-TCR	TCR-TSC
Bus 10	0.943	0.965	0.964
Bus 11	0.94	0.962	0.961
Bus 18	0.952	0.959	0.958
Bus 19	0.945	0.95	0.951
Bus 25	0.943	0.958	0.965
Bus 26	0.939	0.954	0.955
Bus 29	0.939	0.946	0.947
Bus 28	0.935	0.95	0.951
Bus 22	0.975	0.989	0.989

Table 4. 2 Reactive power comparison with SVC simulation

Power	Reactive power Without SVC	Reactive Power [Mvar] Compensated by SVC	
		With SVC	
		FC-TCR	TCR-TSC
External infeed power	8.95Mvar	8Mvar	8Mvar
Transmission loss	2.56Mvar	0.04Mvar	0.02Mvar

The simulation results reveal that the voltage profile achieved for TCR-TSC is better when compared with FC-TCR.

Chapter Five

Conclusions, Recommendations and Future Work

5.1 Conclusions

This thesis discusses in detail the use of different configurations of Static Var Compensators such as FC-TCR and TCR-TSC for reactive power compensation, harmonic filtering and voltage control. Various configurations of using SVCs are investigated and implemented on Addis Ababa Kality II 132/15 kV distribution substation to test their effectiveness in voltage control. The results show that the number of load buses with voltages that recovered to within acceptable limit between 0.95 pu and 1.05pu. It is further observed that adding SVCs at weakest bus in the network will significantly help to improve voltage and the distribution network may be operated within the allowable voltage range. Moreover, it is also concluded that use of SVCs could be a very effective device for voltage control and to improve the power transfer across congested interfaces.

5.2 Recommendations

Based on the findings of this research, it is recommended that SVC controllers may be used for reactive power compensation in the Addis Ababa Kality II 132/15 kV distribution substation. It is further recommended that SVCs may be added at the weakest buses in the network to significantly improve the voltage of distribution substation and operate the network within the allowable voltage range.

5.3 Suggestions for Future Work

The following works are suggested to further extend the research carried out in this thesis.

- A cost benefit analysis of voltage control using SVCs and load interruption as well as to compare the costs of the two methods.
- Performing the simulations studies using different softwares such as Matlab and ETAP (electrical transient analysis program) to test the effectiveness of the proposed method of voltage control as well as to compare the simulation results.

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

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"Cost Comparison of FACTS Devices for Industrial Application –A study" International Journal of Technical Research & Science, Volume 1 Issue 4, July 2016

Appendix A: Kality II and Kality I substation interconnection

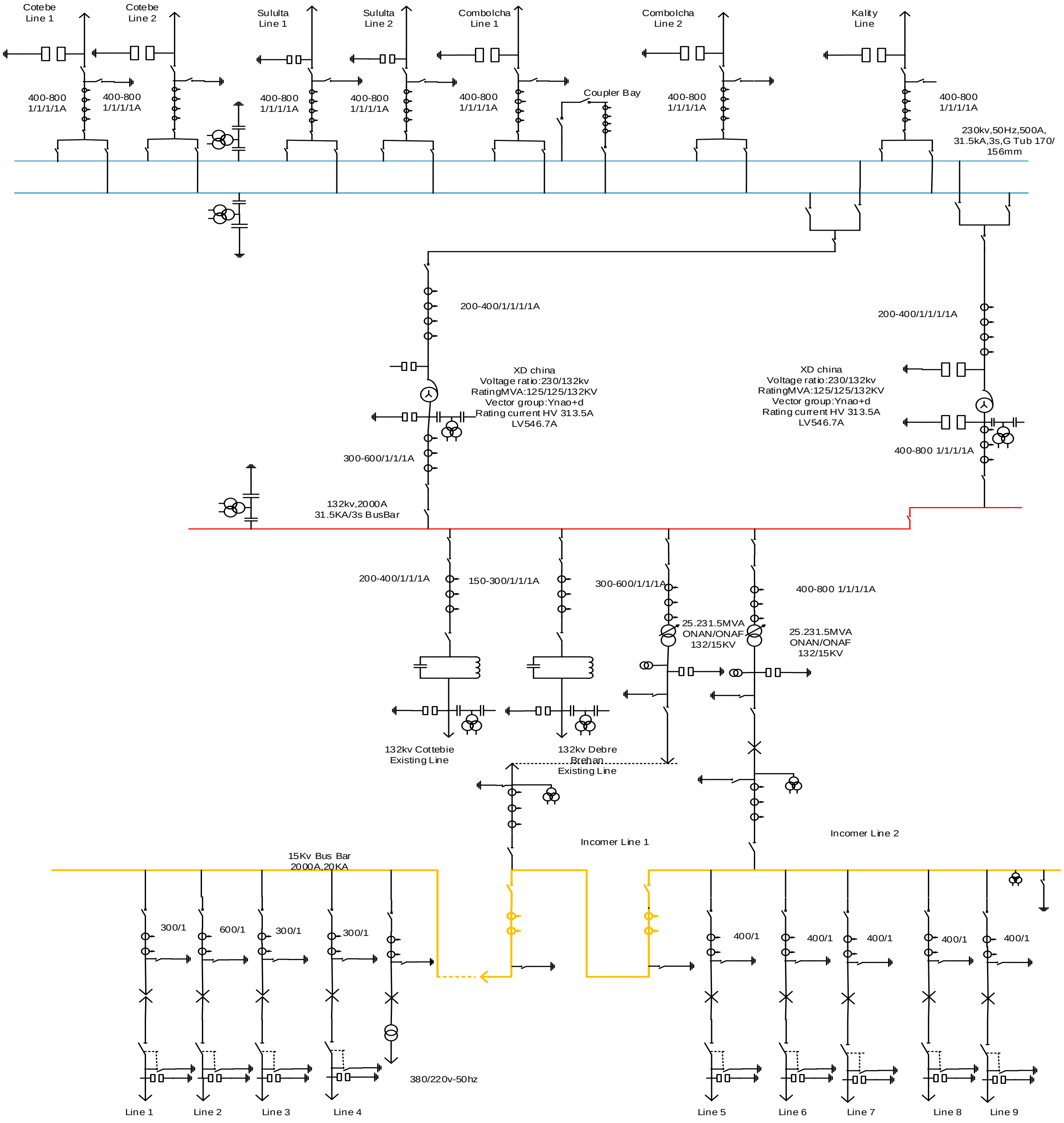

Figure A.1 Kality II and Kality I interconnection diagram

Appendix B: Kality II 15 kV Substation feeder 4 transformer data

Table A:1 Distribution Transformer Feeder 04

	Size (kVA)	**Load (kW)**
KAL 01	315	252
KAL 02	50	40
KAL 03	200	160
KAL 04	630	504
KAL 05	100	80
KAL 06	100	80
KAL 07	300	240
KAL 08	100	80
KAL 09	200	160
KAL 10	200	160
KAL 11	200	160
KAL 12	200	160
KAL 13	50	40
KAL 14	100	80
KAL 15	630	504
KAL 16	100	80
KAL 17	315	252
KAL 18	100	80
KAL 19	200	160
KAL 20	200	160
KAL 21	300	240
KAL 22	200	160
KAL 23	315	252
KAL 24	100	80
KAL 25	200	160
KAL 26	100	80
KAL 27	200	160
KAL 28	100	80
KAL 29	315	252
KAL 30	200	160
KAL 31	315	252
KAL 32	315	252
KAL 33	200	160