APPLICATION OF FACTS DEVICES IN POWER SYSTEMS

By

AZAT PENJIYEV

FINAL PROJECT REPORT

Submitted to the Electrical & Electronics Engineering Programme
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CERTIFICATION OF APPROVAL

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Approved:

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Azat Penjiyev

ABSTRACT

A reliable, stable and economically feasible electric power demand has been increasing rapidly in recent years. The complex interconnected power systems experience stability problems which lead to the overall system interruptions. FACTS (Flexible AC Transmission System) devices are being used to overcome power transmission problems such as power loss, over-loading, instability. This paper discusses the modeling and application of using FACTS (Flexible AC Transmission System) devices in power industry. The previous works of Hingorani, Gyugyi et al on FACTS in power transmission were studied and analyzed. The theory of power line transmission was studied. Two types of FACTS devices exist in power transmission; conventional thyristor based and fully controlled semiconductor based FACTS devices. The paper studies common devices like TCR, SVC, TCSC, VSC, STATCOM, SSSC and UPFC. Simple circuit diagrams and basic mathematical analysis of these devices are presented briefly. As a result the Matlab simulation of STATCOM, SVC and SSSC was run for further analysis of FACTS devices. Detailed analysis and comments on three FACTS devices that were simulated were given in the report.

ACKNOWLEDGEMENTS

I would like to thank University Technology PETRONAS and especially Electric & Electronic Department for giving me an opportunity to research in the area of power transmission.

And I'd like to thank my supervisor, Ir. Perumal, for his continuous help and guidance. It was during this project that I learnt more on power systems, especially transmission of power and had applied Matlab simulations throughout the project work. All these things I learnt will help me in my future career.

Last but not least I'd like to thank all my friends and my family who have been giving me courage throughout the project in order to complete my degree program in Electric & Electronic Engineering.

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LIST OF ABBREVIATIONS

IEEE	Institute of Electrical and Electronics Engineers
EPRI	Electric Power Research Institute
AC	Alternating Current
DC	Direct Current
FACTS	Flexible AC Transmission Systems
FC	Fixed Capacitor
SSSC	Static Synchronous Series Compensator
STATCOM	Static Synchronous Compensator
SVC	Static Var Compensator
TCSC	Thyristor Controlled Series Capacitor
TCR	Thyristor Controlled Reactor
VSC	Voltage Source Converter
UPFC	Unified Power Flow Controller
GTO	Gate Turn-Off

CHAPTER 1

INTRODUCTION

In today's power systems industry there is a rapid increase in number of power consumers. These customers demand not only the power but also stability of it. Power system solutions discarding FACTS devices are not enough to overcome power line overloads and instability of transmission lines. However replacement of existing power transmission could be done although it will cost much or simply the usage of FACTS devices will increase the overall performance of power line transmission [1]. FACTS devices were studied and developed to provide more economically feasible power for customers without power transmission instability.

1.1 Background of study

In the late 1980s the Electric Power Research Institute (EPRI) introduced Flexible AC Transmission System (FATCS) [2]. FACTS devices are used for both long distance transmission power systems. In long distance transmission systems FACTS devices are used to control the voltage, reactive power, steady state and dynamic stability of transmission line. In interconnected systems FACTS are used for control of load flow, voltage stability, and system oscillations [3]. FACTS devices are high-speed electronic devices that increase the power system performance by delivering or absorbing real and/or reactive power. The mostly common FACTS devices in today's power industry are Thyristor-Controlled Reactor, Thyristor-Controlled Series Capacitor (TCSC), Static Var Compensator (SVC), Static Synchronous Compensator (STATCOM), Static Synchronous Series Compensator (SSSC) and Unified Power Flow Controller (UPFC) [4]. These FACTS devices are connected to power system in shunt or series or combination of shunt and series. The TCSC and SSSC devices have series connection with power system whereas SVC and STATCOM are connected in shunt. The UPFC is connected in a combination of both shunt and series.

1.2 Problem Statement

In transmission network there is a challenge in transmission of bulk power from its generation location to customer's side. The increasing complexity creates poor power delivery in manufacturing and services industries that results in power outages and disturbances at the client's side. To overcome these challenges the present transmission systems needs to be increased with the constraint of money and environment [5]. Therefore the introduction of FACTS devices is vitally important for solution of power transmission challenges.

1.3 Objectives and Scope of Study

- To identify the widely used FACTS devices
- To study the incorporation of FACTS devices in power transmission industry
- To learn mathematical representation, operation, stability and security relations of FACTS devices with power transmission systems
- To compare performances of commonly used FACTS devices such as SVC (Static VAR Compensator), STATCOM (Static Condenser) and SSSC (Static Synchronous Series Compensator)
- To simulate the STATCOM and SVC using Matlab and compare their performances
- To simulate and analyze the SSSC using Matlab
- To comment on overall performance of STATCOM, SVC and SSSC

CHAPTER 2

LITERATURE REVIEW AND/OR THEORY

2.1 Background of FACTS

In the last decade huge research was done in the area of power flow and FACTS devices. A large number of researchers have done immense contribution for the development of FACTS devices, their mathematical representation, and steady-state operation. Electric Power Research Institute (EPRI) led to the idea of FACTS technology. Before FACTS were developed the AC power transmission systems were controlled mechanically.

Power electronic controlled devices, such as static VAR compensators, have been used in transmission networks for many years; however, the concept of FACTS as a total network control philosophy was introduced in 1988 by Dr. N. Hingorani from the Electric Power Research Institute (EPRI) in the USA. He proposed [8] the concept of flexible AC transmission systems that included the use of high-power electronics, advanced control centres, and communication links, to increase the usable power transmission capacity to its thermal limit [6]. According to **Hingorani**: "The flexible transmission system is akin to high-voltage dc and related thyristor developments, designed to overcome the limitations of the present mechanically controlled AC power transmission systems". The usage of high speed electronic controllers increases the system performance.
It improves [7]:

- control of power, so that it flows on the prescribed transmission routes
- secure loading of transmission lines to levels nearer to their thermal limits
- greater ability to transfer power between controlled areas
- prevention of cascading outages by limiting the effects of faults and equipment failure

- Damping of power system oscillations, which could damage equipment and limit usable transmission capacity

2.2 FACTS devices potential applications in power industry [23]

- Parallel power flow

It is flow of power from bus bars which are connected in parallel to each other; it can not simply be set power to flow through each circuit, either directly from Bus1 to Bus2. The impedances of circuits control the load sharing; it is inflexible. When the impedances are not same with each other one of the circuits might now have its full thermal capacity when operating in parallel with the other circuit. Thus, in this condition the load can be controlled by using HVDC.

- Stability constraint of maximum transmission line loading

Power flow is simply a function of sending and receiving voltages along the transmission line. There are two cases of instability in power line transmission; transient and dynamic instability. For the former one FACTS devices could be used to increase the stability margins which will allow more circuit loading till it reaches its thermal capacity. And for the latter FACTS devices help to dampen the power oscillations that will prevent loss of synchronism. For instance SSSC is mainly used to dampen the power oscillations in the power transmission line. Voltage instability occurs when the transmission system has insufficient dynamic reactive support. SVC helps to overcome voltage instability with its receiving end capacitive reactive support.

- Reactive power constraint of maximum transmission line loading

The sending and receiving end voltages does exist across the line reactance. Then the line reactive power will be

$Q = \frac{V_{SR}^2}{X_{line}}$, so when the line has grater loading reactive, line absorption will increase. The network must supply reactive power to offset the reactive power absorption of the line. Thus, reactive power compensation is necessary to avoid the power loss of transmission line. FACTS devices could be used to supply reactive power in the network which will prevent the real power loss.

2.3 Conventional thyristor based versus GTO based FACTS devices

Static VAR Compensator (SVC) is one of first generation of FACTS devices in power industry which used thyristor controllers. It was a shunt reactive compensation controller [6]. Static VAR compensator controls only one of the three important parameters (voltage, impedance, phase angle) [6]. The SVC uses conventional thyristor. The thyristors were invented by General Electric in the early 1960s which a four-layer semiconductor device called the silicon controlled rectifier (named later as thyristors) [8]. With the series connection of thyristors high level of power was achieved.

Later on the thyristor were developed that resulted in invention of GTO (Gate turn-off) thyristors. It is more advanced version of conventional thyristor. It has similar switched-on characteristics but with different time of ability to switch-off. GTO turns off when the forward current falls below the holding current level [9]. Comparing to conventional thyristors the GTO thyristors have higher losses and cost [8]. Furthermore the GTO construction and design needs improvement due to its large negative pulses to turn off [9].

Thyristor-controlled series compensator (TCSC) is a second-generation FACTS controller, which controls the effective line reactance by connecting a variable reactance in series with line. The variable reactance is obtained using FCTCR (Fixed Capacitor TCR) combination with mechanically switched capacitor sections in series [1].

Static synchronous compensators (STATCOMs) are GTO (gate turn-off type thyristor) based SVCs. Compared with conventional **SVCs** they do not require large inductive and capacitive components to provide inductive or capacitive reactive power to high voltage transmission systems. An additional advantage is the higher reactive output at low system voltages where a STATCOM can be considered as a current source independent from the system voltage. STATCOMs have been in operation for approximately 5 years [1].

According to Gyugyi's explanation on concept of UPFC [6], there are two controlled variables. First is voltage source which is inserted in series with the line and second is current source which is connected in shunt with the line. He says that both angle and magnitude of voltage are controllable whereas in current only magnitude is controllable parameter.

Table 1 : Tabulated characteristics of common FACTS controllers [12].

FACTS Devices	Control Characteristics
Thyristor-Controlled Reactor (TCR)	Current control, damping oscillation, transient and dynamic stability, voltage stability, fault current limiting
Thyristor-Controlled Series Capacitor (TCSC)	Current control, damping oscillation, transient and dynamic stability, voltage stability, fault current limiting
Static VAR Compensator (SVC)	Voltage control, VAR compensation, damping oscillation, transient and dynamic stability, voltage stability
Static Synchronous Series Compensator (SSSC)	Current control, damping oscillation, transient and dynamic stability, voltage stability, fault current limiting
Static Synchronous Compensator (STATCOM)	Voltage control, VAR compensation, damping oscillation, transient and dynamic stability, voltage stability
Unified Power Flow Controller (UPFC)	Active and reactive power control, voltage control, VAR compensation, damping oscillation, transient and dynamic stability, voltage stability, fault current limiting

2.4 Importance of FACTS devices

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 [25] [26]. 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 [24]. 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 [27]. 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 [25] [28]. 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 [25] [28] [29]. 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 [29]. 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 combination of 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 developed nations.

2.5 Theory of power transmission

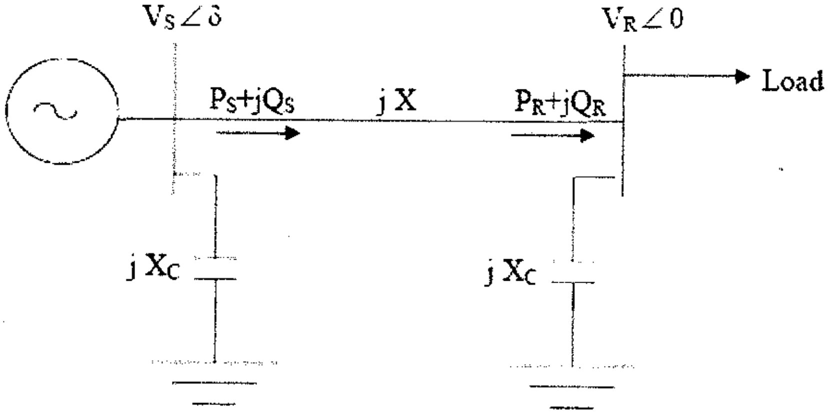


Figure 1 : Simple π model two bus transmission system.

For the power transmission the reactive and real power are important factors. The reactive power and real power equations of above figure are given as [10] [11] [20]:

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

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

and

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

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

The receiving end and sending real and reactive power is found using voltage at receiver and sending side and phase angle difference between the voltages [11] [20]. The phase angle difference is very small in normal power systems.

Ignoring the last term in reactive power equation, it becomes:

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

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

That means the reactive power transferred between two points is found by voltage magnitudes at two buses, series reactance of the line and cosine of the power angle between two points [11].

From the above equations we can conclude that the real power flows from high angle to low whereas the reactive power flows from high voltage to low voltage bus [11].

CHAPTER 3

METHODOLOGY

3.1 Flowchart of the project

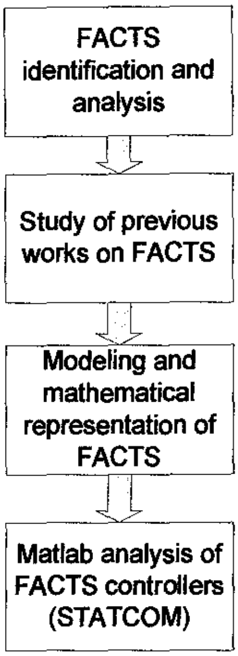


Figure 2 : Basic flowchart of the project.

First of all the concept of FACTS was studied and most common devices in power industry were identified. Various works of famous ones in area of FACTS were studied and compared. Modeling and mathematical representation were studied referring to previous works on FACTS. Matlab simulation analysis of STATCOM was carried for power flow study of FACTS.

3.2 FACTS analysis

IEEE defines FACTS devices as "alternating current transmission system incorporating power electronic-based and other static controllers to enhance controllability and increase power transfer capability".

This technology offers [13]:

- Control of power flows on their transmission routes
- Safe loading of transmission lines to their thermal limits

There are two types of FACTS devices, conventional thyristor-based FACTS controllers and VSC (Voltage Source Converter)-based FACTS controllers. In conventional thyristor-based FACTS the susceptance or impedance is the controlled parameter that is determined by the output of the control system. Whereas in VSC-based FACTS are represented by variable parameters of voltage and/or current [3].

The FACTS devices can be connected to transmission line in series or shunt or both series and shunt. The SVC and STATCOM have shunt connection, whereas TCSC and SSSC have series connection. The UPFC has combination of series and shunt.

3.3 TCR-based FACTS devices

The TCSC and SVC have TCR (Thyristor-Controlled Reactor) connected for the control of susceptance or impedance. The SVC and TCSC are based on representing the controllers as variable susceptances or impedances changing with the firing angle of the TCR, which is used to control voltage, current and/or power of the system [15].

3.3.1 TCR (Thyristor-Controlled Reactor)

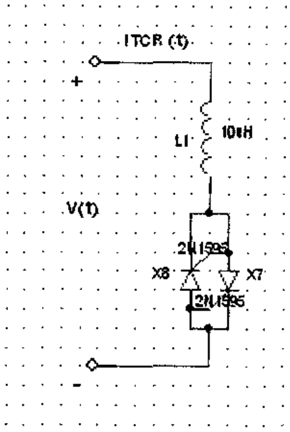


Figure 3 : Basic TCR circuit diagram.

Thyristor pair is the controllable variable in TCR. The TCR consists of a reactor in series with two parallel inverse thyristors. Thyristor controller enables reactor (L) to act as controllable easily influenced element. The two inverse parallel thyristors are gated symmetrically. They control the time for which the reactor conducts and therefore control the fundamental component of the current. The thyristors conduct on alternate half-cycles of the supply frequency depending on the firing angle α or conduction angle σ. It is measured from a zero crossing of current with reference to the voltage zero-crossing. The relation between firing angle and conduction angle as follows:

$$\sigma = 2(\pi - \alpha) \text{ [14]}$$

$$I_{TCR} = -jB_{TCR}V$$

where the B_{TCR} is the susceptances, V is the voltage. Equation derivation referred to [14] is given in the APPENDIX A.

3.3.2 SVC (Static VAR Compensator)

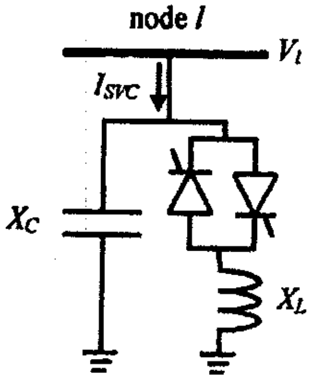


Figure 4 : Basic SVC circuit diagram.

SVC provides fast-acting reactive power compensation on high voltage power transmission networks. It consists of TCR and bank capacitors connected parallel to TCR. It regulates voltage by generating or absorbing reactive power. When system voltage is low, the SVC generates reactive power (SVC capacitive). When system voltage is high, it absorbs reactive power (SVC inductive). Terminal bus voltage is the control variable controlled by SVC [11]. The susceptance of SVC can be controlled using TCR, firing thyristors in a suitable angle range, typically $90^0 \sim 180^0$.

The firing angle control of the thyristor enables the SVC to have instant response. At normal operation, SVC controls the total susceptance by terminal voltage. At minimum or maximum susceptance, SVC acts like a fixed capacitor or fixed inductor. At point B_{max}, all thyristor switched capacitors are switched on and SVC provides rated capacitive current at specified voltage. At point B_{min}, the thyristor-controlled reactor is fully switched on, and all thyristor switched capacitor off which gives inductive current at a defined voltage [11].

In an ideal variable shunt compensator there is no resistive component that draws no active power from the network. But the reactive power is given according to the SVC figure above.

$P = 0$

$Q = -|V|^2 B_{SVC}$

Where V is the voltage at the connection point and B_{SVC} is the equivalent susceptances.

3.3.3 TCSC (Thyristor-Controlled Series Capacitor)

The TCSC is one of important devices of FACTS family power electronic controllers. It provides smooth, rapid and continuous adjustment of transmission line impedance. TCSC consists of TCR (thyristor-controlled Reactor) in parallel with a fixed capacitor.

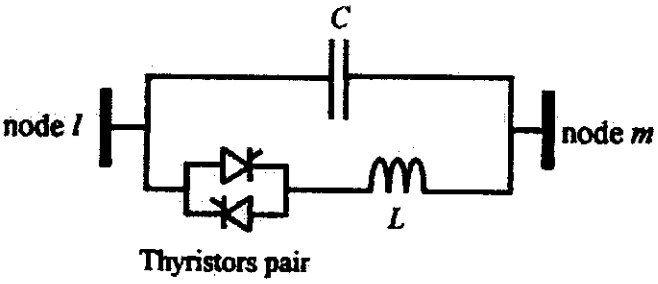


Figure 5 : Basic TCSC circuit diagram.

The active power in the above figure between l and m is represented by voltage magnitude, difference phase angle of voltages and reactance.

$P_{lm} = \frac{|V_l||V_m|}{X_{lm}}\sin(\delta_l - \delta_m)$, when the electrical branch is TCSC controller then regulated active power is:

$P_{lm}^{reg} = \frac{|V_l||V_m|}{X_{TCSC}}\sin(\delta_l - \delta_m)$; where X_{TCSC} is the equivalent reactance of the TCSC controller that can be adjusted to regulate the transfer of active power across the TCSC.

3.4 VSC-based FACTS devices

VSC-based FACTS controllers use voltage source converter. In DC-AC converters the fully controlled semiconductor devices are used. The DC input can be either voltage source (capacitor) or current source (voltage source in series with inductor). So converter can be either voltage source converter or current source converter. VSC topology is used in STATCOM, SSSC and UPFC for economic and performance reasons. As mentioned before in VSC-based devices the output voltage and/or current is the controlled parameter.

3.4.1 STATCOM (Static Compensator)

It consists of one VSC and shunt connected transformer. STATCOM is used for controlling the transmission voltage by reactive power shunt compensation.

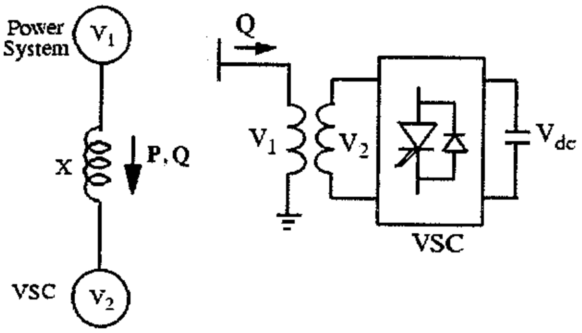


Figure 6 : STATCOM with shunt connected variable voltage source.

STATCOM generates balanced sinusoidal voltages at the fundamental frequency with rapidly controllable amplitude and phase angle [21]. It is the voltage-source

converter, which converts a DC input voltage into AC output voltage in order to compensate the active and reactive power needed by the system.
The STATCOM regulates voltage at its terminal by controlling the amount of reactive power injected into or absorbed from the power system. When system voltage is low, the STATCOM generates reactive power (STATCOM capacitive). When system voltage is high, it absorbs reactive power (STATCOM inductive) [17].

STATCOM can either generate or absorb reactive power by controlling the inverted voltage V_2 with respect to V_1. The active and reactive power representation will be:
$P = \frac{V_1 V_2}{X}\sin(\delta)$ and $Q = \frac{V_1(V_1 - V_2\cos\delta)}{X}$; where V_1 and V_2 is the line voltage of source V_1 and V_2. X is the reactance and δ is the angle of V_1 with respect to V_2. In steady-state operation the voltages V_1 and V_2 are in phase (δ=0).

$$P = \frac{V_1 V_2}{X}\sin(\delta) = 0 \text{ and } Q = \frac{V_1(V_1 - V_2)}{X} = \frac{V_1^2 - V_1 V_2}{X}$$

If $V_1>V_2$, Q is flowing from V_1 to V_2 (STATCOM is absorbing reactive power); if $V_2>V_1$, Q is flowing from V_2 to V_1 (STATCOM is generating reactive power).

A more flexible model STATCOM power flow model can be represented by adjusting the voltage magnitude and phase angle.
$V_2 = |V_2|(\cos\delta_2 + j\sin\delta_2)$; the voltage magnitude is given maximum and minimum limits which are a function of STATCOM capacitor rating. The δ_2 can take any value between 0 and 2π, but in practice it will be close to δ_1.

3.4.2 SSSC (Static Synchronous Series Compensator)

The SSSC has similar diagram as STATCOM. It is based on a DC capacitor fed VSC that generates a three-phase voltage at fundamental frequency; the SSSC injects a voltage Vs (voltage from the figure below) in series with the transmission line where it is connected. The SSSC can directly control the current, and indirectly control the power, flowing through the line by controlling the reactive power exchange between the SSSC and the AC system. Compared to TCSC the SSSC does not directly affect the line impedance [11].

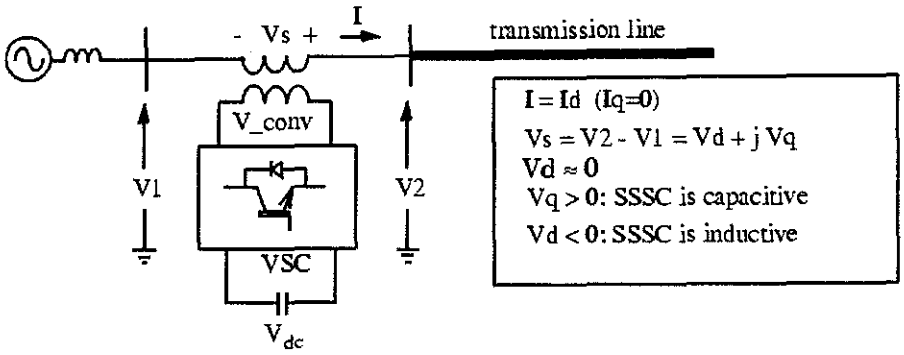


Figure 7 : Single line Diagram of SSSC.

The SSSC does not use any active power source; the injected voltage must stay in quadrature with line current. By varying the magnitude Vq of the injected voltage in quadrature with current, the SSSC performs the function of a variable reactance compensator, either capacitive or inductive. When Vq>0, SSSc is capacitive; Vd<0, SSSC is inductive. The series voltage source of SSSC is represented by:

$Vs = |Vs|(\cos\delta + j\sin\delta)$; Where maximum and minimum limits of Vs magnitude is a function of capacitor rating and phase angle can be between 0 and 2π.

3.4.3 UPFC (Unified Power Flow Controller)

The UPFC is the most multi-functional device in FACTS family. It consists of two VSCs sharing common capacitor on their DC side and a unified control system. The UPFC allows simultaneous control of active, reactive power flow and voltage magnitude at UPFC terminals [22].

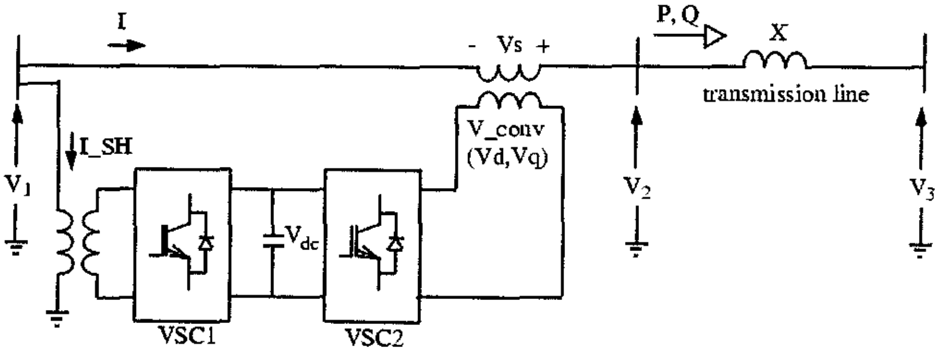


Figure 8 : UPFC circuit diagram.

The active power demanded by series VSC is drawn by shunt VSC from AC network and given to bus at V2 through the DC link. The output voltage of VSC1 is added to nodal voltage at bus V1 to boost the nodal voltage at bus V2. The voltage magnitude of the output voltage V2 gives the voltage regulation whereas the phase angle gives the mode of power flow [20]. The shunt VSC may also generate or absorb reactive power in order to provide independent voltage magnitude regulation at AC system connection point. Two voltage sources are represented as:

$V_1 = |V_1|(\cos\delta_1 + j\sin\delta_1)$ and $V_2 = |V_2|(\cos\delta_2 + j\sin\delta_2)$

And the active power constraint equation will be:

$\mathrm{Re}[\{-V_1 I_1^* + V_2 I_2^*\} = 0$

Like shunt and series voltage sources in STATCOM and SSSC the UPFC voltage sources also would have limits. For the shunt converter: $V_{1min} < V_1 < V_{1max}$ and $0 < \delta_1 < 2\pi$. And for the series converter: $V_{2min} < V_2 < V_{2max}$ and $0 < \delta_2 < 2\pi$.

3.5 FACTS applications

Power transmission systems have steady-state and dynamic limits which lessens the power transaction. Before FACTS were applied fixed or mechanically switched shunt/series capacitors and reactors were used to overcome power system restrictions. FACTS controllers replaced those fixed/mechanical capacitors and reactors due to their slow response. FACTS technology provides security, reliability, efficient transmission capacity and operational flexibility for deregulated power market [11].

Due to its high cost, the FACTS devices should be sufficiently studied in terms of their type, size and location.

3.5.1 Steady-state application of FACTS

The high or low voltage, thermal line and equipment capacities are steady-state limitations of the transmission system [11]. During steady-state limitation, compared to fixed/mechanical capacitor/reactor solutions, FACTS controllers can rapidly control the voltage, current and/or impedance of the transmission system. Economically, the usual solutions (fixed/mechanical control) are more feasible but lack in dynamic response to the disturbance in the system.

3.5.2 Dynamic application of FACTS

The FACTS devices improve the dynamic characteristics of transmission system such as; transient stability, voltage stability and damping oscillations (dynamic stability) [11]. Reducing the main disturbance in the system is one of the most important capabilities of FACTS controllers. The STATCOM could be used for dynamic voltage support in disturbance reduction. The UPFC or TCSC can be used for dynamic flow control during system disturbance impact reduction.

Table 2 : Technical benefits of main FACTS controllers.

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

■
■■ ↓ Better
■■■

3.6 Benefits of FACTS devices [11]

i) Technical benefits

FACTS devices have many technical benefits in the power transmission system. Employing FACTS devices in the existing system does not necessarily require update of current system. FACTS controllers have good utilization of existing system devices.

ii) Reliability and availability

Utilization of FACTS in the power system makes it more reliable and secure in cases of power line failure or overload.

iii) Transient and dynamic stability

FACTS devices overcome transient and dynamic system instabilities by controlling system parameter; current and/or voltage, impedance and power flow.

iv) Cost

Compared to conventional power system solution FACTS devices are more expensive. But in the long run they are more economically feasible. FACTS can be incorporated in the tripped system without renewing the overall system itself.

v) Environmental

FACTS devices are environmentally friendly. They lessen the number of transmission routes in populated areas. More, they do not contain any hazardous material and produce waste pollutants.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Results of STATCOM

The Static Synchronous Compensator (STATCOM) is one the important members of FACTS devices. It is used to supply or absorb reactive power when the line voltage is low or high, respectively. STATCOM uses VSC (voltage source converters) to regulate the power line voltage. It either acts inductive or capacitive. When inductive it absorbs the high line voltage and when capacitive it supplies reactive power due to low voltage in the power line. The connection diagram of power line with STATCOM is given below. The results of simulation were obtained with and without STATCOM.

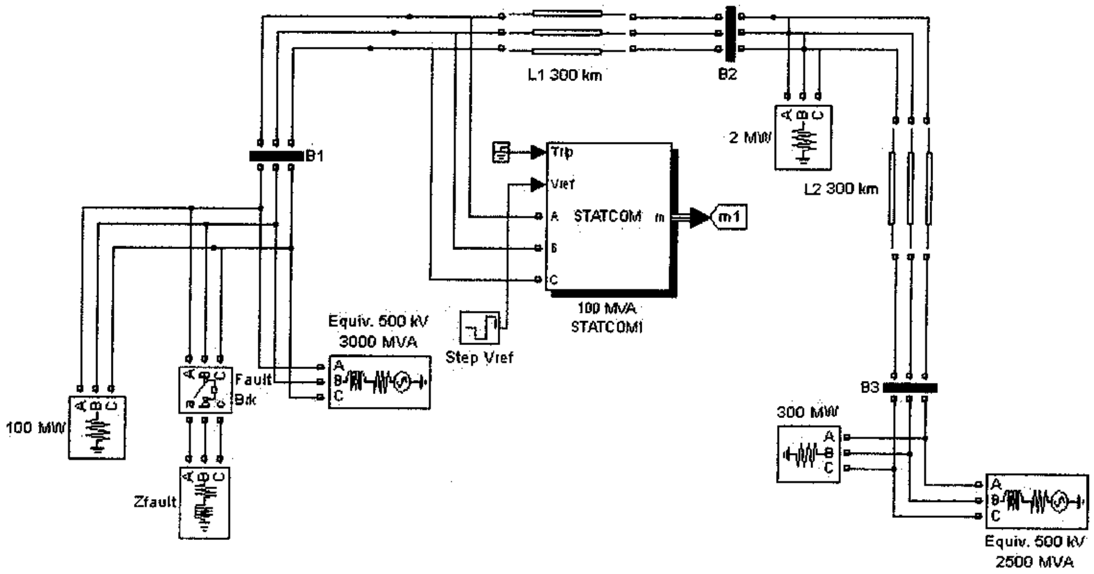


Figure 9 : Simulation block diagram with STATCOM.

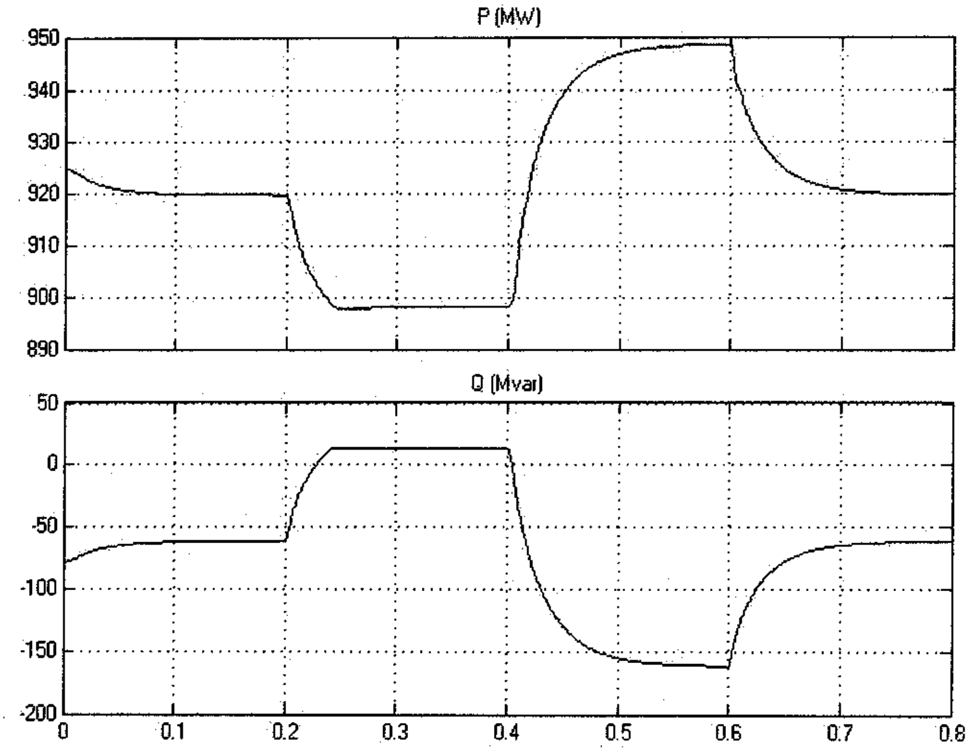


Figure 10 : P and Q results without STATCOM.

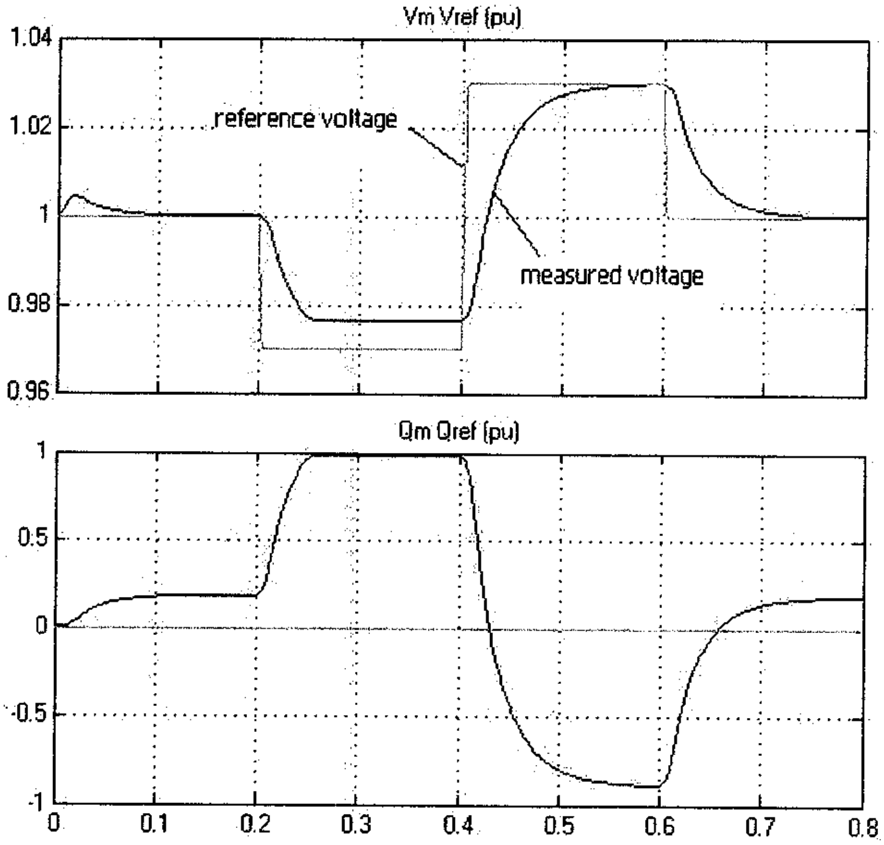


Figure 11 : V and Q results with STATCOM.

4.2 Discussion of STATCOM

The STATCOM is a shunt connected devices in FACTS family. It helps to control power flow and improve the transient stability of the power line. It regulates the line voltage either by supplying or absorbing reactive power. When the power line voltage is low the system needs to be stabilized by reactive power injection, in this situation STATCOM acts as capacitive, generating reactive power for the system. And when the line voltage is high it needs to be reduced to avoid any system failures. Thus, STATCOM absorbs reactive power in order to stabilize the power line, acting as inductive. Phasor model STATCOM that was used in this simulation has two modes of operation; voltage regulation and var control modes. When it is set at voltage regulation mode the sending and receiving end voltages are regulated within limits. And when the var control mode is set the reactive power output is kept as constant, does not vary as shown in below figure.

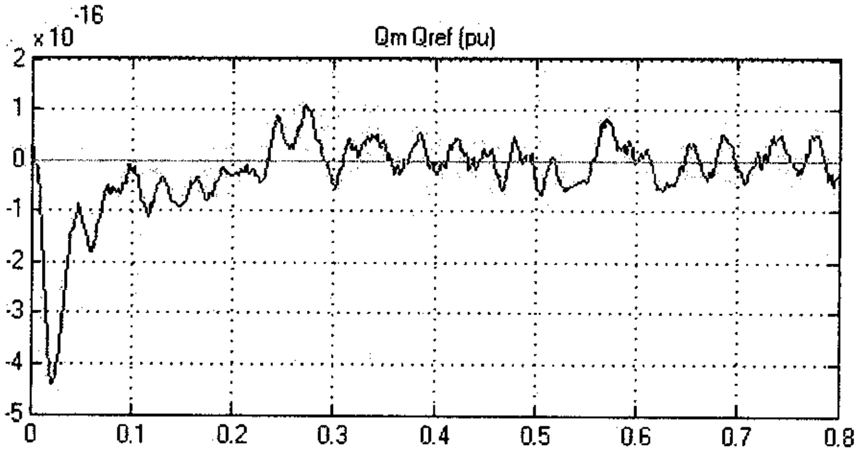


Figure 12 : Q output in var control mode.

When the system was simulated first, without the STATCOM the reactive power can be observed as 0Var when the system voltage is low. However with STATCOM the reactive power is 1p.u for the same time period. And without STATCOM power line absorbs 150Mvar but with STATCOM the reactive power absorbed is 1p.u which gives 100Mvar with 100MVA as its base. Thus, the difference is 50Mvar when the STATCOM is placed in the system.

For the voltage regulation STATCOM has almost similar measured voltage with reference voltage. They are very much similar. The reason is that the droop regulation was set as zero. So, when it is increased, 0.03 for example, the STATCOM measured voltage is not necessarily same with reference voltage. This shows that does not operate as a perfect voltage regulator (Vm does not follow exactly the reference voltage Vref). For a given maximum capacitive/inductive range, this droop is used to extend the linear operating range of the STATCOM. Setting the droop parameter to 0 and the voltage regulator gains back to 5 (Kp) and 1000 (Ki), the measured voltage Vm now is not similar with Vref. [17].

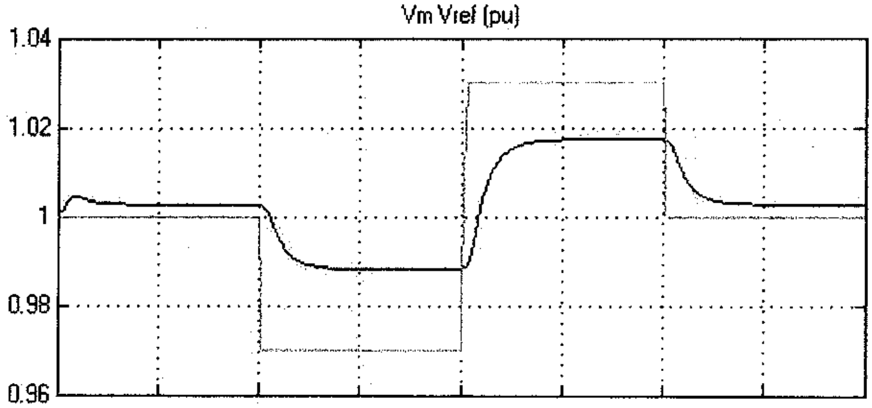


Figure 13 : Voltage output after droop is 0.03.

4.3 Results of SVC

The SVC acts same with STATCOM. It regulates the voltage of the system either by injecting or absorbing reactive power. When system voltage is low, the SVC generates reactive power (SVC capacitive). When system voltage is high, it absorbs reactive power (SVC inductive). In the below figure the SVC is connected to the 500kV system. Susceptance (B), Vmeasured versus Vactual and reactive power (Q) were observed.

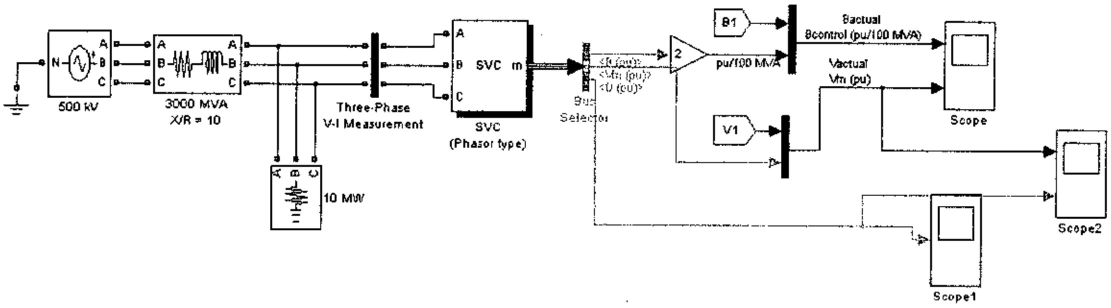


Figure 14 : System with SVC connected.

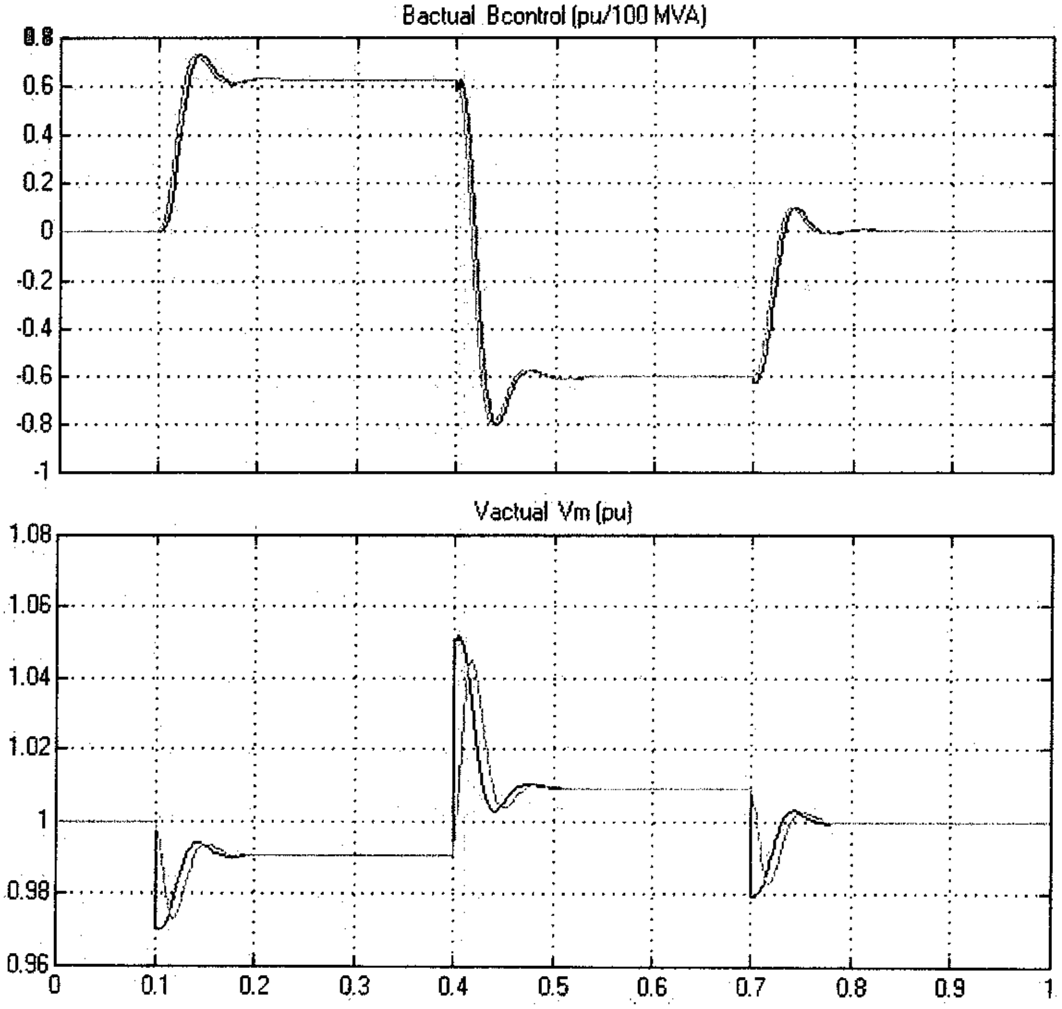


Figure 15 : Susceptance and Voltage output of SVC.

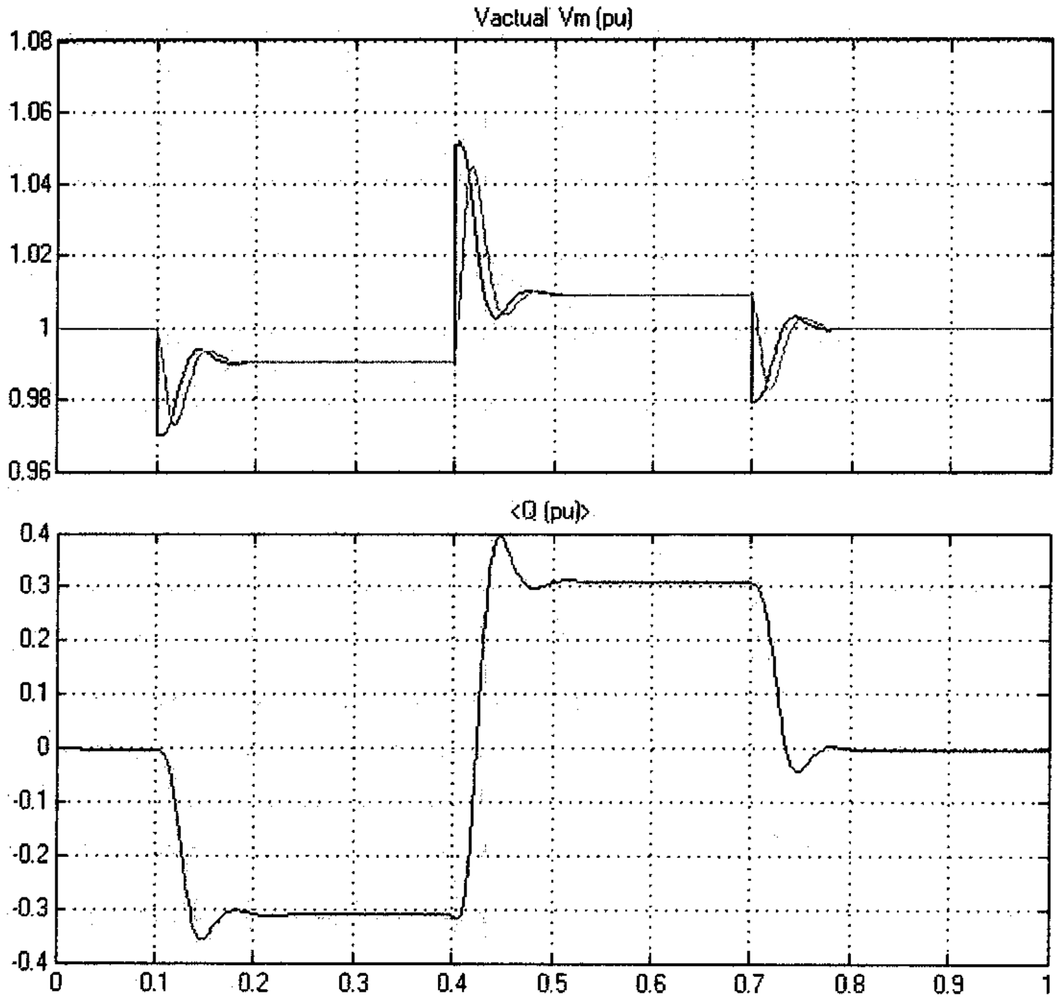


Figure 16 : Voltage and Reactive Power output of SVC.

4.4 Discussion of SVC

SVC was used to regulate voltage on a 500 kV, 3000 MVA system. When system voltage is low the SVC generates reactive power (SVC capacitive). When system voltage is high it absorbs reactive power (SVC inductive). The SVC is rated +200 Mvar capacitive and 200 Mvar inductive. These reactive powers can be changed from the SVC power data block a property which sets limits for reactive powers; capacitive and inductive. Like STATCOM, SVC operates in two modes; voltage regulation and Var control. Voltage regulation mode regulates voltage of the system either by injecting or absorbing reactive power. And Var control mode sets susceptance as fixed, shown in the figure below.

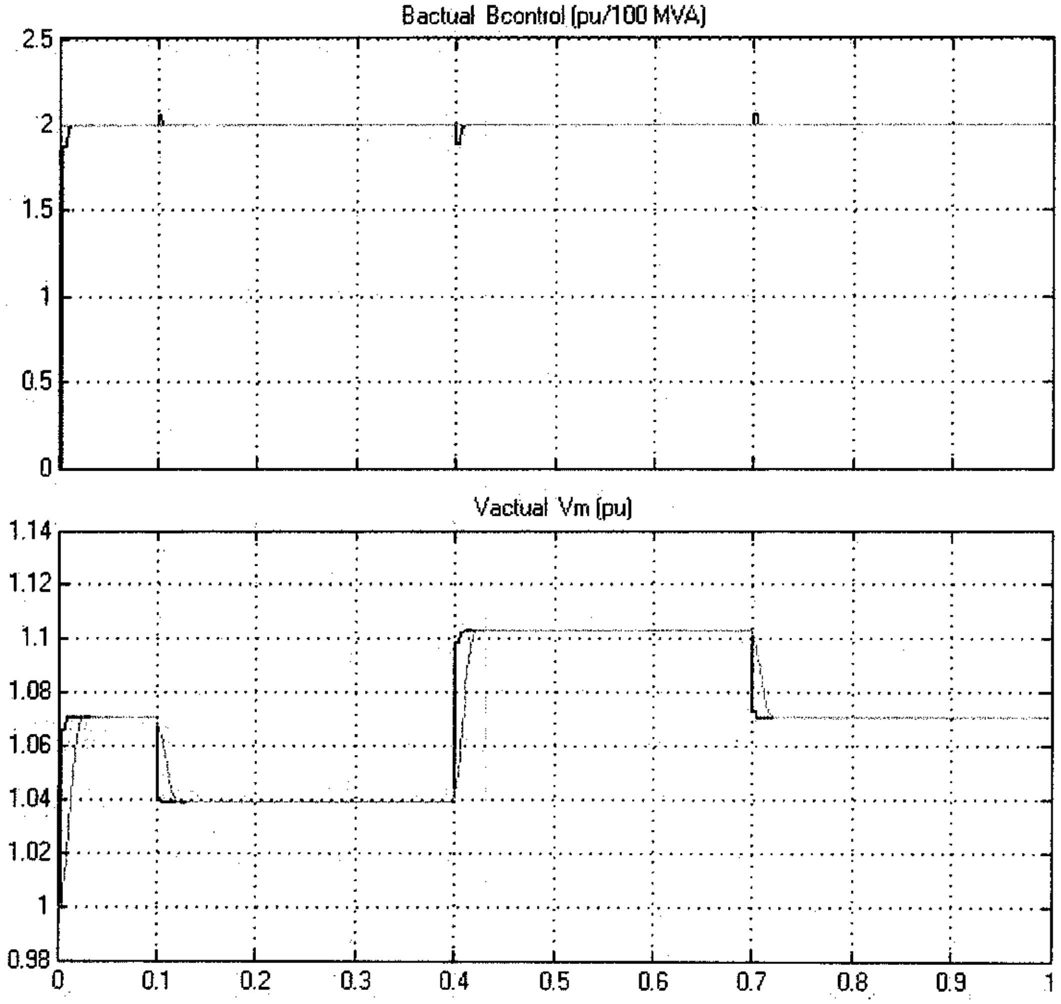


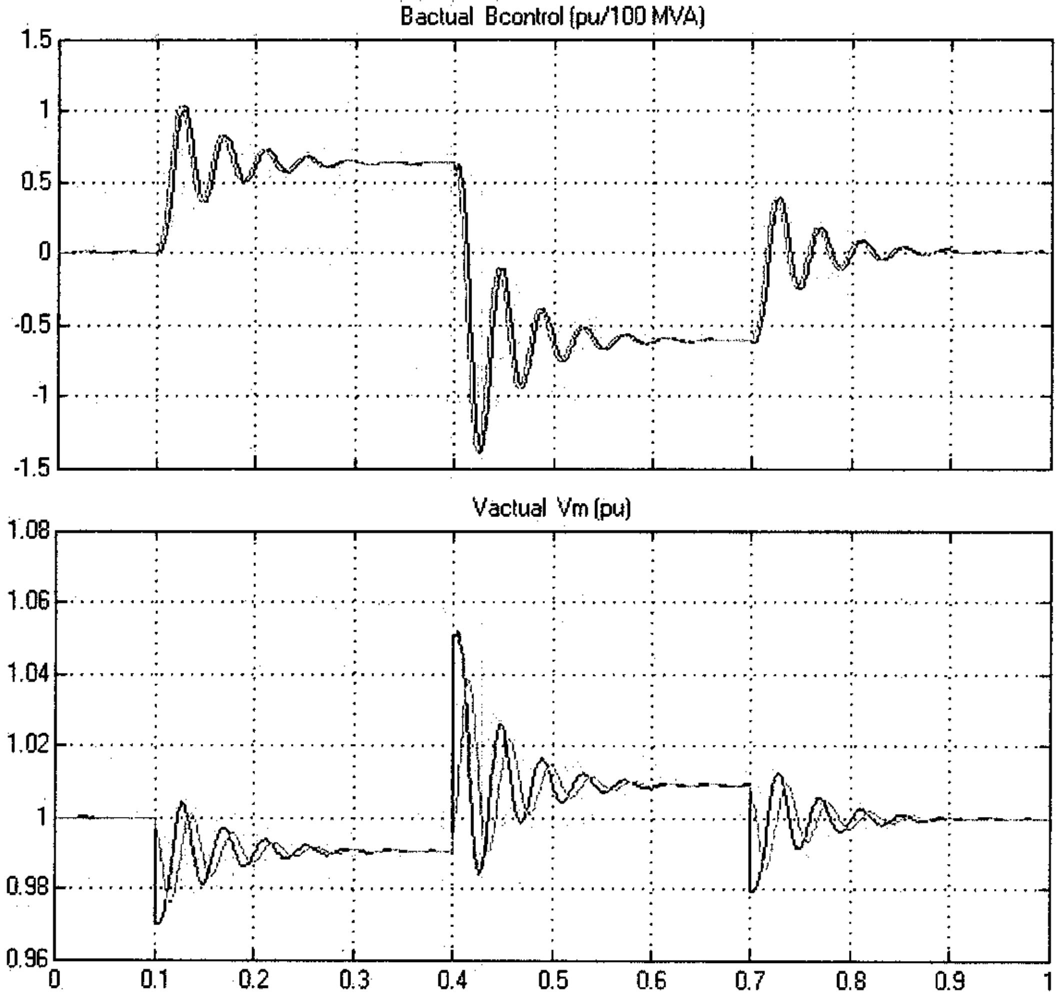
Figure 17 : Susceptance and Voltage output of SVC in Var control mode.

The SVC response speed depends on the voltage regulator integral gain Ki (Proportional gain Kp is set to zero), system strength (reactance Xn) and droop (reactance Xs). If the voltage measurement time constant Tm and average time delay Td due to valve firing are neglected, the system can be approximated by a first order system having a closed loop time constant:

Tc= 1/(Ki*(Xn+Xs))

With given system parameters (Ki = 300; Xn = 0.0667 pu/200 MVA; Xs = 0.03 pu/200 MVA), Tc = 0.0345 s. If the regulator gain is increased or decreased the system strength, the measurement time constant and the valve firing delay Td will no longer be negligible and you will observe an oscillatory response and eventually instability.

Below figure shows the SVC output response when the regulator gain is Ki=2000, as it is seen there is too much oscillation compared to Ki=800.


Bactual Bcontrol (pu/100 MVA)

Vactual Vm (pu)

Figure 18 : Susceptance and Voltage output of SVC when Ki=2000.

The susceptance and voltage oscillation increase when the short-circuit level of the Three-Phase Series RLC branch decreased. The short-circuit level was set as 500 MVA; the results obtained have more oscillation compared to results with 3000MVA.

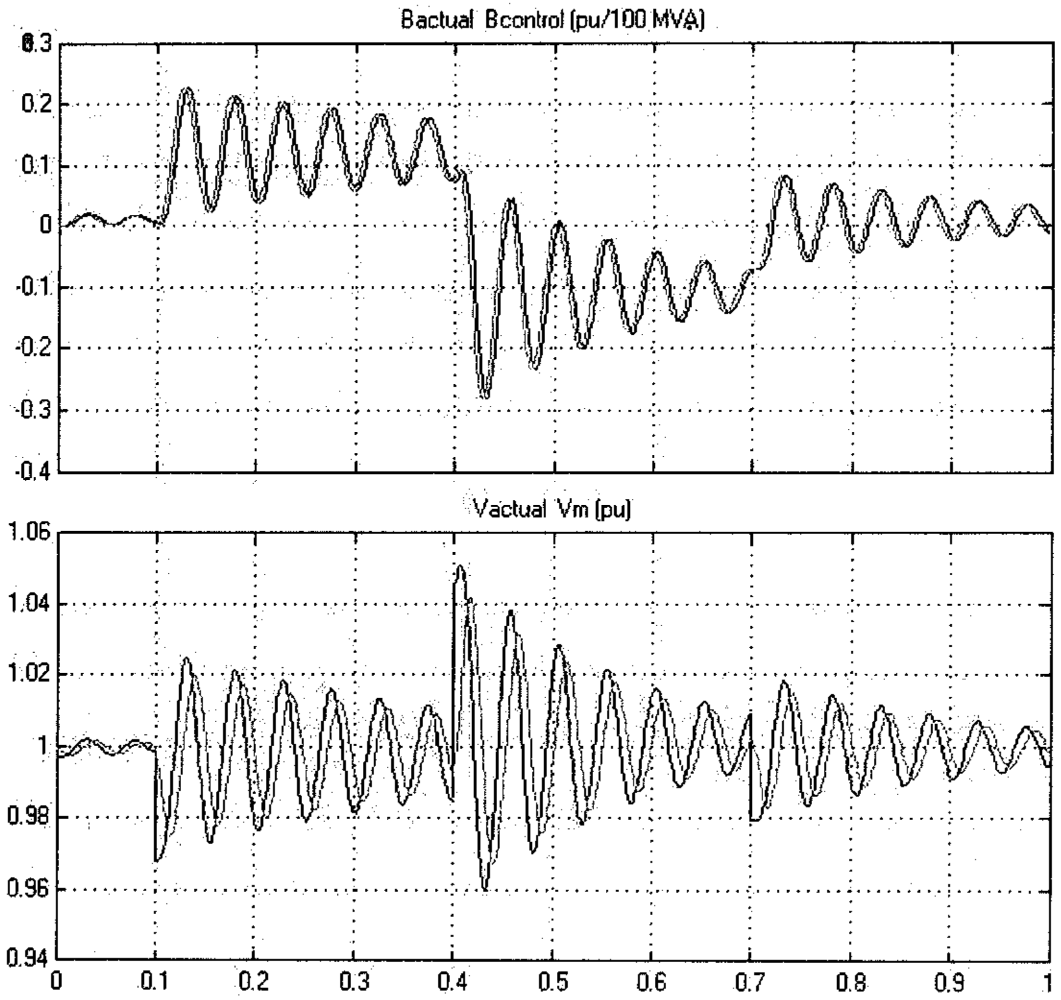


Figure 19 : B and V output of SVC when short-circuit level is 400 MVA.

Steady-State V-I characteristics of SVC operation con be measured. By changing the "Type of Variation" parameter to "Modulation" of the Programmable Voltage Source theoretical and measured V-I characteristics could be observed.

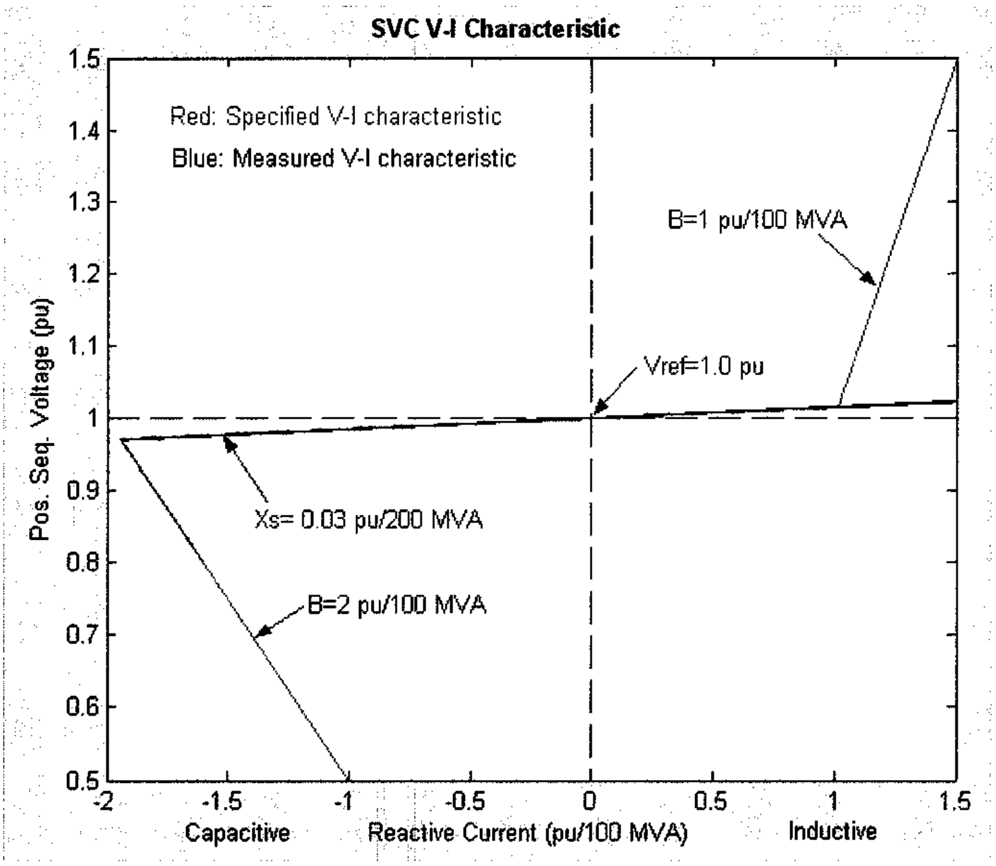


Figure 20 : V-I characteristics.

4.5 SVC versus STATCOM

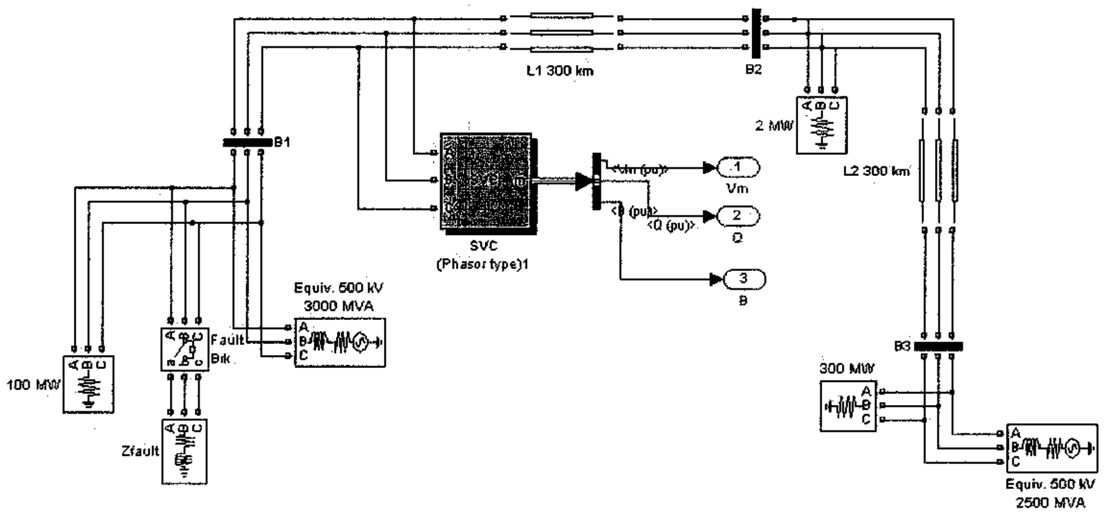


Figure 21 : SVC connected to the same power system of STATCOM

The SVC was connected to the same power system STATCOM was connected to compare their performances. Theoretically they are both voltage regulators either by injecting or absorbing reactive power.

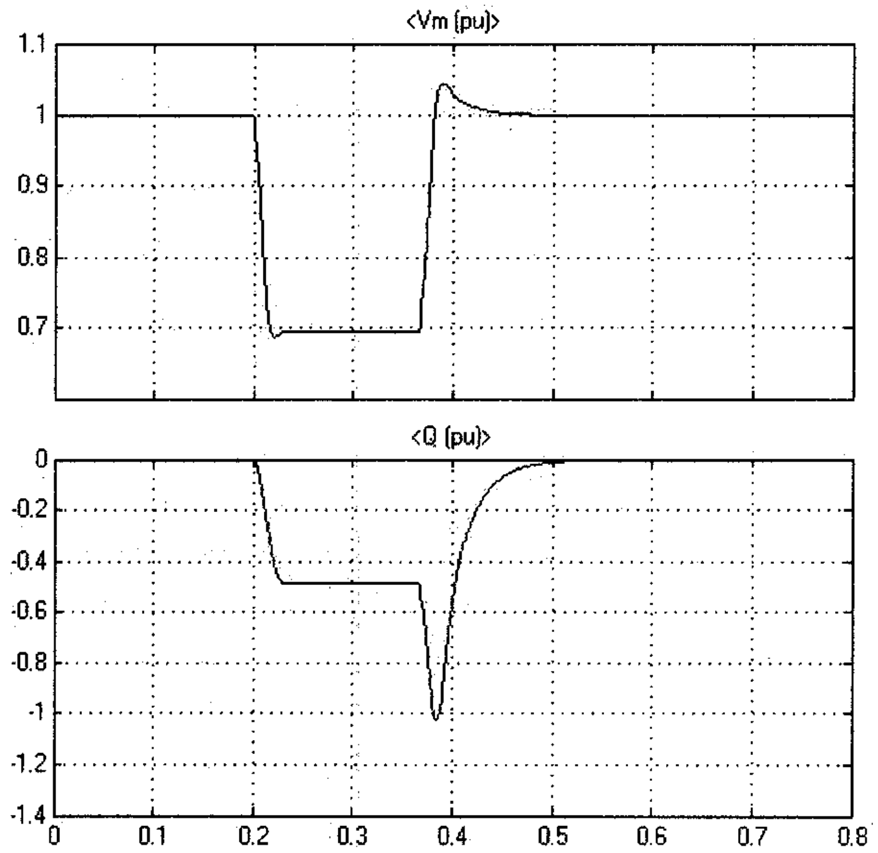


Figure 22 : SVC measured voltage and reactive power output.

So, having SVC connected in the same power system as STATCOM faulty is introduced to check and compare their performances. The comparison graph of SVC versus STATCOM on Vm and Q is given below.

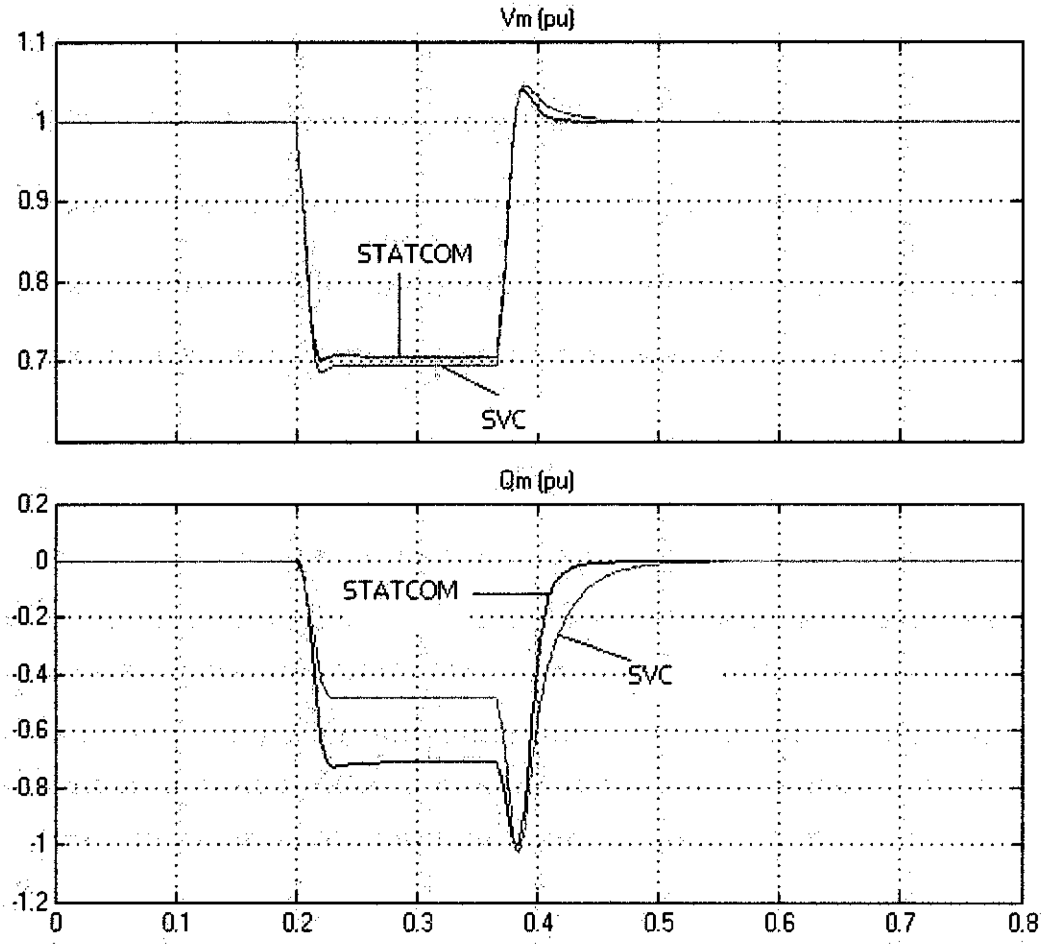


Figure 23 : SVC versus STATCOM.

The STATCOM performs the same function as the SVC. However at voltages lower than the normal voltage regulation range, the STATCOM can generate more reactive power than the SVC. The reactive power generated by the SVC is -0.48pu and the reactive power generated by the STATCOM is -0.72pu. This ability to provide more capacitive power during a fault is one important advantage of the STATCOM over the SVC. In addition, the STATCOM will normally exhibit a faster response than the SVC because with the voltage-sourced converter, the STATCOM has no delay associated with the thyristor firing.

4.6 Results of SSSC

The SSSC is one of important FACTS devices, consists of a voltage-sourced converter and a transformer connected in series with a transmission line. The SSSC injects a voltage of variable magnitude in quadrature with the line current, thereby emulating an inductive or capacitive reactance. This emulated variable reactance in series with the line can then influence the transmitted electric power. In this simulation SSSC was used to dampen the power oscillation of the transmission line, which makes it more stable and reliable.

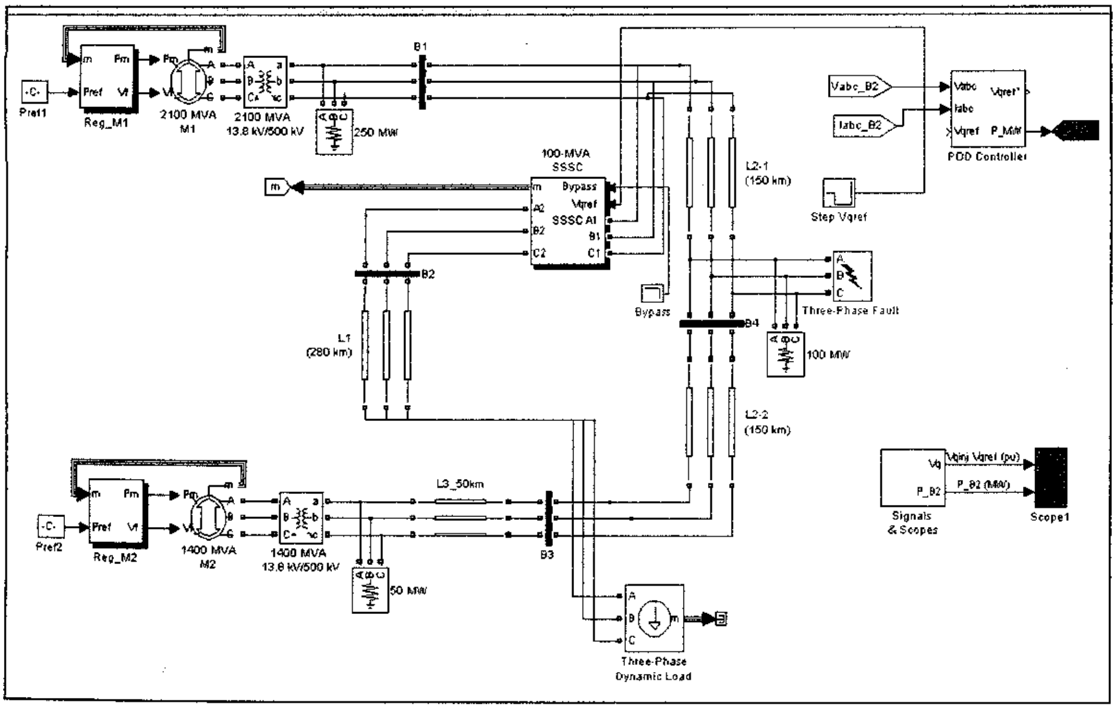


Figure 24 : SSSC simulation diagram.

The power grid consists of two power generation substations and one major load center at bus B3. The first power generation substation (M1) has a rating of 2100 MVA; representing 6 machines of 350 MVA and the other one (M2) has a rating of 1400 MVA, representing 4 machines of 350 MVA. The load center of approximately 2200 MW is modeled using a dynamic load model where the active & reactive power absorbed by the load is a function of the system voltage. The generation substation M1 is connected to this load by two transmission lines L1 and L2. L1 is 280-km long and L2 is split in two segments of 150 km in order to simulate a three-phase fault (using a fault breaker) at the midpoint of the line. The generation substation M2 is also connected to the load bya 50-km line (L3). When the SSSC is bypass, the power flow towards this major load is as follows: 664 MW flow on L1 (measured at bus B2), 563 MW flow on L2 (measured at B4) and 990 MW flow on L3 (measured at B3).

When the POD controller is off, voltage and power outputs of B2 would be as given below.

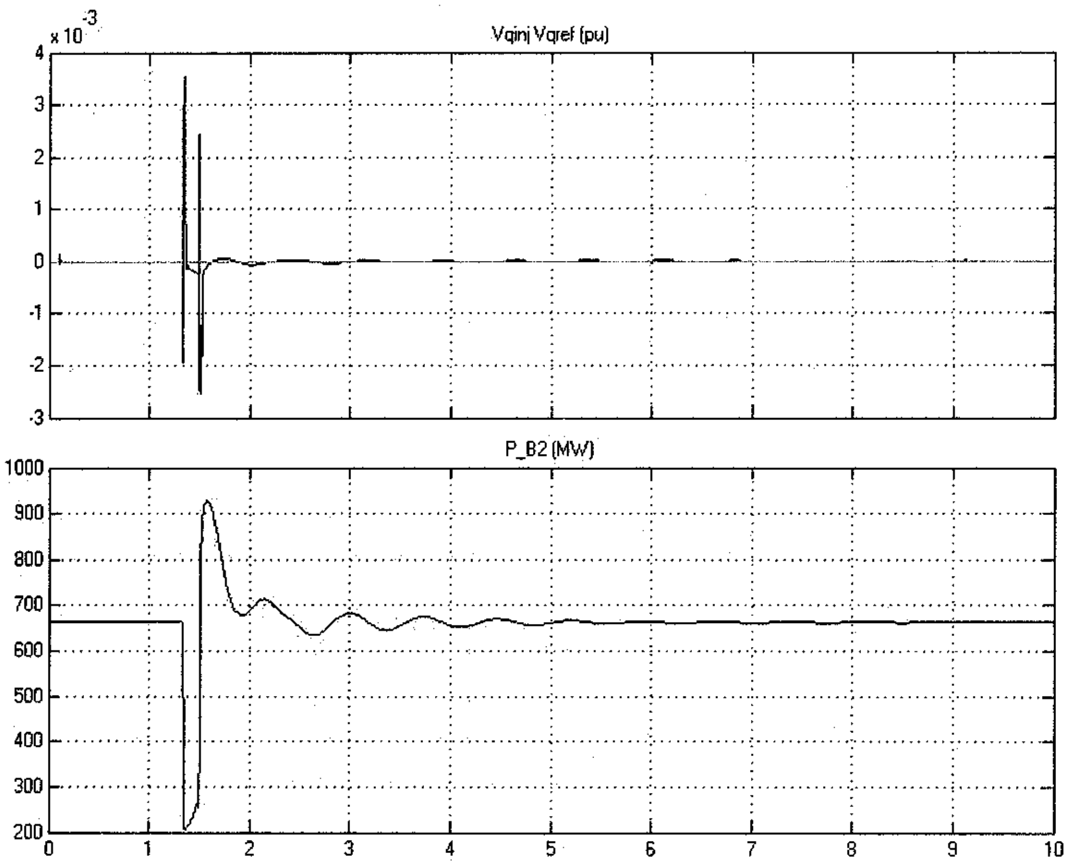


Figure 27 : Power and voltage output of B2 when POD is off.

But, when the SSSC connected system is simulated using POD controller as on, the outputs of power and voltage would be less oscillatory. The POD controller helps the system to be more stable and reliable.

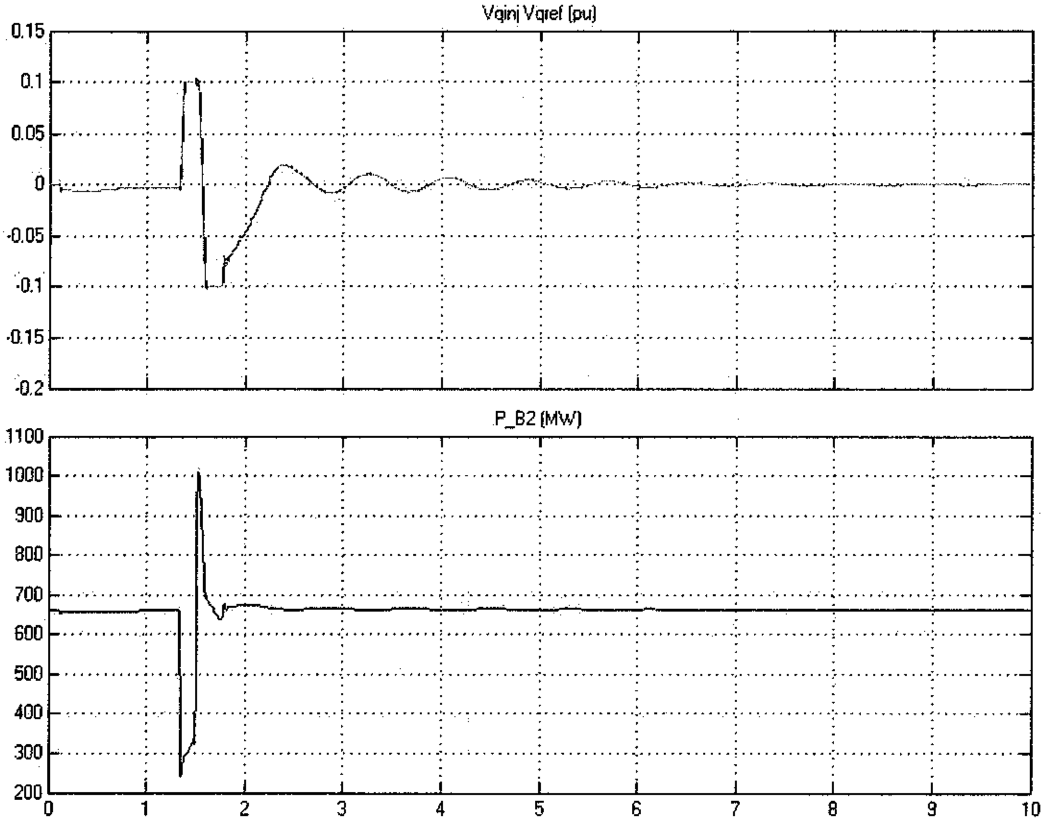


Figure 28 : Power and voltage output of B2 when POD is on.

As it is observed in the below figure the oscillation is less when POD is on compared to POD off condition.

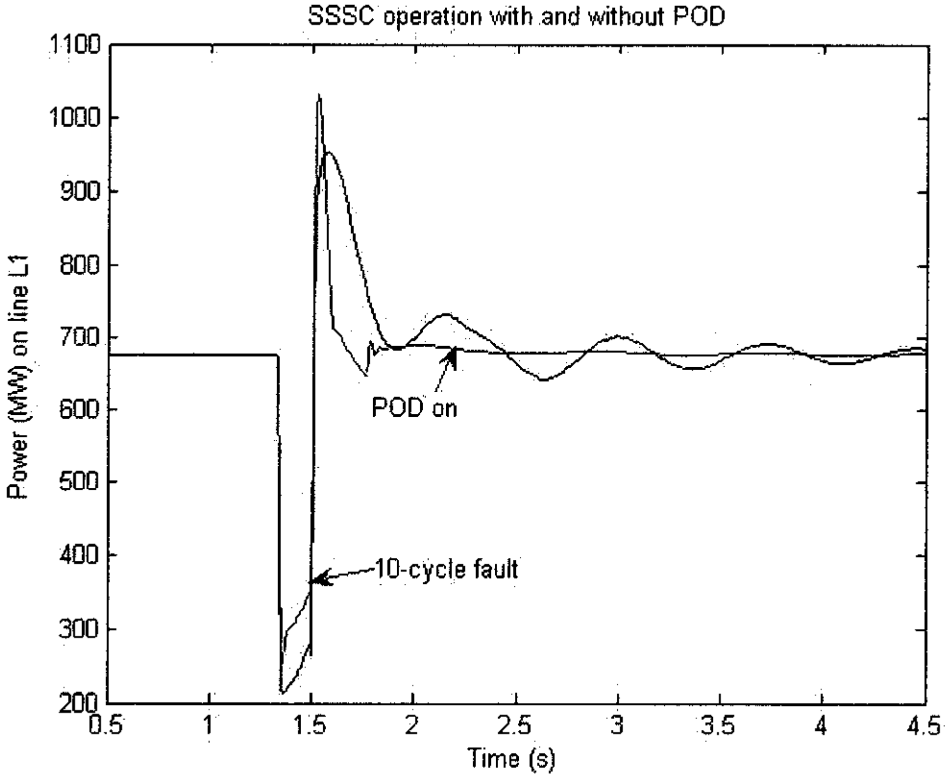


Figure 29 : Power output comparison when POD is on and off.

4.7 Discussion of SSSC

The SSSC plays an important role in stability and reliability of the transmission line. As it is seen in the simulation part, the SSSC is mainly used to dampen the oscillations in the system, both voltage and power oscillations. This damping property provides more stable environment for the power transmission. The controller programmed for damping the power oscillation was used in the latter part of the simulation. The effect of POD controller usage is obviously beneficial for the system.

In fact, SSSC connection in the system already dampens the oscillations occurred, but addition of POD controller lessens the damping time. It is fast for the system to reach steady-state with POD controllers.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

During the project work many papers on FACTS technology were studied and surveyed. Among those it is been concluded that mostly used FACTS devices in power industry are UPFC, TCSC, STATCOM, SVC and SSSC. Their implantation in power transmission and power delivery has been very practical.

Incorporation of FACTS controllers in power system has lead to more flexible, stable, and reliable and secure power consumption. They clearly increase the power system performance, improve quality of supply and also provide optimal utilization of existing sources. FACTS controllers are proven to be effective in power grids in well-developed countries like USA, Canada, and Sweden. 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 FACTS devices. FACTS controllers also increase the load ability, so that additional loads can be added in the system without addition of new transmission and generating facilities.

Mathematical analysis of FACTS devices has been studied in the project. The model representation in terms of active and reactive power was analyzed. Stability, which is the ability of power system to operate on average under normal conditions and regain stability after the interruption or disturbance, with FACTS devices replaced in the system the time response for the stability has increased. These can be observed in the results of STATCOM simulation.

As a comparison of FACTS devices functions the UPFC is the most functional. It has highest load flow control and voltage control compared to others. Whereas the TCSC has the highest transient and dynamic stability. For a system where immediate stability response is needed TCSC is the one to be chosen. In case fast load flow control and voltage control response the UPFC is the preferred one.

STATCOM (Static Synchronous Compensator) is one the key members of FACTS family. It operates as a perfect voltage controller compared to other most common FACTS controllers; ex. TCSC (Thyristor Controlled Series Capacitor). But at the same time SVC has the same voltage controllability as STATCOM. Basically, it regulates the line voltage either by supplying or absorbing reactive power. When the power line voltage is low the system needs to be stabilized by reactive power injection, in this situation STATCOM acts as capacitive, generating reactive power for the system. And when the line voltage is high it needs to be reduced to avoid any system failures. Thus, STATCOM absorbs reactive power in order to stabilize the power line, acting as inductive.

In the simulation run the STATCOM acts as reactive power supplier when the line voltage is low and absorber when it is high. From the simulation it is clearly observed that the reactive power of system has increased after placement of STATCOM. In the first graph, without STATCOM, the reactive power is negative. Whereas in the second output graph, the reactive power has both positive and negative values, meaning that STATCOM acts as both capacitive and inductive. And when the droop regulation is zero the measured voltage follows exactly as the reference voltage of STATCOM. So the STATCOM employment in the power line transmission is obviously beneficial.

SVC (Static VAR Compensator) is another important element of FACTS controllers. It simply operates similar with STATCOM. When system voltage is low, the SVC generates reactive power (SVC capacitive). When system voltage is high, it absorbs reactive power (SVC inductive).

The simulation run using SVC controls the B, susceptance, and measured Voltage of the system. From the Figure 16 of SVC simulation the actual B is same with reference B, making SVC perfect susceptance controller. However, the measured and reference voltages are slightly different. Although they are different, the measured voltage is closely similar to the reference voltage.

From the Figures 18, 19, the susceptance and voltage control becomes more oscillatory when the voltage regulator gain, Ki, is increased and when the three-phase RLC branch short-circuit level is decreased. Thus, to get the less oscillatory performance of SVC in the transmission line the range of gain and short-circuit level should perfectly be determined.

STATCOM and SVC comparison was analyzed.

Theoretically they are both voltage regulators either by injecting or absorbing reactive power. The STATCOM performs the same function as the SVC. However at voltages lower than the normal voltage regulation range, the STATCOM can generate more reactive power than the SVC. The reactive power generated by the SVC is -0.48pu and the reactive power generated by the STATCOM is -0.72pu. This ability to provide more capacitive power during a fault is one important advantage of the STATCOM over the SVC. In addition, the STATCOM will normally exhibit a faster response than the SVC because with the voltage-sourced converter, the STATCOM has no delay associated with the thyristor firing (in the order of 4 ms for a SVC).

SSSC (Static Synchronous Series Compensator) is a vital controller in the power transmission industry. It helps to stabilize the transmission line by damping the voltage and power oscillations.

The SSSC does not use any active power source; the injected voltage must stay in quadrature with line current. By varying the magnitude of the injected voltage in quadrature with current, the SSSC performs the function of a variable reactance compensator, either capacitive or inductive.

As the simulations of all three FACTS devices were run throughout the project each of them has special assistance to keep the transmission line more secure, stable and reliable. However, the STATCOM is preferred to SVC in a fault condition due to its more capacitive power supplication than SVC. And SSSC is mainly used to dampen the voltage and power oscillations in the transmission line. So, depending on the situation confronted any of these three FACTS controllers could be chosen to maintain and improve transmission line security, stability and reliability.

5.2 Recommendation

The application of FACTS devices might be more costly compared to existing technology. The implementation of FACTS is not as easy as other conventional ways to control transmission system security, stability and reliability. But in the long run FACTS devices application will save large amounts of money. Thus, it is recommended to study the feasibility of the existing transmission line control system before applying FACTS controllers.

The fault in the system may occur anytime as long as it operates. Thus, the faulty introduction is recommended in the transmission line system to see its impacts on FACTS controller operations.

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APPENDICES

APPENDIX A

DERIVATION OF I_{TCR}

At the continuous conduction, when the voltage is sinusoidal $v(t)=\sqrt{2}V\sin\omega t$, the instantaneous current of $i_{TCR}(t)$ will be:

$$v = L\frac{di}{dt}$$

$$\frac{v}{L}=\frac{di}{dt}$$

$$\int\frac{v(t)}{L}dt = i(t)$$

$$\frac{1}{L}\int v(t)dt = i(t)$$

$$i_{TCR}(t)=\frac{1}{L}\int_{\alpha}^{\omega t}\sqrt{2}V\sin\omega t dt=\frac{\sqrt{2}V}{L}(-\cos\omega t)_{\alpha}^{\omega t}=-\frac{\sqrt{2}V}{L}(\cos\omega t-\cos\alpha)$$

$$i_{TCR}(t)=\frac{\sqrt{2}V}{\omega L}(\cos\alpha-\cos\omega t)\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Eq.1$$

The $i_{TCR}(t)$ will have equation derived above, in the interval $\alpha \le \omega t \le (\alpha+\sigma)$. In the interval, $\alpha+\sigma \le \omega t \le (\alpha+\pi)$ $i_{TCR}(t)$=0.

From the Eq.1 $i_{TCR}(t)=\frac{\sqrt{2}V}{\omega L}(\cos\alpha-\cos\omega t)$, after the Fourier transform the equation of $i_{TCR}(t)$ will become [18]:

$I_{TCRf1}=\frac{V}{j\omega L\pi}[2(\pi-\alpha)+\sin(2\alpha)]$, f1 is fundamental frequency.

Multiplying numerator and denominator by ***j:***

$$I_{TCRf1}=-\frac{jV}{\omega L\pi}[2(\pi-\alpha)+\sin(2\alpha)],$$

If $B_{TCR}=\frac{2(\pi-\alpha)+\sin 2\alpha}{\omega L\pi}$ is defined as this, then I_{TCR} will be []:

$$I_{TCR}=-jB_{TCR}V\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{Eq.2}$$

APPENDIX B

TABLE OF FACTS CONTROLLERS

Table 1: The role of FACTS controllers in power system operation.

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

APPENDIX C

STAGED DEVELOPMENT OF FACTS DEVICES

FACTS device	TCSC	SVC	TCPAR
Circa 1930-1980 Pre-Thyristor Device	Uncontrolled Series capacitor	Synchronous Condensers, Switched shunt capacitors/reactors	Quad-booster with mechanical tap changer
Circa 1980-200- Basic-Thyristor Devices only	Thyristor controlled series capacitors	Thyristor controlled static var compensator	Quad-booster with mechanical tap changer
Post – 2000 Advanced turn-on and turn-off devices	All electronic series compensator (no large capacitors)	Advanced static var compensator	All electronic phase shifter

APPENDIX D

STEADY-STATE ISSUES [30]

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 the above table

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

APPENDIX E

DYNAMIC ISSUES [30]

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 the above table

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