The Hong Kong Polytechnic University
Department of Electrical Engineering

Implementation and study of FACTS devices in digital real-time simulator

Submitted by
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CERTIFICATE OF ORIGINALITY

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ABSTRACT

FACTS technology provides potential opportunities to improve the steady state and dynamic stabilities of power systems and can have significant impact on power system planning, operation and control. However, FACTS technology comprises complex power electronics and control system which can also produce technical problems which need to be studied or evaluated before FACTS devices are successfully put into operation. Therefore, a lot of researches on FACTS technology is still required and this thesis is a contribution to the continuing research.

Detailed models of the STATCOM, SSSC and UPFC were implemented and tested in MATLAB. These models are more comprehensive than those found in the literature and include detailed representation of the valves and the power electronic components, as well as full control circuit representation. The models are applicable for transient stability studies, and cover a broad range of frequency oscillations. They are also suitable for simulations in unbalanced power system conditions.

This thesis proposed and justified novel steady state and transient state models for STATCOM, SSSC and UPFC. The models were successfully validated in the MATLAB environment for various operating conditions and in realistic representative power system networks. The proposed models could be directly implemented in any power simulation software such as the real-time simulator *Hypersim* which has external programming capabilities for any steady state, dynamic state and transient stability simulations. The proposed models (toolbox) could also provide a better simulation package for the Power System designers in doing network planning or network enhancement under the widely inter-connected power system environment.

The developed FACTS device detailed models include all of the control block and power electronic components as well as the voltage-sourced converters. Furthermore the models were modelled independently of the type of control methodologies used, consequently the models can provide an excellent environment and platform for future advanced control methodology studies of FACTS devices.

PUBLICATIONS

1. Sze, K.M., Snider, L. A., Chung, T. S., Chan, K.W., "An intelligent fuzzy controller for PWM based SSSC to enhance stability of power systems," International Conference on Electrical Engineering 2004, Sapporo, July 2004, Vol. 2, pp.355-360
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3. Sze, K.M., Snider, L. A., Chung, T. S., Chan, K.W., "An intelligent rule base adaptive controller for PWM based SSSC to enhance dynamic performance of power systems," International Conference on Power Systems Transients (IPST) 2003, New Orleans, U.S., July 2003, Vol. 2, pp.355-360

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ABBREVIATIONS

FACTS	Flexible AC Transmission System
STATCOM	Shunt Synchronous Static Compensator
SSSC	Series Synchronous Static Compensator
UPFC	Unified Power Flow Controller
SVC	Static Var Compensator
EMTP	Electromagnetic Transient Program
TSP	Transient Stability Program
TACS	Transient Analysis of Control Systems
EPRI	Electric Power Research Institute
GTO	Gate-Turn Off Thyristor
PWM	Pulse Width Modulation
SPWM	Sinusoidal PulseWidth Modulation
VSC	Voltage-Sourced Converter
CSC	Current-Sourced Converter
TNA	Transient Network Analyzer
TVA	Tennessee Valley Authority
AEP	American Electric Power

Chapter 1: Introduction

1.1 Introduction

FACTS technology provides potential opportunities to improve the steady state and dynamic stability of power systems and can have significant impact on power system planning, operation and control. However, FACTS technology comprises complex power electronics and control system which can also produce technical problems which need to be studied or evaluated before FACTS devices are successfully put into operation. Therefore, a lot of research on FACTS technology is still required and this thesis is a contribution to the continuing research.

The main contributions of this thesis are as follows:

1. Detailed models of the STATCOM, SSSC and UPFC were implemented and tested in MATLAB. These models are more comprehensive than those found in the literature and include detailed representation of the valves and the power electronic components, as well as full control circuit representation. The models are applicable for transient stability studies, and cover a broad range of frequency oscillations. They are also suitable for simulations in unbalanced power system conditions.
2. Novel steady state and transient state models for STATCOM, SSSC and UPFC were successfully validated in the MATLAB environment for various operating conditions and in realistic representative power systems. The proposed models could be directly implemented in any power simulation software such as the real-time simulator Hypersim which has external programming capabilities for any steady state, dynamic state and transient stability simulations.

3. The developed FACTS device detailed models include all of the control block and power electronic components as well as the voltage-sourced converters. Furthermore the models were modelled independently of the type of control methodologies used, consequently the models can provide an excellent environment and platform for future advanced control methodology studies of FACTS devices.

1.2 Background

Most if not all of the world's electric power systems are widely interconnected, involving connections inside utilities' own territories which extend to inter-utility interconnections and then to inter-regional and international connections. This is done for economic reasons, to reduce the cost of electricity and to improve reliability of power supply. [1][2]

We need these interconnections because, apart from delivery, the purpose of the transmission network is to pool power plants and load centres in order to minimize the total power generation capacity and fuel cost. Transmission interconnections enable taking advantage of diversity of loads, availability of sources, and fuel price in order to supply electricity to the loads at minimum cost with a required reliability.

With the development of power industry deregulation and open access, power systems become increasingly more complex to operate. The systems may become more insecure with large power flows with inadequate control and inability to utilize the full potential of transmission interconnections. In recent years, many instability problems of large power systems occurred around the world, resulting in serious damage to national economics and security. These stability problems of large systems also call for new control technology.[1][2]

Developing new control technology to control the network parameters conveniently has always been an ultimate objective. HVDC transmission is a successful example to control network operating parameters and improve the system stability. HVDC systems have the ability to rapidly control the transmitted power. Therefore, they have significant impact on the stability of the associated AC power systems. However, the high cost of HVDC system is still a heavy burden for power systems.

Power electronic technologies have been rapidly developed in recent one or two decades. Some power electronic based devices are already widely used in power systems, in which the HVDC transmission and the conventional thyristor controlled Static VAR compensator are two good examples. There is a fundamental limitation related to the use of the conventional thyristor, since the device can only be turned off at current zero crossings. Fortunately, the successful development of turn-on, turn-off devices (GTOs) which have high unit power capability, high switch speed and low unit loss opened a new world for power electronic based devices applied in power systems. The newly developed FACTS devices are mainly based on this type of technology.

What might be called the first generation of controllers for A.C. Systems, static VAR compensators (SVCs) and resonance dampers, have found used in some power systems for several years (Hingorani 1994). The thyristor controlled series capacitors are also widely used in China. Several FACTS controllers are presently being evaluated (Urbanek et al. 1993), while others have been conceptualized but not yet developed.

The main FACTS devices proposed are listed below.

- Static VAR compensator (SVC)
- Thyristor Controlled Series Compensation (TCSC)
- Unified Power Flow Controller (UPFC)
- Sub-synchronous Resonance Damper (SSR)
- Static Synchronous Compensator (STATCOM)
- Fault Current limiter (FCL)
- Static Synchronous Series Compensator (SSSC)
- Thyristor Controlled Series Reactor (TCSR)
- Dynamic Voltage Regulator (DVR)

1.3 Flexible A.C. Transmission System

Power flow is a function of transmission line impedance, the magnitude of the sending and receiving end voltages, and the phase angle between the voltages. By controlling one or a combination of the power flow arguments, it is possible to control the active, as well as the reactive power flow in the transmission line.

It is quite normal in power system control to install shunt capacitors to support the system voltages. Series capacitors are used to reduce transmission line reactance as well as to increase power transfer capability of transmission lines. Phase shifting transformers are applied to control power flows in transmission lines by introducing an additional phase shift between the sending and received end voltages.

In the past, all these devices were controlled mechanically and their responses were relatively slow. They were useful in steady state operation of power systems. But in dynamic states, their response times are too slow and are not effective enough to damp transient oscillations. If the mechanical controlled systems were made to respond faster, power system security would be improved. This concept was introduced by the Electric Power Research Institute (EPRI) in the late 1980 called Flexible A.C. Transmission Systems (FACTS). In [1], the authors introduced this new concept, initiating a new direction in power system research.

The improvement of voltage and current limits of power electronics devices has lead to very fast development of FACTS devices in the last decade: for example the development of high power GTOs led to the development of STATCOMs which offer significant advantages over the thyristor-controlled SVCs in common use. In the coming future it is likely that high power IGBTs will make PWM controlled FACTS devices feasible for transmission applications. These devices will offer improved speed of response and cause less waveform distortion in the network.[2]

1.4 Benefit of using FACTS devices

FACTS technology provides huge potential possibility to power system operation and control. The main opportunities are summarized as follow: [1][2]

Due to the powerful controllability of FACTS technology, the "free flow" mode of power system operation may be changed into a controlled power flow mode of operation where the power flow through one or more transmission lines is controlled in predetermined manner. Thus, parallel path flows, loop flows and circulating flows of power systems may be easily regulated.

FACTS technology can secure loading of transmission lines near their steady state, short time and dynamic limits. Therefore, the transmission capability of network can be largely increased.

FACTS technology can reduce the generation reserve margins through enhanced, secure transmission interconnections for emergency power with neighboring utilities. Thus, the need for new power plants may be delayed or avoided.

FACTS technology can contain cascading outages by limiting the impact of multiple faults, thereby improving the reliability of power supply.

FACTS technology can undertake and effectively utilize upgrading of transmission lines by increasing voltage and/or current capacity. Therefore, the power quality can be increased.

1.5 Converter-based FACTS controllers

Static Synchronous Compensators (STATCOM), Static Synchronous Series Compensators (SSSC), Unified Power Flow Controllers (UPFC), and Interline Power Flow Controllers (IPFC) form the group of FACTS controllers using switching converter-based synchronous voltage sources. These devices use self-commutated, voltage switching converters to achieve rapidly controllable, static synchronous voltage source or synchronous A.C. current sources. The use of converter-based FACTS controllers generally provides better performance and control when compared with conventional compensation methods, i.e. using Thyristor-Switched Capacitors and Thyristor-Controlled Reactors. Furthermore, they also provide functions of exchanging real power directly with the A.C. system and independent control of reactive power compensation. The STATCOM, similar function to SVC, controls transmission voltage by reactive power shunt compensation. The SSSC offers series compensation by directly controlling the effective transmission impedance on the transmission line. The UPFC can control, individually or in combination, all three effective transmission parameters (voltage, impedance, and angle), the real and reactive power flow in the transmission line. The IPFC is able to control overall real and reactive power for a multi-line transmission system. [1] - [5]

1.5.1 Static Synchronous Compensator (STATCOM)

If the Voltage Source Converter (VSC) is used strictly for reactive power shunt compensation, such as a conventional Static VAR Compensator, the D.C. voltage can be supplied by a relatively small D.C. capacitor, as shown in Figure 1.1. The size of the capacitor is primarily determined by the "ripple" input current encountered with the particular converter design. In this case, the steady-state power exchange between the VSC and the A.C. system can only be reactive. When the VSC is used for reactive power generation the converter itself can keep the capacitor charged to the required voltage operation limit. This is achieved by making the output voltages of the converter lag the system voltage by a small angle. In this way, the converter absorbs a small amount of real power from the A.C. system to replenish its internal losses and keep the capacitor voltage at the operation range. The same control mechanism can be used to increase or decrease the capacitor voltage, and thereby the amplitude of the output voltage of the converter, for the purpose of controlling an energy balance between the input and output during changes of the VAR output. The VSC, operated as a reactive shunt compensator, exhibits operating and performance characteristics similar to those of an ideal synchronous compensator and for this reason this arrangement is called a Static Synchronous Compensator. [1][4][10]

The STATCOM does not require capacitor and reactor banks, and is consequently substantially smaller and cheaper than an SVC. For example, there is a STATCOM system installed at the Tennessee Valley Authority (TVA) indoor Sullivan Substation of 27.4m x 14.6m; all of the STATCOM equipment is installed indoors. [6]

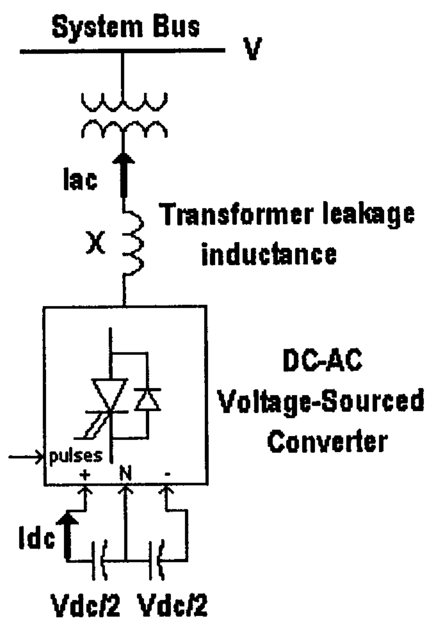


Figure 1.1 Schematic diagram of STATCOM [1]

1.5.2 *Static Synchronous Series Compensator (SSSC)*

The function of the SSSC is to produce an appropriate voltage at the fundamental A.C. system frequency in series with the transmission line in order to effectively modify the line series impedance. If an A.C. voltage source of fundamental frequency, which is locked with a quadrature (lagging) relationship to line current and whose amplitude is made proportional to that of the line current, is injected in series with the line, a series compensation equivalent to that provided by a series capacitor at the fundamental frequency is obtained. [1][3]

However, in contrast to the real series capacitor, the VSC is able to maintain a constant compensating voltage in the face of variable current, or control the amplitude of the injected compensating voltage independent of the amplitude of the line current.

The output voltage of the VSC can be reversed by a simple control action to make it lead the line current by $90°$. In this case, the injected voltage decreases the voltage across the inductive line impedance and, thus, the series compensation has the same effect as if the reactive line impedance was increased. This series compensation is so called the Static Synchronous Series Compensator (SSSC).

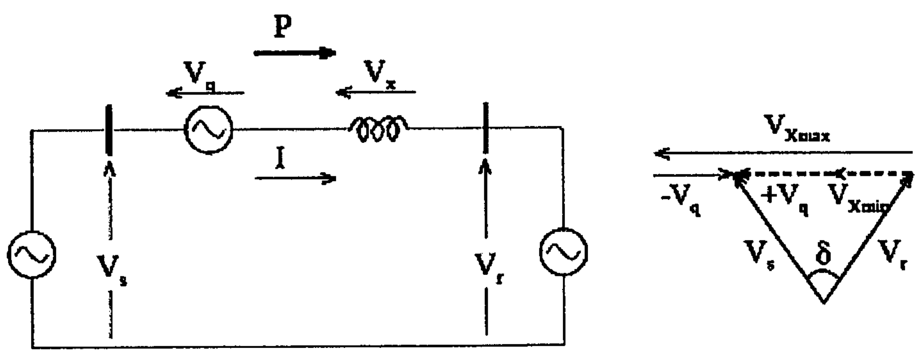


Figure 1.2 Basic two-machine system with synchronous series voltage compensation

1.5.3 Unified Power Flow Controller (UPFC)

The Unified Power Flow Controller (UPFC) is the most versatile FACTS device that has emerged for the control optimization of power flow in electrical power transmission systems. Its concept was proposed by Gyugyi in 1991 [18]. It offers major potential advantages for the static and dynamic operation of transmission lines since it combines the features of both the Static Synchronous Compensator (STATCOM) and the Static Synchronous Series Compensator (SSSC). The UPFC is able to control, simultaneously or selectively, all the parameters affecting power flow in the transmission line (voltage, impedance, and phase angle), and this unique capability is signified by the adjective "unified" in its name. Alternatively, it can independently control both the real and reactive power flows in the line.[1][2][4]
The UPFC can be represented at the fundamental power system frequency by voltage phasor V_{pq} with controllable magnitude V_{pq} ($0 \le V_{pq} \le V_{pq\max}$) and angle ρ ($0 \le \rho \le 2\pi$), in series with the transmission line.

Figure 1.3 shows a UPFC comprising two back-to-back voltage sourced converters. These back-to-back converters, labeled "VSC-1" and "VSC-2" in the figure, are operated by a common D.C. source comprising a capacitor. The basic function of the VSC-1 is to supply or absorb the real power demanded by VSC-2 at the common D.C. terminal to support the real power exchange resulting from the series voltage injection. The DC power demand of VSC-2 is converted back to A.C. by VSC-1 and coupled to the transmission line bus via the shunt-connected transformer. Figure 1.3, shows that if the series VSC controller is disconnected, the shunt connected VSC controller comprised of a D.C. capacitor, VSC-1 and the shunt connected transformer can be operated as a STATCOM device. As the STATCOM can be used to generate or absorb reactive power, the STATCOM output current is in quadrature with the terminal voltage.

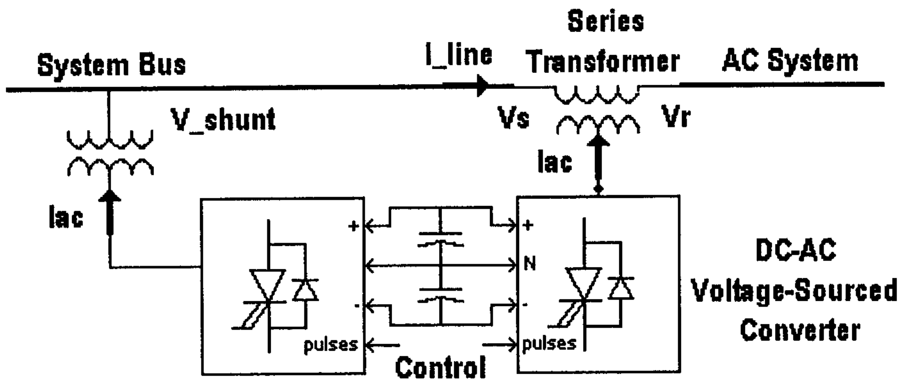


Figure 1.3 Simplified model of UPFC

If the shunt connected VSC is disconnected, the series connected VSC comprised of a D.C. capacitor, VSC-2 and the series connected transformer can be operated as an SSSC. The SSSC can be used to injected a compensating voltage in series to the transmission line through the series transformer; the current flowing through the VSC is the transmission line current, and the series injected voltage can create a virtual impedance in series with the transmission line.

The injected voltage V_{SR} is in quadrature with the transmission line current I_{line} with the magnitude being controlled independently of the line current. Hence, the shunt and series connected VSC controllers of the UPFC can be used to generate or absorb reactive power independently of each other.

1.6 Inter-area Oscillations

FACTS controllers could play a major role in the mitigation of low frequency oscillations that often arise between areas in a large interconnected power network. [1][7][8]These oscillations are due to the dynamics of inter-area power transfer and often exhibit poor damping when the aggregate power transfer over a corridor is high relative to the transmission strength. Inter-area oscillation can severely restrict system operations by requiring the curtailment of electric power transfers as an operational measure. These oscillations can also lead to widespread system disturbances if cascading outages of transmission lines occur due to oscillatory power swings. As power system reliability became increasingly important, the requirement for a system to be able to recover form a fault cleared by a relay action was added to the system design specifications. Rapid automatic voltage control was used to prevent the system's generators loosing synchronism, following a system fault. [9][10][11][12]

Fast excitation systems; however, tend to reduce the damping of system oscillations. Originally, the most affected were those between electrically closely coupled generators. Special stabilizing controls were designed to damp these oscillations. In 1950s and 1960s, electric power utilities found that they could achieve more reliability and economy by interconnecting to other utilities, often through quite long transmission lines. In some cases, when the utilities inter-connected, low frequency growing oscillations prevented the interconnection from being retained. From an operating point of view, oscillations are acceptable as long as they decay. However, oscillations are a characteristic of the system; they are initiated by the normal small changes in the system load. There is no warning to the operator if a new operating condition causes an oscillation to increase in magnitude. An increase in tie line flow of a small value may make the difference between decaying oscillations, which are acceptable and increasing oscillations, which have the potential to cause system collapse. Of cause, a major disturbance may finally result in growing oscillations and a system collapse. Such was the case in the August 1996 collapse of the Western of the Western US/Canada interconnected power system. The progress of this collapse was recorded by the extensive monitoring system which has been installed, and its cause is explained clearly in [13][14]. The damping of electromechanical oscillations between interconnected synchronous generators is necessary for secure system operation. The oscillations of one or more generators in an area with respect to the rest of the system are called local modes, while those associated with groups of generators in different areas oscillating against each others are called inter-area modes. As an example, in the two local modes of each area and the inter-area mode are the three fundamental modes of oscillation. They are each due to the electromechanical torques, which keep the generators in synchronism. The frequencies of the oscillations depend on the strength of the system and on the moment of inertia of the generator rotors. These frequencies are in the range of 0.1-2.5 Hz, in most practical cases. These oscillations are usually observed from generator speed deviations, and they also can be observed in other system variables such as voltage signal at each tie line end. However, the frequencies of the local modes may be very close and it may not be possible to recognize them separately in the tie bus voltage responses. Local modes are largely determined and influenced by local states. Inter-area modes are more difficult to study as they require detailed representation of the entire interconnected system and are influenced by global states of larger areas of the power network. This has led to an increased interest in the nature of these modes and in developing methods to damp them.

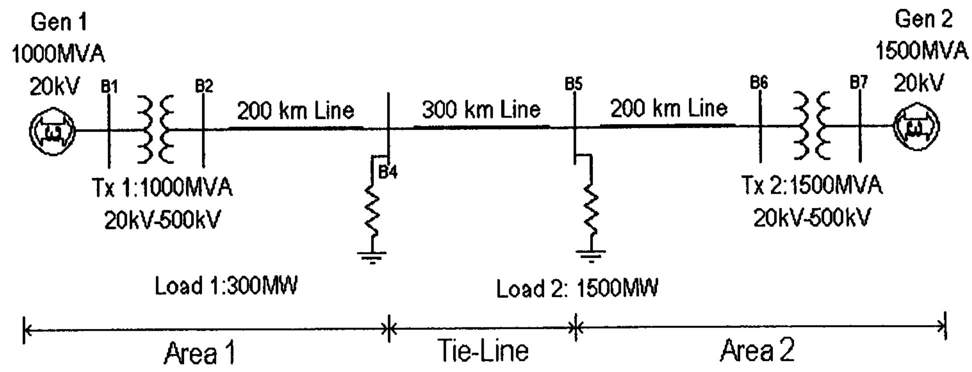


Figure 1.4 Interconnected Power System

1.7 Research Objectives

FACTS application studies require careful planning and coordination in the specification, design and operating stage of a project. Before meaningful results can be obtained from application studies, representative models for the transmission system and relevant FACTS controllers need to be established and verified.

This means that an analytical toolbox that enables the full potential of these controllers to be studied should support emerging FACTS technology. This toolbox, consisting mainly of hardware and software simulations, can be used to determine steady state, dynamical and transient behaviour of FACTS controllers consist mainly of hardware and software simulations. Hardware simulations of a reduced system, for example TNA studies, allow adequate representation of the real controller, with real time control and performance of some system components. However, its application is limited, owing to restrictions in terms of the extent of the AC system representation, and it may be uneconomical depending on availability and overhead costs.

On the other hand, digital or software simulations have become increasingly reliable for assessing both steady state and dynamic performance of a power system. Due to the rapid development of power system simulators, simulations provided cost effective and feasible ways to model and study the power system behaviour with FACTS devices installed.

In current practice, power flow programs such as PSSE are used in system planning studies. In addition, these studies provide initial conditions for transmission system dynamic and transient stability studies. The power flow results are also used to establish steady state ratings and to identify appropriate location for installing a new FACTS controller in the system, and to reduce the number of alternatives under planning stage. Simplified and reliable models, which take into account steady state limits of the transmission system and FACTS controllers are essential, so that preliminary studies of both the technical and cost & benefits can be done in a simpler way.

1.8 Scope and Objective of the Thesis

Prediction and damping of inter-area oscillations is difficult as detailed representation of the entire interconnected system is required and the oscillations and are influenced by global states of large areas of power network.

The main objectives of this research work are listed as follows:

1. Discussions in detail of modelling and simulation of VSC-based FACTS controllers, i.e., STATCOM, SSSC and UPFC. The basic functions of the controllers are established by comparing them with other FACTS controllers.
2. Model different FACTS devices including STATCOM, SSSC and UPFC in detail in the MATLAB environment and study the possibility of implementing these models in the real-time HYPERSIM simulator.
3. Study the operating principle and control methodologies of these FACTS devices by doing steady state and dynamic state simulation studies under MATLAB environment.
4. Design robust centralized controllers for FACTS devices for damping power system inter-area oscillations using intelligence adaptive control and fuzzy logic techniques.
5. Investigate the performance of the designed controllers in damping power system inter-area oscillation and compare their performances in damping the power system oscillations.

6. Study the possibility of implementing the designed controllers into HYPERSIM real time simulator. Moreover, study the performance of FACTS controllers under the real time simulation environment and compare with the results with offline simulations.

1.9 Thesis Outline

Chapter 2 summarizes the general technology related to power semiconductor devices and Voltage-Source Converter (VSC) suitable for FACTS controllers. The operating principles, main circuit configurations, functions and general control strategies of Voltage-Sourced Converters (VSC) are discussed. The VSC controllers were modeled in SimPowerSystem, MATLAB and the models are used to illustrate the basic VSC waveforms for six-pulse, twelve-pulse and PWM operation of a VSC.

Chapter 3 presents the basic design and operating principles of a STATCOM FACTS device together with the detailed STATCOM control circuit design. A 12-pulse PWM-controlled STATCOM model and a 3-level 48-pulse inverter STATCOM are modeled and implemented in the SimPowerSystem, MATLAB. Simulation studies, which are based on 500kV representative power systems (rather than a simple single-machine/infinite bus representation), are performed to study the steady state and dynamic state performance of the STATCOM models which were developed for simulation purposes.

Chapter 4 describes the methods of control and modulation of power flow in a transmission line using Static Synchronous Series Compensator (SSSC). The SimPowerSystem, MATLAB simulations, which includes detailed representations of 3-phase 3-level 12-pulse PWM controlled SSSC and three level 48-pulse full-wave bridge inverter controlled SSSC, and the control circuit studied. The developed control strategies for both PWM controlled SSSC and 3-phase 3-level

48-pulse full-wave bridge inverter controlled SSSC use typical d-q transformations.

The development of the SSSC full models are tested with realistic test systems. The presented detailed models of the SSSC are particularly useful in control and protection circuits design, as these realistically reproduce the controller response in a power system.

In chapter 5, the application potential of multi-functional FACTS Controllers of the Unified Power Flow Controller, based on the back-to-back voltage-sourced converter arrangement, is presented. The basic design, operating principles and control blocks of the UPFC are explained together with the SimPowerSystem detailed model of the controller. Some representative power systems are used to demonstrate the UPFC operation in practical system conditions. Different control schemes for the shunt and series converters are implemented in the SimPowerSystem and tested in the detailed UPFC model. The results obtained for representative power systems are used to compare the different control strategies.

In chapter 6, the application of the STATCOM, SSSC and UPFC towards improving the transient stability of power systems is presented. The FACTS devices were simulated in SimPowerSystem, MATLAB and the dynamic performances of the STATCOM, SSSC and UPFC are compared using representative power system simulations.

Chapter 7 presents an analysis of novel control strategies for FACTS controllers, including intelligent rule-based controllers and fuzzy logic controllers. The proposed fuzzy logic controller uses the steady state relations electrical power as the input signals and does not require a dynamic model of the system for a satisfactory control design. It is not sensitive to the variation of system structure, parameters and operation points and can be easily implemented in a large scale nonlinear system.

Another novel proposal is an intelligent error driven integrator for FACTS devices, which is based on the concept of the error excursion plane where the stabilizing action is scaled by the magnitude of the power, voltage and reactance error signal in order to ensure adequate compensation. The proposed rule based design is robust and tolerates system parameter variations as well as modelling inaccuracies, since the control level is only scaled by input error signals.

Comparative studies of the proposed control schemes were carried out in the SimPowerSystems (MATLAB) environment. The simulation comprises a detailed (device-level) model of PWM-based SSSC and the associated control systems, installed in a tie line of an interconnected two-area EHV system. The SSSC is mainly applied to control the power through the tie-line.

Case studies show that, when equipped with modern control systems, the SSSC can be very effective in maintaining the transient and oscillatory stability of a power system by providing extra damping to power flow oscillations and machine angle oscillation.

In chapter 8, an interface between EMTP and TSP is demonstrated. Interfacing the two simulators, EMTP (HYPESIM) and TSP, can combine the electromagnetic and electromechanical simulations into a single simulation environment in order to make optimal use of the relative advantages of both simulation types.

A case study was carried out on a two-area system, with and without the connection of an SSSC to damp system oscillations. The SSSC was connected directly and through the interface, and it was found that the interface functioned well during a system fault. The simulation results obtained from the HYPERSIM real-time simulator agree with the results obtained by Matlab. This is a step toward to the development to a fully digital real-time broadband simulator.

Chapter 2. Basic Operating Principles of Voltage-sourced Converters

2.1 Introduction

This chapter summarized the general information of power semiconductor devices and Voltage-Source Converter (VSC) suitable for FACTS controllers. The operating principles, main circuit configurations, functions and general control strategies of Voltage-Sourced Converters (VSC) will be discussed. The VSC controllers were modeled in SimPowerSystem, MATLAB and the models were used to illustrate the basic VSC waveforms for six-pulse, twelve-pulse and PWM operation of a VSC.

2.2 Various types of self-commutating converters

There are two basic categories of self-commutating converters: Voltage-Sourced Converter (VSC), which is fed with a dc voltage source across its dc terminals, and Current Source Converter (CSC), which has a D.C. current source connected to its D.C. side. In general, these converters behave as voltage or current sources which can be used to generate output voltage or current waveforms of different magnitude and phase angle. In CSC, direct current always is unidirectional while the power reversal takes place through reversal of D.C. voltage polarity. To achieve this, the CSC implementation requires semiconductor switches with symmetrical bi-directional voltage blocking capability. On the other hand, for a VSC, the D.C. voltage always has one polarity while the power exchange is achieved by reversal of D.C. current and, therefore, the VSC requires only unidirectional voltage blocking. For performance and economics reasons, voltage source converters are preferred for FACTS applications and this thesis mainly study the voltage source converters. [1][15][16][17]

2.3 High Power Gate Turn-Off Semiconductor Devices

In order to produce the desired output waveforms, the semiconductor switches in the VSC must have a basic turn-off capability, or an auxiliary circuit has to be provided to produce "force commutation". These fully controllable semiconductor switches are also called bimodal switches in which current flow can be both initiated and extinguished by gate control. Furthermore, Conventional thyristor-based converters, being without turn-off capability, can only be current-sourced converters, whereas turn-off device-based converters can be of either type.

Although high power GTOs up to 6000V and 6000A ratings are now commercially available [16], currently available GTOs of limited current ratings much be connected in series to obtain the power ratings of required of VSCs for Transmission system applications. The present GTO technology allows a robust connection of a relatively high number of GTOs connected in series to form a turn-off valve required for high voltage VSCs. The disadvantages of GTO thyristors are high switching losses and significant losses in required snubber circuits, therefore, the switching frequency is limited to a maximum frequency of about 300 to 500Hz [17]. Nowadays, new technologies in high power semiconductor switches have brought a new family of new semiconductor switches with turn-off capabilities such as Insulated Gate Bipolar Transistors (IGBT), MOS Turn-Off Thyristor (MTO), Emitter Turn-Off Thyristors, and Intergrated Gated-Commutated Thyristors (IGCT).

Owing to their fast development high power IGBTs have become the choice in a wide range of low and medium power applications with ratings up to a few tens of megawatts. The advantages of this semiconductor device are its fast turn-on and turn-off capabilities with a relatively low power loss, and thus they can be used in Pulse Width Modulation (PWM) converters operating at high frequencies. Being a transistor device, it has a relatively high forward voltage drop, but low switching losses and good current limiting capability.

The development of the GTO into MTO, ETO and IGCT introduced a wide range of new turn-off thyristor devices for FACTS controller applications. High power semiconductor switches with turn-off capability are more expensive and have higher losses than thyristors without turn-off capability; however, they have positive significant impact on overall system cost and have many performance advantages. The availability and performance characteristics of power semiconductor switches will have a great influence over circuit and control design. For example, power semiconductor switches with low turn-on and turn-off losses and high switching frequency can be used for applications in PWM converters. On the other hand, these switches have lower power ratings and, therefore, are limited to low and medium power applications. Power semiconductor switches with higher losses and lower switching frequency, but with higher power rating, would be considered for circuit concepts that need, for example, only one turn-on and turn-off per cycle.

2.4 Basic Operating Principles of Voltage-Sourced Converter

2.4.1 Basic Circuit Configuration

Voltage-Sourced Converters transform D.C. voltage into A.C. voltage of controllable frequency, magnitude and phase angle through appropriate switching sequence. The output A.C. voltage could be fixed or variable magnitude, at a fixed or variable frequency. For FACTS applications, the output A.C. voltage has a fixed frequency equal to the fundamental frequency of a power system in which the FACTS controllers are connected. [1][2]

By controlling the D.C. voltage and the gain of the converter constant, it is possible to control the output voltage with variable magnitude. The output A.C. voltage has a waveform similar to a square wave, and hence these Voltage-source converters are called square-wave converters. However, the output voltage waveform of these converters carries low order harmonics which require harmonic filtering for the output voltage. Besides, the output voltage magnitude can be controlled within limited range that depend the D.C. capacitor voltage and current ratings. The D.C. voltage should not exceed the maximum voltage rating of the D.C. capacitor and should be constantly above a certain level to avoid thyristor firing failure due to low voltage conditions.

On the other hand, keeping the input D.C. voltage constant and varying the gain of the converter can control the converter output voltage. This kind of control of the output voltage magnitude is normally accomplished by Pulse-Width-Modulation (PWM) control; the converter gain in this case is defined as the ratio of the A.C. Output voltage to the D.C. input voltage. There are various pulse-width-modulation schemes to shape the output A.C. voltage to be as close to a sine wave as possible. Although PWM control methodologies are well developed, PWM control is still considered uneconomical in high power applications due to the high switching losses and unavailability of fast switching turn-off capable power electronic devices. When high power IGBTs become available and with further improvements in high voltage power electronics, the PWM techniques should become more competitive.

Figure 2.1 shows a simplest circuit configuration of a three-phase voltage-sourced converter which is a two-level bridge composed of six valves. Each valve comprises semiconductor turn-off capable switches each with an anti-parallel diode connected across the switch. The switches should be designed only for forward blocking voltage, and the diodes are used to ensure that the voltage polarity of each switch is unidirectional. However, each converter arm, made of two valves, can conduct current in both directions, providing the converter with the capability to behave as an inverter or a rectifier.

The current is assumed positive if it flows from the A.C. to the D.C. side (rectifier operation) while the current is assumed to be negative when it flows from the D.C. to the A.C. side (inverter operation). On the A.C. side, depending on the connection of the converter transformer, the output voltage of the converter can be connected in parallel or in series with the power system. If the converter is connected in parallel with the A.C. power system, i.e. STATCOM, it is used to inject capacitive or inductive current into the power system in order to regulate the system voltage at its point of connection. On the other hand, if the converter is connected in series with transmission line, it is used to generate a controllable phase-shifted voltage to regulate the total voltage drop / rise in the line, so as to control real and reactive power flow through the transmission line. [1][2]

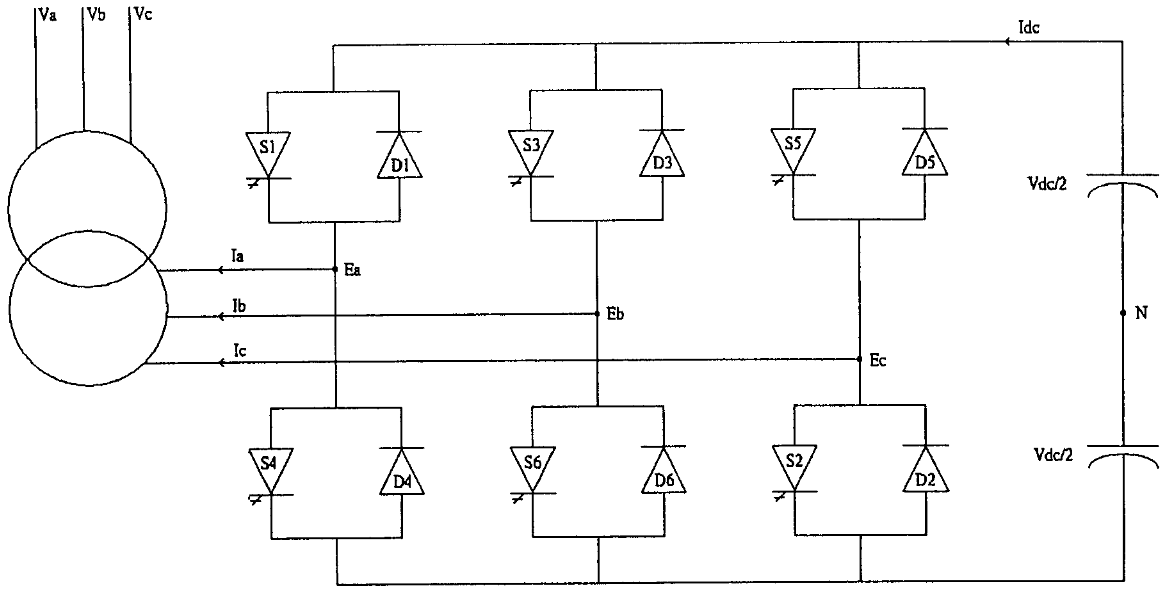


Figure 2.1 *Three-phase two-level Voltage-sourced Converter*

2.4.2 Operating Principle and Basic Relationship

In the three-phase, two-level VSC shown in figure 2.1, there are six controlled switches used to produce the converter output voltage from the input D.C. voltage. There are also six uncontrolled switches (diodes) to provide a path for inductive current to flow whenever the controlled switch in the same leg is switched off. The A.C. current is the result of interaction of the converter output voltage with the A.C. system and can have any phase relationship with respect to the voltage. It is necessary for a VSC like this to prevent two switches on at the same time, in any leg. Since there are three converter legs for the three phase voltages, each 120^0 apart, there are always three switches on at the same time, one on each phase leg. To satisfy system requirements, there is always a complete conduction path between the D.C. capacitor and the A.C. system. It should be mentioned that there is never a sequence where three controlled switched, one on each phase, conduct at the same time. It is always a combination of two controlled switches and one uncontrolled switch conducting and vice versa. As a mater of fact, the switching pattern changes every 30^0 as indicated in Table 2.1 [1][2]

Period	Phase A	Phase B	Phase C
$0 \to \frac{\pi}{6}$	D1	D6	S5
$\frac{\pi}{6} \to \frac{\pi}{3}$	D1	S6	S5
$\frac{\pi}{3} \to \frac{\pi}{2}$	D1	S6	D2
$\frac{\pi}{2} \to \frac{2\pi}{3}$	S1	S6	D2
$\frac{2\pi}{3} \to \frac{5\pi}{6}$	S1	D3	D2
$\frac{5\pi}{6} \to \pi$	S1	D3	S2
$\pi \to \frac{7\pi}{6}$	D4	D3	S2
$\frac{7\pi}{6} \to \frac{4\pi}{3}$	D4	S3	S2
$\frac{4\pi}{3} \to \frac{3\pi}{2}$	D4	S3	D5
$\frac{3\pi}{2} \to \frac{5\pi}{3}$	S4	S3	D5
$\frac{5\pi}{3} \to \frac{11\pi}{6}$	S4	D6	D5
$\frac{11\pi}{6} \to 2\pi$	S4	D6	S5

Table 2.1 Switching pattern for three-phase two-level VSC

Each valve is closed for 180^0, as described in Table 2.1 and shown later in the waveform V_a of figure 2.3. The waveform shows a square-wave waveform representing the voltage of A.C. bus phase a with respect to a hypothetical D.C. capacitor midpoint N, with peak voltages of $\pm\frac{V_{dc}}{2}$. As shown in Table 2.1, from 0 to π, the upper valve D1 and S1 conducts while the lower valve D4 and S4 conducts from π to 2π. three legs have their timing $\frac{2\pi}{3}$ apart; the upper valve D3 and S3 in the leg of phase b starts conducting $\frac{2\pi}{3}$ after the leg of phase a, while the upper valve D5 and S5 in the leg of phase c waits for $\frac{4\pi}{3}$ to start with its condition. The Fourier analysis of phase voltage v_a, which is basically a periodical square wave with amplitude $\frac{V_{dc}}{2}$, shows a waveform composed of odd harmonics including third and its multiple harmonics.

$$v_a(t) = \frac{4}{\pi}(\frac{V_{dc}}{2})[\cos\omega t - \frac{1}{3}\cos 3\omega t + \frac{1}{5}\cos 5\omega t - \frac{1}{7}\cos 7\omega t + ...] \qquad \text{Equation (2.1)}$$

2.5 Harmonic Reduction using multi-bridge converter technique

It is important to assure that in high voltage and power FACTS devices applications, harmonics should be kept at satisfactory levels. For example, the number of six-pulse two-level bridges in the multi-bridge converter can be increased to cancel certain low frequency harmonics. It is also possible to increase the number of the bridges from to reduce harmonic content. The advantage of the latter is that the fundamental component of the output voltage can be controlled even though the D.C. voltage is kept constant and the switching frequency is equal to the fundamental frequency [18]. There are different categories of PWM techniques and a complete overview can be found in [19].

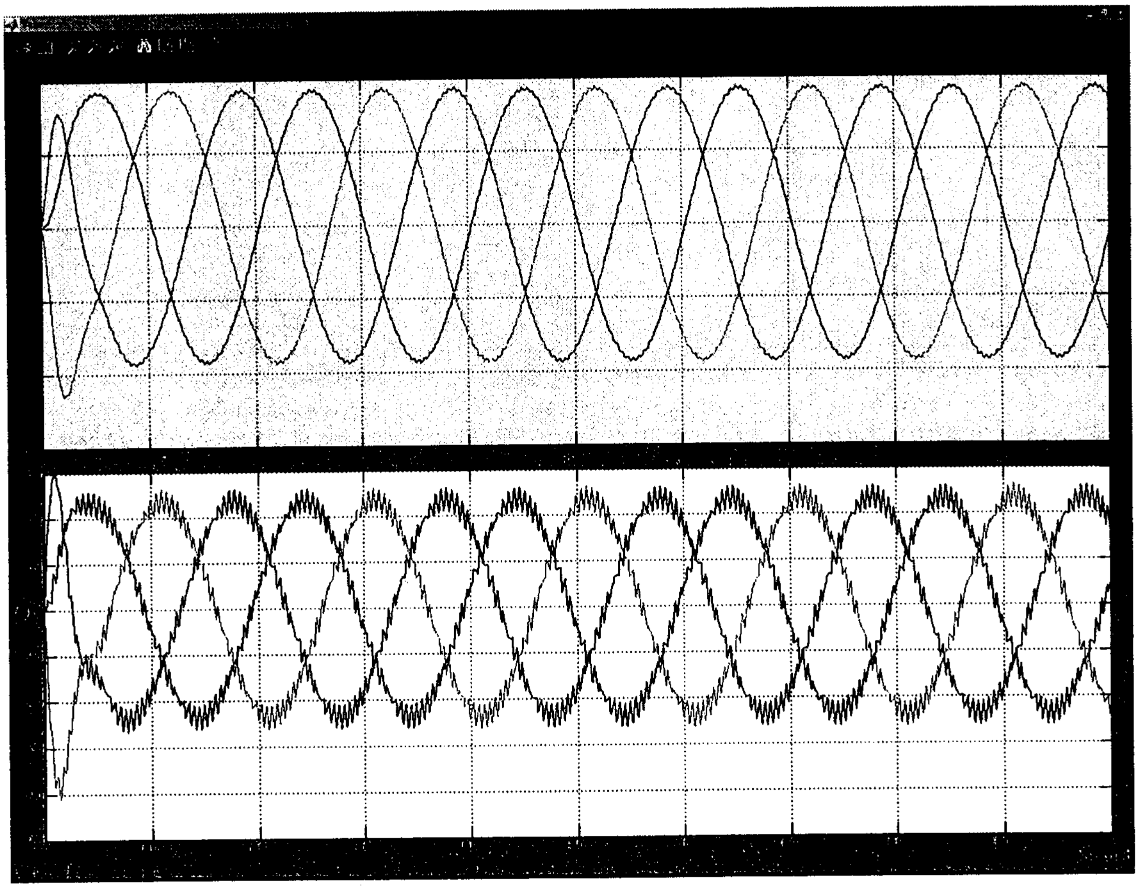


Figure 2.4 Simulation result of a three-phase two-level PWM VSC

2.6 Two-Level Multi-Bridge Converter and Three-Phase 48-pulse Full-wave Bridge converter

The output voltage and current waveforms of the voltage-sourced converter output voltage and current shown in Figure 2.4 are far from sinusoidal. The output voltage waveform of the six-pulse converter contains harmonics of frequencies of $(6k \pm 1)f$, and its current is composed of frequencies of $6k \times f$, where f is fundamental frequency and k = 1,2,3, ... Passive filters can filter some of the harmonics but this method is considered to be expensive, particularly at low frequencies, where L and C passive filter components have large values and ratings.[1]

One way to reduce the harmonics level present in the converter output waveforms is to increase the number of converters. This method involves multi-connected, out-of-phase six pulse converters. A 6n –pulse converter can be obtained through series connection of n six-pulse converters operated from a common D.C. source with a successive $\frac{2\pi}{6n}$ phase displacement. The six-pulse converter output voltage waveforms are shifted by transformers with appropriate secondary winding configurations to cancel the phase displacement of the converter. The transformed outputs of all converters are in phase with each other and are summed by the series connection of all corresponding primary windings. It is necessary to have separate transformers for each converter, otherwise phase shifts in the non-characteristic harmonics, i.e. 6n – order harmonics, will result in a large circulating current due to a common core flux [16]. Transformer primary side windings should not be connected in parallel to the same three-phase A.C. buses for the same reason. Therefore, the harmonics present in the waveform of a general P-pulse converter are $(P \pm 1)f$ in the output voltage and $P \times f$ in the output current where $P = 6n$ and n = 1,2,3,.... Since the order of the lowest harmonic present in the output current is the same as the pulse number, and the order of the lowest harmonic contained in the output voltage is the pulse number minus one, the harmonic spectrum improves rapidly by increasing the number of converters, and consequently by increasing the pulse number. In the STATCOM application of [15], eight six-pulse converters are connected through appropriate transformer configure to form a 48-pulse converter configuration.

In order to demonstrate the benefits of this method, a twelve-pulse converter i was simulated, and comprising two six-pulse converters connected in series. Their output waveforms are summed using two three-phase two-winding transformers. The transformer connection is shown in Figure 2.5, while the voltage and current waveforms for each winding are shown in Figure 2.6. As we can see from Figure 2.5 and Figure 2.6, the voltages of the second converter are connected to a delta winding, and hence the phase-to-phase voltage is shifted by 30° to be in phase with the phase-to-neutral voltage from the first converter. This arrangement puts the non-characteristic harmonics, i.e., harmonics of order different from $12n \pm 1$, in phase opposition. [1]

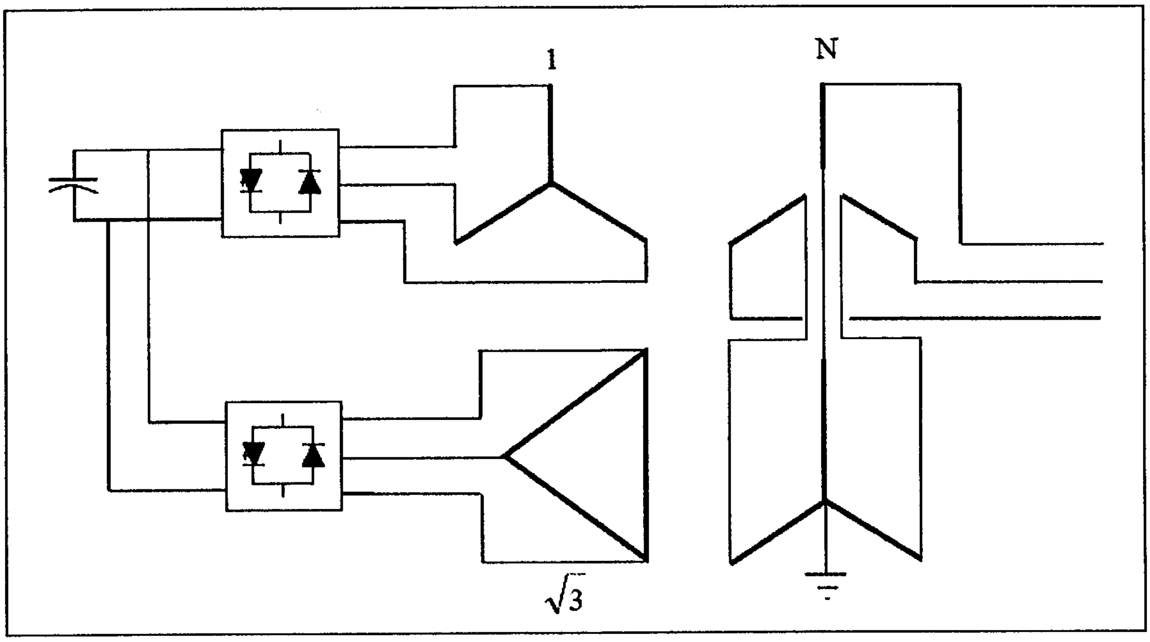


Figure 2.5 *Three-phase 12-pulse full-wave bridge inverter*

The magnitude of the converter output voltage is controlled by changing the input D.C. voltage, which is a disadvantage of this kind of arrangement as compared to PWM converters. On the other hand, the amount of harmonics generated by the converter can be controlled and reduced to acceptable levels by increasing the number of converters in the multi-converter arrangement.

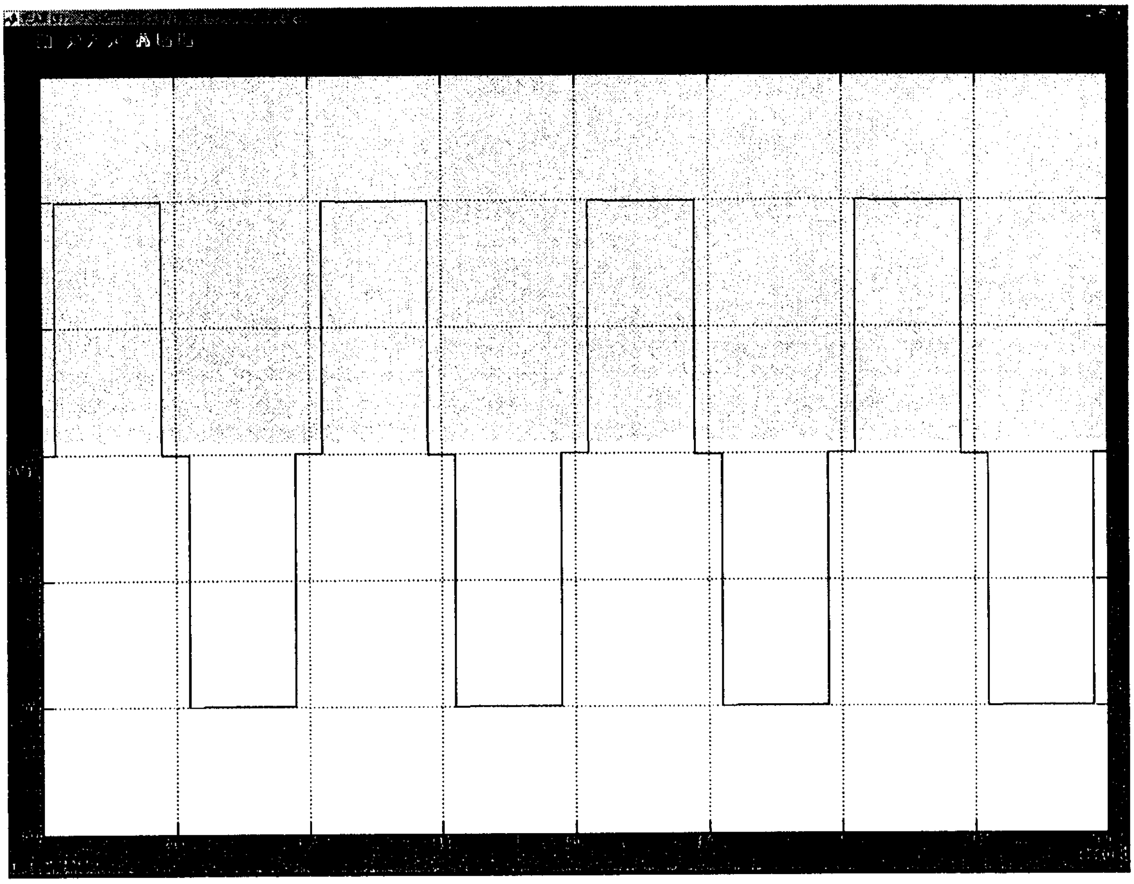


Figure 2.6 Output voltage waveform of the 3-phase 12-pulse inverter

2.7 Pulse Width Modulation (PWM) Converter

One main advantage of PWM converters is the possibility of controlling the converter output voltage by controlling the converter gain. There are several PWM techniques used with different converter configurations suggested by different authors [1][17][18][19]. In the most popular PWM method, the width of each pulse is varied in proportion to the amplitude of a sine wave or so-called control waveform [17][20] as seen in Figure 2.7.

In the two-level three-phase voltage-sourced converter shown in Figure 2.1, the switches are controlled such that the turn-on and turn-off pulses correspond to the crossing points of the control waveform with the carrier waveform of corresponding phase. The frequency of the carrier waveform determines the fundamental frequency of the output voltage (50 Hz or 60 Hz). The frequency modulation ratio is the ratio between frequencies of the carrier and control waveforms, i.e.,

$$m_f = \frac{f_{carrier}}{f_{control}}$$

By varying the amplitude of the control waveform $A_{control}$ from zero to the amplitude of the carrier waveform $A_{carrier}$, the pulse width can be varied from $0°$ to $180°$. The modulation ratio m_a defines the ratio between the control and carrier waveforms:

$$m_a = \frac{A_{control}}{A_{carrier}}$$

The waveform v_{an} in Figure 2.7 shows the phase a to the D.C. midpoint voltage, which fluctuates between $-\frac{V_{dc}}{2}$ and $+\frac{V_{dc}}{2}$. The amplitude of the fundamental frequency component of the phase-to-dc midpoint voltage is m_a times $\frac{V_{dc}}{2}$:

$$V_{aN,\max} = m_a \frac{V_{dc}}{2}$$

The waveform v_{bN} in Figure 2.7 is the output voltage of phase b to the D.C. midpoint, which lags v_{aN} by $120°$. The phase-to neutral voltage v_{aN} is calculated as the difference between the voltage of the floating neutral n of the wye-connected secondary of the step-down transformer, i.e. v_{nN}, and the D.C. midpoint voltage where:

$$v_n = \frac{v_{aN} + v_{bN} + v_{cN}}{3}$$

Since m_f is chosen to be an odd integer (9 for the waveforms shown in Figure 2.7), the phase-to-neutral and the phase-to-phase voltage result in an odd symmetry as well as a half-symmetry. Therefore, Fourier analysis of the converter output voltages shows that only the coefficients of the sine series are finite, while those for the cosine series are zero. This fact indicates that only odd harmonics are present, while the even harmonics disappear from the waveforms of V_{an} and V_{ab}.

The frequency modulation ratio m_f has an influence over the order of harmonics that appear as sidebands centered on the switching frequency and its multiples, i.e. around harmonics m_f, $2m_f$, $3m_f$, etc. The frequencies at which harmonics occur are:

$$\begin{aligned} &m_f, m_f \pm 2, \\ &2m_f, 2m_f \pm 1, \\ &3m_f, 3m_f \pm 2, \\ &4m_f, 4m_f \pm 1, \end{aligned} \qquad \text{Equation (2.2)}$$

It is important to mention that in three-phase VSCs, third harmonics are eliminated. Also, if the frequency modulation ratio is chosen to be a multiple of 3, even the harmonics of the order of m_f are cancelled out in the converter output voltage waveforms.

2.8 Demonstration of harmonic level generated by different VSCs

Figure 2.7 shows the system configuration of the simulation which demonstrates the harmonic level of the output voltage waveform of a 3-level PWM voltage-sourced converter and a 3 phase 48-pulse full-wave bridge.. The system is basically a PWM based or 48-pulse full-wave Bridge VSC connected to a pure resistive load. The 48-pulse full-wave bridge inverter consists of four 3-phase 3-level inverters coupled with four phase shifting transformers. For the 3-level PWM voltage-sourced converter, there is only one turn-on avoltage can be controlled by varying the width of the voltage pulses, and/or the amplitude of the D.C. bus voltage. In addition, by having multiple pulses per cycle, and varying the width if the pulses to vary the amplitude of the A.C. voltage, it is able to vary the A.C. output voltage and to reduce the low-order harmonics.

For the phase shifting transformers, the transformer arrangement is designed to neutralize all odd harmonics up to 45^{th} harmonic except for the 23^{rd} and 25^{th}. Y and delta transformer secondary configuration can be used to cancel the 5+12n harmonics (i.e. 5, 17, 29, 41 ...) and 7+12n harmonics (i.e. 7, 19, 31, 43 ...). In addition, the 15^0 phase shift between the two groups of transformers (Tr1Y and Tr1D lagging by 7.5^0) allows cancellation of 11+24n harmonics (i.e. 11, 35...) and 13+24n harmonics (i.e. 13, 37...). Furthermore, all of the 3n harmonics are not transmitted by the delta and ungrounded Y transformers. Therefore, the first harmonics which are not cancelled by the transformers are the 23^{rd}, 25^{th}, 47^{th} and 49^{th} harmonics. By choosing the appropriate conduction angle for the three-level inverter ($Q = 172.5^0$), the 23^{rd} and 25^{th} harmonics can be minimized. The first significant harmonics generated by the inverter will then be 47^{th} and 49^{th}. Using a bipolar D.C. Voltage, the 3 phase 48-pulse full-wave bridge inverter can then generate a 48-step voltage approximating a sine wave.

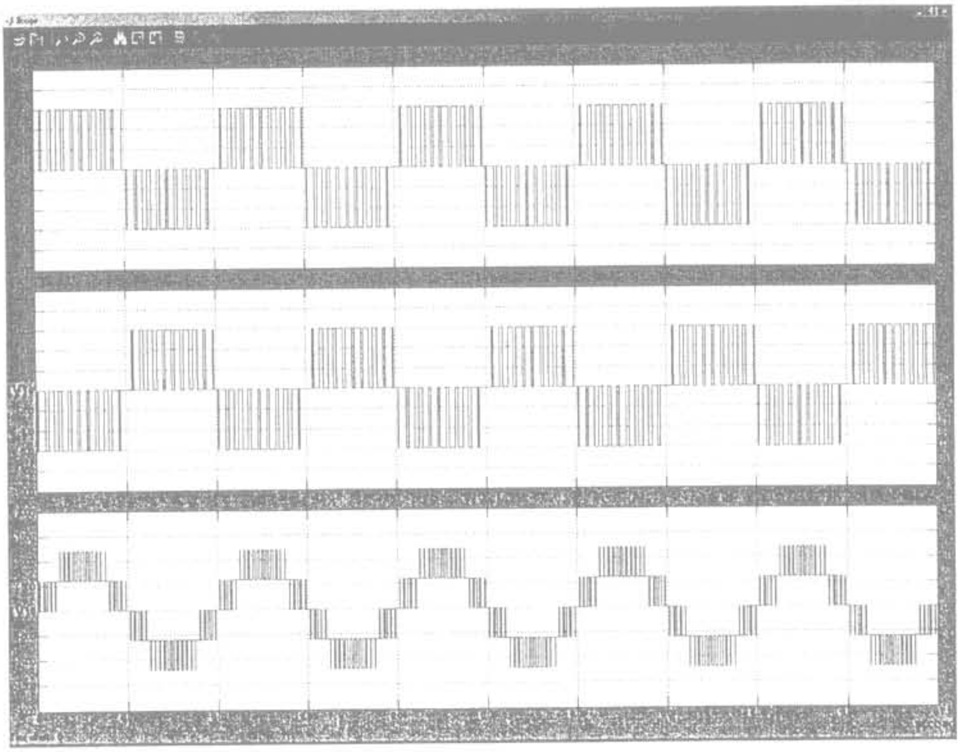


Figure 2.7 Simulation of PWM-based inverter

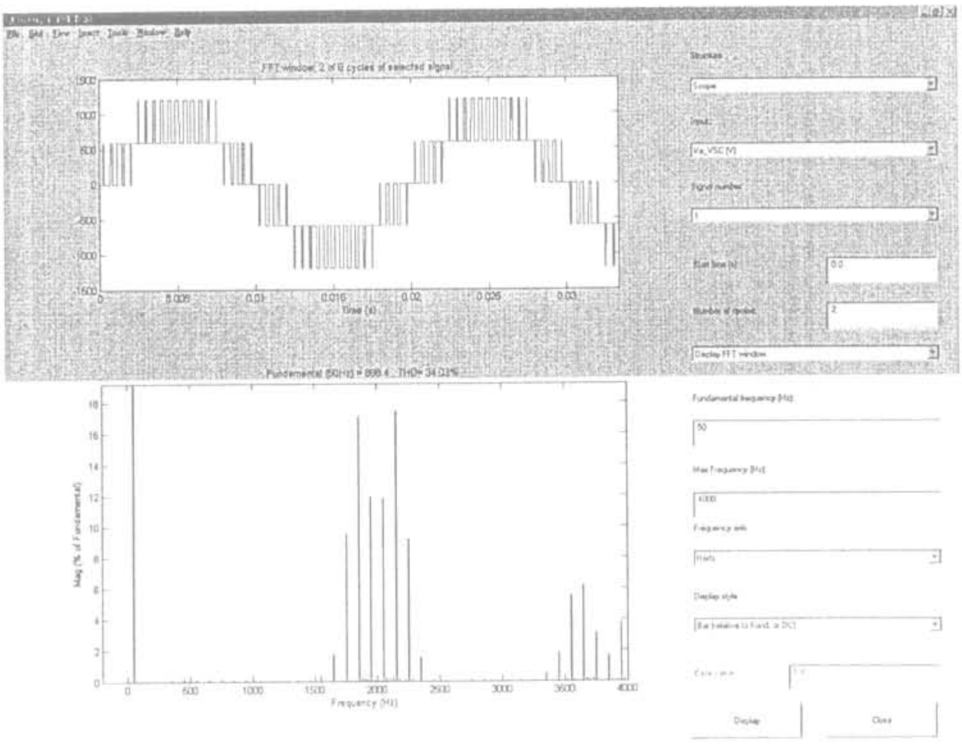


Figure 2.8 Harmonic distortion of the PWM-based inverter

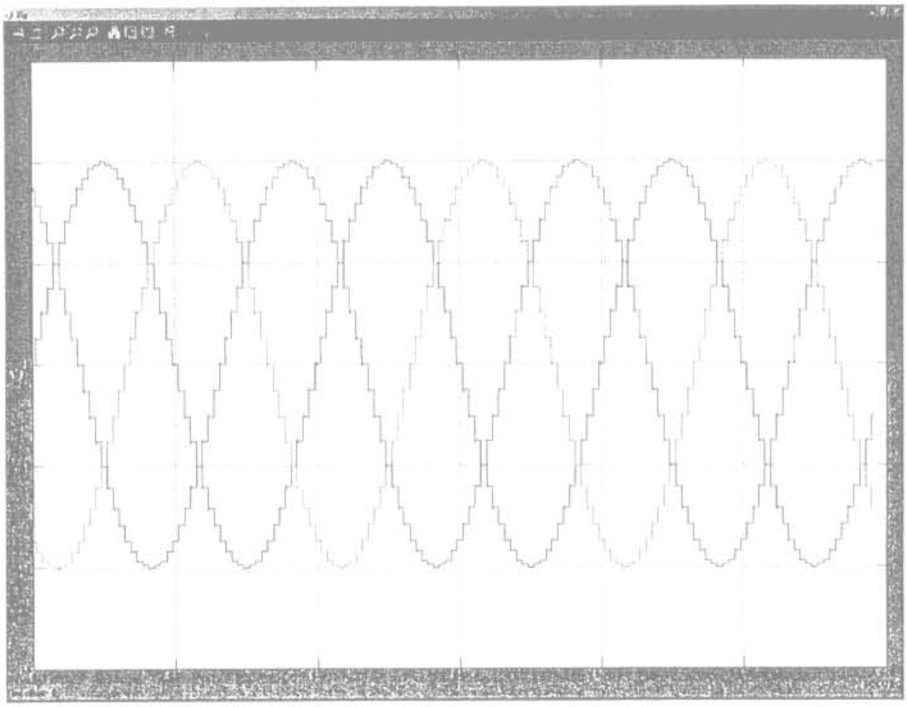


Figure 2.9 three phase voltage output of the multi-bridge inverter

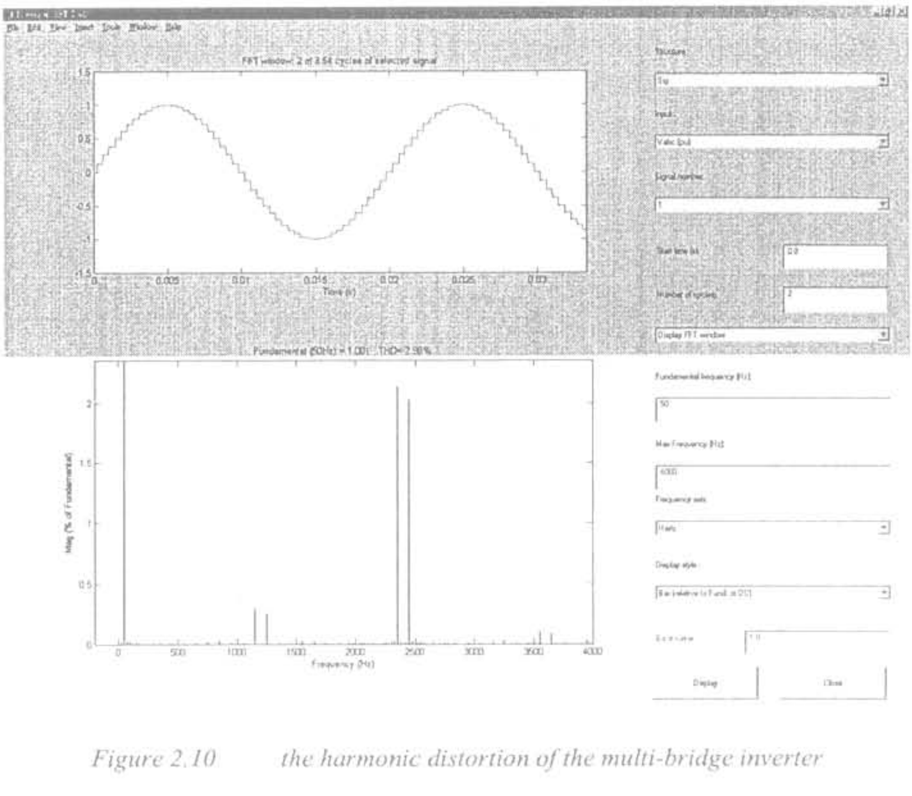


Figure 2.10 the harmonic distortion of the multi-bridge inverter

2.9 Summary

This chapter has discussed the fundamentals of forced-commutated VSCs, with emphasis on high power applications. The basic relationships for VSCs were formulated to provide a basis for the discussions and results in the following chapters.

The operation principles of a VSC were explained briefly for two control methods: square-wave and PWM. The analogy and comparison of square-wave and PWM controlled methods were also given. Note that multi-level voltage-sourced converters are not within the scope of the thesis.

Chapter 3. Static Synchronous Compensator – STATCOM

3.1 Introduction

This Chapter presents the basic design and operating principles of a STATCOM FACTS device together with the detailed STATCOM control circuit design. A 12-pulse PWM-controlled STATCOM model and a 3-level 48-pulse inverter STATCOM were modeled and implemented in the SimPowerSystem, MATLAB. Simulation studies, which were based on 500kV representative power systems (rather than a simple single-machine/infinite bus representation), were performed to study the steady state and dynamic state performance of the STATCOM models which were developed for simulation purposes.[1][2][4]

The presented STATCOM models are modelled in detail which includes all of the power electronic based voltage-sourced converter parts and phase-shifting transformer parts. These models are a very useful toolbox in MATLAB for doing power system design and simulation. The designed control systems for the 12-pulse and PWM-controlled STATCOM use typical d-q transformation to obtain D.C. signals for control purposes [21][22][23]. The STATCOM operating and control limits are included in the models, which makes these models suitable for both steady state and transient stability studies.

3.2 Basic Operating Principles

The STATCOM is made up of a coupling transformer, a VSC, and a D.C. energy storage device. The energy storage device is a relatively low-rated D.C. capacitor, and hence the STATCOM is only capable of reactive power exchange with the transmission system. If a D.C. storage battery or other D.C. voltage source were used to replace the D.C. capacitor, the controller could be used to control and exchange real and reactive power with the transmission system. A simpified model of a STATCOM is shown in Figure 3.1. [1][3]

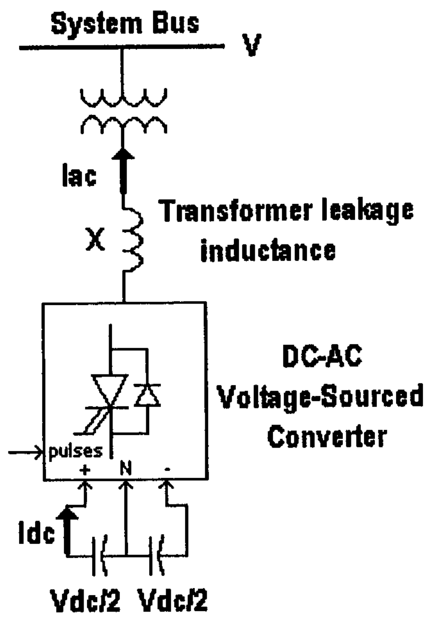


Figure 3.1 Simplified STATCOM model

The STATCOM's output voltage magnitude and phase angle can be controlled. By changing the phase if the valve firing angle α, the voltage across the D.C. capacitor can be controlled, so as to control the magnitude of the converter A.C. output voltage, such that $V_{out} = kV_{dc}$ where k depends on the converter configuration, the number of switching pulses and the converter controls. The difference between the converter output voltage and the A.C. system bus voltage can be used to determine the flow of reactive power in or out the system through the coupling transformer. [1][3]

The switching losses of the converter and the current required to charge the D.C. capacitor to a satisfactory D.C. voltage level are supplied by the real power flow through the converter. The capacitor is charged and discharged during the course of each switching cycle, but in steady state, the average capacitor voltage remains constant. In steady state, the switching losses of the valves are supplied from the ac system. The ability of STATCOM to absorb / supply real power depends on the size of D.C. capacitor and the real power losses due to switching. Since the D.C. capacitor and the losses are relatively small, the amount of real power transfer is also relatively small. This implies that the STATCOM's output A.C. current I_{ac} has to be approximately $\pm 90^0$ with respect to A.C. system voltage at its line terminals.

3.3 STATCOM Control Systems

The controller of a STATCOM is used to operate the inverter in such a way that the phase angle between the inverter voltage and the line voltage is dynamically adjusted as the STATCOM generates or absorbs desired VAR at the point of connection. Fig 3.2 shows a simplified diagram of the STATCOM with an inverter voltage , E_1, and a tie reactance, X_{tie}, connected to a system with a voltage source, V_{th}, and a Thevenin reactance, X_{th}. When the inverter voltage is higher than the system voltage, the STATCOM "sees" an inductive reactance connected at its terminal. Hence, the system "sees" the STATCOM as a capacitive reactance and the STATCOM is considered to be operating in a capacitive mode. Similarly, when the system voltage is higher than the inverter voltage, the system "sees" and inductive reactance connected at its terminal. Hence, the STATCOM "sees" the system as a capacitive reactance and the STATCOM is considered to be operating in an inductive mode. [1][3][21][22][23]

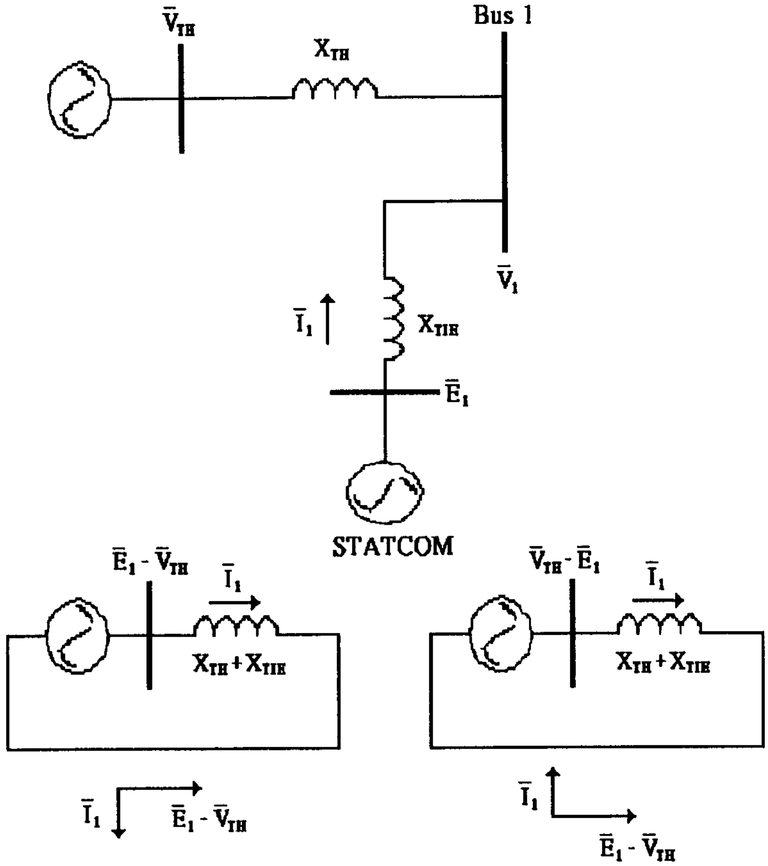


Figure 3.2 STATCOM operate in capacitive and inductive modes

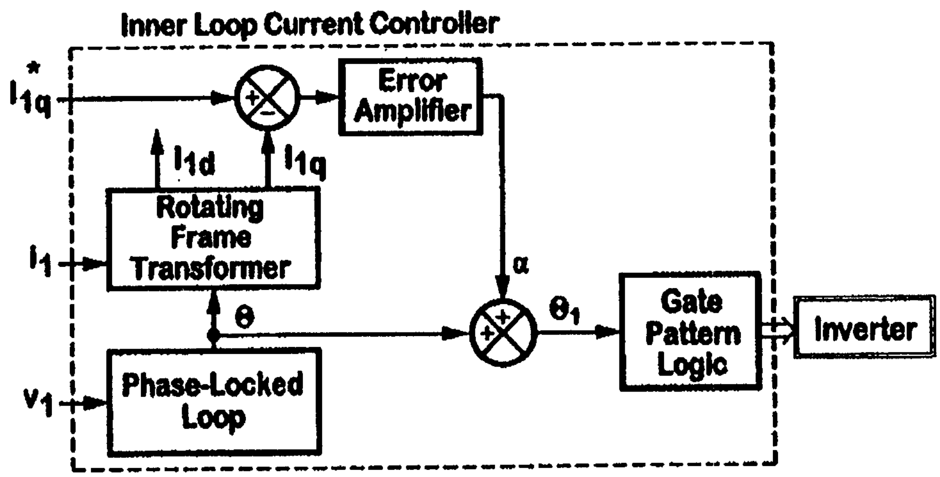


Figure 3.3 Current control block diagram of a STATCOM

Figure 3.2 shows the reactive current block diagram of the STATCOM. An instantaneous 3-phase set of line voltages, V_1, at Bus 1 is used to calculate the reference angle, theta, which is phase-locked to the phase a of the line voltage, V_{1a}. An instantaneous 3-phase set of measured inverter currents, I_1, decomposed into its real or direct component, I_{1q}, respectively. The quadrature component is compared with the desired reference value, I_{1q}*, and error is passed through an error amplifier which produces a relative angle, α, of the inverter voltage with respect to the line voltage. The phase angle, theta1, of the inverter voltage is determined by the relative angle, alpha, of the inverter voltage and the phase-lock-loop angle, theta. The reference quadrature component, I_{1q}*, of the inverter current is defined to be either positive if the STATCOM is emulating an inductive reactance or negative if it is emulating a capacitive reactance. The DC link capacitor voltage, V_{dc}, is dynamically adjusted in relationship with the inverter voltage. The control scheme described above shows the implementation of the inner current control loop which regulates the reactive current flow through the STATCOM regardless of the line voltage. However, if one is interested in regulating the line voltage, an outer voltage control loop must be implemented. The outer voltage control loop will automatically determine the reference reactive current for the inner current control loop which, in turn, will regulate the line voltage. [1][3][21][22][23]

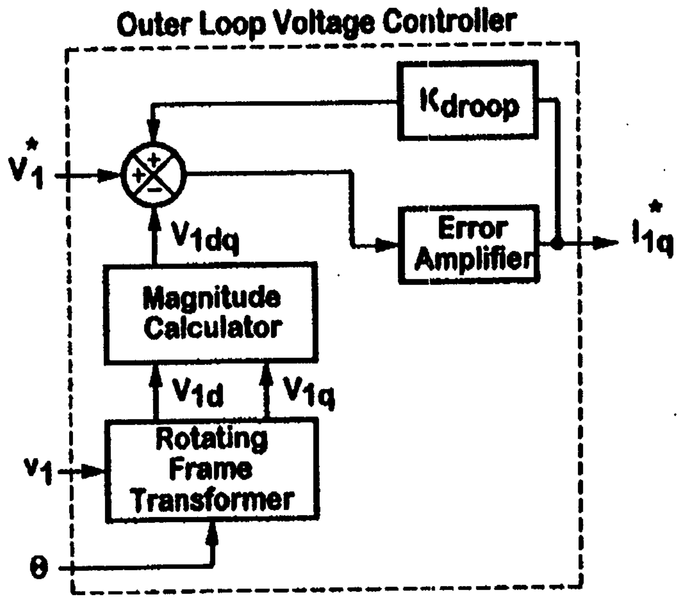


Figure 3.4 Voltage control block diagram of a STATCOM

Figure 3.4 shows the voltage control block diagram of the STATCOM. An instantaneous 3-phase set of measured line voltages, V_1, at Bus 1 is decomposed into its real or direct component, V_{1d}, and reactive quadrature component, V_{1q}, respectively. The magnitude of the bus voltage, V_{1dq}, is compared with the desired reference value, V_1*, (adjusted by the droop factor, K_{droop}) and the error is passed through an error amplifier which produces the reference current, I_{1q}*, for the inner current control loop. The droop factor, K_{droop}, is defined as the allowable voltage error at the rated reactive current flow through the STATCOM. [1][3][21][22][23]

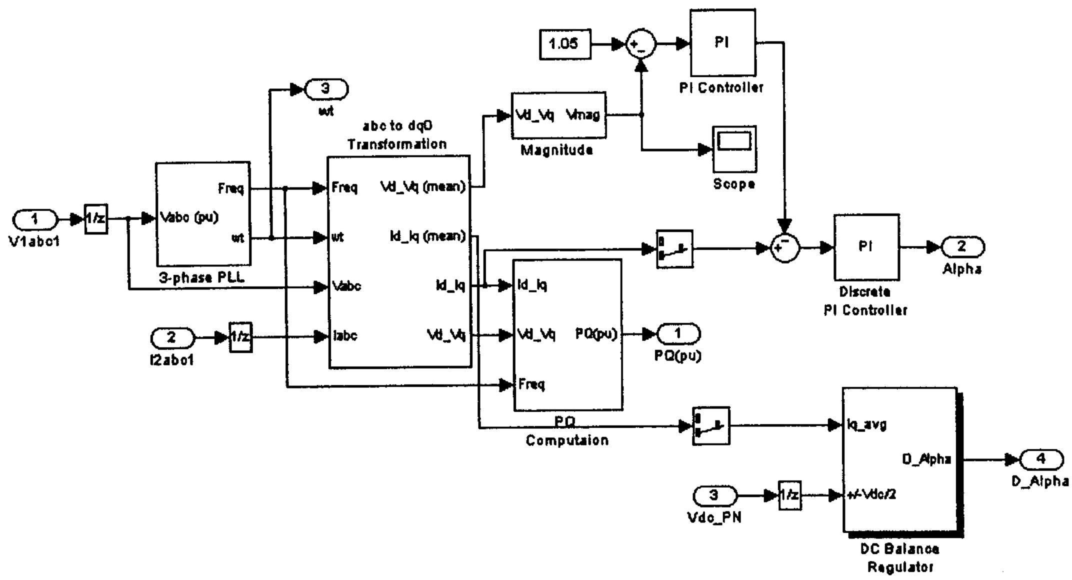


Figure 3.5 Detailed control block diagram of STATCOM

Figure 3.5 shows the detailed control block diagram of the STATCOM. The instantaneous 3-phase set of measured line voltages and current, D.C. voltages of the capacitor banks, reference voltage, reference reactive power and reference reactive current are required as the inputs of the STATCOM control block. The phase locked loop block synchronizes GTO pulses to the system voltage and provides a reference angle to the measurement system. The measurement system block computes the positive-sequence components of the STATCOM voltage and current by using park's transformation. The Voltage regulation is preformed by two PI regulators from measured voltage V_{mes} and the reference voltage V_{ref}, the Voltage regulator block (outer loop) computes the reactive current reference voltage I_{qref} used by the Current Regulator block (inner loop). Finally, the STATCOM controller will then generate the firing pulses to the 48-pulse full wave bridge inverter in order to control the reactive current injection to the power system. [1][3][21][22][23]

3.4 Simulation of a STATCOM

The performance of a typical STATCOM was studied in detail using simulation. A STATCOM model was developed in the MATLAB environment using the power system toolbox called SimPowerStytem. The model was studied using a single machine infinite bus system, shown in figure 3.6(a), (b). The system consists of a 250MW, 20kV generator with Automatic Voltage Regulator (AVR) and a $\Delta - Y$ step-up transformer feeding (a) pure resistive load of 100MW, (b) pure resistive load of 100MW and $\pm$50MW reactive load through a 300 km transmission line.

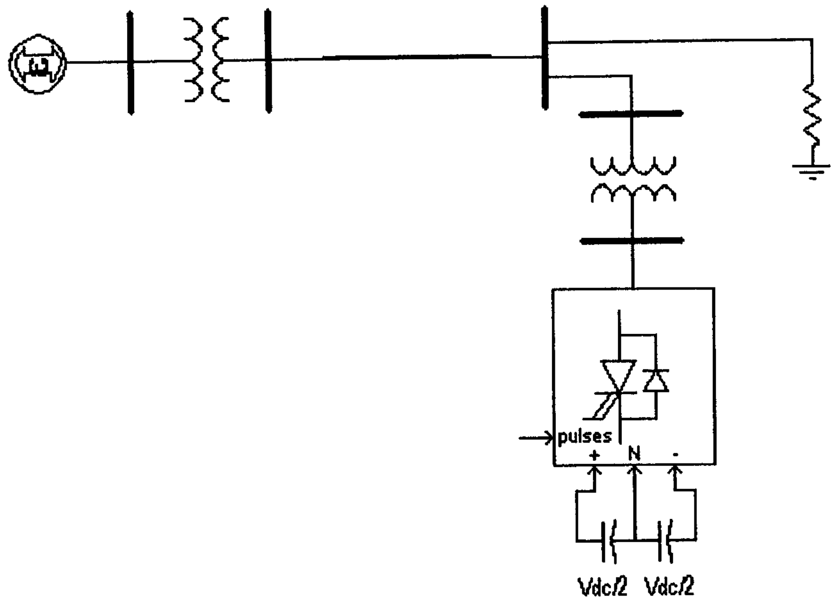


Figure 3.6a *Single machine to infinite bus system with pure resistive load*

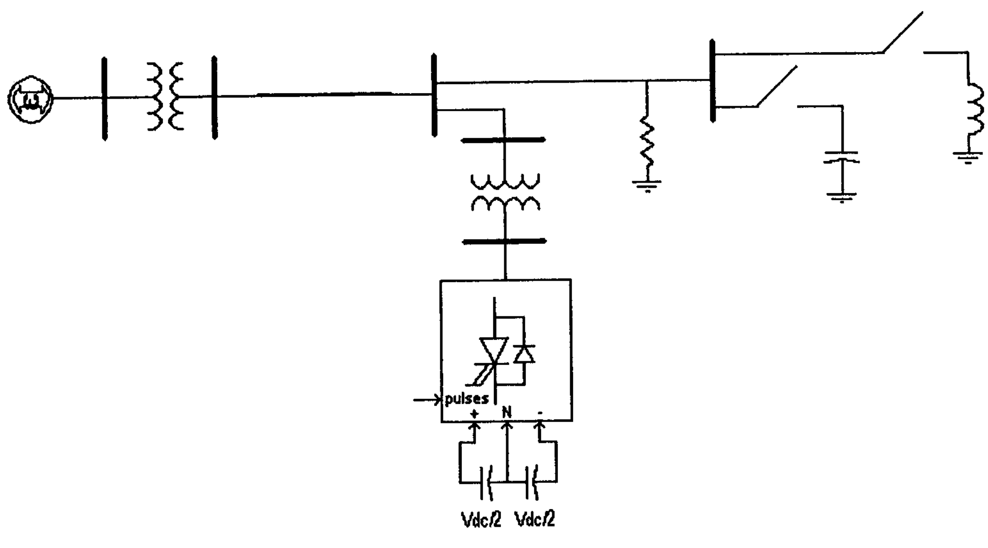


Figure 3.6b *Single machine to infinite bus system with various loading*

The simulation results for the test system with and without the STATCOM shown in Figure 3.6 (a) are shown in Figures 3.7 (a) and (b). In this simulation, the voltage level of the input voltage source of the tested system was varied at time (i) 3s and (ii) 6s. The STATCOM is applied to maintain the receiving end (Load Centre) voltage level control. From the simulation results shown in Figure 3.7 (a) and (b), we can note that the measured receiving end voltage at the load centre was maintained unchanged even though the sending end voltage varied between time (i) 3s to (ii)6s.

Figure 3.8 (a) and (b) shows the simulation results for the tested system with and without the STATCOM shown in Figure 3.6 (b). From the simulation results, we can note that with the STATCOM installed, the representative power system is able to maintain its voltage level and its reactive power level as well as it steady state stability.

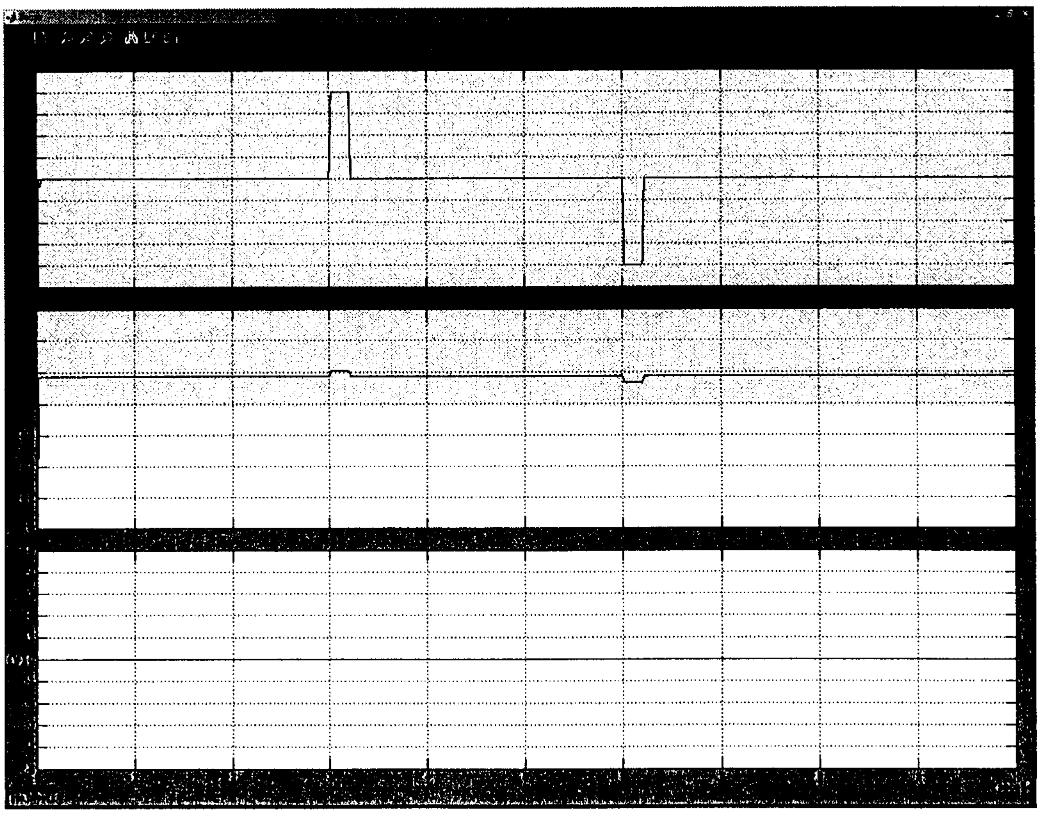


Figure 3.7(a) Simulation results of the tested system without STATCOM

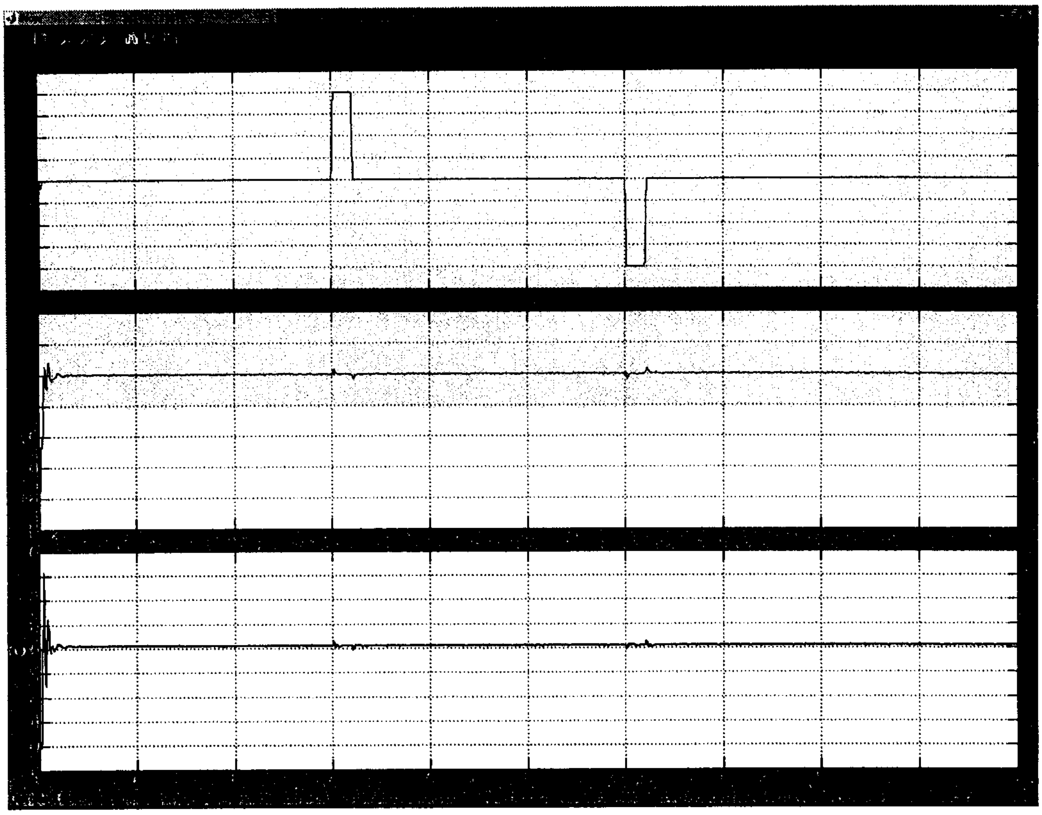


Figure 3.7(b) *Simulation results of the tested system with STATCOM*

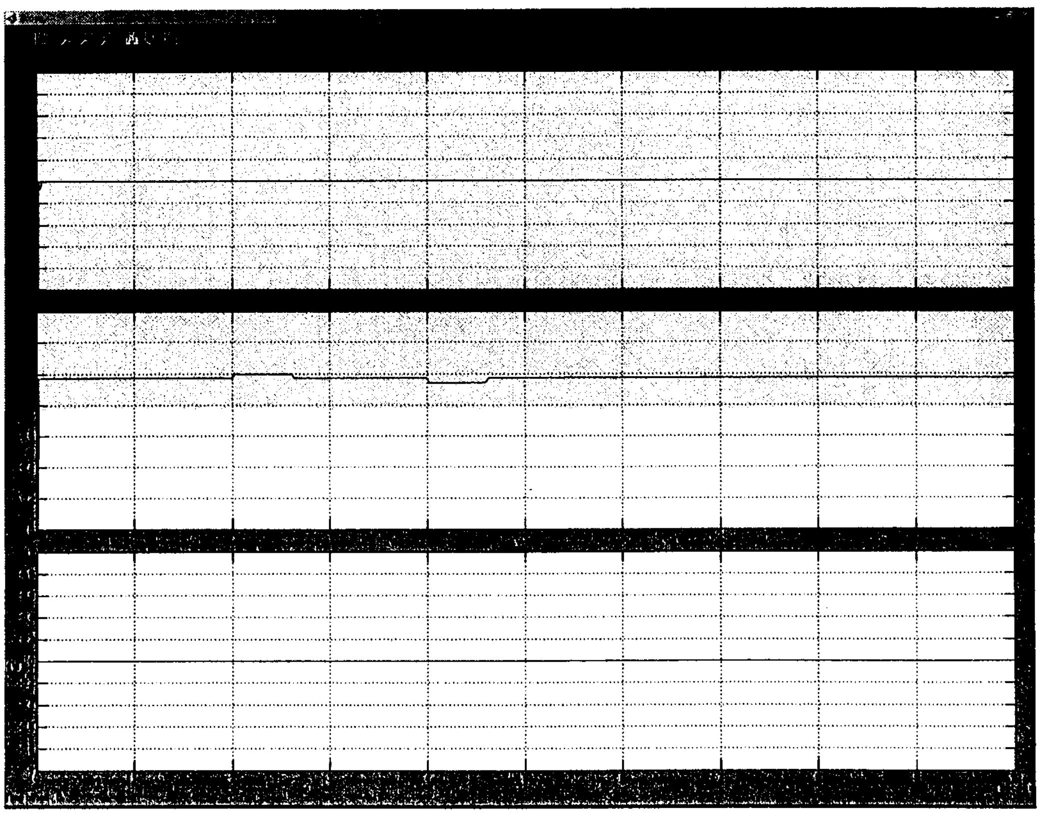


Figure 3.8(a) *Simulation results of the tested system without STATCOM*

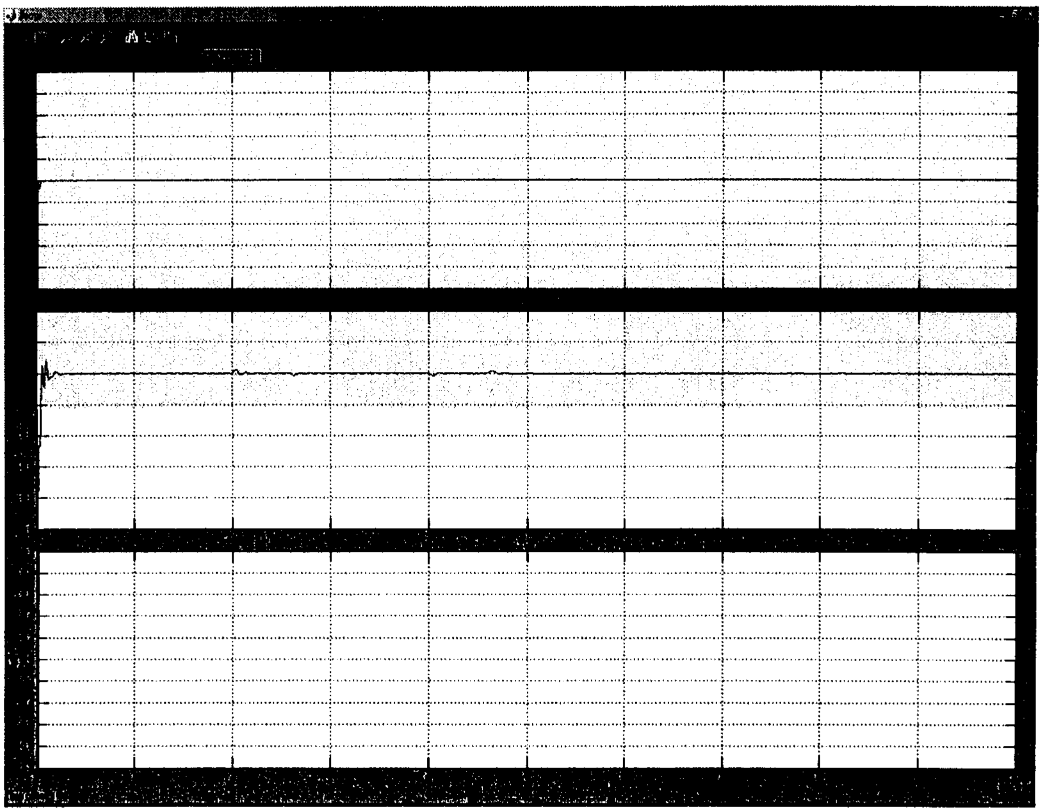


Figure 3.8(b) Simulation results of the tested system with STATCOM

3.5 Summary

This Chapter described the basic design and operating principles of a STATCOM, FACTS device together with the detailed STATCOM control circuit design. A 12-pulse PWM-controlled STATCOM model and a 3-level, 48-pulse inverter STATCOM were successfully modelled and implemented in the SimPowerSystem, MATLAB. Simulation studies, which were based on 500kV representative power systems (rather than a simple single-machine/infinite bus representation), were modelled to study the steady state and dynamic state performance of the STATCOM models which were developed for simulation purposes.

The presented STATCOM detailed models include all of the power electronic based voltage-sourced converter parts and phase-shifting transformer parts. These models will be a very useful toolbox in Matlab for doing power system design and simulation. The designed control systems for the 12-pulse, PWM-controlled STATCOM use typical d-q transformation to obtain D.C. signals for control purposes. The STATCOM operating and control limits are included in the models, which makes the models suitable for both realistic steady state and transient stability studies.

The model includes a detailed representation of the valves and the accompanying snubber circuits. Also, the PWM based STATCOM was modeled in MATLAB using a single 2-level voltage-sourced converter. The presented time-domain simulations in MATLAB verified the successful operation of the designed controller, and demonstrated the successful application of STATCOM controllers.

Chapter 4. Static Synchronous Series Compensator - SSSC

4.1 Introduction

This chapter describes the methods of control to modulate the power flow in a transmission line using Static Synchronous Series Compensator (SSSC). SimPowerSystem. MATLAB simulations, which include detailed representations of 3-phase, 3-level, 12-pulse PWM controlled SSSC and three level, 48-pulse full-wave bridge inverter controlled SSSCs, as well as the respective control circuits were used to evaluate the performance of the FACTS devices.

There is more material in the literature dealing with the STATCOM and UPFC operating principles and their control circuit designs compared with the SSSC operating characteristics, especially for control circuits design. This thesis explains in detail the SSSC operation and control circuit design, which is be beneficial for future FACTS application research.

The developed of the full SSSC models were tested with realistic power system simulations. The detailed models of the SSSC developed in this research are particularly useful in control and protection circuits design, as the models realistically reproduce the controller response in a power system.

4.2 Basic Principles of Active and Reactive Power Flow Control

Active and reactive power in a transmission line depend on the voltage magnitudes and phase angles at the sending and receiving ends as well as the line impedance. The sending and receiving end voltages are assumed to be fixed and can be interpreted as points in large power systems where voltages are "firmed". [1][3]

In the following analysis the series impedance of the line is assumed to be purely inductive. The receiving end is modeled as an infinite bus with a fixed angle of $0°$. [1][2][3]

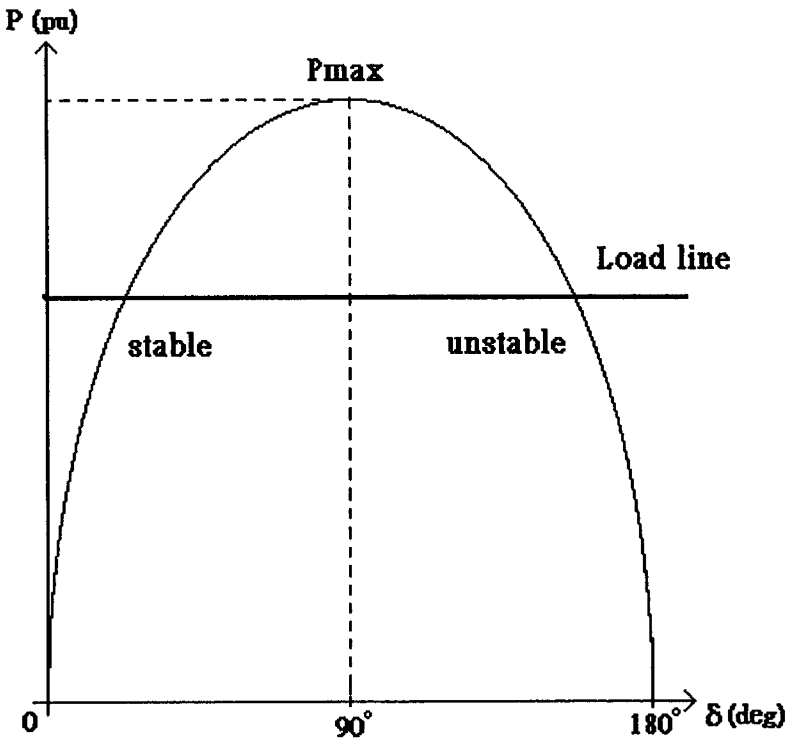


Figure 4.1 Transmitted power P vs transmission angle δ as function of the degree of series capacitive compensation.

Complex, active and reactive power flows in this transmission system are defined, respectively, as follows:

$$S_R = P_R + jQ_R = V_R I^*$$

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

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

Similarly, for the sending end:

$$P_S = \frac{V_S V_R \sin\theta}{X} = P_{\max}\sin\theta$$

$$Q_R = \frac{V_R^{\,2} - V_S V_R \cos\theta}{X}$$

where V_S and V_R are the magnitudes (in RMS values) of sending and receiving end voltages, respectively, while Q is the phase-shift between sending and receiving end voltages.

The sending and receiving active power flows, P_S and P_R, are considered equal since the system is assumed to be lossless. As can be seen in Figure 4.1, the maximum active power transfer occurs, for the given system, at a power or load angle θ equal to $90°$. Maximum power would occur at a different angle if the transmission losses are included. The system is stable depending on whether the derivative $\frac{dP}{d\theta}$ is positive or negative. The steady state limit is reached when the derivative is zero. [1][3]

In practice, a transmission system is never allowed to operate close to its steady state limit, as some margin is required in order for the system to be able to handle disturbances such as load changes, faults, and switching operations. As can be seen in Figure 4.1, the intersection between a load line representing sending end mechanical (turbine) power and the electrical load demand line defines the steady state value of θ; a small increase in mechanical power at the sending end increases the angle. For an angle above $90°$, increased demand results in less power transfer, which causes the generator to and further increases the angle, making the system potentially unstable; on the left side intersection, however, the increased the angel θ increases the electric power to match the increased mechanical power. In determining an appropriate margin for the load angle θ, the concepts of dynamic or small signal stability and transient or large signal stability are often used. By the IEEE definition, dynamic stability is the ability of the power system to maintain synchronism under small disturbance whereas transient stability is the ability of a power system to maintain synchronism when subjected to a severe transient disturbance such as a fault or loss of generation [24]. Typical power transfers correspond to power angles below $30°$; to ensure steady state rotor angle stability, the angles across the transmission system are usually kept below $45°$ [25].

Closer inspection of equation (1.2) and (1.4) shows that the real or active power transfer depends mainly on the power angle; inspection of equations (1.3) and (1.5) shows that the reactive power requirements of the sending and receiving ends are excessive at high angles and high power transfers. It is also possible to conclude that reactive power transfer depends mainly on voltage magnitudes, with flows from the highest voltage to the lowest voltage, while the direction of active power flows depends on the sign of the power angle.

Equations (1.2) to (1.5) show that the power flow in the transmission line depends on the transmission line reactance, the magnitudes of sending and receiving end voltages and the phase angle between the voltages. FACTS controllers must be able to control these parameters in real-time and, thus, vary the transmitted power according to system conditions. The ability to control power rapidly, within appropriately defined boundaries, can increase transient and dynamic stability, as well as the damping of the system. For example, an increase or decrease of the value of transmission line reactance X, as can be seen from equations (1.2) and (1.4), increases or decreases the value of maximum power transfer P_{max}. For a given power flow, a change of X also changes the angle between the two ends. Regulating the magnitudes of sending and receiving ends voltages, V_S and V_R, respectively, can also control power flow in a transmission line. However, these values are subject to tight control due to load requirements that limit the voltage variations to a range between 0.95 and 1.05 p.u., and hence cannot influence the power flows in a desired range. From the equations of reactive power flow, (1.3) and (1.5), it can conclude that the regulation of voltage magnitude has much more influence over the reactive power flow than the active power flow.

Of the FACTS controllers of interest here, the STATCOM has the ability to increase/decrease the terminal voltage magnitude and, consequently, to increase/decrease power flows in the transmission line. The SSSC controls power flow by changing the effective series reactance of the line, whereas the UPFC can control all these parameters simultaneously, i.e., the terminal voltage magnitude, the reactance of the transmission line and the phase angle between the sending and receiving end voltages.

It was shown that FACTS controllers can be used to control steady state active and reactive power flow, but it should also noted that these fast controllers could have pronounced, positive impact on transient and dynamic conditions in a power system if designed properly. By appropriately using these FACTS controllers, it is possible to, for example, increase damping in power system. In [26], damping of power oscillations, caused by a nearby fault, is achieved by using feedback control to efficiently modulate active power flow on the transmission line through a UPFC. It is documented fact that the core of voltage instability is lack of reactive power support in a power system [25]; the STATCOM has the ability to control reactive power absorption/generation, and since its time response is very fast, sometimes even less than one cycle, it can be used to effectively prevent this problem.

4.3 Basic Operating Principles

The SSSC controller consists of a solid-state VSC with GTO thyristor switches, or any other semiconductor switches with basic turn-off capability valves, DC capacitor, a series transformer and main controller. Several VSCs can be connected together through transformers to form a complex and custom made design configuration. The number of valves and the various configurations of the transformer depend on the designed A.C. waveforms generated by the SSSC. On the other hand, the A.C. output waveforms of PWM-controlled SSSC controllers depend on the switching frequency. [1][2][3]

The secondary end of the series transformer winding is connected in series with a transmission line, thus allowing series compensation and voltage injection to the line. The SSSC is used to generate a virtual capacitance or inductance in series with the transmission line, and hence can be utilized as a transmission line power flow controller. Basically, it generates in its output terminals a quasi-sinusoidal voltage of variable magnitude in quadrature with the transmission line current, if the SSSC loses are neglected. As a result, the series injected voltage emulates a virtual capacitive or inductive reactance in series with a transmission line, which can be used to increase or decrease the effective transmission line reactance, resulting in a decrease or increase of the power flow in the transmission line.

In general, the SSSC can be considered as an ideal synchronous voltage source as it can produce a set of three-phase A.C. voltages at the desired fundamental frequency of variable and controllable amplitude and phase angle. SSSC can generate or absorb reactive power from a power system and can generate or absorb real power, independently from the reactive power, if an energy storage device instead of the D.C. capacitor is used in the SSSC.

The SSSC is typically restricted to only reactive power exchange with the nearby A.C. system, neglecting the small amount of real power used to cover the circuit and switching losses, because of the relatively small SSSC capacitor. If the D.C. capacitor were replaced with an energy storage system, the controller would be able to exchange real power with the A.C. system and compensate for the transmission line resistance. Alternatively, a STATCOM could send real power to the SSSC trough a common D.C. capacitor. The combined controller formed by this connection is called a Unified Power Flow Controller (UPFC), as explained in more detail in Chapter 5.

Figure 4.2 shows a simplified model of SSSC where the dc capacitor has been replaced by an energy storage device such as a high energy battery installation to allow active as well as reactive power exchanges with the A.C. System. The SSSC's output voltage magnitude and phase angle can be varied in a controlled manner to influence power flows through transmission line. The phase difference of the injected voltage V_{pq}, with respect to the transmission line current I_{line}, determines the exchange of real and reactive power with the A.C. system.

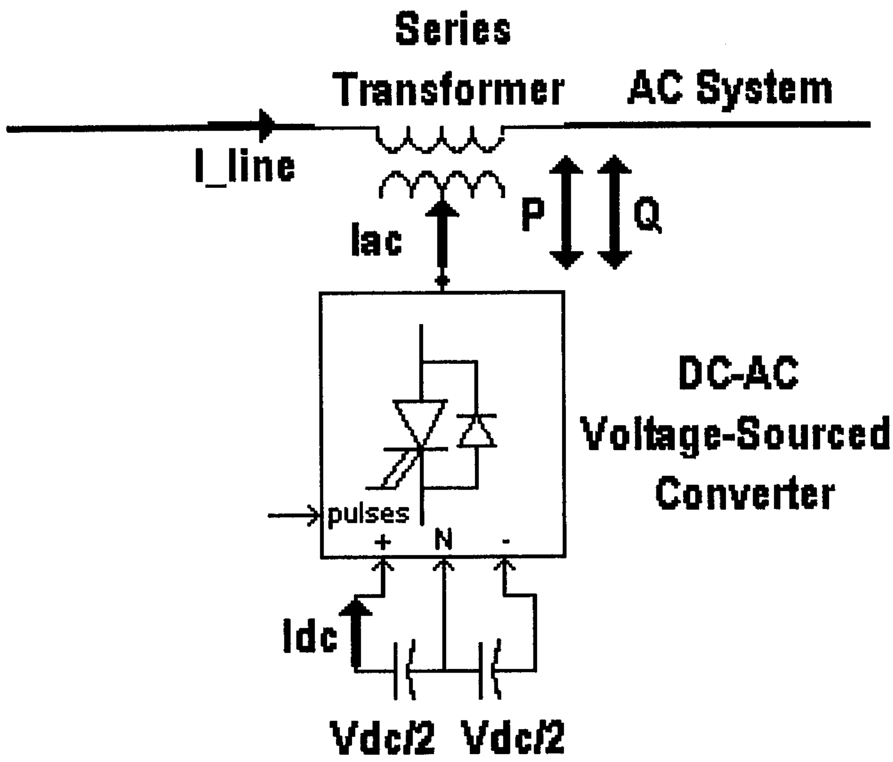


Figure 4.2 Simplified model of SSSC

Figure 4.3 shows the SSSC operation in four quadrants, again assuming an energy storage device connected at the SSSC's input terminals. The line current phasor I_{line} is used as a reference phasor while the injected SSSC voltage phasor is allowed to rotate around the centre of the circle defined by the maximum inserted voltage V_{pq}^{max}. Theoretically, SSSC operation in each of the four quadrants is possible, but there are some limitations to injected SSSC voltage due to operating constraints of practical power system.[1][2][3]

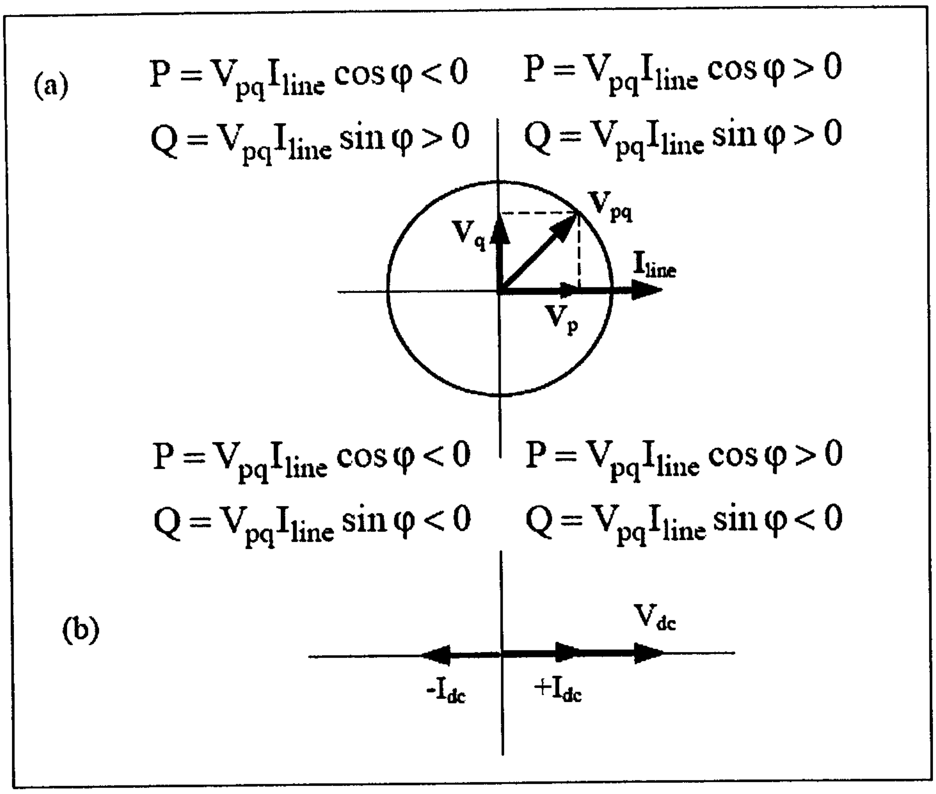


Figure 4.3 SSSC phasor diagram

In the capacitive mode, the injected SSSC voltage lags the transmission current by 90^0. In this case, the SSSC operation is similar to the operation of a series capacitor with variable capacitance kX_c, i.e., $V_{pq} = -jkX_cI_{line}$, where k is a variable. By this action, the effective transmission line reactance is reduced while the voltage across the impedance is increased, leading to an increase in the line current and transmitted power. This action is illustrated in Figure 4.3.

It is also possible to reverse the injected SSSC voltage by 180^0, i.e., $-V_{pq} = jkX_cI_{line}$, causing an increase in the transmission line reactance, which results in a decrease of the line current and transmitted power. In Figure 4.3, it is assumed that the SSSC losses are zero and, therefore, the series injected voltage is in perfect quadrature with the line current, leading or lagging.

The operating conditions that limit the SSSC operation from the power system point of view are also described in Figure 4.4. The SSSC can increase as well as decrease the power flow in the transmission line by simply reversing the operation from capacitive to inductive mode. In the inductive mode, the series injected voltage is in phase with the voltage drop developed across the line reactance; thus, the series compensation has the same effect as increasing the reactance. If the series inserted voltage magnitude is larger than voltage drop across the uncompensated line, i.e., $V_{pq} \geq V_{line}$, the power flow will reverse. This fact can limit the SSSC operation to values of $V_{pq} \leq V_{line}$, as in practice, it would be unlikely to use the SSSC for power reversal. Also, if the rating of the SSSC controller is high, it is possible to increase or decrease the receiving end voltage above or below the typical operating voltage range of 0.95p.u. – 1.05 p.u., but with possible negative consequences for other system devices.

The SSSC output current corresponds to the transmission line current, which is affected by power system impedance, loading and voltage profile, as well as by the actions of the SSSC. Thus, the relationship between the SSSC and the line current is complex. The fundamental component of the SSSC output voltage magnitude is, on the other hand, directly related to the D.C. voltage that is either constant or kept within certain limits, depending on the chosen design and control of the SSSC.

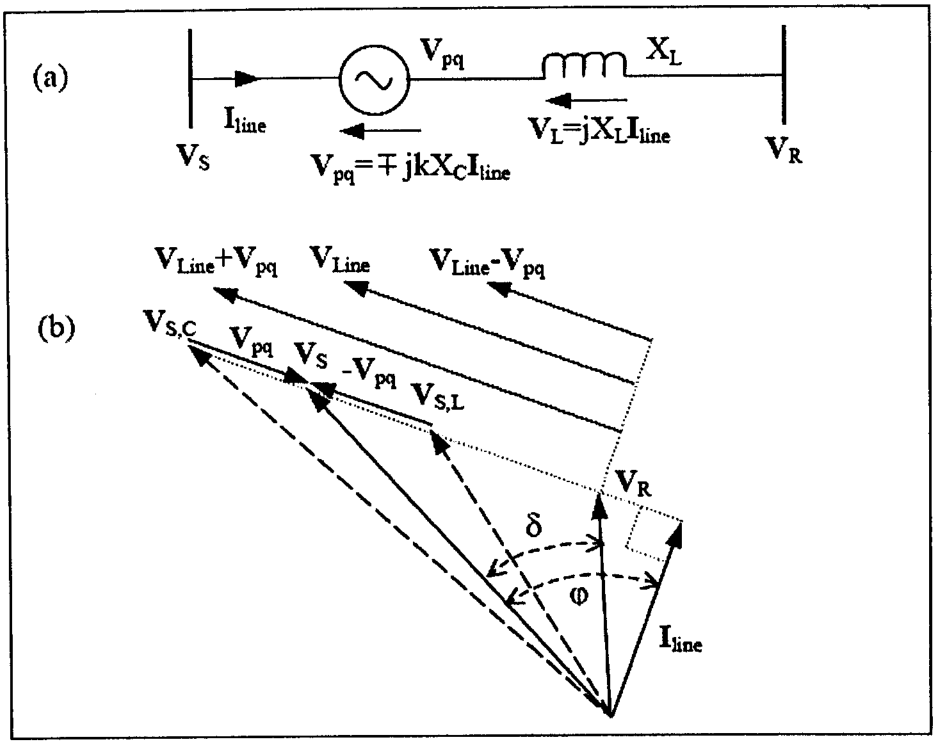


Figure 4.4 Series Compensation by a SSSC

The SSSC output voltage phase angle is correlated to the line current phase angle by plus or minus few degrees for example, to account for changes in the D.C. voltage. It has to be noted that the injected SSSC voltage V_{pq} is different from the SSSC output voltage V_{sssc}, due to the voltage drop or rise across the series transformer reactance, i.e.:

$$V_{pq} = V_{SSSC} \mp X_{tr} I_{line} \quad (4.1)$$

where the negative sign corresponds to capacitive operation, while the positive sign corresponds to inductive operation of the SSSC and X_{tr} stands for the series transformer reactance. This voltage difference between the injected and output SSSC voltage can be small in the case of transmission line currents, but it can be significant in high loading conditions.

The active and reactive power exchanged between the SSSC and the transmission line can be calculated as follows:

$$P_{pq} = V_{pq} I_{line} \cos\phi \quad (4.2)$$

$$Q_{pq} = V_{pq} I_{line} \sin\phi \quad (4.3)$$

where Q represents the angle between the injected SSSC voltage and transmission line current.

Inspection of the equation (4.2) and (4.3), considering that the angle between the SSSC output voltage and line current is approximately 90^0, shows that the SSSC real power should be small compared to the reactive power. This is expected, since the real power going into the SSSC is used only to cover for the losses and charging of the D.C. capacitor, i.e.,

$$P_{pq} = P_{dc} + P_{loss} \quad (4.4)$$

The losses in the SSSC circuit are due to the transformer windings and especially due to the switching of the GTO valves.

4.4 SSSC Control Systems

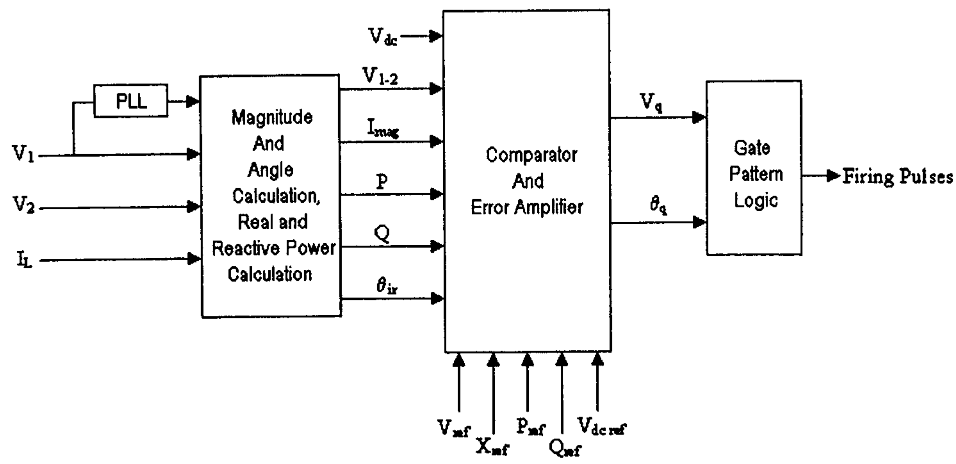


Fig. 4.5 Simplified control block diagram of the SSSC

Figure 4.5 shows the simplified control block diagram of the SSSC. An instantaneous 3-phase set of line voltages, V_1, at the transmission line is used to calculate the reference angle, θ, which is phase-locked to the red phase of the line voltage, V_{1R}. An instantaneous 3-phase set of line currents, I, is measured and the amplitude and the relative angle, θ_{ir}, of the line current with respect to the phase-locked-loop angle , θ are calculated by using Park's Transformation. [1][2][3]

In the Constant Impedance Emulation Mode, the calculated magnitude of the line current, I_{mag}, is multiplied by the compensating reactance reference, X_{ref}, and the result is the injection voltage magnitude, V^*_{ref}. The phase angle of the line current, θ_i, is then added to the phase angle of the line voltage, θ_v, and the result, θ_{ir}, is used to calculate θ_q. The phase angle, θ_q, of the injected voltage is either θ_{ir} + 90 if the required compensating reactance is inductive or θ_{ir} - 90 if the required compensating reactance is capacitive. The compensating reactance demand, X_{ref}, is either negative if the SSSC is emulating an inductive reactance or positive if it is emulating a capacitive reactance.

In Constant Voltage Injection Mode, the insertion voltage amplitude demand, V_{ref}, may be specified and the SSSC will inject the desired voltage almost in quadrature with the line current.

In Constant Power Control Mode, the calculated instantaneous power P is compared to the active power reference, P_{ref}, so as to control the injected voltage magnitude and phase angle. [1][2][3]

4.5 Demonstration of Application of SSSC

This simulation illustrates the use of the SSSC controller for constant power control. The circuit diagram of the simulation is shown in Figure 4.6.

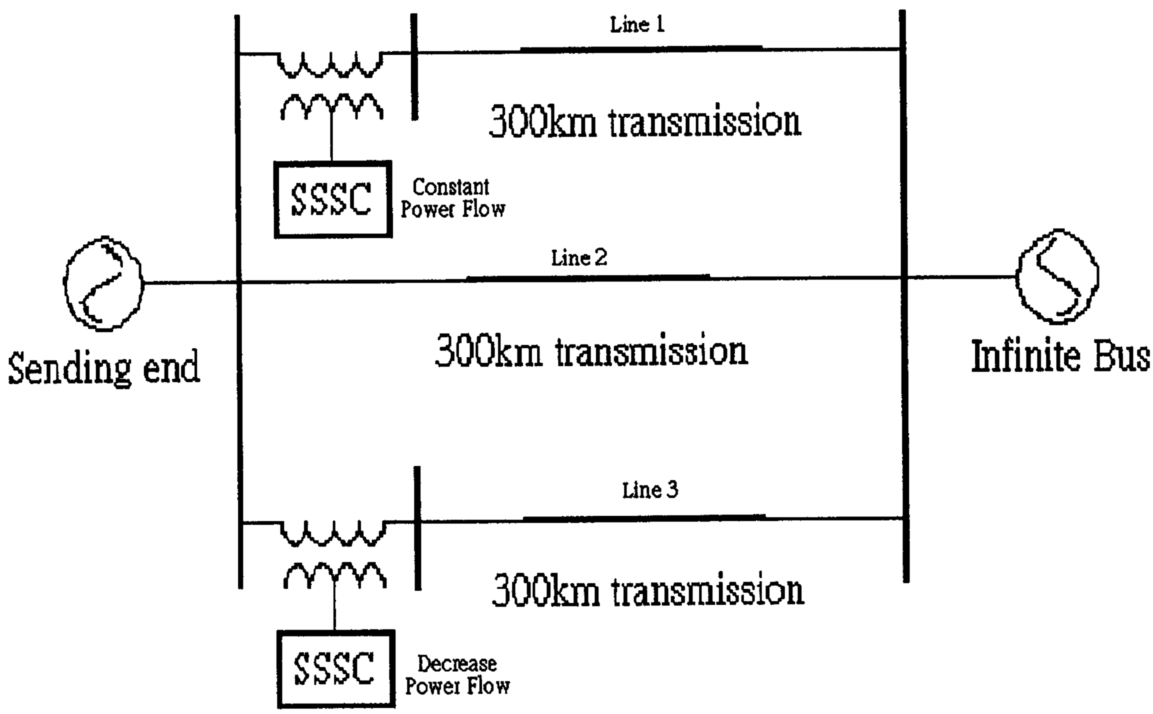


Figure 4.6 Circuit diagram of a three line system with 2 SSSC to control power flow

4.6 Results of the simulation

Figure 4.7 Results of the simulation

The results representing the control of the active power flow and prevention of loop flow on the transmission lines by using the SSSC-P_{ref} are shown on figure 4.7. From the results, we can see that the power flow on the transmission line 3 by applying SSSC-P_{ref} decreased from 3.72 pu to 3.5 pu. Line 3 keeps transmitting the desired active power to the receiving end after the SSSC-p_{ref} operated. Theoretically, the drop of power flow on line 3 will increase the power flow through line 1 and line 2. In this case, the power flow on line 1 is not affected since there is another SSSC on line 1 which is able to maintain constant power flow through the line. Therefore, only the power flow on line 2 is increased. From the results, we can see that the new control method developed by using the power flow as the reference is able to maintain constant power flow and prevent loop flow.

4.7 Relationship between the line current and the compensated voltage

The feasibility of controlling power flow by SSSC is shown by the results obtained from the POWER SYSTEM BLOCKSET in MATLAB simulation, as depicted in figure 4.8. The relationship between the line current and the compensated voltage as well as the active and reactive power flow on the line are show in figure 4.8. In the figure, we can see that the active power flow goes up during the capacitive compensation and goes down during inductive compensation. We can also see that the line current is leading the compensated voltage by 90 ° during capacitive compensation while it is lagging the compensated voltage by 90 ° during inductive compensation.

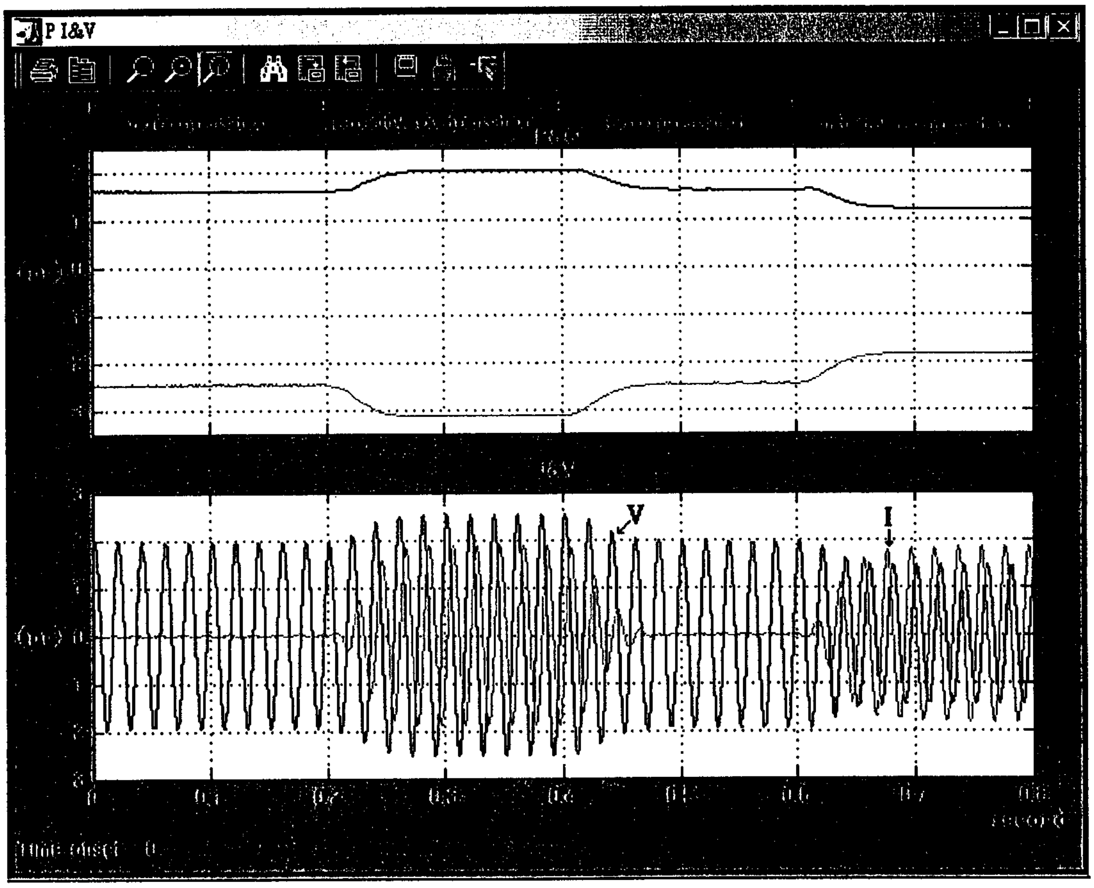


Figure 4.8 the relationship between line current and compensated voltage, the active and reactive power flow

4.8 Summary

This chapter described in detail the SSSC operating principles and control circuit design. The methods of control and modulation of power flow in a transmission line using Static Synchronous Series Compensator (SSSC) were also discussed. SimPowerSystem, MATLAB simulations were developed, which included detailed control system representation, as well as representations of 3-phase, 3-level, 12-pulse PWM controlled SSSC and 3- level, 48-pulse full-wave bridge inverter controlled SSSCs. Control strategies for both PWM controlled SSSC and 3-phase, 3-level

48-pulse full-wave bridge inverter controlled SSSC made use of typical d-q transformations.

The SSSC models will be a very useful toolbox in MATLAB for doing power system design and simulation. The SSSC operating and control limits are included in the models, which make the SSSC models suitable for both steady state and transient stability studies with practical constraints.

The SSSC models were tested with representative power system simulations. Finally, the steady state operating performances of the SSSC of power flow control in individual transmission line were demonstrated with simple power system simulations.

Chapter 5. Unified Power Flow Controller – UPFC

5.1 Introduction

In this chapter the potential applications of the multi-functional FACTS device *Unified Power Flow Controller*, which is based on the back-to-back voltage-sourced converter arrangement, is presented. The basic design, operating principles and control blocks of the UPFC are explained together with the SimPowerSystem detailed model of the controller. Representative power system simulations are used to demonstrate the UPFC operation in practical system conditions. Different control schemes for the shunt and series converters are implemented in the SimPowerSystem and tested in the detailed UPFC model. The results obtained for representative power system are used to compare the different control strategies.

5.2 Basic Operating Principle of UPFC

A Unified Power Flow Controller can be considered as a synchronous voltage source which can be applied to exchange both real and reactive power with the transmission system. The UPFC can be represented at the fundamental frequency (50 Hz or 60 Hz) by a voltage phasor V_{pq} with controllable magnitude V_{pq} ($0 \le V_{pq} \le V_{pq\_max}$) and angle ρ ($0 \le \rho \le 2\pi$), in series with the transmission line, as shown in Figure 5.1. [1][2][4]

Figure 5.1 shows a UPFC comprising two back-to-back voltage sourced converters. These back-to-back converters, labeled "VSC-1" and "VSC-2" in the figure, are operated by a common D.C. source comprising a capacitor. The basic function of the VSC-1 is to supply or absorb the real power demanded by VSC-2 at the common D.C. terminal to support the real power exchange resulting from the series voltage injection. The DC power demand of VSC-2 is converted back to A.C. by VSC-1 and coupled to the transmission line bus via the shunt-connected transformer.

Figure 5.1 shows that if the series VSC controller is disconnected, the shunt connected VSC controller comprised of a D.C. capacitor, VSC-1 and the shunt connected transformer can be operated as a STATCOM device. As the STATCOM can used to generate or absorb reactive power, the STATCOM output current is in quadrature with the terminal voltage.

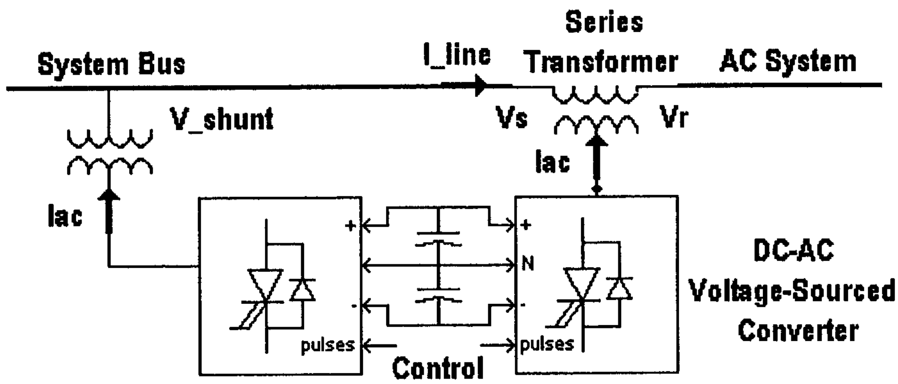


Figure 5.1 Simplified model of UPFC

If the shunt connected VSC is disconnected, the series connected VSC comprised of a D.C. capacitor, VSC-2 and the series connected transformer can be operated as an SSSC. The SSSC can be used to injected a compensating voltage in series to the transmission line through the series transformer; the current flowing through the VSC is the transmission line current, and the series injected voltage can create a virtual impedance in series with the transmission line.

The injected voltage V_{SR} is in quadrature with the transmission line current I_{line} with the magnitude being controlled independently of the line current. Hence, the shunt and series connected VSC controllers of the UPFC can be used to generate or absorb reactive power independently of each other.

If the two VSCs are operating at the same time, the shunt and series connected controllers of the UPFC can basically function as ideal A.C. to A.C. converters in which real power can flow either direction through the D.C. link and between the A.C. terminals of the two converters. The real power can be transferred from VSC-1 to VCS-2 and vice versa, and hence it is possible to introduce positive or negative phase shifts between voltages V_S and V_R. The series injected voltage V_{SR} can have any phase shift with respect to the terminal voltage V_S. Therefore, the operating area of the UPFC becomes a circle with a radius defined by the maximum magnitude of V_{SR}, i.e., $V_{SR\text{-}max}$.

VSC-2 is used to generate the voltage V_{SR} at fundamental frequency, with variable magnitude $0 \le V_{SR} \le V_{SR,\max}$ and phase shift $0 \le \beta \le 2\pi$. The harmonic content in the voltage V_{SR} depends on the design and control of the VSC. This voltage is added in the series to the transmission line and directly to the terminal voltage V_S by the series connected coupling transformer. The transmission line current passes through the series transformer, and in the process exchanges real and reactive power with the VSC-2. This implies that the VSC-2 has to be able to deliver and absorb both real and reactive power.

The shunt-connected branch associated with VSC-1 is used primarily to provide the real power demanded by VSC-2 through the common D.C. link terminal. Also, since VSC-1 can generate or absorb reactive power independently of the real power; it can be used to regulate the terminal voltage V_S such that VSC-1 regulates the voltage at the input terminals of the UPFC.

Another important role of the shunt UPFC branch is a direct regulation of the D.C. capacitor voltage, and consequently an indirect regulation of the real power required by the series UPFC branch. The amount of real power required by the series converter plus the circuit losses have to be supplied by the shunt converter. Real power flow from the series converter to the shunt converter is possible and in some cases desired. In this case, the series converter would supply the required real power plus the losses to the shunt converter.

The amount of the real and reactive power that can be exchanged with the power system and the UPFC is basically the sum of the shunt and series converter ratings.

The power rating of a converter is derived by the product of the maximum continuous operating voltage and maximum continuous operating current. For VSCs, the maximum continuous operating current is determined by the maximum current turn-off capability of the semiconductor switch. The series converter maximum voltage is determined based on the functions that the UPFC is designed to perform. The functions could be control the power flow control in the transmission line or damping of power oscillations. The maximum current is usually taken to be the thermal line current limit, which basically implies that the converter switches have to be designed to withstand that level of current to be compatible with the line.

The shunt converter is installed to supply real power to the series converter and to perform the bus voltage control. The lowest continuous shunt converter rating is determined by the maximum real power exchanged between the series and the A.C. system, which is typically 20 to 50% of the total power rating of the series converter [27]. The maximum continuous rating should take into account the amount of reactive power needed for voltage control at the point of connection with the A.C. system.

5.3 Basic Operating Modes for the UPFC

5.3.1 Shunt Inverter

The shunt inverter is operated in such a way as to draw a controlled current from the line. One component of this current is automatically determined by the requirement to balance the real power of the series inverter. The remaining current component is reactive and can be set to any desired reference level (inductive or capacitive) within the capability of the inverter. The reactive compensation control modes of the shunt inverter are very similar to those commonly employed on conventional static VAR compensators. [1][2][4][26][27]

VAR Control Mode – In VAR control mode, the reference input is an inductive or capacitive VAR request. The shunt inverter control translates the VAR reference into a corresponding shunt current request and adjusts the gating of the inverter to establish the desired current. The control uses current feedback signals obtained form current transformers (CTs) typically located on the bushings of the shunt coupling transformer. A feedback signal representing the dc bus voltage, Vdc, is also required.

Automatic Voltage Control Mode – In voltage control mode, the shunt inverter reactive current is automatically regulated to maintain the transmission line voltage at the point of connection to a reference value, with a defined droop characteristic. The droop factor defines the per unit voltage error per unit of inverter reactive current within the current range of the inverter. The automatic voltage control uses voltage feedback signals obtained from accurate voltage transformers (VTs) measuring the voltage, V_1, at the substation bus feeding the shunt coupling transformer.

5.3.2 Series Inverter

The series inverter controls the magnitude and angle of the voltage injected in series with the line. This voltage injection is always intended to influence the flow of power on the line, but the actual value of the injected voltage can be determined in several different ways. These include:

Direct Voltage Injection Mode – the series invert simply generates a voltage vector with magnitude and phase angle requested by reference input. A special case of direct voltage injection is when the injected voltage is kept in quadrature with the line current to provide purely reactive series compensation.

Phase Angle Shifter Emulation Mode – the series inverter injects the appropriate voltage so that the voltage, V2, is phase shifted relative to the voltage V1 by an angle specified by reference input.

Line Impedance Emulation Mode – the series injected voltage is controlled in proportion to the line current so that the series insertion transformer appears as an impedance when viewed from the line. The desired impedance is specified by reference input and in general it may be complex impedance with resistive and reactive components of either polarity. Naturally care must be taken in this mode to avoid values of negative resistance or capacitive reactance that would cause resonance or instability.

Automatic Power flow Control Mode – the UPFC has the unique capability of independently controlling both the real power flow, P, on a transmission line and the reactive power, Q, at a specified point. This capability can be appreciated by interpreting the series injected voltage, Vinj, as a controllable two dimensional vector quantity. This injected voltage vector can be chosen appropriately to force any desired current vector (within limits) to flow on the line, hence establishing a corresponding power flow. In automatic power flow control mode, the series injected voltage is determined automatically and continuously by a vector control system to ensure that the desired P and Q are maintained despite system changes. The transmission line containing the UPFC thus appears to the rest of the power system as a high impedance power source or sink. This is an extremely powerful mode of operation that has not previously been achievable with conventional line compensating equipment. It has far reaching possibilities in regard to power flow scheduling. Automatic power flow control can also be used dynamically for power oscillation damping as discussed in a later section. [1][2][4][26][27]

In each of the control modes for the series inverter, the feedback signals representing, V1 are used, together with additional feedback signals from meters measuring V2 on the line side of the series insertion transformer. The control system also makes use, as needed, of transmission line current feedback signals typically obtained from current transformers located on the primary bushings of the series insertion transformer.

5.4 UPFC Control

Although the UPFC has many possible operating modes, it is anticipated that the shunt inverter will generally be operated in automatic voltage control mode and the series inverter will typically be in automatic power flow control mode. Accordingly, block diagrams are shown in Figure 5.3 and Figure 5.4, giving greater detail of the control schemes for each inverter operating in these modes. It must be noted that these control schemes are typical but that they may vary in detail from one installation to another. Also, for clarity, only the most significant features are shown and less important signal processing and limiting has been omitted. The control schemes assume that both the series and shunt inverters generate output voltage with controllable magnitude and angle, and that the dc bus voltage will be held substantially constant. This may not always be the case, as discussed in the next section. [1][2][4][26][27]

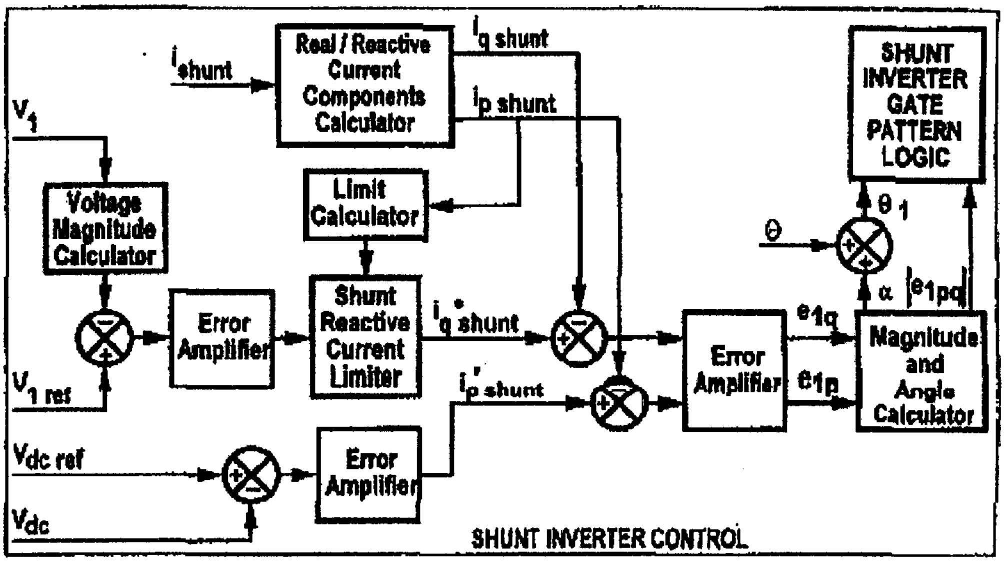


Fig 5.3 *Block diagram of shunt Inverter Control*

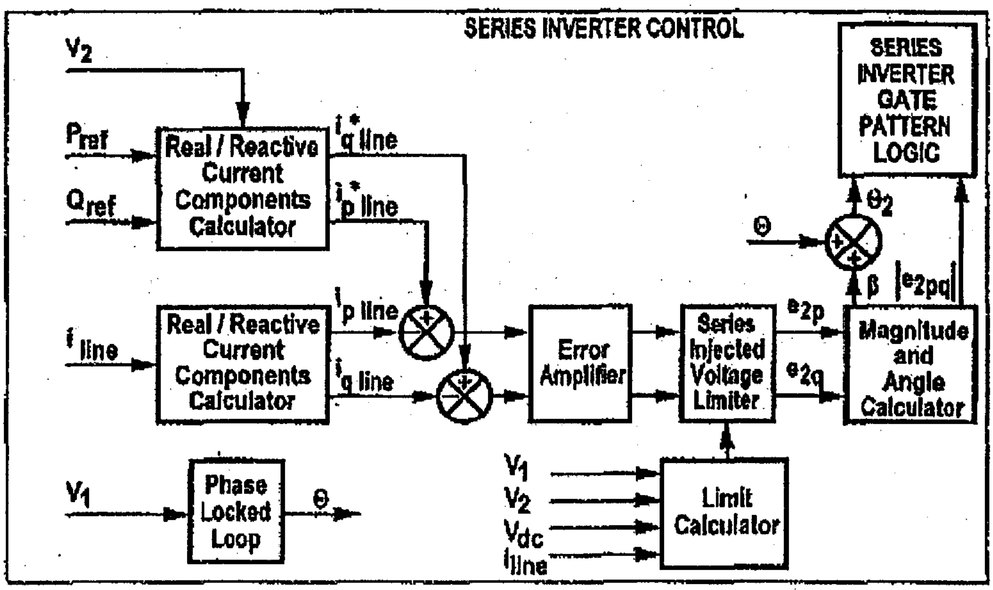


Fig 5.4 *Block diagram of series Inverter Control*

The automatic power flow control for the series inverter is achieved by means of a vector control scheme that regulates the transmission line current, using a synchronous reference frame in which the control quantities appears as dc signals in the steady state. The appropriate reactive and real current components are determined for a desired P_{ref} and Q_{ref}, Compared with the measured line currents, and used to drive the magnitude and angle of the series inverter voltage. Note the series injected voltage limiter in the forwards path of this controller that takes account of practical limits n series voltage, as discussed in the following session.

A Vector control scheme is also used for the shunt inverter. In this case the controlled current is the current delivered to the line by the shunt inverter. In this case, however, the real and reactive components of the shunt current have a different significance. The reference for the reactive current, $I_{q\,shunt}$, is generated by an outer voltage control loop, responsible for regulating the ac bus voltage, and the reference for the real-power bearing current, $I_{p\,shunt}$, is generated by a second voltage control loop that regulates the dc bus voltage. In particular, the real power negotiated by the shunt inverter is regulated to balance the dc power from the series inverter and maintain a desired bus voltage. The dc voltage reference, $V_{dc\,ref}$, may be kept substantially constant. For the shunt inverter the most important limit is the limit on shunt reactive current as a function of the real power being passed through the dc bus. This prevents the shunt inverter current reference from exceeding its maximum rated value. [1][2][4][26][27]

5.5 Steady State Simulations:

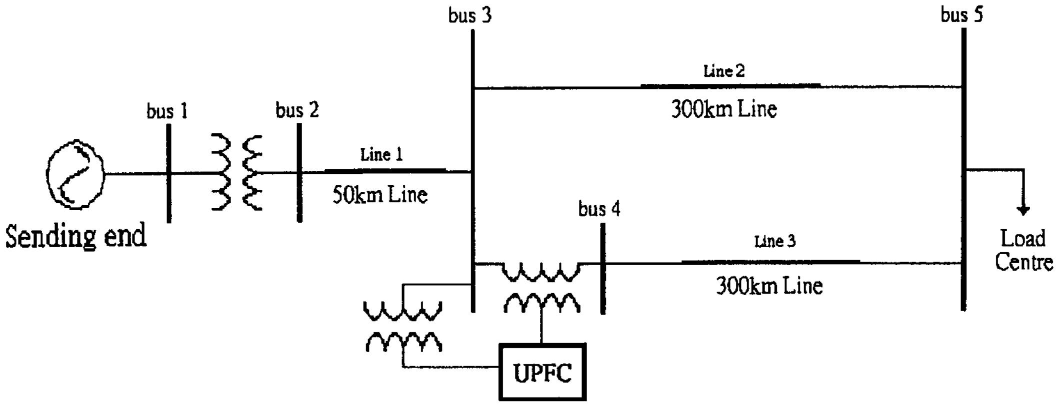


Figure 5.5 Representative network with UPFC installed

The static performances of the UPFC were evaluated by using the above representative power system shown in Figure 5.5. The diagram shown a simple power system network with UPFC installed between bus 3 and bus 4. The system consisted of a 20kV, 1000MW equivalents generator model, a 20kV/500kV transformer and three 500kV transmission lines. The equivalent system was connected to a load centre of 1000MW which is located at bus 1. A 100MW and 100MVar UPFC is installed at bus 3 in order to regulate the bus voltage and control the active and reactive power on the bus of the 500kV network. At t = 2s, the UPFC operated as limited the power flow through the transmission line 3 from 505MW to 450MW. At t = 4s, the UPFC operate again and controlled the flow through the transmission line 3 from 450MW to 560 MW.

5.6 Simulation Results:

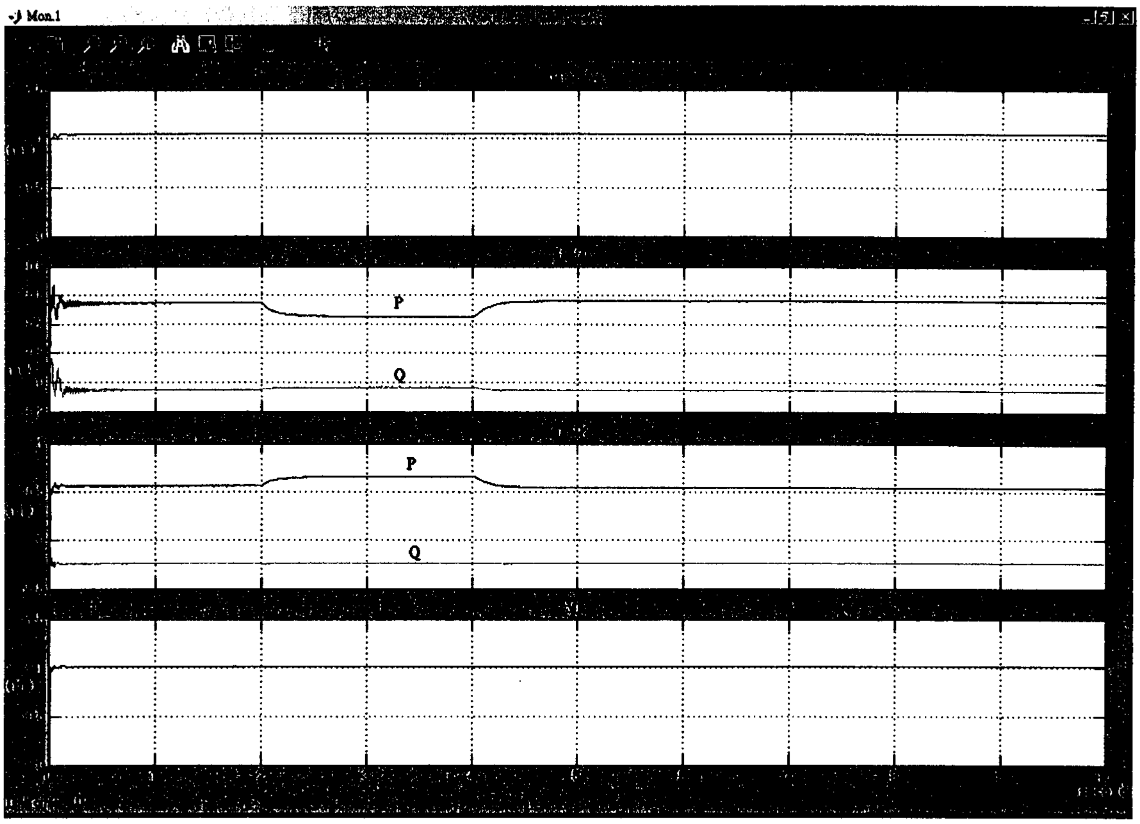


Figure 5.6 Voltage profile and the active and reactive power flow through line 2 and 3

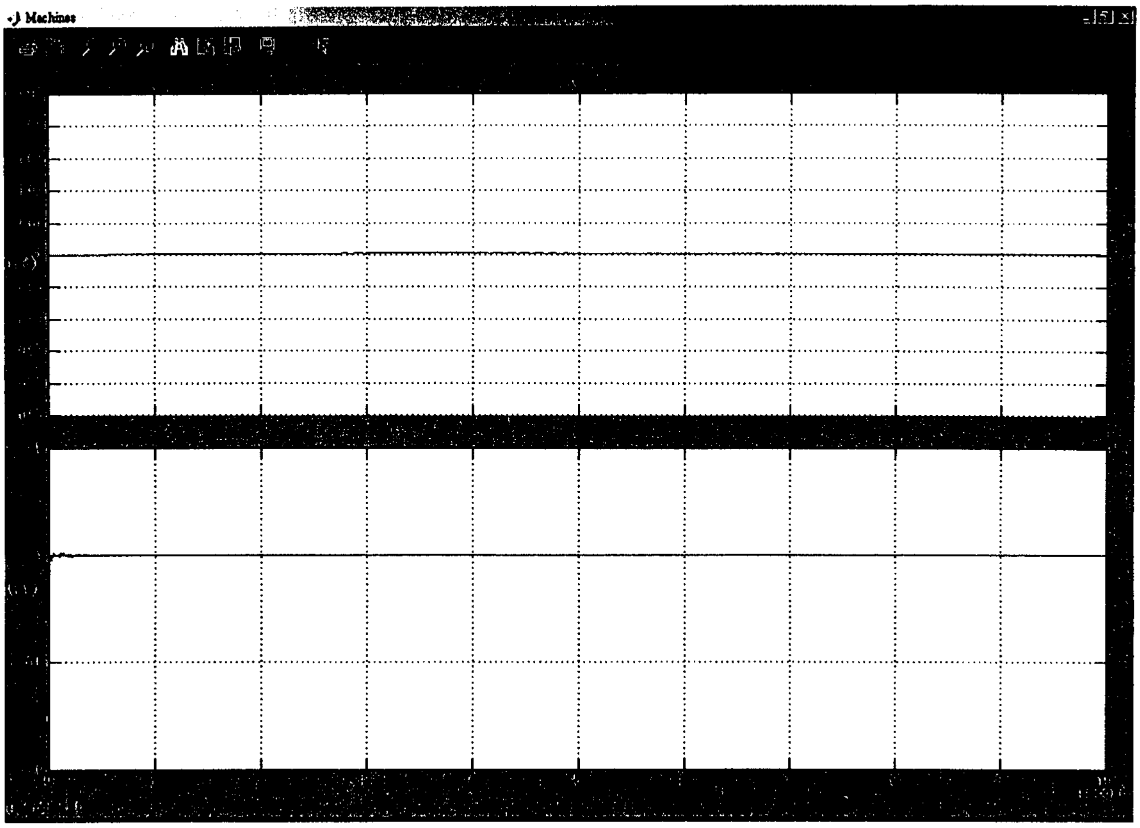


Figure 5.7 The angular frequency and the output voltage of the generator (source)

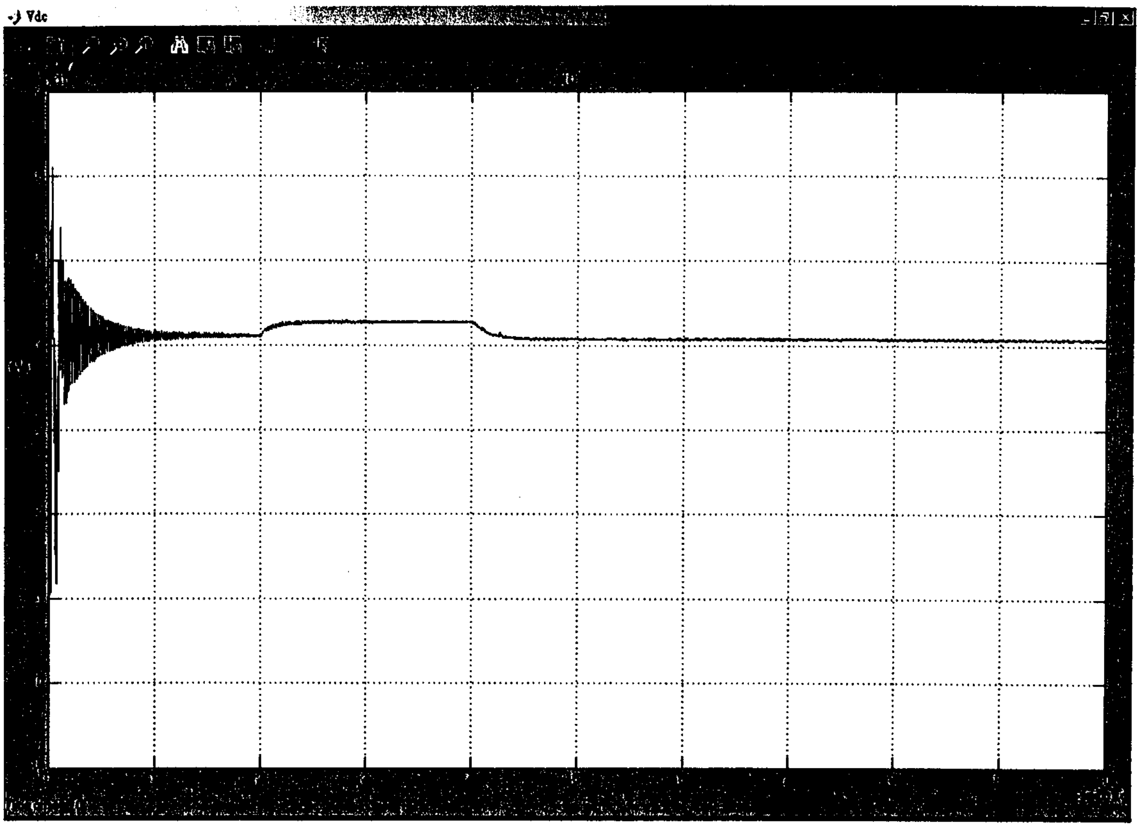


Figure 5.9 The capacitor bank voltage (V_{dc}) of the inverters

The results of the simulation using UPFC to control active and reactive power flow on the transmission lines as well as controlling the bus voltage are shown in Figure 5.6 -5.8. Figure 5.6 shows the voltage profile and the active and reactive power flow through the Line 2 and 3 with the power flow control regulated by the UPFC on the representative network. The steady state simulation mainly comprises three different states which are listed in the following table:

Time (s)	Line 2	Line 3
0-2	560MW, -24MVAR	505MW, -55MVAR
2-4	658MW, -23.8MVAR	450MW, -35MVAR
4-6	546MW, -24MVARR	560MW, -56MVAR

Table 5.1 Steady state simulation states

From the results shown in Figure 5.6-5.9, we can see that active and reactive power flow of the Line 3 were successfully controlled by applying UPFC controller. The sending end voltage, receiving end voltage as well as the generation side were not affected as the UPFC is operating.

5.7 Summary

This Chapter presents the fundamentals of a UPFC, explaining in detail the operating principles and limits as well as practical ratings of the equipment. Also, for the purpose of demonstrating the power flow control capabilities of the UPFC, the basic relationships and differences between a UPFC compensated and an uncompensated transmission line were discussed.

An MATLAB implementation of the UPFC was explained, together with a detailed description of the various control schemes. Since independent control of real and reactive powers within the equipment limits is possible, the UPFC control objectives and schemes can vary significantly, thus, some of the most significant control schemes and objectives were described in detail here.

The results of time-domain simulations in the Matlab demonstrated the adequacy of proposed control schemes, given the fast proper response of the series converter.

Chapter 6: Transient Stability Study of Power Systems with FACTS Controllers

6.1 Introduction

Transient stability is the ability of the power system to maintain synchronism when subjected to a severe transient disturbance such as fault on transmission facilities, loss of generation, or sudden change of a large load. The resulting system response involves large excursions of generator rotor angles, power flows, bus voltages and is influenced by the nonlinear power-angle relationship. Stability of the power system depends on both the initial operating state of the system and the severity of the disturbance.

In this chapter, the application of the STATCOM, SSSC and UPFC towards improving the transient stability of power systems is presented. The FACTS devices were simulated in SimPowerSystem, MATLAB and the dynamic performances of the STATCOM, SSSC and UPFC were compared using representative power system simulations.

6.2 Operating principle of FACTS to enhance the transient stability

Different FACTS devices affect transient stability in different ways. The basic operating characteristic of the SSSC, for example, is to control the active power flow by changing the effective reactance, line current and the phase angle between the sending end and the receiving end.

The active and reactive power flow of a transmission line can be expressed as:

Without compensation:

$$P = \frac{V_s V_r}{X_L}\sin(\delta_s - \delta_r) = \frac{V^2}{X_L}\sin\delta$$

and

$$Q = \frac{V_s V_r}{X_L}(1 - \cos(\delta_s - \delta_r)) = \frac{V^2}{X_L}(1 - \cos\delta)$$

With the series compensation by the SSSC:

$$P_q = \sin\delta = \frac{V^2}{X_L(1 - \frac{X_q}{X_L})}\sin\delta$$

and

$$Q_q = \frac{V^2}{X_{eff}}(1 - \cos\delta) = \frac{V^2}{X_L(1 - \frac{X_q}{X_L})}(1 - \cos\delta)$$

In practice, the voltage levels of the sending end and receiving end are set to be constant during normal operation. If the active power flow of the system is set to be constant, reducing the effective line reactance will change the value of the phase angle between the sending end and the receiving end. [1][2]

The normalized power P versus angle δ plots are shown in figure 6.2 as a function of the compensated voltage V_q. In order to compare the different the maximum power transfer with and without the SSSC, $S = X_q/X_L$ was set to 1/3, and 1/5.

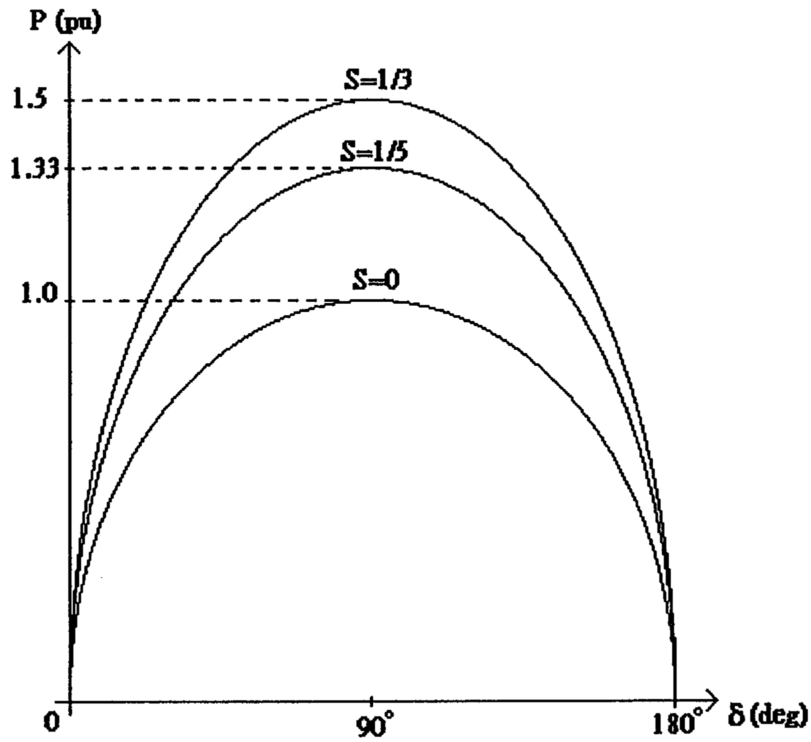


Figure 6.1 Transmitted power P vs transmission angle δ as function of the degree of series capacitive compensation.

Figure 6.1 shows that the series capacitive compensated voltage increases the transmitted power by a fixed percentage of that transmitted by the compensated line at a given phase angle, δ. The SSSC increases the active transmitted power by a fixed fraction of the maximum power transmittable by the uncompensated line, independent of the phase angle δ in the important range of the $0° < \delta < 90°$.

Assuming a constant power transfer from the sending end to the receiving end, the phase angle between the sending end and the receiving end will be decreased if the SSSC is operated as series capacitive compensation. Therefore, by using the static synchronous series compensator, the critical clearing time and critical clearing angle will be increased.

6.3 Transient Stability Simulation of Representative Power System

The dynamic performances of the STATCOM, SSSC and UPFC were evaluated in a representative two area system shown in Figure 6.2. The system consists of two individual areas interconnected by a 300 km tie-line. During normal operating conditions, the interconnecting tie-line carries 680 MW from area 1 to area 2. [1][2][3][4][5]

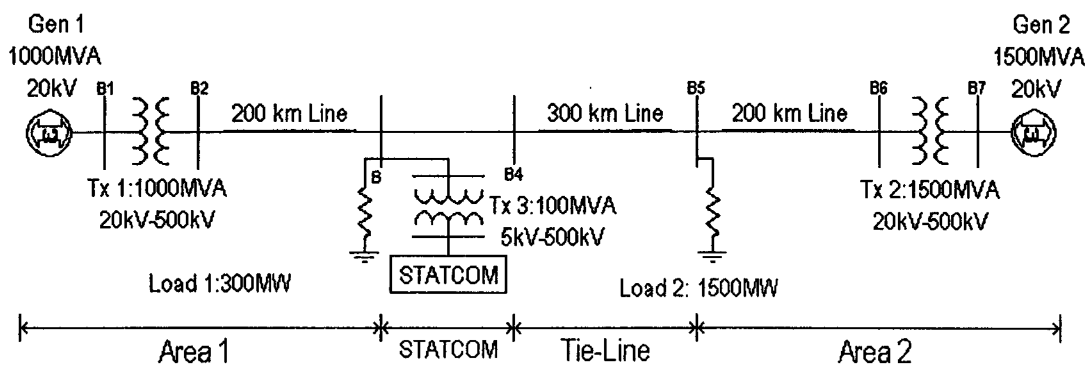


Fig. 6.2(a) A representative interconnected areas network with STATCOM installed

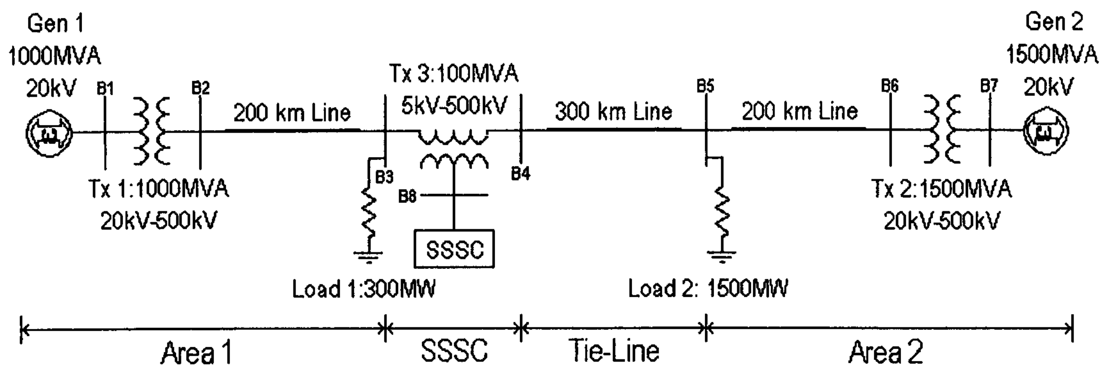


Fig. 6.2(b) A representative interconnected areas network with SSSC installed

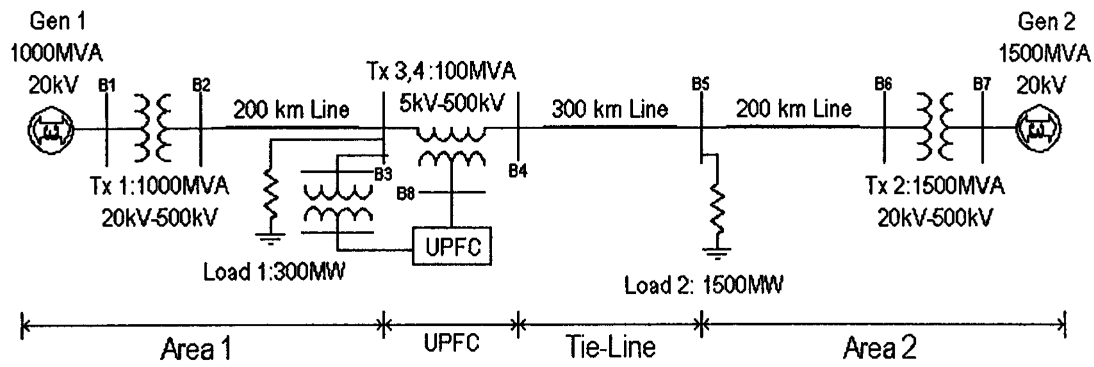


Fig. 6.2(c) A representative interconnected areas network with UPFC installed

Figure 6.2(a) shows the tested representative interconnected areas network with a STATCOM installed in shunt connection with the bus 3. Figure 6.2 (b) and (c) shows the representative interconnected areas network with SSSC and UPFC installed between bus 3 and bus 4 (one of the ends of the interconnected tie-line). In normal operation, the FACTS device will inject constant voltage and current into the system in order to maintain constant power flow through the tie-line.

A symmetrical 3-phase phase-to-ground fault was applied at Bus 2 as follows:

Stage 1: Normal operating state, t = 0s to 1s

Stage 2: During the three-phase fault, t = 1s to 1.12s

Stage 3: After the three-phase fault and system recovering state, t = 1.2s to 10s

The results of the simulation with (i) STATCOM, (ii) SSSC and (iii) UPFC presented in Figure 6.3(a), (b) – Figure 6.5(a), (b). Figure 6.3(a) and (b) show the simulation results of the representative interconnected power system with STATCOM and Figure 6.4(a) and (b) show the simulation results of the representative power system with SSSC while the simulation results of the simulations with UPFC applied are shown in Figure 6.5(a) and (b).

Form the simulation result, it is noted that the active and reactive power flow oscillations through the tie-line were successfully damped by installing a STATCOM, SSSC or UPFC into the system. By comparing Figure 6.3(a), 6.4(a) and 6.5(a), we can see that the SSSC and UPFC are more effective in damping active power flow oscillations, and both of the SSSC and UPFC controller provide substantial improvement of the dynamic performance of the system, damping the system oscillations in less than five seconds. There are fewer swings and no non-linearity of the active power flow through tie-line with SSSC and UPFC when compared with the performance of STATCOM controller.

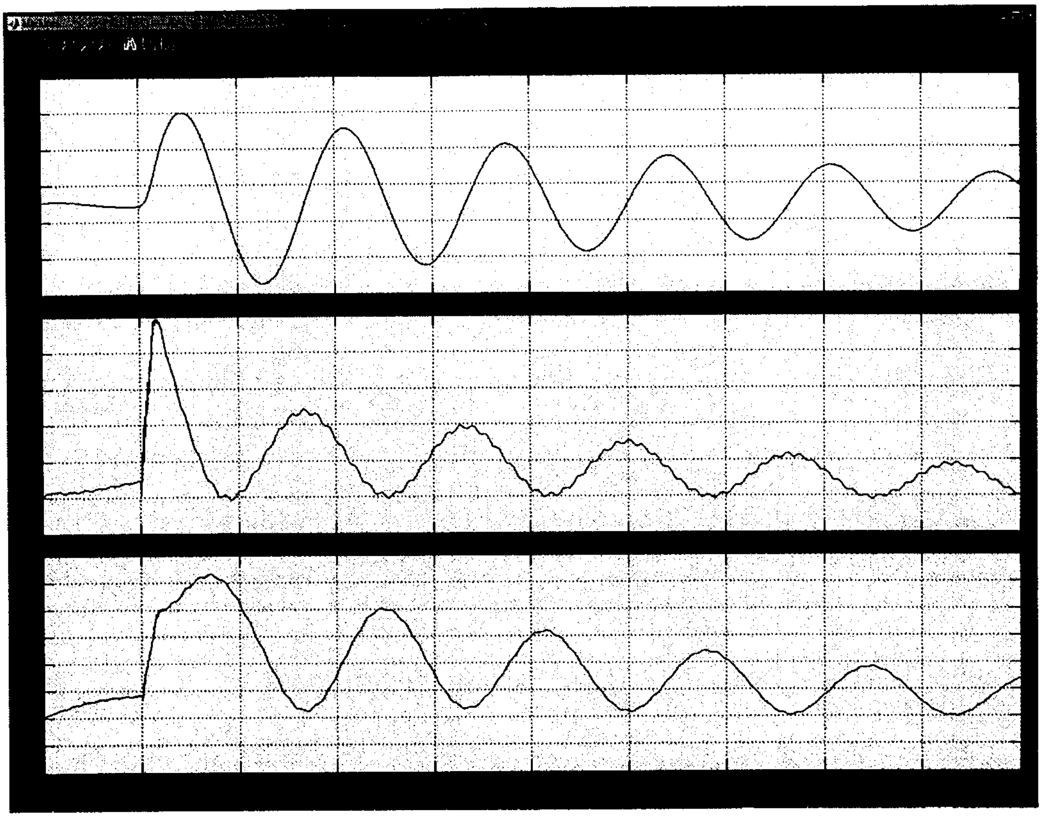


Figure. 6.3(a) Simulation results of Delta-theta of the two generators with STATCOM

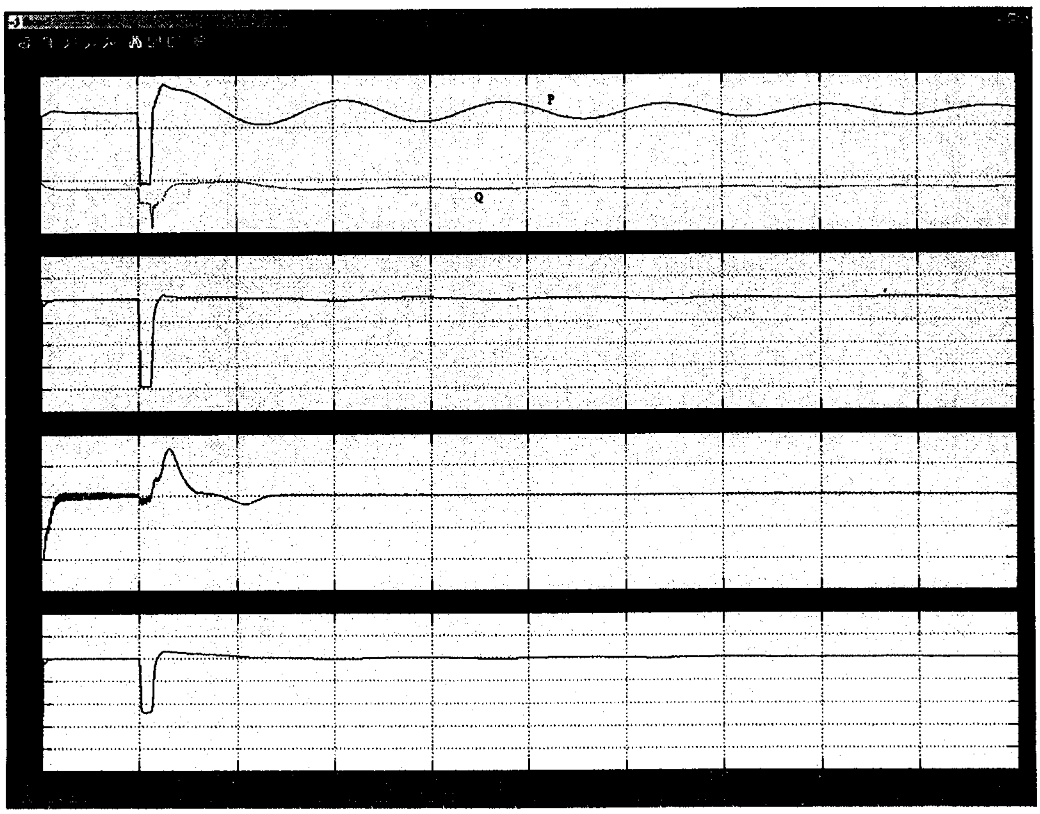


Figure 6.3(b) Simulation results of the voltage level and active and reactive power flow with STATCOM

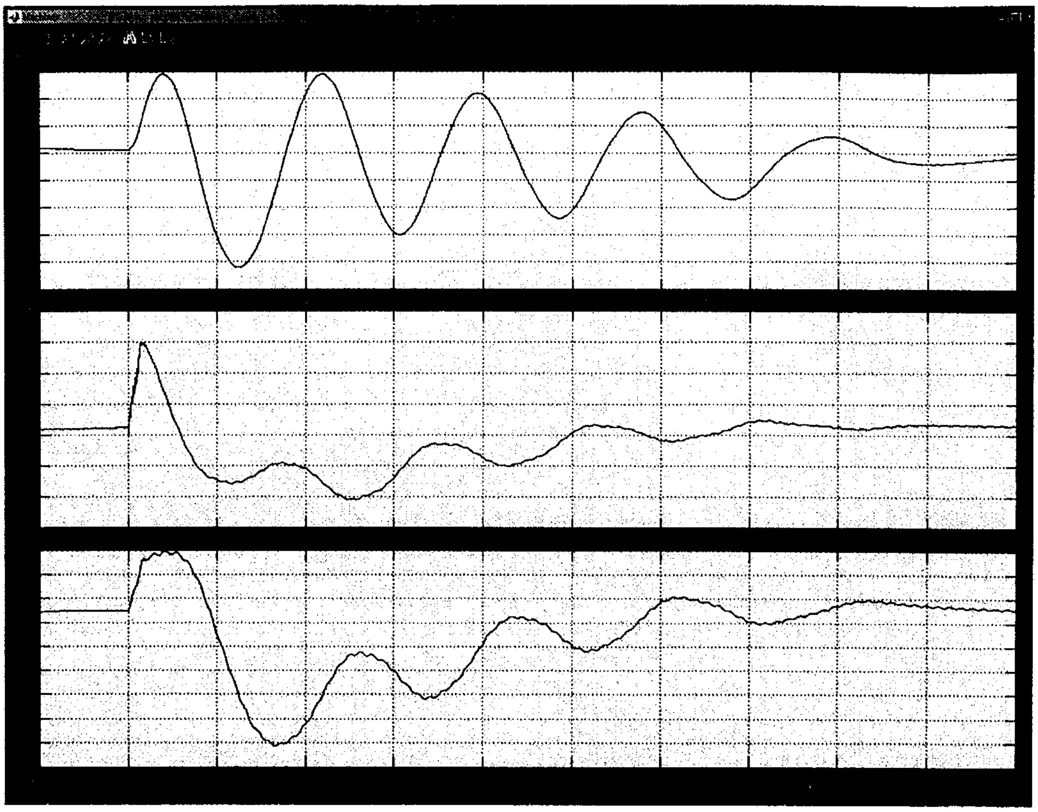


Figure 6.4(a) *Simulation results of Delta-theta of the two generators with SSSC*

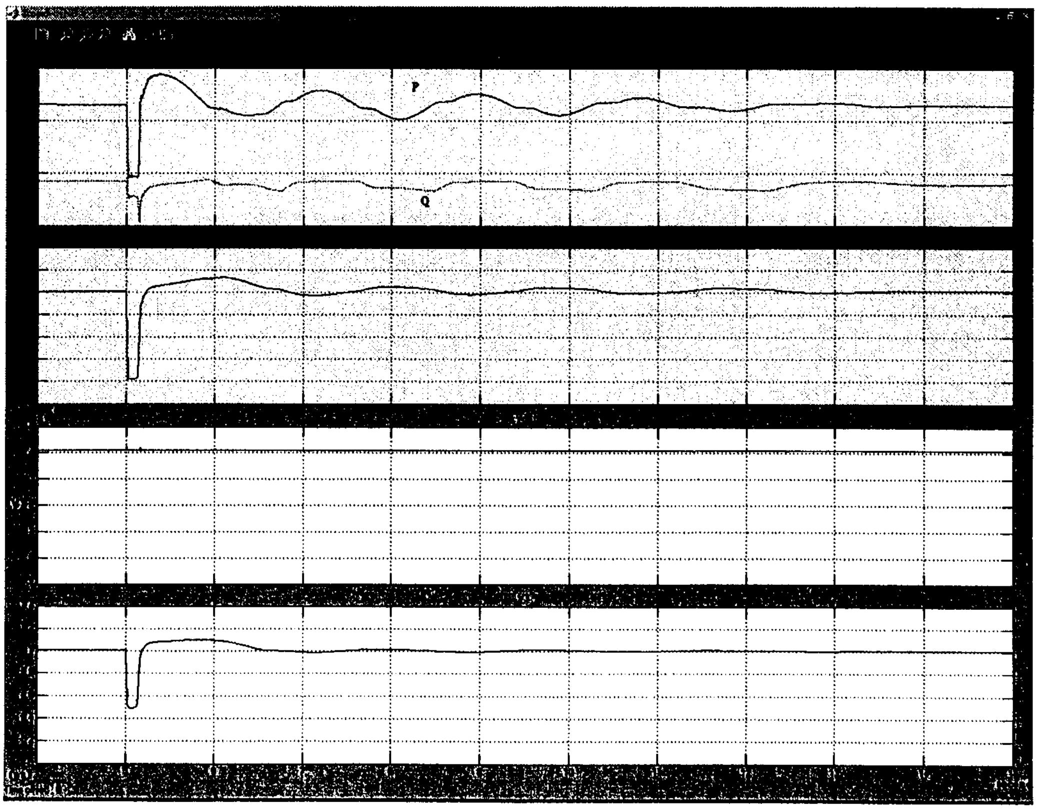


Figure 6.4(b) *Simulation results of the voltage level and active and reactive power flow with SSSC*

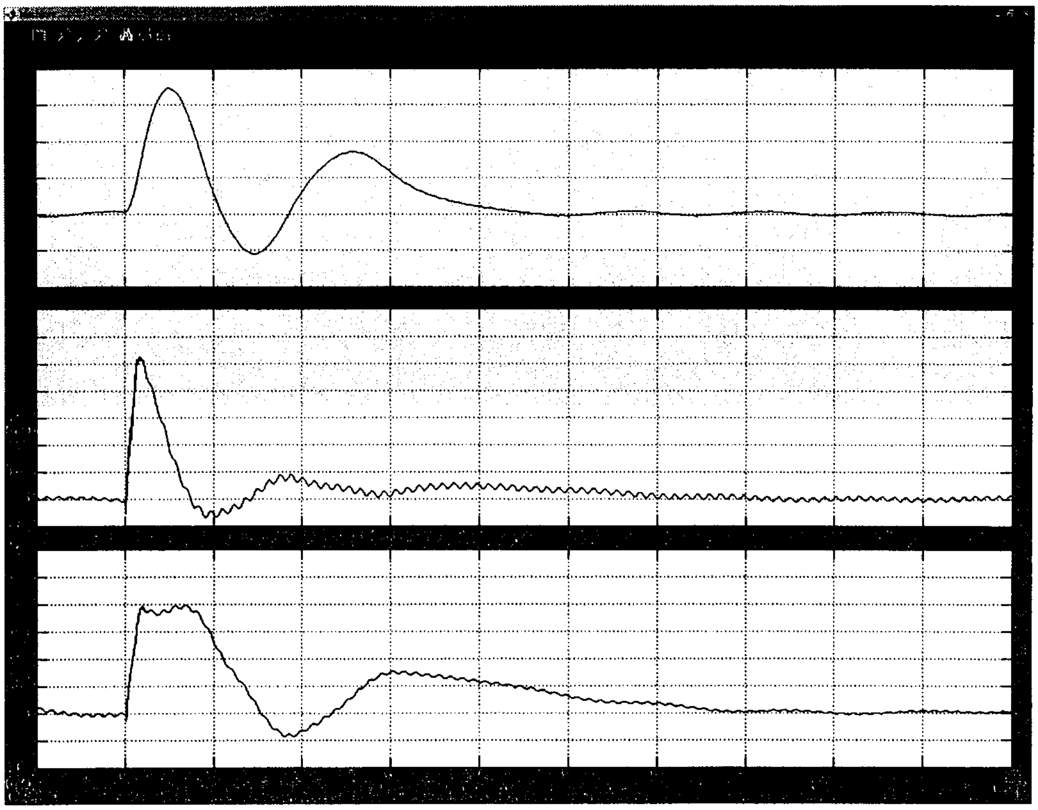


Figure 6.5(a)   Simulation results of Delta-theta of the two generators with UPFC

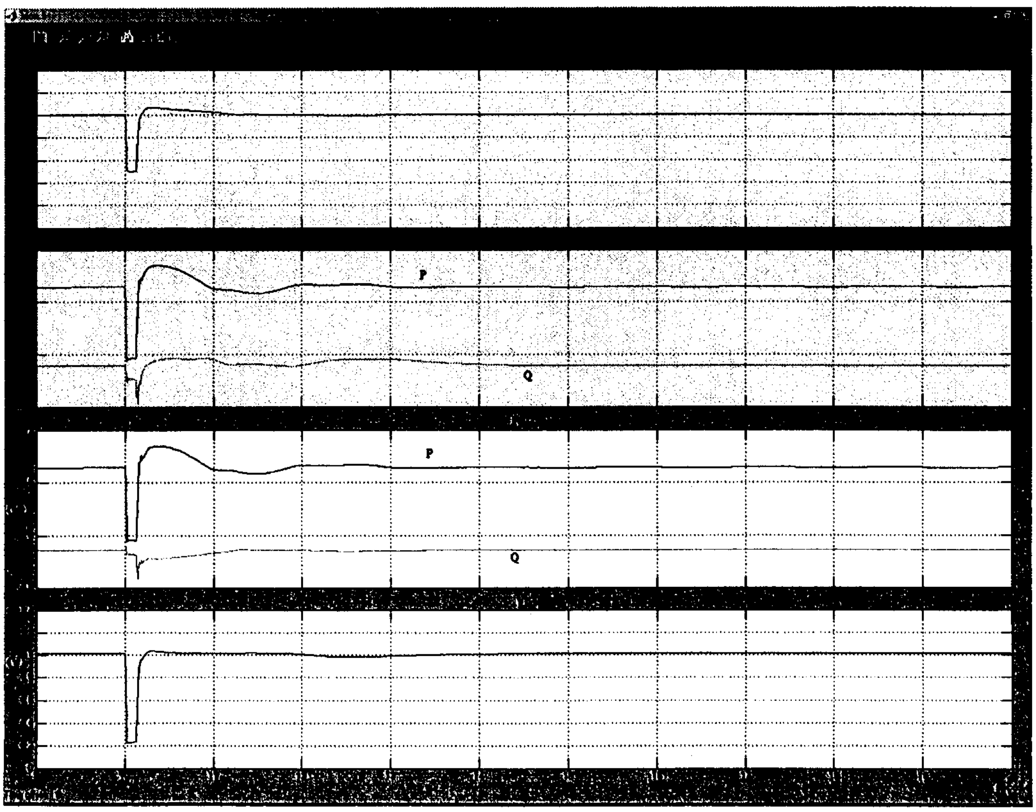


Figure 6.5(b)   Simulation results of the voltage level and active and reactive power flow with UPFC

Chapter 7 Intelligent Control Application in FACTS Devices

7.1 INTRODUCTION

This Chapter presents an analysis of novel control strategies for FACTS controllers, including intelligent rule-based controllers and fuzzy logic controllers. The proposed fuzzy logic controller uses the steady state relations electrical power as the input signals and does not require a dynamic model of the system for a satisfactory control design. It is not sensitive to the variation of system structure, parameters and operation points and can be easily implemented in a large scale nonlinear system. Another novel proposal is an intelligent error driven integrator for FACTS devices, which is based on the concept of the error excursion plane where the stabilizing action is scaled by the magnitude of the power, voltage and reactance error signal in order to ensure adequate compensation. The proposed rule based design is robust and tolerates system parameter variations as well as modeling inaccuracies, since the control level is only scaled by input error signals.

Comparative studies of the proposed control schemes were carried out in the SimPowerSystems (MATLAB) environment. The simulation comprises a detailed (device-level) model of PWM-based SSSC and the associated control systems, installed in a tie line of an interconnected two-area EHV system. The SSSC is mainly applied to control the power through the tie-line.

Case studies show that, when equipped with modern control systems, SSSC can be very effective in maintaining the transient and oscillatory stability of a power system by providing extra damping to power flow oscillations and machine angle oscillation.

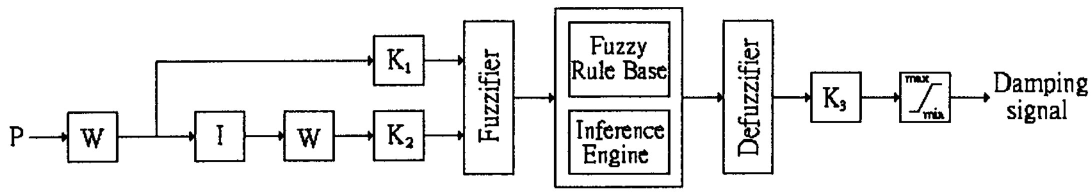
7.2 INTELLIGENT CONTROL METHODS FOR FACTS APPLICATIONS

The effectiveness of FACTS devices are determined largely by the control strategy. FACTS are utilized in applications including current control, damping oscillations, improving transient and dynamic stability, as well as voltage stability. In order to improve the static and dynamic performances of the FACTS controllers, intelligent control methods for FACTS devices applications, the Static Synchronous Series Compensator is used as an example, were developed and is presented in this Chapter of this thesis. The intelligent error driven integrator is based on the concept of the error excursion plane where the stabilizing action is scaled by the magnitude of the power error signal, voltage error signal and the reactance error signal in order to ensure adequate compensation. [28] The proposed rule based design is robust and tolerates system parameter variations as well as modeling inaccuracies, since the control level (Gain of the PI controller) is only scaled by the input error signal.

The PI regulator inside the SSSC controller is used to control the output magnitude of the compensated voltage of the Static Synchronous Series Compensator. In order to shorten the response time of the SSSC, prevent undesired oscillation of the output voltage and improve the power system stability, an intelligent error driven integrator was developed applied to the SSSC controller

7.3 FUZZY LOGIC DAMPING CONTROLLER (FLDC) [29][30][31]

Figure 7.1 shows the block diagram of the proposed Fuzzy Logic Damping Controller (FLDC). The input signal is the tie-line real power, and the output is the damping signal which is used as the series inverter input controller signal.



W: Washout block, I: Integration

Figure 7.1 Fuzzy Logic Damping Controller for the SSSC

The proposed fuzzy supplementary controller block is basically a non-linear PI-type fuzzy logic controller with two inputs and one output. The real power though the tie-line and its integral are used as the input signals of the FLDC and the output of the FLDC is sent to the main controller for voltage injection into the tie-line. The two gains K_1 and K_2 are multiplied by the two inputs individually to make $P_1 = K_1P$ and $P_1' = K_2P'$. The gain K_3 for the output signal is also applied to scale the output signal of the defuzzifier as the damping signal.

Each input, for the fuzzy rule base, is divided into seven linguistic values or fuzzy subsets, which are PL (positive large), PM (positive medium), PS (positive small), ZE (zero), NS (negative small), NM (negative medium) and NL (negative large). Figure 7.2 shows the membership function of the input signals namely magnitude of the error signal and rate of change of the error signal.

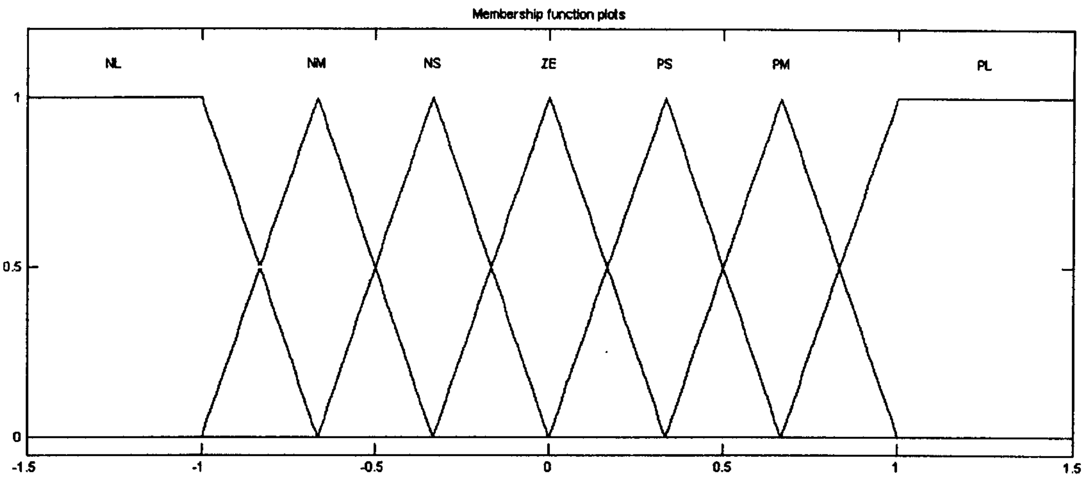


Figure 7.2 Membership functions for input and output signals

Table 7.1 illustrates the fuzzy control rules in the form of a decision table which can be express as the following equation:

IF K_1X_1 is A_i and K_2X_2 is B_i THEN output K_3Y is C_i

where A_i and B_i are the input fuzzy sets with triangular membership functions, while C_i is the output fuzzy set with triangular membership function. These linguistic values are determined from the results of the simulation. Finally, the centroid defuzzification is used to compute the output values.

P(x)\ P(x)	NL	NM	NS	ZE	PS	PM	PL
NL	NL	NL	NL	NM	NS	NS	ZE
NM	NL	NM	NM	NM	NS	ZE	PS
NS	NL	NM	NS	NS	ZE	PS	PM
ZE	NL	NM	NS	ZE	PS	PM	PL
PS	NM	NS	ZE	PS	PS	PM	PL
PM	NS	ZE	PS	PM	PM	PM	PL
PL	ZE	PS	PS	PM	PL	PL	PL

Table 7.1 Fuzzy rule-base table

The differentiable Gaussian membership function is used to fuzzify the two input signals. The triangular function is used to defuzzify the output fuzzy sets. Five fuzzy sets are defined for each of the input signals and seven fuzzy sets are defined for the output signal. [29][30][31]

7.4 Error Driven Controller for SSSC

SSSCs are utilized in applications including current control, damping oscillations, improving transient and dynamic stability, as well as voltage stability. The effectiveness of THE SSSC is determined largely by the control strategy. In order to improve the static and dynamic performances of the SSSC, an intelligent error driven integrator for Static Synchronous Series Compensator was developed and is presented in this Chapter. The intelligent error driven integrator is based on the concept of the error excursion plane where the stabilizing action is scaled by the magnitude of the power error signal, voltage error signal and the reactance error signal in order to ensure adequate compensation. [28] The proposed rule based design is robust and tolerates system parameter variations as well as modeling inaccuracies, since the control level (Gain of the PI controller) is only scaled by the input error signal.

The PI regulator inside the SSSC controller is used to control the output magnitude of the compensated voltage of the Static Synchronous Series Compensator. In order to shorten the response time of the SSSC, prevent undesired oscillation of the output voltage and improve the power system stability, an intelligent error driven integrator was developed and applied to the SSSC controller.

7.5 Intelligent Error Driven Integrator

The intelligent error driven integrator is based on the concept of the on-line gain scheduling with adjustment based on the magnitude of the input error signal [28]. Figure 7.3 shows the structure and the detailed block diagram of the intelligent error driven integrator.

The control equations are shown as following:

$$P_{er} = K_1 \frac{P_e}{P_{ref}} \, p.u.$$

$$P_{e'} = P_{er} + P_e$$

$$P_1 = (F(s) \times P_e)^2$$

$$P_2 = (K_2 P_e)^2$$

$$K_g = K_3 \sqrt{P_1^2 + P_2^2}$$

where P_e is the input error signal P_{ref} is the reference power, K_1, K_2 and K_3 are the selected modulation gain the intelligent integrator, and F(s) is a transfer function which is used to calculate the rate-of-change of the error signal and perform the filter effect of the error signal by a second order filter to avoid undesired hunting, oscillation and instability of the system due to the unsuitable output of the intelligent integrator.

At any sampling time instant t:

$$P_{in}(t) = K_g(t) P_{e'}(t)$$

where P_{in} (t) is the input signal of the integrator at any sampling time (t).

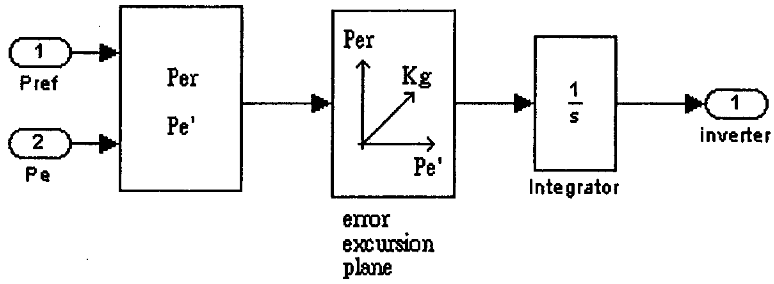


Figure 7.3 Structure of the intelligent error driven Integrator

7.6 Application of SSSC to Improving Transient Stability

7.6.1 Interconnected areas network

The dynamic performances of the SSSC with fuzzy logic damping controller (FLDC) and intelligent error driven integrator were evaluated in a representative two area system shown in Figure 7.4. The system consists of two individual areas interconnected by a 300 km tie-line. During normal operating conditions, the interconnecting tie-line carries 680 MW from area 1 to area 2. [1][2][28][29][30]

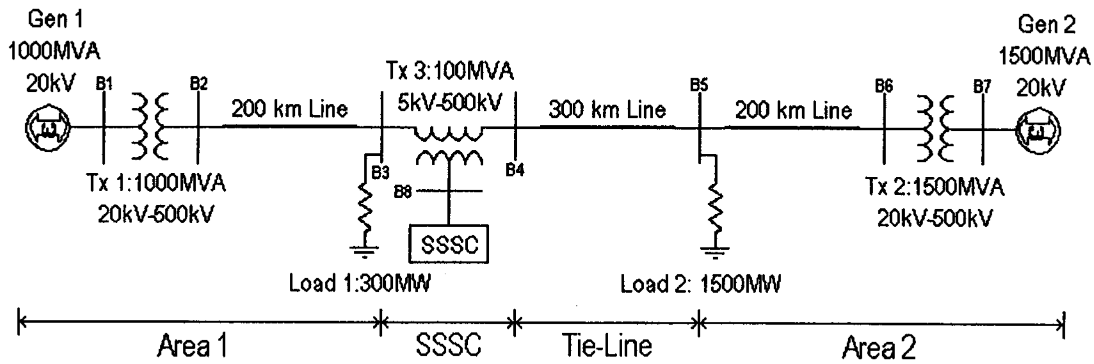


Figure 7.4 A representative interconnected areas network

An SSSC is installed between bus 3 and bus 4 (one of the ends of the interconnected tie-line). In normal operation, the SSSC will inject constant voltage into the system in order to maintain constant power flow through the tie-line.

A symmetrical 3-phase phase-to-ground fault was applied at Bus 2 as follows:

Stage 1: Normal operating state, t = 0s to 1s

Stage 2: During the three-phase fault, t = 1s to 1.12s

Stage 3: After the three-phase fault and system recovering state, t = 1.2s to 10s

The results of the simulation with (i) no SSSC, (ii) SSSC with FLDC and (iii) SSSC with intelligent error driven integrator are presented in Figure 7.5 – 7.6. Figure 7.5 and 7.6 show the comparisons of the active and reactive power flow through the tie-line with and without SSSCs. The comparisons of the rotor angle difference and the machine speeds of the generators with and without SSSCs are shown in Figure 7.7 and 7.8.

Figure 7.5 and 7.6 show that the active and reactive power flow oscillations through the tie-line were successfully damped by installing an SSSC into the system. From Fig. 7.5, we can see that the SSSC is very effective in damping active power flow oscillations, and both of the FLDC and adaptive controller provide substantial improvement of the dynamic performance of the SSSC, damping the system oscillations in less than four seconds. There are fewer swings and no non-linearity of the active power flow through tie-line with FLDC-SSSC when compared with the performance of adaptive controller. Furthermore, as can be seen in Fig. 7.7, the adaptive controller is effective in eliminating steady state errors. The SSSC with the adaptive control system is also effective in improving angle stability, as can be seen in Figure 7.7, where after the first swing; the maximum rotor angle difference between the two areas is reduced by more than 50%. The FLDC-SSSC is even more effective in improving angle stability compared to that of the Adaptive SSSC. There is less angle oscillation with the FDLC-SSSC than with the Adaptive SSSC , which is able to damp down the angle and power flow oscillation faster.

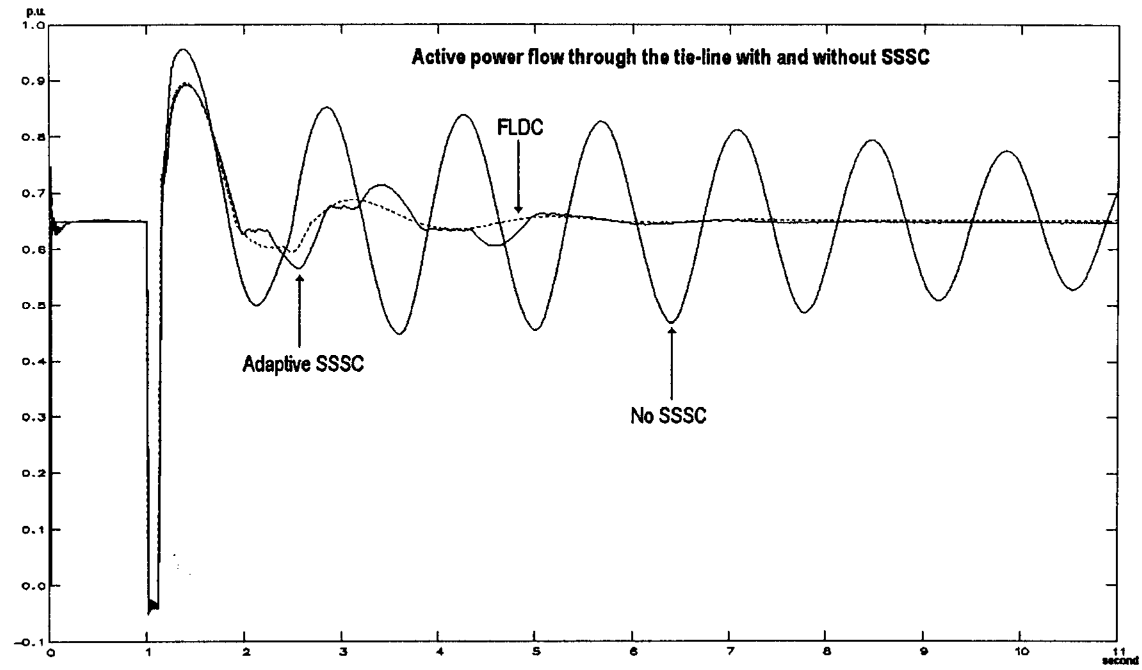


Figure 7.5 Simulation results of the active power flow with adaptive and FLDC SSSC

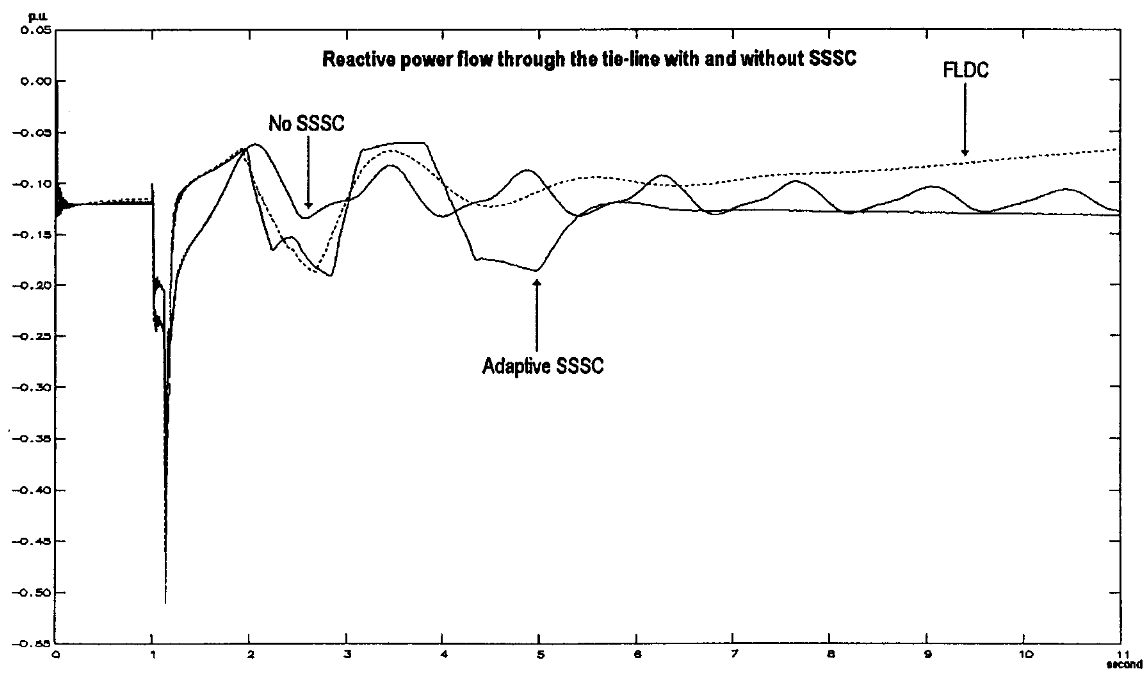


Figure 7.6 Simulation results of the reactive power flow with adaptive and FLDC SSSC

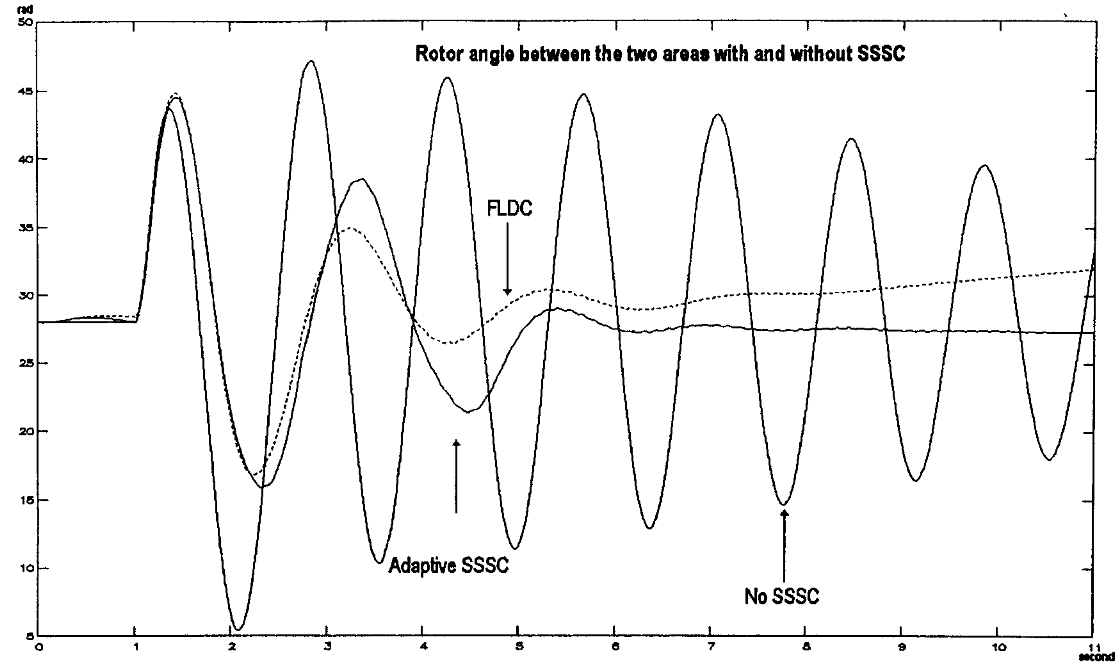


Figure 7.7 Simulation results of Delta-theta of the two generators with adaptive and FLDC SSSC

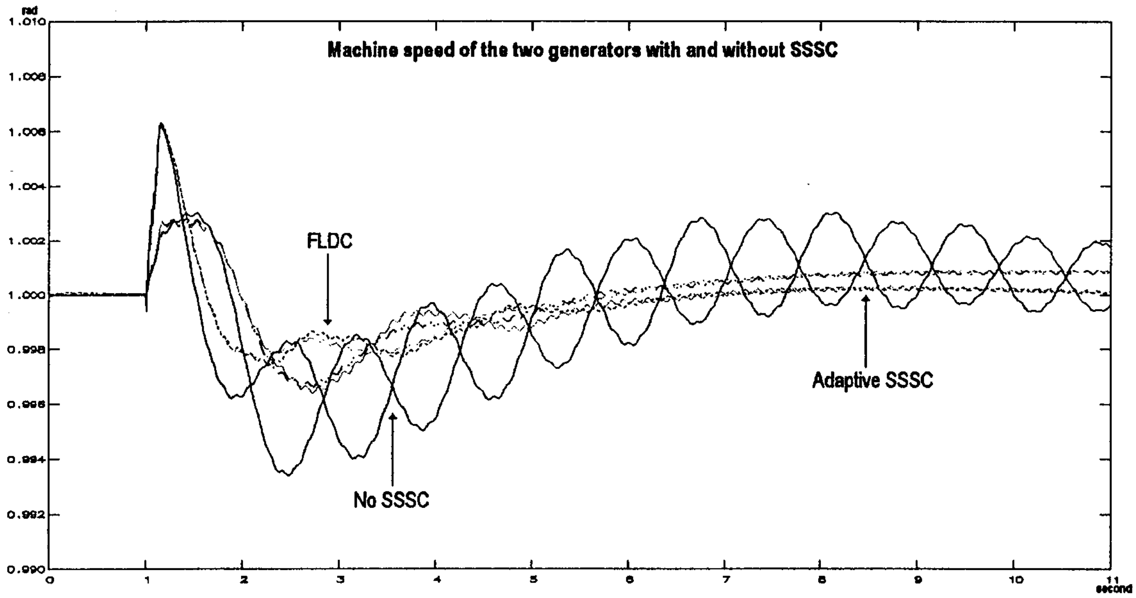


Figure 7.8 Simulation results of machine speeds of the two generators with adaptive and FLDC SSSC

7.7 Conclusions

This Chapter presents the application of a Static Synchronous Series Compensator, SSSC, to improve the transient stability of power system and the use of the Fuzzy Logic Damping Controller and adaptive controller to improve the dynamic performance of the SSSC.

Different control methods of the SSSC such as constant voltage injection control, constant impedance emulation control and constant power control modes were described in the paper. Fuzzy Logic Damping Controller in which proportional and integral gains are tuned online based on fuzzy inference rules and an adaptive PI controller incorporating on-line gain scheduling and adjustment based on the magnitude of the input error signal were developed so as to improve the dynamic performance of the SSSC, including better damping ability to power flow oscillation and inter-area power flow oscillations.

Chapter 8 FACTS devices studies under EMTP and TSP Interfacing Environment

8.1 INTRODUCTION

A power system is a high order non-linear dynamic system with a transient response ranging in bandwidth from electromechanical transients (less than 1 Hz) to electromagnetic transients (up to several mega Hz). Traditionally, electromagnetic and electromechanical transient studies are carried out using separate simulators and compromises are required to deal with the respective shortcomings of the different simulators.

Currently, developments in simulation technology involve interfacing different simulators in order to capitalize on the relative advantages of each, towards the realization of a practicable hybrid broadband simulator. There have been number of papers published related to the topic of interfacing the two kinds of simulators. Heffernan et al. first proposed the detailed modelling of an HVDC system within stability based A.C. system framework. The D.C. system was modelled using state variable techniques while the ac system was represented by a conventional stability program.

The interface locations were the converter terminals and the interface variables were rms power and an FFT derived fundamental frequency voltage [32]. Another common approach to study power systems contain of HVDC and FACTS devices is by modelling them in EMTP [33][34]. This Chapter presents the techniques I used to realize a broadband simulator capable of running in real-time.

8.2 REAL TIME BROADBAND SIMULATOR

With today's real-time fully digital simulators Electromagnetic Transient Programs (EMTP) and Transient Stability Programs (TSP) can be run in real time. However, both EMTP and TSP simulators have their own limitations [35][36]. Real-time EMTP simulators, with time steps as low as 50μs, can represent power electronic devices and control systems associated with FACTS and HVDC transmission systems at the device level, however they are impracticable for representing large systems, and dynamic equivalents are required. On the other hand, TSP can solve very large systems in real time, typically with the time steps of several milliseconds, and FACTS devices can only be represented by simplified mathematical equivalents. This limitation makes it difficult to represent malfunctions of FACTS devices in transient stability studies.

By interfacing a real-time EMTP type simulator (HYPERSIM [35]) with a TSP simulator, we can create a hybrid simulator where, conceptually, the power system being studied can be considered as a multi-layered system in which each layer has its own time step. Large power systems can be simulated in real time with no need for dynamic equivalents and would have the capability of 'zooming in' to model in detail parts of the system, FACTS devices and HVDC terminals.

8.3 INTERFACING TECHNIQUES

There are fundamental differences between the two simulators: the TSP is a phasor-like solution, balanced and without distortion, while the EMTP waveforms can be unbalanced and distorted. The passing of data between the two programs requires some pre-manipulation (e.g. extraction of fundamental components of waveforms), which also must be done in the real-time environment. Furthermore, the mechanisms involved in the transfer of data lead to time delays, which must be compensated with appropriate prediction routines. Some of the problems in interfacing the two simulators have been solved and they will be discussed in this Chapter.

8.3.1 The Interface

The HYPERSIM and TSP sub networks are interfaced via an interface bus as shown in Figure 8.1. The interface is based on the replacement of each sub network by a controlled voltage source connected to a series element common to both sub networks. Changes in one sub network are reflected to the other sub network through changes in their respective voltage sources.

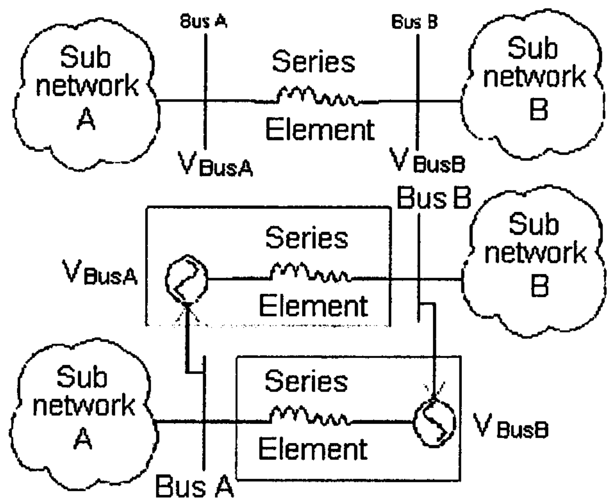


Fig8.1 Voltage equivalent representations

The power system being studied is divided into two sub networks which are not interconnected via any power elements. At the interface, the sub networks are connected to each other and exchange information by connecting transceivers (which convert a power signal into a control signal) between them. The two sub networks are simulated as separate tasks in HYPERSIM. A User Code Block (UCB), which is an element block in HYPERSIM which allows C-like programming, is introduced between the interfaced subsystems. The calculated equivalent values are transferred through the UCB so that the solutions of one type will be compatible with the other type. Algorithms are incorporated in HYPERSIM by using UCB to facilitate the interface

8.4 Factors which influence the interface

Prediction - the transceivers and the controlled voltages source each introduce a one time-step delay, the consequence of which is to introduce a phase angle error of 1.8 degree (based on a time step of 50 μs) between the sub networks. To eliminate the error, second order prediction algorithms were introduced as shown in Figure 8.2.

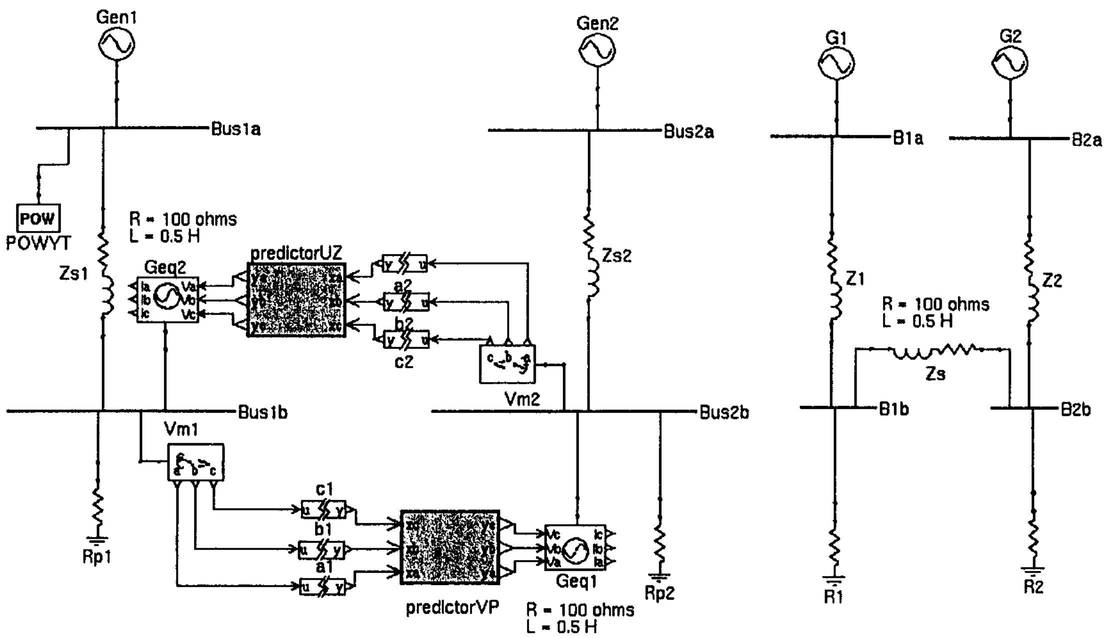


Figure 8.2 Circuit diagram of a simple network with 'predictor'

The improvement realized by the predictor is evident in Figure 8.3, where the phase difference between the original and sub networks at the interface buses is shown. The phase error is contained to within ±0.0004 degree, which should be acceptable for the purposes of hybrid simulation.

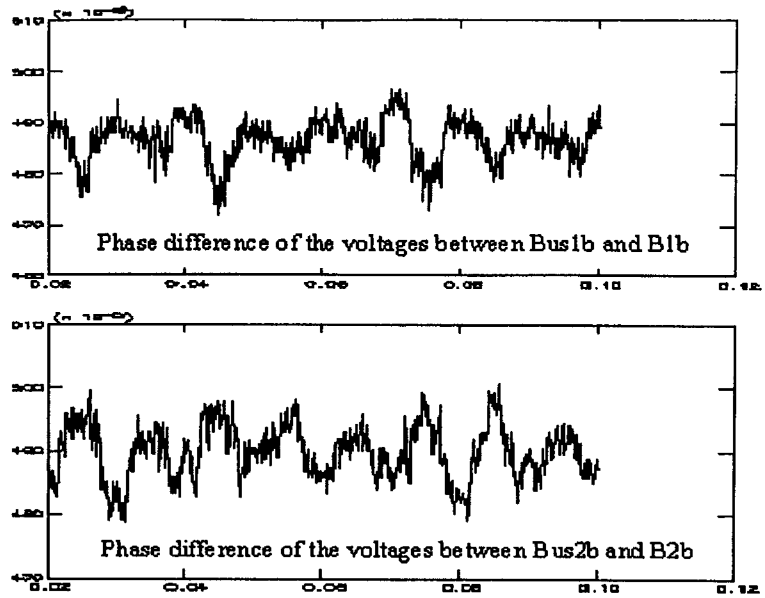


Figure 8.3 Results with second order prediction algorithm

Extraction - The EMTP waveform waveforms have to be converted from distorted, unbalanced three phase instantaneous representation into an equivalent distortionless, balanced single-phase fundamental frequency representation to be sent to the TSP program. Therefore, it is necessary to extract the fundamental components of the voltages and currents from the distorted waveforms of the voltages and currents, in real time.

Three methods were evaluated: discrete Fourier analysis [37], digital filter [38] and curve fitting [37] [39]. The three algorithms were applied to the same network to compare the response in real time simulation, and curve fitting algorithm was finally chosen as the extractor.

Figure 8.4 illustrates a network with a signal phase fault applied on phase B in the middle of a 300 km line for 5 cycles. The curve fitting algorithm was used to extract the distorted waveform of the voltage due to the line fault, and the results are shown in Figure 8.5. While the extraction process took some 5 minutes in Power System Blockset, it only required 20μs using a UCB in HYPERSIM running on an SGI computer. This is sufficiently fast for real-time simulation purposes.

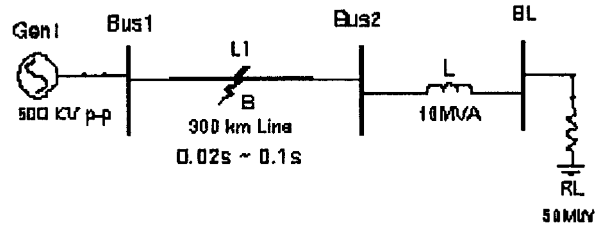


Figure 8.4 System with signal phase line fault

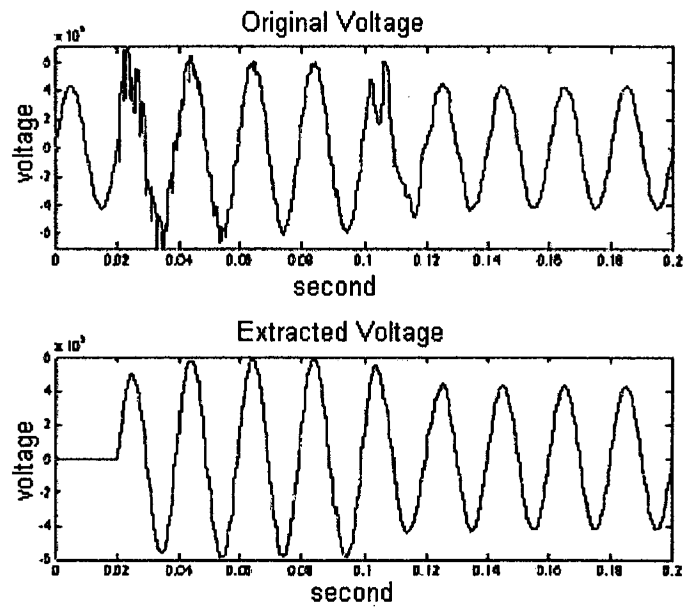


Fig. 5Results of the above system

8.5 CASE STUDY

The performance of the interface with the FACTS controller we modelled was evaluated using a simulation of a system compromising two machines, representative two machine 500kV power system with an SSSC installed. [1] [3] [40] [42]

The local system has a fault level of 50GVA and is modelled by an equivalent three-phase thermal generator rated at 5000MW, 20KV. In the local system, there is a 3000MW resistive load centre. The remote system is represented by an equivalent three-phase thermal generator rated 1000MW, 20KV with fault level of 10000MVA, and a 300MW resistive load centre. The two systems are interconnected by a 100km transmission line. In steady-state the remote system supplies 670MW of active power to the local system. At 0.1 second, a three fault last for 6 cycles occurs in the remote area close to the high voltage side of the transformer. The fault was cleared at 0.22 second.

A comparison of the transient simulations done in SimPowerSystem and Hypersim are shown as the following figures: Figure 8.7 shows the output current, angular frequency of the rotor, terminal voltage and the output power of the two synchronous generators and Figure 8.8 shows the power flow through the tie line. The results of the two simulation engines are almost identical.

In order to improve system damping, an SSSC was connected. Both dynamic controls as well as effective impedance of the tie line were used to stabilize the power flow through the interconnection.

The results of the transient simulations with the SSSC in SimPowerSystem [41], and HYPERSIM are the same as the case without SSSC except for the power flow through the tie line

As shown in Figure 8.9, we can see that the power flow oscillations were successfully damped when the SSSC was applied to improve the transient performance of the system: the system returns to steady state within 5 seconds.

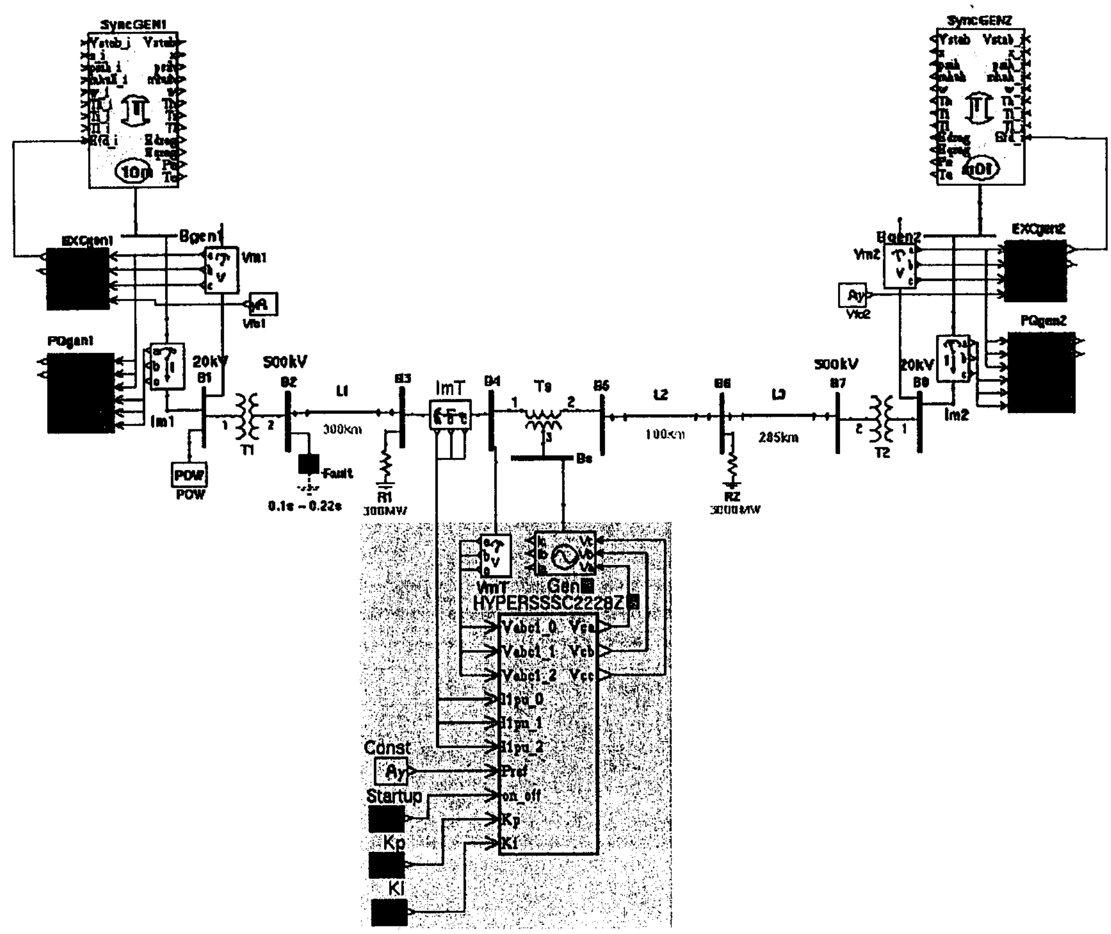


Figure 8.6 Circuit diagram of a system without SSSC

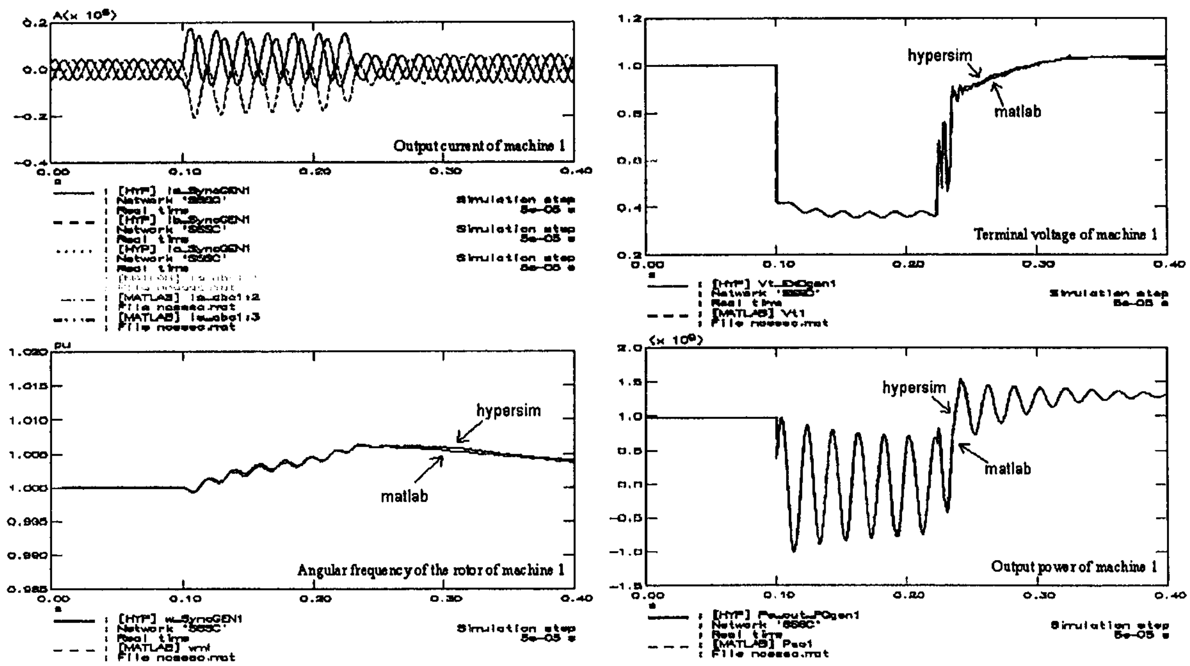


Figure 8.7 Comparison of results in Matlab and Hypersim of system without SSSC

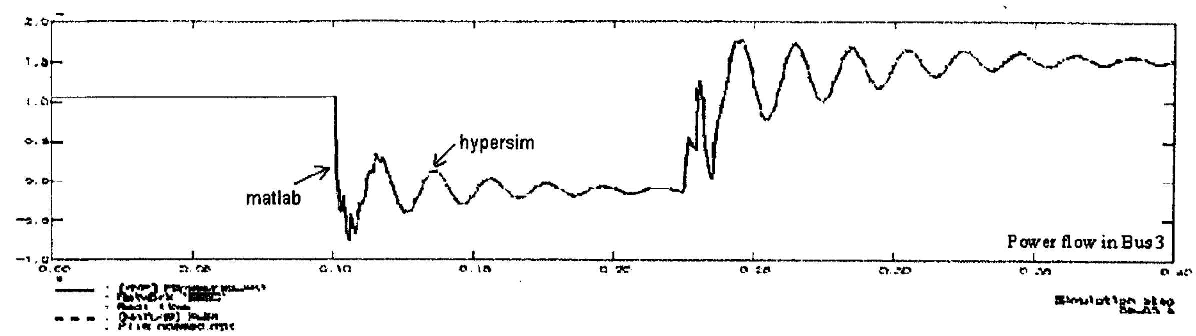


Figure 8.8 *Comparison of results in Matlab and Hypersim of system without SSSC*

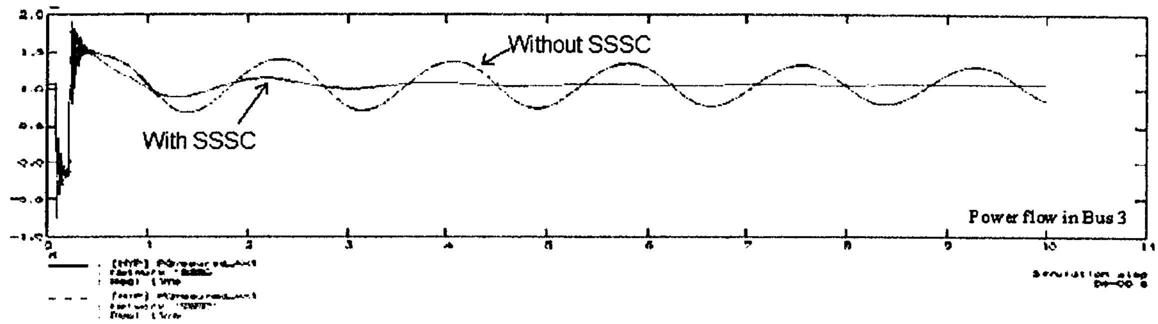


Figure 8.9 *Comparison of results of system with and without SSSC*

8.6 Connection of the SSSC via an Interface

For the same network, the SSSC was connected via the interface described above. The voltages at the interface bus were compared in order to demonstrate the feasibilities of interfacing systems with non-linear devices.

The system with the interface is shown in the Figure 8.10, and the results are shown in Figure 8.11. Before and after the fault is applied to the system, the voltage response at the interface bus is the same for the directly connected SSSC and the SSSC connected through the interface. While during the fault there are some small differences. In the original system, the distorted waveforms on the interface bus, while in the system with the interface, the voltages at the interface bus are sinusoidal because of the extractors.

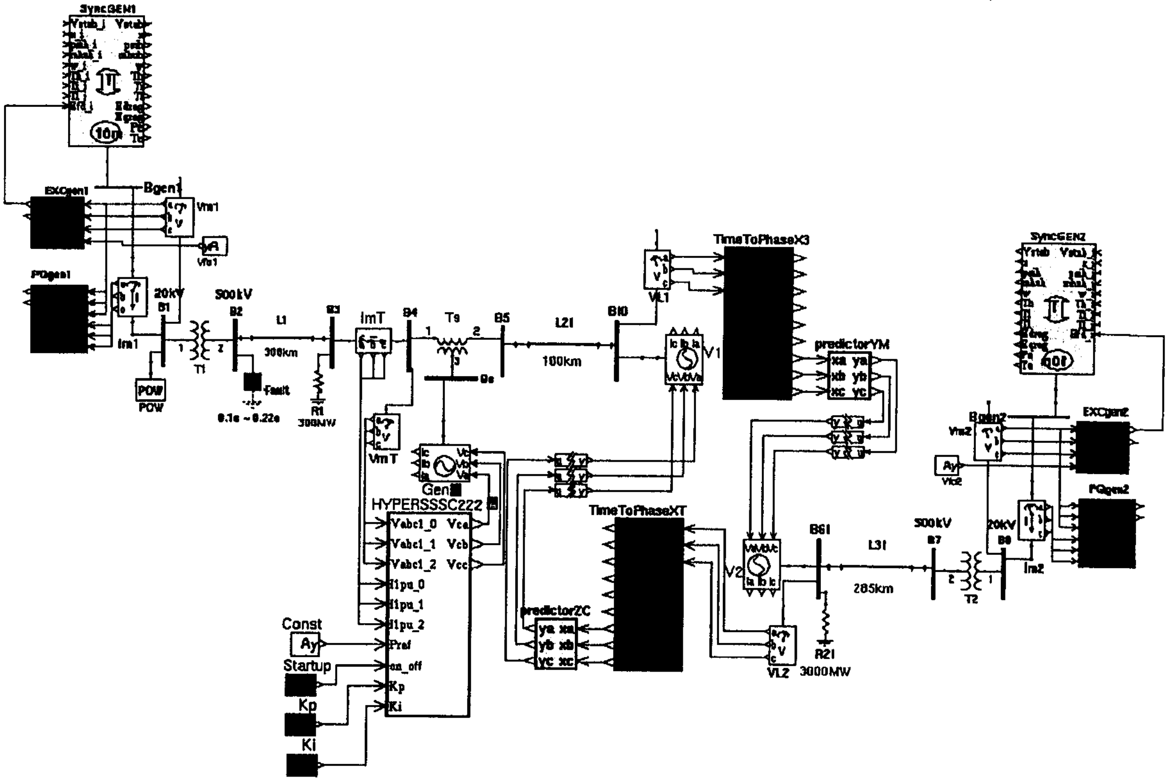


Figure 8.10 *Circuit diagram of a system with SSSC and interface*

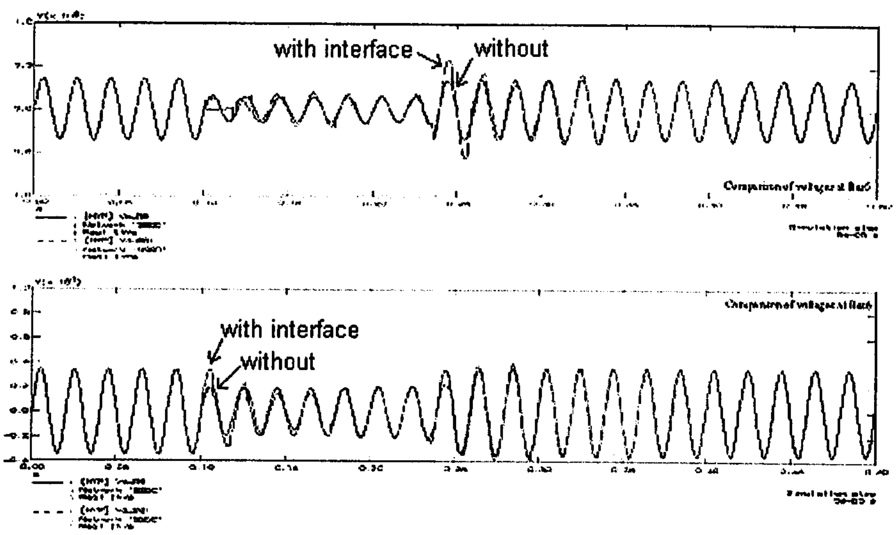


Figure 8.11 *Comparison of results of system with and without interface*

8.7 CONCLUSION

In this chapter, an interface between EMTP and TSP has been demonstrated. Interfacing the two simulators, EMTP (HYPESIM) and TSP, can combine the electromagnetic and electromechanical simulations into a single simulation environment in order to make optimal use of the relative advantages of both simulation types.

A case study was carried out on a two area system, with and without the connection of an SSSC to damp system oscillations. The SSSC was connected directly and through the interface, it was found that the interface functioned well during a system fault. The simulation results obtained from Hypersim real-time simulator obey the results obtained by Matlab. Therefore, we can believe that the SSSC works well in the Hypersim real-time simulator. This is a significant step toward to the development to a fully digital real-time broadband simulator.

Chapter 9 Conclusion

9.1 Summary of Work

FACTS technology provides potential opportunities to improve the steady state and dynamic stabilities of power systems and can have significant impact on power system planning, operation and control. However, FACTS technology comprises complex power electronics and control system which can also produce technical problems which need to be studied or evaluated before FACTS devices are successfully put into operation. Therefore, a lot of researches on FACTS technology is still required and this thesis is a contribution to the continuing research.

The fundamentals of forced-commutated VSCs, with emphasis on high power applications were discussed in detail in this thesis. The basic relationships for VSCs were formulated to provide a basis for the discussions and results in the thesis. The operating principles of a VSC were explained briefly for two control methods: square-wave and PWM. The analogy and comparison of square-wave and PWM controlled methods were also given.

The basic design and operating principles of a STATCOM, FACTS device together with the detailed STATCOM control circuit design were discussed briefly. A 12-pulse PWM-controlled STATCOM model and a 3-level, 48-pulse inverter

STATCOM were successfully modeled and implemented in the SimPowerSystem, MATLAB. Simulation studies, which were based on representative 500kV power systems rather than the much simpler systems used other research, typically comprising a simple single-machine/infinite bus representation. The studies include evaluation of the steady state and dynamic state performance of the STATCOM models.

The presented STATCOM detailed models include all of the power electronic based voltage-sourced converter parts and phase-shifting transformer parts. These models will be a very useful toolbox in Matlab for doing power system design and simulation. The designed control systems for the 12-pulse, PWM-controlled STATCOM use typical d-q transformation to obtain D.C. signals for control purposes. The STATCOM operating and control limits are included in the models, which makes the models suitable for both realistic steady state and transient stability studies.

The model includes a detailed representation of the valves and the accompanying snubber circuits. Also, the PWM based STATCOM was modeled in MATLAB using a single 2-level voltage-sourced converter. The presented time-domain simulations in MATLAB verified the successful operation of the designed controller, and demonstrated the successful applications of STATCOM controllers.

The SSSC operating principle and control circuit design as well as the methods of control and modulation of power flow in a transmission line using Static Synchronous Series Compensator (SSSC) were discussed in detail in chapter 4. The SimPowerSystem, MATLAB simulations, which include detailed representations of 3-phase, 3-level, 12-pulse PWM controlled SSSC and three level 48-pulse full-wave bridge inverter controlled SSSC, and the associated control circuits were used for the studies. The developed control strategies for both PWM controlled SSSC and 3-phase, 3-level, 48-pulse full-wave bridge inverter controlled SSSC make use of typical d-q transformations.

The full SSSC models were tested with representative simulations of power systems. Finally, the steady state operating performances of the SSSC of power flow control in individual transmission line were similarly demonstrated.

The fundamentals of a UPFC, explaining in detail the operating principles and limits as well as practical ratings of the equipment were presented in Chapter 5. The purpose of demonstrating the power flow control capabilities of the UPFC, the basic relationships and differences between a UPFC compensated and an uncompensated transmission line were discussed.

An MATLAB implementation of the UPFC was explained, together with a detailed description of the various control schemes. Since independent control of real and reactive powers within the equipment limits is possible, the UPFC control objectives and schemes can vary significantly, thus, some of the most significant control schemes and objectives were described in detail here.

The results of time-domain simulations in the Matlab demonstrated the adequacy of proposed control schemes, given the fast proper response of the series converter.

The application of a Static Synchronous Series Compensator, SSSC, to improve the transient stability of power system and the use of the Fuzzy Logic Damping Controller and adaptive controller to improve the dynamic performance of the SSSC were also discussed in this thesis..

Different control methods of the SSSC such as constant voltage injection control, constant impedance emulation control and constant power control modes were described in this thesis. Fuzzy Logic Damping Controllers in which proportional and integral gains are tuned online based on fuzzy inference rules and an adaptive PI controller incorporating on-line gain scheduling and adjustment based on the magnitude of the input error signal were developed so as to improve the dynamic performance of the SSSC, including better damping ability of power flow oscillations and inter-area power flow oscillations. The above study is one of the main contributions of this research since it can provide an excellent platform for future steady-state and transient studies which involve advance controlled FACTS devices.

An interface between EMTP and TSP was also demonstrated. Interfacing the two simulators, EMTP (Hypersim) and TSP, can combine the electromagnetic and electromechanical simulations into a single simulation environment in order to make optimal use of the relative advantages of both simulation types.

A case study was carried out on a two area system, with and without the connection of an SSSC to damp system oscillations. The SSSC was connected directly and through the interface, and it was found that the interface functioned well during a system fault. The simulation results obtained from the Hypersim real-time simulator replicate the results obtained by Matlab. Consequently, we can believe that the SSSC works well in the Hypersim real-time simulator. This is a step towards the development to a fully digital real-time broadband simulator.

9.2 Contribution of the thesis

The main contributions of this thesis are as follows:

1. Detailed models of the STATCOM, SSSC and UPFC were implemented and tested in MATLAB. These models are more comprehensive than those found in the literature and include detailed representation of the valves and the power electronic components, as well as full control circuit representation. The models are applicable for transient stability studies, and cover a broad range of frequency oscillations. They are also suitable for simulations in unbalanced power system conditions.

2. This thesis proposed and justified novel steady state and transient state models for STATCOM, SSSC and UPFC. The models were successfully validated in the MATLAB environment for various operating conditions and in realistic representative power system networks. The proposed models could be directly implemented in any power simulation software such as the real-time simulator *Hypersim* which has external programming capabilities for any steady state, dynamic state and transient stability simulations. The proposed models (toolbox) could also provide a better simulation package for the Power System designers in doing network planning or network enhancement under the widely inter-connected power system environment.

3. The developed FACTS device detailed models include all of the control block and power electronic components as well as the voltage-sourced converters. Furthermore the models were modeled independently of the type of control methodologies used, consequently the models can provide a excellent environment and platform for future advanced control methodology studies of FACTS devices.

9.3 Future Work

Since the Matlab model of the SSSC model had been successfully ported into Hypersim real-time simulator and studied with some representative power system, the Matlab models of the STATCOM and UPFC should be ported into Hypersim real-time simulator and studied.

The studies of FACTS devices under EMTP and TSP interfacing environment should be continued by applying the full device models of the FACTS devices modeled in this project in the interfacing environment developed by Dr Su [43]under the Hypersim environment. The studies should be continued under real-time digital simulator environment with large scale power system models.

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