Sudan University of Sciences and Technology

College of Engineering

Electrical Engineering

Study of Voltage Improvement in Gamoyia Substation by Adding Static VAR Compensator (SVC)

دراسة تحسين الجهد في محطة الجموعية بإستخدام المعوض الإستاتيكي (SVC)

A Project Submitted In Partial Fulfillment for the Requirements of the Degree of B.Eng. (Honor) In Electrical Engineering

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الآية

قال تعالى:

(أَلَمْ تَرَ أَنَّ اللَّهَ أَنزَلَ مِنَ السَّمَاء مَاء فَأَخْرَجْنَا بِهِ ثَمَرَاتٍ مُّخْتَلِفًا أَلْوَانُهَا وَمِنَ الْجِبَالِ جُدَدٌ بِيضٌ وَحُمْرٌ مُّخْتَلِفٌ أَلْوَانُهَا وَغَرَابِيبُ سُودٌ {27} وَمِنَ النَّاسِ وَالدَّوَابِّ وَالْأَنْعَامِ مُخْتَلِفٌ أَلْوَانُهُ كَذَلِكَ إِنَّمَا يَخْشَى اللَّهَ مِنْ عِبَادِهِ الْعُلَمَاء إِنَّ اللَّهَ عَزِيزٌ غَفُورٌ {28})

صدق الله العظيم

سورة فاطر الآيات {27-28}

DEDICATION

I dedicate this humble work to the purest and the strongest love l have felt in my heart, to the nicest word my tongue tell her, to who the paradise is made under her feed

My dear mother.

To the crown of my head, to the merciful heart that bears the hardships for us, to who instilled in us the love science, learning, honesty and loyalty

My dear father.

To those whom knew us the meaning of live, love and sacrifice

My brothers and sisters.

To the candles that burn to light our way

My teachers at all levels.

To all my friends and everyone who encouraged me and did not forget me in his prayer.

And for those whom in my memory and not in my note.

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ABSTRACT

The expansion in the demand which faces by GAM substation causes voltage stability problems and makes the voltage out of the allowable limits. The purpose of this project is to compensate the reactive power for improve the voltage in GAM substation, SVC was used to investigation this purpose.

In this study the analyses of load flow have done by ETAP software in the normal loading condition, 50% and 150% of loading by using three different SVCs and MATLAB software was used to study dynamic state. The important results were obtained that voltage was improved, good results obtained when the rating of SVC in substation was increased. Also when SVC at bus33kv.

المستخلص

التوسع في الطلب الذي تواجهه محطة الجموعية أدى إلي حدوث مشاكل في إستقرار الجهود و إيصالها إلي حدود أقل من المسموح به . الغرض من هــذا المشــروع تعــويض القــدره الردفعليه لتحسين الجهد في محطة الجموعية ولتحقيق اهداف الدراسه تم اســتخدام معــوض إستاتيكي(SVC).

تم عمل تحليل لسريان القدره للمحطه بإستخدام برنامج الإيتاب في الحاله الطبيعيــة وعنــد زيادة الحمولة إلي 150% وإنخفاضها إلي 50% من قيمتها الطبيعية وذلك بإســتخدام ثلاثــة معوضات إستاتيكية مختلفة، وبإستخدام برنامج الماتلاب تم دراسه التغيرات الديناميكية.

توصلت الدراسة الي عدة نتائج من اهمها ان الجهد قد تحسن و عند زيادة ســعة المعــوض الإستاتيكي svc قد حقق نتائج مرغوبه وعند وضع المعوض الإستاتيكي svc عند باسبار33 ك. ف اعطي تحسين افضل من وضعه عند باسبار110 ك. ف .

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LIST OF ABBREVIATIONS

GAM	Gamoyia
EHV	Extra High Voltage
MSR	Mechanically Switched Reactor
MSC	Mechanically Switched Capacitor
HV	High Voltage
LV	Low Voltage
FACTS	Flexible Ac Transmission Systems
SVC	Static VAR Compensator
STATCOM	Static Synchronous Compensator
SSSC	Static Synchronous Series Compensator
IPFC	Inter Line Power Flow Controller
UPFC	Unified Power Flow Controller
SR	Saturated Reactor
TCR	Thyristor Controlled Reactor
TSC	Thyristor Switched Capacitor
TSR	Thyristor Switched Reactor
TCT	Thyristor Controlled Transformer

CHAPTER ONE

INTRODUCTION

1.1 General Concepts:

Electrical energy has a fundamental role in the economic growth of any society as all the residential, commercial and industrial sectors are dependent on it. Electrical energy is generated in generation plants and transferred to distribution substation to deliver it to load center through transmission lines. Electrical power transmitted and delivered to consumers must be of good quality. The quality of electricity supply may be measured in term of: constant voltage, frequency and power factor, balance phases, sinusoidal wave form, lack of interruption and ability to withstand fault and to recover quickly.

In recent years, electrical power transfer and delivery to consumers is subjected to many problems in consequence of many issues. Among these issues are the substantial power demand increase, due to the growth in industrial and economic while expansion of power generation and transmission is severely limited. Also, electrical power is transmitted for long distances from generation stations to load centers. The demand increase may cause excessive voltage drop, and transmission of power for long distances causes voltage increase/decrease. On the other hand, dynamically changing loads dynamically affect the quality power. So to overcome such problem and keep the system voltage within specified limits and regulate voltage that must be achieved by controlling production ,absorption and flow of reactive power through the network. There are many methods to regulate voltage in any part in the network. In generation, controlling of voltage terminal by controlling excitation of generator by using AVR. In transmission line and distribution system many voltage regulating equipments are used. These include shunt capacitor, shunt reactor, synchronous condenser, and tap changing transformer. Development in power electronic devices led to new compensation devices such as FACTS devices to control reactive power for many merits. One widely used FACTS device is the Static VAR Compensator (SVC). A SVC can improve the voltage profiles in the transient and steady state; therefore it can improve the quality and performance of the electric services.

1.2 Problem Statement:

In the last two decades demand of power is increasing rapidly but we have limited resources of power generation resulting transmission line getting heavily loaded and facing stability problems, voltage sage and reactive power issues. These constraints affect the quality of power delivered.

1.3 The objectives:

The objectives of this project are summarized in following points

1. To perform load flow analysis in GAM sub-station.
2. To compensate re'active power by using SVC to improve voltage in GAM sub-station.
3. To select the best location of SVC within GAM sub-station.
4. To determine rating of the SVC to be used in GAM substation.

1.4 The Methodology:

At first, steady state load flow analysis (with and without SVC) is performed by using ETAP software, to study effect of SVC in voltage profile at buses of GAM sub-station during peak and light load condition, then using MATLAB software to simulate GAM sub-station to study dynamic load flow.

1.5 Project Layout:

Chapter two is introduce transmission line, and methods of reactive power and voltage control. Chapter three discuss the Static VAR Compensator (construction, type, operation principle, characteristics, applications and limitation), discuss STATCOM, comparison between SVC and STATCOM and load flow analysis. In chapter four the results with and without SVC and their influence at the GAM sub-station are presented. Finally, chapter five lists the conclusion and recommendation of study.

CHAPTER TWO

BACK GROUND

2.1 Introduction:

Generation, Transmission, and Distribution systems are the main components of an electric power system. The purpose of transmission network is to transfer electric power from generating units at various locations to the distribution system which ultimately supplies the load. Transmission lines also interconnect neighboring utilities which permits not only economic dispatch of power within regions during normal conditions, but also transfer of power between regions during emergencies. Normally, transmission lines imply the bulk the bulk transfer of power by high voltage links between main load centers. On the other hand, distribution system is mainly responsible for the conveyance of this power to the consumers by means of lower voltage networks, so there will be need to sub-stations at the side of transmission and the side of distribution. The components of sub-stations are transformers (step up at generation side and step down at distribution side), reactive power compensation devices such as capacitor banks, reactor banks, SVC… etc.

All transmission lines in a power system exhibit the electrical properties of resistance, inductance, capacitance, and conductance. The inductance and capacitance are due to the effects of magnetic and electric fields around the conductor. The shunt conductance accounts for leakage currents flowing across insulators and ionized path way in the air. The leakage currents are negligible compared to the current flowing in the transmission lines and may be neglected [1, 2].

2.2 Overhead transmission lines:

A transmission circuit consists of conductors, insulators, and usually shield wires. Transmission lines are hung overhead from a tower usually made of steel, wood or reinforced concrete with its own right-of-way. Steel towers may be single-circuit or double-circuit designs. Multi-circuit steel towers have been built, where the tower supports three to ten 69-KV lines over a given width of right-of-way. Less than 1 percent of the nation's total transmission lines are placed underground. Although underground ac transmission would present a solution to some of the environmental and aesthetic problems involved with overhead transmission lines, there are technical and economic reasons that make the use of underground ac transmission prohibitive.

The selection of an economical voltage level for the transmission line is based on the amount of power and the distance of transmission. The voltage choice together with the selection of conductor size is mainly a process of weighing RI^2 losses, audible noise, and radio interference level against fixed charges on the investment [1].

2.3 Transmission Line Characteristics:

Transmission line characteristic includes resistance, inductance and capacitance.

2.3.1 Line resistance:

The resistance of the conductor is very important in transmission efficiency evaluation and economic studies. The dc resistance of a solid round conductor is given by

$$R = \frac{\rho l}{A} \qquad (2.1)$$

Where R =resistivity of conductor

l=length of conductor

A =cross sectional area of conductor

2.3.2Inductance of three – phase transmission lines:

2.3.2.1 Transpose line:

A model of per– phase transmission line is required in most power system analysis. One way to regain symmetry in good measure and obtain a per–phase model is to consider transposition. This consists of interchanging the phase configuration every one– third the length so that each conductor is moved to occupy the next physical position in regular sequence.

$$L = 0.2 \ln\frac{GMD}{Ds} \text{mH/km} \qquad (2.2)$$

Where

$$GMD = \sqrt[3]{D_{12}D_{23}D_{13}} \qquad (2.3)$$

$$Ds = r' = re^{-\frac{1}{4}} \qquad (2.4)$$

2.3.2.2 Inductance of composite conductors:

$$L_x = 2 \times 10^{-7} \ln\frac{GMD}{GMR_x} \quad \text{H/meter} \qquad (2.5)$$

Where

$$GMD = \sqrt[mn]{(D_{aa'}D_{ab'} \dots D_{am}) \dots (D_{na'}D_{nb'} \dots D_{nm})} \qquad (2.6)$$

$$GMR_x = \sqrt[n^2]{(D_{aa}D_{ab} \dots D_{an}) \dots (D_{na}D_{nb} \dots D_{nn})} \qquad (2.7)$$

Where $D_{aa} = D_{bb} = D_{nn} = r'_x$ (2.8)

2.3.3 Capacitance of three – phase lines:

Capacitance per phase to neutral is

$$C = \frac{2\pi\varepsilon_\circ}{\ln\frac{GMD}{r}} \quad \text{F/km} \qquad (2.9)$$

Recalling □0 = 8.85×10^{-12} F/m and converting to μF per kilometer, we have, or capacitance to neutral in μF per kilometer is

$$C = \frac{0.0556}{\ln\frac{GMD}{r}} \mu\text{F/km} \qquad (2.10)$$

$$GMD = \sqrt[3]{D_{12}D_{23}D_{13}} \qquad (2.11)$$

2.4 Voltage stability:

A major factor contributing to voltage instability is the voltage drop in the line impedance when active and reactive powers flow through it. As a consequence, the capability of the transmission network for power transfer and voltage support reduces. Voltage stability of a system is endangered when a disturbance increases the reactive power demand beyond the sustainable capacity of available reactive power resources.

Voltage stability can be classified into: large disturbance voltage, small disturbance, long term and short term voltage stability. The classifications are illustrated in Figure 2.1.

2.4.1 Large disturbance:

It refers to the system's ability to maintain steady voltage following large disturbances such as, system faults, loss of generation or circuit contingencies. The study period of interest may be from few seconds to tens of minutes.

2.4.2 Small disturbance:

It is concerned with the ability of the system to maintain acceptable level of steady voltages, when subjected to small perturbations such as incremental changes in system load.

2.4.3 Short-terms voltage stability:

It involves dynamics of fast acting load components such as induction motors, electronically controlled loads, and HVDC converters. The study period of interest is in the order of several seconds.

2.4.4 Long –term voltage stability:

It involves slower acting equipment such as tap-changing transformers, thermostatically controlled loads, and generator current limiters. The study period of interest may extend to several or many minutes, and long term simulations are required for analysis of system dynamic performance.

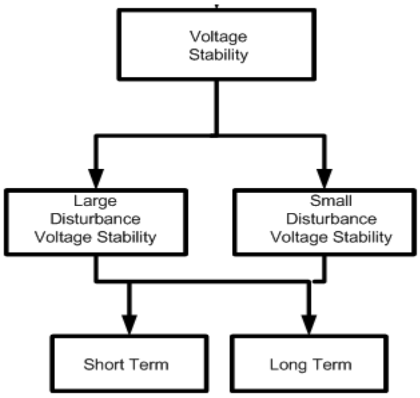


Figure 2.1: classifications of voltage stability

2.5 Reactive Power and Voltage Control:

Reactive power (Q):

It is consequence of an AC system. Reactive power is used to build up magnetic fields. It is measured in VAR, KVAR, MVAR& calculated as $Q = Ssin(x)$ or $Q = Ptan(x)$.

For efficient and reliable operation of power systems, the control of voltage and reactive power should satisfy the following objectives:-

A. Voltages at the terminals of all equipment in the system are within acceptable limits. Both utility equipment and customer equipment are designed to operate at a certain voltage rating. Prolonged operation of the equipment at voltages outside the allowable range could adversely affect their performance and possibly cause them damage.

B. System stability is enhanced to maximize utilization of the transmission system.

C. The reactive power flow is minimized so as to reduce RI^2 and XI^2 losses to a practical minimum. This ensures that the transmission system operates efficiently.

The problem of maintaining voltages within the required limits is complicated by the fact that the power system supplies power to a vast number of loads and is fed from many generating units. As loads vary the reactive power requirements of the transmission system vary. Since reactive power cannot be transmitted over long distances, voltage control has to be effected by using special devices dispersed throughout the system. This is in contrast to the control of frequency which depends on the overall system active power balance. The proper selection and coordination of equipment for controlling reactive power and voltage are among the major challenges of power system engineering [18].

2.6 Production and Absorption of Reactive Power:

Synchronous generators can generate or absorb reactive power depending on the excitation. When overexcited they supply reactive power, and when under excited they absorb reactive power. The capability to continuously supply or absorb reactive power is, however, limited by the field current, armature current, and end-region heating limits. Synchronous generators are normally equipped with automatic voltage regulators which continually adjust the excitation so as to control the armature voltage.

Overhead lines, depending on the load current, either absorb or supply reactive power. At loads below the natural (surge impedance) load, the lines produce net reactive power; at loads above the natural load, the lines absorb reactive power.

Underground cables, owing to their high capacitance, have high natural loads. They are always loaded below their natural loads, and hence generate reactive power under all operating conditions.

Transformers always absorb reactive power regardless of their loading. Loads normally absorb reactive power. A type load bus supplied by a power system is composed of a large number of devices. The composition changes depending on the day, season, and weather conditions. The composite characteristics are normally such that a load bus absorbs reactive power. Both active power and reactive power of the composite loads vary as a function of voltage magnitudes. Loads at low-lagging power factors cause excessive voltage drops in the transmission network and are uneconomical to supply. Industrial consumers are normally charged for reactive as well as active power; this gives them an incentive to improve the load power factor by using shunt capacitors.

Compensating devices are usually added to supply or absorb reactive power and thereby control the reactive power balance in a desired manner [18].

2.7 Implement The Compensation in The Network:

Shunt compensation of reactive power can be employed either at load level, substation level or at transmission level. Compensation should be provided as close as possible to the consumption point to avoid having to distribute this power in other part of network. Location is primarily determined by the reason for compensation.

- A: Direct compensation.
- B: Group compensation.
- C: Central compensation at LV side.
- D: Central compensation at HV side.

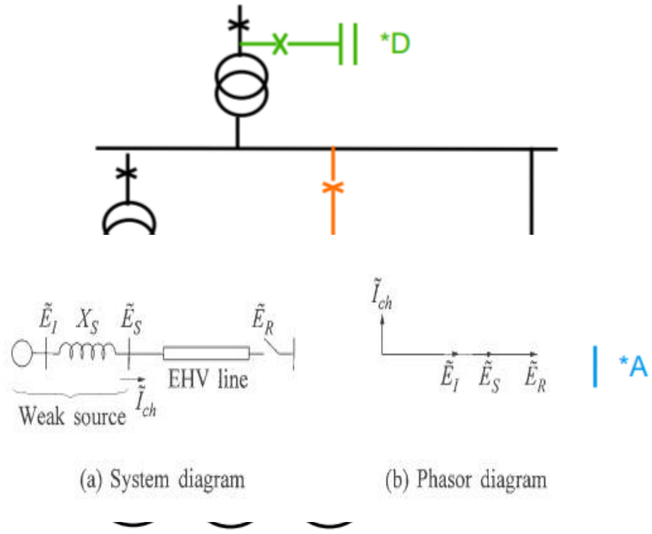


Figure 2.2: implementation of the compensation in the network

2.8 Traditional Method of Voltage Control:

There are many methods to control the voltage such as shunt reactor, shunt capacitor, synchronous condenser and tap changer transformer.

2.8.1 Shunt reactor:

Shunt reactor are used to compensate line capacitance effects by limiting voltage rise when a circuit is open or when operating under light loads .they are used for EHV over head lines longer than150-200km as shown in Figure 2.3. Shunt reactor is absorption the reactive power generation in line due to rise voltage. If the shunt reactor were not employed the reactive power generator by capacitance can cause high voltage at the receiving end of the line.

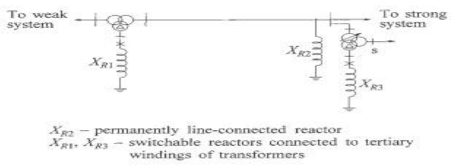


Figure 2.3: EHV line connected to a weak system

Shunt compensate reduce the maximum power limit of the line. In case line shunt are switched out under heavy loads condition. The max power transfer can be considerably increase, but voltage variation due to sudden load throw off are likely to be unacceptably high. In actual practice some of shunt reactors are kept connected permanently so as to avoid voltage increased due sudden fall in load from heavy load condition [20].

The output characteristic (V-I) is linear in the operating rang as shown in Figure 2.4 and deviates from linearity for iron-core or shrouded iron reactors due to saturation are breaker.

$$V_L = jX_L(-jI_L) = X_L I_L \quad (2.12)$$

$$I_L = \frac{V_L}{X_L} = \frac{V_L}{\omega L} \quad (2.13)$$

$$Q_L = \frac{{V_L}^2}{\omega L} \quad (2.14)$$

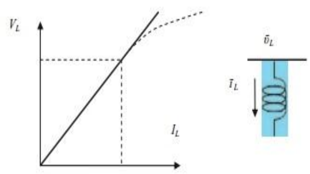


Figure 2.4: V-I characteristic

Shunt reactors may be connected to low voltage tertiary winding of transformer, through a suitable circuit breaker as shown in Figure 2.5. EHV shunt reactor may be connect to transmission line without any EHV circuit breaker ,in some application tapped reactors with on voltage tap-change control facilities have been used to allow a variation of reactance value [18].

Figure 2.5: connection of shunt reactor

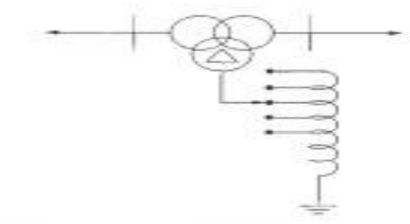


Figure 2.6: Tapped reactor

- **Mechanically Switched Reactors (MSR):**

During heavy load conditions, shunt reactor must be disconnected for this reason they are equipped with switching devices, MSR are used only on short lines supplied by weak system. The basic scheme of the MSR typically consists of a shunt reactor connected by circuit breaker or disconnect switch to transmission line bus-bar or transformer tertiary windings. Response time is equal to the switching line given by circuit breaker arrangement, which is on order of100ms following initiation of an operating instruction. Frequent switching is not possible, normal switching frequency is 2-4time /day with reactors connected under alight system load condition and disconnected under heavy system load condition. Shunt reactors in used range from a few MVARs to hundreds of MVARs at HV-EHV application [20].

2.8.2 Shunt capacitor:

Shunt capacitor supply reactive power and boost local voltages. They are used throughout the system and are applied in wide range of size.

Shunt capacitor were first used in mid 1910s for power factor correction. The early capacitors employed oil as the dielectric, because of large size and weight and high cost, their use at the time was limited. In1930s introduction of dielectric materials and other of improvement in capacitor construction brought about significant reduction in price and size. The used of shunt capacitor has increased phenomenally since the late1930s [18].

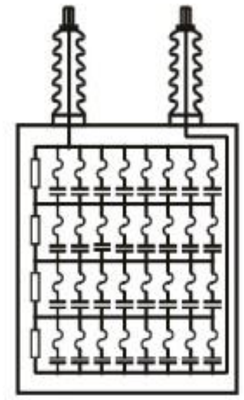


Figure 2.7: shunt capacitor

It is always connected to the bus rather than to the line. They are connected either directly to winding of the main transformer. Shunt capacitor banks are breaker switched either automatically by voltage relay or manually.

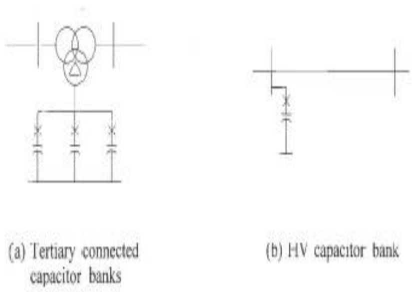


Figure 2.8: connection of shunt capacitor

2.8.2.1 Application to distribution system:

Shunt capacitor are used extensively in distribution system for power factor correction feeder voltage control. Distribution capacitors are usually switched by automatic means responding to simple time clocks or to voltage or current sensing relay. The objective of power factor correction is to provide reactive power close to point where it is being consumed by means of fixed "permanently connected "and switched shunt capacitor of various voltage levels throughout the distribution system because the most of loads having lagging power factor that they absorbing reactive power. And switched shunt capacitor are also used extensively for voltage control for voltage stability.

2.8.2.2 Application to transmission system:

Shunt capacitor are used to compensate for theXI^2losses intransmission system and to ensure satisfactory voltage levels during heavy loading conditions [18].

- **Mechanically Switched Capacitor (MSC):**

The basic scheme of mechanically switched capacitor typically consists of a single capacitor unit or bank of capacitor units connected to the power system either directly by a circuit breakers or via a transformer, pre-strike and re-strike circuit breaker are need to avoid system over voltage due to capacitor switching transient possibly damped by series small reactors which also reduce harmonics. Response time is equal to the switching time dictated by circuit breaker arrangement, which is on order of 100ms following initiation of an operating instruction. Frequent switching is not possible unless discharge devices are provided. Normal switching frequency2-4time/day with capacitors connected under heavy system load and disconnected under light system load conditions [20].

Shunt capacitor is use range in size from a few KVARs at low voltage (VL) in single unit to hundred of MVARs in bank of units at EHV applications.

2.8.3 Synchronous condensers:

Synchronous condensers machine running without a prime mover or mechanical load, by controlling the field excitation, it can be made to either generate or absorb reactive power, with a voltage regulator, can automatically adjust the reactive power output to maintain terminal voltage, It draws a small amount of active power from power system to supply losses. The efficiency of machines is very high because values of the losses are percentage of KVA rating is very low (4-6present).

Synchronous condensers have used since the1930s for voltage and reactive power control both transmission and sub-transmission levels, they are often connected to tertiary winding transformer. Asynchronous condenser provides a step-less automatic power factor correction with ability to produce up 150%aditional MVARs. Condenser can be installed inside or outside and are relatively small in size. The system produces no switching transient and is not affected by system electrical harmonics, some harmonics can even be absorb by condenser.

It can provide voltage support even during a short power outage. Unlike other form of shunt compensation it has an internal voltage source and better able to cope with low system voltage condition.

Recent applications of synchronous have been mostly at HVDC converter station connected to weak system, they are used there to increase the network strength by improving short circuit capacity and to improve commutation voltage [7].

2.8.4 Use of Tap Changing Transformer:

All power transformers and many distribution transformers has taps in one or more windings for changing ratio that's for controlling voltage at all levels.

The principle of regulating the secondary voltage is based on changing the number of turns on primary or secondary.

There is always a tapping on the HV winding which when connected to the rated voltage gives rated voltage on the LV side.

They are two types of tap changing transformer:

2.8.4.1 Off load tap changing:

This is the cheapest method of changing the turn ratio of transformer, it needs disconnection of transformer from the supply before changing the tap. This adjustment is made by tapping the respective windings as required and taking connections of tapping to some position near the top of the transformer. It is affected manually through hand holes provided in the core, the reconnection can be made by carrying the tapping leads through the cover for changing either by hand or by manually operated switches. The commonly used switches are:

1. Vertical tapping switches.
2. Face -plate switches.

2.8.4.2 On load tap changing:

Such an arrangement is employed for changing the turn-ratio of the transformer to regulate the system voltage while the transformer is delivering load. Now a day almost the large power transformers are provided with on load tap changer. The tap changer is in the form at a selector switch. The changer is operated by motor operated during mechanism by local or remote control and a handle is also fitted for manual operated in case of on emergency.

The essential features of on load tap changing are that during its operating the main circuit should not be opened to prevent sparking and no part of the winding shout get short circuit. All types of on load tap circuit are provided with impedance, which is introduce to limited the short circuit current during the operation of tap changer. The impedance may be either a resistor or center -tapped reactor on basis of which the on load tap changer can in general, be classified as resistor or reactor type [20].

2.9 Modern Method of Voltage Control (FACTS):

The rapid development of power electronics technology provides exciting opportunities to develop new power system equipment for better utilization of existing systems. Since 1990 a number of control devices under the term FACTs technology have been proposed and implemented.

According to IEEE, FACTS, which is the abbreviation of Flexible AC Transmission systems, is defined as follows:

"Alternating current transmission systems is combination of power electronics components and others static controllers, to enhance controllability and increase power transfer capability of the network in power system, one widely used FACTs device is the Static VAR Compensator (SVC). A SVC can improve the voltage profiles in the transient and steady state; therefore it can improve the quality and performance of the electric services. It can be controlled externally by using different types of controller switch can improve voltage stability of a large scale power system.

SVC application studies require appropriate power system models and study methods to solve particular problems. There are several studies which are required for an SVC application:

- Load flow studies.
- Harmonic studies.

- Transient stability studies, both small and large disturbances.
- Fault studies.

FACTs devices can be effectively used for power flow control, load sharing among parallel corridors, voltage regulation, and enhancement of transient stability and mitigation of system oscillations. FACTs employ high speed thyristors for switching in or out transmission line components such as capacitors, reactors. In general, FACTs controllers can be divided into four categories:

i. Series.
ii. Shunt.
iii. Combined series-series controllers.
iv. Combined series- shunt controllers.

All series controllers inject voltage in series with the line .If the voltage is in phase quadrature with the line, the series controller only supplies or consumes variable reactive power. The shunt controllers may be variable impedance, variable source or a combination of these. All shunt controllers inject power into the system at the point of connection. Combined series –series controllers which could be a combination of separate series controllers which are controlled in a coordinated manner or it could be a unified controller. Combined series –shunt controllers are either controlled in a coordinated manner or a unified power flow controller with series and shunt elements.

The development of FACTs controllers has followed two different approaches .The first approach employs reactive impedance or a tap changing transformer with thyristor switches as controlled elements, this type like SVC .The second approach employs self –commutated static converters as controlled voltage sources ,and this include the Static synchronous series compensator (STATCOM), the static synchronous series compensator (SSSC) ,the unified power flow controllers (UPFC) ,and the latest the inter line power flow controller (IPFC)[3].

2.9.1 Types of FACTS:

2.9.1.1 Shunt FACTS:

It is such as Static Var Compensator (SVC) and Static Synchronous Compensator (STATCOM)**.**

1. Static Var Compensator (SVC):

These comprise capacitor bank fixed or switched (controlled) or fixed capacitor bank and switched reactor bank in parallel. These compensators draw reactive (leading or lagging) power from the line thereby regulating voltage, improves stability (steady-state and dynamic), control overvoltage and reduce voltage flicker. These also reduce voltage and current unbalances.

2. Static Synchronous Compensator (STATCOM):

It is a static synchronous generator operated as a shunt connected Static VAR Compensator whose capacitive or inductive output current can be controlled independent of the ac system voltage. SVC controls transmission voltage by reactive shunt compensation. STATCOM based on a voltage sourced converter and a current sourced converter .Normally a voltage source converter is preferred for most converter based FACTs controllers.

STATCOM can be designed to be an active filter to absorb system harmonics.

2.9.1.2 Series FACTS:

It is such as Thyristor Controlled Series Capacitor (TCSC) and Static Synchronous Series Compensator (SSSC).

1. Thyristor Controlled Series Capacitor (TCSC):

It is a series-controlled capacitive reactance that can provide continuous control of power on the ac line over a wide range. The principle of variable-series compensation is simply to increase the fundamental-frequency voltage across a fixed capacitor in a series compensated line through appropriate variation of the firing angle.

2. Static Synchronous Series Compensator (SSSC):

It is a series connected controller. Though it is like STATCOM, but it is output voltage is in series with the line. It thus controls the voltage across the line and hence it is impedance.

2.9.1.3 Inter line power flow controller (IPFC):

It is a compensation of two or more static synchronous series compensators which are coupled via a common dc link to facilitate bi-directional flow of real power between the ac terminals of the SSSCs, and are controlled to provide independent reactive series compensation for the control of real power flow in each line and maintain the desired distribution of reactive power flow among the lines. Thus it manages a comprehensive overall real and reactive power management for a multi-line transmission system.

2.9.1.4 Unified power flow controller:

This controller is a combination of STATCOM and SSSC which are a combination of STATCOM and SSSC which are coupled via a common dc link to allow bi-directional flow of real power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM. These are controlled to provide concurrent real and reactive series line compensation without an external energy source. The UPFC, by means of angularly unconstrained series voltage injection, is able to control, concurrently / simultaneously or selectively the transmission line voltage, impedance, and angle or, alternatively, the real and reactive line flows, the UPFC may also provide independently controllable shunt reactive compensation [3].

2.9.2 Possible Benefits from FACTs Technology:

Within the basic system security guidelines, the FACTs devices enable the transmission system to obtain one or more of the following benefits:

- Control of power flow as ordered. This is the main function of FACTS devices. The use of power flow control may be to follow a contact, meet the utilities own needs, ensure optimum power flow, ride through emergency conditions or a combination of them.
- Increase utilization of lowest cost generation, one of the principal reasons for transmission interconnections is to utilize the lowest cost generation. When this cannot be done it follows that there is not enough cost effective transmission capacity. Cost effective enhancement of capacity will therefore allow increased use of lowest cost generation.
- DS (dynamic stability) enhancement. This FACTs additional function includes the TS (transient stability) improvement, POD (power damping oscillations) and VS (voltage stability) control.
- Increase the loading capability of lines to their thermal capabilities, including short term and seasonal demands.
- Increased system reliability.
- Elimination or deferral of the need for new transmission lines.
- Added flexibility in sting new generation.

- Provide secure tie line connections to neighboring utilities and regions thereby decreasing overall generation reserve requirements on both sides.
- Upgrade of transmission lines.
- Increased system security.
- Reduce reactive power flow, thus allowing the lines to carry more active power.
- Loop flow control.

CHAPTER THREE

STATIC VAR COMPENSATOR

3.1 Introduction:

The Static VAR Compensator (SVC) is today considered a very mature technology. It has been used for reactive power compensation since the 1970s. There are multiple applications within power systems, e.g. to increase power transfers a cross limited interfaces, to dampen power oscillations and to improve the voltage stability margins. An 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). 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. It should be noted that the SVC current will contain some harmonic content, something that needs attention in the design process. The SVC can be used to control the voltage level at a specific bus with the possibility of adding additional damping control. This can effectively dampen oscillations in the power system such as sub synchronous resonances (SSR), inter-area oscillations and power oscillations. SVCs are used at a large number of installations around the world and is still considered an attractive component to improve the performance of AC power systems.

3.2 Static VAR Compensator (SVC):

Static VAR compensators are shunt connected static generators or/and absorbers whose outputs are varied so as to control specific parameters of an electric power system. SVCs overcome the limitation of mechanically switched shunt capacitors or reactors [18]. The following are the basic types of reactive power control elements which make up all or part of any staticvar system:

-Saturated reactor (SR).
-Thyristor-controled reactor (TCR).
-Thyristor-switched capacitor (TSC).
-Thyristor-switched reactor (TSR).
-Thyristor-controled transformer (TCT).
-Self or line commutated converter (SCC/LCC).

3.2.1 Thyristor-controled reactor (TCR):

The basic elements of a TCR are a reactor in series with a bidirectional thyristor switch as shown in Figure 3.1.

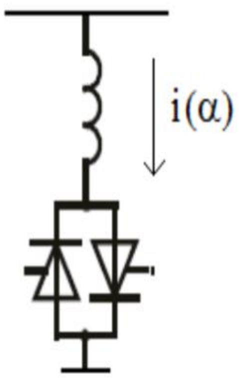


Figure 3.1: TCR scheme

The thyristor conducts on alternate half cycles of supply frequency depending on the firing angle (α). The magnitude of the current in the reactor can be varied continuously by the method of delay angle control from maximum (α =0) to zero at (α =90), as illustrated in Figure 3.2. The adjustment of current in the reactor can take place only once in each half cycle, in the zero to 90 interval. This restriction results in a delay of attainable current control. The worst case delay when changing the current from maximum to zero, is a half cycle applied voltage [19].

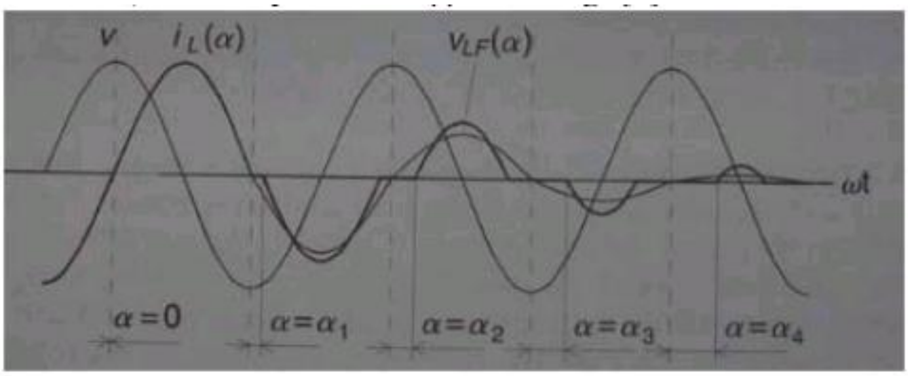


Figure 3.2: current of reactor at different value of firing angle

The amplitude (α) of the fundamental reactor current (α) can be expressed as a function of angle (α) [19]:

$$I_l(\alpha) = \frac{v}{\omega_l} * \left(1 - \left(\frac{2}{\pi} * \alpha\right) - \left(\frac{1}{\pi} * \sin 2\alpha\right)\right) \quad (3.1)$$

Where:

$I_l \equiv$ the current of reactor.

$\alpha \equiv$ firing angel of TCR.

V ≡ the amplitude of the applied ac voltage.

L ≡ the inductance of the thyristor-controled reactor.

ω ≡ the angular frequency of the applied voltage.

It is clear that the TCR can control the fundamental current continuously from zero (valve open) to a maximum (valve closed) as if it was a variable reactive admittance. Thus, an effective admittance, BL(α),can be defined as:

$$BL(\alpha) = \left(\frac{1}{\omega L}\right) * \left(1 - \left(\left(\frac{2}{\pi}\right) * \alpha\right)\right) - \left(\left(\frac{1}{\pi}\right) * \sin 2\alpha\right) \qquad (3.2)$$

BL ≡admittance of reactor.

As we can see the admittance varies in the same manner as fundamental current. At each delay angle(α) an effective admittance can be defined which determines the magnitude of an effective current in the TCR at a given applied voltage. The magnitude of the applied voltage, thus the magnitude of the corresponding current as well, will be limited by the ratings of the power components used. Therefore a TCR can be operated anywhere in the defined V-I area, the boundaries of which are determined by its maximum attainable admittance voltage and current ratings.

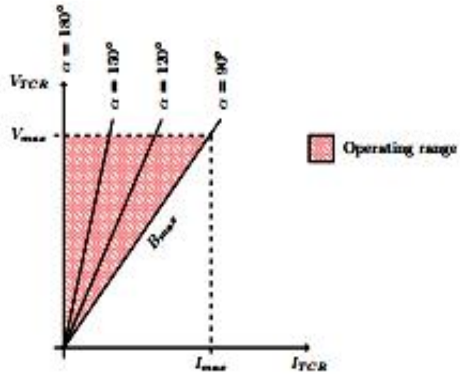


Figure 3.3: V-I characteristic of TCR

If the TCR switching is restricted just to a fixed delay angle (α) =0, then it becomes a thyristor-switched reactor TSR, which provides a fixed inductive admittance. Several TSRs can provide a reactive admittance controllable in a step like manner.

The problem in using TCR is that as (α) is increased from 0 to 90, the current waveform becomes less and less sinusoidal, thus the TCR generate harmonics. For identical positive and negative current half cycles, only odd harmonics are generated. For the three phase system the preferred arrangement is to have the three single phase TCR elements connected in delta Figure 3.4. Thus for balance conditions all triple harmonics circulate within the closed delta and are therefore absent from the line currents. Elimination of5^{th}and7^{th} harmonics can be achieved by using two 6-pulse TCRs of equal ratings fed from two secondary windings of step down transformer, one connected in Y and the other connected in delta as shown in Figure 3.3. Since the voltages applied to TCRs have phase difference of 30,5^{th} and7^{th}harmonics are eliminated from the primary side current. With 12-pulse scheme, the lowest order harmonics are 11^{th} and 13^{th}. These can be filtered with simple bank capacitor [16].

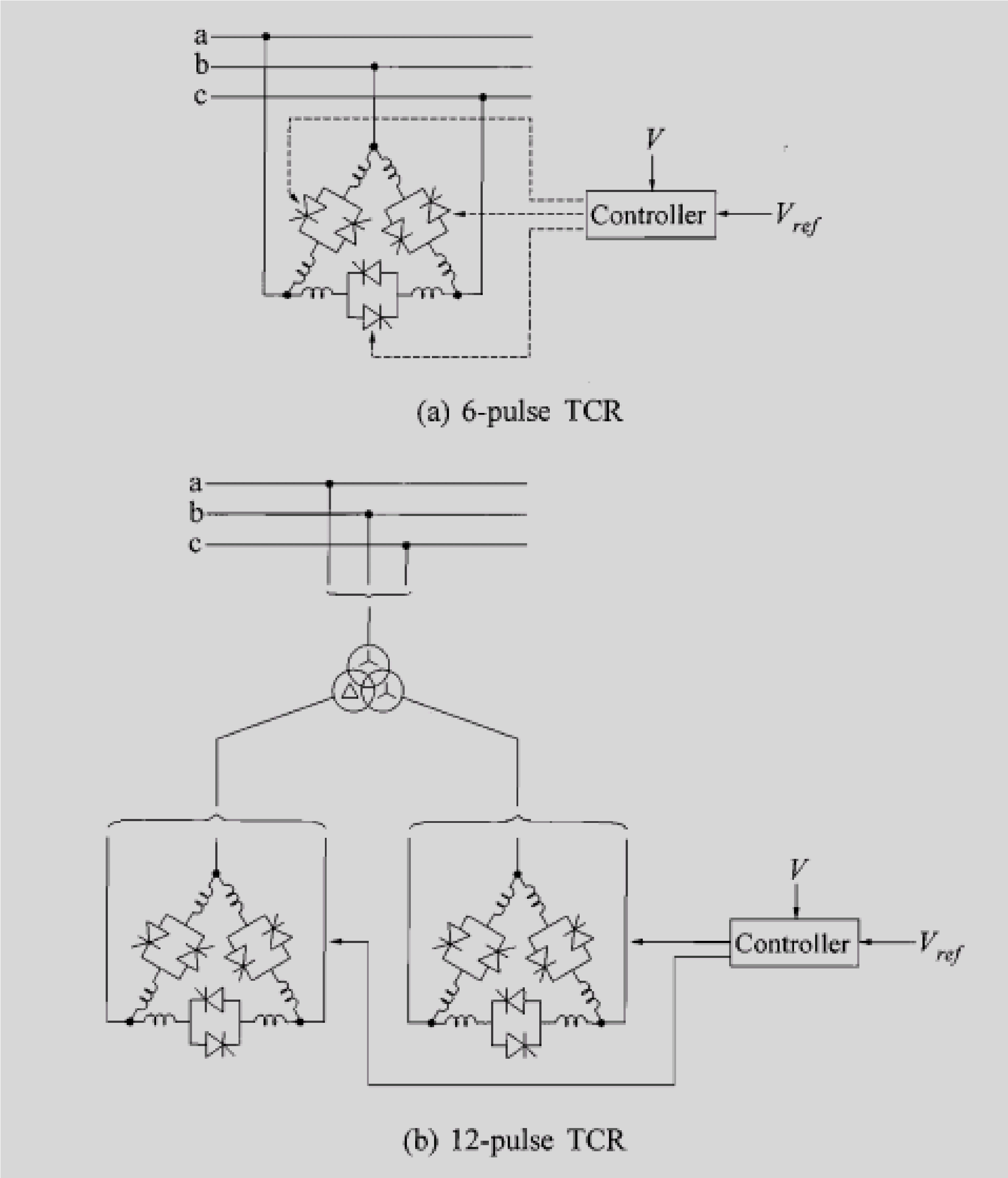


Figure 3.4: three phase TCR arrangement

3.2.2Thyristor-switched capacitor (TSC):

A thyristor-switched capacitor scheme consists of a capacitor bank split up into appropriately sized units, each of which switched on or off by using thyristors switches. Single phase consists of a capacitor, a bidirectional thyristor valve and a small inductor as shown in Figure 3.5. This reactor is needed to reduce switching transients, to dump inrush currents and it also is preventing from the resonance with network [19].

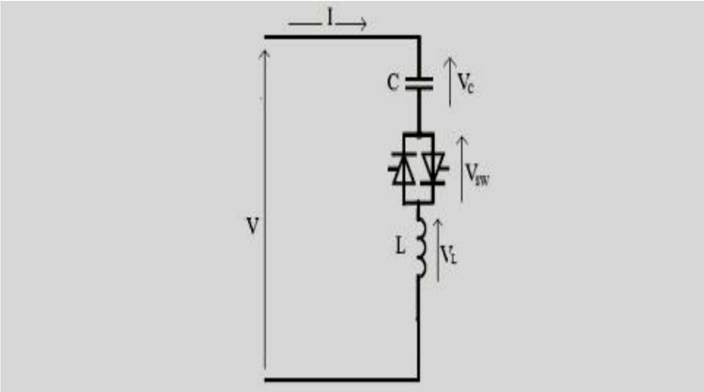


Figure 3.5: TSC scheme

When the thyristor valve is closed and the TSC is connected to a sinusoidal ac voltage source $v = V\ sin\ (\omega t)$, the current in the brunch is given by:

$$I(\omega t) = v * \left(\frac{n^2}{n^2-1}\right) * (\omega c cos\omega t) \tag{3.3}$$

where:

$$n = \frac{1}{\sqrt{\omega^2 LC}} = \sqrt{\frac{X_c}{X_l}} \tag{3.4}$$

The switching off capacitors excites transients which may be large or small depending on the resonant frequency of the capacitors with the external system. The disconnected capacitor stays charged, so the voltage across the non-conducting thyristor valve varies between zero and peak to peak value of the applied ac voltage. When the capacitors voltage remains unchanged, the TSC bank can be switched in again without any transient, at the appropriate peak voltage of the applied voltage. For positively charged capacitor the switching in is at positive peak of applied voltage, for negatively charged capacitor switching in is at negative peak of applied voltage. Usually the capacitor bank is discharged after disconnection, therefore the reconnection can be done at some residual capacitor voltage.

The transient free conditions can be summarized as two simple rules. One, if the residual capacitor voltage is lower than the peak ac voltage, then the correct instant of switching is when the instantaneous ac voltage becomes equal to the capacitor voltage. Two, if the residual voltage of the capacitor is higher or equal to the peak ac voltage, then the correct switching is at the peak of ac voltage at which the thyristor valve voltage is minimum.

Due to the fact that the capacitor switching must take place at the specific instant in each cycle, a TSC branch can provide only a step like change in the reactive current. The current in the TSC branch varies linearly with applied voltage according to the capacitors admittance as shown in Figure 3.6

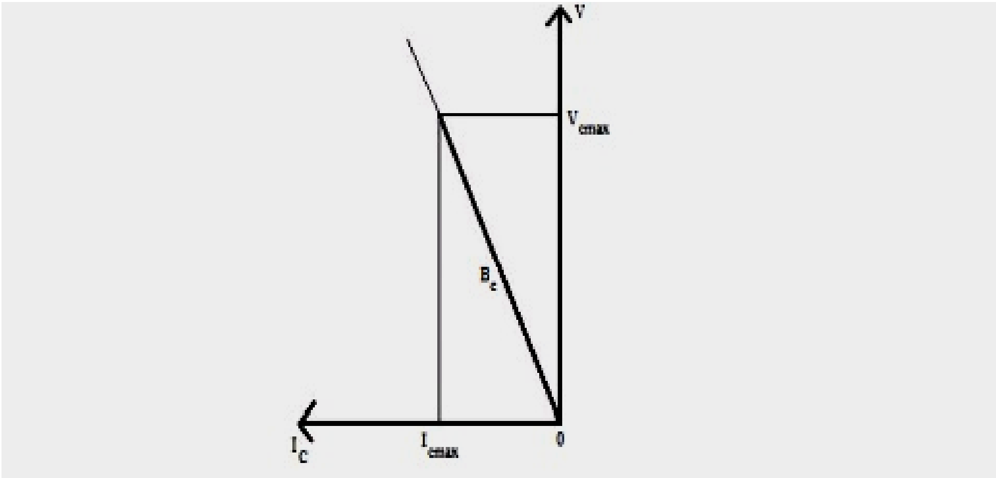


Figure 3.6: V-I characteristic of TSC

If the TSC consists of couple parallel connected elements and controller Figure 3.6, the operating area becomes more flexible and it can regulate the bus voltage in a bigger range.

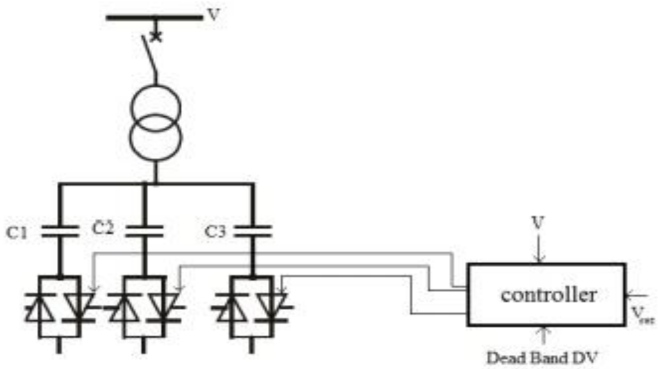


Figure 3.7: TSC scheme

When bus voltage deviates from the reference value beyond the dead band, the control switches in or out one or more capacitor banks until the voltage returns inside the dead band. The illustration of this kind of bus voltage regulation by TSC is shown in Figure 3.8.

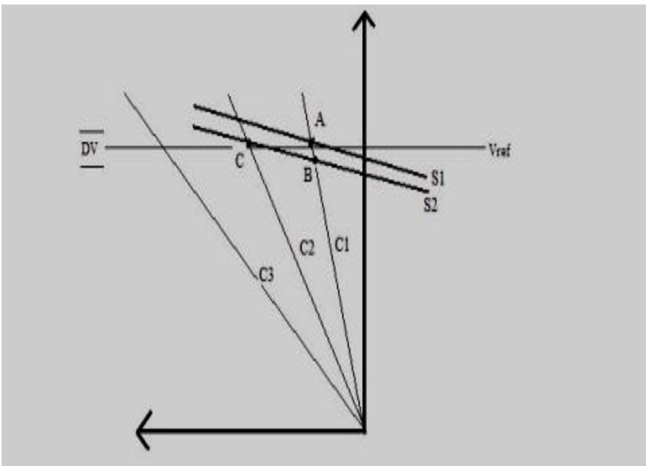


Figure 3.8:V-I characteristic

We can see that the voltage control is stepwise. It is determined by the rating and number of parallel connected units. The bus voltage in this example is controlled within the range (+/-) DV/2, where DV is dead band. When the system is operating so that it's characteristic is SI, then capacitor will be switched in and the operating point of the system will be in A. If some fault happens, and system characteristic will change to there will be a sudden bus voltage drop to the value represented by operating point B. The TSC control switches in bank to change the operating point to C, and thus bringing the voltage within desired range. The time taken for executing a command from the controller ranges from half cycle to one cycle [16].

3.3 Static VAR Systems SVS:

A static VAR compensation scheme with any desired control range can be formed by using combinations of the elements described above. The SVS configuration depends on the different system requirements: the required speed of response, size range, flexibility, losses and costs.

3.3.1 Fixed capacitor, thyristor-controlled reactor (FC-TCR):

The FC-TCR arrangement of the SVS is shown in Figure 3.9. The current in the reactor is varied in the same manner as in the thyristor-controlled reactor, so is being changed by firing delay angle control. The FC-TCRs output VAR generation is the sum of fixed capacitor VAR generation and the variable VAR absorption of the Thyristor-controlled reactor.

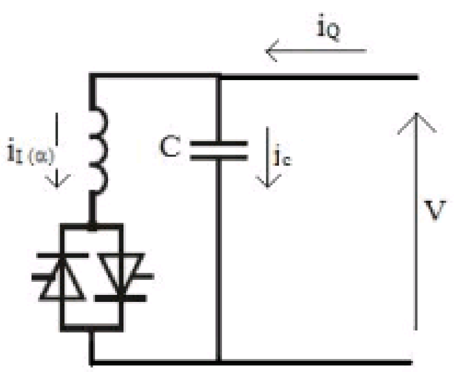


Figure 3.9: single phase FC-TCR

To control total VAR output FC-TCR regulator varies delay angle (α). At the maximum capacitive VAR output, the thyristor-controlled reactor is off

(α) =90. To decrease the capacitive output, the current in the reactor is increased by decreasing delay angle. At zero VAR output the capacitive and inductive currents become equal and thus capacitive and reactive VARS cancel out. With further decrease of delay angle the inductive current becomes larger than the capacitive current, resulting in a net inductive VAR output. At zero delay angle the thyristor-controlled reactor conducts current over full 180 degree interval, resulting in maximum inductive VAR output.

Thus to this kind of VAR output regulation the V-I operation area of the FC-TCR is defined by the maximum attainable capacitive and inductive admittances and by the voltage and current ratings of the major components: capacitor, reactor, thyristor valve.

The V-I operating area of FC-TCR is illustrated in Figure 3.9.

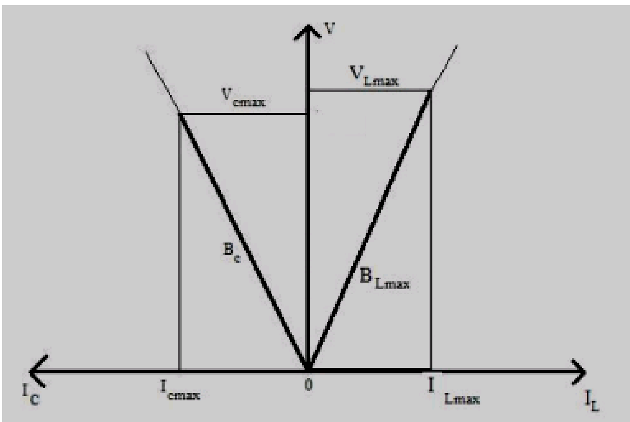


Figure 3.10: operating V-I area of FC-TCR

3.3.2 Thyristor-switched capacitor, thyristor-controlled reactor:

For a given capacitive output range TSC-TCR usually consists of n TSC branches and one TCR branch. The operation of TSC-TCR can be described as follows:

The total capacitive output range is divided into n intervals. In the first interval, the output of the VAR generator is controllable in the zero to /n, where is the total rating provided by all TSC branches. In this interval one capacitor bank is switched in simultaneously the current in the TCR is set by appropriate firing angle so that the sum of VAR output of the TSC and that of the TCR equals to the capacitive output required [19].

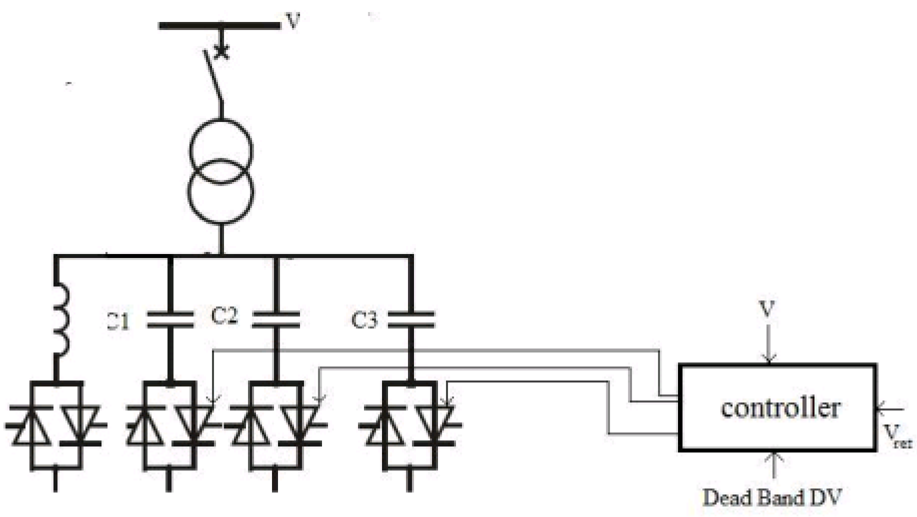


Figure 3.11: TSC-TCR scheme

To ensure that the switching conditions at the endpoints of the intervals are not indeterminate, the VAR rating of the TCR has to be larger than that of one TSC in order to provide enough overlap between switching in and switching out VAR levels.

The V-I characteristic (shown in figure 3.12) of TSC-TCR is very similar to FC-TCRs characteristic. The only difference is that the TSC-TCR can control capacitive current in bigger range depending on the amount of TSC branches used in particular device.

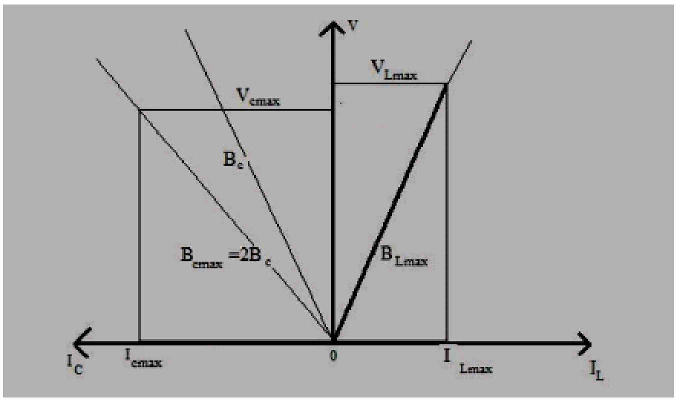


Figure 3.12: Operating V-I area of TSC and TCR

The response of the TSC-TCR depending on the number of TCR branches used. The maximum switching delay in a single TSC with a charged capacitor is one cycle whereas the maximum switching delay of the TCR is only half of a cycle. However, if the TSC consists of more than two branches, there is high probability that one or more capacitor banks will be available with the charge of desired polarity.

Above described examples of SVS are treated recently as technically out of date solutions, because of many limitation like for example, their performance depends on the ac system voltage. If some fault in the system causes big drop in voltage the SVS will not be able to react properly.

Devices which performance does not depend on ac system voltage generate reactive power directly without the use of ac capacitors or reactor, by various switching of power converters. These devices are called static synchronous compensators STATCOM.

3.4 General System Configurations:

A Static VAR Compensator mainly consists of following component:-

1- Step-down transformer.
The static VAR compensator is normally installed at low voltage side of main transformer, otherwise a step-down transformer is needed to reduce the voltage.

2- Medium voltage switchgear.
The medium voltage switchgear typically includes isolating switches, grounding switches and transformers. It can be installed indoor or outdoor.

3- Linear (air-core) reactor.
The air-core reactor in static VAR compensator has high stability and high linearity. It is used to absorb reactive power under the control of thyristors. Usually the air-core reactor is series connected to the thyristor valve in delta-connection and then connect the delta bridge to power grid.

4- Thyristor valve.
The thyristor valve is the main control part in a SVC system. It is composed of several series/paralleled connected thyristors and its auxiliary components.

5- Capacitor/filter bank.

The capacitor/filter banks can supply sufficient capacitive reactive power to power grid and filter the harmful harmonics. The filter is composed of capacitors, reactors and resistors, providing capacitive reactive power to the entire system. In practical, the capacitor/filter banks are divided into several sub-banks which can be switched-in/switched-off by mechanical breakers or other electrical switches according to the actual situation.

6- Water Cooling System.

The heat produced by thyristor valve will be harmful to thyristors if the heat is not dissipated in time. The deionizer water cooling system is sufficient for the thyristor valves which have a high operating voltage. The cooling system uses the de-ionized pure water for internal cooling and regular industrial recycling water for external cooling.

7- SVC control and protection system.

The key functions of SVC control and protection system are:

- Generating the control pulses to the valve at suitable time to fire the thyristors.
- Monitoring the SVC system to provide operation condition, fault record or self-checking information.
- Switching in/out the FC in order Protecting each component to ensure the safe operation of SVC.
- Friendly Human-Machine Interface.

3.5 Advantages of SVC:

- Fast.
- Precise regulation of voltage and unrestricted.
- Transient free capacitor switching.

3.6 Application of SVC:

Since their first application in the late 1970s, the use of SVCs in transmission system has been increasing steadily by virtue at their ability to provide continuous and rapid control at reactive power and voltage,

SVCs enhance several aspects of transmission system performance .Application to date include the following:-

- Control of temporary (power frequency) over voltage.
- prevention of voltage collapse.
- Enhancement of transient stability.
- Enhancement of damping of system oscillation.

At the sub transmission and distribution system levels:

SVCs are used for balancing the three phase of systems supplying unbalanced load, and reduce the reactive power exchange, improve the power factor, reduce distribution system losses and reduce damage caused by frequent switch in of capacitor banks . They are also used to minimize fluctuation in supply voltage caused by respective -impact loads [16].

At industrial consumers:

The electronic rectifiers applied to the electrolysis power supply and mill machine requires large amount of reactive power. The SVC system can not only supply sufficient reactive power, but also eliminate the harmonics generated by rectifiers and prevent the equipment from the voltage fluctuation.

The use of AC arc furnace usually comes with heavy harmonics and large negative sequence current. Large amount of reactive power demand and reactive power variation result in the voltage fluctuation and flicker, which also reduces the operation efficiency.

At wind power plant:

For small hydro-power plant or wind power plant in some remote locations, the connected large power grid cannot efficiently provide enough reactive power, or the excess reactive power may result in a serious voltage drop and large line losses. Installing an SVC system at the connection point can efficiently stabilize the voltage at the connection point to an acceptable level and maximally prevent the harmful impact caused by faults in the power grid.

3.7 Disadvantages of SVC:

- Limited capacity according to the volumes of capacitors and reactor in the site.

- High cost.

- Reactive power of capacitor effected by low voltage and there the product decreases.

3.8 The STATCOM:

The STATCOM (or SSC) is a shunt-connected reactive-power compensation

device that is capable of generating and/ or absorbing reactive power and in

which the output can be varied to control the specific parameters of an electric power system. It is in general a solid-state switching converter capable of generating or absorbing independently controllable real and reactive power at its output terminals when it is fed from an energy source or energy-storage device at its input terminals. Specifically, the STATCOM considered in this chapter is a voltage-source converter that, from a given input of dc voltage, produces a set of 3-phase ac-output voltages, each in phase with and coupled to the corresponding ac system voltage through a relatively small reactance (which is provided by either an interface reactor or the leakage inductance of a coupling transformer). The dc voltage is provided by an energy-storage capacitor.

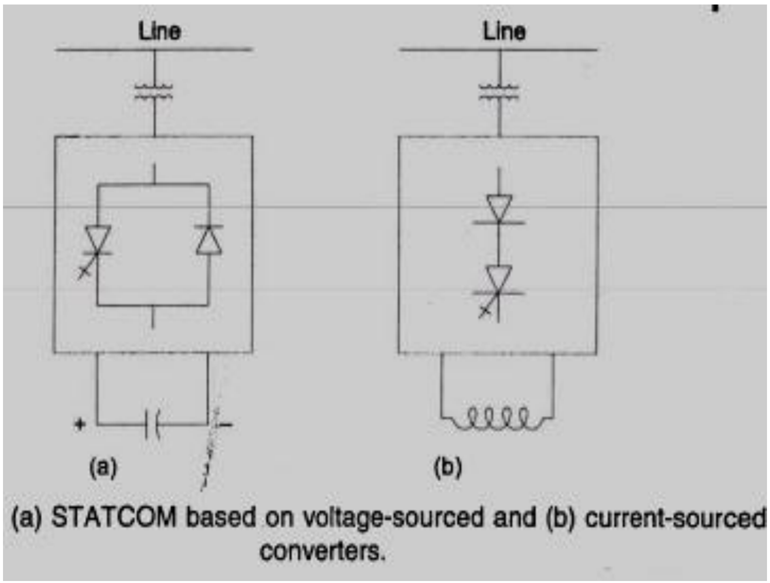


Figure3.13: The STATCOM

A STATCOM can improve power-system performance in such areas as the following:

1. The dynamic voltage control in transmission and distribution systems.

2. The power-oscillation damping in power-transmission systems.

3. The transient stability.

4. The voltage flicker control.

5. The control of not only reactive power but also (if needed) active power in the connected line, requiring a dc energy source.

Furthermore, a STATCOM does the following:

1. It occupies a small footprint, for it replaces passive banks of circuit elements by compact electronic converters.

2. It offers modular, factory-built equipment, thereby reducing site work and commissioning time.

3. It uses encapsulated electronic converters, thereby minimizing its environmental impact.

A STATCOM controller provides voltage support by generating or absorbing reactive power at the point of common coupling without theneed of large external reactors or capacitor banks.

3.9. V-l characteristic:

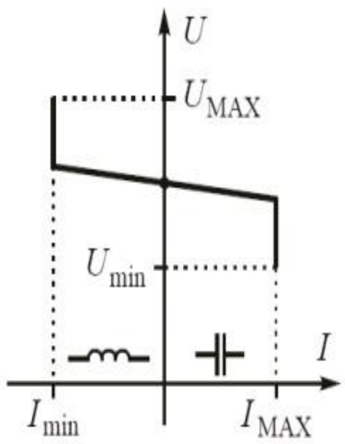


Figure 3.14: V-I operating area of STATCOM

Figure 3.13 shows that the STATCOM can be operated over its full output current range even at very low voltage, typically 0,2 p.u. system voltage levels. The maximum capacitive or inductive output current of the STATCOM can be maintained independently of the ac system voltage.

3.10 Comparison between SVC and STATCOM:

It may be noted that in the normal linear operating rang of the V-I characteristic and functional compensation capability of the STATCOM and SVC are similar. However, the basic operating principle of the STATCOM which with a converter based VAR generator, function as a shunt connected synchronous voltage source, are basically different from those of the svc, since svc function as a shunt connected, controlled reactive admittance this basic operational renders the STATCOM to have overall superior function characteristics better performance and greater application flexibility as compared to svc.

The ability of STATCOM to maintain full capacitive output current at low system voltage also makes it more effective than svc improving the transient (first swing) stability.

The STATCOM has small size and the area requirement is small than SVC.

3.11 Why Use SVC and not STATCOM:

It is use because it is much cheaper than STATCOM and it is more often used all over the word. SVC gives a continuous and fast regulation of voltage which is regulated according to the slope of SVC.

3.12 Load Flow Analysis:

Power flow studies, commonly referred to as load flow, are essential of power system analysis and design. Load flow studies are necessary for planning, economic operation, scheduling and exchange of power between utilities. Load flow study is also required for many other analyses such as transient stability, dynamic stability, contingency and state estimation.

Network equations can be formulated in a variety of forms. However, node voltage method is commonly used for power system analysis. The network equations which are in the nodal admittance form results in complex linear simultaneous algebraic equations in terms of node currents. The load flow results give the bus voltage magnitude and phase angles and hence the power flow through the transmission lines, line losses and power injection at all the buses.

3.13Bus Classifications:

Four quantities are associated with each bus. These are voltage magnitude$|V|$, phase angle δ, real power P and reactive power Q. In a load flow study, two quantities are to be obtained through the solutions. The system buses are generally classified into three categories.

Slack bus: Also known as swing bus and taken as reference where the magnitude and phase angle of the voltage are specified, this bus provide the additional real and reactive power to supply the transmission losses, since these are unknown until the final solution is obtained.

Load bus: Also known as PQ bus. At these buses the real and reactive powers are specified. The magnitude and phase angle of the bus voltage are unknown until the final solution is obtained.

Voltage controlled buses: Also known as generator buses or regulated buses or $P - |V|$ buses. At these buses, the real power and voltage magnitude are specified. The phase angles of the voltages and the reactive power are unknown until the final solution is obtained. The limits on the value of reactive power are also specified.

3.14Newton Raphson Method:

Newton – Raphson method is an iterative method which approximates the set of non-liner simultaneous to a set of linear equations using Taylor's series expansion and the terms are restricted to first order approximation.

Newton – Raphson (NR) method is more efficient and practical for large power systems. Main advantage of this method is that the number of iterations required to obtain a solution is independent of the size of the problem and computationally it is very fast. Here load flow problem is formulated in polar form.

$$P_i = \sum_{k=1}^{n} |V_i||V_k||Y_{ik}| \cos(\theta_{ik} - \delta_i + \delta_k) \quad (3.5)$$

$$Q_i = -\sum_{k=1}^{n} |V_i||V_k||Y_{ik}| \sin(\theta_{ik} - \delta_i + \delta_k) \quad (3.6)$$

Equation (2.9) and (2.10) constitute a set of nonlinear algebraic equations in terms of the independent variables, voltage magnitude in per unit and phase angles in radians, we can easily observe that two equations for each load bus given by eqn. (3.5) and (3.6) and one equation for each voltage control bus, given by eqn. (3.5). Expanding eqns. (3.5) and (3.6) in Taylor-series and neglecting higher-order terms.

$$\begin{bmatrix} \Delta P_2^{(p)} \\ \vdots \\ \Delta P_2^{(p)} \\ \hline \Delta Q_2^{(p)} \\ \vdots \\ \Delta Q_2^{(p)} \end{bmatrix} = \left[\begin{array}{ccc|ccc} \left(\frac{\partial P_2}{\partial \delta_2}\right)^{(p)} & \cdots & \left(\frac{\partial P_2}{\partial \delta_n}\right)^{(p)} & \left(\frac{\partial P_2}{\partial |V_2|}\right)^{(p)} & \cdots & \left(\frac{\partial P_2}{\partial |V_n|}\right)^{(p)} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \left(\frac{\partial P_2}{\partial \delta_2}\right)^{(p)} & \cdots & \left(\frac{\partial P_2}{\partial \delta_n}\right)^{(p)} & \left(\frac{\partial P_2}{\partial |V_2|}\right)^{(p)} & \cdots & \left(\frac{\partial P_2}{\partial |V_n|}\right)^{(p)} \\ \hline \left(\frac{\partial P_2}{\partial \delta_2}\right)^{(p)} & \cdots & \left(\frac{\partial P_2}{\partial \delta_n}\right)^{(p)} & \left(\frac{\partial P_2}{\partial |V_2|}\right)^{(p)} & \cdots & \left(\frac{\partial P_2}{\partial |V_n|}\right)^{(p)} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \left(\frac{\partial P_2}{\partial \delta_2}\right)^{(p)} & \cdots & \left(\frac{\partial P_2}{\partial \delta_n}\right)^{(p)} & \left(\frac{\partial P_2}{\partial |V_2|}\right)^{(p)} & \cdots & \left(\frac{\partial P_2}{\partial |V_n|}\right)^{(p)} \end{array}\right] \begin{bmatrix} \Delta \delta_2^{(p)} \\ \vdots \\ \Delta \delta_2^{(p)} \\ \hline \Delta |V_2|^{(p)} \\ \vdots \\ \Delta |V_n|^{(p)} \end{bmatrix} \quad (3.7)$$

We obtain, in the above equation, bus-1 is assumed to be a slack bus.

Eqn. (2-29) can be written in short form i.e.,

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} \quad (3.8)$$

3.15 Modeling of SVC:

In order to investigate the impact of SVC on power systems appropriate SVC model is very important. In this section, SVC and it's mathematical model well be introduced. SVC is built up with reactors and capacitors controlled by thyristor valves which are in parallel with a fixed capacitor bank (FC-TCR) or switched capacitors (TSC-TCR).

$$I_{SVC} = jB_{SVC}V_K \quad (3.9)$$

$$Q_{SVC} = Q_K = -B_{SVC}{V_K}^2 \quad (3.10)$$

$$B_{SVC} = B_c - B_{TCR} = \frac{1}{X_C * X_L}\left(X_L - \frac{X_C}{\pi}(2(\pi - \alpha) + \sin 2\alpha)\right) \quad (3.11)$$

$$X_L = \omega * L \quad (3.12)$$

$$X_C = \frac{1}{\omega * C} \quad (3.13)$$

$$Q_K = \frac{-{V_K}^2}{X_C * X_L}\left(X_L - \frac{X_C}{\pi}(2(\pi - \alpha_{SVC}) + \sin 2\alpha_{SVC})\right) \quad (3.14)$$

Where:

V_K ≡ SVC bus voltage.

B_{SVC} ≡ SVC susceptance in p. u.

X_C ≡ Capacitive reactance.

X_L ≡ Inductance reactance.

Q_{SVC} ≡ MVA rating of SVC.

α ≡ Firing angle of SVC.

I_{SVC} ≡SVC current.

ω ≡ the angular frequency of the applied voltage.

3.16 V-I characteristics:

The SVC can be operated in two different modes:

1- In voltage regulation mode (the voltage is regulated within limits as explained below).

2- In VAR control mode (the SVC susceptance is kept constant) When the SVC is operated in voltage regulation mode, it implements the V-I characteristic as shown in Figure3.14 as long as the SVC susceptance B stays within the maximum and minimum susceptance values imposed by the total reactive power of capacitor banks (B_{Cmax}) and reactor banks(B_{Lmax}), the voltage is regulated at the reference voltageV_{ref}. However, a voltage droop is normally used (usually between 1% and 4% at maximum reactive power output) and the V-I characteristic has the slope indicated in the Figure3.15

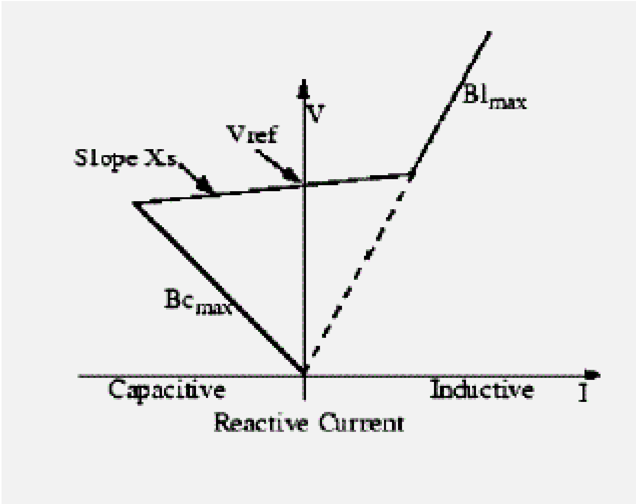


Figure 3.15: V-I characteristic of SVC

$$V = v_{ref} + x_s.\mathrm{I} \tag{3.15}$$

If SVC is fully capacitive (B = B_{Cmax})

$$\mathrm{V} = -\frac{1}{\mathrm{B_{Cmax}}} \tag{3.16}$$

If Svc is fully Inductive (B = B_{Lmax}),

$$\mathrm{V} = \frac{1}{\mathrm{B_{Lmax}}} \tag{3.17}$$

V ≡Positive sequence voltage (pu)

I ≡Reactive current (pu/Pbase) (I > 0 indicates an inductive current)

X_S ≡Slope or droop reactance (pu/Pbase)

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Case Study: GAM Sub-station:

GAM sub-station is one of important sub-stations in the Sudanese electric power grid. it is fed by two circuits (220)KV from AlMarkhyat and Aljabal sub-stations and feeds Banat sub-station (110)KV. It has three (150/150/50)MVA main transformers (220/110/33)KV. As the result of growth in demand GAM sub-station confronts voltage stability problems.

4.2 Performed Studies

Both steady state, and dynamic state studies are performed. In this section results of both studies are presented.

4.3 Steady State Results:

Different operating conditions are considered. These are the normal load , 50% of load, and150% of load.

4.3.1 Case (1): GAM sub-station without SVC:

Load flow is performed for GAM sub-station at normal load and the results show that there was under voltage at bus 33KV and bus 110kv, bus 220KV at normal voltage. When the load of sub-station was decrease to 50% of load the voltage at all buses were increased and When the load of sub-station was increased to 150% of load the voltage at buses were decreased . As can be seen in Figure 4.1.

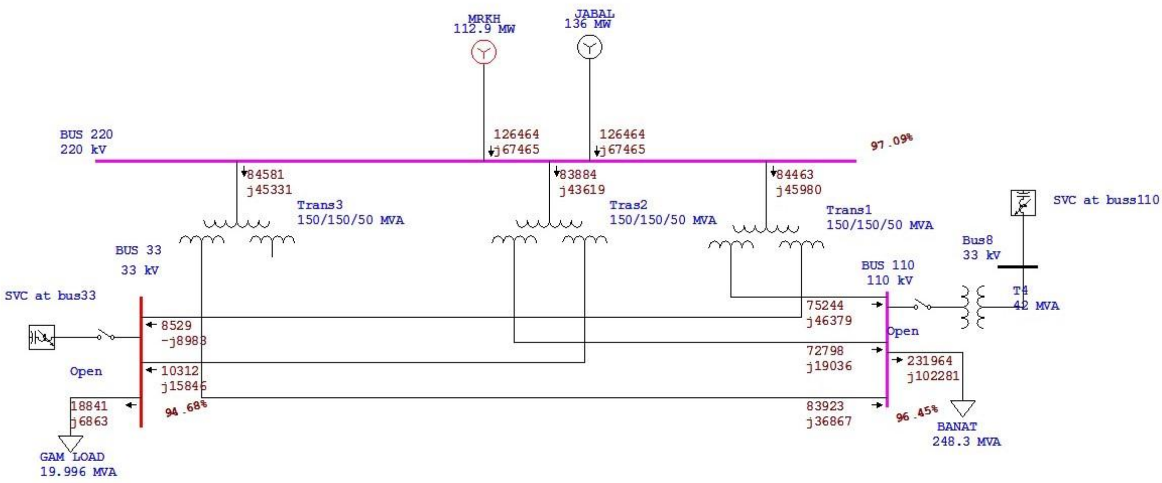


Figure 4.1: load flow results of GAM sub-station without SVCs.

4.3.2 Case(2): improving of voltage by using SVC at bus 33KV:

SVC1 was used at bus 33KV to improve voltage at different loading conditions (normal load, 50% of load and 150% of load) and the results show that not all voltages of buses were improved; therefore SVC1 was replaced by different SVCs (which their ratings shown in Table 4.1) until all voltages of buses were improved.

Table 4.1: ratings of different SVCs:

Different SVCs	Q_l(MVAR)	Q_c(MVAR)
SVC1	-55	15.9
SVC2	-55	23.8
SVC3	-55	31.8

Load flow results show that bus 220kV (which is slack bus) is not affected by using SVC at different load conditions as can be seen in Figure 4.2.

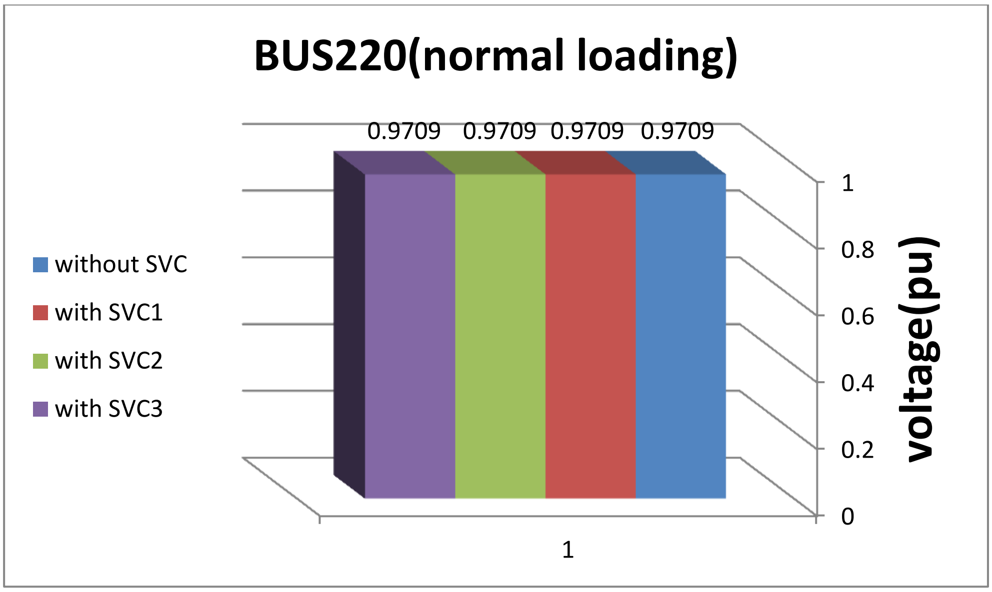
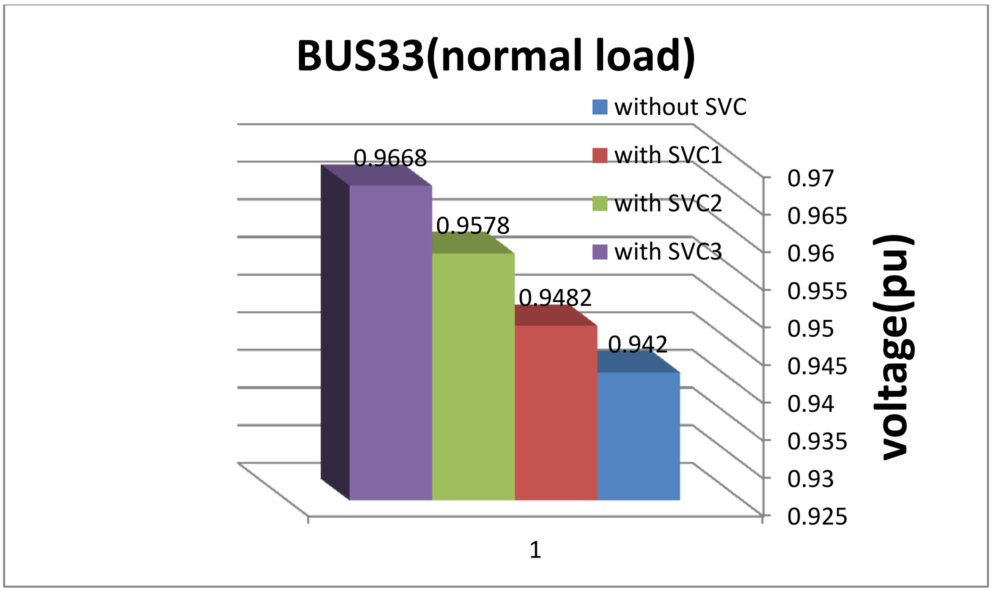
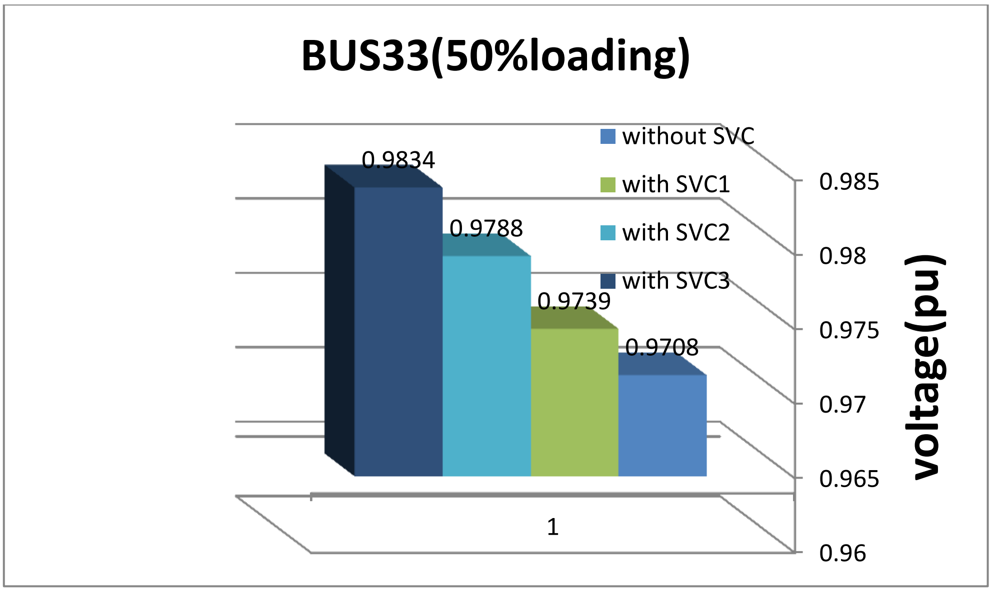


Figure 4.2: voltages at bus 220 KV

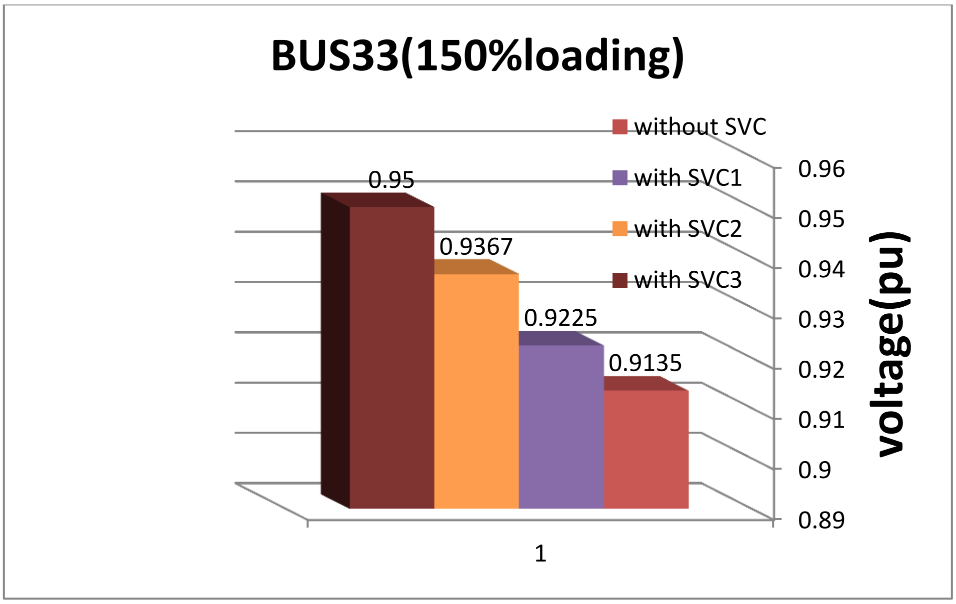
Load flow results show that the voltage at bus 33kV (at different load conditions) was more improving when SVC with high rating was used as can be seen in Figure 4.3 which is illustrates a comparison between voltages of bus 33KV with and without SVCs.



(a): voltage at bus 33KV at normal load



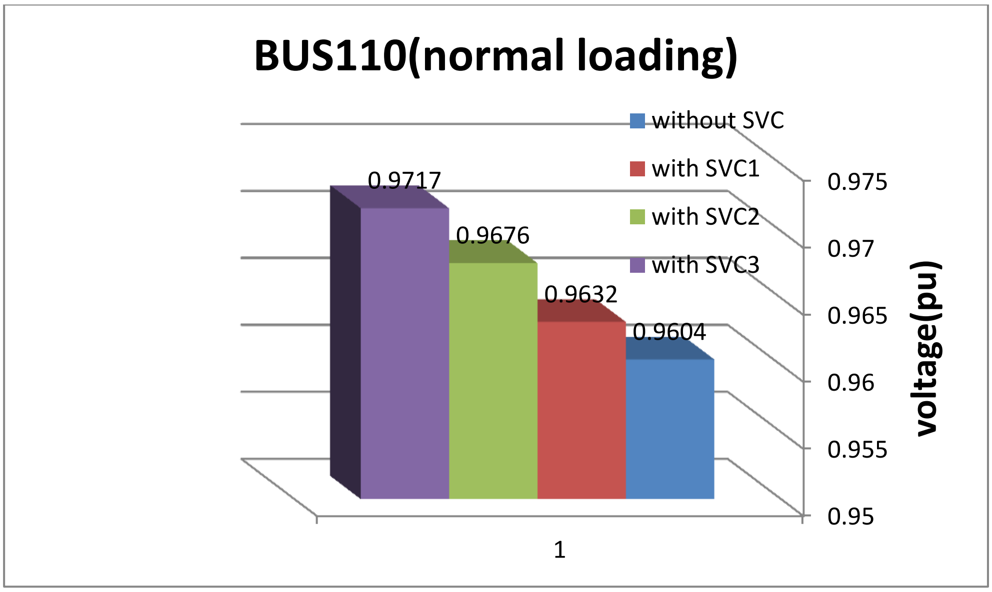
(b): voltage at bus 33KV at 50% loading



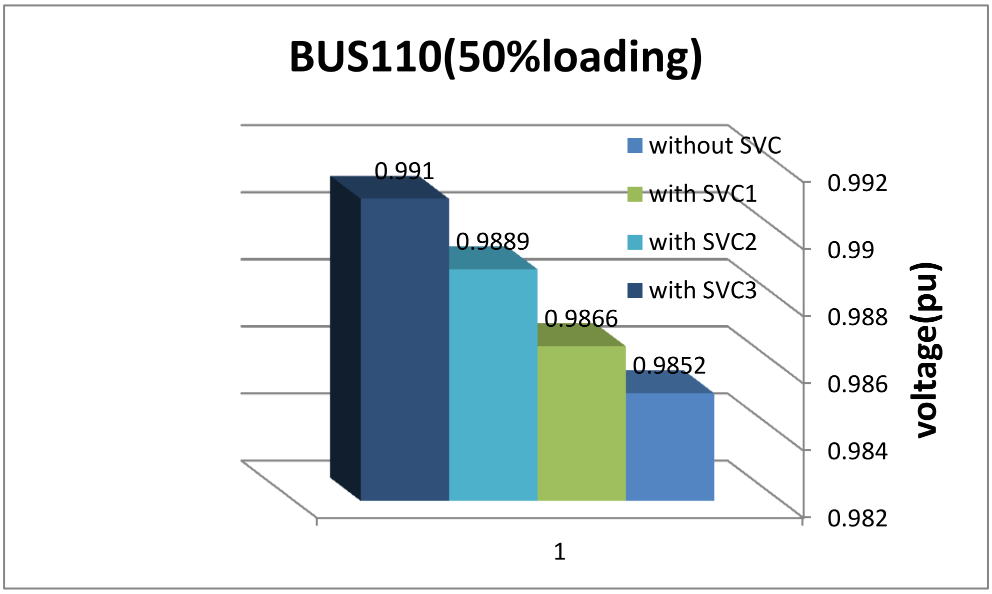
(c): voltage at bus 33KV at 150% loading

Figure 4.3: comparison between voltages of bus 33KV

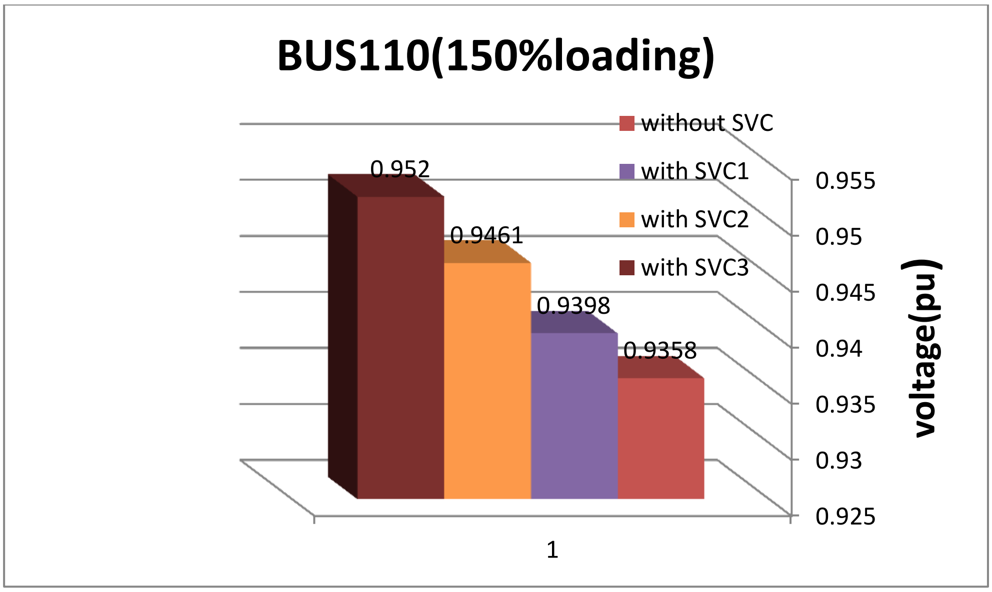
Load flow results show that the voltage at bus 110kV (at different load conditions) was more improving when SVC with high rating was used as can be seen in Figure 4.4 which is illustrates, a comparison between voltages of bus 110KV with and without SVCs.



(a): voltage at bus 110KV at normal load



(b): Voltage at bus 110KV at 50% loading

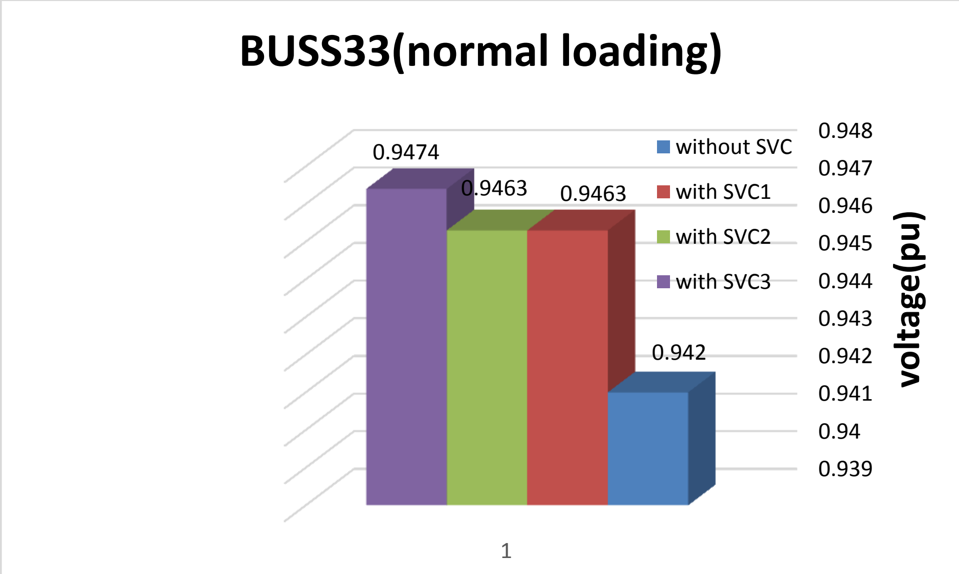


(c): Voltage at bus 110KV at 150% loading

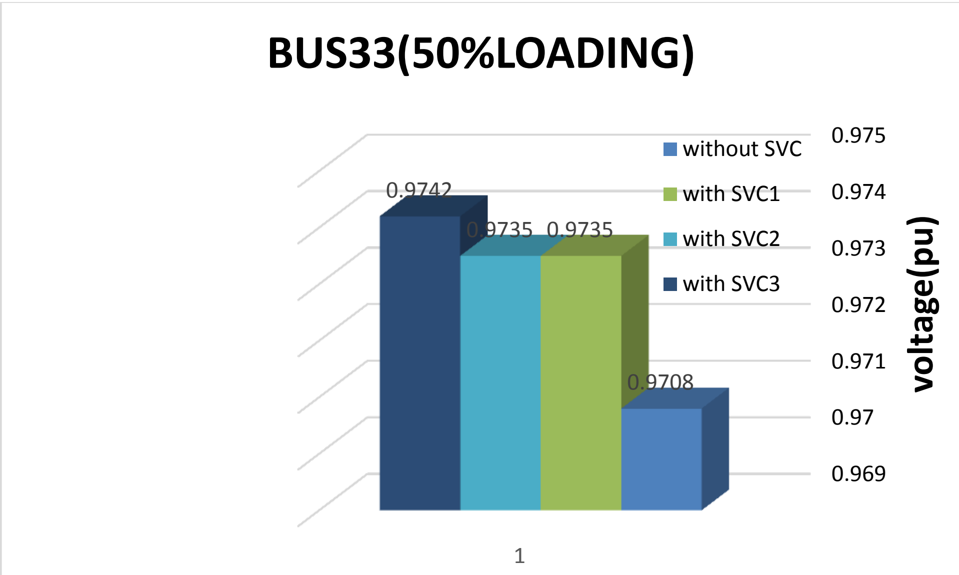
Figure 4.4 Comparison between voltages of bus 110KV

4.2.3 Case(3): improving of voltage by using SVC at bus 110KV:

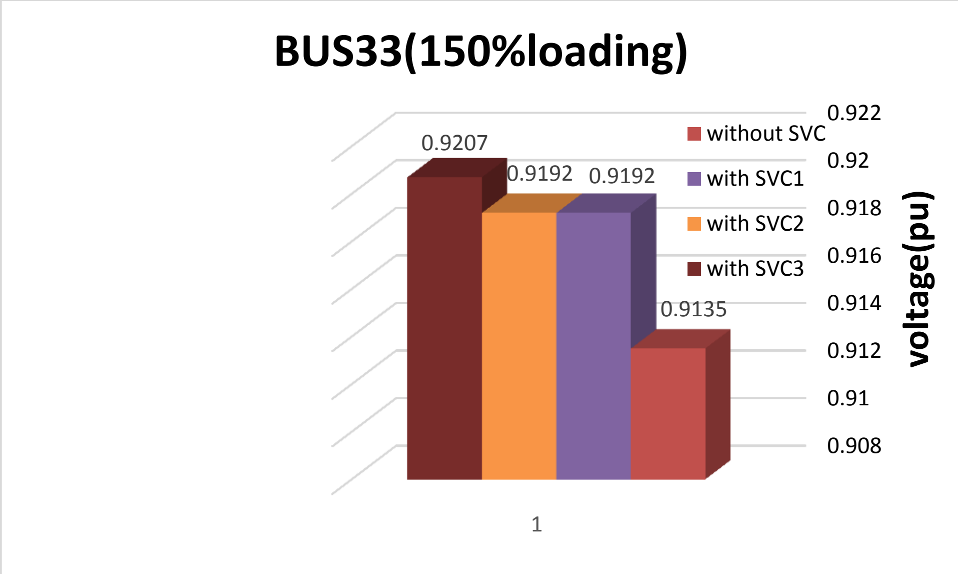
Load flow results show that the voltage at bus 33kV (at different load conditions) was more improving when SVC with high rating was used as can be seen in Figure 4.5 which is illustrates, a comparison between voltages of bus 33KV with and without SVCs.



(a): voltage at bus 33KV at normal load



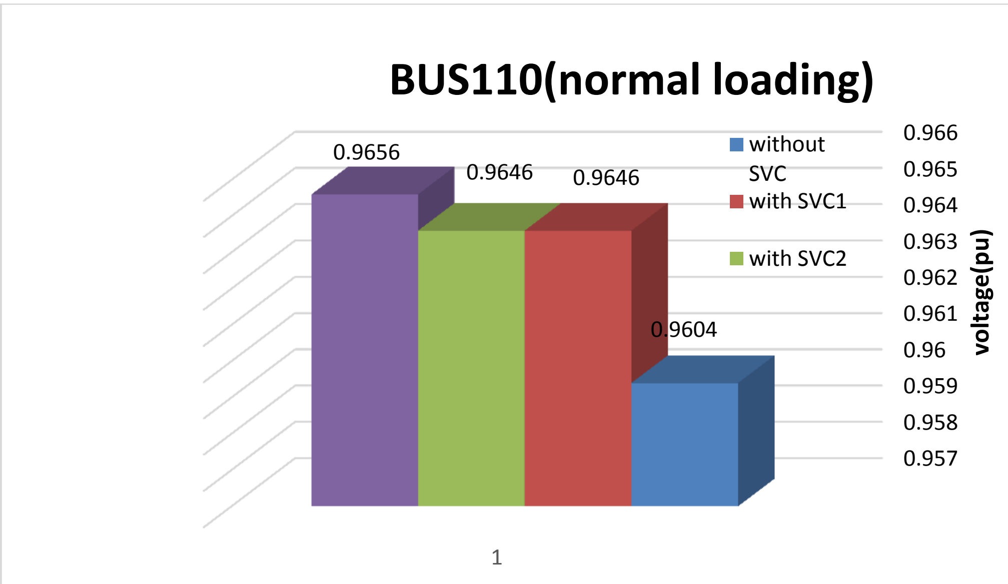
(b): voltage at bus 33KV at 50% loading



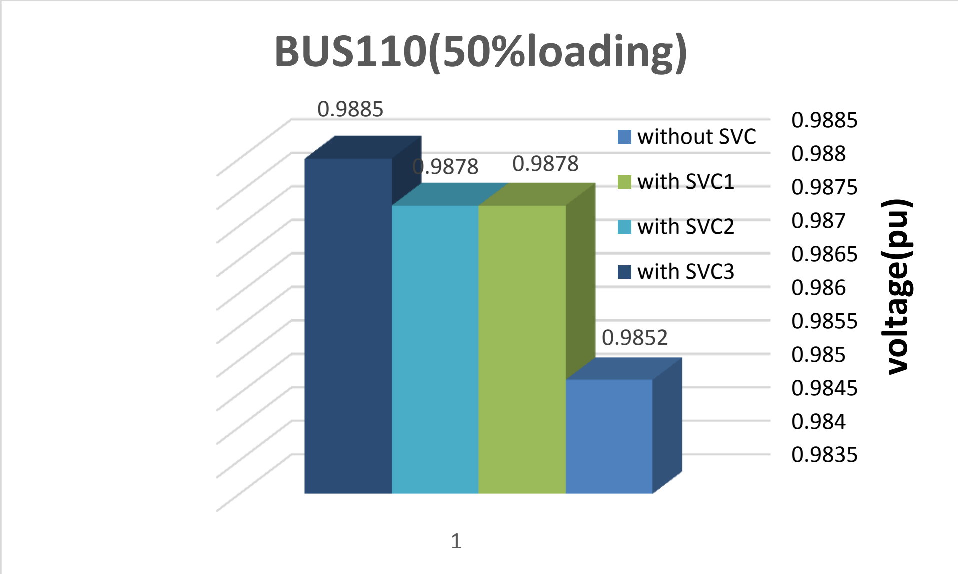
(c): Voltage at bus 33KV at 150% loading

Figure 4.5: Comparison between voltages of bus 33KV

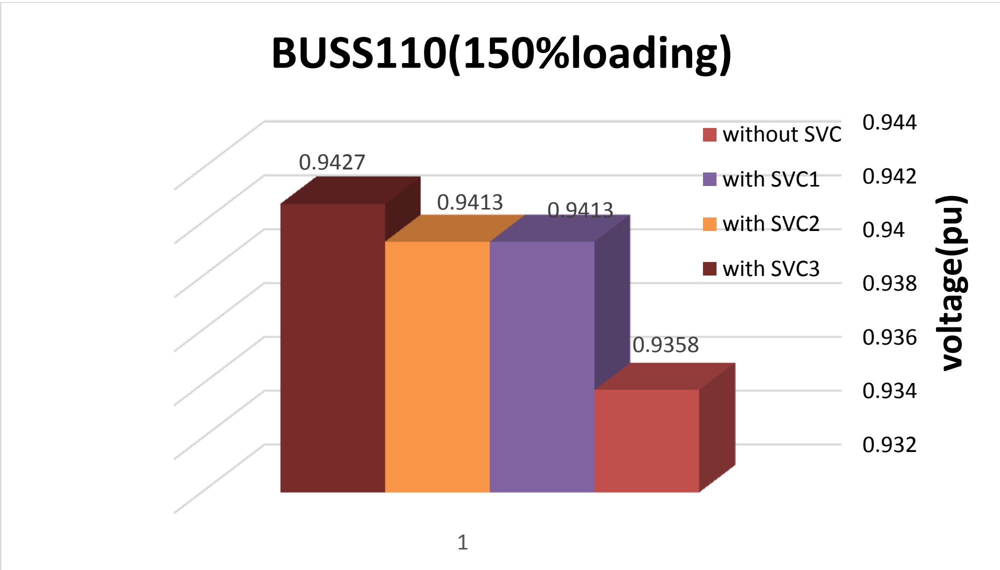
Load flow results show that the voltage at bus 110kV (at different load conditions) was more improving when SVC with high rating was used as can be seen in Figure 4.6 which is illustrates, a comparison between voltages of bus 110KV with and without SVCs.



(a): Voltage at bus 110KV at normal load



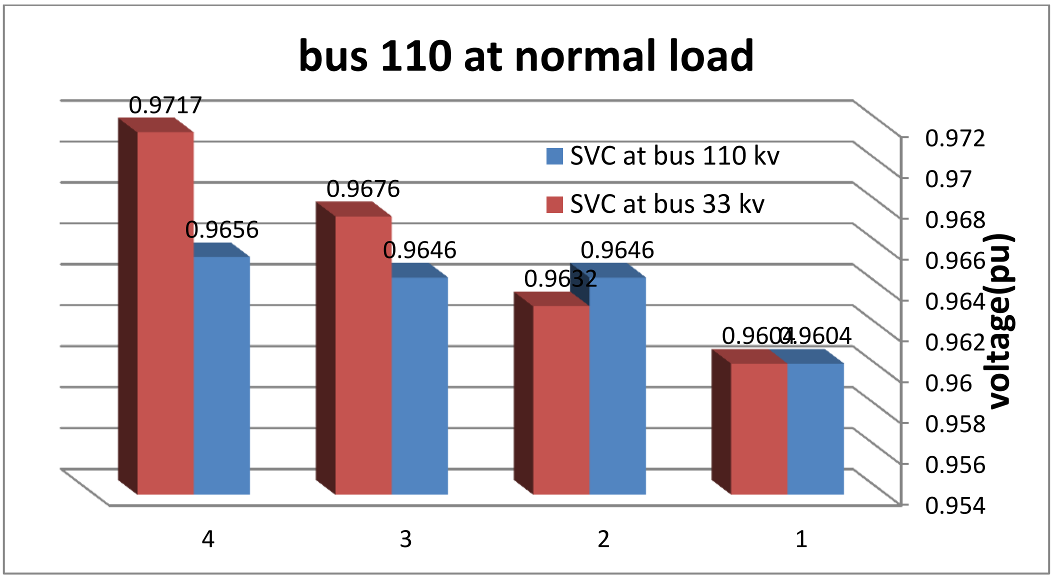
(b): Voltage at bus 110KV at 50% loading



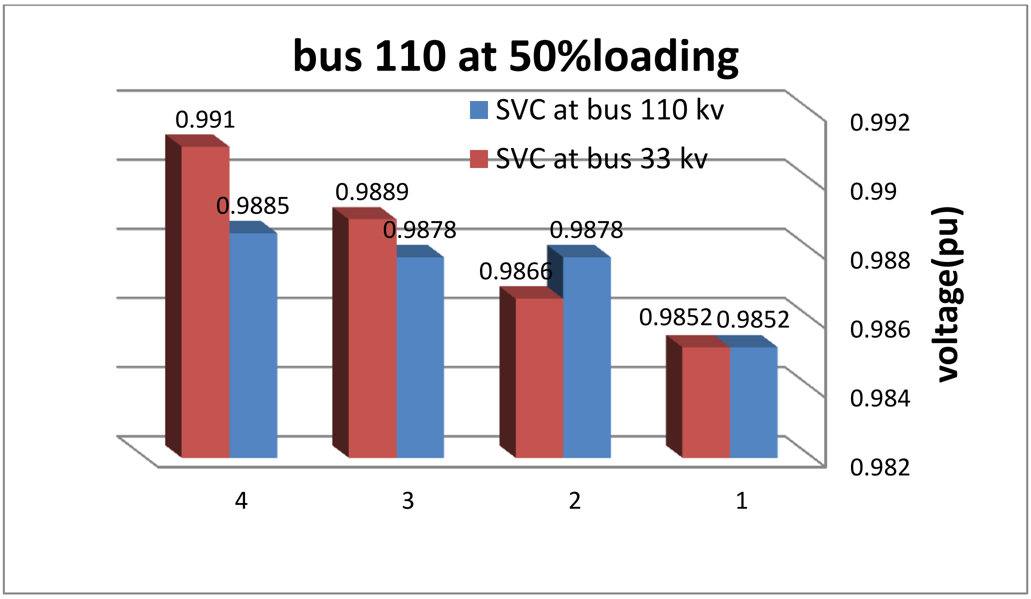
(c): Voltage at bus 110KV at 150% loading

Figure 4.6 Comparison between voltages of bus 110KV

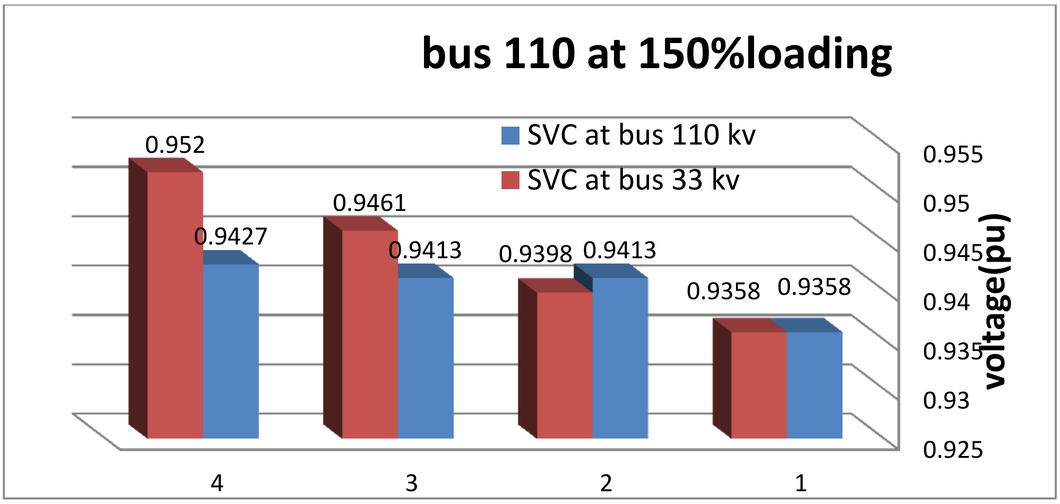
Figure 4.7 show a comparison between installing SVC at bus 110kv and bus 33 kv, the result show that when SVC was installed at bus 33 kv the voltages at bus 110 kv and 33 kv were more improving than installing it at bus 110 kv , this means the best location of installing SVC at bus 33kv as can be seen in Figure 4.7.



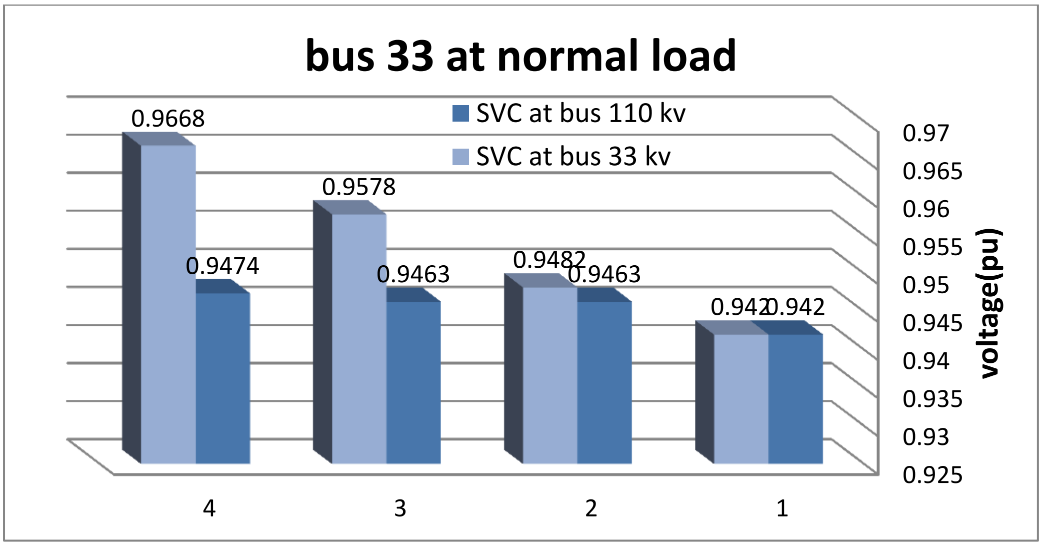
(a):voltage at bus 110 at normal load



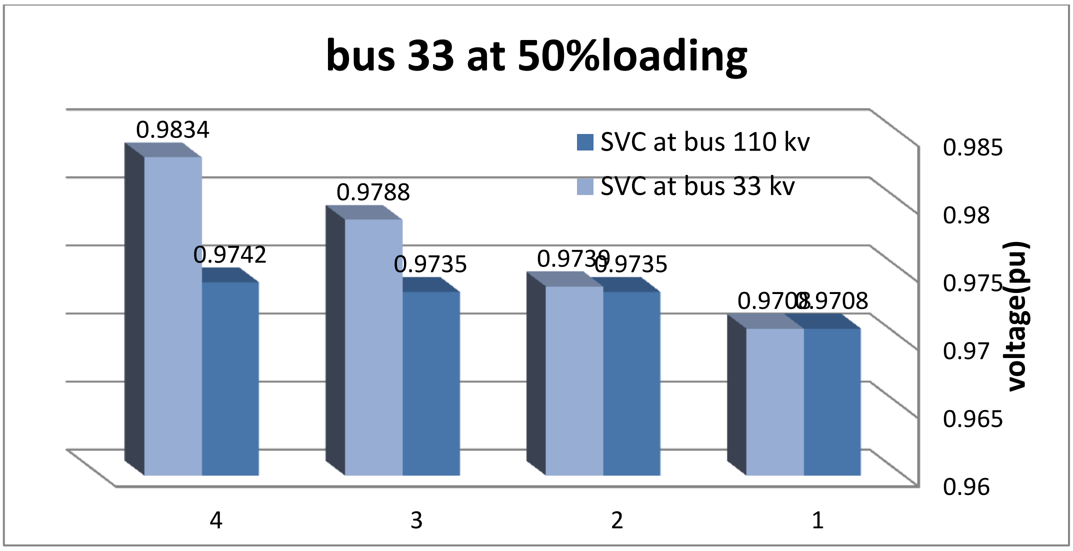
(b):voltage at bus 110 at50%loading



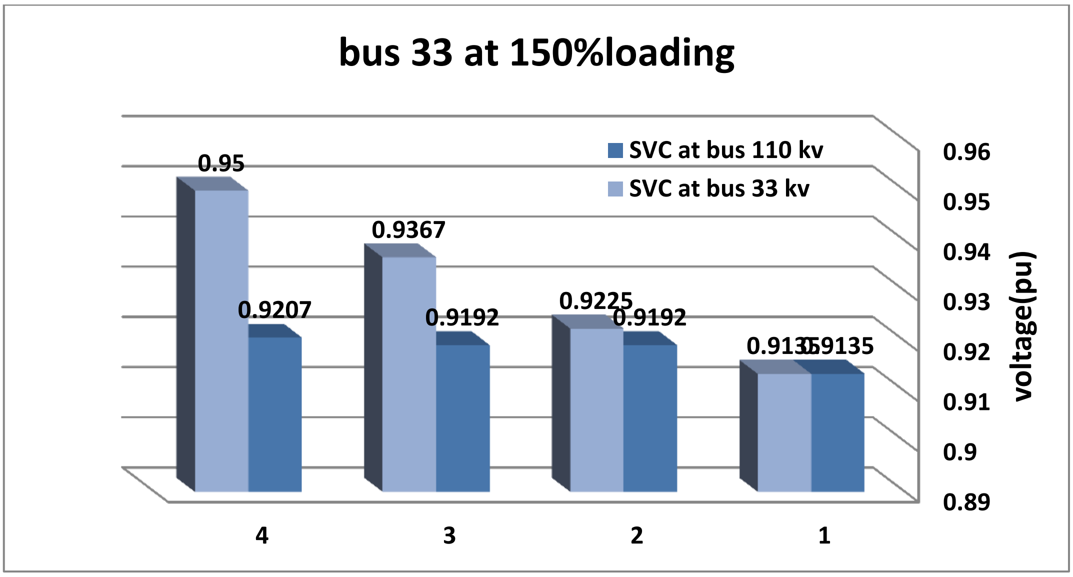
(c):voltage at bus 110 at150%loading



(d):voltage at bus 33 at normal load



(e):voltage at bus 33 at 50%loading



(f):voltage at bus 33 at150%loading

Figure 4.7Comparison between location of SVC at bus 110kv and bus 33kv

4.4 Dynamic State Study Results:

4.4.1 single phase SVC:

Molding of single phase SVC has done(as can be seen in figure 4.8) to measure the reactive power of capacitors, reactive power of reactor, and total reactive power of SVC at different firing angles, at α=0 TSC operates with full capacitive, at α=180 TSC is out of service. When α decrease the reactive power generated by TCR will increase.

The change of inductor voltages and bidirectional thyristor voltages compared with change in firing angle, as can be seen in figure 4.9 .

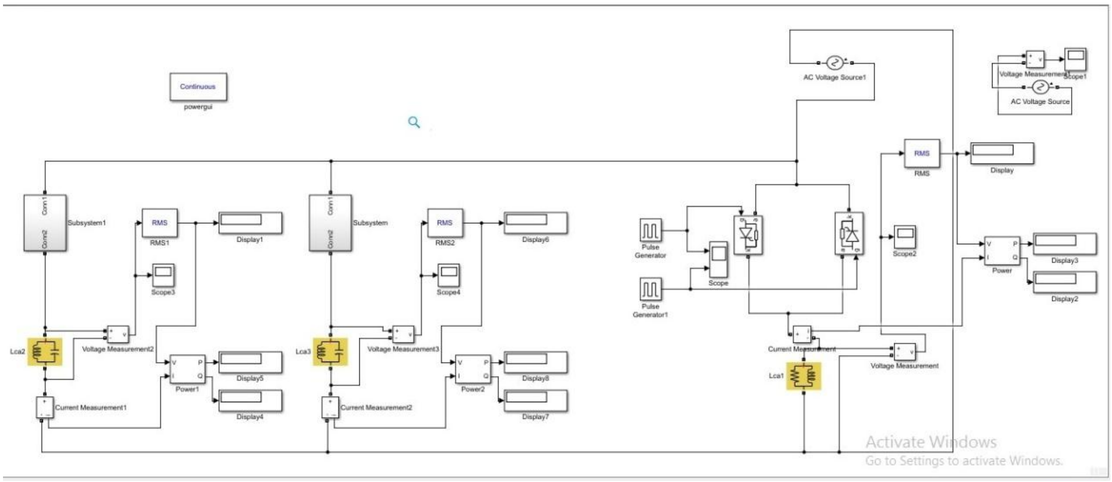
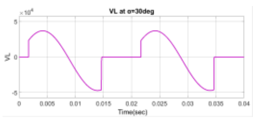
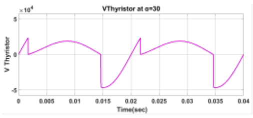


Figure 4.8: single phase SVC

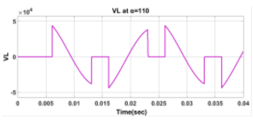


(a) Voltage of the inductor at firing angle(30)deg

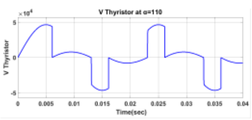


(b)Voltage of the thyristor at firing angle(30) deg

Figure 4.9 the voltage in inductor and bidirectional thyristor when firing angel was (30)deg.

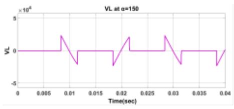


(a) Voltage of the inductor at firing angle (110) deg



(b)Voltage of the thyristor at firing angle (110) deg

Figure 4.10 voltage of the inductor and bidirectional thyristor when firing angel was (110)deg



(a) Voltage of the inductor at firing angle (150) deg

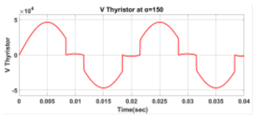


Figure 4.11 voltage of the inductor and bidirectional thyristor when firing angel was (150)deg

4.4.2 Dynamic results of GAM substation with SVC:

This section illustrates simulation of GAM sub-station with SVC and the response of SVC for dynamic changes in voltage. For simplicity, the dynamic changes in voltage are created using a programmable voltage source. Voltage change made follows the pattern given in Table 4.2.

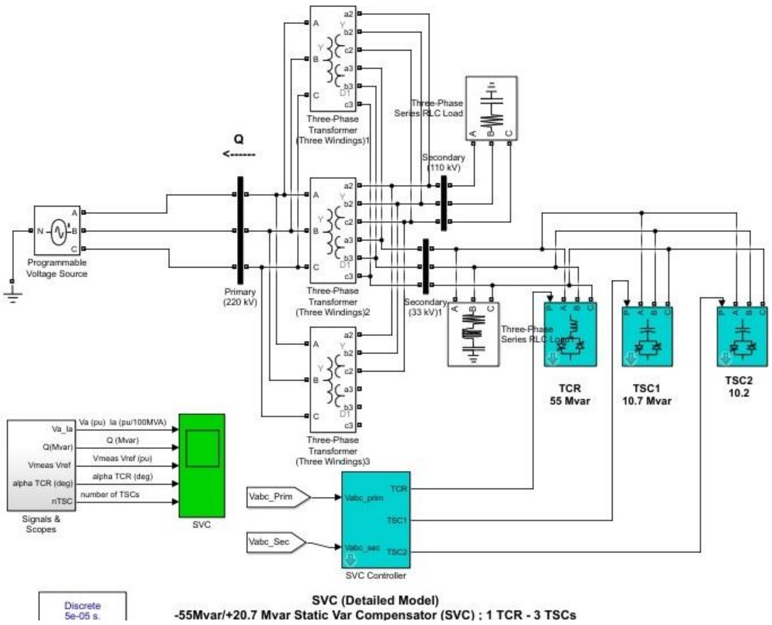


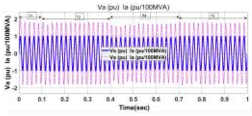
Figure 4.12 Modeling GAM sub-station with SVC

Table 4.2: Voltage changes of the programmable source

Voltage (kv)	1.0	1.025	0.93	1.0

Initially the voltage source was set at 1.0p.u., the SVC was initially out of service, during T_1 the operation point was obtained with TSC1 in service and TCR almost at full conduction as can be seen in Figure 4.16. During T_2 the voltage was suddenly increased to 1.025p.u. The SVC reacts by absorbing reactive power,TSC1 is out of service and firing angle of TCR is decreased as can be seen in Figures 4.14,15,16,17 respectively. During T_3 the voltage was suddenly lowered to 0.93p.u. The SVC reacts by generating reactive power to bring the voltage back to 1p.u, during this period the two TSCs are in service as can be seen in figures 4.14,15,16 respectively .

Finally, during T_4 the voltage was increased to 1.0p.u and the SVC reactive power was reduced to zero, TSCs are out of service and TCR is out of service as can be seen in Figures 4.14,15,16,17 respectively.



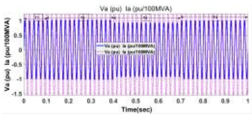


Figure 4.13 : Voltage and current of the programmable source.

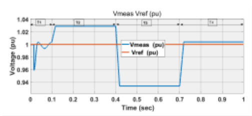


Figure 4.14: The measure voltage and reference voltage.

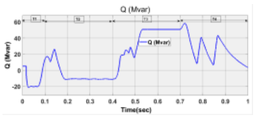


Figure 4.15 Generating and absorbing reactive power.

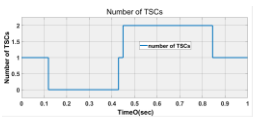


Figure 4.16 The number of TCR witche it intering.

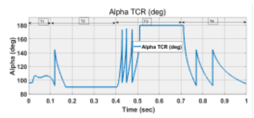


Figure 4.17 Firing angel of TCR

B_{Cmax} ≡ Maximum capacitive susceptance (pu/Pbase) with all TSCs in service, no TSR or TCR

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion:

This report research focuses on solving the problems of poor dynamic performance and voltage regulation.

After analysis of load flow by using ETAP and simulation by using MATLAB, GAM sub-station was found suffer from under voltage. To solve this problem SVC was installed in GAM sub-station to solve the voltage problem. As a consequence voltages at the load buses were improved but didn't obtain desired requirement. Good result obtained when different SVCs were installed in GAM sub-station and when SVC installed at bus 33kv.

5.2 Recommendations:

There are some recommendations:

SVC which was used in this report research has limited capacity according to the rating of capacitors and reactor in the sub-station; therefore in the future studies should consider higher rating of capacitors and reactor. Also future studies can focus in using STATCOM as an alternative.

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APPENDIX

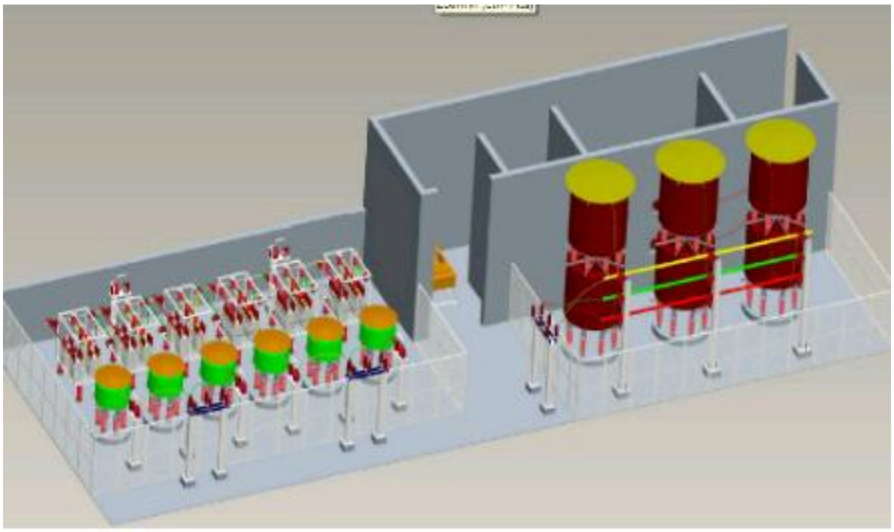

Figure A-1: Equipment of SVC

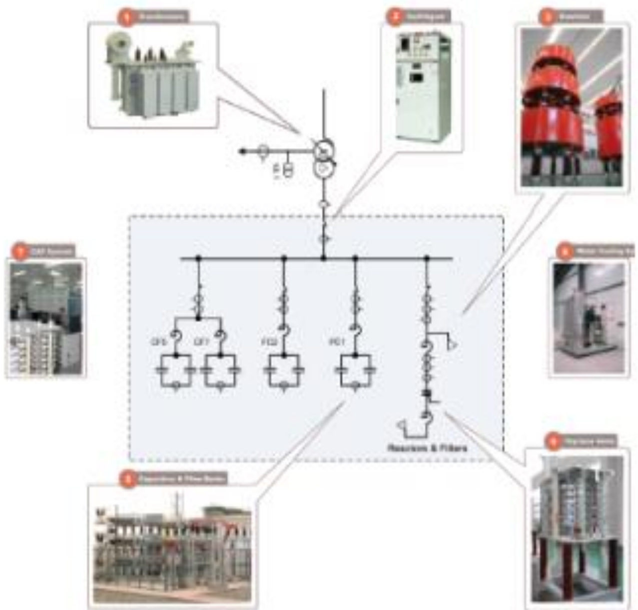

Figure A-2: System configuration

Figure A-3: Thyristor valve of SVC

Figure A-4: Cooling system of thyristor

Figure A-5: Location of SVC transformer (110/33)kv