Application of FACTS Controllers in Thailand Power Systems

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Executive Summary

Increasing attention has been devoted to electricity sector development in the developing countries in the recent past. This is due to the fact that the development of electric power sector historically links to the economic advancement of the country. However, given the other commitments the developing countries have (e.g. transportation, health care, education), they cannot fully focus all investment on the electricity sector. This is where the Flexible AC Transmission Systems (FACTS) technology coming into effect. With relatively low investment, compared to new transmission or generation facilities, these FACTS technology allows the industries to better utilize the existing transmission and generation reserves, while enhancing the power system performance.

Moreover, the current trend of deregulated electricity market also favors the FACTS controllers in many ways. FACTS controllers in the deregulated electricity market allow the system to be used in more flexible way with increased in various stability margins.

FACTS controllers are products of FACTS technology; a group of power electronics controllers expected to revolutionize the power transmission and distribution system in many ways. FACTS controllers are beginning to appear in the developing countries, as the need for such controllers is recognized well by research communities in this area, and electric power utilities. The FACTS controllers clearly enhance power system performance, improve quality of supply and also provide an optimal utilization of the existing resources.

FACTS controllers are proven to be effective in power grids in well-developed countries (e.g. USA, Canada, Sweden). The economical viability of these controllers is justified through the long list of benefits that these controllers have, compared to the traditional controllers. FACTS technology can boost power transfer capability by 20-30% by increasing the flexibility of the systems. Power interchange with neighboring countries becomes easier and effective with these controllers. FACTS controllers can also increase the loadability or “distance” to voltage collapse of power system, so that additional loads can be added in the system without addition of new transmission and generating facilities.There are number of FACTS controllers/devices that have been developed depending upon the targeted goals to be achieved. Each one has its own characteristic behavior, capability and limitations.

In this project, various applications, both static and dynamic in nature, of FACTS controllers has been thoroughly, especially for the EGAT power system. Also, focus has been given on the application of the controllers in the electricity supply industry reformed environment. Technical issues like, types, capacity and placement and other pertinent information (e.g. best control input signal to improve the dynamic performance) for various applications has been studied with possible new theoretical contributions in the placement and controller input signals. Finally, all these concepts has been applied and tested on EGAT’s (Electricity Generating Authority of Thailand) power system. This will be a very good contribution for both the research community, in this filed, and electric utilities around the world, especially in Thailand.

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ABBREVIATIONS

ABB	Asea Brown Boveri Ltd.
AC	Alternating Current
ATC	Available Transfer Capability
CSC	Convertible Static Controller
DC	Direct Current
EGAT	Electricity Generating Authority of Thailand
EPRI	Electric Power Research Institute
FACTS	Flexible AC Transmission Systems
FC	Fixed Capacitor
IEEE	Institute of Electrical and Electronics Engineers
IPFC	Interline Power Flow Controller
LF	Loading Factor
LM	Loading Margin
MLM	Maximum Loading Margin
PWM	Pulse Width Modulation
SSR	Sub Synchronous Resonance
SSSC	Static Synchronous Series Compensator
STATCOM	Static Synchronous Compensator
STATCON	Static Synchronous Condenser
SVC	Static Var Compensator
TCSC	Thyristor Controlled Series Capacitor
TCPS	Thyristor Controlled Phase Shifting Transformer
TCR	Thyristor Controlled Reactor
TSC	Thyristor Switched Capacitor
TSSC	Thyristor Switched Series Capacitor
UPFC	Unified Power Flow Controller
VSI	Voltage Source Inverter

Chapter 1

Introduction

1.1. Overview

Modern electric power utilities are facing many challenges due to ever-increasing complexity in their operation and structure. In the recent past, one of the problems that got wide attention is the power system instabilities [1]-[3]. With the lack of new generation, transmission facilities and over exploitation of the existing facilities geared by increase in load demand make these types of problems are more imminent in modern power systems. In recent years, several major phenomena have been observed and reported in many countries such as France, Belgium, Sweden, Germany, Japan, the United States, etc [2]. These phenomena usually result in widespread blackouts. Information gathered and preliminary analysis, so far, from the most recent blackout incident in North America on 14th August 2003, are pointing the finger on voltage instability due to some unexpected contingency [4]. Even through it is premature to make it as a conclusive remark, the voltage instability could have had a major role in the incident as has been the case in the past in major blackout incidents. In this incident, reports indicate that approximately 50 million people interrupted from continuous supply for more than 15 hours [4]. Most of the incidents are believed to be related to heavily stressed system where large amounts of real and reactive power are transported over long transmission lines while appropriate real and reactive power resources are not available to maintain normal system conditions. Many electric utilities have made lot of efforts in system study in order to relieve the system from stability problem.

Instability in power system could be relieved or at least minimized with the help of most recent developed devices called Flexible AC Transmission System (FACTS) controllers [3], [5]. The use of Flexible AC Transmission System (FACTS) controllers in power transmission system have led to many applications of these controllers not only to improve the stability of the existing power network resources but also provide operating flexibility to the power system. In addition, with relatively low investment compared to new transmission or generation facilities, these FACTS technology allows the industries to better utilize the existing transmission and generation reserves, while enhancing the power system performance. They clearly enhance power system performance, improve quality of supply and also provide an optimal utilization of the existing resources [6].

FACTS devices are a family of high-speed electronic devices, which can significantly increase the power system performance by delivering or absorbing real and/or reactive power [3], [5], [6]. There are many types of FACTS controllers available in real power system and some are under research. Static Var Compensator (SVC), Static Synchronous Compensator (STATCOM), Thyristor-Controlled Series Capacitor (TCSC), Static Synchronous Series Compensator (SSSC) and Unified Power Flow Controller (UPFC) are popular FACTS devices [6]. They can be connected to power system at any appropriate location, in series, in shunt or in a combination of series and shunt. The SVC and STATCOM are connected in shunt, whereas TCSC and SSSC are connected in series. UPFC is connected in a combinationof both shunt and series.

Application of FACTS to enhance power system stability is an important issue. The problems that are to be faced in the planning stage are appropriate type, location, size and setting for these controllers for various applications. In order to address this problem, an effort is made in this project to study technical issues of FACTS controllers in types, capacity and placement, and other pertinent information relating to power system in developing nations.

1.2. History of Development

FACTS has come a long way since the early 1970s, when the concept was developed for generating controllable reactive power through switching power converters. What is now considered the first FACTS device was the Static Var Compensator (SVC), which was brought to the market by, the Electric Power Research Institute (EPRI) two decade ago. This compensator consists of a fast thyristor switch controlling a shunt capacitor bank and/or a reactor, to provide dynamic shunt compensation. Dynamic shunt compensation automatically and instantaneously adjusts the reactive power output smoothly thus maintaining the voltage at required level. Conventional thyristors and silicon controlled rectifiers formed the technological foundation for this device. More than 800 SVCs are being installed worldwide both for utility and industrial (specially in electric arc furnace and rolling mills) purposes. Even the utilities in developing countries took the benefit of SVCs since its invention. ABB remains the pioneer in the deployment of SVC and has supplied 55% of the total installation and more than half of which were being installed during 1980s. Approximatley 13% of the utility scale SVCs supplied by ABB were being installed in Asian countries. Table 1.1. below shows list of SVCs installed in Asian countries. Though the list is not complete is shows the trend of deployment of SVCs.

Table 1.1 List of utility scale SVCs in Asia

S.N.	Year Installed	Country	Capacity, MVAR	Voltage level (kV)	Place
1	1981	China	120	500	CNTIC - Wu Han II
2	1981	China	120	500	CNTIC - Wu Han I
3	1986	Thailand	80	115	EGAT - Chumphon
4	1987	China	290	500	Guangdong Gen. Pow. Co. - Jiang Men
5	1987	China	270	500	CNTIC - Dalian
6	1987	Iran	300	420	Tavanir - Omdieh
7	1987	Saudi Arabia	200	380	SCECO E - Shedgum
8	1987	Saudi Arabia	200	380	SCECO E - Faras
9	1987	Srilanka	20	132	CEB - Galle
10	1987	Yemen	80	132	YGEC Alsthom - Sanaa
11	1988	Singapore	100	230	Kallang Basin Substation
12	1988	Singapore	50	230	Labrador substation
13	1988	India	45	132	TNEB - Madurai
14	1988	India	45	132	TNEB - Trichur
15	1988	India	45	132	TNEB - Singaropet
16	1988	Srilanka	20	132	CEB - Chunnakam
17	1989	Thailand	190	500	EGAT - Tha Tako 1
18	1989	Thailand	190	500	EGAT - Tha Tako 2
19	1991	Malaysia	200	275	NEB - K1 North2
20	1991	Malaysia	200	275	NEB - K1 North1
21	1992	India	280	400	NTPC - Kanpur 2
22	1992	India	280	400	NTPC - Kanpur 1
23	1992	Iran	300	420	TAVINIR – Omedieh

S.N.	Year Installed	Country	Capacity, MVAR	Voltage level (kV)	Place
24	1995	Indonesia	-25 to 50	150	Jember substation (Bali)
25	1995	Thailand	-50 to 300	230	EGAT - Bang Saphan
26	1999	South Korea	200	345	KEPCO - Seo-Daegu
27	1999	Saudi Arabia	150	380	SCECO C - Riyadh I
28	1999	Saudi Arabia	150	380	SCECO C - Riyadh II
29		Japan	-20 to +80	500	Tokyo
30		Japan	-40 MVA		Osaka

A later member of this first generation of FACTS devices, the Thyristor Controlled Series Capacitor (TCSC), uses silicon controlled rectifiers to manage a capacitor bank connected in series with a line, enabling a utility to transfer more power on a particular transmission line. Testing of the first single phase TCSC began in 1991 by American Electric Power Co., based in Columbus, Ohio. In 1992, the Western Area Power Administrator, based in Golden, Colorado, installed worlds first three phase TCSC that raises the capacity of a transmission line by almost 30%. Since then, there has been significant breakthrough in the research and development of TCSC. In 1998, ABB commissions the world’s first full scale TCSC for Sub-synchronous Resonance (SSR) mitigation in 400 kV grid in Sweden. Again in 1999, ABB commissions the full scale TCSC for damping of power oscillations in a 500 kV power system interconnection in Brazil. Though series compensation has long been used in transmission system in Asian countries, the use of controllable series compensation like TCSC has just beginning to emerge. At the end of year 2004 three TCSC came into operation; two in China and one in India, bringing Asia into the forefront of the advanced FACTS technology. Table 1.2. below lists all the major TCSC installations in the world.

Table 1.2 List of TCSC installations

S.N	Year Installed	Country	Capacity, MVAR	Voltage level (kV)	Purpose	Place
1	1992	USA	2x165	230	To increase power transfer capability	Kayenta substation, Arizona
2	1993	USA	208	500	Controlling line power flow and increased loading	C.J.Slatt substation on the Slatt-Buckley 500 kV line in Northern Oregon
3	1998	Sweden		400	SSR mitigation	Stöde
4	1999	Brazil		500	To damp interarea low freq (0.2 Hz) oscillation	1. FC at Maraba (348MVAR) 2. FC at Imperatriz (161MVAR) 3. FSC at Colinas (2x161MVAR) 4. FC at Miracema (161MVAR) 5. TCSC at Imperatriz (107MVAR) 6. TCSC at Sarra de Mesa (107 MVAR)
5	2002	China	55 controlled 350 fixed	500	Stability improvement, low-frequency oscillation mitigation	Pinguo substation, State power south company, Guangzhou
6	2004	India	118 controlled 788 fixed	400	Compenstion, Damping of interregional power oscillation	Raipur substation
7	2004	China		220	Increase Stability margin, supress low frequency oscillation	North-West China Power System

The second generation of FACTS which is based on voltage source converters (VSC), known as STATCOM (STAtic synchronous COMpensator), has a very promising future application. It is recognized to be one of the key advanced technologies of future power system. STATCOM has several advantages of being small/compact, high response speed and no harmonic pollution etc. The technology of STATCOM improving transmission system capability has been successfully applied in power systems in developed countries, such as Japan, USA and UK and its application in China has a good beginning by Tsinghua University and Henan Power Authority and will develop rapidly. It is also quite interesting to note that the Bharat Heavy Electric Limited (BHEL), India was successful in developing distribution scale STATCOM also known as D-STATCOM which has successfully been installed in industry. The worlds first commercial STATCOM (±80 MVA, 154 kV) was developed by Mitsubishi Electric Power Products, Inc. and installed at Inuyama substation in Japan in 1991. STATCOM also finds its application in industries for flicker reduction. There are around 20 STATCOM operating successfully around the world. Table 1.3. below list the some of the major utility scale STATCOM which is in operation.

Table 1.3 List of utility scale STATCOM

S. N	Year Installed	Country	Capacity, MVAR	Voltage level (kV)	Purpose	Place
1	1991	Japan	± 80 MVA	154	Power system and voltage stabilization	Inumaya substation
2	1992	Japan	50 MVA	500		Shin Shinano Substation, Nagona
3	1995	USA	± 100 MVA	161	To regulate bus voltage	Sullivan substation in TVA power system
4	1996	China	± 20 MVA		reactive compensation, improve system stability and damp system oscillation	China
5	2001	UK	0 to +225	400	Dynamic reactive compensation	East Claydon 400 kV Substation
6	2001	USA	-41 to +133	115	dynamic reactive compensation for fast voltage support during critical contingencies	VELCO Essex substation
7	2003	USA	± 100	138	to relieve transmission system constraints in the area through dynamic var control during pak load conditions	SDG&E Talega substation

A complementary second-generation FACTS controller is the Static Synchronous Series Compensator (SSSC), which is simply a series version of STATCOM. This series-connected device could perform the functions of a thyristor-connected series capacitor to increase or decrease the power flow along a specific line.

Combining the static compensator and the synchronous series capacitor into a single device with a common control system represents the third generation of FACTS. The device is known as “Unified Power Flow Controller (UPFC)”. It has the unique ability to simultaneously control all three parameters of power flow (voltage, line impedance and phase angle). In this configuration, the series-capacitor component, connected in series with a line, injects an AC voltage with controllable magnitude and phase angle. The static-compensator component, connected as a shunt, supplies or absorbs the real power demanded by the series capacitor through a common DC link, and provides var control.

The first utility demonstration of a Unified Power Flow Controller is being constructed at the Inez substation of American Electric Power in 1998. Recently, 80 MVA UPFC were being constructed at Gangjin substation in South Korea. Table 1.4. below shows the list of UPFC.

Table 1.4. List of UPFC

S.N	Year Installed	Country	Capacity, MVA	Voltage level (kV)	Purpose	Place
1	1998	USA	± 320	138	Dynamic voltage support and added real power supply facility	AEP Inez substation
2	2003	South Korea	80	154		Gangjin substation

The most recent development in the field of FACTS controllers is the “Convertible Static Compensators (CSC)”. The CSC offers the full flexibility by allowing its converters to be connected in shunt (STATCOM), in series (SSSC), in shunt/series (UPFC) or in series/series (IPFC) with two lines.

The worlds first CSC was installed at New York Power Authority’s Marcy 345 kV substation, which is capable of operating in eleven different control modes. The CSC consists of two 100 MVA inverters, two 100 MVA series transformers and a single 200 MVA shunt transformers. The shunt portion of the CSC came into operation in 2001. The full scale CSC came into operation in early 2004.

1.3. Statement of Problems

Most of electric power supply in the globe are widely interconnected, involving connections inside utilities’ own territories which extend to inter-utility interconnections and then to inter-regional and internal connections. This is done for economic reasons, to reduce the cost of electricity, and to improve reliability of power supply. However, as power transfer grows, the power system becomes increasely more complex to operate and the system can become less secure for riding through the major outages. It may lead to large power flow wih inadequate control, excessive reactive power in various parts of the system, large dynarmic swings between different parts of the system and bottlenecks, and thus the full potential of transmission interconnections cannot be utilized.

Power system stability issues and thermal constraints limit transmission capacity. To meet the increasing load demand and satisfy the stability and reliability criteria, either existing transmission and generation facilities must be utilized more efficiently, or new facilities should be added to the systems. Given the constraints, such as lack of investment and difficulties in getting new transmission line right-of ways, the later is often difficult. The former can be achieved by using FACTS controllers as seen in well-developed power systems throughout the world.

The introduction of the FACTS devices extends the possibility that current through a line can be controlled at a resonable cost enables large potential of increasing the capacity of existing lines, and use of one of the FACTS devices to enable corresponding power to flow through such lines under normal and contingency conditions. Several authors have demonstrated the importance of FACTS controllers for steady state and transient stability studies [7]-[10]. However, there are number of FACTS controllers/devices that have been developed depending upon the targeted goals to be achieved. Each one has its own characteristic behavior, capability and limitations. Thus, attention is paid in this project to study various applications, both static and dynamic in nature, of FACTS controllers, especially for the developing countries. Also, focus will be given on the application of the controllers in the electricity supply industry deregulated environment. Technical issues like, types, capacity and placement and other pertinent information for various applications will be studied.

1.4. Research Objective

Various applications of FACTS controllers in power systems in developing countries will be thoroughly studied in this project, along with development of methodologies to find the correct size, suitable installation locations and other pertinent information. Emphasize will be given to the application of these in Thailand power system, especially in competitive electricity market.

1.5. Scope and Limitation

The project description can be summarized in the following.

1. Literature survey on various FACTS controllers and their application in developed countries. Identification of various problems faced by the power systems in the developing world, more emphasize will be given to identifying the problems in EGAT power systems.
2. Identification of type, size, installation location and other pertinent information for solving various problems identified in step 1, through simulation and analysis on test systems.
3. System data collection, both dynamic and static, from EGAT.
4. Static aspects: Application of the concept and methodology developed in step 3 to EGAT power system.
5. Special consideration for the application of these controllers in a competitive electricity environment.

1.6. Organization of Report

This report is organized in six chapters as follows:

Chapter 1 provides an introduction of FACTS devices and history of development of these devices and their practical installations around the world.

Chapter 2 discusses various controls and stability limits in power systems. Some examples are also presented to illustrate the limits.

Chapter 3 presents the idea behind Flexible AC Transmission System, with various FACTS controllers currently available in details. Then controllers relative costs area also included in this chapter.

Chapter 4 focuses on FACTS applications. A number of practical applications of FACTS devices both in dynamic and static time frame are also given in this chapter.

Chapter 5 presents and discusses the simulation results, i.e. application of FACTS in Thailand power system.

Chapter 6 summarizes major conclusion of this work.

Chapter 2

Power System Control and Limits

The modern transmission system is a complex network. The transmission lines interconnect all the generator stations and all the major load points in the power system. These lines carry large blocks of power that can be routed in any desired direction on the various links of the transmission system to achieve the desired power delivery. In addition, the main characteristic of today's transmission system is an overall loop structure, in contrast to early day transmission systems, which were mostly radial, supplying power from generator to a defined load. Steady-state power transmission may be limited by the so-called parallel or loop power flows. These flows often occur in a multi-line, interconnected power system, resulting in overloaded lines with thermal or voltage limit problems.

Power systems employ rotating synchronous machines for electric power generation. It is a fundamental requirement to useful power exchange that all synchronous machines in the system operate in synchronism with each other maintaining a common system frequency. However, power system are exposed to various dynamic disturbances, which may cause a sudden change in the real and reactive power balance of the system and consequent problem in certain machines. The ability of the system to recover from disturbances and regain the steady-state synchronism under stipulated contingency conditions becomes a major design and operating criterion for transmission capacity. This ability is usually characterized by power system stability limits. According to the above discussion, the ability of the power system to serve the load is mainly limited by two factors: power flow on the lines and stability limits of the power system. These issues are important and require some studies for many utilities in order to make use of the transmission in proper ways.

In this chapter, some fundamentals regarding power system control and stability will be discussed in order to provide some idea and realize the cause of the problems. In the first section, the basic relationships of power flow in a transmission line will be derived. Subsequently, power flow control and stability limits will be mentioned in the following sections.

2.1. Background

Before proceeding to the fundamentals of power system control and stability limits, some factors influencing active and reactive power flows on the power system are needed to be discussed. The power transfer between two buses is related to some parameters:

- Sending and receiving bus voltages
- Power angles between two buses
- Series impedances of the transmission line connecting the two buses.

Let us consider a simple two bus radial system as shown in Figure 2.1. The transmission line between the sending bus and the receiving bus is represented by equivalent π-model and line resistance has been neglected for simplicity. Usual notation for voltage and power has been used with subscript "S" for sending end and "R" for receiving end. "X" denotes the line reactance and "Xc" stands for line charging capacitance.

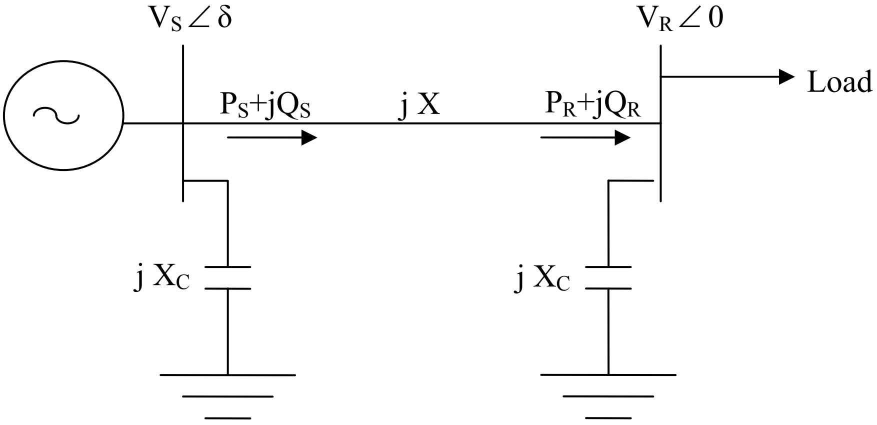

Figure 2.1 A simple two bus radial system.

Equations that described the power transfer at the sending end and the receiveing end buses can then be written as (2.1) and (2.2), respectively. Similarly, the reactive power equations can also be written as (2.3) and (2.4).

$$P_S = \frac{V_S V_R}{X} \sin\delta \tag{2.1}$$

$$P_R = \frac{V_S V_R}{X} \sin\delta \tag{2.2}$$

$$Q_S = \frac{V_S^2 - V_S V_R \cos\delta}{X} - \frac{V_S^2}{X_C} \tag{2.3}$$

$$Q_R = \frac{-V_R^2 + V_S V_R \cos\delta}{X} + \frac{V_R^2}{X_C} \tag{2.4}$$

From equations (2.1) and (2.2), the active power transfer is determined by sending and receiving end voltages, series reactance of the line and phase angle difference between the sending and receiving end voltages. Normally, in power system, the power angle difference between two buses is small (less than 20 degree); the active power transfer equation can be reduced to

$$P_S = \frac{V_S V_R}{X} \delta \quad , \qquad P_R = \frac{V_S V_R}{X} \delta \tag{2.5}$$

In short, the active power transfer between two buses in the power system is directly proportinal to the angle difference between the two buses, and sending end power is equal to the receiving end power as the losses in the system is negligible.

The reactive power transfer equation is more complex than the active power transfer equation, as seen from equations (2.3) and (2.4). However, few simplifications can be applied to make the equations useful for operations by ignoring the last term in the equations (2.3) and (2.4), representing the effect of line charging. Thus, the reactive power equations simplifies to

$$Q_S = \frac{V_S^2 - V_S V_R \cos\delta}{X} \tag{2.6}$$

$$Q_R = \frac{-V_R^2 + V_S V_R \cos\delta}{X} \tag{2.7}$$

As seen in equations (2.6) and (2.7), the reactive power transferred between two points is therefore determined by voltage magnitudes at two buses, series reactance of the line and consine of the power angle between two points.

In normal power system operations, the power angle between two connected buses is small, so the reactive power transfer equation can be further simplied to

$$Q_S = \frac{V_S^2 - V_S V_R}{X} \tag{2.8}$$

$$Q_R = \frac{-V_R^2 + V_S V_R}{X} \tag{2.9}$$

From equations (2.8) and (2.9), the reactive power transferred between two points is therefore simply determined by voltage magnitudes at two buses and series reactance of the line.

From equations (2.8) and (2.9), one would state that reactive power does normally flow from the high to low voltage bus. In summary, active power always transfer from high angle to low angle, whereas reactive power normally flows from high voltage to low voltage.

2.2. Power Flow Control

It has been recognized from the previous section that the steady-state transferable power can be increased by adjusting transmission line reactance and angle difference betweeen two buses. Practically, the basic approaches to increase the transferable power are by shunt connected Var compensation, series Var compensation and phase angle regulation.

Shunt connected var compensation and series var compensation are reactive power compensation schemes. The purpose of this reactive compensation is to change the natural electrical characteristics of the transmission line to make it more compatible with the previaling load demand. The shunt compensation are applied to maintain the voltage level under various system conditions. The series compensation is often employed to estabish a virtual short line by reducing the inductive line impedance and thereby electrcial length. A phase angle regulation is employed to control the angle of the line. By means of controlling impedance or phase angle, power flow control can be achieved. Another approach to control power flow is the injection of appropriate voltage, which is the fundamental concept of voltage-source based FACTS devices.

Other complications may arise if the series capacitor is mechanically controlled. A series capactitor in a line may lead to subsynchronous resonance. This resonance occurs when one of the natural frequencies of the shaft of a multiple-turbine generation unit coincides with 50 minus the electrical resonance frequency of the capacitor with inductive impedance of the lines. This may damage the shaft of turbine generators. This problem can be prevented with the application of FACTS controller.

2.3. Power System Limit

For reliability, power system has to be operated within power transfer limits. The limits will constrain the generation and transmission of active and reactive power in the system. They are usually divided into three broad categories, namely thermal, voltage and stability limits.

2.3.1. Thermal Limit

Thermal limits are due to thermal capability of power system equipments. As power transfer increases, current magnitude increases, a key to thermal damage. For example, in a power plant, sustained operation of units beyond their maximum operation limits will result in thermal damage. The damage may be to the stator windings or to rotor windings of unit. Both active and reactive powers play a role to current magnitude.

Out in the system, transmission lines and associated equipment must also operated within thermal limits. Sustained excessive current flow on an overhead line causes the conductors to sag thus decreasing the ground clearance and reducing safety margins. Extreme levels of current flow will eventually damage the metallic structure of the conductors producing permanent sag.

Unlike overhead lines, underground cables and transformers must depend on insulation other than air to dissipate the generated heat. These types of equipment are tightly restricted in the amount of current they can safely carry. For the equipment, sustained overloading will result in a reduction in services life due to damage to the insulation. Most power system equipment can be safely overloaded. The important aspect is how much is the overload and how long it does.

2.3.2. Voltage Limit

Both utility and customer equipment are designed to operate at a certain rated or nominal supply voltage. A large, prolonged deviation from this nominal voltage can adversely affect the performance of, as well as cause serious damage to, system equipment.

Current flowing through the transmission lines may produce an unacceptably large voltage drop at the receiving end of system. This voltage drop is primarily due to the large reactive power loss, which occurs as the current flows through the system. If the reactive power produced by generators and other sources are not sufficient to supply the system's demand, voltage will fall, outside the acceptable limit that is typically ± 6% around the nominal value.

System often requires reactive support to help prevent low voltage problems. The amount of available reactive support often determines power transfer limits. A system may be restricted to a lower level of active power transfer than desired because the system does not posses the required reactive power reserves to sufficiently support voltage.

2.3.3. Stability Limit

Power system stability may be broadly defined as the ability of a power system to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance. Instability in a power system may be manifested in many different ways depending on the system configuration and operating mode. Traditionally, the stability problem has been one of maintaining all synchronous machines in synchronism. This aspect of stability is influenced by the dynamics of generator rotor angles. The stability in power system can be broadly classified into two categories, namely angle stability and voltage stability.

Angle stability limits are limits imposed to ensure that system torque and power angles remain controllable. When a system is angle unstable, power and torque angles are no longer controllable. The angles may reach high magnitudes and rapidly vary over a wide range. A system may enter a period of angle instability following a large system disturbance. System operator lose their ability to control power transfer and are typically helpless as the system can enter an unstable condition very rapidly following a major disturbance. Voltage stability limit, on the other hand, is the limit caused by reactive power deficiency. In order to understand these limits in detail, the angle stability will be discussed at first.

From equations (2.1) and (2.2), active power flow between any two points is strongly dependent upon the phase angles. The plot of the active power transfer versus the phase angles is called the power-angle curve. The power-angle curve is a plot of the MW transferred between two buses as the angle spread is varied. The maximum power transfer between any two strong buses occurs when the angle spread between these same two buses is 90 degree.

The power system operates at the intersection of the mechanical power input line and the power-angle curve at 100 MW and 35 degree, respectively as shown in Figure 2.2. Assume the mechanical power input stays constant while the angle spread rises above 35 degree. As angle spread increases the electrical power transfer increases. More power is now being transferred out of the generator than mechanical power is being brought in, causing the rotor to decelerate and frequency of the system to decrease. In contrast, as the angle spread decreases, the electrical power transfer decreases. More power is now being brought into the generator than is being transferred out. This will cause the rotor to accelerate and make the system frequency to increase. The angle spread can only change if there is relative acceleration or deceleration. More detail on the impact of the change in angle spread will be discussed by various system events.

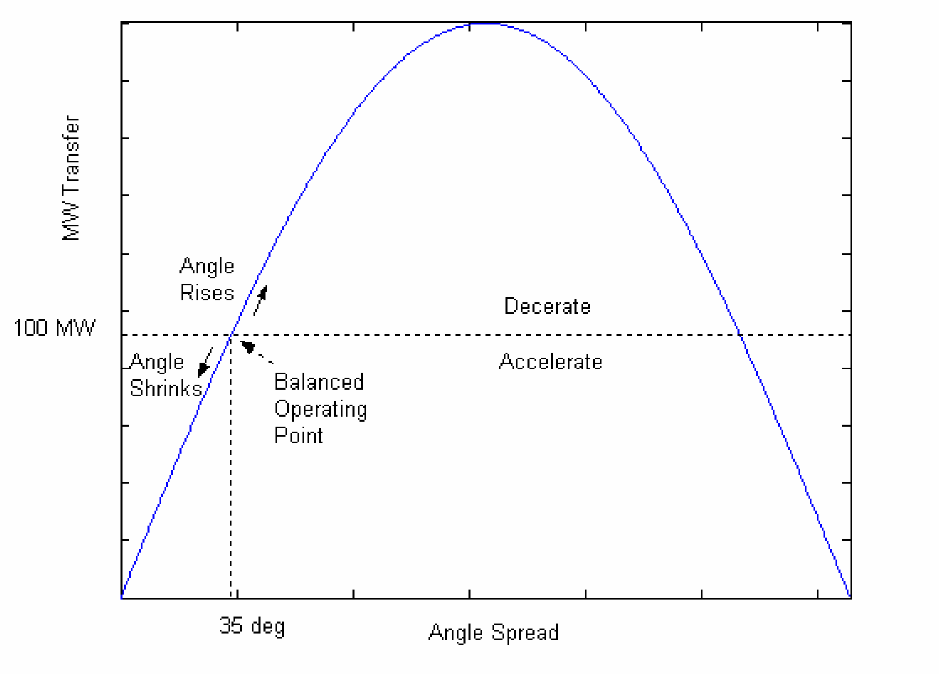

Figure 2.2 Power-Angle curve

The analysis of power system angle stability is a study of the dynamic performance of the power system. The term dynamic performance refers to the changing values of power flows, voltages, angles, and frequency, following a large or small system disturbances. The angle stability is broadly divided into two classification: transient stability and small signal stability.

2.3.4. Transient Stability

Transient stability is defined as the ability of the power system to maintain synchronism when subjected to a severe transient disturbance. It is determined by how the system responds to a severe disturbance. A system is transiently stable if it can survive the initial disturbance but it is transiently unstable if it cannot survive. For the transiently stable system, a large disturbance suddenly occurs, the system angle spread starts to increase but reaches a peak and then starts to decline, making the system transiently stable. The resulting system response involves large excursions of generator rotor angles. Stability depends on both the initial operating state of the system and the severity of the disturbance. Transient stability is sometimes called first swing stability as the instability often occurs during the first angle swing.

To illustrate the transient stability and instability of the system, see Figure 2.3, which shows angle spread of two systems: transiently stable and unstable, after a large disturbance.

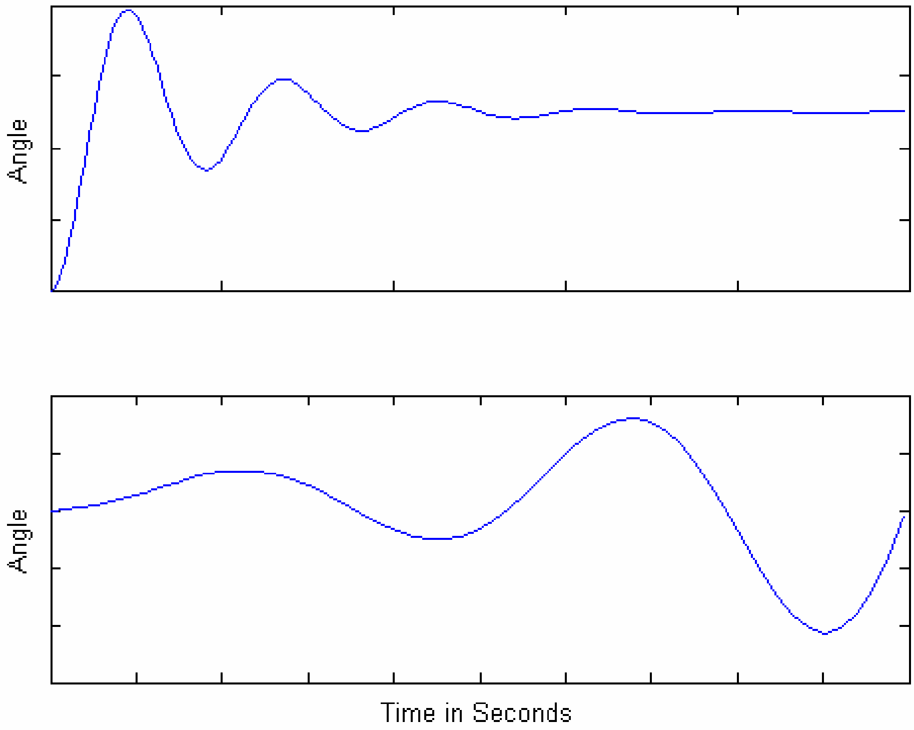

Figure 2.3 Angle deviation of the transiently stable system (a) and unstable system (b).

Many power systems restrict their power transfers due to transient stability concerns. In general, power systems with long transmission lines and remote generation are most susceptible to transient instability.

The way to analyze the transient stability limit is to study the change of rotor angle of all synchronous machines connected to the system after the system was subjected to a large disturbance. Numerical integration techniques are used in analyzing the transient stability of power systems.

2.3.5. Small Signal Stability

Small signal stability or oscillatory stability is the ability of the power system to be in synchronism after subject to a small disturbance. Oscillatory stability is characterized by the magnitude and duration of power system oscillations. Oscillation to voltage, frequency, angle and power flows can be triggered by many different events. This may involve generation control such as malfunctioning excitation system. These oscillations could grow so large that a system becomes oscillatory unstable.

Oscillatory instability may start as a harmless low magnitude power oscillation. Eventually, the oscillation could grow so large that the system starts to unravel. Transmission lines and generators may trip due to the oscillations. Oscillatory instability may take hours to develop or it may occur within a few seconds following a severe disturbance. The system may recover from a severe disturbance but it could gradually enter into a period of severe oscillations and become oscillatory unstable. Figure 2.4 shows the systems, which are small signal stable, oscillatory stable and unstable.

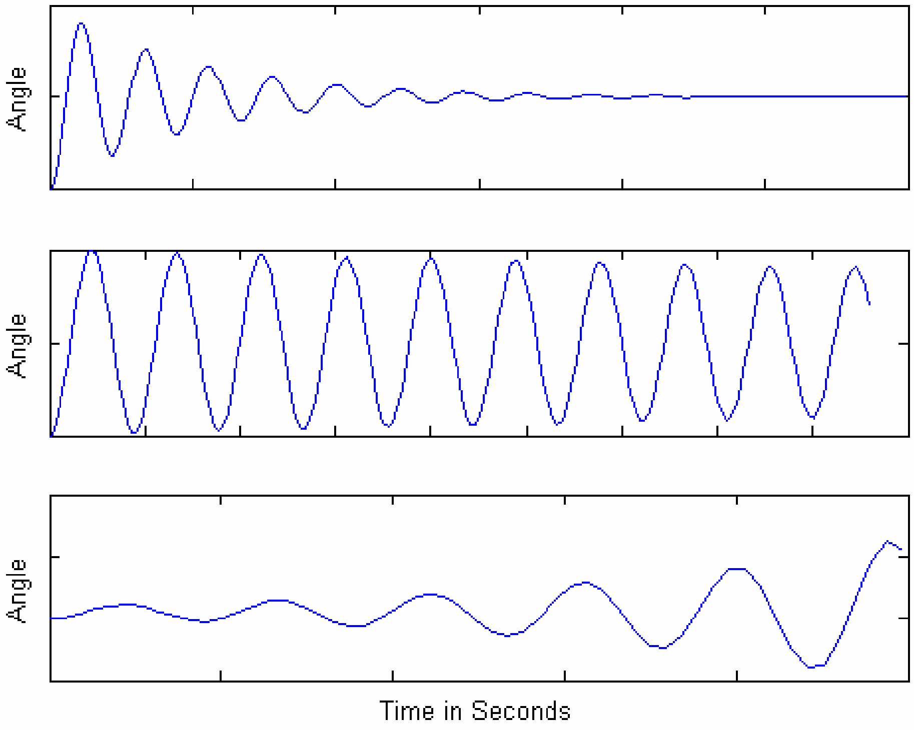

Figure 2.4 Angle deviation of small signal stable system (a), oscillatory stable system (b), and unstable system (c).

Utilities study their systems to determine safe power transfer limits. Stability limits are determined using computer analytical software tool. The entire power system is modeled to ensure that allowable power transfer limits do not expose the system to an unreasonable change of angle instability. The locations of eigenvalues of the system in the left half plane are used to investigate the small system stability of the power system.

Angle stabilities even do occasionally occur. Usually automatic protective equipment will activate to minimize the severity and spread of the disturbance. The critical elements that can save the system stability problems are FACTS devices, power system stabilizer and synchronous condensers.

2.3.6. Voltage Stability

Voltage stability of the system is the ability of power system to maintain adequate voltage magnitude so that when the system nominal load is increased, the actual power transferred to that load will increase. The main factor causing the voltage instability is the lack of reactive power supply in the system.

Voltage stability can be broadly classified based on time of simulation into two categories: static voltage stability and dynamic voltage stability. In dynamic consideration, studies include dynamic effects of equipments such as transformer tap changers, induction motor, load, etc. whereas static study considers load variation as a slow process over long period of time. Most of problem found in power system realizes voltage collapse as a static phenomenon. Static study is appropriate for the bulk power system study, which involves enormous number of buses and generators.

Static voltage instability is mainly associated with reactive power imbalance. Slowly developing changes in the power system occur that eventually lead to a shortage of reactive power and declining voltage. This phenomenon can be seen from the plot of the voltage at receiving end versus the power transferred. The plots are popularly referred to as P-V curve or “Nose” curve. Figure 2.5 shows examples of PV curves of base case and systems with various shunt compensation devices.

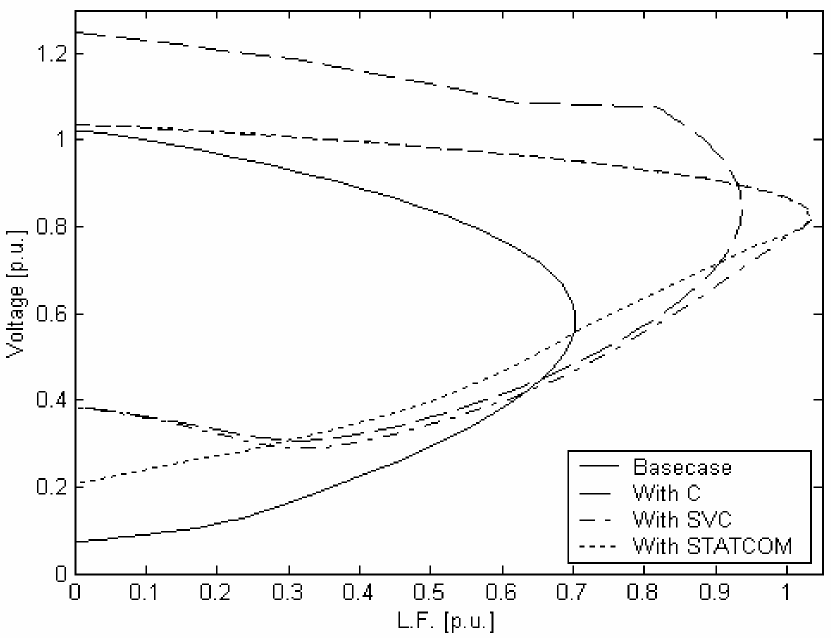

Figure 2.5 PV curves of Base Case, with various shunt controllers.

As the power transfer increases, the voltage at the receiving end decreases. Eventually, the critical (nose) point, the point at which the system reactive power is out of use, is reached where any further increase in active power transfer will lead to very rapid decrease in voltage magnitude. Before reaching the critical point, the large voltage drop due to heavy reactive power losses can be observed. The only way to save the system from voltage collapse is to reduce the reactive power load or add addition reactive power prior to reaching the point of voltage collapse. FACTS devices are a group of power electronics devices that can provide reactive power to the system in order to increase voltage stability margin.

Figure 2.6 shows various stability limits of power systems.

The thermal limits are always the highest and are concerned for short transmission lines up to a hundred miles. Voltage limits are always higher than the stability (transient or small signal) stability limits. Voltage (stability) limits are constraints for medium length transmission lines form 100 to 300 miles. Various dynamic stability limits are the lowest in power system and are constraints for long transmission lines of more than 300 miles.

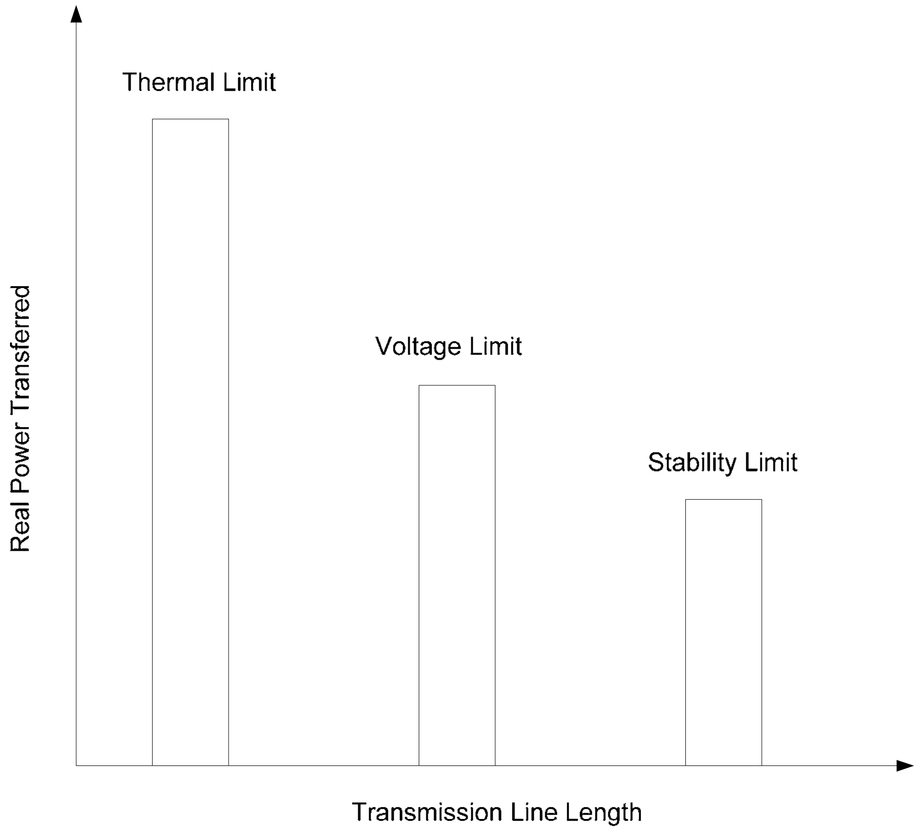

Figure 2.6 Power system limits.

By using appropriate FACTS controllers, it is possible to move various limits of power system close to thermal limits.

Chapter 3

Flexible AC Transmission System

3.1. Introduction

At present, power systems are highly complex and are typically composed of thousand of buses and hundreds of generators. New installations of power system equipment and facilities are primarily determined based economic and environmental considerations. In addition, new transmission lines are expensive and take considerable amount of time to build and put in operation. Given these conditions, in order to meet ever increasing power demands, electric utilities must rely on power export/import arrangements through existing transmission system. The current market environment also promotes the maximum utilization of existing facilities and favors power exchange from neighboring countries. These situations have resulted in an increased possibility of transient, oscillatory and voltage instability, which are now brought into concerns in many utilities both in planning and operation states. Moreover, the trend of the re-regulated power system operation has caused some other problems, such as congestion of transmission line corridors.

The recent development and use of Flexible AC Transmission System (FACTS) controllers in power transmission system have led to many applications of these controllers not only to improve the stability of the existing power network but also to provide operating flexibility to the power system. FACTS controllers, developed by Electric Power Research (EPRI) and Westinghouse Electric Corporation (Westinghouse), help utilities meet both the growing demand for electric power and the emerging challenges of open transmission access. The new devices, coupled with better computer and communications technology, offer the potential for enhanced system control both during the steady state operation and especially following system disturbance.

FACTS devices are defined by the IEEE as “alternating current transmission system incorporating power electronic-based and other static controllers to enhance controllability and increase power transfer capability”. From the above definition, two main objectives of such devices can be restated as follows:

- To increase the power transfer capability of the transmission networks
- To provide direct control of power flow over designated transmission routes.

With these objectives, the FACTS controllers may provide significant benefits in terms of greater flexibility and extended stability margin of power systems. To accomplish the objectives, FACTS devices increase the power system performance by delivering or absorbing real and/or reactive power. There are many types of FACTS controllers available; Static Var Compensator (SVC), Static Synchronous Compensator (STATCOM), Thyristor-Controlled Series Capacitor (TCSC), Static Synchronous Series Compensator (SSSC) and Unified Power Flow Controller (UPFC) are well-known FACTS devices. They can be connected to a transmission line at any appropriate location in series, in shunt or in a combination of series and shunt. The SVC and STATCOM are connected in shunt, whereas TCSC and SSSC are connected in series. UPFC is connected in series and shunt combination.

Although FACTS devices can offer high-speed control for enhancing power system, one important disadvantage of power electronic based controllers is more cost per unit of rating than that of similar conventional equipment. Table 3.1 gives an idea about the cost of various shunt controllers compared to that of shunt capacitor [6].

Table 3.1 Cost comparison of shunt controllers

Shunt Controller	Cost (US $)
Shunt Capacitor	8/kVar
Series Capacitor	20/kVar
SVC	40/ kVar controlled portions
TCSC	40/ kVar controlled portions
STATCOM	50/ kVar
UPFC Series Portions	50/ kVar Through power
UPFC Shunt Portions	50/ kVar controlled

While the cost of FACTS devices is much higher, it provides smooth and fast response to secure power system during normal and steady state operations. Shunt capacitor, on the other hand, provides coarse response and cannot control voltage at the connected bus. Accordingly, these FACTS controllers along with their properties in rapid and fast response can provide the appropriate control for the stability improvement, especially for voltage stability.

This chapter is intended to provide an overview and appropriate models of some well known FACTS controllers in order to provide the merits and applications of FACTS to the operations of transmission and distribution systems. Shunt and series FACTS compensation including their overview and representation models are presented in section 3.2 and 3.3, respectively. Finally UPFC, a combination of shunt and series compensation, is described in details in section 3.4.

Understanding the behaviors and characteristics of these FACTS devices are necessary. Features and characteristics along with their model representations will be discussed in the next sections.

3.2. Shunt Compensation Devices

There are many FACTS controllers currently available in utilities. Generally, FACTS devices are divided into three categories: shunt devices, series devices and shunt-series devices. SVC and STATCOM are examples of FACTS devices those are connected in shunt.

3.2.1 Static Var Compensator (SVC)

Prior to development of SVC, the adjustment of voltage in transmission system, other than generator and synchronous compensator, was made possible only by mechanically switched shunt reactors and capacitors. The switching of shunt reactors and capacitors is normally crude, causing abrupt voltage changes along with voltage and current transient. The SVC, on the other hand, provides rapid and fine adjustment of voltage, which is desirable in power system control and operation.

From the system point of view, SVC is a shunt connected static var generator/load whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific power system variables. SVC is similar to a synchronous compensator in that it is used to supply or absorb reactive power but without rotating part. It operates similar to an automatic voltage regulator system to set and maintain a target voltage level. The basic structure and stability model of this controller are shown in Figures 3.1 and 3.2, respectively.

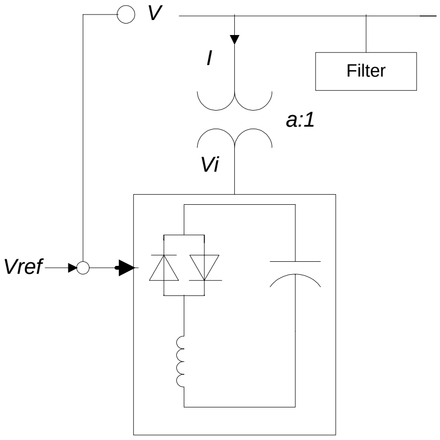

Figure 3.1 Basic structure of SVC.

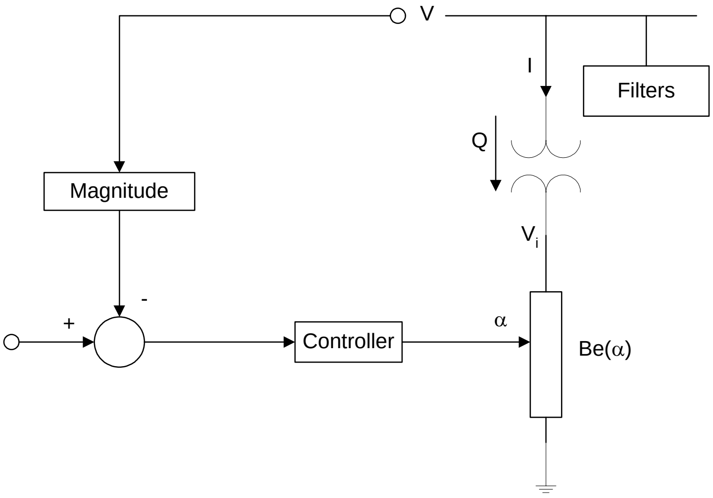

Figure 3.2 Stability Model of SVC.

SVC is composed of a controllable shunt reactor and shunt capacitor(s), as shown in Figure 3.1. Typically, the power system control variable controlled by SVC is the terminal bus voltage. In Figure 3.2, total susceptance of SVC can be controlled by firing thyristors in an appropriate angle range, typically 90^0~180^0. Consequently, it represents the controller with variable impedance that is changed with the firing angle of TCR. The Terminal or V-I Characteristics of SVC is illustrated in Figure 3.3.

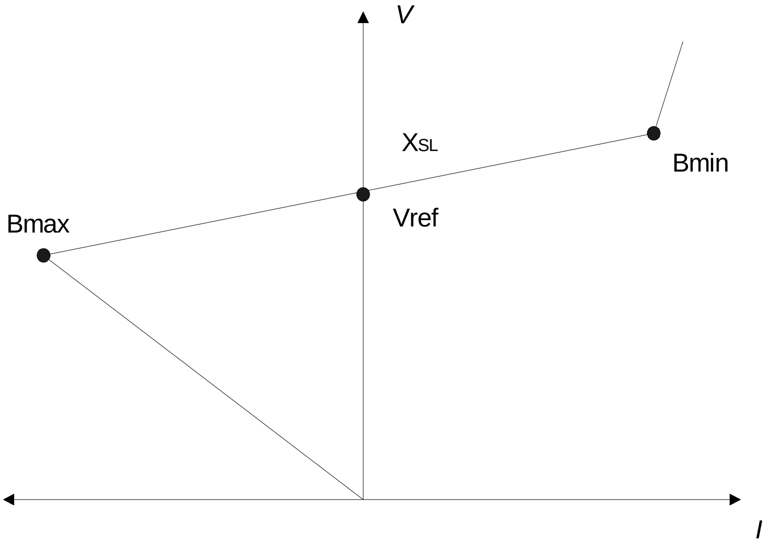

Figure 3.3 Terminal characteristic of SVC.

During the normal operation, SVC can control the total susceptance according to the terminal voltage. However, at limits, minimum or maximum susceptance, SVC behaves like a fixed capacitor or fixed inductor. At point B_{max}, all thyristor switched capacitor are switched on, with SVC providing rated capacitive current at specified voltage. At point B_{min}, the thyristor-controlled reactor is fully switched on, and all thyristor switched capacitor off to give inductive current at a defined voltage.

SVC can immediately provide reactive power support when the system has voltage problem due to a trip of an important generator or transmission line. In some applications, it can be used as an aid to improve stability; SVC can perform the duty of providing rapidly controlled vars more appropriately during the first angle swing and thus, by maintaining the voltage, inherently improve transient stability. In addition, it is possible with a SVC not only to maintain a reference voltage level, but also to modulate the reference voltage signal in order to improve system damping.

The basic elements of SVC may consist of:

- The fixed capacitor (FC) which provides a permanently connected source of reactive power designed also to behave as a harmonic filter.
- The thyristor controlled reactor (TCR) which consists of bi-directional thyristor valves in series with shunt reactors. These thyristor may be switched at any point over the half wave (90-180 electrical degree behind the voltage wave) to provide fully adjustable control over the full range of rated reactive power absorption.
- The thyristor switch capacitor (TSC) which has bi-directional thyristor value connecting shunt capacitors. A series reactor in each phase limits inrush current. Switching on TSC provides the generating reactive power either fully on or fully off. A double voltage will appear across the valve immediately after it is switched off, therefore a valve requires higher valve rating than for a TCR of the same MVar rating.

Note that not all SVCs need all the above elements. There are two popular configurations of SVC; One is a Fixed Capacitor (FC) and Thyristor controlled Reactor (TCR) configuration and the other one is Thyristor Switched Capacitor (TSC) and TCR configuration. Figure 3.4 shows losses versus output for these two types of SVC: FC+TCR and TCR+TSC. The former requires less capital equipment but provide high losses in inductive operation. In the latter, the switched capacitor steps can be arranged to give a different loss curve. The choice is optimized by consideration of both the equipment cost and the capitalized cost of losses at the expected normal operating points. Note that choosing appropriate size is one of the important issues in SVC application in voltage stability enhancement.

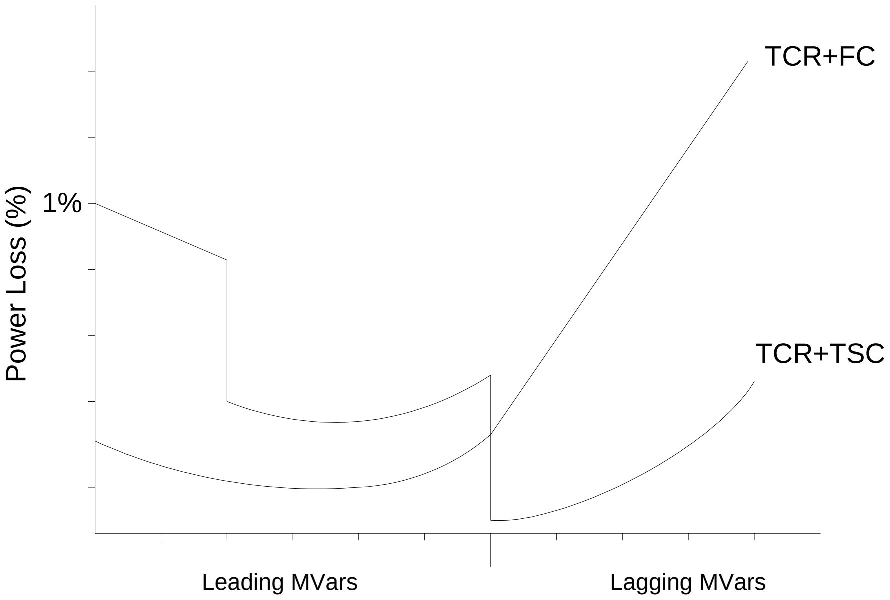

Figure 3.4 Typical SVC loss curves for TCR+FC and TCR+TSC.

In power system study, it is important to include appropriate model of SVC with all necessary elements of the SVC controller along with its non-linearity. The validated p.u. Differential-Algebraic Equations (DAEs) corresponding to this model are [11]:

$$\begin{bmatrix} \dot{x}_c \\ \dot{\alpha} \end{bmatrix} = f(x_c, \alpha, V, V_{ref}) \tag{3.1}$$

$$0 = \underbrace{\begin{bmatrix} B_e - \dfrac{2\alpha - \sin 2\alpha - \pi(2 - X_L / X_C)}{\pi X_L} \\ I - V_i B_e \\ Q - V_i^2 B_e \end{bmatrix}}_{g(\alpha, V, V_i, I, Q, B_e)} \tag{3.2}$$

where, all variables are clearly defined in Figure 3.2, and X_C and f(.) stand for the control system variables and equations, respectively. These equations represent limits not only on the firing angle α, but also on the current *I*, the control voltage *V* and the SVC voltage V_i as well as the reactive power.

The SVC steady state model can be obtained by replacing the equations (3.1) and (3.2) with

$$0 = \begin{bmatrix} V - V_{ref} - X_{SL} I \\ g(\alpha, V, V_i, I, Q, B_e) \end{bmatrix} \tag{3.3}$$

which can be directly included in any power flow program with the proper handling of firing angle limits. Note that equation (3.2) provides the relationship between SVC susceptance (Be) and α, *I* and *Q*.

The SVC control limits are normally represented as limits on the firing angle α, which is in $\alpha_m < \alpha < \alpha_M$, where α_m and α_M are minimum and maximum firing angles, respectively. If there is no solution within these limits, the firing angle is fixed at the corresponding limit and V_{ref} is then allowed to change. The procedure of handling the control limits is depicted in Figure 3.5 below:

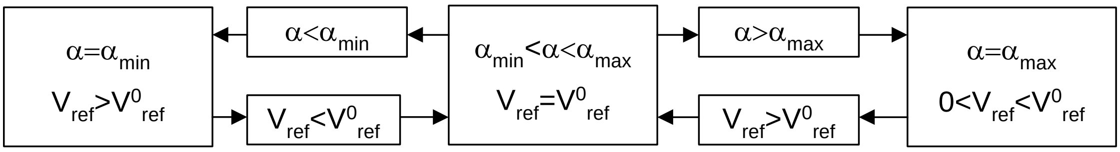

Figure 3.5 Handling of limits in the SVC steady state model.

3.2.2 Static Synchronous Compensator (STATCOM)

The STATic synchronous COMpensator (STATCOM), previously referred to as a STATic synchronous CONdensor (STATCON), is based on a solid state synchronous voltage source that is analogous to an ideal synchronous machine without rotating mass. It generates a balanced set of sinusoidal voltages at the fundamental frequency with rapidly controllable amplitude and phase angle. As shown in Figure 3.6, STATCOM is the voltage-source converter, which converts a DC input voltage into AC output voltage at fundamental frequency in order to compensate the active and reactive power needed by the system. The reference signals Q_{ref} and P_{ref} can control the amplitude V and phase angle β of output voltage, respectively.

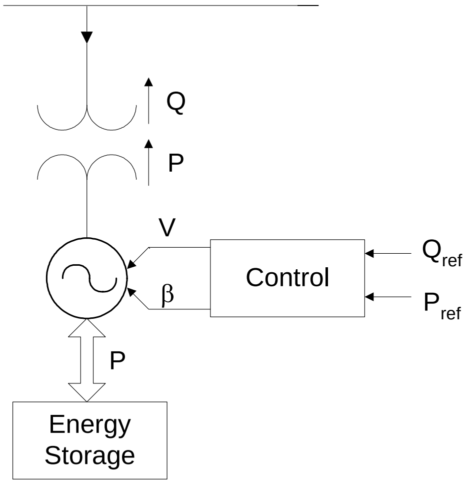

Figure 3.6 Generalized synchronous voltage source.

Varying the amplitude of output voltage can control the reactive power exchange between the inverter and the AC system. If the amplitude of the output voltage is increased above that of AC system voltage, the inverter generates reactive power for the AC system. If the amplitude of the output voltage is decreased below that of the AC system, the inverter absorbs the reactive power. If the output voltage is equal to the AC system voltage, the reactive power exchange is zero.

The real power exchanges between the inverter and the AC system can be controlled by altering the phase angles between the inverter output and the AC system voltages. The inverter supplies real power to the AC system if the inverter output voltage is made to lead the corresponding AC system voltage. Conversely, the inverter absorbs real power from the AC system, if the inverter output voltage is made to lag the AC system voltage.

The basic structure and V-I characteristic of STATCOM are shown in Figures 3.7 and 3.8, respectively. As can be seen from Figure 3.8, the controller can provide both capacitive and inductive compensation and is able to control output current over the rated maximum capacitive or inductive range independent of the AC system voltage. It can provide full capacitive output current at any practical system voltage. This is in contrast to the SVC which can supply only a diminishing output current with decreasing system voltage as determined by the designed maximum equivalent capacitive admittance. This type of controller is, therefore, more effective than the SVC in providing transmission voltage support and the expected stability improvements. In general, a reduction of more than 50 % in the physical size of installation can be expected from STATCOM compared to SVC. Also, for steady state reactive support, a STATCOM is capable of supporting higher loads than what would be possible with a SVC of comparable MVAr rating.

The STATCOM may have an increased transient rating in both the inductive and capacitive operating regions, which can further enhance its dynamic performance. The conventional SVC can increase transient var absorption capability only. This is because it has no means to transiently increase the var generation since the maximum capacitive current it can draw is strictly determined by the value of its maximum capacitance and the magnitude of the system voltage. The transient rating of the STATCOM is dependent on the characteristics of the power semiconductors used and the maximum junction temperature at which the devices can be operated. Furthermore, this controller does not significantly alter the existing system impedance, which is an advantage over the static var compensators (SVCs).

In summary, STATCOM has better characteristics over SVC; when the system voltage drops enough to force the STATCOM output to ceiling, its maximum reactive power output will not be affected by the voltage magnitude. Therefore, it exhibits constant current characteristics when the voltage is low under the limit. The steady state power exchange between the controller and the AC system is mostly reactive, as active power is only consumed to supply for the internal losses.

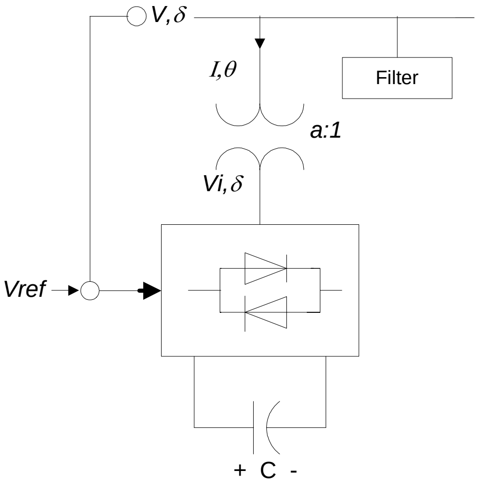

Figure 3.7 Basic structure of STATCOM.

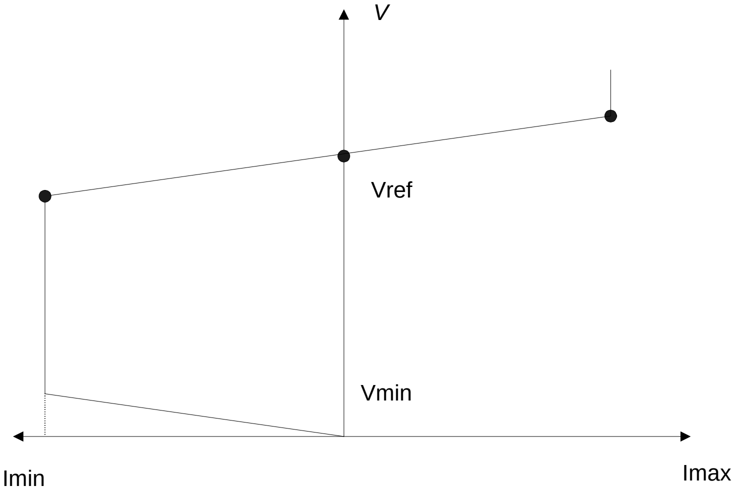

Figure 3.8 Terminal characteristic of STATCOM.

There are two techniques for controlling the STATCOM. The first technique, referred to as phase control, is to control the phase shift β to control the STATCOM output voltage magnitude. The other technique referred to as Pulse Width Modulation (PWM) on the other hand allow for independent control of output voltage magnitude and phase shift (phase angle of the output voltage); in this case, the DC voltage is controlled separately from the AC output voltage.

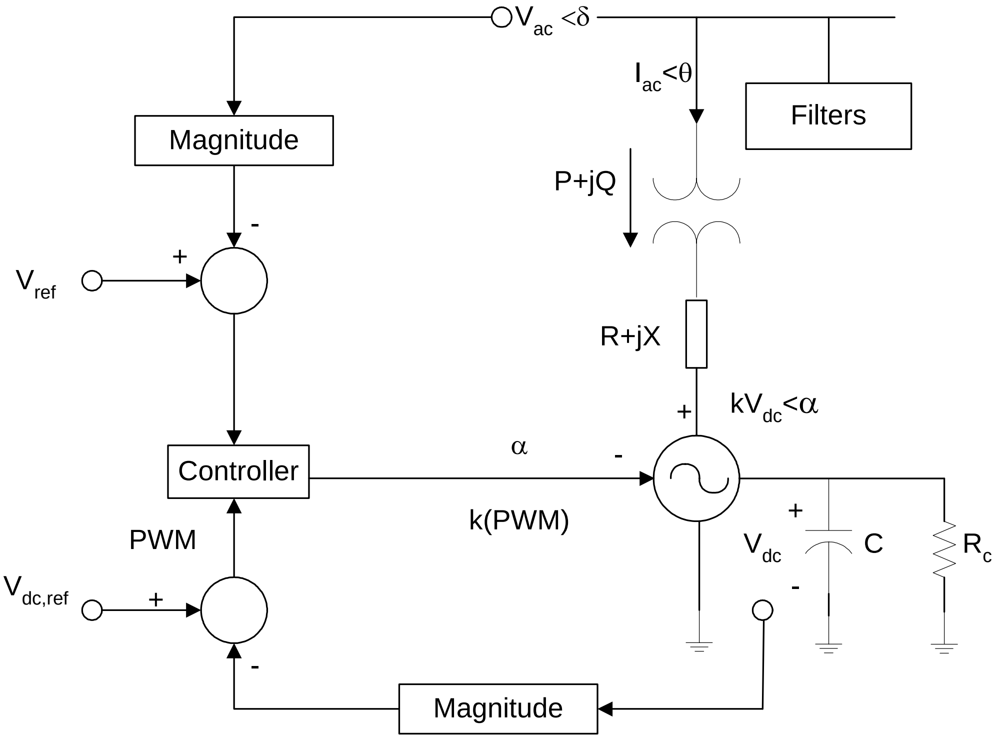

Figure 3.9 Stability Model of STATCOM.

STATCOM should be modeled to cover the limits in both control and operation. Instead of representing STATCOM by a synchronous machine as in the conventional method, the appropriate models of the controller should be used to have a more accurate result. To fulfill that, the p.u. Differential-Algebraic Equations (DAEs) corresponding to this model are described as follows [11]:

$$\begin{bmatrix} \dot{x}_c \\ \dot{\alpha} \\ \dot{m} \end{bmatrix} = f(x_c, \alpha, m, V, V_{dc}, V_{ref}, V_{dc,ref}) \tag{3.4}$$

$$\dot{V}_{dc} = \frac{VI}{CV_{dc}}\cos(\delta-\theta) - \frac{1}{R_c C}V_{dc} - \frac{R}{C}\frac{I^2}{V_{dc}} \tag{3.5}$$

$$0 = \underbrace{\begin{bmatrix} P - VI\cos(\delta-\theta) \\ Q - VI\sin(\delta-\theta) \\ P - V^2G + kV_{dc}VG\cos(\delta-\alpha) + kV_{dc}VB\sin(\delta-\alpha) \\ Q + V^2B - kV_{dc}VB\cos(\delta-\alpha) + kV_{dc}VG\sin(\delta-\alpha) \end{bmatrix}}_{g(\alpha,k,V,V_{dc},\delta,I,\theta,P,Q)} \tag{3.6}$$

where, all variables are clearly defined on Figure 3.9, m is modulation index, and X_c and f(.) stand for the control system variables and equations, respectively.

The steady state model of STATCOM can be readily obtained from equations (3.4)-(3.6) as;

$$0 = \begin{bmatrix} V - V_{ref} \pm X_{SL} I \\ V_{dc} - V_{dcref} \\ P - V_{dc}^2 / R_C - RI^2 \\ g(\alpha, k, V, V_{dc}, \delta, I, \theta, P, Q) \end{bmatrix} \tag{3.7}$$

which can be directly included in any power flow program with the proper handling of limits, to analyze the static voltage stability of power system with STATCOM.

The limits on current I , as well as any other limits on the steady state model variables, such as the modulation ratio represented by k or the voltage phase angle α, can be directly incorporated in this model as depicted as an example in Figure 3.10 below:

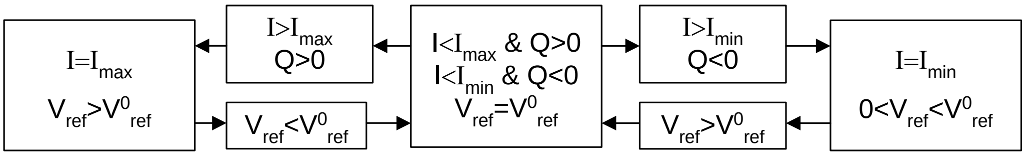

Figure 3.10 Handling of limits in the STATCOM steady state model.

In order to understand the models for STATCOM, some mathematical explanations are shown based on Figure 3.9. Assuming that all signals are sinusoidal, the instantaneous power flowing into the inverter from the AC bus may be represented by

$$p = 3V_{ac} I_{ac} \cos(\delta - \theta) \tag{3.8}$$

where, V_{ac} and I_{ac} are the rms values of the terminal line-to-neutral voltage and line current of th,e controller, respectively, and δ and θ stand for phases of voltage and line current.

The AC system voltage may be controlled using the phase shift α between the bus phase voltage v_{ac} and the corresponding output voltage of inverter v_{inv}, i.e.,

$$v_{ac} = \sqrt{2} V_{ac} \sin(wt + \beta) \tag{3.9}$$

$$v_{inv} = \sqrt{2} V_{inv} \sin(wt + \beta + \alpha) \tag{3.10}$$

Neglecting losses, for $\alpha < 0^0$, the inverter output voltage lags the bus voltage and the capacitor charges ($p > 0$), whereas for $\alpha > 0^0$, the inverter AC voltage leads the bus voltage and the capacitor discharge ($p < 0$). Hence, this controller is synchronized with respect to the AC terminal voltage. Observe that the rms inverter voltage v_{inv} may be defined as

$$V_{inv} = kV_{dc} \tag{3.11}$$

where, V_{dc} is the average DC voltage on the capacitor, and *k* is a constant corresponding to the magnitude of the fundamental frequency component of the fourier series representation of the inverter output voltage. For example, for phase control, $k = 0.9$ for a 12-pulse inverter, and for PWM control k is a controlled variable, which is defined as $\sqrt{3/8}\, m$.

The power balance between the AC and DC sides is given by

$$p = 3V_{ac}I_{ac}\cos\left(\delta - \theta\right) = V_{dc}I_{dc} + 3a^2RI_{ac}^2 \tag{3.12}$$

$$= V_{dc}\left(C\frac{dV_{dc}}{dt} + \frac{V_{dc}}{R_C}\right) + 3a^2RI_{ac}^2 \tag{3.13}$$

where, *a* is the transformer turn ratio, *R* is a resistance in series with the VSI used to represent the losses on the AC side of the converter, and R_C is a resistance in parallel with the inverter capacitor *C* used to model the DC converter losses and the charging/discharging time constant of this capacitor. Hence, it follows that the V_{dc} voltage changes are approximated by the nonlinear differential equation as

$$\frac{dV_{dc}}{dt} = 3\frac{V_{ac}I_{ac}}{CV_{dc}}\cos\left(\delta - \theta\right) - \frac{1}{R_C C}V_{dc} - 3\frac{a^2R}{C}\frac{I_{ac}^2}{V_{dc}} \tag{3.14}$$

and the p.u. equation is, therefore,

$$\dot{V}_{dc} = \frac{VI}{CV_{dc}}\cos(\delta - \theta) - \frac{1}{R_c C}V_{dc} - \frac{R}{C}\frac{I^2}{V_{dc}} \tag{3.15}$$

Equation (3.15) is same as the equation (3.5). Equation (3.4) corresponds to the control system model used for the STATCOM whereas equation (3.6) regards to power flow equation at the connected bus. Equation (3.7) along with the limits of firing angle (α) can be included in any power flow program for appropriate representation of STATCOM.

As already discussed, the main objective of shunt FACTS devices is to deliver/absorb reactive power. The devices can increase the power transfer capacity and indirectly control the power flow of transmission lines by adjusting the reactive power at the connected bus. To have a direct control over the power flow in a transmission line, series compensation devices are required. The series compensation devices will be discussed in the following section.

3.3. Series Compensation Devices

In the previous section, shunt compensation controllers have been discussed in details for their representations and appropriate models. In this section, however, the group of controllers, which are predominantly series in nature, is elaborated. At first, the conventional series FACTS device, which is Thyristor Controlled Phase Shifting Transformers (TCPS), is discussed. Subsequently, thyristor controlled based series compensators: TCSC and Thyristor Switched Series Compensator (TSSC) are presented. Finally, voltage source inverter based compensators, SSSC, is discussed.

3.3.1 Thyristor Controlled Phase Shifting Transformers (TCPS)

The basic function of the TCPS is to provide means to control power flow in a transmission line by inserting a variable quadrature voltage in series with the transmission line. The power flow which is proportional to phase angle difference between sending end and receiving end voltages of the line can be controlled by varying the magnitude of the series quadrature voltage. Historically, this has been accomplished by specially connected mechanical regulating transformers.

The potential benefits of TCPS, especially, in transient alteration of power include:

- The damping of system oscillations.
- The mitigation of transient or post-disturbance voltage dips due to heavy line loading.
- The mitigation of heavy through-flows, which might cause cascading relay action, out-of-step conditions or abnormal reactive consumption.

3.3.2 Thyristor Controlled Series Compensator (TCSC)

It is obvious that power transfer between areas can be affected by adjusting the net series impedance. One such conventional and established method of increasing transmission line capability is to install a series capacitor, which reduces the net series impedance, thus allowing additional power to be transferred. Although this method is well known, slow switching times and large discrete segments of mechanical switching devices are the limitations of its uses. Thyristor controllers, on the other hand, are able to rapidly and continuously control the line compensation over a continuous range with resulting flexibility. Controllers used for series compensation have to date been developed in two different configurations: the Thyristor Controlled Series Compensator (TCSC) and Thyristor Switched Series Compensator (TSSC).

a) TCSC

TCSC controllers use thyristor-controlled reactor (TCR) in parallel with capacitor segments of series capacitor bank. The basic structure and stability model of the device are shown in Figure 3.11 and 3.12, respectively. The combination of TCR and capacitor allow the capacitive reactance to be smoothly controlled over a wide range and switched upon command to a condition where the bi-directional thyristor pairs conduct continuously and insert an inductive reactance into the line. For operation in the capacitive region, the maximum voltage constrains operation, whereas inductive operation is limited by the maximum firing delay (α). Between these constraints is an additional limiting characteristics related to harmonics, which can cause additional heating in the surge reactor and thyristors.

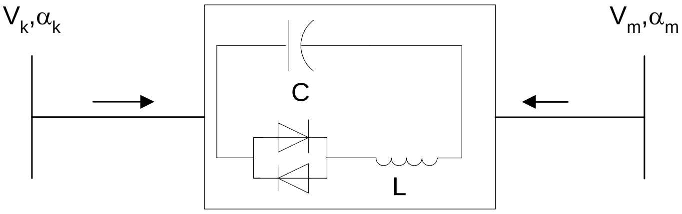

Figure 3.11 Basic structure of TCSC.

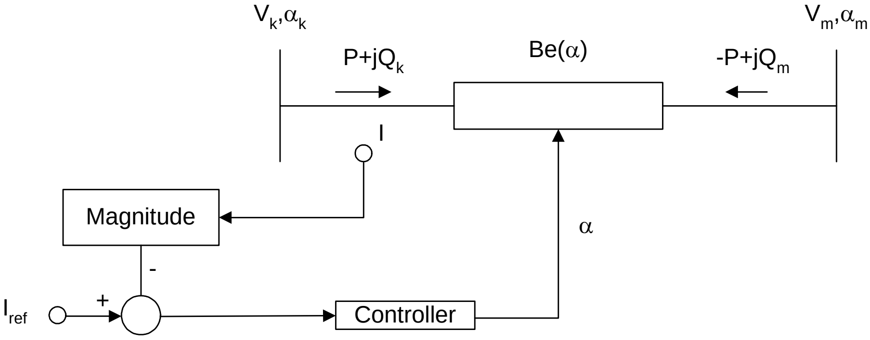

Figure 3.12 Stability model of TCSC.

b) TSSC

TSSC controllers use thyristor switches in parallel with segments of the series capacitor bank to rapidly insert or remove portions of the bank in discrete steps. The only difference is that the reactor is in series with the thyristors and sized as small as possible to limit thyristor current under transient conditions. TSSC controllers have the ability to switch capacitor segments between the bypassed and blocked conditions to achieve two levels of compensation on the transmission line. By combining several thyristor modules and capacitor segments, additional ranges in the compensation level can be realized.

Compared with TSSC, the TCSC allows higher level of series compensation with significantly reduced risk of SSR interaction. It can be quickly switched to bypass mode with resulting inductive reactance effective in reducing short-circuit current levels. TCSC and TSSC controllers can be used to quickly bypass the series capacitors for protection from fault induced over voltages and to rapidly reinsert the capacitors after fault clearing to improve system recovery following network disturbances. The introduction of these and other series compensation systems into a transmission line increases the steady-state electrical losses, which vary with line current and operating point. This should be considered at the planning stage when selecting the most suitable location and configuration.

As stated in the previous paragraph, TCSC is more common compared to TSSC, so it will be more useful to investigate the device in this study. Suitable models those are able to handle control limits and operation constraints are very crucial. The p.u. DAEs corresponding to this device are shown as follows [11]:

$$\begin{bmatrix} \dot{x}_c \\ \dot{\alpha} \end{bmatrix} = f(x_c, \alpha, V, V_{ref}) \tag{3.16}$$

$$0 = \underbrace{\begin{bmatrix} P + V_k V_m B_e \sin\left(\delta_k - \delta_m\right) \\ -V_k^2 B_e + V_k V_m B_e \cos\left(\delta_k - \delta_m\right) - Q_k \\ -V_m^2 B_e + V_k V_m B_e \cos\left(\delta_k - \delta_m\right) - Q_m \\ B_e - B_e\left(\alpha\right) \\ \sqrt{P^2 + Q_k^2} - I V_k \end{bmatrix}}_{g\left(\alpha, V_k, V_m, \delta_k, \delta_m, I, P, Q_k, Q_m, B_e\right)} \tag{3.17}$$

where, all variables are obviously identified in Figure 3.12,

$$\begin{aligned} B_e\left(\alpha\right) = {} & \pi\left(k_x^4 - 2k_x^2 + 1\right)\cos k_x\left(\pi - \alpha\right) / \\ & \{X_C[\pi k_x^4 \cos k_x\left(\pi - \alpha\right) \\ & - \pi \cos k_x\left(\pi - \alpha\right) - 2k_x^4 \alpha \cos k_x\left(\pi - \alpha\right) \\ & + 2\alpha k_x^2 \cos k_x\left(\pi - \alpha\right) - k_x^4 \sin 2\alpha \cos k_x\left(\pi - \alpha\right) \\ & + k_x^2 \sin 2\alpha \cos k_x\left(\pi - \alpha\right) - 4k_x^3 \cos^2 \alpha \sin k_x\left(\pi - \alpha\right) \\ & - 4k_x^2 \cos\alpha \sin\alpha \cos k_x\left(\pi - \alpha\right)]\} \end{aligned} \tag{3.18}$$

and

$$k_x = \sqrt{\frac{X_C}{X_L}} . \tag{3.19}$$

The steady state model of TCSC can be easily obtained from (3.16)-(3.19) as

$$0 = \begin{bmatrix} B_e - B_{e,ref} \\ g\left(\alpha, V_k, V_m, \delta_k, \delta_m, I, P, Q_k, Q_m, B_e\right) \end{bmatrix} \tag{3.20}$$

which can be directly introduced to the power flow program. Again, the limits of firing angles have to be considered in the study.

The TCSC control limits are basically limited on the firing angle α, which is in $\alpha_m < \alpha < \alpha_M$, where α_m and α_M are minimum and maximum firing angles, respectively. If there is no solution within these limits, the firing angle is fixed at the corresponding limit and the control mode is simply switched to reactance control. The procedure to handle the control limit is depicted in Figure 3.13 below:

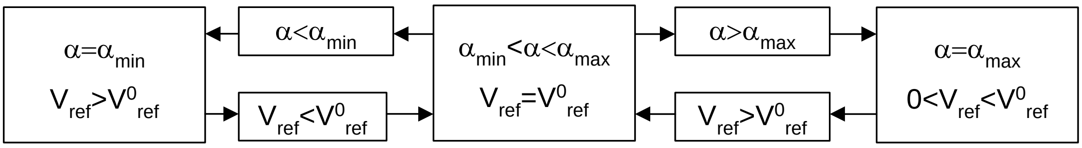

Figure 3.13 Handling of limits in the SVC steady state model.

3.3.3 Synchronous Series Compensator (SSSC)

The solid-state synchronous voltage source employing an appropriate DC to AC inverter with gate turn-off thyristor can be used for series compensation of transmission lines. One of the equipment that can achieve this task is SSSC. The SSSC is similar to the STATCOM as illustrated in Figure 3.14, as it is based on a DC capacitor fed VSI that generates a three-phase voltage at fundamental frequency, which is then injected in a transmission line through a transformer connected in series with the system.

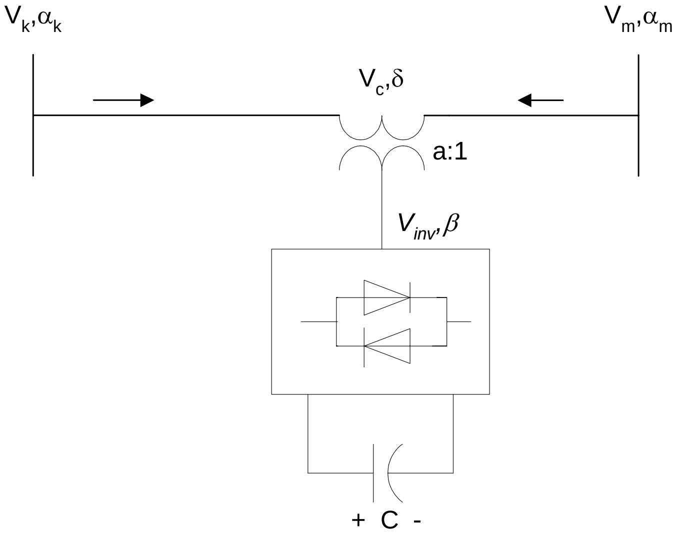

Figure 3.14 Basic structure of SSSC.

The main control objective of the SSSC is to directly control the current, and indirectly the power, flowing through the line by controlling the reactive power exchange between the SSSC and the AC system. The main advantage of this controller over a TCSC is that it does not significantly affect the impedance of the transmission system and, therefore, there is no danger of having resonance problem.

To understand the device more, some explanations are expressed related to its main concept and fundamentals. From the Figure 3.14, the solid-state voltage source produces an appropriate voltage at the fundamental AC system frequency, in series with the line to partially cancel the voltage drop. The output of the solid-state synchronous voltage source is locked with a lagging relationship to the line current and injected in series with the line. If the magnitude of the injected voltage is made proportional to that of the line current, a series compensation equivalent to that provided by a series capacitor at the fundamental frequency is obtained. Mathematically, this voltage source can be defined as follows:

$$V_C = -jkXI_{ac} \tag{3.21}$$

where, V_C is the injected compensating voltage phasor, I_{ac} is the line current phasor, X is the series line impedance, and k is the degree of series compensation (continuously variable over the range $0 < k < 1$). For conventional series compensation k is defined as X_C / X, where X_C is the impedance of the series capacitor.

The strategy of SSSC is to control the rms magnitude I_{ac} of the AC current and the rms magnitude V_C of the controller's AC phasor voltage, therefore to control the reactive power delivered or absorbed by the controller. If the reactance of the coupling transformer is assumed to be small, the AC output voltage is directly controlled through the VSI voltage magnitude V_{inv}, which can be easily changed by charging or discharging the capacitor. In steady state, assuming minimum controller losses, the phase shift β of the inverter voltage V_{inv} with respect to the AC current i_{ac} is approximately -90^0 if the controller is delivering reactive power (capacitive), or $+90^0$ if it is absorbing reactive power (inductive). The charging and discharging of the capacitor, and hence the change of DC voltage V_{dc}, and the associated magnitude V_{inv}, is controlled by smoothly changing the phase shift β. Hence, for transient changes in β such that $-90^0 < \beta < 90^0$, the controller absorbs active power and the capacitor charges; for $\beta < -90^0$ and $\beta > 90^0$, the controller delivers active power and the capacitor discharges.

In the operation, the generalized series synchronous compensator is considered as shown in Figure 3.15. Assume that the injected voltage (V_C) in series with the line can be achieved if the DC energy storage has an infinite capacity. The phase angle of voltage can thus be chosen independently of the line current between 0 and 2π with a magnitude which is variable between zero and a defined maximum value $V_{C,\max}$. This implies that the synchronous voltage source must be able to generate and absorb both real and reactive power. The reactive power is therefore internally generated or absorbed by the inverter. However, the real power is supplied from, or absorbed by, the DC energy storage device, which normally produces a little active power flow from the system in steady state operation, just enough to supply the controller losses.

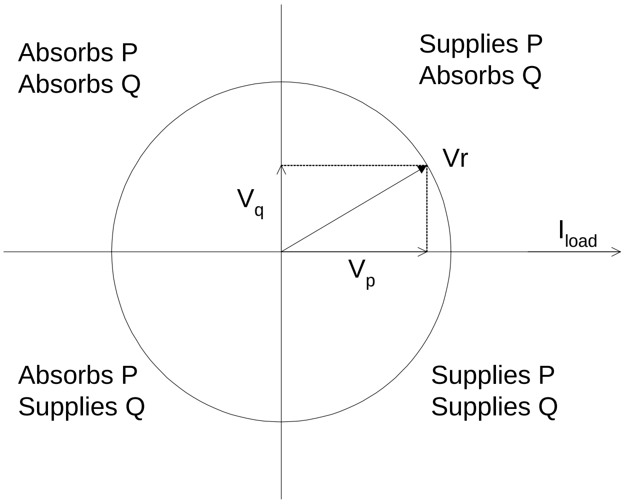

Figure 3.15 Operation diagram of SSSC.

The SSSC rating imposes a maximum limit on V_C, the injected voltage. Losses are primarily a function of line current flow, with some lesser dependency on the magnitude of voltage being injected. The reactance of step-down transformer should be smaller than that of a typical voltage transformer, so that this reactance does not significantly affect the power transfer capabilities of the transmission line.

The p.u. DAEs of SSSC including the control and operation limits can be elaborated as follows [11]:

$$\begin{bmatrix} \dot{x}_c \\ \dot{\beta} \\ \dot{m} \end{bmatrix} = f(x_c, \beta, m, I, V_{dc}, I_{ref}, V_{dcref}) \tag{3.22}$$

$$\dot{V}_{dc} = \frac{VI}{CV_{dc}}\cos(\delta - \theta) - \frac{G_C}{C}V_{dc} - \frac{R}{C}\frac{I^2}{V_{dc}} \tag{3.23}$$

$$0 = \underbrace{\begin{bmatrix} P_k - V_k I\cos(\delta_k - \theta) \\ Q_k - V_k I\sin(\delta_k - \theta) \\ P_m - V_m I\cos(\delta_m - \theta) \\ Q_m - V_m I\sin(\delta_m - \theta) \\ P - P_k + P_m \\ Q - Q_k + Q_m \\ P - V^2 G + kV_{dc}VG\cos(\delta - \beta) + kV_{dc}VB\sin(\delta - \beta) \\ Q + V^2 B - kV_{dc}VB\cos(\delta - \beta) + kV_{dc}VG\sin(\delta - \beta) \end{bmatrix}}_{g(\beta, k, V_{dc}, V_k, V_m, V, \delta_k, \delta_m, \delta, I, \theta, P_k, P_m, P, Q_k, Q_m, Q)} \tag{3.24}$$

where, all variables are defined in Figure 3.16.

To realize the models in power flow program, equations (3.22)-(3.24) are used as

$$0 = \begin{bmatrix} I - I_{ref} \\ V_{dc} - V_{dcref} \\ P - G_C V_{dc}^2 - RI^2 \\ g(\beta, k, V_{dc}, V_k, V_m, V, \delta_k, \delta_m, \delta, I, \theta, P_k, P_m, P, Q_k, Q_m, Q) \end{bmatrix} \tag{3.25}$$

which can be incorporated into the power flow program.

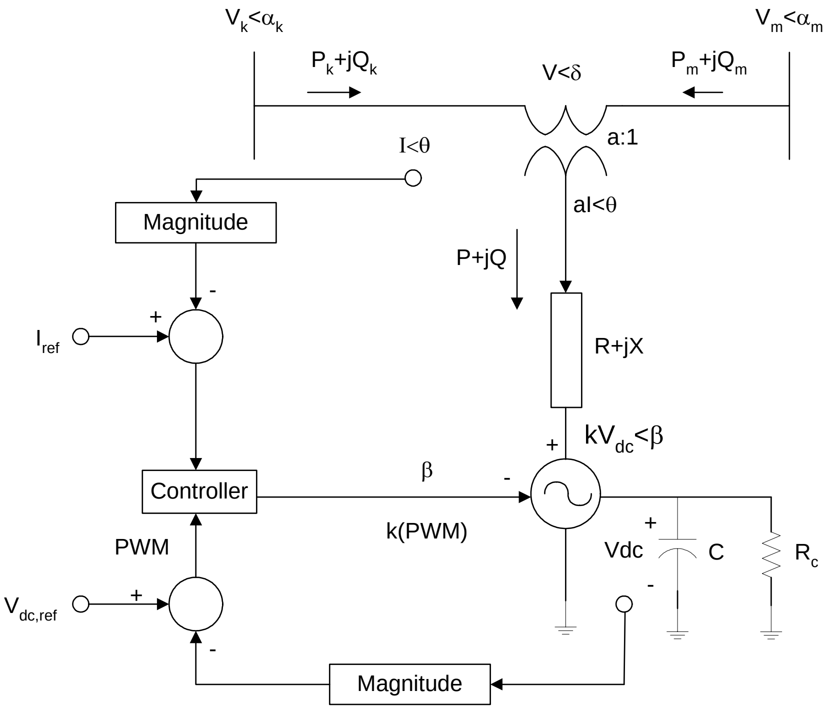

Figure 3.16 Stability model of SSSC.

The limits on current I, as well as any other limits on the steady state model variables, such as the modulation ratio represented by k or the voltage phase angel α, can be directly incorporated in this model as depicted as an example in Figure 3.17 below:

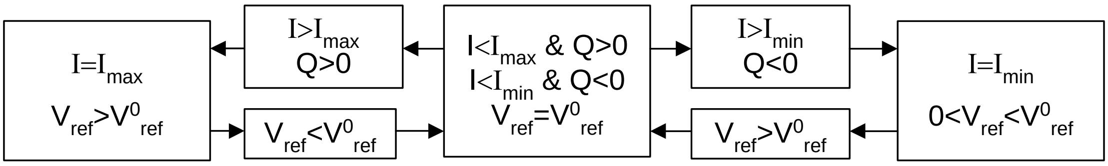

Figure 3.17 Handling of limits in the SSSC steady state model.

In order to understand the appropriate model representation, the mathematical details of the devices can be explained from Figure 3.16. Assuming that all signals are sinusoidal, the instantaneous power flowing into the inverter from the AC bus can be represented by

$$p = 3VI\cos(\delta - \theta) \tag{3.26}$$

where V and I are the rms values of the series voltage and line current of the controller, respectively, and δ and θ stand for the phases of those voltage and line current.

For the SSSC, the AC system current may be controlled using the phase shift β between the terminal line current i_{ac} and the corresponding output voltage of the inverter v_{inv}, i.e.,

$$i_{ac} = \sqrt{2}I\sin(wt + \gamma) \tag{3.27}$$

$$v_{inv} = \sqrt{2}\,kV_{dc}\sin(wt + \gamma + \beta)\,. \tag{3.28}$$

Neglecting losses, the inverter rms voltage magnitude V_{inv} increases when $-90^0 < \beta < 90^0$, as the capacitor charges ($p > 0$); V_{inv} decreases when $\beta < -90^0$ or $\beta > 90^0$, since the capacitor discharge ($p < 0$). Hence, this controller is synchronized with respect to the AC terminal current.

The power balance between the AC and DC sides is given by;

$$p = 3VI\cos\left(\delta - \theta\right) = V_{dc}I_{dc} + 3a^2RI^2$$

$$= V_{dc}\left(C\frac{dV_{dc}}{dt} + \frac{V_{dc}}{R_C}\right) + 3a^2RI^2 \tag{3.29}$$

where, a is the transformer turn ratio, R is a resistance in series with the VSI used to represent the losses on the AC side of the converter, and R_C is a resistance in parallel with the inverter capacitor C used to model the DC converter losses and the charging/discharging time constant of this capacitor. Hence, it follows that the V_{dc} voltage changes are approximated by the nonlinear differential equation (3.30).

$$\frac{dV_{dc}}{dt} = 3\frac{V\,I}{CV_{dc}}\cos\left(\delta - \theta\right) - \frac{1}{R_C C}V_{dc} - 3\frac{a^2R}{C}\frac{I^2}{V_{dc}}. \tag{3.30}$$

and the p.u. equation is, therefore,

$$\dot{V}_{dc} = \frac{VI}{CV_{dc}}\cos(\delta - \theta) - \frac{G_C}{C}V_{dc} - \frac{R}{C}\frac{I^2}{V_{dc}}. \tag{3.31}$$

As already mentioned, shunt compensation devices can deliver/absorb reactive power at the connected bus in order to control voltage at that bus. Series compensation devices, on the other hand, can modify the reactive power of the connected line, which is the power flow control. By combining shunt and series compensation devices to form a single controller, we can exploit the benefit of these both controllers. This device is known as UPFC, which will be discussed in details in the following section.

3.4. Unified Power Flow Controller (UPFC)

It is well known that UPFC is a powerful and versatile concept for power flow control that has capability of changing power flow. The rapid and almost instantaneous responses make it suitable for many applications requiring effective steady-state power flow control and/or transient and dynamic stability improvement.

The UPFC consists of two identical voltage-source inverters: one in shunt and the other one in series with the line; the general scheme is illustrated in Figure 3.18. Two inverters, namely shunt inverter and series inverter, which operate via a common DC link with a DC storage capacitor, allow UPFC to independently control active and reactive power flows on the line as well as the bus voltage. Active power can freely flow in either direction between the AC terminals of the two inverters through the DC link. Although, each inverter can generate or absorb reactive power at its own AC output terminal, they cannot internally exchange reactive power through DC link. The VA rating of the injected voltage source is determined by the product of the maximum injected voltage and the maximum line current at which power flow is still provided.

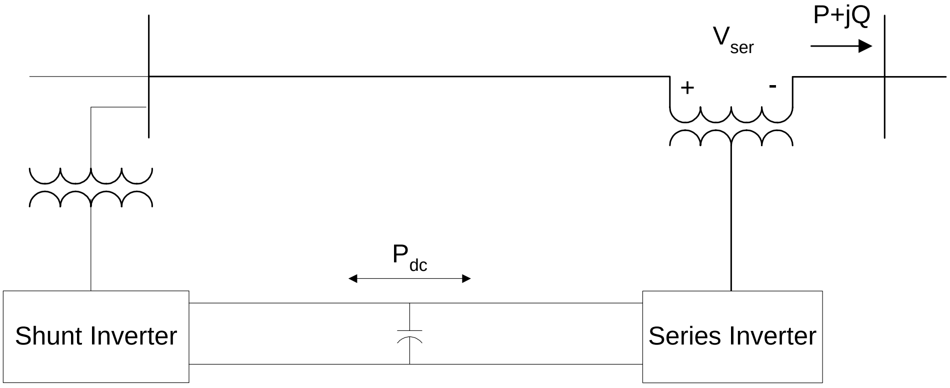

Figure 3.18 UPFC configuration.

The shunt inverter provides local bus voltage control when operated by itself as a STATCOM. When operated in conjunction with the series inverter, the shunt inverter has two functions:

- To control bus voltage by reactive power injection to the power system
- To supply active power to the series inverter via the DC link for series flow control.

The series inverter, on the other hand, provides line power flow control by injecting an AC voltage with controllable magnitude and phase angle at the power frequency, in series with the line via an insertion transformer. This injected series voltage is, in effect, a synchronous series AC voltage source, which provides active series compensation for line voltage control and angle regulation through the transmission line current. The transmission line currents flow through this voltage sources resulting in active and reactive power exchange between the inverter and the AC system. The active power exchanged at the series AC terminal is converted by the inverter into DC power that appears at the DC link as positive or negative active power demand and transfer to the other converter located at the other side of the line.

It is obvious that the operation of UPFC is very important since it affect both the transmission line flow and voltage magnitude. Operation limit and control constraints of UPFC are very crucial to realize the actual operation of the device. To realize that, the validated pu. Differential-Algebraic Equations (DAEs) corresponding to this model can be derived as follows [11]:

$$\begin{bmatrix} \dot{x}_c \\ \dot{\alpha} \\ \dot{\beta} \\ \dot{m}_{sh} \\ \dot{m}_{se} \end{bmatrix} = f(x_c, \alpha, \beta, m_{sh}, m_{se}, V_k, V_l, V_{dc}, \delta_k, \delta_l, P_{l,ref}, Q_{l,ref}, V_{k,ref}, V_{dc,ref}) \quad (3.32)$$

$$\begin{aligned}\dot{V}_{dc} = {} & \frac{V_k I_{sh}}{CV_{dc}}\cos(\delta_k - \theta_{sh}) + \frac{V_m I_l}{CV_{dc}}\cos(\delta_m - \theta_l) \\ & -\frac{G_C}{C}V_{dc} - \frac{R_{sh}}{C}\frac{I_{sh}^2}{V_{dc}} - \frac{R_{se}}{C}\frac{I_l^2}{V_{dc}}\end{aligned} \tag{3.33}$$

$$0 = \underbrace{\begin{bmatrix} P_{sh} - V_k I_{sh}\cos(\delta_k - \theta_{sh}) \\ Q_{sh} - V_k I_{sh}\sin(\delta_k - \theta_{sh}) \\ P_{sh} - V_k^2 G_{sh} + k_{sh}V_{dc}V_k G_{sh}\cos(\delta_k - \alpha) + k_{sh}V_{dc}V_k B_{sh}\sin(\delta_k - \alpha) \\ Q_{sh} + V_k^2 B_{sh} - k_{sh}V_{dc}V_k B_{sh}\cos(\delta_k - \alpha) + k_{sh}V_{dc}V_k G_{sh}\sin(\delta_k - \alpha) \end{bmatrix}}_{g_{sh}(\alpha, k_{sh}, V_k, V_{dc}, \delta_k, I_{sh}, \theta_{sh}, P_{sh}, Q_{sh})} \tag{3.34}$$

$$0 = \underbrace{\begin{bmatrix} P_k - P_{sh} - V_k I_l\cos(\delta_k - \theta_l) \\ Q_k - Q_{sh} - V_k I_l\sin(\delta_k - \theta_l) \\ P_l - V_m I_l\cos(\delta_m - \theta_l) \\ Q_l - V_m I_l\sin(\delta_m - \theta_l) \\ P_k - P_l - P_{sh} - P_{se} \\ Q_k - Q_l - Q_{sh} - Q_{se} \\ P_{se} - V^2 G_{se} + k_{se}V_{dc}VG_{se}\cos(\delta - \beta) + k_{se}V_{dc}VB_{se}\sin(\delta - \beta) \\ Q_{se} + V^2 B_{se} - k_{se}V_{dc}VB_{se}\cos(\delta - \beta) + k_{se}V_{dc}VG_{se}\sin(\delta - \beta) \end{bmatrix}}_{g_{se}(\beta, k_{se}, V_{dc}, V_k, V_l, V, \delta_k, \delta_l, \delta, I_l, \theta_l, P_k, P_l, P_{sh}, P_{se}, Q_k, Q_l, Q_{sh}, Q_{se})} \tag{3.35}$$

$$0 = \underbrace{\begin{bmatrix} I_k\cos(\theta_k) - I_{sh}\cos(\theta_{sh}) - I_l\cos(\theta_l) \\ I_k\sin(\theta_k) - I_{sh}\sin(\theta_{sh}) - I_l\sin(\theta_l) \\ P_k - V_k I_k\cos(\delta_k - \theta_k) \\ Q_k - V_k I_k\sin(\delta_k - \theta_k) \end{bmatrix}}_{g_{con}(V_k, \delta_k, I_k, I_{sh}, I_l, \theta_k, \theta_{sh}, \theta_l, P_k, Q_k)} \tag{3.36}$$

where, all variables are illustrated in Figure 3.19.

The UPFC steady state model can be obtained by using the equations (3.34) – (3.38) as;

$$0 = \begin{bmatrix} V_k - V_{k,ref} \\ V_{dc} - V_{dc,ref} \\ P_{se} - P_{se,ref} \\ Q_{se} - Q_{se,ref} \\ P_{sh} - P_{se} - G_C V_{dc}^2 - R_{sh}I_{sh}^2 - R_{se}I_l^2 \\ g_{sh}(\alpha, k_{sh}, V_k, V_{dc}, \delta_k, I_{sh}, \theta_{sh}, P_{sh}, Q_{sh}) \\ g_{se}(\beta, k_{se}, V_{dc}, V_k, V_l, V, \delta_k, \delta_l, \delta, I_l, \theta_l, P_k, P_l, P_{sh}, P_{se}, Q_k, Q_l, Q_{sh}, Q_{se}) \\ g_{con}(V_k, \delta_k, I_k, I_{sh}, I_l, \theta_k, \theta_{sh}, \theta_l, P_k, Q_k) \end{bmatrix} \tag{3.37}$$

which again can be incorporated into the power flow program.

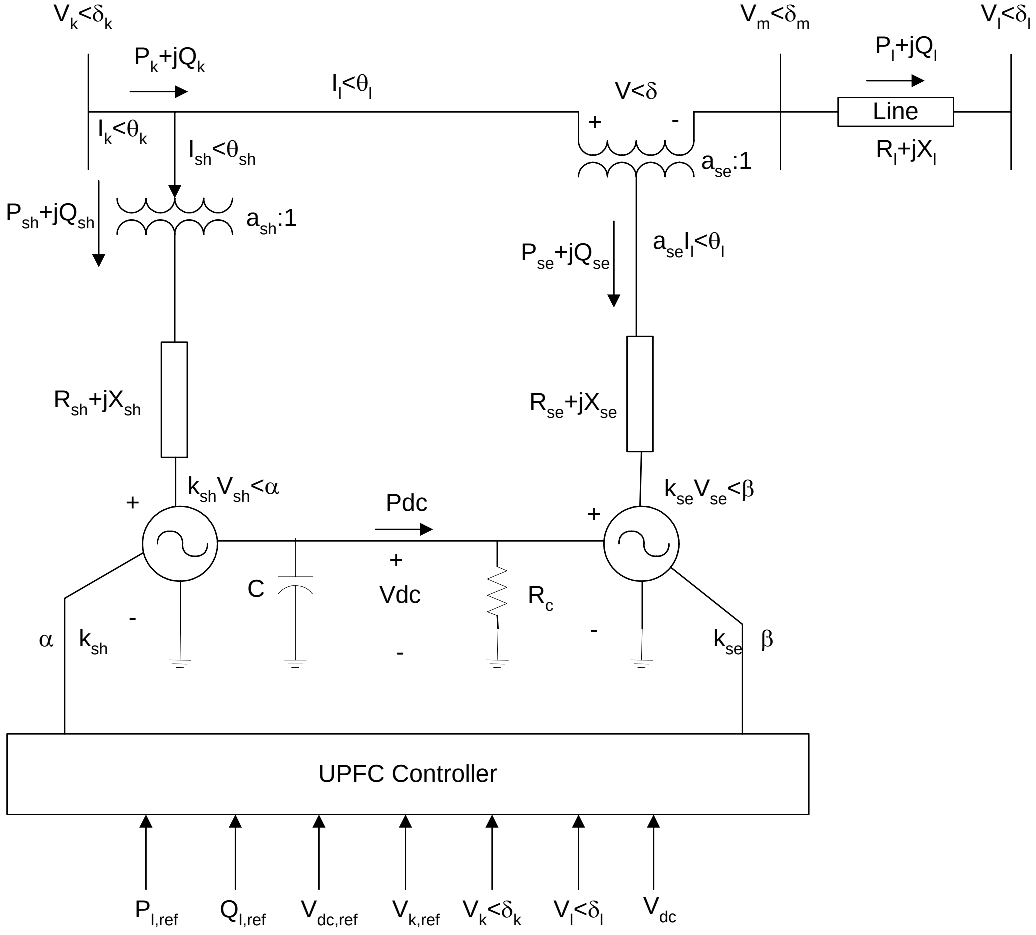

Figure 3.19 Stability model of UPFC.

The limits of UPFC can be divided into two limits: shunt compensation limits and series compensation limit. Shunt compensation limits are basically firing angle and V_{dc} limits, which can be handled in the same way as the case of STATCOM. Series compensation limit, however, involves the capacity of the series compensation, which incorporates the active and reactive power limits.

Application of FATS to enhance stability of the power system is an important issue. The problems facing in planning and operation are where to place, what size is the appropriate size for these controllers, and what appropriate control input signal should be used to improve dynamic performance. In the following two sections, the sizing and placement techniques available up to date will be discussed.

3.5. Sizing of FACTS Devices

Sizing of FACTS devices depends upon the amount of reactive power needed by the system to achieve the appropriate response. This can be identified by introducing synchronous condensor, which can deliver large amount of reactive power at the connected bus. Amount of reactive power needed at connected bus is the amount of reactive power needed by the system, which is the size of the FACTS devices.

Another way of dealing with this problem is to use optimization technique. It is well acknowledged that linear programming method could be devoted to find the optimal size of SVC, which requires alleviating over and under voltage during normal and contingency conditions. The method could then be applied to obtain the capacity of the appropriate model shunt compensation devices: SVC and STATCOM. There is wide consensus that the capacity of series compensation would rate on the MVA rating calculated from current flow and series voltage across the series compensation device, which mostly depend on control and configuration of the power system.

By the above understanding, an effort is compiled in this study to find the optimal size of shunt compensation. Optimization technique based on linear programming is utilized. The implication of the methodology can be revealed in the formulation as follows:

$$\text{Min} \qquad F = \Delta Q_{SVC\,or\,STATCOM} \tag{3.38}$$

$$\text{Subject to} \qquad V_i^{\min} - V_i \le 0 \tag{3.39}$$

$$V_i - V_i^{\max} \le 0, \tag{3.40}$$

where, $\Delta Q_{SVC\,or\,STATCOM}$ is the net rating of SVC or STATCOM ; $V_i^{\min}$ and $V_i^{\max}$ are the minimum and maximum desired magnitude of voltage at bus i, respectively; and V_i is the actual magnitude of the voltage at bus i.

3.6. Placement of FACTS Devices

The placement of FACTS devices is based on angle stability and voltage stability. For transient stability, the placement is based on how the devices can improve transient stability based on the response of the devices. This can be achieved by introducing FACTS in a bus and consider the angle improvement at that bus. Similarly, for the small signal stability, the placement is depend upon the improvement of the location of eigenvalues. For voltage stability, the placement of shunt FACTS devices is based on the location, which results in effect in voltage at as many buses as possible.

There are many placement technique based on voltage stability. The shunt compensation devices should be placed at the weakest bus or weakest area. Weakest bus identification is addressed commonly based on contributions of modal analysis method or tangent vector method. Nonetheless, ambiguity has been arised on placement of series compensation and UPFC in the power system. However, this can be place according to some possibility of locations.

Chapter 4

Facts Application

4.1. Introduction

In chapter 2, we look at various power system limits. These limits can be classified as steady state limits and dynamic stability limits. These inherent power system limits, restrict power transaction and lead to under utilization of the existing transmission resources. Traditionally, fixed or mechanically switched, shunt and series capacitors and reactors were being used to solve much of the problem. There are restrictions as to the use of these conventional devices. Desired performance was not being able to achieve effectively. Wear and tear in the mechanical components and slow response were the heart of the problems. It is where the FACTS controllers find its application. FACTS controllers are designed to remove such limitations and meet operator's goals without having to undertake major system additions. Given the nature of power electronic equipment, FACTS solutions will be justified wherever the application requires rapid response, frequent variation in output and/or smoothly adjustable output.

Further, new areas for FACTS are being envisaged in the deregulated power market. In the competitive environment, there will be an increase need for a more optimal and profitable operation of the power system. So it is inevitable that the network will be operated in a stressed condition or close to their limits. There will be growing concern about reliability and security as well. So the operational reliability and financial profitability will put pressure on the transmission providers to efficiently utilize and control the existing transmission infrastructure. This is where the power electronic based equipments, such as FACTS, provide proven technical solutions to address new operating challenge. FACTS technologies allow for improved transmission system operation with minimal infrastructure investment, environmental impact, and implementation time compared to the construction of new transmission line. FACTS technology provides solutions for efficiently increasing transmission system capacity so as to relieve congestion, increase ATC, improve reliability and enhance operation and control**.**

Another important potential application of FACTS in deregulated market is operational flexibility. In deregulated electricity market, there will be obligation on part of the network operator to fulfill various electricity supply contracts between the market participants. FACTS controllers has the capability to allow the network to operate in flexible manner by controlling the changing power flows in the network.

The use of particular FACTS controllers depends on the type of the problem. Some FACTS devices are capable of addressing multiple power system problems and other FACTS devices sometime may be suitable to solve particular problem. The final choice may be guided by cost criteria. Detailed study of the transmission system and proper modeling of FACTS devices is required for simulation to ascertain its effectiveness. FACTS controllers are expensive and hence left very little room for an incorrect assessment, about type, location and size during planning and analysis phase.

4.2. Steady State Application

The main steady-state transmission limitations are high or low voltage, thermal capabilities of lines and equipment, loop flows, excessive short-circuit levels and post-contingency conditions. Generally, FACTS controllers are not required to correct steady-state limitations. However, if action must be implemented quickly (e.g. post-contingency), a FACTS controller may be advantageous. Table 4.1 describes the application of various FACTS controllers along with their conventional counterpart in addressing these limitations. The primary advantage of FACTS controllers, over its conventional counter part is the rapid control of current, voltage and/or impedance following disturbance. The conventional solutions are normally less expensive than FACTS devices, but limited in their dynamic behavior. We will look at each steady state issues in detail.

Table 4.1 Steady-State Issues [12]

Issues	Problem	Corrective Action	Conventional Solution	New Equipment (FACTS)
Voltage Limits	Low voltage at heavy load	Supply reactive power	Shunt capacitor, SVC, series capacitor	TCSC, STATCOM
	High voltage at light load	Remove reactive power supply	Switch EHV line and/or shunt capacitor	TCSC, TCR
		Absorb reactive power	Switch shunt capacitor, shunt reactor, SVC	TCR, STATCOM
	High voltage following outage	Absorb reactive power	Add reactor	TCR
		Protect equipment	Add arrestor	TCVL
	Low voltage following outage	Supply reactive power	Switch, shunt capacitor, reactor, SVC, switch series capacitor	STATCOM, TCSC
		Prevent overload	Series reactor, PAR	IPC, TCPAR, TCSC
	Low voltage and overload	Supply reactive power and limit overload	Combination of two or more equipments	IPC, TCSC, UPFC, STATCOM
Thermal Limits	Line/transformer overload	Reduce overload	Add line/transformer	TCSC, TCPAR, UPFC
			Add series reactor	TCR, IPC
	Tripping of parallel circuit	Limit circuit loading	Add series reactor, capacitor, PAR	IPC, UPFC, TCR
Loop Flows	Parallel line load sharing	Adjust series reactance	Add series capacitor/reactor	IPC, UPFC, TCSC
		Adjust phase-angle	Add PAR	TCPAR
	Post-fault sharing	Rearrange network or use “Thermal Limit” actions	PAR, series capacitor or reactor	IPC, TCSC, UPFC, TCR, TCPAR
	Flow direction reversal	Adjust phase-angle	PAR	IPC, TCPAR, UPFC
Short-Circuit Levels	Excessive breaker fault current	Limit short-circuit current	Add series reactor, fuses, new circuit breaker	TCR, IPC, SCCL, UPFC
		Change circuit breaker	Add new circuit breaker	
		Rearrange network	Split bus	IPC

Legend for Table 4.1

IPC = Interphase Power Controller
LTC = Transformer-Load Tap Changer
NGH = Hingorani Damper
PAR = Phase-Angle Regulator
SCCL = Super-Conducting Current Limiter
SVC = Static Var Compensator
STATCOM = Static Synchronous Compensator
TCPAR = Thyristor Controller Phase-Angle Regulator
TCSC = Thyristor Controller Series Capacitor
TCVL = Thyristor Controller Voltage Limiter
TSBR = Thyristor Switched Braking Resistor
TSSC = Thyristor Switched Series Capacitor
UPFC = Unified Power Flow Controller

4.2.1. Voltage Control

Under steady-state conditions, high loading and low voltage can be a limiting factor. The proper corrective action is to supply reactive power so as to correct the load power factor and to compensate for the reactive losses in lines and transformers. Traditionally, mechanically switched shunt capacitors (MSC) and reactors (MSR) were used for voltage control. In fact, heavy use of these devices is responsible, at least in part, for some voltage control problems today. Shunt compensation may lead to either severe over voltages if heavily loaded systems break up following a failure or large voltage sensitivity to changes in load or transfers (as we know reactive power provided by capacitors drops with the square of the voltage and reactive losses increases with the square of the voltage, compounding the drop in voltage accompanying a load or transfer increase).

Unfortunately, as system loading increases utilities are finding that an increasing share of reactive losses need to be supplied from dynamic devices such as generators, synchronous compensators and SVCs. Also, increasing amounts of reactive reserves are needed to cover “voltage contingencies”. This may mean adding shunt capacitor banks to keep generators operating near unity power factor so they can respond to voltage emergencies, and, when feasible, adding capacitor banks that can be switched on quickly and automatically following voltage contingencies. Some utilities have installed SVCs; and other is considering STATCOMs. Tables 1.1 and 1.3 in chapter 1, provide some real world application of these devices.

During light load conditions, voltages may rise to unacceptable levels unless the reactive shunt power sources are removed or shunt reactors are brought into service. In the case of a small tap along a long transmission corridor, mechanically switched shunt capacitors or reactors can be used to supplement the action of conventional load tap changers. This intermediate station may be the location of an SVC if synchronous stability and/or damping of oscillations are issues. Or, a STATCOM could be a good option, if the area has significant voltage sensitive load.

4.2.2. Increase Thermal Loading

On a steady-state basis, equipment thermal limits represent a technical problem for which specific action is required. These hard limits can be removed only by adding transmission equipment or rearranging the network.

Conventional solutions to transmission thermal overloads include a series reactor, series capacitors in parallel circuits, or phase angle regulating transformers (PARs). The series reactor option can be acceptable in tightly-meshed networks where the reactor does not cause an undue voltage drop. If the series reactor or capacitor approach is not acceptable, the PAR solution is available.

4.2.3. Post-Contingency Voltage Control

Depending on the change in network configuration caused by the outage, unacceptably high or low voltage conditions can result and thermal limits may be exceeded. Low voltage following an outage is one of the most widespread causes of transmission limitations. Indeed, most major transmission line loading levels are set by the maximum acceptable voltage drop and/or the minimum voltage a line loss would cause at other locations in the network, if not in neighboring systems. The voltage drop due to the loss of a major line can be accompanied by circuit overloads, at the same voltage or at lower voltage levels.

If only the final under voltage problem is of concern, the proper corrective actions to supply reactive power from mechanically switched shunt capacitors or to switch off shunt reactors. In some cases, immediate control of the post-contingency rms voltage may be required to prevent loss of voltage sensitive load and/or prevent undesired protective relay operations. Conventional solutions include mechanically switched shunt capacitors, reactors, series capacitors, or static var compensators (SVCs). A STATCOM may offer better voltage support than a SVC.

When low voltages are accompanied by thermal overload conditions, a more efficient corrective action may be required to prevent the overload condition. Sometimes, this can be accomplished by re-dispatching generation, using existing transmission equipment to redirect part of the power flow to parallel circuits. Conventional solutions to post-contingency thermal issues include switched series reactors or capacitors, phase-angle regulators (PARs) or a network configuration change. When both corrective actions are required (supply of reactive power and flow control), more complex conventional solutions involving two or more items of equipment are required. If a rapid solution to the voltage drop is needed to prevent load loss, the preferred FACTS controllers are those capable of supplying reactive power and controlling flows, including IPC, UPFC and TCSC.

In the case of high post-contingency voltages, the conventional solutions are to switch in shunt reactors, switch off shunt capacitors or apply an SVC with a suitable absorption rating. In extreme cases, such as major load shedding on long radial networks, the rapid insertion of an overvoltage protective device such as the Thyristor Controlled Voltage Limiter (TCVL) may be the only viable solution.

4.2.4. Loop Flows

Loop flow is electric energy flow that travels over a transmission system without that flow being scheduled on the transmission system. In can be the result of another transmission provider scheduling and selling more capacity that its own transmission system will accommodate without regard for its impacts on other interconnected transmission system. Such loop flows occur when an entity fails to curtail its transactions when the transmission needed to support those transactions is no longer available.

The solutions to loop flows are the same as solutions for steady-state thermal issues. However, in the loop flow case, some or all the appropriate solutions may be in a part of the network owned by another utility. Moreover, changing generation may not be an economic option. Thus, PARs and series capacitors are well known conventional solutions, to solve loop flow problem.

Among the FACTS devices available, the IPC, UPFC, TCSC and the TCPAR may provide options to rapidly control loop flows. If the network with loop flow problems involves two voltage levels, the IPC is well suited; since it has the ability to decouple the management of the reactive power at both voltage levels while controlling the active power flow. Otherwise, the UPFC or TCSC may provide an appropriate solution. If only rapid active power control is required and voltage support is not a concern, the TCPAR may be an elegant solution.

They might also be used individually or in combination to control the flow through lines and transformers and thereby maximize the utilization of existing transmission facilities.

4.2.5. Short-Circuit Level

Too often the solution adopted in response to excessive short-circuit levels is to separate the network into different sections, resulting in loss of flexibility and the ability to serve certain loads.

Conventional corrective actions, without opening the network, are to insert current limiting reactors or to replace the over-duty circuit breakers with other having higher interrupting capability. FACTS solutions for such applications need to limit their own contribution to faults. The IPC has this ability. Future technologies that hold promise to limit short-circuit contributions include the super-conducting current limiters (SCCL).

4.2.6. Power flow control

Serie compensation can be used in power systems for power flow control in steady state. In the case of transmission lines with sufficient thermal capability, compensation can therefore relieve possible overloading of other, parallel lines. TCSC can be effectively used for the purpose.

4.3. Dynamic Application

The dynamic behavior aspects of transmission systems that can be improved with the use of FACTS controllers include transient stability, damping oscillations (also called dynamic stability) and voltage stability. Again, from the planning point of view, one of the most important capabilities expected of FACTS applications is to be able to reduce the impact of the primary disturbance. The impact reduction for contingencies can be achieved through dynamic voltage support (STATCOM), dynamic flow control (TCPAR and TCSC) or both the UPFC and IPC (with power electronics). Table 4.2 describe the application of these controllers along with their conventional counterpart is addressing dynamic power system problems.

Table 4.2 Dynamic issues [12]

Issues	Type of System	Corrective Action	Conventional Solution	New Equipment or control solution
Transient Stability	A, B, D	Increase synchronizing torque	High-response exciter, series capacitor	TCSC, TSSC, UPFC
	A, D	Absorb kinetic energy	Braking resistor	TCBR, SMES, BESS
	B, C, D	Dynamic flow control	HVDC	IPC*, TCPAR, UPFC, TCSC
Damping	A	Damp 1 Hz oscillations	Exciter stabilizer, SVC	TCSC, STATCOM
	B, D	Damp low frequency oscillations	SVC	IPC*, TCPAR, UPFC, NGH, TCSC, STATCOM
Post-Contingency Voltage Control	A, B, D	Dynamic voltage support	SVC	STATCOM, UPFC, IPC*
		Dynamic flow control	SVC	UPFC, IPC*, TCPAR
		Dynamic voltage support and flow control	SVC	IPC*, UPFC, TCSC
	A, B, C, D	Reduce impact of contingency	SVC	TCSC, STATCOM. IPC, UPFC
Voltage Stability	B, C, D	Reactive support	SVC, shunt capacitor	STATCOM, UPFC
		Network control actions	LTC, reclosing, HVDC control	UPFC, IPC, TCSC, STATCOM
		Generation control	High-response exciter	
		Load control	Under-voltage load shedding	Demand-Side Management Programs

A. Remote Generation – Radial Lines
B. Interconnected Areas
C. Tightly meshed network
D. Loosely meshed network

Legend for table 4.2

BESS = Battery Energy Storage System
IPC = Interphase Power Controller
IPC* = Interphase Power Controller
LTC = Transformer-Load Tap Changer
NGH = Hingorani Damper
PAR = Phase-Angle Regulator
SCCL = Super-Conducting Current Limiter
SMES = Super-Conducting Magnetic Energy Storage
STATCOM = Static Synchronous Compensator
SVC = Static Var Compensator
TCPAR= Thyristor Controller Phase-Angle Regulator
TCSC = Thyristor Controller Series Capacitor
TCVL = Thyristor Controller Voltage Limiter
TSBR = Thyristor Switched Braking Resistor
TSSC = Thyristor Switched Series Capacitor
UPFC = Unified Power Flow Controller

4.3.1. Transient Stability Improvement

To improve transient stability, control devices must do one of the following (generally, within 0.2 to 0.4 seconds of fault clearing); extract energy from the sending-end generators, facilitate supply of energy to the slowed receiving system or increase the synchronizing power flowing from the sending end to the receiving end.

The conventional solutions for increasing synchronizing torques have been to equip generators with high response exciters and to shorten equivalent transmission distances with series capacitors. However, series capacitor compensated transmission network could be facing sub-synchronous resonance (SSR) problem. This can be overcome through an installation of appropriate FACTS controllers.

A FACTS extension to a conventional series compensation approach is the TSSC, where blocks of series capacitors can be switched in and out to enhance power transfer during swings, thus increasing transient and dynamic stability margins.

The additional continuous control capability of the TCSC can also improve transient stability because it can be designed to provide a much higher level of compensation immediately following the fault clearing. In addition, the continuous control has the capability of damping both subsynchronous resonance and electromechanical oscillations. Other FACTS controllers can also be used to enhance the transfer of synchronizing power.

SVC or STATCOM, near the electrical center of the sending and receiving system can hold voltage or even raise voltage above nominal to transiently increase synchronizing power transfer. A TCPAR could control the effective angle between the sending and the receiving systems to extend the period over which synchronizing power is high. A UPFC, depending on the control strategy, can provide the benefits of a TCSC, PAR, SVC or a STATCOM. Moreover, a UPFC could also limit fault current (when the fault is downstream of the UPFC) by applying a series voltage that mimics a series reactor. The second generation IPC (with power electronics to modulate its operating point) could provide the benefits noted for series capacitors and also provide voltage support.

A mechanically switched breaking resistor can be used control transient stability problems as is done in WSCC system for several years. A TCBR can also solve the problem. The TCBR allows the controlled insertion of the breaking resistor, more than once if necessary, during the critical period of the first swings.

Both SMES and BESS energy storage systems can extract energy from sending end generator or supply energy to receiving end generators, depending on their location within the network.

4.3.2. Oscillation Damping (Dynamic stability)

Dynamic instability is characterized by sustained or growing power oscillations between generators or groups of generators. Generally, oscillations are in the range of 0.2 to 1.5 Hz. However, higher frequencies are possible for oscillations between electrically close generators.

The conventional solutions for damping the oscillation are to use stabilizing signals acting through high-response exciter at the generating stations (i.e. power system stabilizers) or through an SVC modulating the voltage at an intermediate system point.

Basically, any FACTS controller used for controlling transient stability can be modulated to provide dynamic damping. However, controllers that operate in series with the transmission line are generally more effective. FACTS solutions include the STATCOM whose action would be similar to the SVC. A TCSC, used to modulate transmission line impedance, can have the same damping action. Other FACTS solutions like use of TCPAR, BESS and SMES are also possible for damping power oscillations.

4.3.3. Voltage Stability Enhancement

Voltage stability (instability/collapse) is a totally different form of power system dynamic problem. Contrary to the loss of electromechanical stability, voltage instability is a possible consequence of progressive increase in load until the point of collapse is reached, beyond which little can be done except to prepare for system restoration. The collapse phenomenon is typically slow, over several minutes, depending on the time-varying behavior of the loads. The following conventional corrective actions are possible;

- Reserve reactive support must be used, i.e. switched shunt capacitors and SVCs.
- Network control actions: coordinate system LTCs, reclose lines automatically, use HVDC station reactive power control capabilities.
- Load control: automatic undervoltage load shedding or operator initiated load shedding.
- Generator control action: remove generation to mitigate a transmission overload, add local generation or trade real power for reactive power on critical generation.

FACTS studies on easing voltage instability problems have been confined, so far, to the application of the SVC and the more recent alternative, the STATCOM.

A more difficult form of voltage instability, sometimes referred to as “transient voltage instability” is becoming an increasing problem. This form of voltage instability is, the long recognized problem of “induction motor instability”. Induction motor instability is an increasing problem as transmission system becomes more heavily loaded. Following a system fault, certain induction motors may either be already stalled or absorb a disproportional high reactive power compared with active power in their recovery to operating speed. In the absence of established solutions, certain FACTS devices (like the STATCOM), which are fast acting and have the potential for high short time overload ratings, may be helpful.

4.4. Technical Benefit of FACTS

Table 4.3 below depicts the usefulness of different principal FACTS devices.

Table 4.3 Technical benefits of main FACTS devices

	Load Flow Control	Voltage Control	Transient Stability	Dynamic Stability
SVC	■	■■■	■	■■
STATCOM	■	■■■	■■	■■
TCSC	■■	■	■■■	■■
UPFC	■■■	■■■	■■	■■

■
■■ ↓ Better
■■■

In sections 4.2 and 4.3, we look and at the specific static and dynamics issues and corresponding conventional and FACTS solutions. Based on this, we can summarize the generalized benefits of FACTS application in transmission system as follows:

4.4.1 Better Utilization of Existing Transmission System Assets

In many countries, increasing the energy transfer capacity and controlling the load flow of transmission lines are becoming very important, especially in de-regulated power markets, where electricity supply and demand changes rapidly depending on the behavior of the market participants. Frequently, adding new transmission lines to meet increasing electricity demand is limited by economical and environmental constraints. FACTS devices help to meet these requirements with the existing transmission systems.

4.4.2 Increased Transmission System Reliability and Availability

Transmission system reliability and availability is affected by many different factors. Although FACTS devices cannot prevent faults, they can mitigate the effects of faults and make electricity supply more secure by reducing the number of line trips. For example, a major load rejection results in an over voltage of the line which can lead to a line trip. SVC’s or STATCOM’s counteract the over voltage and avoid line tripping.

4.4.3 Increased Dynamic and Transient Stability

Long transmission lines, interconnected grids, impacts of changing loads and line faults can create instabilities in transmission systems. These can lead to reduced line power flow, loop flows or even to line trips. FACTS devices stabilize transmission systems with resulting higher energy transfer capability and reduced risk of line trips.

4.4.4 Increased Quality of Supply for Sensitive Industries

Modern industries depend upon high quality electricity supply including constant voltage, and frequency and no supply interruptions. Voltage dips, frequency variations or the loss of supply can lead to interruptions in manufacturing processes with high resulting economic losses. FACTS devices can help provide the required quality of supply. Using STATCOM with Superconducting Magnetic Energy Storage (SMES) is envisaged to solve many of the power quality problems that effect sensitive industries.

4.4.5 Environmental Benefits

FACTS devices are environmentally friendly. They contain no hazardous materials and produce no waste of pollutants. FACTS can help distribute the electrical energy more economically through better utilization of existing installations thereby reducing the need for additional transmission lines.

Chapter 5

Simulation Results

Although the power system of EGAT, Thailand is small in terms of installed capacities, peak demand and area covering, compared to those of developed countries such as US, Japan, etc., there were some “minor” instability incidents in some regions of the country such as southern region, northern region, etc. These instability incidents are mainly caused by cancellation of power station projects, which results in over exploitation of the existing transmission facilities. Due to this reason, EGAT, the single utility responsible for generation facility, has devoted lot of investment in installing new transmission line facilities and/or FACTS controllers in order to relieve the system from angle and voltage stability limits and hence related instability problems.

Angle stability study is one of major instability issues in Thailand power system. EGAT has been succeeded in the study related to angle stability using commercial software, PSS/E program. The study is normally done by system control and operation division and planning division of EGAT. Voltage stability study, on the other hand, is one of important issues that need more attention, especially, in congested power system like near-future power system of Thailand. In addition, with the government policy, the third party access will be initiated to promote the economic transactions in the power system in the very near future. The availability of the transmission system is calculated based on Available Transfer Capability (ATC) of the system. According to the above, this section is devoted to investigate voltage stability assessment of Thailand with SVC, STATCOM and TCSC along with the Available Transfer Capability (ATC) of Thailand power system. The study could help EGAT and other utilities in controlling their systems in a more secure and reliable manner and foresee the system situation prior to the activation of the third party access.

In this chapter, voltage stability assessment of Thailand is studied in Section 5.1 including the weakest buses identification, voltage control settings of SVCs, PV curves, losses, application of SVC and STATCOM. Section 5.2 presents the study of ATC of Thailand power system. Finally, the conclusion and recommendation are given in Section 5.3.

5.1 Voltage Stability of Thailand Power System

5.1.1 Weakest Buses of Thailand Power System

The weakest bus of the system is defined as the bus (or substation) that is nearest to experiencing a voltage collapse. The weakest bus can be identified using tangent vector. If one can identify the weakest buses in the system, the voltage stability of the system can be improved by introducing reactive power sources at those buses. In emergency condition, load shedding can be applied at the weakest buses to bring the system back from voltage instability. Table 5.1 shows the first seven weakest buses of Thailand power system, based on tangent vector at the collapse point. From Table 5.1, bus CM2-5, located in the north, is considered as the most weakest bus of the system. Most of weak buses are located in the north of the country. This is due to high load consumption in Chaing Mai province, where a most famous tourist city is located.

Table 5.1 Tangent vectors of the first seven weakest buses

Weakest Bus Number	Bus Names	|Tangent Vectors|
1	CM2-5	0.1064
2	CTG-2	0.0638
3	CTG-1	0.0637
4	LN2-1	0.0636
5	LN2-2	0.0605
6	CM2-4	0.0597
7	CTG	0.0569

5.1.2 Voltage Control Settings of SVC and STATCOM

SVC is installed in Thailand power system. There are two SVC controllers, one located at the Thatako (TTK) substation, between northern and central regions (SVC1), and the other one located at the Bangsapan (BSP) substation, between southern and central regions of the country, (SVC2). The capacity of SVC1 is ±150 MVar whereas SVC2 capacity is +300 and –50 MVar.

An important parameter of SVC to improve voltage stability is voltage setting. The appropriate voltage setting can increase loading margin of the system. If the plot of LM of the system and voltage settings of SVCs is known, one can identify the most appropriate voltage settings of SVCs. Fig. 5.1 shows the relationships between the LMs and voltage settings. From Fig. 5.1, it is obvious that setting the controlled voltages of SVC1 at 1.03 and SVC2 at 1.06 p.u., respectively, would yield the highest voltage stability margin. Hence, these voltage settings are used for the rest of the study.

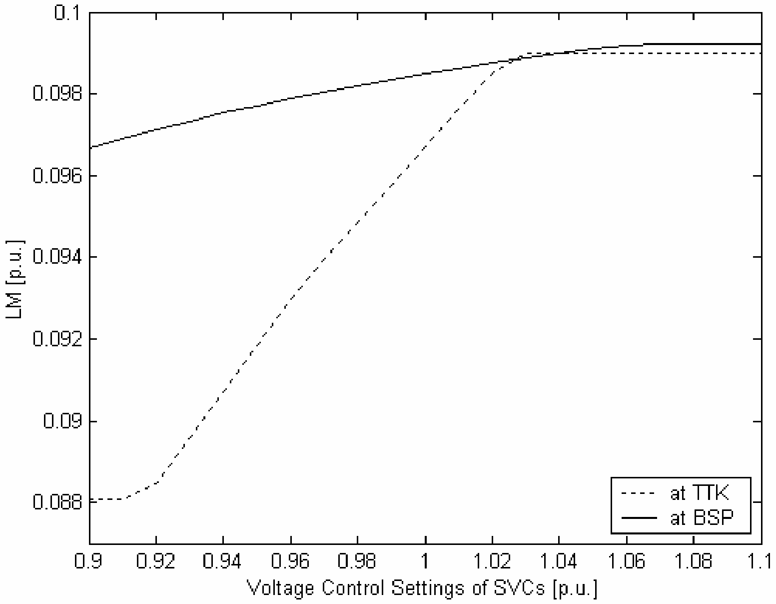

Fig. 5.1 Plot of LM versus voltage setting of existing SVCs.

5.1.3 PV Curves and Losses of Thailand Power System

5.1.3.1 PV Curves

Conventionally, in EGAT system study, the SVCs are represented by shunt capacitors and synchronous condenser with MVA capacities corresponding to SVC. The characteristics of SVC are not the same as those of shunt capacitor and synchronous compensator. Shunt capacitor provides no voltage control while synchronous compensator provides constant reactive power at the limit. According to the above, appropriate representation of SVC is required. Fig. 5.2 compares PV curves of the system with capacitor and with SVC representations. From Fig. 5.2, LM of the system is 0.0992 p.u. or 1,800 MW with appropriate representation of SVC. If the SVC is represented by capacitor, the LM of the system is .09679 p.u., lower than that of appropriate representation. Note that voltage is lower and decreased more sharply in case of capacitor representation due to no voltage control for shunt capacitors. It is obvious that the actual representation of SVC is required for static voltage stability study.

LM of Thailand power system is 0.0992 p.u. which is about 1,800 MW. This implies that the system load can be increased by the total of 1800 MW from base load prior to the voltage collapse point.

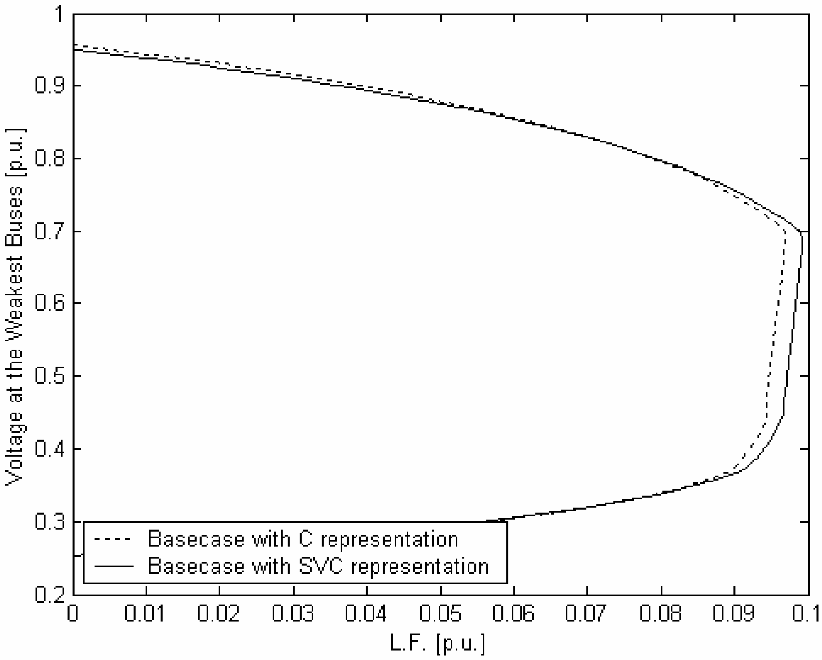

Fig. 5.2 PV curves of Thailand power system with C and SVC representation at TTK substation.

5.1.3.2 Real and Reactive Power Losses

Reactive power losses are one of the main factors that drive the system to the voltage collapse [13]. At the collapse point, losses of the system are much larger than those of the base load, and would grow in the exponential fashion with increase in load in the system. Fig. 5.3 shows real and reactive power losses of the system versus various LFs for Thailand power system. From Fig. 5.3, one can see that the reactive losses of the system are negative at the beginning and become positive and much larger when the load is high. The negative reactive power at the beginning is due to by the reactive power support, mainly from 500 kV transmission lines. It is also observed from the Fig. 5.3 that the real power losses are much lower than reactive power losses. Reactive power losses are the major factor that drives the system to the voltage collapse point, not the real power losses, for the case of Thailand power system. In the stressful conditions, reactive losses are very high, while real power losses are low. This is because reactive power support is depleted prior to the real power support due to reactive power limit of generators and SVCs and high reactive power losses caused by huge amount of power being transferred from remote power stations.

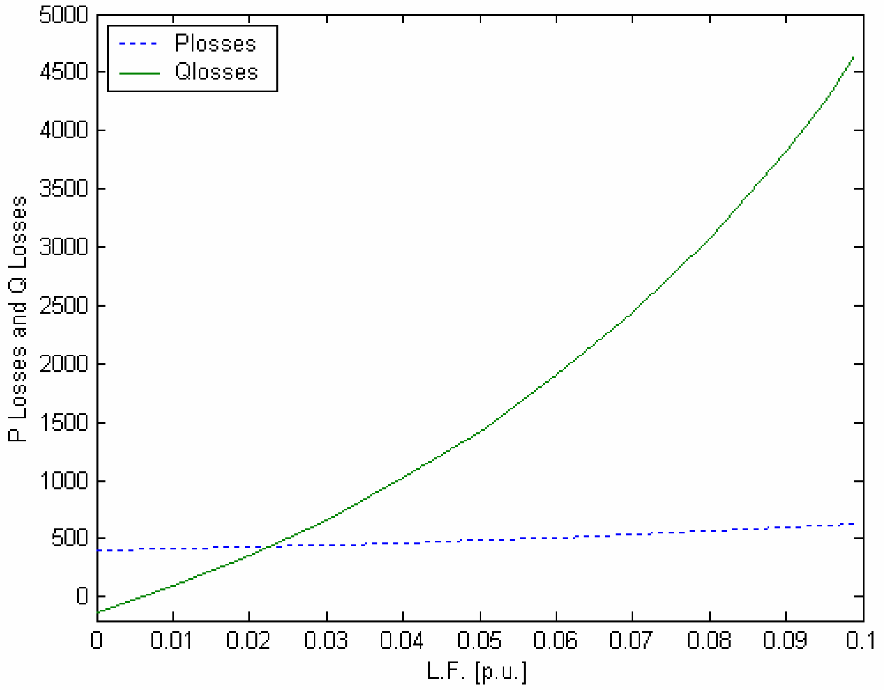

Fig. 5.3 Real and Reactive Power Losses of Thailand System at Various LFs.

5.1.4 Voltage Stability Study with SVC and STACOM

The weakest bus of the system is at CM2-5 for the business as usual case of EGAT system. Providing reactive power support at the bus located in the north can increase LM of the system. When the generation is dispatched appropriately based on the MLM approach [14], the LM of the system can be increased. The weakest bus of the system is changed from buses CM2-5 to BSP if generators are dispatched according to MLM approach [14]. Thus, in this section, the study is done for two cases, business as usual case and MLM case.

In general, STATCOM controller is better than SVC in terms of constant reactive power output during low and high voltage, so STATCOM is used as the first choice. In business as usual case, since the weakest bus of the system is at 22 kV bus, the STATCOM is placed at the nearest 115 kV bus, which is CM2 substation. In MLM case, the weakest bus of the system is at BSP substation. Since SVC2 is already connected to BSP substation, the study is done by doubling the capacity of the SVC2. However, appropriate size of SVC is another important issues in static voltage stability studies.

Figures. 5.4 and 5.5 show the PV curves of the system having STATCOM installed at CM2 and the system having SVC installed at BSP substation, respectively. From Fig. 5.4, there is not much improvement in terms of LMs for the case of STATCOM because the weakest of the system is changed from CM2-5 to BSP. From Fig. 5.5, in the case of MLM and double capacity of SVC2, LM of the system can be increased to 0.14000 p.u., which is the highest LM for Thailand power system.

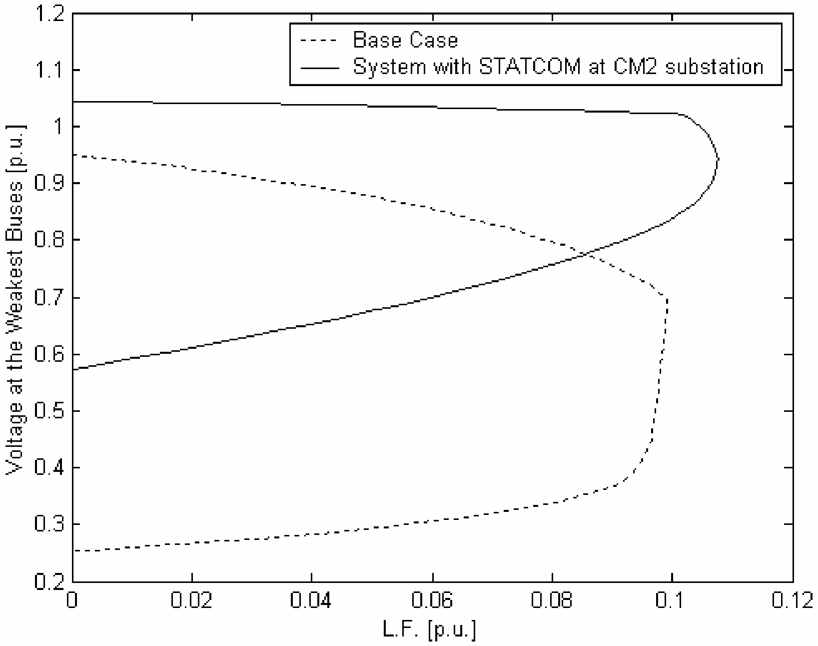

Fig. 5.4 PV curves of base case and system with STATCOM installed at CM2 substation.

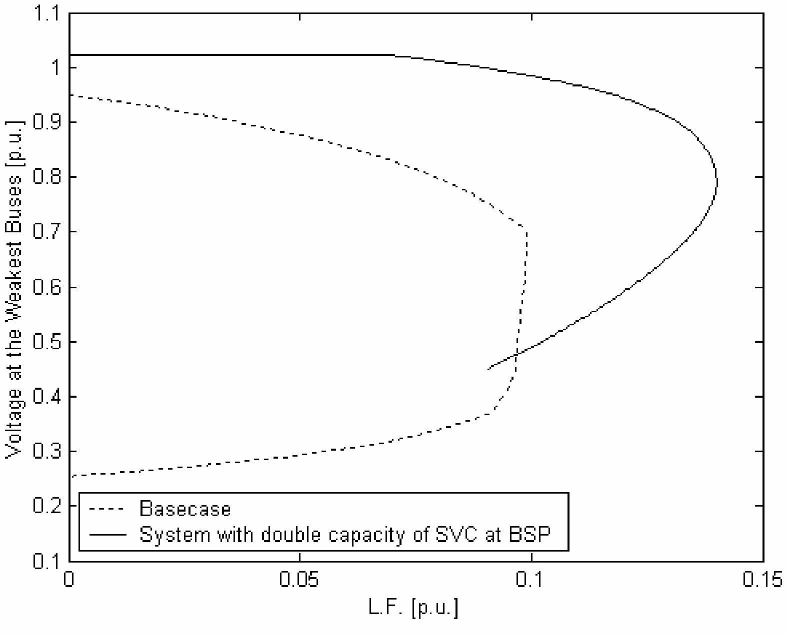

Fig. 5.5 PV curves of base case and system with double capacity of SVC at BSP substation.

Tie line connecting central and southern regions of Thailand is weakest in terms of angle stability. Table 5.2 show power flow of tie line between central and southern regions without and with SVC at BSP at LF=0 and LM. From Table 5.2, introducing SVC at BSP substation can increase power flow capability of tie line BSP-SRT related to voltage stability.

Table 5.2 Power Flow of Line BSP-SRT without and with SVC

Cases	Power Flow in Line BSP-SRT [MW]
Base Case at LF =0	121.14
Base Case at LF =0.0992 (LM)	168.35
Base Case with SVC at LF =0.14 (LM)	188.78

Table 5.3 gives real and reactive power losses of Thailand power system without and with SVC at BSP. From Table 5.3, it is obvious that losses of the system are decreased when SVC is introduced.

Table 5.3 Real and reactive power losses of the system without and with SVC

Cases	Real Power Losses [MW]	Reactive Power Losses [MVar]
Base Case at LF =0.0992 (LM)	628.5623	4636.154
Base Case with SVC at LF =0.0992 (LM)	552.5364	2468.438
% Loss Reduction with SVC	12.1 %	46.8 %

5.1.5 Voltage Stability Study with TCSC

TCSC controller is one of series-type FACTS controllers. It is used to control power flow in the transmission lines by adjusting series impedance of the transmission line. The purpose of TCSC is to supply reactive power in the series transmission line with a control variable such as power flow in the line.

In Thailand power system, the weakest bus of the system is located at distribution substation, so introducing TCSC controller in the transmission system may not help increase LM of the system. Fig. 5.6 shows PV curves of the system with and without TCSC controller at a 500 kV MM3-TTK line. From Fig. 5.6 , it is obvious that introducing the TCSC controller at one of 500 kV MM3-TTK transmission line does not increase LM of the system.

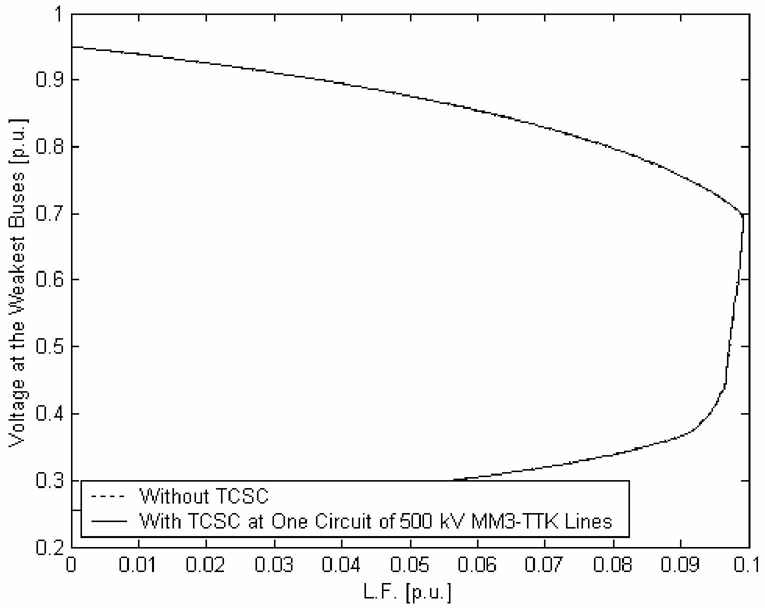

Fig. 5.6 PV curves of the system with and without TCSC controllers at one of 500 kV MM3-TTK transmission lines.

5.1.6 Contingency Ranking

Contingency ranking is one of important issues in voltage stability assessment. The criterion for operation and control of the power system in Thailand is to be able to handle N-1 contingency of any generator, equipment or transmission line. This criterion has to be achieved at the planning stage. PV curves of three worst contingencies in Thailand power system are plotted in Fig.5.7. From Fig. 5.7, it is obvious that N-1 of SVC at BSP is the worst contingency since it reduces LM of the system the most.

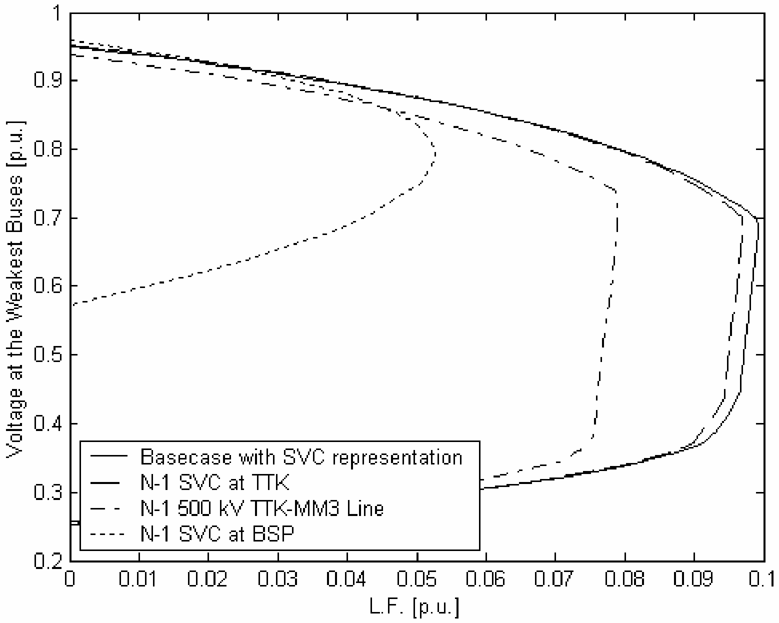

Fig. 5.7 PV curves of the system with base case and three worst contingencies.

5.2 Available Transfer Capability of Thailand Power System

Thailand power system is composed of 20 power stations including EGAT power stations and IPPs. Among the stations, there are only 3 power stations that have more than 2000 MW capacities. Table 5.4 shows power stations that have more than 2000 MW generation capacity.

Table 5.4 Generation Capacities of Power Stations with More Than 2000 MW Installed Capacity

Plant Names	Generation Capacities in MW
RB	2600.0
MM	2238.4
BPK	2060.2

In practice, load increase can be served only by high capacity power stations. Generators at MM stations have the lowest generation cost because they use coal as the main fuel to produce electricity. Thus, generation at this station is always controlled at the maximum generation. According to the above, in this section, only 2 power stations, namely RB and BPK power station shown in Table 5.4 are used to dispatch power to serve the load increase. It is noted that both stations are located in the central region (Area 1) of the country.

The point to point ATC is calculated with the help of UWPFLOW. Since there are only four regions in the country, namely central (Area 1), northeastern (Area 2), southern (Area 3) and northern (Area 4) regions, there are only three possibilities of point to point ATC, namely, Area 1-Area 2 (A1-2), Area 1- Area 3 (A1-3) and Area 1- Area 4 (A1-4).

In the following study, Thailand power system with existing facilities is used to obtain ATC of base case at the first stage. After that, ATC of the system with new SVC and STATCOM are compared with that of base case to find out the benefit of the devices in terms of ATC.

5.2.1 Base Case

Prior to the investigation of these shunt controllers, the ATC without FACTS devices are studied. The results of PV curves and LM of the system are illustrated in Fig. 5.8 and Table 5.5, respectively.

Since there are only three possibilities of source-sink used to obtain point to point ATC in Thailand power system, only three PV curves of source-sink of A1-2, A1-3 and A1-4 are shown in Fig 5.8. From Fig. 5.8, obviously, ATC of A1-3 is lowest, while that of A1-2 is highest. This implied that region 3 is the weakest region of the country in terms of ATC while region 2 is the most well behaved region of the country. Table 5.5 shows the ATC in terms of MW and per unit values obtained from Fig. 5.8. From Table 5.5, load can be increased up to 3704.4, 2255.7, 3314.8 MW for the cases A1-2, A1-3 and A1-4, respectively.

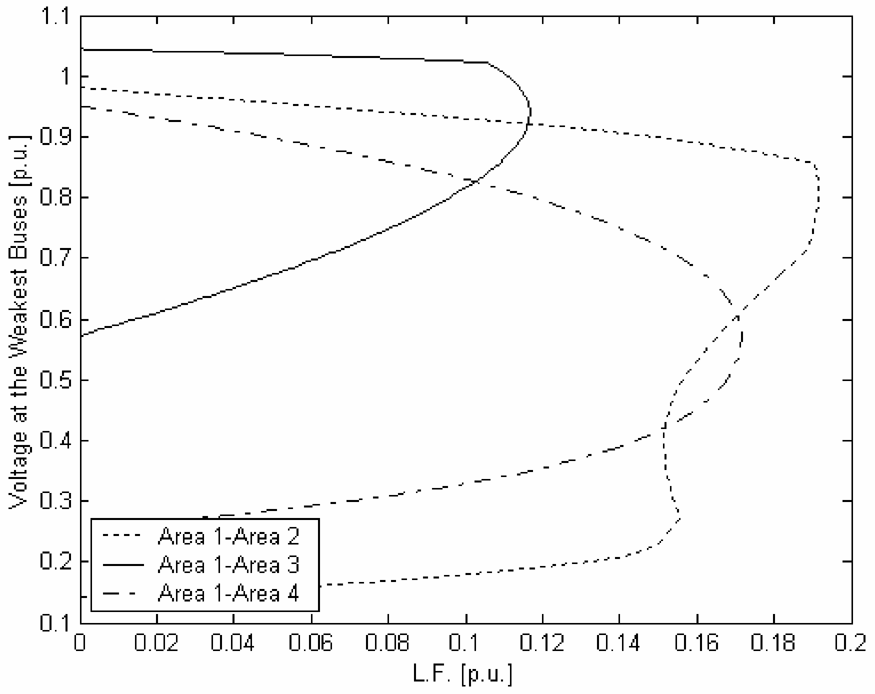

Fig. 5.8 PV curves of base case for A1-2, A1-3 and A-4 cases.

Table 5.5 LM of Base Case for A1-2, A1-3 and A-4 cases shown in Fig. 5.8

Source-Sink	LM [p.u.]	LM [MW]
Area 1 – Area 2	0.19168	3704.4
Area 1 – Area 3	0.11672	2255.7
Area 1 – Area 4	0.17152	3314.8

5.2.2 Base Case with STATCOM at CM2 Substation

The weakest bus of Thailand power system is at bus CM2-5, which is located at 22 kV CM2 substation. In order to increase ATC of the system in case of A1-4, STATCOM with 200 MVA capacity is introduced at the nearest 115 kV substation, CM2 substation. Fig. 5.9 shows PV curves of all possibilities for ATC calculation. It is obvious that ATC is increased with the help of STATCOM. Table 5.6 shows the ATC values for different cases. From Table 5.6, the ATC can be improved about 84.6 % compared to that of base case in A1-4 case if STATCOM is introduced. The significant improvement is arrived from the reactive power support and voltage control of STATCOM.

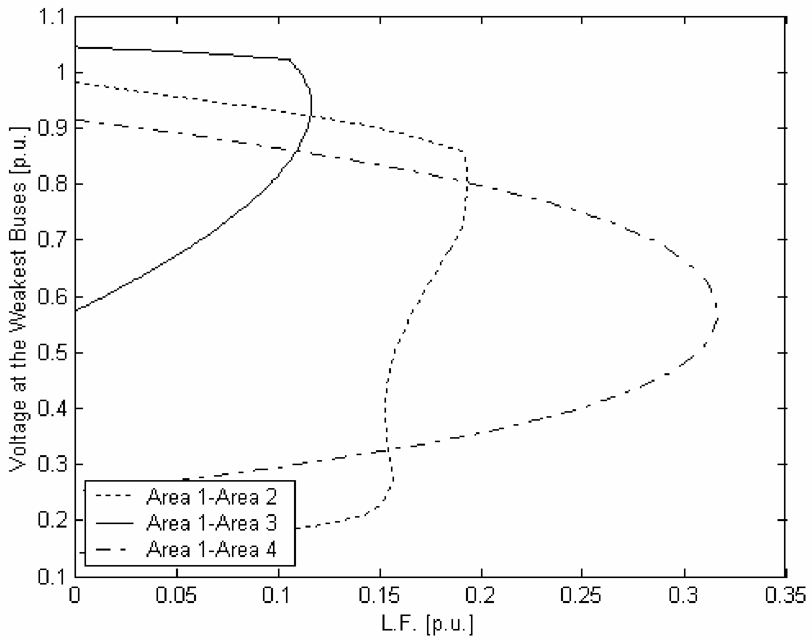

Fig. 5.9 PV curves of base case with STATCOM at CM2 substation for A1-2, A1-3 and A-4 cases.

Table 5.6 LM of Base Case for with STATCOM at CM2 substation A1-2, A1-3 and A-4 cases shown in Fig. 5.9

Source-Sink	LM [p.u.]	LM [MW]	% Improvement with STATCOM
Area 1 – Area 2	0.19299	3729.7	0.68 %
Area 1 – Area 3	0.11676	2256.5	0.04 %
Area 1 – Area 4	0.31660	6118.5	84.58 %

5.2.3 Base Case with more SVC at BSP Substation

Region 3 is the weakest region of the country in terms of ATC. In order to increase ATC in the region, one can introduce shunt FACTS controller at the weakest bus of the region. It is found that the weakest bus of region 3 is at BSP substation, where SVC is located. To increase ATC of the region, another 300 MVA SVC is introduced at that bus. This means that the capacity of SVC is doubled, now. Fig. 5.10 shows PV curves for all possibilities for ATC calculation with additional 300 MVA SVA at BSP substation. It is obvious that ATC is increased with the help of SVC. Table 5.7 shows numerical result of ATC. From Table 5.7, the ATC can be improved about 67.22 % compared to that of base case. It becomes obvious that SVC offers higher amount of ATC compared to the system without the device. The significant improvement is also arrived from the reactive power support and voltage control of SVC.

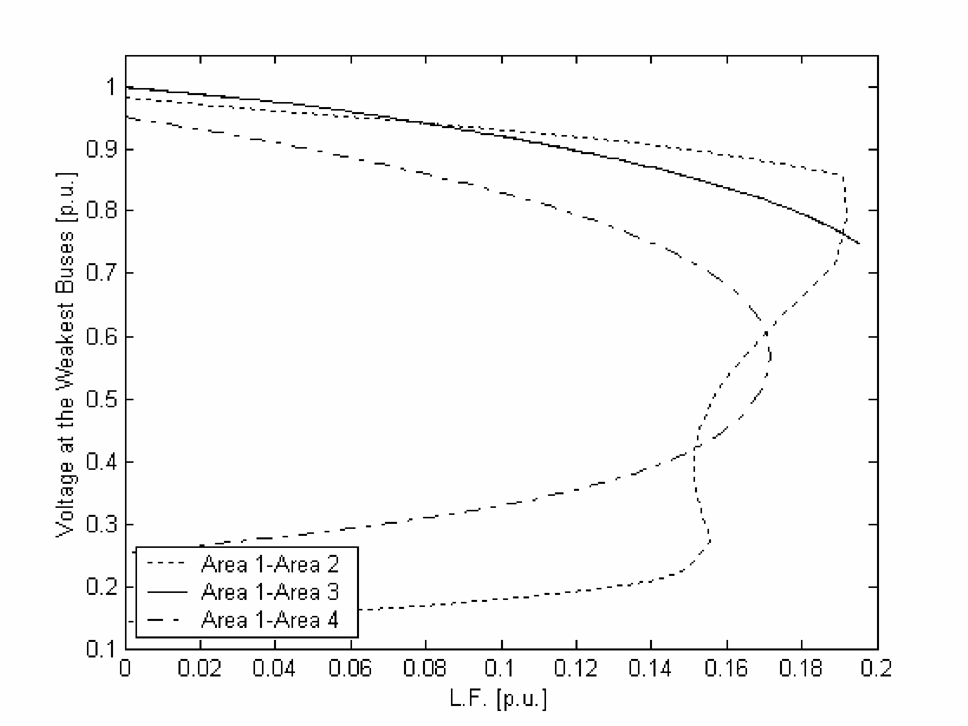

Fig. 5.10 PV curves of base case with SVC at BSP substation for A1-2, A1-3 and A-4 cases.

Table 5.7 LM of Base Case for with SVC at BSP substation A1-2, A1-3 and A-4 cases shown in Fig. 5.10

Source-Sink	LM [p.u.]	LM [MW]
Area 1 – Area 2	0.19170	3704.8
Area 1 – Area 3	0.19518	3772.0
Area 1 – Area 4	0.17154	3315.1

5.2.4 Base Case with more STATCOM at LE Substation

Region 2 is considered as the strongest region among northern, southern and northeastern regions. If ATC of region 2 is needed to be increased, one can suggest to introduce STATCOM at the weakest bus of the region. The weakest bus of the Region 2 is at LE-1 substation. In order to increase ATC of the system in case of A1-2, STATCOM with 200 MVA capacity is introduced at the LE-1 substation. Fig. 5.11 shows PV curves for all possibilities for ATC calculation. It is obvious that ATC is increased with the help of STATCOM. Table 5.8 shows the ATC results. From Table 5.8, the ATC can be improved only 4.4% compared to that of base case. The small improvement is due to the distribution of the load throughout the region.

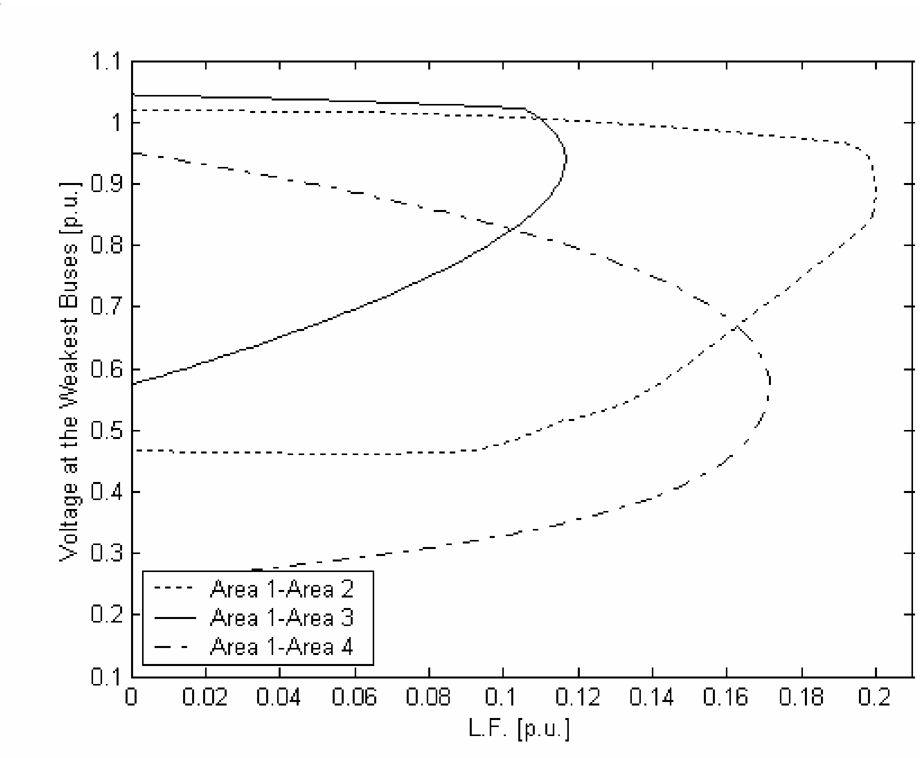

Fig. 5.11 PV curves of base case with STATCOM at LE substation for A1-2, A1-3 and A-4 cases.

Table 5.8 LM of Base Case for with STATCOM at LE substation A1-2, A1-3 and A-4 cases shown in Fig. 5.11

Source-Sink	LM [p.u.]	LM [MW]
Area 1 – Area 2	0.20015	3868.1
Area 1 – Area 3	0.11672	2255.7
Area 1 – Area 4	0.17153	3315.0

5.3 Conclusion

This chapter presents the studies of voltage stability assessment and Available Transfer Capability (ATC) of Thailand power system. In voltage stability study, loading margin of the system is about 1800 MW for business as usual case based on system on the most recent peak day, March 30th 2004. The weakest bus of the system is located in the north of the country. However, when the generators are dispatched based on MLM approach, the weakest bus lies in the south. Reactive power losses are the main factor driving the system to voltage instability.

Installing STATCOM in the north of the country does not provide much improvement in terms of LM. However, installing SVC in the south with appropriate dispatching can give large improvement in terms of voltage stability margin. Contingency of SVC at BSP substation is the worst contingency of the system.

From the ATC studies, southern region is the weakest region in term of ATC. Introducing SVC at BSP can increase ATC of that region. When STATCOM where being used at the weakest bus in terms of voltage stability in the north, ATC of that region is increased. However, this arrangement does not increase the ATC of the southern region.

So, in conclusion we can say that by allowing generators to be dispatched according to MLM approach will make the southern region weakest in terms of both voltage stability and ATC. So, by installing SVC in the south, both the voltage stability margin and ATC of that region can be increased significantly.

Chapter 6

Conclusion

With the history of more than three decades and widespread application in recent years, FACTS controllers has established itself as a proven and mature technology. The operational flexibility and controllability that, FACTS has to offer, will be one of the most important tool for the system operator in the changing utility environmnt. In view of the various power system limits, FACTS provides the most reliable and efficient solution. Application of FACTS for stability imporvement will be of great concern because of the series of blackouts that has occurred in recent years. FACTS also helps to better utilize the existing transmission resources, where the utilities are facing the problem of transmission expansion because of the strict environmental constraints. This all indicates that there is a great potential for its application in the years to come.

Various types of FACTS controllers like SVC, TCSC, STATCOM, SSSC, UPFC, IPFC and CSC are being developed, studied and most of them are already in use in practical power system. The choice of particular controllers however, depends on application rquirement and performance desired. The analysis starts with the system study and identifying the problems associated with the existing system. Static as well as dynamic analysis are to be performed in order to make sure that the system is secure in base case as well as in the case of critical contingency. There are various issues that are to be dealt with during the planning stage of FACTS implementation. The most important issues are related to modelling, optimal location, optimal size and cost of FACTS controllers.

The result of the simulation carried out on EGAT power system indicates that by employing SVC or STATCOM in the weakest bus of the system, the loading margin can be greatly increased. The result also shows the effectiveness of SVC and/or STATCOM in enhancing the ATC of the EGAT power system.

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