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Voltage Improvement by Using Static VAR compensator (SVC)

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الآية

بسم الله الرحمن الرحيم

قال تعالى:

﴿إِنَّ رَبَّكُمُ اللَّهُ الَّذِي خَلَقَ السَّمَاوَاتِ وَالْأَرْضَ فِي سِتَّةِ أَيَّامٍ ثُمَّ اسْتَوَىٰ عَلَى الْعَرْشِ يُغْشِي اللَّيْلَ النَّهَارَ يَطْلُبُهُ حَثِيثًا وَالشَّمْسَ وَالْقَمَرَ وَالنُّجُومَ مُسَخَّرَاتٍ بِأَمْرِهِ ۗ أَلَا لَهُ الْخَلْقُ وَالْأَمْرُ ۗ تَبَارَكَ اللَّهُ رَبُّ الْعَالَمِينَ﴾

صدق الله العظيم

سورة الأعراف الآية (54)

DEDICATION

Although it has six years studying in Sudan University, it is an experience that will stay with us forever.

First of all, we would like to thanks our parent; they have inspired us throughout the life and have taught us never to give up.

We would also like to thank our sisters and brothers for their support.

Finally, we would like to thank the Department of Electrical and nuclear Engineering for supporting us during these years of study.

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ABSTRACT

The expansion in the demand and loads growth on the stations led to problems in voltage stability and system parameters are pushed below their permissible limits. The purpose of this project is to compensate the reactive power to improve the voltage in the stations (Al-Markhiyyat, Azirqab, Mahdia, Omdurman, Pant, Al-Muqrin, Al-Shajarah). The static VAR compensator was used and installed in the Mahdia substation to achieve the goal of the study and was performed in three cases followed, Normal operation case, the case of increasing the load to 30%, and the case of loss of generation in the Bant substation.

The study which found that after the installing SVC, the voltage has improved in all the substations, and the best improvement was in Mahdia substation because SVC was installed in Mahdia substation.

مستخلص

التوسع في الطلب الذي تواجهه المحطات بصورة عامة ادى الى حدوث مشاكل في استقرار الجهود وايصالها الي حدود أقل من المسموح به. الغرض من هذا المشروع تعويض القدرة الرد فعليه لتحسين الجهد في المحطات (المرخيات, الأزيرقاب, المهدية, أمدرمان, بانت, المقرن, الشجرة) وتم استخدام معوض الجهد الاستاتيكي في محطة المهدية لتحقيق هدف الدراسة, تم عمل تحليل لانسياب القدرة للنظام تحت الدراسة باستخدام برنامج الايتاب في الحالة الطبيعية وفي حالة زيادة الحمولة الي 30%, وفي حالة فقد التوليد في محطة بانت, توصلت الدراسة الي ان الجهد قد تحسن في كل المحطات و افضل نتيجة في محطة المهدية بسبب وضع معوض الجهد الاستاتيكي بها .

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LIST OF SYMBOLS

Q	Reactive power, MVAR
S	Apparent Power, KVA
P	Active power, MW
V_L	Reactor voltage, V
X_L	Reactor reactance, Ω
L_L	Reactance, H
ω	Frequency, rad/sec
ω_0	The nominal angular frequency of the system, rad/sec
α	Thyristor firing angle
ω_r	The TSC resonant frequency, rad/sec
V_{c0}	Voltage across the capacitor at t = 0, Voltage
B_C	The capacitor susceptance
B_L	The reactor susceptance
X_C	Capacitor reactance, Ω
V	Positive sequence voltage, p.u
I	Reactive current, p.u./phase
X_s	Slope or droop reactance, p.u./Phase
B_{cmax}	Maximum capacitive susceptance, p.u./Phase
B_{lmax}	Maximum inductive susceptance, p.u./Phase
I_{svc}	SVC current, Amp
B_{svc}	SVC susceptance
Q_{svc}	SVC reactive power injected at bus M

LIST OF ABBREVIATIONS

FACT	Flexible AC Transmission System
SVC	Static Var Compensator
VAR	Voltage-Ampere-reactive
ETAP	Electrical Transient Analysis Program
AC	Alternating Current
IEEE	Institute OF Electrical and Electronics Engineers
STSTCOM	Static Compensator
TCR	Thyrister Controlled Reactance
TCSC	Thyrister Controlled Series Capacitor
SSSC	Solid State Series Controlled
UPFC	Unified Power Flow Controlled
IPC	Interphase Power Controlled
PS	Phase Shifter
FC	Fixed capacitance
DC	Direct current

Chapter One

INTRODUCTION

1.1 Over View:

In the last decade’s power systems have faced new challenges due to deregulation, permanent increase in demand, the increased dependence of modern society upon electricity has forced power systems to operate with very high reliability and with almost 100% availability [1].

Electrical power transfer and delivery to consumers is subjected to many problems in consequence of many issues. Among these issues is 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, The way to counteract this problem is by reducing the reactive power Load in the system or by adding new reactive generation systems in the weakest points in the system, thereby, increasing the voltage at those points [2], 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 equipment’s 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 [3].

1.2 Statement of Problem:

The voltage level of the system changes when there is change in load and the drop in the voltage leads to an increased demand for the reactive power. If this drop is not met by the power system leads to a further decline in the bus voltage. This decline eventually leads to a progressive rapid decline of voltage at that location, which may have a cascading effect on neighboring regions that causes voltage collapse. In this research Static VAR Compensator (SVC) is used to maintain the voltage within the limits. SVC will either supply the reactive power or absorb the reactive power.

1.3 Thesis Objectives:

The objectives of this project are summarized in following points:

1. To perform load flow analysis in parts of Khartoum substations Network (Almarkhiat, Alizergab, Almahadia, Omdurman, Banat, Almugran, Alshagara) .
2. To compensate reactive power by using SVC to improve voltage profile in parts of Khartoum substations Network.

1.4 Research Methodology:

To study effect of SVC in voltage profile in parts of Khartoum substations Network, and load flow analysis with and without SVC is performed by using ETAP software.

1.5 Project layout:

This project contains five chapters. Chapter one consists of general concept, problem statements, objective, methodology and project layout. Chapter two represent literature review which consists of introduction, common disturbances in power systems, Reactive Power, Voltage Stability, and Voltage Control by traditional and modern method. Chapter three contains of general information about static variable compensator such as introduction, operation principle, Advantages of SVC, SVC Components and Configuration, and Control Concept. Chapter four shows the simulation result and discussion, finally, chapter five which consists of conclusion and recommendation.

Chapter Two
Literature Review

2.1 Introduction:

Modern society has relied consistently on electrical power, requiring higher demands of power stability and power quality.

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; normally transmission lines imply 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 [4].

Before the widespread use of power electronic equipment, microprocessors for Industrial control, and automation in factories and offices, minor variations in power did not seriously affect the operation of conventional equipment such as lights and induction motors. If the supply voltage dipped because of a fault (i.e., a sag in voltage occurred), the lights just dimmed, and the induction motor produced a lower output. These days the effects of power interruptions are rather costly [5].

2.2 Common disturbances in power systems:

The common disturbances in a power system are:

a. Voltage sag.

b. Voltage swells.

c. Momentary interruptions.

d. Transients.

e. Voltage unbalance.

f. Harmonics.

g. Voltage fluctuations.

All these types of disturbances, such as voltage sags, voltage swells, and interruptions, can be classified into three types, depending on their duration:

A. Short-duration voltage variation:

A voltage sag (dip) is defined as a decrease in the root-mean-square (rms) voltage at the power frequency for periods ranging from a half cycle to a minute.11 It is caused by voltage drops due to fault currents or starting of large motors. Sags may trigger shutdown of process controllers or computer system crashes.

A *voltage swell* is defined as an increase up to a level between 1.1 and 1.8 pu in rms voltage at the power frequency for periods ranging from a half cycle to a minute.

An *interruption* occurs when the supply voltage decreases to less than 0.1 pu for a period of time not exceeding 1 min. Interruptions can be caused by faults, control malfunctions, or equipment failures [6].

B. long-duration voltage variations:

An ***under voltage*** is a decrease in the rms ac voltage to less than 90% at the power frequency for a duration longer than 1 min. These can be caused by switching on a large load or switching off a large capacitor bank. 1.11 Under voltages are sometimes due to a deliberate reduction of voltage by the utility to lessen the load during periods of peak demand.

An under voltage will lower the output from capacitor banks that a utility or customer will often install to help maintain voltage and reduce losses in the system by compensating for the inductive nature of many conductors and loads.

An ***overvoltage*** is an increase in the rms ac voltage to a level greater than 110% at the power frequency for duration longer than 1 min. These are caused by switching off a large load or energizing a capacitor bank. Incorrect tap settings on transformers can also cause under voltages and over voltages. As these can last several minutes, they stress computers, electronic controllers, and motors. An overvoltage may shorten the life of power system equipment and motors [6].

C. Transients:

Transients can be classified into two categories, impulsive and oscillatory.

1. Impulsive transients:

An impulsive transient is a sudden no power frequency changes in the steady-state condition of voltage or current, or both, which is unidirectional in polarity (either positive or negative).

Impulsive transients are normally characterized by their rise and decay times.

They can also be described by their spectral content. For example, a 1.2-/50-*m*s 4000-V impulsive transient rises to its peak value of 4000 V in 1.2 *m*s, and then decays to half its peak value in 50 *m*s. The most common cause of impulsive transients is lightning.

2. Oscillatory Transients:

An *oscillatory transient* consists of a voltage or current whose instantaneous value
changes polarity rapidly. It is described by its spectral content.

2.2.1 Voltage Imbalance:

Voltage imbalance (unbalance) is defined as the ratio of a negative- or zero-sequence component to a positive-sequence component. The voltage imbalance in a power system is due to single-phase loads. In particular, single-phase traction loads connected across different phases produce negative-phase-sequence voltages, which in many cases have to be reduced to less than 2% with the help of SVCs.

Severe voltage imbalance can lead to derating of induction motors because of excessive heating. Voltage imbalance can also occur from a blown fuse on one phase of a three-phase bank. There are occasions when a severe voltage imbalance greater than 5% can occur from single-phasing conditions.

Voltage or current imbalance is estimated sometimes (less commonly) using the following definition: Maximum deviation from the average of the three-phase voltages (or currents) divided by the average of the three-phase voltages (or currents) [6].

2.2.2 Harmonics:

When a nonlinear load is supplied from a supply voltage of 60-Hz or 50-Hz frequency, it draws currents at more than one frequency, resulting in a distorted current waveform. Fourier analysis of this distorted current waveform resolves it into its fundamental component and different harmonics. Harmonics are sinusoidal voltages or currents having frequencies that are integer multiples of the fundamental frequency (usually 60 Hz or 50 Hz in power systems).

Harmonic distortion is a growing concern for many customers and the utilities because of increasing application of power electronics equipment. The nonlinear Harmonic-producing devices can be modeled as current sources that inject harmonic currents into the power system.

2.2.3 Power Frequency Variations:

At any instant, the frequency depends on the balance between the load and the capacity of the available generation, when dynamic balance changes, small changes in frequency occur. In modern interconnected power systems, frequency is controlled within a tight range as a result of good governor action. Frequency variations beyond ±0.1 Hz are likely to occur under fault conditions or from the loss of a major load or generating unit. However, in isolated systems, governor response to abrupt load changes may not be adequate to regulate them within the narrow bandwidth required by frequency-sensitive equipment.

Voltage notching can sometimes cause frequency or timing errors on power electronic machines that count zero crossings to derive frequency or time. The voltage notch may produce additional zero crossings that can cause frequency or timing errors and affect the performance of digital electric clocks [6].

2.2.4 Voltage Fluctuations:

Loads that exhibit continuous, rapid variations in load current can cause voltage Variations erroneously referred to as flicker. ANSI C84.1-1992 recommends that the system voltages should lie in the range 0.9–1.1 pu.

IEC 1000-3-3 (1994) defines various types of voltage fluctuations, the IEC 1000-3-3 (1994), Type (d) is characterized as systematic variations of voltage envelopes or a series of random voltages.

Arc furnaces are the most common cause of voltage fluctuations in the transmission and distribution system. Voltage fluctuations are defined by their rms magnitude expressed as a percentage of the fundamental magnitude. They are the response of the power system to the varying load, and light flicker is the response of the lighting system as observed by the human eye. Even though flicker is caused by voltage fluctuations, some authors use the term "voltage flicker" to represent either of these terms.

Voltage fluctuations generally appear as a modulation of the fundamental frequency. Hence, the magnitude of voltage fluctuations can be obtained by demodulating the waveform to remove the fundamental frequency and then measuring the magnitude of the modulation components, typically, magnitudes as low as 0.5% can result in perceptible light flicker if the frequencies are in the range of 6–8 Hz.

2.3 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.

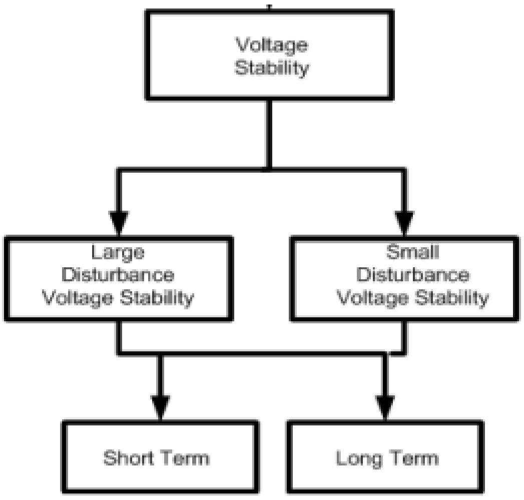

Figure 2.1: classifications of voltage stability

2.4 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

$$Q=S\sin(\varphi) \text{ or } Q=P\tan(\varphi) \quad (2.1)$$

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

1. 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 the damage.
2. System stability is enhanced to maximize utilization of the transmission system.
3. 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 [7].

2.5 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.

2.6 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.

2.6.1 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 overhead lines longer than150-200km. 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.

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 [8].

The output characteristic (V-I) is linear in the operating rang as shown in Figure 2.2 and deviates from linearity for iron-core or shrouded iron reactors due to saturation are breaker.

$$V_l = jX(-jI_l) = X_l L_l \tag{2.1}$$

$$I_l = \frac{V_l}{X_l} = \frac{V_l}{\omega l} \tag{2.2}$$

$$Q_l = \frac{V_l^2}{\omega l} \tag{2.3}$$

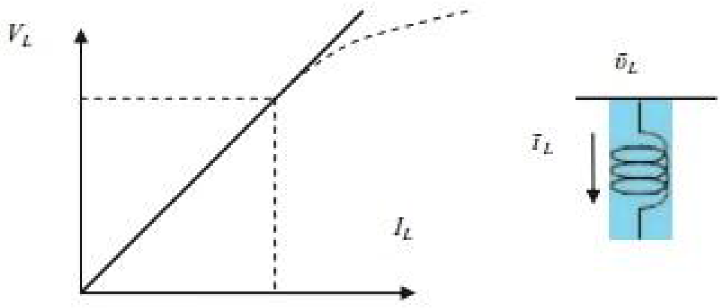

Figure 2.2: V-I characteristic

Shunt reactors may be connected to low voltage tertiary winding of transformer, through a suitable circuit breaker as shown in Figure 2.3. 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 [7].

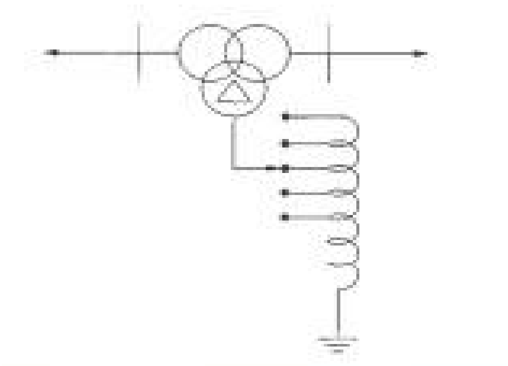

Figure 2.3: Tapped reactor

2.6.2 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 [7].

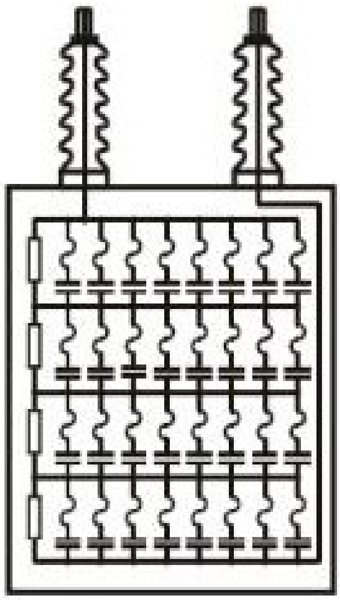

Figure 2.4: shunt capacitor

It is always connected to the bus rather than to the line figure 2.5. They are connected either directly to winding of the main transformer. Shunt capacitor banks are breaker switched either automatically by voltage relay or manually.

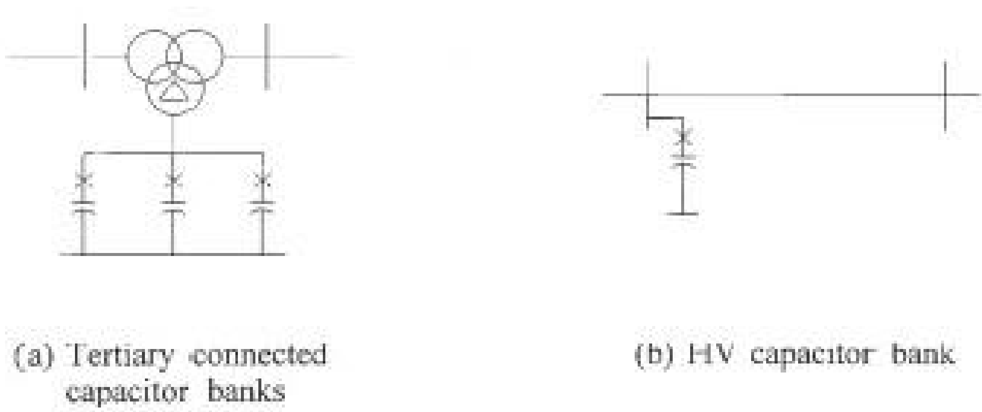

Figure 2.5: connection of shunt capacitor

2.6.3 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 absorbed 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 [9].

2.6.4 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.

2.7 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.

2.8 FACTS devices:

FACTS controllers intend for steady-state operation are as follows (IEEE/CIGRE, 1995):

- Thyristor-controlled phase shifter (PS): this controller is an electronic phase-shifting transformer adjusted by thyristor switches to provide a rapidly varying phase angle.
- Load tap changer (LTC): this may be considered to be a FACTS controller if tap changes controlled by thyristor switches.

- Thyristor -controlled reactance (TCR): this is a shunt- controlled, Thyristor-controlled reactance the effective reactance of which is varied in a continuous manner by partial conduction control of the Thyristor value.
- Thyristor-controlled series capacitor (TCSC): this consists of a cerise capacitor paralleled by a Thyristor-controlled reactor in order to provide smooth variable series compensation.
- Interphase power controller (IPC): this is a series-connected controller comprising two parallel blanchers, one inductive and capacitive, subject to separate phase-shifted voltage magnitudes. active power control is set by independent or coordinated adjust-mint of the two phase shifting sources and the two variable reactance's. Reactive power control is independent of active power.
- Static compensator (STATCOM): this is a solid-state synchronous connected in shunt with the ac system. The output current is adjusted to control either the nodal voltage magnitude or the reactive power injected at the bus.
- Solid state series controller (SSSC): this controller is similar to the STATCOM but it is connected in series with the AC system. The output current is adjusted to control either the nodal voltage magnitude or the reactive power injected at one of the terminal of the series connected transformer.
- Unified power flow controller (UPFC): this consists of a static synchronous series compensator (SSSC) and a STATCOM, connected in such a way that they share a common DC capacitor. The UPFC, by means of an angularly, the transmission line impedance, the nodal voltage magnitude, and the active and reactive power flow through it. It may also provide independently controllable shunt reactive compensation.
- Static VAR compensator (SVC): This is a shunt-connected static source or sinks reactive power.
- High –voltage direct-current (HVDC) link: this is controller comprising a rectifier station and an inverter station, joined either back –to –back or through a DC cable.

Table (2.1): The role of FACTS controllers in power system operation:

Operating problem	**Corrective action**	**FACTS controller**
Voltage limits		
Low voltage at heavy load	Supply reactive power	STATCOM, SVC,
High voltage at low load	Absorb reactive power	STATCOM, SVC, TCR
High voltage following an outage	Absorb reactive power; prevent overload	STATCOM, SVC, TCR
Low voltage following an outage	Supply reactive power; prevent overload	STATCOM, SVC
Thermal limits		
Transmission circuit overload	Reduce overload	TCSC, SSSC, UPFC, IPC, PS
Tripping of parallel circuits	Limit circuit loading	TCSC, SSSC, UPFC, IPC, PS
Loop flows		
Parallel line load sharing	Adjust series reactance	IPC, SSSC, UPFC, TCSC, PS
Postfault power flow sharing	Rearrange network or use thermal limit actions	IPC, TCSC, SSSC, UPFC, PS
Power flow direction reversal	Adjust phase angle	IPC, SSSC, UPFC, PS

CHAPTER THREE

STATIC VAR COMPENSATOR (SVC)

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. 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 [10].

3.2 Operating Principles:

The Static VAR Compensator (SVC) is composed of the capacitor banks/filter banks and air-core reactors connected in parallel. The air-core reactors are series connected to Thyristor. The current of air-core reactors can be controlled by adjusting the fire angle of Thyristors.

The SVC can be considered as a dynamic reactive power source. It can supply capacitive reactive power to the grid or consume the spare inductive reactive power from the grid. Normally, the system can absorb the reactive power from a capacitor bank, and the spare part can be consumed by an air-core shunt reactor.

As mentioned, the current in the air-core reactor is controlled by a Thyristor valve. The valve controls the fundamental current by changing the fire angle, ensuring the voltage can be limited to an acceptable range at the injected node (for power system VAR compensation), or the sum of reactive power at the injected node is zero which means the power factor is equal to 1 (for load VAR compensation).

Current harmonics are inevitable during the operation of Thyristor controlled rectifiers, thus it is essential to have filters in a SVC system to eliminate the harmonics. The filter banks can not only absorb the risk harmonics, but also produce the capacitive reactive power.

The SVC uses closed loop control system to regulate bus bar voltage, reactive power exchange, power factor and three phase voltage balance.

3.3 Advantages of SVC:

Advantages of SVCs over simple mechanically switched compensation schemes are their near-instantaneous response to change in the system voltage. For this reason, they are often operated at close to their zero-point in order to maximize the reactive power correction. They are in general cheaper, higher-capacity, faster, and more reliable than dynamic compensation schemes such as synchronous compensators (condensers). In a word:

1. Improved system steady-state stability.

2. Improved system transient stability.

3. Better load division on parallel circuits.

4. Reduced voltage drops in load areas during severe disturbances.

5. Reduced transmission losses.

6. Better adjustment of line loadings.

3.4 SVC Components:

This section presents the different “building blocks” that are commonly used when designing an SVC. The components are presented individually to describe their influence on the grid. We will also briefly discuss some of the problems associated with the components and how these could be handled. This is done to give some insight into how an SVC operates [10].

The different building blocks presented in this section are illustrated in figure 3.1:

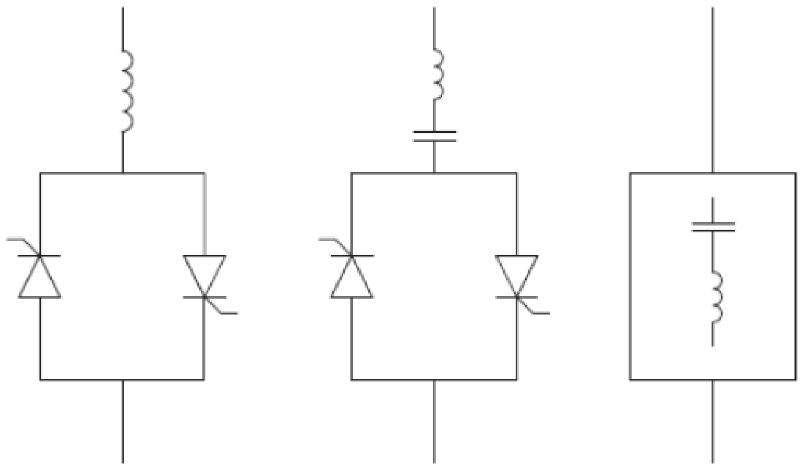

Figure 3.1: One-line diagram of the common SVC components.

3.4.1 Thyristor Switched Capacitor:

The Thyristor switched capacitor (TSC) is a shunt connected capacitor that is switched ON or OFF using Thyristor valves [31]. Figure 3.1(b) shows the one-line diagram of this component. 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 [10].

We assume that the TSC in figure 3.1(b) comprises the capacitance C, the inductance L and that a sinusoidal voltage is applied

$$v(t) = V \sin(\omega_0 t) \tag{3.1}$$

Where ω_0 is the nominal angular frequency of the system, i.e. $\omega_0 = 2\pi f_0$ = 2π50 rad/s in a 50 Hz system.

The current through the TSC branch at any given time is determined by: [10]

$$I(t) = I\cos(\omega_0 t + \alpha) - I\cos(\alpha)\cos(\omega_r t) + nBc\left(V_{c0} - \frac{n^2}{n^2-1} V\sin(\alpha)\right)\sin(\omega_r t)$$

(3.2)

Where α is the Thyristor firing angle, ω_r is the TSC resonant frequency, V_{c0} is the voltage across the capacitor at t = 0. The current amplitude I is determined by:

$$I = V\frac{BcBl}{Bc+Bl} \qquad (3.3)$$

Where Bc is the capacitor susceptance and BL is the reactor susceptance and n is given by:

$$n = \frac{1}{\sqrt{\omega^2 LC}} = \sqrt{\frac{X_C}{X_l}} \qquad (3.4)$$

X_c and X_l above are the reactances of the capacitor and reactor. The TSC resonant frequency, ω_r, is defined by:

$$\omega_r = n\omega_0 = \frac{1}{\sqrt{LC}} \qquad (3.5)$$

We can alternatively express the magnitude of the TSC current (3.3):

$$I = V\frac{BcBl}{Bc+Bl} = VB\frac{n^2}{n^2-1} \qquad (3.6)$$

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

$$I = VB_c \qquad (3.7)$$

Comparing (3.6) and (3.7) we notice that adding the reactor L amplifies the current by $n^2/(n^2-1)$. As n is determined by X_l and X_c, shown in (3.4), 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 .

Careful design of the TSC can thus avoid a resonance with the connected grid. However, the oscillatory component of the current (3.2) is still something that has to be taken care of. The following section provides some insight into how these currents could be limited to a minimum [10].

3.4.2 Thyristor Switched Reactor:

The Thyristor switched reactor (TSR) is a shunt-connected reactor in series with a Thyristor valve that is used to switch the reactor ON or OFF. A one-line diagram of a TSR is shown in figure 3.1(a).

Basically, the TSR fulfills the same purpose as the shunt-connected mechanically switched reactor which has been employed in the AC transmission system since its early days. The only difference between these two components is that the former uses a Thyristor to switch the reactor in and out of operation, while the latter uses a mechanical switch. Compared to the mechanical switch, the Thyristor allows the switching process to be a lot faster another advantage is that it will not face the same limitations on wear and tear as a mechanical switch, which is only capable of a finite number of switches. The higher investment cost could possibly be earned by the reduction in service and maintenance costs of the mechanical switches [10].

As the switched reactor is not a common component in SVC installations, only this short description is provided for the sake of completeness. The controllable reactor is a much more useful and common component and this will be described in the following section [10].

3.4.3 Thyristor Controlled Reactor:

The Thyristor controlled reactor (TCR) can be represented by the same one line diagram as for the previously mentioned TSR, shown in figure 3.1a. By enforcing partial conduction of the Thyristor valve, the effective reactance of the inductor may be varied in a continuous manner.

This is achieved by controlling the firing angle α of the Thyristor valve, thus controlling the TCR susceptance and its ability to absorb reactive power. As the firing angle can be varied continuously from zero to full conduction, the field of operation of the TCR is much greater compared to the discretely switched TSR.

The operation range of the firing angle lies between 90° and 180°, which respectively corresponds to full conduction and no conduction.

Operating within the firing angle interval, $0° \leq \alpha < 90°$, introduces a DC offset to the reactor current which disturbs the Thyristor valve [11]. Thus, this interval should be avoided.

We assume that a TCR branch with inductance L is connected to the AC voltage given by:

$$v(t) = V\sin(\omega) \qquad (3.7)$$

The voltage induces a current through the reactor described by the differential equation:

$$\mathrm{v(t)} = \mathrm{L}\frac{di}{dt} \qquad (3.8)$$

which, via integration, provides the expression of the TCR current:

$$\mathrm{i(t)} = \frac{1}{L}\int_{\alpha}^{\omega t} v(t)dt = \frac{1}{L}\int_{\alpha}^{\omega o} V\sin(\omega_0\, t)dt = -\frac{V}{\omega oL}\cos(\omega_0\, \mathrm{t}\,) + D \qquad (3.9)$$

Where D is a constant of integration.

The two intervals of conduction for the Thyristor valve are:

$$\alpha < \omega_0 t < 2\pi - \alpha \quad (3.10a)$$

$$\pi + \alpha < \omega_0 t < 3\pi - \alpha \quad (3.10b)$$

Where (3.10a) is the positive half period and (3.10b) is the negative.

We calculate the TCR current (3.9) by determining the integration constant D for the two intervals in (3.10), which gives us the following:

$$I(t) = \frac{V}{\omega_0 L}(\cos(\alpha) - \cos(\omega_0 t)) \quad (3.14a)$$

$$I(t) = -\frac{V}{\omega_0 L}(\cos(\alpha) - \cos(\omega_0 t)) \quad (3.14b)$$

Figure 3.4 shows the reactor current for three different firing angles. Full conduction is achieved at α = 90◦ and the reactor current decreases as α increases. This can easily be seen as currents corresponding to α = 90◦, 120◦ and 150◦ are plotted together with the grid voltage v(t) [10].

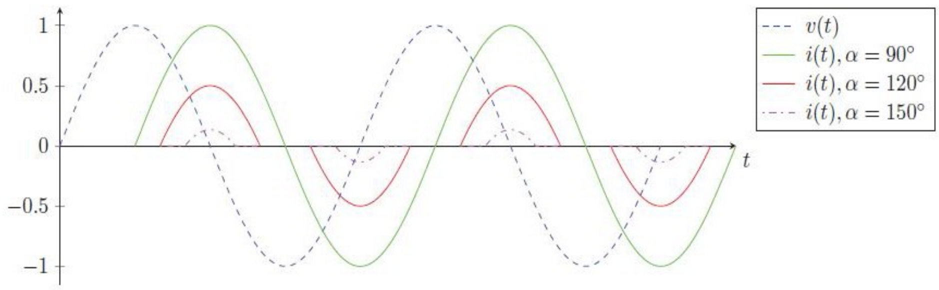

Figure 3.2: Current through the TCR for different firing angles α, with the applied voltage shown as the blue, dashed line.

3.5 System Configuration:

The system configuration represented by figure (3.3)

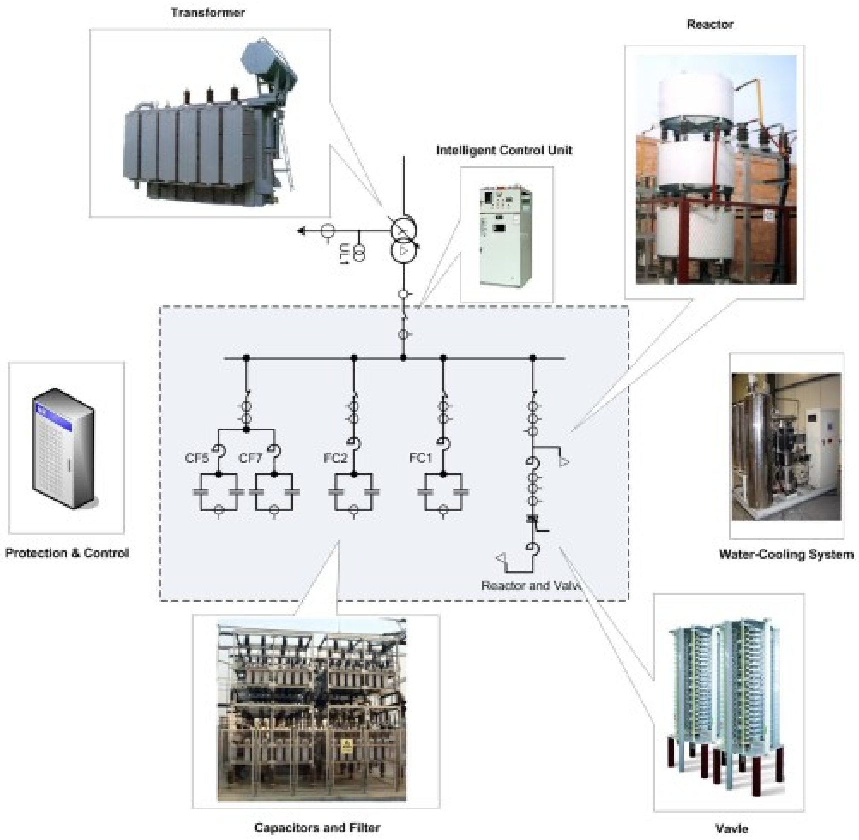

Figure (3.3) System Configuration

3.5.1 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.

3.5.2 switch-gear:

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

3.5.3 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.

3.5.4 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. The Thyristors are triggered by electrical lighting system and it adopts water cooling as the main cooling method.

3.5.5 Capacitor/filter banks:

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.

3.6 Common SVC Topologies:

The general SVC installation comprises two ranges of operation; inductive and capacitive. When designing the SVC, we need to consider both the required control performance and cost of the potential components.

As the SVC is usually designed to be continuously operated, we would need a TCR in the installation. Adding a TCR will introduce harmonics to the SVC current. To minimize the injection of harmonics caused by the TCR, a filter network is usually included in the SVC installation.

In many SVC installations, a shunt connected fixed capacitance (FC) is used to inject reactive power to the grid as this would provide a cheaper solution. The fixed capacitance is usually partly or fully substituted by the filters used to dampen the TCR induced harmonics. Using this FC-type configuration would not need the expensive Thyristor valves and could thus be equipped with simpler control equipment.

Considering the FC-TCR type SVC, it can be noted that losses will increase as we increase the current through the TCR. Therefore, it is usually installed where the output is mostly capacitive as in e.g. industrial applications for power factor control. Combining the TSC and TCR to make up the SVC would be a more advantageous approach for transmission system applications. This configuration makes it possible to minimize the losses by dividing the total capacitance into a number of Thyristor switched capacitances. This allows us to minimize the current through the TCR and will thus minimize the losses [10].

To summarize, the most common topologies when designing SVC systems are:

- Fixed capacitors & Thyristor controlled reactor (FC-TCR).
- Thyristor switched capacitors & Thyristor controlled reactor (TSC-TCR).

3.7 SVC V-I Characteristic:

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, it implements the following V-I characteristic. 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 voltage Vref. 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 Figure (3.4) The V-I characteristic is described by the following three equations [12].

SVC is in regulation range (-B_{cmax}< B <B_{lmax}) (3.12)

$$V=\frac{1}{B_{cmax}} \quad (3.13)$$

$$V = V_{ref} + X_{si} \quad (3.14)$$

SVC is fully inductive (B=B_{lmax})

Where,

V = Positive sequence voltage (p.u)

I = Reactive current (p.u./Phase) (I > 0 indicates an inductive current)

X_s = Slope or droop reactance (p.u./Phase)

B_{cmax} = Maximum capacitive susceptance (p.u./Phase) with all TSCs in service, no TSR or TCR

B_{lmax} = Maximum inductive susceptance (p.u./Phase) with all TSRs in service or TCRs at full conduction, no TSC

Phase = Three-phase base power

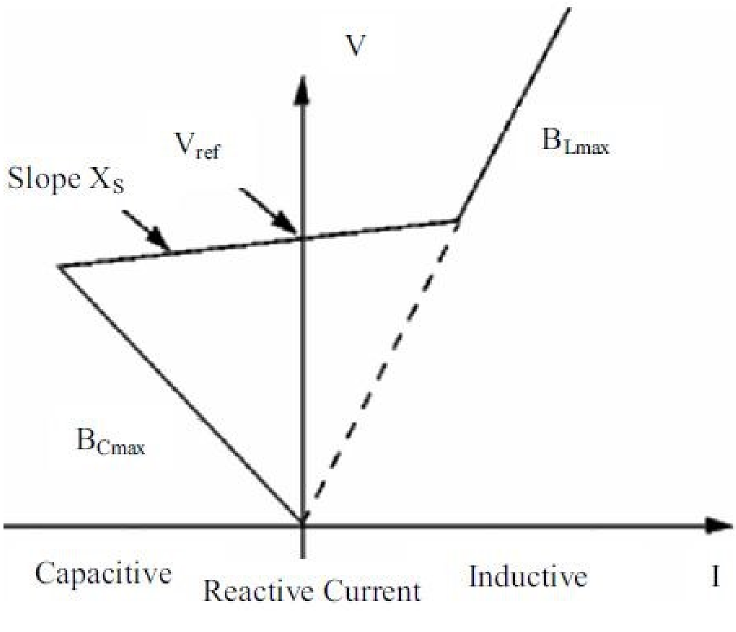

Figure 3.4: The V-I Characteristic Curve of SVC

3.8 Modelling of SVC:

SVC is a Shunt FACTS device which is considered a variable impedance type device. The SVC uses conventional Thyristors to achieve fast control of shunt connected capacitors and reactors. The configuration of the SVC is shown in Figure (3.5), which basically consists of a fixed Capacitor (C) and a Thyristor controlled reactor (L). The firing angle control of the Thyristor banks determines the equivalent shunt admittance presented to the power system [13].

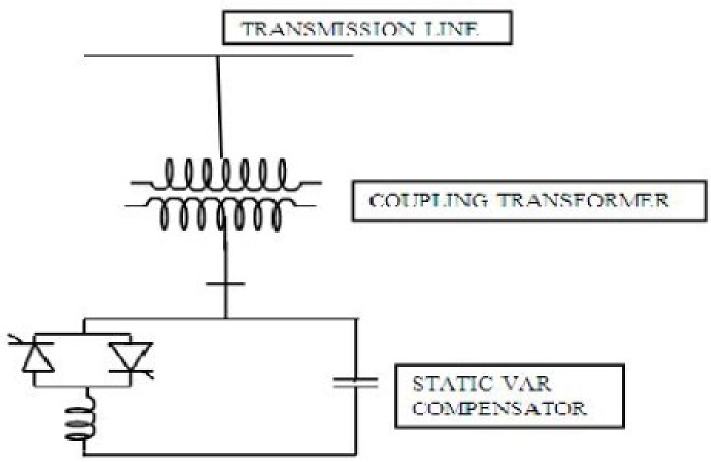

Figure 3.5: SVC connected to a transmission line

$$I_{svc} = j\, B_{svc}\, V_m \qquad (15)$$

The reactive power injected at bus m is

$$Q_{svc} = Q_m = I_{svc}\, V_m = -\, {V_m}^2 B_{svc} \qquad (3.16)$$

Where

$$B_{svc} = \frac{1}{X_c X_l}\, \frac{X_l - X_c}{\pi}\, [2(\pi - \alpha_{svc}) + \sin \alpha_{svc}] \qquad (3.17)$$

3.9 Control Concept of SVC:

An SVC is a controlled shunt susceptance (B) as defined by the SVC control settings that injects reactive power (Q) into the system based on the square of its terminal voltage. Figure (3.5) illustrates a TCR/FC SVC, including the operational concept. The control objective of the SVC is to maintain a desired voltage at the high-voltage bus. In the steady-state, the SVC will provide some steady-state control of the voltage to maintain it the high-voltage bus at a pre-defined level [14].

If the high-voltage bus begins to fall below its set point range, the SVC will inject reactive power (Q_{net}) into the system (within its controlled limits), thereby increasing the bus voltage back to its desired voltage level. If bus voltage increases, the SVC will inject less (or TCR will absorb more) reactive power (within its controlled limits), and the result will be to achieve the desired bus voltage. From Figure (3.6), +Q_{cap} is a fixed capacitance value, therefore the magnitude of reactive power injected into the system, Q_{net}, is controlled by the magnitude of -Q_{ind} reactive power absorbed by the TCR [14].

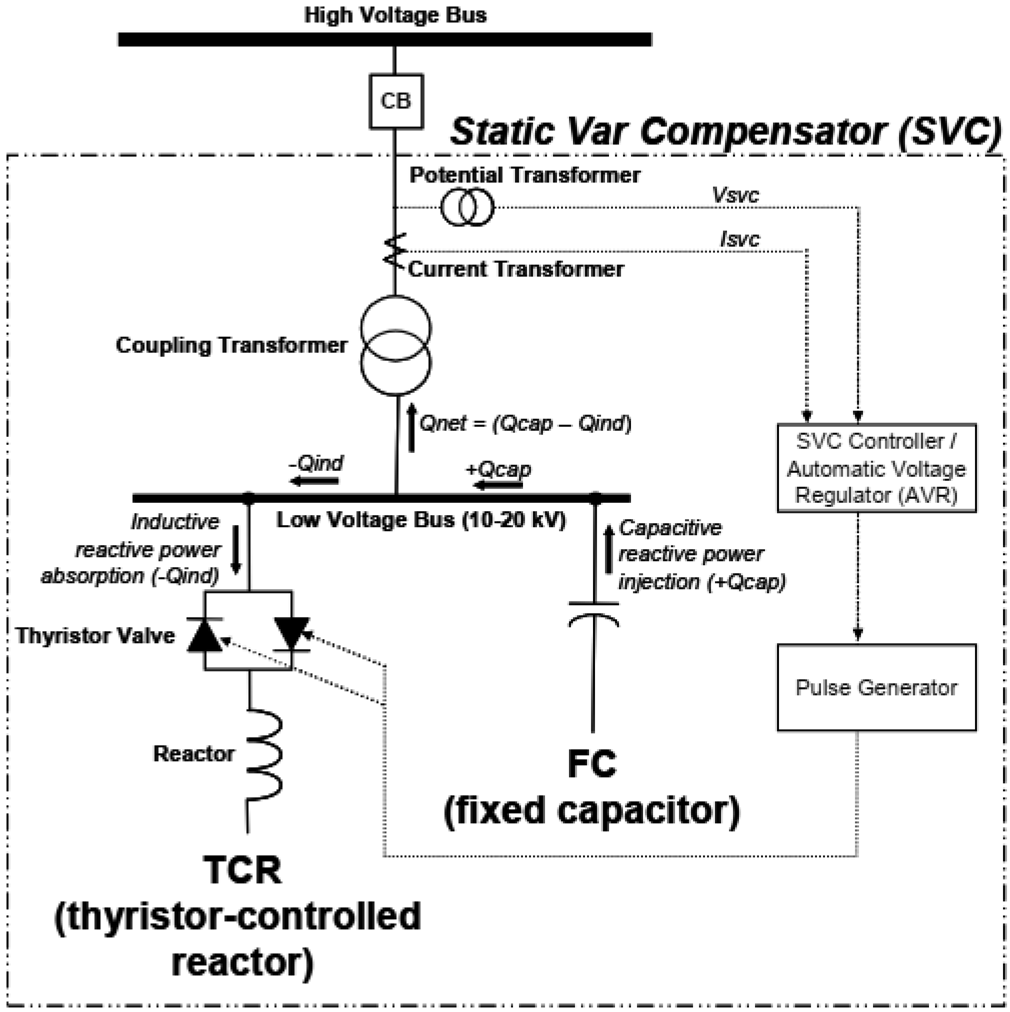

Figure 3.6: SVC with control concept briefly illustrated

The fundamental operation of the Thyristor valve that controls the TCR is described here. The Thyristor is self-commutates at every current zero, therefore the current through the reactor is achieved by gating (or firing) the Thyristor at a desired conduction angle (or firing angle) with respect to the voltage waveform. Figure (3.7) describes the relationship between the fundamental frequency TCR current and firing angle [14].

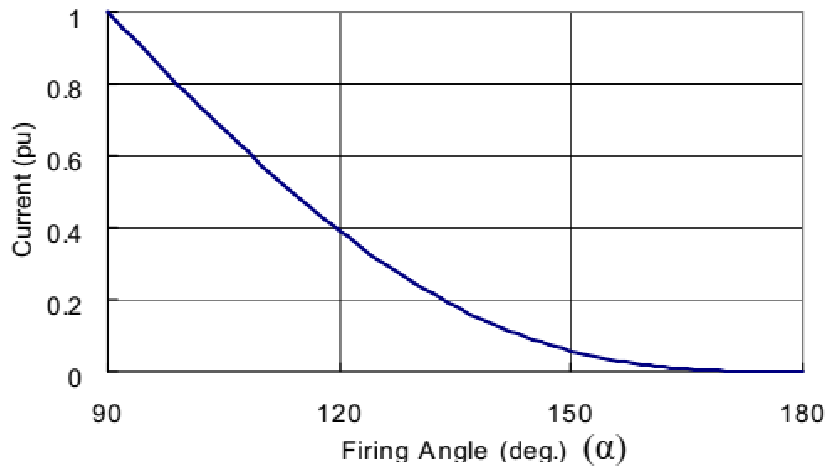

Figure 3.7: Illustration of the relationship between TCR current and firing angle

CHAPTER FOUR

SIMULATION AND RESULT

4.1 Introduction:

In this chapter the voltage stability was studied for parts of Khartoum substations Network which composed of (Almarkhiat, Alizergab, Almahadia, Omdurman, Banat, Almugran and Alshagara with voltage levels of (500, 220, 110, 33)), the simulation was performed using ETAP software, the study was carried out for three scenarios: Normal operation, 30% overload and generation outages in Bant substation.

4.2 System Data:

The system data was obtained from the Sudanese Electrical Transmission Company as in appendix A. The loads, capacitor, and generation were set to compensator the parts which were not taken from National Sudanese Network; Figure 4.1 shows the study case at normal operation.

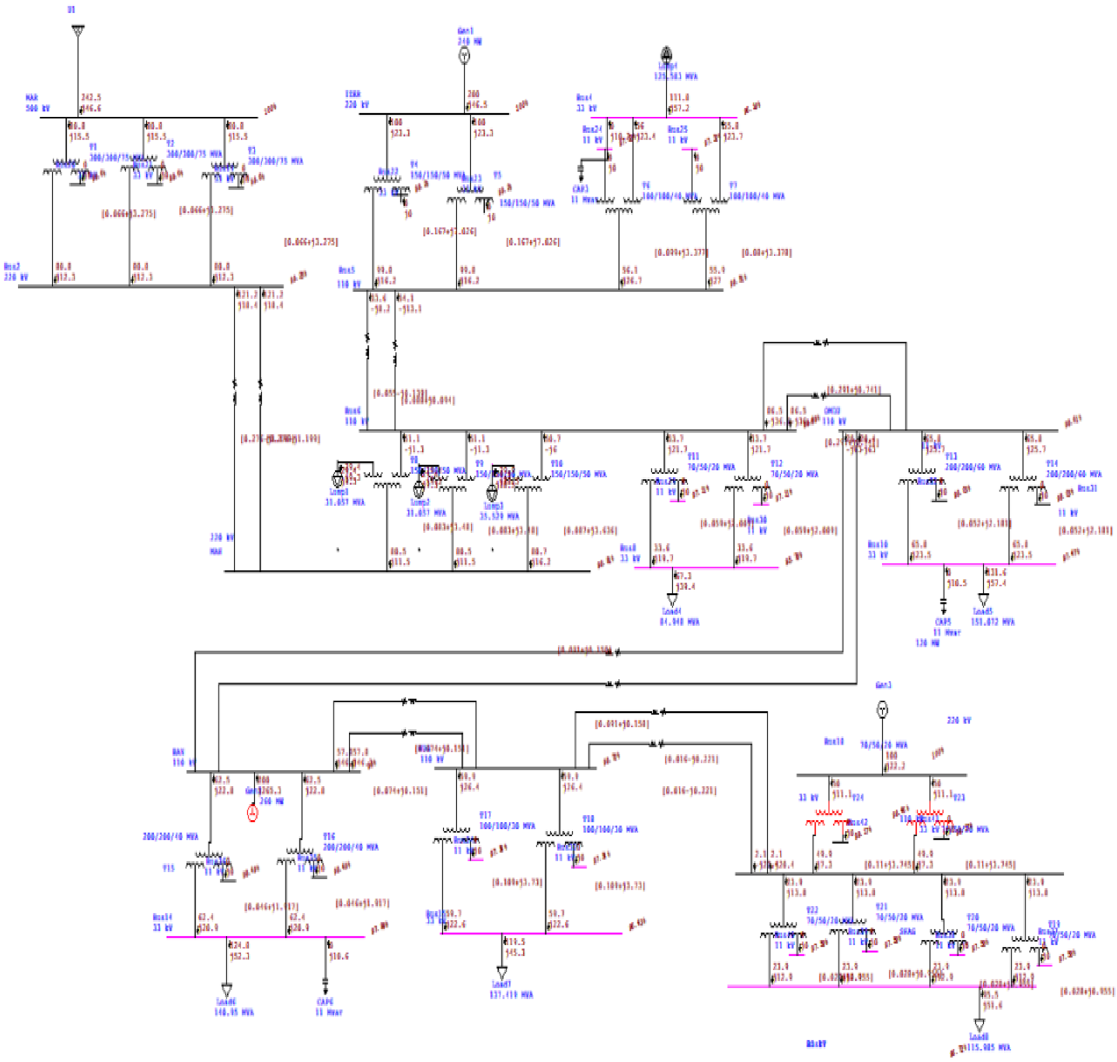

Figure 4.1The system at normal operation

4.3 Results:

4.3.1 Case one: System at normal operation:

After running the simulation for system at normal load as in, the results of voltage profile as in Figure 4.2 show that there is under voltage at Almahdia low voltage bus bar (33KV) and Alizergab bus bar from Table 4.1.

Table 4.1: Load flow result at normal operation

Bus name	Voltage magnitude (%)
BAN2	99.276
IZER2	99.351
IZER3	97.727
MAH1	99.432
MAH2	99.326
MAH3	97.227
MAR2	99.617
MUG1	99.746
MUG2	97.881
OMDU1	99.596
OMDU2	98.773
SHAG1	99.520
SHAG3	98.162

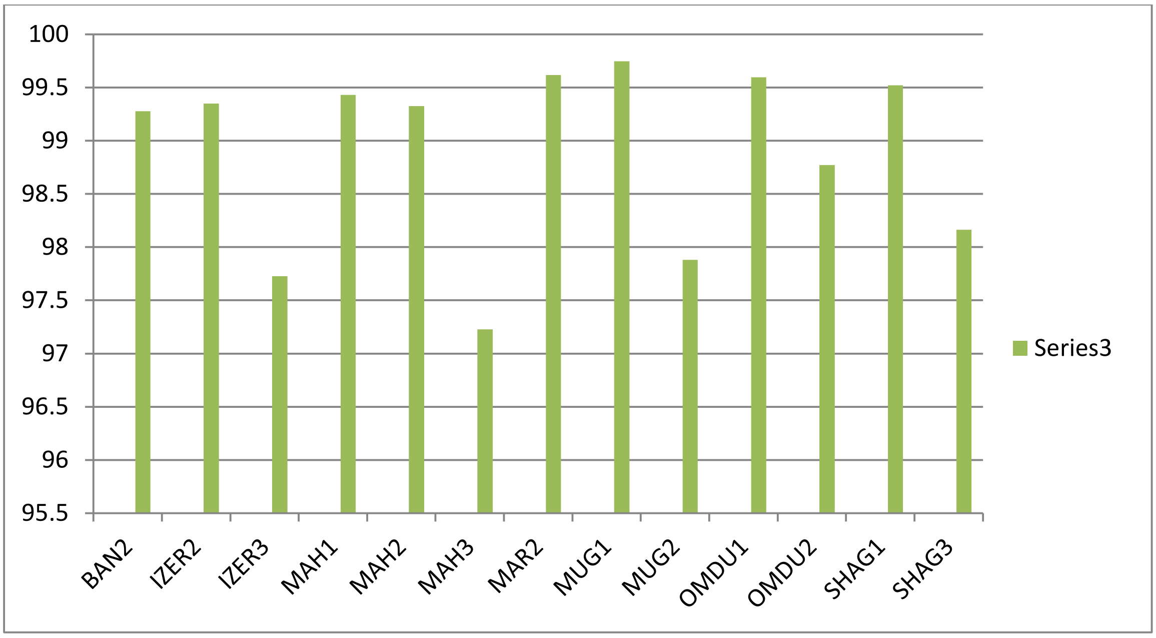

Figure 4.2: voltage profile of system at normal operation.

4.3.2 Case two 30% overload:

The loads of all sub-station were increased by 30%, load flow analysis has been done, and the voltage magnitude of all buses recorded in table 4.2, the weakest bus is MAH3 (95.778%).

The SVC was connected to MAH3 and load flow analysis was carried out, the voltage profile improved in all the buses and MAH3 improved from 95.778% to 96.44%.

Table 4.2: Load flow result at case two

Bus name	Voltage magnitude (%) without **SVC**	Voltage magnitude (%) with **SVC**
BAN1	98.999	99.114
BAN2	97.993	98.107
IZER2	98.514	98.629
IZER3	96.184	96.304
MAH1	98.911	98.971
MAH2	98.485	98.620
MAH3	95.778	96.446
MAR2	99.248	99.299
MUG1	98.717	98.828
MUG2	96.430	96.539
OMDU1	98.607	98.729
OMDU2	97.474	97.595
SHAG1	98.465	98.567
SHAG3	96.715	96.815

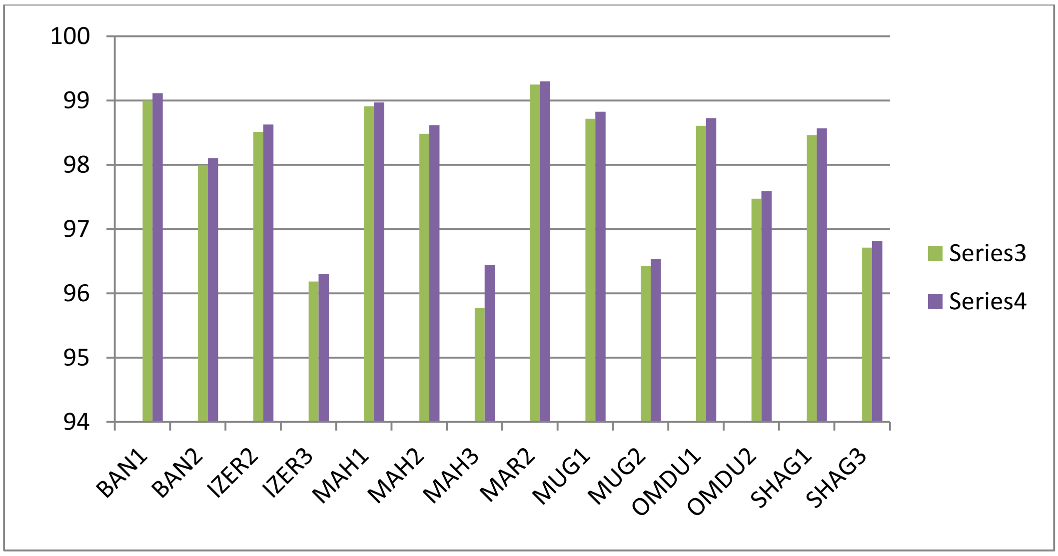

Figure 4.3: The system at overload operation with and without **SVC**

4.3.3 Case three: Loss of generation in Banat Substation:

The generator was connected in Banat substation was out of service, table 4.3 shows the bus voltages at all buses with and without SVC, and figure 4.4 shows the comparison of voltage profiles before and after adding the SVC.

Table 4.3: Load flow result at case three

Bus name	Voltage magnitude (%) without **SVC**	Voltage magnitude (%) with **SVC**
BAN1	94.409	94.598
BAN2	93.726	93.913
IZER2	96.174	96.357
IZER3	94.457	94.646
MAH1	97.505	97.600
MAH2	95.615	95.829
MAH3	93.595	94.624
MAR2	98.093	98.174
MUG1	94.326	94.509
MUG2	92.563	92.742
OMDU1	94.738	94.936
OMDU2	93.955	94.152
SHAG1	94.568	94.735
SHAG3	93.277	93.442

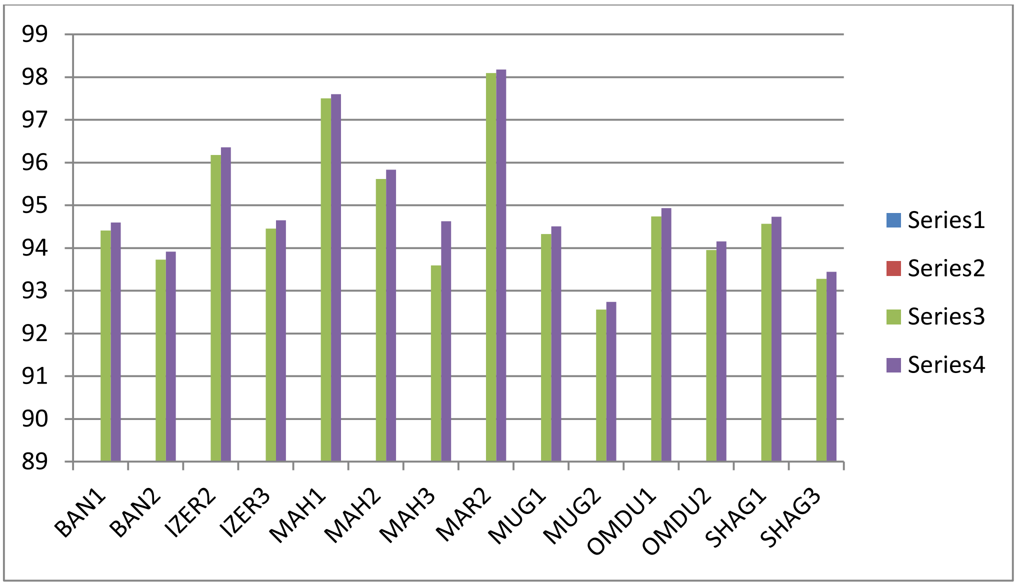

Figure 4.4: the system at case three with and without SVC

CHAPTER FIVE
CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion:

Static VAR compensator (SVC) are easier to insert in the network sine they are connected to the grid through a power transformer.

According to the results obtained from the simulation when using ETAP software, the Static VAR compensator has proved it ability to improve the voltage profile. In the case of 30% increase in load, the voltage increased after installing SVC in all buses (in the weakest bus MAH3 from 95.778% to 96.44%). In case of loss of generation also the results showed improvement in voltage profile.

5.2 Recommendations:

- To study the optimum location for SVC which has been selected without optimization.
- Investigate the SVC effect in case of transient stability.
- To study the effect of SVC on transmission losses and power transfer capability.
- Use another types of FACTs.

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APPENDIX A

SYSTEM DATA

Three winding transformer data:

Transformer Name	MVA rating			Rated voltage (kV)		
	Primary	Secondary	tertiary	Primary	Secondary	tertiary
T1	300	300	75	500	220	33
T2	300	300	75	500	220	33
T3	300	300	75	500	220	33
T4	150	150	50	220	110	33
T5	150	150	50	220	110	33
T6	100	100	40	110	33	11
T7	100	100	40	110	33	11
T8	150	150	50	220	110	33
T9	150	150	50	220	110	33
T10	150	150	50	220	110	33
T11	70	50	20	110	33	11
T12	70	50	20	110	33	11
T13	200	200	60	110	33	11
T14	200	200	60	110	33	11
T15	200	200	60	110	33	11
T16	200	200	40	110	33	11
T17	100	100	30	110	33	11
T18	100	100	30	110	33	11

T19	70	50	20	110	33	11
T20	70	50	20	110	33	11
T21	70	50	20	110	33	11
T22	70	50	20	110	33	11
T23	70	50	20	220	110	33
T24	70	50	20	220	110	33

Generation date:

Gen No	**Gen name**	**Voltage magnitude (KV)**	**limits**	
			MW	**MVAR**
1	MAR1	500	400	1000
2	IZER1	220	200	123.949
3	BAN1	110	200	140
4	SHG1	220	100	100

Line data:

From	To	Length (Km)	R Ohm/Km	X Ohm/Km	B Ohm/Km
MAR2	**MAH1**	21	0.067	0.269	4.11
IZER3	**MAH2**	8	0.067	0.269	4.11
MAH2	**OMDU1**	9.3	0.067	0.269	4.11
OMDU1	**BAN1**	5.9	0.067	0.269	4.11
BAN1	**MUG1**	3.8	0.067	0.269	4.11
MUG1	**SHAG1**	11	0.067	0.269	4.11

Load data:

Bus name	Load	
	MW	MVAR
MAR1	67.8	27.7
IZER3	86	44
MAH3	56.4	33
MAH1 N1	29.6	9.4
MAH1 N2	29.6	9.4
MAH1 N3	30.2	18.715
OMDU2	106.5	46.5
BAN1	100	41.9
MUG2	128.5	48.7
SHAG3	78.5	42.4

APPENDIX B

The system figure