1.1 Background

In recent years, several blackouts related to voltage stability problems have occurred in many countries. In particular, 2003 was an intense year regarding blackouts with a total of 6 major ones affecting the United State of America (US), the United Kingdom (UK), Denmark, Sweden and Italy. The U.S-Canadian blackout of August 14th, 2003 affected approximately 50 million people in eight U.S. states and two Canadian provinces. In the same year, on September 23rd 2003, the Swedish/Danish system went down affecting 2.4 million customers and five days later, September 28th, another major blackout occurred in continental Europe which resulted in a complete loss of power throughout Italy [1]. In 2009 the famous blackout in national electricity of Sudan, that was result in complete loss of electricity service in Sudan.

The objective in power systems operation is to serve energy with acceptable voltage and frequency to consumers at minimum cost. Reliability and security are also important parameters for power system and should be satisfied, by reliability it’s meant that the system has adequate reserves in the face of changing energy demand and by security it’s meant that upon occurrence of contingency, the system could recover to its original state and supply the same quality service as before. All these objectives can be achieved by proper planning, operating and control of generation and transmission system. But one of the major problems in power system that can contribute to prevent achievement these objective is voltage instability [1].

A voltage instability phenomenon deals with voltage collapse characterized by a progressive and uncontrollable drop of the load voltage.
The voltage collapse may occur not only in response to a system contingency but also due to inadequate reactive power supports usually observed in a heavily loaded system[2].

Voltage stability refers to the ability of a power system to maintain steady voltages at all the buses in the system after being subjected to a disturbance from a given initial operating condition [1]. The term voltage collapse, often used to describe the voltage instability phenomenon, is the process by which the sequence of events accompanying voltage instability leads to a blackout or abnormally low voltages in a significant part of the power system[3]. The main symptoms of voltage collapse are – low voltage profiles, heavy reactive power flows, inadequate reactive power support, and heavily loaded systems. Voltage Instability and the problem of voltage collapse can cause the major blackout in the power system [4].

The only 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 [5]. There are many conventional controllers such as transformer tap changers, phase shifters which are used for improving Voltage Stability. But, these controllers are not fast in response and have so many Limitations. To avoid these drawbacks, FACTS devices are proposed, to get fast response and also used to study the Voltage Stability in the power system [4], its provide technical solutions to voltage stability problems. Especially due to the increasing need for fast response for power quality and voltage stability, the shunt dynamic Var compensators such as Static Var Compensators (SVC) and Static Synchronous Compensators (STATCOM) have become feasible alternatives to a fixed reactive source, and therefore have received intensive interests. Usually placing adequate shunt FACTS devices at the weakest bus enhances static voltage stability margins. The weakest bus is defined as the bus, which is nearest to experiencing a voltage collapse [6]. However, FACTS
controllers should be located and sized carefully to obtain the desired reactive power support optimally [7].

1.2 Problem Statement

The increase in power demand has forced the power system to operate closer to its stability limit. Voltage instability and line overloading have become challenging problems due to the strengthening of power system by various means. The nature of voltage stability can be analysed by the production, transmission and consumption of reactive power. One of the major causes of voltage instability is the reactive power unbalancing which occurs in stressed condition of power system [8].

As investment cost of FACTS controllers is very high, these devices must be placed optimally in a power system.

1.3 Objectives

The objectives of this thesis are:
Enhancement static voltage stability and reduce the flows in heavily loaded lines, resulting in a low system loss and improved stability of network by using of Flexible Alternating Current Transmission Systems (FACTS) With the insertion of SVC, and how these devices are placed in the power system, namely on their optimal location and size.

1.4 Methodology

The optimal location for reactive power compensation for the improvement of static voltage stability margin is considering identified by the "weakest bus" of the system. The weakest bus of the system can be identified using the L-indices for a given load condition, and is computed for all load buses, this index required determining load flow analysis in steady state. The bus with the highest L-index value will be the most vulnerable bus in the system and hence this method helps in identifying the weak areas in the system which critical reactive power needs support.
In order to get a rough estimate of reactive power support needed from SVC, at the weakest bus and the corresponding load margin for a given load and generation direction, a synchronous compensator with no limit on reactive power was used at the weakest bus by PSAT Simulink. The amount of reactive power generated at the maximum loading point from the synchronous compensator was used as optimal size of SVC.

SVC implemented on standard IEEE-14 system and the simulation is carried out using NEPLAN software.

1.5 Thesis Layout
This thesis is consisting from six chapter and details as follows:
Chapter one : introduction and it’s involve Background, problem statement, objective and methodology.
Chapter Two: provides Introduction to reactive power fundamental and FACTS devices and their application in power system
Chapter Three: describes the operation and Advantages of the Static Var Compensator (SVC). V-I Characteristic and Control of SVC also discussed in this chapter.
Chapter Four: provides an explanation of voltage stability concept, Classification and Methods of Improving voltage stability analysis.
Chapter Five: shows the simulation results of the optimal allocation and sizing of the SVC device, to improve the static voltage stability. Finally discussion result of applying SVC device to IEEE 14-bus benchmark.
Chapter Six :Conclusion and Recommendations
CHAPTER TWO

REACTIVE POWER FUNDAMENTAL AND FACTS

2.1 Introduction

VAR compensation is defined as the management of reactive power to improve the performance of ac power systems. The concept of VAR compensation embraces a wide and diverse field of both system and customer problems, especially related with power quality issues, since most of power quality problems can be attenuated or solved with an adequate control of reactive power. In general, the problem of reactive power compensation is viewed from two aspects: load compensation and voltage support. In load compensation the objectives are to increase the value of the system power factor, to balance the real power drawn from the ac supply, compensate voltage regulation and to eliminate current harmonic components produced by large and fluctuating nonlinear industrial loads [10], [11]. Voltage support is generally required to reduce voltage fluctuation at a given terminal of a transmission line. Reactive power compensation in transmission systems also improves the stability of the ac system by increasing the maximum active power that can be transmitted. It also helps to maintain a substantially flat voltage profile at all levels of power transmission, it improves HVDC (High Voltage Direct Current) conversion terminal performance, increases transmission efficiency, controls steady-state and temporary over-voltages [12], and can avoid disastrous blackouts [13].

Series and shunt VAR compensation are used to modify the natural electrical characteristics of ac power systems. Series compensation modifies the transmission or distribution system parameters, while shunt compensation changes the equivalent impedance of the load. In both cases, the reactive
power that flows through the system can be effectively controlled improving the performance of the overall ac power system. Traditionally, rotating synchronous condensers and fixed or mechanically switched capacitors or inductors have been used for reactive power compensation. However, in recent years, static VAR compensators employing thyristor switched capacitors and thyristor controlled reactors to provide or absorb the required reactive power have been developed [14]. Flexible AC Transmission Systems, also known as FACTS, have been developed and represent a new concept for the operation of power transmission systems. In these systems, the use of static VAR compensators with fast response times play an important role, allowing to increase the amount of apparent power transfer through an existing line, close to its thermal capacity, without compromising its stability limits. These opportunities arise through the ability of special static VAR compensators to adjust the interrelated parameters that govern the operation of transmission systems, including shunt impedance, current, voltage, phase angle and the damping of oscillations [12].

2.2 Relationship Between Reactive Powers and Voltage

The simple system which consists of one load fed by an infinite bus through a transmission line is shown on Figure (2.1). By definition, the voltage magnitude and frequency are constant at the infinite bus [15].

![Figure 2.1: Circuit representation of simple system](image-url)
Now Figure (2.1) will be considered, the transmission resistance is neglected. The load voltage magnitude and phase angle are $V$ and $\theta$ respectively.

![Phasor diagram of simple system](image)

**Figure 2.2: Phasor diagram of simple system**

From figure (2.2) easily to compute that:

$$|BC| = X|I|\cos \varphi = E|\sin \theta| \Rightarrow I|\cos \varphi = \frac{E}{X} \sin \theta$$  \hspace{1cm} (2.1)

$$|AC| = X|I|\sin \varphi = E|\cos \theta| - V \Rightarrow I|\sin \varphi = \frac{E}{X} \cos \theta - \frac{V}{X}$$  \hspace{1cm} (2.2)

The active power is given by $P = |V|I|\cos \varphi$. So it can be easily computed that:

$$P = \frac{EV}{X} \sin (\theta)$$  \hspace{1cm} (2.3)

This equation is first load-flow equation.

The reactive power is given by $Q = |V|I|\sin \varphi$, thus the second load flow equation:

$$Q = \frac{EV}{X} \cos (\theta) - \frac{V^2}{X}$$  \hspace{1cm} (2.4)

From equations (2.3),(2.4) observed $P$ effected by $\theta$ and $Q$ effected by $V$

### 2.3 Limits to Power Flow in a Transmission System

It is desired to utilize the transmission capacity to its best use taking into account loading capability and contingency conditions, but there is a limit to the loading capability of transmission lines [16]. The limits to power flow over transmission lines are classified as:

- Thermal
- Voltage drop Limits
• Stability
• Loop Flow

2.3.1 Thermal Limits
Thermal limit of a transmission line is a function of the temperature, environmental conditions, physical structure of the conductor, and ground clearance. Line losses convert electrical energy to heat and heat weakens the power lines conductor. This “lost” electrical power heats the power lines and causes the conductor to expand and the line to sag. At some temperature the conductor becomes soft enough to be permanently damaged by the line’s weight. At a higher temperature the conductor will melt and break. Hence thermal limit imposes a limit on the power flow through the transmission line [16].

2.3.2 Voltage drop limits
As load increases, voltage at receiving substation decreases. For the equipments to operate properly, the voltage should not be allowed to fall below a specified value. This limits the power transfer [16].

2.3.3 Stability Limits
These are a number of stability concerns that limit the transmission capability. These include[16]:
  i. Transient Stability
  ii. Steady State stability
  iii. Voltage collapse
  iv. Loop Flow

i. Transient Stability
During fault on a transmission line, at a generator station, or at a substation there is a possibility of rotor angle increasing very rapidly. This leads to reduction in transfer of power from generating end to the sending end. However, mechanical power produced by the turbine remains constant during the fault, and there is consequently an imbalance between mechanical power
input to the generator and electrical power output, with mechanical power being in excess. This excess mechanical power is converted to accelerating power and the generator increases its rotational velocity. This may cause the generator to lose synchronism if the fault is not cleared quickly. The resulting system response involves large excursions of generator angles and is influenced by the nonlinear power-angle relationship. The transient stability of generator depends upon the generator loading, fault clearing time and generator reactance etc. [16].

**ii. Steady State Stability**

It is defined as the ability of the power system to maintain synchronism under small disturbances. Such disturbances occur continually on the system because of small variations in loads and generation. The disturbances are considered sufficiently small for linearization of system equations to be permissible for purpose of analysis [16].

**iii. Voltage Collapse**

A system enters a state of voltage instability when a disturbance, increase in load demand, or change in system condition causes a progressive and uncontrollable drop in voltage. Voltage collapse is the process by which the sequence of events accompanying voltage instability leads to low unacceptable voltage profile in a significant part of the power system [16].

**iv. Loop Flow**

In an interconnected power system, power flowing between a generator and a customer moves through all lines connecting the two points. Power follows the path of the least resistance according to the laws of physics. Power flow is inversely proportional to transmission line impedance rather than current capacity of transmission lines. Neighboring transmission systems are usually connected together in a large network. This results in an exchange of power between different areas, and is termed as loop power flow. Loop flows are difficult to control and can damage the transmission equipments [16].
2.4 Reactive Power Compensation Principles

In a linear circuit, the reactive power is defined as the ac component of the instantaneous power, with a frequency equal to 100 / 120 Hz in a 50 or 60 Hz system. The reactive power generated by the ac power source is stored in a capacitor or a reactor during a quarter of a cycle, and in the next quarter cycle is sent back to the power source. In other words, the reactive power oscillates between the ac source and the capacitor or reactor, and also between them, at a frequency equals to two times the rated value (50 or 60 Hz). For this reason it can be compensated using VAR generators, avoiding its circulation between the load (inductive or capacitive) and the source, and therefore improving voltage stability of the power system. Reactive power compensation can be implemented with VAR generators connected in parallel or in series. The principles of both, shunt and series reactive power compensation alternatives, are described below[12].

2.4.1 Shunt Compensation

Figure (2.3) and Figure (2.4) shows the principles and theoretical effects of shunt reactive power compensation in a basic ac system, which comprises a source V1, a power line and a typical inductive load. Figure (2.3) shows the system without compensation, and its associated phasor diagram. In the phasor diagram, the phase angle of the current has been related to the load side, which means that the active current IP is in phase with the load voltage V2. Since the load is assumed inductive, it requires reactive power for proper operation and hence, the source must supply it, increasing the current from the generator and through power lines. If reactive power is supplied near the load, the line current can be reduced or minimized, reducing power losses and improving voltage regulation at the load terminals. This can be done in three ways: a) with a capacitor, b) with a voltage source, or c) with a current source. In Figure (2.4), a current source device is being used to compensate the reactive component of the load current (I_Q). As a result, the system voltage
regulation is improved and the reactive current component from the source is reduced or almost eliminated [12].

If the load needs leading compensation, then an inductor would be required. Also a current source or a voltage source can be used for inductive shunt compensation. The main advantages of using voltage or current source VAR generators (instead of inductors or capacitors) is that the reactive power generated is independent of the voltage at the point of connection [12].

![Diagram of shunt compensation without reactive compensation](image1)

**Figure (2.3):** Principles of shunt compensation in a radial ac system Without reactive compensation.

![Diagram of shunt compensation with a current source](image2)

**Figure (2.4):** Principles of shunt compensation in a radial ac system Shunt compensation with a current source.

### 2.4.2 Series Compensation

VAR compensation can also be of the series type. Typical series compensation systems use capacitors to decrease the equivalent reactance of a power line at rated frequency. The connection of a series capacitor generates reactive power that, in a self-regulated manner, balances a fraction of the
line's transfer reactance. The result is improved functionality of the power transmission system through:

i) increased angular stability of the power corridor,
ii) improved voltage stability of the corridor,
iii) optimized power sharing between parallel circuits.

Like shunt compensation, series compensation may also be implemented with current or voltage source devices, as shown in Figure(2.5) and Figure(2.6). Figure(2.5) shows the same power system of Figure(2.3) also with the reference angle in \( V_2 \), and Figure(2.6) the results obtained with the series compensation through a voltage source, which has been adjusted again to have unity power factor operation at \( V_2 \). However, the compensation strategy is different when compared with shunt compensation. In this case, voltage \( V_{COMP} \) has been added between the line and the load to change the angle of \( V_2 \), which is now the voltage at the load side. With the appropriate magnitude adjustment of \( V_{COMP} \), unity power factor can again be reached at \( V_2 \). As can be seen from the phasor diagram of Figure(2.6), \( V_{COMP} \) generates a voltage with opposite direction to the voltage drop in the line inductance because it lags the current \( I_p \).[12]

![Figure 2.5: Principles of series compensation without compensation.](image-url)
2.5 Traditional Var Generators

In general, VAR generators are classified depending on the technology used in their implementation and the way they are connected to the power system (shunt or series). Rotating and static generators were commonly used to compensate reactive power.

3.1.- Fixed or mechanically switched capacitors [17][18].
3.2.- Synchronous Condensers [9].
3.3.- Thyristorized VAR Compensators [19].

2.6 FACTS Devices Compensation

FACTS devices, which are power electronic based devices can change parameters like impedance, voltage and phase angle. They also helps to reduce flows in heavily loaded lines, resulting in an increased load ability, low system loss, improved stability of the network, reduced cost of production and fulfilled contractual requirement by controlling the power flows in the network. They provide control facilities, both in steady state power flow control and dynamic stability control. The possibility of controlling Power flow in an electrical power system without generation rescheduling or topological changes can improve the performance considerably [8].

Figure (2.6): Principles of series compensation with compensation.
2.7 FACTS Applications

The various applications of FACTS controllers/devices in restructured multi-machine power systems to enhance power system performance. One of the greatest advantages of utilizing FACTS controllers in power system is that, FACTS controller can be used in three states of the power system [20].

- Steady state,
- Post transient steady state.
- Transient and

However, the conventional devices find little application during system transient or contingency condition.

A) Steady State Application

Various steady state applications of FACTS controllers includes control of voltage (low and high), increase of thermal loading limit, post-contingency voltage control, loop flows control, reduction in short circuit level and power flow control [20].

- Power Flow Balancing and Control
- Available Transfer Capability (ATC) Improvement
- Loading Margin Improvement
- Congestion Management
- Reactive Power and Voltage Control

B) Dynamic Application

Various Dynamic applications of FACTS controllers include oscillation damping (dynamic stability), transient stability improvement and voltage stability enhancement. One of the most important capabilities expected of FACTS applications is to reduce the impact of the primary disturbance [20].

- Dynamic Voltage Control
- Oscillation Damping
- Transient Stability Enhancement
- Subsynchronous Resonance (SSR) Elimination
- Power Systems Interconnection
2.8 Classification of FACTS Controllers Based on Power Electronic Devices

In Figure (2.7), left hand side column of FACTS-devices employs the use of thyristor valves or Converters, They have low switching frequency and low losses. The devices of the right hand side column of the Figure (2.7) has more advanced technology of voltage source converters Pulse width modulation technique is used to control the magnitude and phase of the voltage. They have high modulation frequency [21].

![FACTS Diagram](image)

Figure 2.7: Overview Of major FACTS devices in terms of on power electronic devices

2.8.1 Thyristor Based FACTS Devices

Thyristor based FACTS devices have low switching frequency and low losses.

i. **Static Var Compensator (SVC)**

Static VAr Compensator (SVC): A shunt-connected static VAr generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of the electrical power system (typically bus voltage) [22].
SVC uses conventional thyristors to achieve fast control of shunt-connected capacitors and reactors. The configuration of the SVC is shown in Figure(2.8). A shunt connected static var generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control bus voltage of the electrical power system. Variable shunt susceptance model of SVC is shown in Figure(2.8) [22].

As far as steady state analysis is concerned, both configurations can modelled along similar lines. The SVC structure shown in Figure (2.8) is used to derive a SVC model that considers the Thyristor Controlled Reactor (TCR) firing angle as state variable. This is a new and more advanced SVC representation than those currently available. The SVC is treated as a generator behind an inductive reactance when the SVC is operating within the limits. The reactance represents the SVC voltage regulation characteristic. The reason for including the SVC voltage current slope in power flow studies is compelling. The slope can be represented by connecting the SVC models to an auxiliary bus coupled to the high voltage bus by an inductive reactance consisting of the transformer reactance and the SVC slope, in per unit (p.u) on the SVC base. A simpler representation assumes that the SVC slope, accounting for voltage regulation is zero. This assumption may be acceptable as long as the SVC is operating within the limits, but may lead to gross errors if the SVC is operating close to its reactive limits [22].
The current drawn by the SVC is,

\[ I_{SVC} = jB_{SVC} V_K \quad (2.5) \]

The reactive power drawn by SVC, which is also the reactive power injected at bus k is,

\[ Q_{SVC} = Q_K = -V_K^2 B_{SVC} \quad (2.6) \]

Where, \( V_K \) = voltage at bus k
\( B_{SVC} \) = Susceptance
\( Q_{SVC} \) = reactive power drawn by SVC.

**ii. Thyristor Controlled Series Compensator (TCSC)**

It is designed based on the thyristor based FACTS technology that has the ability to control the line impedance with a thyristor-controlled capacitor placed in series with the transmission line. It is used to increase the transmission line capability by installing a series capacitor that reduces the net series impedance thus allowing additional power to be transferred. TCSC device consists of three main components: Capacitor bank, bypass inductor and two bidirectional thyristors [21].

**2.8.2 Voltage Source Converter Based FACTS Devices**

Voltage source converters based mainly on Insulated Gate Bipolar Transistors (IGBT) or Insulated Gate Commutated Thyristors (IGCT). Pulse width modulation technique is used to control the magnitude and phase of the voltage. They have high modulation frequency.

**i. Static Synchronous Series Compensator (SSSC)**

Static Synchronous Series Compensator is based on solid-state voltage source converter designed to generate the desired voltage magnitude independent of line current. SSSC consists of a converter, DC bus (storage unit) and coupling transformer. The dc bus uses the inverter to synthesize an ac voltage waveform that is inserted in series with transmission line through the transformer with an appropriate phase angle and line current. If the injected voltage is in phase with the line current it exchanges a real power and if the
injected voltage is in quadrature with line current it exchanges a reactive power. Therefore, it has the ability to exchange both the real and reactive power in a transmission line [21].

ii. Static Synchronous Compensator (STATCOM)
It is designed based on Voltage source converter (VSC) electronic device with Gate turn off thyristor and dc capacitor coupled with a step down transformer tied to a transmission line. It converts the dc input voltage into ac output voltages to compensate the active and reactive power of the system. The STATCOM has better characteristics than SVC and it is used for voltage control and reactive power compensation. STATCOM placed on a transmission network improve the voltage stability of a power system by controlling the voltage in transmission and distribution systems, improves the damping power oscillation in transmission system, and provides the desired reactive power compensation of a power system [21].

iii. Unified Power Flow Controller (UPFC)
It is designed by combining the series compensator (SSSC) and shunt compensator (STATCOM) coupled with a common DC capacitor. It provides the ability to simultaneously control all the transmission parameters of power systems, i.e. voltage, impedance and phase angle. It consists of two converters – one connected in series with the transmission line through a series inserted transformer and the other one connected in shunt with the transmission line through a shunt transformer. The DC terminal of the two converters is connected together with a DC capacitor. The series converter control to inject voltage magnitude and phase angle in series with the line to control the active and reactive power flows on the transmission line. Hence the series converter will exchange active and reactive power with the line [21].
2.9 Classification of Facts Devices in Terms of Connection

FACTS controllers can be divided into four categories based on their connection in the network:

2.9.1 Series Compensators

It controls the effective line parameters by connecting a variable reactance in series with the transmission line. This increases the transmission line capability which in turn reduces transmission line net impedances[23]. In principle, all series controllers inject voltage in series with the line. Even variable impedance, provided by some of the FACTS controllers, multiplied by the current flow through it represents an injected series voltage in the line[24]. Examples of series compensators are Static Synchronous Series Compensators (SSSC) and Thyristor Controlled Series Compensators (TCSC). SSSC injects voltage in series with the transmission line where it is connected while TCSC performs the function of a variable reactance compensator, either in the capacitive or inductive mode. Series compensators operating in the inductive region will increase the electric length of the line there by reducing the lines ability to transfer power. In the capacitive mode will shorten the electrical length of the line, thus increasing power transfer margins Adjusting the phase angle difference across a series connected impedance can also control the active power flow [23]. A typical connection in a line, having series impedance \( z_{ij} = r_{ij} + jx_{ij} \) is shown in Figure (2.9).

![Series FACTS controller](image)

Figure 2.9: Series FACTS controller

2.9.2 Shunt Compensators

The operational pattern is same with an ideal synchronous machine that generates balanced three phase voltages with controllable amplitude and phase angle[23]. In principle, all shunt controllers inject current into the
system at the point of connection. SVC and STATCOM are the two most widely used shunt controllers. Even variable shunt impedance provided by shunt controller, such as SVC, cause a variable current injection into the bus/line. As long as the injected current is in phase quadrature with the bus voltage, the shunt controller only supplies or consumes variable reactive power. Any other phase relationship will involve handling of real power as well [24].

**Figure 2.10: Shunt FACTS controller**

### 2.9.3 Series-Series Compensator

It is the combination of two or more static synchronous compensators coupled through a common dc link to enhance bi-directional flow of real power between the ac terminals of SSSC and are controlled to provide independent reactance compensation for the adjustment of real power flow in each line and maintain the desired distance of reactive power flow among the power lines. Example of series – series compensator is Interline Power Flow Controller (IPFC) [23].

**Figure 2.11: Combined series-series FACTS controller**
2.9.4 Series-Shunt Compensator

It allows the simultaneous control of active power flow, reactive power flow and voltage magnitude at the series shunt compensator terminals. The active power control takes place between the series converter and the AC system, while the shunt converter generates or absorbs reactive power so as to provide voltage magnitude at the point of connection of the device and the AC system. Example of the series-shunt compensator is the unified power flow controller (UPFC) and thyristor controlled phase shifter [23].

![Series FACTS controller](image)

Figure 2.12: Combined series-shunt FACTS controller

2.10 Optimal Allocation and Sizing of FACTS Devices

Having made the decision to install a FACTS device in the system, there are main issues that must be addressed: what type of device should be used, how much capacity should it have, and where in the system should it be placed. Assuming that the cost of a particular device is a function of its capacity, it would not be desirable to install a device that is overall larger for its intended purpose. For example, if the capacity of a series connected FACTS device is larger than the rating of the transmission line in which it will be installed would not be economic since the line limit would prohibit the device from being used to its full potential. Likewise, if the device is too small and it can not handle as much power flow as the transmission line, the utility has effectively reduced the rating of the associated transmission line, keeping in mind the potential for later line upgrade [25].

Like the discussion of where to place the FACTS device, the choice of which type of devices will have the highest impact in the desired effect. For
instance, a Shunt type devices should be considered when reactive power control or voltage support is necessary. Series compensation type devices may not perform well in lines with high reactive power flow. Also, the relative cost of the devices will have a considerable effect on which device is chosen. It is likely that the cost of a device is inversely proportional to the maturity of the technology. This would indicate that the SVC, a Shunt type devices, is among the cheapest and the UPFC, Series-Shunt Compensator devices, would be one of the more expensive [25].

Table (2.1): Cost comparison of various controllers

<table>
<thead>
<tr>
<th>Capacitor and FACTS</th>
<th>Cost(US$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shunt capacitor</td>
<td>8/kvar</td>
</tr>
<tr>
<td>Series capacitor</td>
<td>20/kvar</td>
</tr>
<tr>
<td>SVC</td>
<td>40/kvar Controlled portions</td>
</tr>
<tr>
<td>TCSC</td>
<td>40/kvar Controlled portions</td>
</tr>
<tr>
<td>STATCOM</td>
<td>50/kvar</td>
</tr>
<tr>
<td>UPFC series portions</td>
<td>50/kvar Through power</td>
</tr>
<tr>
<td>UPFC shunt portions</td>
<td>50/kvar Controlled portions</td>
</tr>
</tbody>
</table>

The decision of where to place a FACTS device is largely dependant on the desired effect and characteristics of the specific system. One possible method for determining the optimal location of the device is to simulate the operation of the device in all the possible locations of installation. However, this could be very time consuming specially for large systems [25].

2.11 FACTS Controllers Intended For Steady-State Operation [7, 8]

- 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 the tap changes are controlled by thyristor switches.
• Thyristor-controlled reactor (TCR): this is a shunt-connected, thyristor-controlled reactor, the effective reactance of which is varied in a continuous manner by partial conduction control of the thyristor valve.

• Thyristor-controlled series capacitor (TCSC): this controller consists of a series 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 branches, one inductive and one capacitive, subjected to separate phase-shifted voltage magnitudes. Active power control is set by independent or coordinated adjustment of the two phase-shifting sources and the two variable reactances. Reactive power control is independent of active power.

• Static compensator (STATCOM): this is a solid-state synchronous condenser 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 terminals 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 unconstrained, series voltage injection, is able to control, concurrently or selectively, 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.
Power electronic and control technology have been applied to electric power systems for several decades. HVDC links and static VAR compensators are mature pieces of technology:

- **Static VAR compensator (SVC):** this is a shunt-connected static source or sink of reactive power.
- **High-voltage direct-current (HVDC) link:** this is a controller comprising a rectifier station and an inverter station, joined either back-to-back or through a DC cable. The converters can use either conventional thyristors or the new generation of semiconductor devices such as gate turn-off thyristors (GTOs) or insulated gate bipolar transistors (IGBTs).

The FACT devices used intensively in power system to solve many operational problems. Table (2.2) summarized some of the common uses of FACTS devices in power system network.
Table (2.2): The role of FACTS controllers in power system operation

<table>
<thead>
<tr>
<th>Operating problem</th>
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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) [27].

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 [27].

3.2 Advantages of SVC

Advantages of SVC The main advantage of SVCs over simple mechanically switched compensation schemes is 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 [28]:

1. Improved system steady-state stability.
2. Improved system transient stability.
4. Reduced voltage drops in load areas during severe disturbances.
5. Reduced transmission losses.
3.3 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 [27].

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

![Diagram of SVC components](image)

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

3.3.1 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 [27].

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

\[ v(t) = V \sin(\omega_0 t) \]  

(3.1)

where \( \omega_0 \) is the nominal angular frequency of the system, i.e. \( \omega_0 = 2\pi f_0 = 2\pi 50 \) rad/s in a 50 Hz system.
The current through the TSC branch at any given time is determined by [27]:

\[ i(t) = I \cos(\omega_o t + \alpha) - I \cos(\alpha) \cos(\omega_r t) + nB_c \left( V_{co} - \frac{n^2}{n^2 - 1} V \sin(\alpha) \right) \sin(\omega_r t) \]  

(3.2)

where \( \alpha \) is the thyristor firing angle, \( \omega_r \) is the TSC resonant frequency, \( V_{co} \) is the voltage across the capacitor at \( t = 0 \). The current amplitude \( I \) is determined by:

\[ I = V \frac{B_c B_L}{B_c + B_L} \]  

(3.3)

where \( B_c \) is the capacitor susceptance and \( B_L \) is the reactor susceptance and \( n \) is given by:

\[ n = \frac{1}{\sqrt{\omega_o^2 L C}} = \frac{X_C}{\sqrt{X_L}} \]  

(3.4)

\( X_C \) and \( X_L \) above are the reactances of the capacitor and reactor. The TSC resonant frequency, \( \omega_r \), is defined by:

\[ \omega_r = n \omega_o = \frac{1}{\sqrt{L C}} \]  

(3.5)

The alternatively express the magnitude of the TSC current (3.3):

\[ I = V \frac{B_c B_L}{B_c + B_L} = VB_c \frac{n^2}{n^2 - 1} \]  

(3.6)

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

\[ I = VB_c \]  

(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 \( L \) \( C \) 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 [27].
3.3.2 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 [36]. 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.
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 [27].

3.3.3 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 [27].
This is achieved by controlling the firing angle $\alpha$ 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 [27].
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° ≤ α < 90°, introduces a DC offset to the reactor current which disturbs the thyristor valve [36]. Thus, this interval should be avoided.

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

\[ v(t) = V \sin(\omega_o t) \]  

(3.7)

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

\[ v(t) = L \frac{di}{dt} \]  

(3.8)

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

\[ i(t) = \frac{1}{L} \int_{\alpha}^{\omega_o t} v(t) dt = \frac{1}{L} \int_{\alpha}^{\omega_o t} V \sin(\omega_o t) dt = -\frac{V}{\omega_o L} \cos(\omega_o t) + D \]  

(3.9)

where D is a constant of integration.

The two intervals of conduction for the thyristor valve are

\[ \alpha < \omega_o t < 2\pi - \alpha \]  

(3.10a)

\[ \pi + \alpha < \omega_o t < 3\pi - \alpha \]  

(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:

\[ i(t) = \frac{V}{\omega_o L} (\cos(\alpha) - \cos(\omega_o t)) \]  

(3.11a)

\[ i(t) = -\frac{V}{\omega_o L} (\cos(\alpha) + \cos(\omega_o t)) \]  

(3.11b)

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

![Figure 3.2: Current through the TCR for different firing angles $\alpha$, with the applied voltage shown as the blue, dashed line.](image)

### 3.4 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 [27].

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 [27].

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 a simpler control equipment [27].

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 [27].

To summarize, the most common topologies when designing SVC systems are [27]:

- fixed capacitors & thyristor controlled reactor (FC-TCR)
- thyristor switched capacitors & thyristor controlled reactor (TSC-TCR)

### 3.5 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 \( B_{c_{\text{max}}} \) and reactor banks \( B_{l_{\text{max}}} \), the voltage is regulated at the reference voltage \( V_{\text{ref}} \). 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 Figure (3.3). The V-I characteristic is described by the following three equations[29]:

SVC is in regulation range \((-B_{c_{\text{max}}} < B < B_{l_{\text{max}}})\)

\[
V = \frac{I}{B_{c_{\text{max}}}} \tag{3.12}
\]

\[
V = V_{\text{ref}} + X_s I \tag{3.13}
\]

SVC is fully inductive \((B = B_{l_{\text{max}}})\)

\[
V = \frac{I}{B_{l_{\text{max}}}} \tag{3.14}
\]

Where,

\( V \) = Positive sequence voltage (p.u.)

\( I \) = Reactive current (p.u./\( P_{\text{base}} \)) \((I > 0 \text{ indicates an inductive current})\)
\[ X_s = \text{Slope or droop reactance (p.u./} P_{\text{base}}) \]
\[ B_{\text{Cmax}} = \text{Maximum capacitive susceptance (p.u./} P_{\text{base}}) \text{ with all TSCs in service, no TSR or TCR} \]
\[ B_{\text{Lmax}} = \text{Maximum inductive susceptance (p.u./} P_{\text{base}}) \text{ with all TSRs in service or TCRs at full conduction, no TSC} \]
\[ P_{\text{base}} = \text{Three-phase base power} \]

Figure 3.3: The V-I Characteristic Curve of SVC

### 3.6 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(3.4), 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 [30].

Figure 3.4: SVC connected to a transmission line
\[ I_{SVC} = jB_{SVC}V_m \]  
(3.15)

The reactive power injected at bus m is

\[ Q_{SVC} = Q_m = I_{SVC}V_m = -V_m^2 B_{SVC} \]  
(3.16)

Where

\[ B_{SVC} = \frac{1}{X_C X_L \pi} \left[ 2(\pi - \alpha_{svc}) + \sin \alpha_{svc} \right] \]  
(3.17)

A Jacobian matrix that accounts for the SVC is given as

\[
\begin{bmatrix}
\Delta P_m \\
\Delta P_k \\
\Delta Q_m \\
\Delta Q_k
\end{bmatrix} =
\begin{bmatrix}
\frac{\partial P_m}{\partial \delta_m} & \frac{\partial P_m}{\partial \delta_k} & 0 & V_k \frac{\partial P_m}{\partial V_k} \\
\frac{\partial P_k}{\partial \delta_m} & \frac{\partial P_k}{\partial \delta_k} & 0 & V_k \frac{\partial P_k}{\partial V_k} \\
\frac{\partial Q_m}{\partial \delta_m} & \frac{\partial Q_m}{\partial \delta_k} & 0 & V_k \frac{\partial Q_m}{\partial V_k} \\
\frac{\partial Q_k}{\partial \delta_m} & \frac{\partial Q_k}{\partial \delta_k} & 0 & V_k \frac{\partial Q_k}{\partial V_k}
\end{bmatrix}
\begin{bmatrix}
\Delta \delta_m \\
\Delta \delta_k \\
\Delta \alpha_{svc} \\
\Delta |V_k|
\end{bmatrix}
\]  
(3.18)

Where

\[
\frac{\partial Q_m}{\partial \alpha_{svc}} = \frac{2V_k^2}{\pi X_L} [\cos(2\alpha_{svc}) - 1] \]  
(3.19)

\[ \Delta \alpha_{svc} \] is found from inversion of the Jacobian matrix. The variable is then updated by

\[ \alpha_{svc}^{n+1} = \alpha_{svc}^n + \Delta \alpha_{svc}^n \]  
(3.20)

The control strategy of SVC is considered as

\[
B_{SVC} = \begin{cases} 
B_{SVC}^{MAX}, & \text{if } \omega \geq -\beta \omega_{max} : \text{during the first swing} \\
K\omega, & B_{SVC}^{Min} \leq K\omega \leq B_{SVC}^{MAX} : \text{in subsequent swing}
\end{cases}
\]

Here \( \omega_{max} \) is the maximum speed of the machine and it is usually at fault clearing and \( \beta \) is a small positive constant. \( K \) is a positive gain and its value depends on SVC rating[30].

### 3.7 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 [31].

If the high-voltage bus begins to fall below its set point range, the SVC will inject reactive power \( (Q_{\text{net}}) \) 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 (3.5), \( +Q_{\text{cap}} \) is a fixed capacitance value, therefore the magnitude of reactive power injected into the system, \( Q_{\text{net}} \), is controlled by the magnitude of \(-Q_{\text{ind}}\) reactive power absorbed by the TCR[31].

![SVC schematic diagram]

Figure 3.5: 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 (3.6) describes the relationship between the fundamental frequency TCR current and firing angle [31].

Figure 3.6: Illustration of the relationship between TCR current and firing angle.

Figure (3.7) further illustrates the thyristor valve operating characteristics of a thyristor controlled reactor. The firing pulses are on the order of 10 μs. So it is concluded that as the firing angle increases above 90 degrees, the current in the TCR is reduced. Referring back to Figure (3.5), the “Pulse Generator” block after the AVR block utilizes the concepts discussed here and illustrated in Figures (3.6) and (3.7) to determine the firing angle for the thyristor valve controlling the reactor.

Figure 3.7: Illustration of the relationship between TCR current and firing angle (or conduction angle).
4.1 Introduction

To ensure reliable operation, a power system has to be designed to withstand a large number of different disturbances. This is achieved by designing and operating the power system such that the most probable contingencies will not cause any loss of load, i.e. except at the direct connection to the equipment affected by the fault. It is especially important for the power system to be able to cope with the most severe contingencies without risking an uncontrolled spread of power interruptions (blackouts) [27].

Keeping the voltages within predefined intervals is challenging by the fact that most power systems are quite complex. Loads connected to the system will vary over time, therefore the reactive power demand of the system will also vary. This will again lead to a variation of the voltage level as reactive power and voltage are closely coupled. Faults, disconnections and other contingencies also affect the demand of reactive power and voltage level in the system. It is crucial to keep a close eye on how the voltage level is varying throughout the power system and to make sure it is kept within the required limits. The goal is to have a power system that is “voltage stable” [27].

Voltage stability is defined as the ability of a power system to maintain steady state voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition [27]. A power system would thus be characterized as unstable if a disturbance led to an uncontrollable drop in voltage. This unstable event is termed as a “voltage collapse” or “voltage instability”. The main cause of instability is the power systems lacking ability to meet the demand for reactive power.
Hence, problems with voltage instability most often occurs in heavily stressed power systems [27].

### 4.2 Classification of Power System Stability

- **Rotor angle stability** is the ability of interconnected synchronous machines of a power system to remain in synchronism. Angle stability is associated with the balance between the mechanical torque of the generating units turbine and the electromagnetic torque of its generator [32].

- **Frequency stability** refers to the ability of the power system to maintain the system frequency within acceptable limits under normal operation or following a system disturbance. The condition to be met is the maintainance of the equilibrium between the active power injected into the system on one hand, and the sum of the power absorbed by the loads and the system’s active power losses on the other hand [32].

- **Voltage stability** refers to the ability of the power system to maintain voltages within acceptable limits at all buses of the system under normal operating conditions or after being subjected to a disturbance. The robustness of a system to voltage instability derives from the capability of the system to meet the reactive power demands at all buses across the network [32].

![Figure 4.1: Classification of power system stability](image)
4.3 Voltage Stability
Voltage stability can also called “load stability”. A power system lacks the capability to transfer an infinite amount of electrical power to the loads. The main factor causing voltage instability is the inability of the power system to meet the demands for reactive power in the heavily stressed systems to keep desired voltages. Other factors contributing to voltage stability are the generator reactive power limits, the load characteristics, the characteristics of the reactive power compensation devices and the action of the voltage control devices [33].
Voltage collapse typically occurs in a power system which is heavily loaded, faulted and/or has reactive power shortages. Voltage collapse is a form of system instability that involves many power system components and their variables simultaneously. Voltage collapse often involves the entire power system, although it usually has a relatively larger involvement of one particular area of the power system [34].

4.4 Causes of Voltage Instability
There are several power system changes known to contribute to voltage instability or collapse. Some of these are cited below [34]:

- High reactive power consumption at heavy loads.
- Difference in transmission of reactive power under heavy loads.
- Generators, synchronous condensers or SVC reaching reactive power limits.
- Action of tap-changing transformers
- Load recovery dynamics
- Line tripping, generator outages and Occurrence of contingencies.
- Voltage sources are too far from load centers.
- Unsuitable locations of FACTS controllers.
- Poor coordination between multiple FACTS controllers.
4.5 Classification of Voltage Stability

For analysis purposes, voltage stability can be classified, in two ways: according to the time frame of their evolution (long-term or short-term voltage stability) or to the disturbance (large disturbance or small disturbance voltage stability) [30].

Large-disturbance voltage stability refers to the system’s ability to maintain steady voltages following large disturbances such as system faults, loss of generation, or circuit contingencies. This ability is determined by the system and load characteristics, and the interactions of both continuous and discrete controls and protections. Determination of large-disturbance voltage stability requires the examination of the nonlinear response of the power system over a period of time sufficient to capture the performance and interactions of such devices as motors, under-load transformer tap changers, and generator field-current limiters. The study period of interest may extend from a few seconds to tens of minutes [30].

Small-disturbance voltage stability refers to the system’s ability to maintain steady voltages when subjected to small perturbations such as incremental changes in system load. This form of stability is influenced by the characteristics of loads, continuous controls, and discrete controls at a given instant of time. This concept is useful in determining, at any instant, how the system voltages will respond to small system changes. With appropriate assumptions, system equations can be linearized for analysis thereby allowing computation of valuable sensitivity information useful in identifying factors influencing stability[30].

Therefore, voltage stability may be either a short-term or a long-term phenomenon:

- Short-term voltage stability 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, and analysis requires solution of appropriate system differential
equations; this is similar to analysis of rotor angle stability. Dynamic modeling of loads is often essential. In contrast to angle stability, short circuits near loads are important. It is recommended that the term transient voltage stability not be used [30].

- Long-term voltage stability 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. Stability is usually determined by the resulting outage of equipment, rather than the severity of the initial disturbance [30].

4.6 Static voltage stability analysis techniques

Static voltage stability analysis techniques are based on the power flow formulation. The power flow formulation consists of the solution of a large set of nonlinear algebraic equations. The static analysis techniques are concerned with the following main aspects [34]:

- Determination of the stability of the given operating condition [34].
- The proximity of the given operating point to voltage instability [34].
- Identification of areas or buses to voltage instability (If the system is unstable) [34].
- In general, static voltage stability analysis provides answer regarding the margin and mechanism of voltage stability [34].

The common methods used for determination of the weakest point in power network in order to connect reactive power devices:

4.6.1 Continuation Power Flow

Continuation power flow is a static method which is used to find a static voltage stability margin. It calculates a set of voltage values for all the loading conditions starting from the base case to the maximum loading case [34].
4.6.2 Modal Analysis
Modal or eigenvalue analysis of the system Jacobian matrix (J) near the point of collapse can be used to identify buses vulnerable to voltage collapse and locations which are suitable for VAr injection [34].

4.6.3 Optimal Power Flow
The voltage stability analysis tools such as continuation power flow are based on concepts or techniques developed from bifurcation analysis of power system. Recent methods of VAr planning however use optimization-based formulation [34].

4.6.4 Contingency Analysis
Linear estimation method are used to approximate the values when more than one type of errors are encountered which lead to erroneous estimate in power system. The estimation errors [35].

4.6.5 Voltage stability indices
The purpose of voltage stability indices is to determine the point of voltage instability, the weakest bus in the system and the critical line referred to a bus. These indices are referred either to a bus or a line [35]:

i. **P-V Curve**
As the power transfer increases, the voltage at the receiving end decreases. Finally, the critical or nose point is reached. It is the point at which the system reactive power is out of use. The curve between the variation of bus voltages with loading factor ($\lambda$) is popularly called as P-V curve or ‘Nose’ curve. PV curves are used to determine the loading margin of the power system. The margin between the voltage collapse point and the current operating point is used as voltage stability criterion [35].

ii. **Q-V Curve**
With the help of Q-V curve, it is possible for the operators, to know the maximum reactive power that can be added to the bus before reaching minimum voltage limit. The MVAr distance from the operating point to the
bottom of the Q-V curve is called as the reactive power margin. Q-V curve can be used as an index for voltage stability limit. The point where \( \frac{dQ}{dV} = 0 \) is the point of voltage stability limit [35].

**iii. \( V/V_o \) Index**

The ratio \( V/V_o \) at each bus shows the voltage stability map of the system. \( V \) is the bus voltage at certain load obtained from load flow study. Voltages \( V_o \) are obtained by solving load flow of the system at an identical state but with all the loads set to zero. This index allows immediate detection of weakest bus and corrective action can be taken to prevent the voltage instability [35].

**iv. \( L \)-index**

In order to become of practical value the indicator \( L \) has to be extended to the multi-node system, there are two categories of nodes which have to be distinguished. One is characterized by the behaviour of the PQ-node which stands for a type of consumer node, the other comprise the generator nodes which may be given by a PV-node or by the slack node. The transmission system itself is linear and allows a matrix representation of the power systems. The power system can be expressed as [14]:

\[
I_{bus} = Y_{bus} V_{bus} \quad \text{(4.1)}
\]

Consider a system where,

\( n=\text{total number of buses, with } 1, 2...g \text{ generator buses (g)} \)

\( g+1, g+2, ..., g+s \text{ SVC buses(s)}, \)

\( g+s+1, g+s+2,...., n \text{ the remaining buses(r=n-g-s)} \)

A load flow result is obtained for a given system operating condition, which is otherwise available from the output of on-line state estimator.

\[
\begin{bmatrix} I^G \\ I^L \end{bmatrix} = \begin{bmatrix} Y^{GG} & Y^{GL} \\ Y^{LG} & Y^{LL} \end{bmatrix} \begin{bmatrix} V^G \\ V^L \end{bmatrix} \quad \text{(4.2)}
\]

\[
I^G = Y^{GG} V^G + Y^{GL} V^L \quad \text{(4.3)}
\]

\[
I^L = Y^{LG} V^G + Y^{LL} V^L \quad \text{(4.4)}
\]
Where \( I^G, I^L \) and \( V^G, V^L \) represent currents and voltages at the generator nodes and load nodes and \( j=g+1, g+2, \ldots, n \).

Therefore

\[
V^L = [Y_{LL}]^{-1}I^L - [Y_{LL}]^{-1}Y_{LG}V^G \tag{4.5}
\]

\[
I^G = Y_{GL}[Y_{LL}]^{-1}I^L + (Y^{GG} - Y^{GL}[Y_{LL}]^{-1}Y^{LG})V^G \tag{4.6}
\]

Equations (4.5) and (4.6) in matrix form

\[
\begin{bmatrix}
V^L \\
I^G
\end{bmatrix} = \begin{bmatrix}
[Y_{LL}]^{-1} & [Y_{LL}]^{-1}Y_{LG} \\
Y_{GL}[Y_{LL}]^{-1} & (Y^{GG} - Y^{GL}[Y_{LL}]^{-1}Y^{LG})
\end{bmatrix}\begin{bmatrix}
V^G \\
V^L
\end{bmatrix} \tag{4.7}
\]

Where

\[
FLG = -[Y_{LL}]^{-1}Y_{LG} \tag{4.8}
\]

are the required values which are obtained by repeated solutions of sparse linear equations.

An L-index value away from 1 and close to 0 indicates improved system security. For an unloaded system with generator/ load buses voltage \( 1.0 \angle 0 \), the L indices for load buses are close to zero, indicating that the system has maximum stability margin. For a given network, as the load/ generation increases, the voltage magnitude and angles change near maximum-power-transfer condition and the voltage stability index \( L_j \) (at bus \( j \)) values for load buses approaches unity, indicating that system is close to voltage collapse. While different methods give a general picture of the proximity of the system to voltage collapse, the L-index gives a scalar number to each load bus. Among the various indices for voltage stability and voltage collapse predication, the L-index gives fairly consistent results. The L-index for a given load condition is computed for all the load buses and the maximum of the L-indices gives the proximity of the system to voltage collapse [14].
Using load flow results the L-index for the \( j \)th node can be rewritten as:

\[
L_j = \left| 1 - \sum_{i=1}^{g} F_{ji} \frac{v_i}{v_j} \theta_{ij} + \delta_i - \delta_j \right| \tag{4.9}
\]

Or:

\[
L_j = \text{MAX} \left[ 1 - \left( \sum_{i=1}^{g} F_{ji} \frac{V_i}{V_j} \right) \right] \tag{4.10}
\]

The advantage of L-index method lies in the computation speed of very fast, simplicity, reliability and it can give a good indication about the critical power a system can maintain before collapse over the whole region and for all the cases studied.

4.7 Dynamic Voltage Stability Analysis Technique

Power systems are large dynamical systems with significant nonlinearities [7]. Therefore, the traditional methods of voltage stability investigation which are dependent on static analysis using the conventional power flow model cannot always capture these dynamics. Dynamic analysis is required for this purpose. The dynamic analysis includes linearized system analysis and time domain analysis. The linearized analysis is used to study the nonlinear behavior such as bifurcations. The time domain analysis is used to study the impact of large disturbances and time evolution of various system state and control variables[33].but in this thesis is not included [33].

4.8 Methods of Improving Voltage Stability

While planning and operating power system the main objective of studying voltage stability is to increase the power transfer capability of the system by eliminating the voltage stability limits [36].

There are many aspects of voltage stability and solutions associated to the voltage stability in terms of generation, transmission and distribution. The
objective is to find low cost solution whenever possible which requires special controls and effective power system operation methods. The main objective of power system engineer is to provide good quality of reliable supply [36].

4.8.1 Generation System

In order to improve power system voltage stability at the generation level we need to consider, planning control and protection and operation maintenance [36].

i. Planning

The reliability aspect of supply can be improved by sitting generating plants in load areas. The policy makers should advise the advantages of sitting power plants near the load centers as otherwise you need to have transmission systems which reduces the reliability levels of the supply. However, environmental factors must also be kept in mind. For this gas turbines in load areas should encourage for fast start-up. This should normally be used for real power generation. As mentioned earlier specifying lower power factor generation, increase the fast acting reactive power reserves of the generators. If generators normally operate near unity power factor, the reduced generator losses will reduce the life cycle cost increase of the larger (Higher MVA) lower p.f. machines [36].

Load tap changing (LTC) on step up generator transformer and auxiliary transformers have advantages for voltage stability as these transformers (LTC) allow the transmission side voltages to be maintained at the highest possible value without regard to terminal voltage of the alternator [36].

ii. Excitation System Control and Protection

In order to improve transient stability, high initial response and high ceiling excitation systems help induction motors reaccelerate after the fault. The generator high side voltage should be kept as possible by using line drop compensation or by outer control loop. The high voltage operation of
transmission lines minimises the increase in reactive power losses when ever a disturbance takes place. This is one of the most effective methods of improving the voltage stability. If fast changes in generation could counteract the fast changes in load, voltage stability can be insured. In attempting fast changes in generation we effectively counteract the fast load restoration by tap changing and generator current limiting. The protection of alternator for voltage stability means the maloperation of alternator under minor abnormal conditions should be avoided [36].

**iii. Operation**

During peak load period, power import over the transmission network should be reduced, instead demand should be met by using less economical sources like gas turbines within the load area. If there is loss of generation within the load area spinning reserves should be available within the load area. The generation control should rapidly activate the spinning reserve [36].

It may sometimes be advantageous to reduce real power loading of alternators in load areas to allow higher reactive power loading and power should be rescheduled over lightly loaded lines. Reactive power loading of alternators should be closely monitored. The control operator should know the reactive power capability of generators. Shunt capacitor should be used to maintain fast acting reactive power reserves at generators [36].

**4.8.2 Transmission System**

It has already mentioned that the transmission lines should be designed for high thermal capacity, low loss and high surge impedance loadings double circuit EHV lines should be encouraged [36].

**i. Reactive Power Compensation**

Extra high voltage transmission line require shunt reactors for energisation and under lightly loaded conditions. These shunt switched off by the operator during voltage emergencies or by the under voltage relays. There are instances mentioned in literature when there have been voltage collapse
because of not disconnecting the shunt reactors during voltage emergencies as these reactors further pull down the voltage resulting in voltage collapse. Mechanically switched shunt capacitor and SVC improve voltage stability.

The effectiveness of static VAr sources or capacitors can be justified if the post contingency condition can be tolerated for a short periods of time. However, if the post contingency condition is severe enough to cause immediate system problems such as motor stalling, fast active reactive compensation devices are required. Flexible AC transmission system (FACTS) devices are being used in power systems for this purpose [36].

**ii. Controls**

Automatic on-load tap changing on large EHV auto transformers can improve voltage stability. By regulating the voltage the reactive power output of shunt capacitors and the line charging increases which results in decrease in the reactive power losses. Tap changing at bulk power delivery substation and at distribution voltage regulators will not occur because of the faster regulation of high voltage system. Voltage sensitive load will, however, be restored faster and under voltage load shedding will not be effective [36].

The tap changing will sag the EHV voltage which can be compensated by capacitor bank insertion, by tripping the shunt reactors and control of EHV-side voltage at generators. It is possible even to prevent starting of longer term voltage instability if remote signals are used for fast switching of shunt capacitors or shunt reactors following a disturbance [36].

Another control is automatic line reclosing whenever a short circuit is to be cleared. For transient stability the reclosing is very fast. However, for slower form of voltage stability this does not need to be fast e.g. ten seconds delay allows time for electromechanical oscillation and generator torsional oscillations to die down. The longer delay provides better opportunity for successful reclosing as more time is available for arc deionization. Automatic reclosing should be faster than capacitor switching, tap changing or load shedding [36].
iii. Protective Relaying

A protective relay for over head lines is expected to be operated whenever there is a short circuit on the line. However these relays have mal-operated even under overload conditions, thus causing black outs. The main culprit in this regard has been zone 3 impedance relay. With protective relaying provided on the system such as breaker failure relaying and bus protection locale back up, there is no need to use zone 3 relays. These should be done away with. On sub transmission lines over current relay instead of impedance relays, should be used [36].

4.8.3 Distribution and Load Systems

Voltage is basically load stability and effective solutions to voltage stability can be found at the problem source. Upgrading sub transmission and distribution circuits for energy conservation will help voltage stability by reducing feeder impedance. Use of higher voltage distribution circuit will improve voltage stability [36].

i. Capacitor Banks

Shunt capacitor banks should usually be located on the regulated side of LTC voltage regulators. The shunt capacitor banks thus act as constant reactive power sources. Control of voltage using switched shunt capacitors or series capacitors rather than LTC transformers and distribution voltage regulators, will improve voltage stability [36].

ii. Tap Changing

A simple but effective method to improve voltage stability is to prevent LTC transformer tap changing for low unregulated side (transmission side) voltage. This is most effective at substation serving high p.f. loads or high shunt compensated loads. If the load is at some distance from LTC transformer, tap changer blocking may not be desirable [36].
CHAPTER FIVE

SIMULATION AND RESULTS

5.1 IEEE 14-Bus Test System Case Study

The modified IEEE 14-bus test system is used throughout the study. A single line diagram of the modified IEEE 14 bus test system is depicted in Figure(5.1), which consists of five synchronous machines, including three synchronous compensators used only for reactive power support and two generators located at buses 1 and 2. In the system, there are twenty branches and fourteen buses with eleven loads totaling 259MW and 81.4 MVAR. Line data and bus data are shown in appendix (A) [37].

Figure 5.1: Single line diagram of IEEE 14 bus test system.
5.2 Power Flow Analysis

Power flow or load flow is the solution obtained for the power system under static (steady state) conditions of operation, the symmetrical steady state is, Power Flow Solutions Method is mentioned as follow:

i. Gauss-Seidel method [38].

ii. Newton–Raphson method [38].

iii. Fast-Decoupled Load Flow Methods [38].

iv. DC Load Flow Analysis [39].

In this study Newton-Raphson method was used to obtain the power-flow solution.

5.3 Normal system without SVC

The system is simulate in NEPLAN software environment using the operational data given in appendix (A). The network operated above normal condition with loading point ($\lambda$) equal 1.4. The total connected loads at system buses is 362.6 MW plus 113.96 Mvar. The recorded bus voltage is given in table (5.1). The international voltage at all the buses will be within $\pm$ 5%.

Table (5.1): Voltage magnitudes for Base case Without SVC

<table>
<thead>
<tr>
<th>Bus NO.</th>
<th>Before Placement of SVC $V_M$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>106</td>
</tr>
<tr>
<td>2</td>
<td>99.7</td>
</tr>
<tr>
<td>3</td>
<td>92.82</td>
</tr>
<tr>
<td>4</td>
<td>92.73</td>
</tr>
<tr>
<td>5</td>
<td>93.93</td>
</tr>
<tr>
<td>6</td>
<td>95.87</td>
</tr>
<tr>
<td>7</td>
<td>94.06</td>
</tr>
<tr>
<td>8</td>
<td>98.36</td>
</tr>
<tr>
<td>9</td>
<td>91.3</td>
</tr>
<tr>
<td>10</td>
<td>90.9</td>
</tr>
<tr>
<td>11</td>
<td>92.8</td>
</tr>
<tr>
<td>12</td>
<td>93.32</td>
</tr>
<tr>
<td>13</td>
<td>92.38</td>
</tr>
<tr>
<td>14</td>
<td>88.81</td>
</tr>
</tbody>
</table>
Table (5.1) shown voltage profile at all buses. It can be seen that buses 3,4,5,7,9,10,11,12 and 14 are standing out as the most critical.

![Figure 5.2: Voltage profile for base case without SVC](image)

The voltage stability enhancement by static var compensation SVC and must be chosen optimal size and location of these device.

### 5.4 Optimal Size of SVC

The capacity of shunt FACTS controller can be determined by a synchronous compensator with no limit on reactive power was used at weak bus at "normal load in this case $\lambda = 1.4$". The amount of reactive power generated at the normal loading from the synchronous compensator was found to be 26.2987 MVar, but any increase in load, small disturbance and fault the SVC cannot generate any of reactive power, so the amount of reactive power generated at the maximum loading point from the synchronous compensator is optimum capacity and its found about 100 MVar, connected at bus no. 14 and its voltage setting is kept at 100%.

### 5.5 Optimal location of SVC by Using L-index

The optimal location of SVC to improvement of static voltage stability margin is by considering the identified “weakest bus” of the system. The weakest bus of the system is identified using the L-indices [11] for a given
load condition, and is computed for all load buses. The estimated value of L-index is varying between 0 and 1. Based on this value, it is possible to identify the voltage stability margin. If the estimated value approaches 1 refers the voltage collapse where as the estimated value approaches 0 refers the under no-load condition, otherwise the system is under normal operating condition. The higher values for L-indices are indicative of most critical buses and thus maximum of L-indices ($L_{\text{max}}$) is an indicator of proximity in the system to represent voltage collapse.

Table (5.2): IEEE 14-bus L-index for the base case

<table>
<thead>
<tr>
<th>Bus NO.</th>
<th>L-Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.0474</td>
</tr>
<tr>
<td>5</td>
<td>0.0406</td>
</tr>
<tr>
<td>7</td>
<td>0.0487</td>
</tr>
<tr>
<td>9</td>
<td>0.0772</td>
</tr>
<tr>
<td>10</td>
<td>0.0775</td>
</tr>
<tr>
<td>11</td>
<td>0.0449</td>
</tr>
<tr>
<td>12</td>
<td>0.0292</td>
</tr>
<tr>
<td>13</td>
<td>0.0425</td>
</tr>
<tr>
<td>14</td>
<td>0.0965</td>
</tr>
</tbody>
</table>

Table (5.2) Show the weakest buses in system IEEE 14 bus ,Results indicate that the bus14 has highest L-index among the load buses. Thus the bus 14 is the weakest bus and is the optimal location for the reactive power support. Based on the studies carried out with the developed model the following are the results obtained based on L-index method.
5.6 Normal System With SVC Connected to Bus 14

If SVC is connected to bus 14, the aim of control is to keep the voltage at that bus at 100 %, when it is near to the peak load condition i.e. for loading factor $\lambda = 1.4$. Here it is found that the SVC injects 25.675 MVAR to bus 14 in order to keep the voltage magnitude at 100 %.

Table (5.4) gives the voltage magnitude in percentage (%) for all buses of the system with SVC connected to bus 14.
Table (5.3): Voltage magnitudes after Placement of SVC at bus 14

<table>
<thead>
<tr>
<th>Bus</th>
<th>after Placement of SVC $V_M$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>106</td>
</tr>
<tr>
<td>2</td>
<td>101.09</td>
</tr>
<tr>
<td>3</td>
<td>95.26</td>
</tr>
<tr>
<td>4</td>
<td>95.83</td>
</tr>
<tr>
<td>5</td>
<td>96.77</td>
</tr>
<tr>
<td>6</td>
<td>102.04</td>
</tr>
<tr>
<td>7</td>
<td>99.48</td>
</tr>
<tr>
<td>8</td>
<td>103.57</td>
</tr>
<tr>
<td>9</td>
<td>97.99</td>
</tr>
<tr>
<td>10</td>
<td>97.58</td>
</tr>
<tr>
<td>11</td>
<td>99.26</td>
</tr>
<tr>
<td>12</td>
<td>100.21</td>
</tr>
<tr>
<td>13</td>
<td>99.8</td>
</tr>
<tr>
<td>14</td>
<td>100</td>
</tr>
</tbody>
</table>

Figure 5.4: voltage magnitudes After placement of SVC at bus 14
The voltage profile when value of $\lambda = 1.4$ before placement of SVC as compared to the system after placement of SVC shown in Figure (5.6). It clearly shows that the use of SVC at the weakest bus - bus number 14 - The voltage profile is improved at all buses.

5.7 Normal System With SVC Connected To Bus 10 and 9

If SVC is connected to buses 10 & 9. The aim of control is to keep the voltage at these buses at 100%, when it is near to the peak load condition.
Table (5.4): Voltage magnitude for 14-bus test system without and with SVC connected to bus 14,10 and 9

<table>
<thead>
<tr>
<th>Bus</th>
<th>after Placement of SVC at bus 14</th>
<th>after Placement of SVC at bus 10</th>
<th>after Placement of SVC at bus 9</th>
<th>Injected SVC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$V_M$ (%)</td>
<td>$V_M$ (%)</td>
<td>$V_M$ (%)</td>
<td>MVAR</td>
</tr>
<tr>
<td>1</td>
<td>106</td>
<td>106</td>
<td>106</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>101.09</td>
<td>101.15</td>
<td>101.31</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>95.26</td>
<td>95.39</td>
<td>95.69</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>95.83</td>
<td>96</td>
<td>96.39</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>96.77</td>
<td>96.86</td>
<td>97.15</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>102.04</td>
<td>101.75</td>
<td>101.87</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>99.48</td>
<td>100.01</td>
<td>100.97</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>103.57</td>
<td>104.08</td>
<td>105</td>
<td>0</td>
</tr>
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<td>9</td>
<td>97.99</td>
<td>98.73</td>
<td>100</td>
<td>29.537</td>
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<td>10</td>
<td>97.58</td>
<td>100</td>
<td>99.23</td>
<td>26.514</td>
</tr>
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<td>0</td>
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<td>12</td>
<td>100.21</td>
<td>99.46</td>
<td>99.67</td>
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<td>99.8</td>
<td>98.67</td>
<td>98.96</td>
<td>0</td>
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<tr>
<td>14</td>
<td>100</td>
<td>95.97</td>
<td>96.84</td>
<td>25.675</td>
</tr>
</tbody>
</table>

Figure 5.7: Voltage magnitudes before & after Placement of SVC at buses 14,10 and 9
Figure 5.8: voltage magnitudes before & after Placement of SVC at buses
14,10 and 9

Figure (5.7) and (5.8) shown the IEEE 14 bus without SVC & after of SVC is connected to bus 14,10 & 9, the aim of control is to keep the voltage at these buses at 100% , for loading factor $\lambda = 1.4$.

SVC injects 25.675 MVAr to bus 14 in order to keep the voltage magnitude at 100% when svc is connected to bus 14.

SVC injects 26.514 MVAr to bus 10 in order to keep the voltage magnitude at 100% when SVC is connected to bus 10. and SVC.

SVC injects 29.537 MVAr to bus 14 in order to keep the voltage magnitude at 100% when SVC is connected to bus 9.

Table (5.4) & figures (5.7),(5.8) gives the voltage magnitude in percentage for all buses of the system without SVC and after connected SVC to bus 14,10 & 9. The results obtained had shown the improvement of voltage magnitude in almost all buses as compared to the system without any FACTS controllers, but the good improvement of voltage occur at the SVC insert in bus 14.
5.8 Active and Reactive Power Losses

Static var compensator (SVC) also can be used to minimization of transmission losses.

Table (5.5): Shown Active and Reactive Power Losses before & after Placement of SVC at bus 14

<table>
<thead>
<tr>
<th>From Bus</th>
<th>To Bus</th>
<th>P_Loss</th>
<th>Q_Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>3</td>
<td>5.4199</td>
<td>18.7708</td>
</tr>
<tr>
<td>1</td>
<td>5</td>
<td>6.7567</td>
<td>22.9578</td>
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<tr>
<td>1</td>
<td>2</td>
<td>10.6869</td>
<td>27.0382</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>1.1282</td>
<td>2.4439</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>0.9719</td>
<td>-0.4972</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>2.1274</td>
<td>3.3058</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>3.8957</td>
<td>8.3536</td>
</tr>
<tr>
<td>6</td>
<td>13</td>
<td>0.594</td>
<td>1.1698</td>
</tr>
<tr>
<td>6</td>
<td>12</td>
<td>0.1939</td>
<td>0.4035</td>
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<tr>
<td>6</td>
<td>11</td>
<td>0.2217</td>
<td>0.4643</td>
</tr>
<tr>
<td>12</td>
<td>13</td>
<td>0.0229</td>
<td>0.0207</td>
</tr>
<tr>
<td>11</td>
<td>10</td>
<td>0.0753</td>
<td>0.1764</td>
</tr>
<tr>
<td>9</td>
<td>14</td>
<td>0.2563</td>
<td>0.5452</td>
</tr>
<tr>
<td>9</td>
<td>10</td>
<td>0.0185</td>
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<td>0</td>
<td>2.6162</td>
</tr>
<tr>
<td>13</td>
<td>14</td>
<td>0.2057</td>
<td>0.4188</td>
</tr>
</tbody>
</table>

Figure 5.9: Active power losses (MW) before & after Placement of SVC at bus 14
Figure 5.10: Reactive power losses (MVAr) before & after Placement of SVC at bus 14

Figure 5.11: Total Active and Reactive power losses before & after Placement of SVC at bus 14

Figure (5.10) & Figure (5.11) shown compare active & reactive power losses before & after placement of SVC at bus 14.

Figure(5.11) shown the real power loss is reduced after placement of SVC from 32.575 MW to 30.607 MW & Reactive power loss is reduced after placement of SVC from 107.874 MVAr to 96.833 MVAr.
CHAPTER SIX

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

In this work, the optimal location and size of SVC devices is found to improve voltage stability assessment & minimize active & reactive power loss of the standard IEEE -14 bus test system with base case and with SVC.

L-indices technique is used to identify weakest bus in the system, the higher values for L-indices found at bus number 14, Therefore that is more suitable location for SVC. The SVC FACTS device is employed and voltage profile of the system is enhanced and losses are reduced after using SVC.

a synchronous compensator with no limit on reactive power was used at the weakest bus in the system (bus number 14), The amount of reactive power generated at the maximum loading point from the synchronous compensator that is optimum size and it's found about 100 MVAr.

6.2 Recommendations

The recommended future work may be:

- Using Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) algorithm to find optimal location and size of SVC.
- Several types of FACTS devices can also implement into the system at the same time.
- Study and finding one or more location and size for the SVC when large fault occur.
REFERENCES


[34] Bishnu Prasad Sapkota “Voltage Stability Assessment And Enhancement Of A Large Power System Using Static And Dynamic Approaches”, PHD thesis, Arizona State University May 2010


[37] Power System Test Archive-UWEE (University of Washington) available Online,


## APPENDIX (A)

### Table 1: IEEE 14-bus data [37]

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1.06</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>1.045</td>
<td>0</td>
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<td>1</td>
<td>0</td>
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