TRANSIENT STABILITY ENHANCEMENT OF MULTIMACHINE POWER SYSTEM USING FACTS DEVICES

A DISSERTATION

Submitted in partial fulfillment of the requirements for the award of the degree

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ELECTRICAL ENGINEERING

(With Specialization in Power System Engineering)

By

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CADIDATE'S DECLARATION

This is to certify that the report, which is being presented in this dissertation titled **"Transient stability enhancement of Multimachine power system using FACTs Devices"** in partial fulfillment of the requirements for the degree of **Masters of Technology** in **Electrical Engineering**, with specialization in **Power System Engineering**, submitted in the **Department of Electrical Engineering, Indian Institute of Technology, Roorkee** is an authentic record of my own work under the guidance of **Dr. Vinay Pant**, Asst. Professor, Electrical Engineering Department, Indian Institute of Technology, Roorkee and **Dr. Ramnarayan Patel**, Lecturer, Electrical Engineering Department, Indian Institute of Technology, Roorkee.

I have not submitted the matter embodied in this report for the award of any other degree or diploma.

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Place: Roorkee

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CERTIFICATE

This is to certify that the above statement made by the student is correct to the best of my knowledge.

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ABSTRACT

Power system engineers are currently facing challenges to increase the power transfer capabilities of existing transmission system. Flexible AC Transmission system (FACTs) controllers can balance the power flow and thereby using the existing power system network most efficiently. Because of their fast response FACTs controllers can also improve the stability of an electrical power system by helping critically disturbed generators to give away the excess energy gained through the acceleration during fault. Thyristor controlled series compensator (TCSC) is an important device in FACTs family and is widely recognized as an effective and economical means to solve the power system stability problem.

TCSC controller, the first generation of FACTs, can control the line impedance through the introduction of a thyristor-controlled capacitor in series with the transmission line. TCSC is used as series compensator in transmission system. The TCSC controller can be designed to control the power flow, to increase the transfer limits or to improve the transient stability. The TCSC controller can provide a very fast action to increase the synchronization power through quick changing of the equivalent capacitive reactance to the full compensation in the first few cycles after a fault, hence subsequent oscillations are damped.

In the present work TCSC controller for multi-machine power system is designed using SIMULINK (a software tool associated with MATLAB). Multi-machine power system with turbine and governing system is modeled. Modeling is done for system with TCSC controller. Effect of TCSC controller parameter variation on rotor angle is also studied. A detailed analysis is conducted for the proposed controller for different fault clearing time. It has been observed that TCSC controller can improve the stability margin significantly.

TCSC controller provides variable impedance, which is required for the compensation. The presented controller is suitable only in capacitive zone. For the transition from a capacitive vernier mode to bypass mode the TCSC controller can be modeled with detailed dynamics.

CONTENTS

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NOMENCLATURE

α	Firing angle of thyristor
α_0	Initial firing angle of thyristor
β	Angle of advance
σ	Conduction angle of thyristor
σ_0	Initial conduction angle
C	Capacitor
C_F	Fixed series capacitor
I_m	Maximum current
$i_S(t)$	Variable current source
$i_T(t)$	Thyristor current
k	Compensation ratio
L_S	Thyristor controlled reactor
u	Switching variable
v_C	Nonsinusoidal capacitor voltage
V_{CF}	Fundamental frequency component of voltage
X_C	Nominal reactance of the fixed capacitor only
X_P	Inductive reactance of inductor connected in parallel with fixed capacitor
X_{TCSC}	Reactance provided by TCSC controller
T_S	Synchronizing torque coefficient
T_D	Damping torque coefficient
K	TCSC controller gain
T_w	wash out block time constant
T_1, T_2	lag/lead block time constants
$\Delta\delta$	Rotor angle variation
ω	Rotor Speed
$\Delta\omega$	Speed deviation
X_L	Line Reactance
ANN	Artificial neural network

FACTs	Flexible AC transmission system
NETOMAC	Network torsion machine tool
SMIB	Single machine infinite bus power system
STATCOM	Static synchronous compensator
SVC	Static Var compensator
TCPST	Thyristor controlled phase shifting transformer
TCSC	Thyristor controlled series capacitor
UPFC	Unified power flow controller

1.1 Introduction

With the economic development and rapid infrastructure changes, the electric utilities are facing many challenges to meet the heavily increasing demands of electric power. However, in the process of expanding and interconnecting of power systems various problems arise, such as:

- On account of the irregular distribution of the energy sources, and vast amount of transfer of electric power over long distance between the generating station and the load center, huge power losses in the lines occur.

- In the interconnected power system, the power flow from the generator to the consumers is dependent on the location of the generation node, of the consumer nodes and on the transmission paths available, i.e. on the power system topology and electrical characteristics of the lines involved, the result is transmission bottlenecks and unwanted parallel paths or loop flows.

- To meet the load and electric load and electric market demand, new lines should be added to the power system but because of the variety of environmental land use and regulatory pressures, the growth of electric power transmission lines in many parts of the world is restricted.

- In the large-scale power system, the stability becomes more critical; several large-area power failures due to damaging of the power system stability resulted in enormous economic losses in the world.

- The cost of transmission lines and losses, as well as difficulties encountered in building new transmission lines, would limit the available transmission capacity.

The economic and ecological reasons, the building of new transmission lines and the expanding of existing transmission systems are becoming difficult. In this situation it is necessary to utilize the power transmission system at its maximum capacity to meet increasing demand of electrical energy.

1.2 Power system Stability

Stability of power system has been major concern in system operation. This arises from the fact that in steady state (under normal conditions) the average electrical speed of all the generators must remain the same anywhere in the system. This is termed as the synchronous operation of a system. Any disturbance small or large can affect the synchronous operation. Loss of synchronism can occur between one machine and the rest of the system or group of machines. For example, there can be a sudden increase in the load or loss of generation. Another type of disturbance is the switching out of a transmission line, which may occur due to overloading or a fault. The stability of a system determines whether the system can settle down to a new or original steady state after the transients disappear.

With electric power system, the change in electrical torque of a synchronous machine following a perturbation can be resolved into two components:

$$\Delta T_e = T_S \Delta\delta + T_D \Delta\omega$$

Where, $T_S \Delta\delta$ is the component of torque change in phase with the rotor angle perturbation $\Delta\delta$ and is referred as the synchronizing torque component; T_S is the synchronizing torque coefficient.

$T_D \Delta\omega$ is the component of torque in phase with the speed deviation $\Delta\omega$ and is referred as the damping torque component; T_D is the damping torque coefficient.
System stability depends on the existence of both components of torque for each of the synchronous machines.

The disturbance can be divided into two categories (a) small (b) large. A small disturbance is one for which the system dynamics can be analyzed from linearization equations (small signal analysis). The small (random) changes in the load or generation can be termed as small disturbances. Initial power flow on that line may be considered as a small disturbance if the initial power flow on that line is not significant. However, faults, which result in a sudden dip in the bus voltages, are large disturbances and require remedial action in the form of clearing of the fault. The duration of the fault has a critical influence on system stability.

Stability of a system is divided in two broad classes. Namely, steady state stability or small signal stability and transient stability.

A power system is said to be steady state stable for a particular operating condition if, following any small disturbance, it reaches a steady state operating condition which is identical or close to the pre disturbance operating condition.

A power system is transiently stable for a particular steady state operating condition and for a particular (large) disturbance or sequence of disturbances if, following that (or those) disturbances it reaches an acceptable steady state operating condition. It is important to note that, while steady state is a function only of the operating condition, transient stability is a function of both the operating condition and the disturbance(s). Transient stability is described in detail in following section.

1.3 Transient stability

Transient stability is the ability of the power system to maintain synchronism when subjected to a severe transient disturbance. The resulting system response involves large excursions of generator rotor angles and is influenced by the nonlinear power angle relationship. Stability depends on both the initial operating state of the system and the severity of the disturbance. In large power systems, transient instability may not always occur as first swing instability; it could be result of several modes of oscillation causing large excursions of rotor angle beyond the first swing.

In transient stability studies the study period of interest is usually limited to 3 to 5 seconds following the disturbance, although it may extend to about ten seconds for very large system with dominant inter-area modes of oscillation. Transient stability limits the available transfer capacities.

1.4 Factors Influencing Transient Stability

Transient stability of the generator is dependent on the following:

- How heavily the generator is loaded
- The generator output during the fault. This depends on the fault location and type.
- The fault clearing time
- The post fault transmission system reactance.
- The generator reactance. A lower reactance increases peak power and reduces initial rotor angle.
- The generator inertia. The higher the inertia, the slower the rate of change in angle. This reduces the kinetic energy gained during fault.
- The generator internal voltage magnitude.
- The infinite bus voltage magnitude.

At present the most practical available method of transient stability analysis is time domain simulation in which the nonlinear differential equations are solved by using step-by-step numerical integration techniques. A method known as the equal area criteria can be used for a quick prediction of stability. This method is based on the graphical interpretation of the energy stored in the rotating mass as an aid to determine if the machine maintains its stability after a disturbance. This method is only applicable to one machine system connected to an infinite bus or two-machine system. The equal area criterion is used to determine the maximum additional power, which can be applied for stability to be maintained.

1.5 Transient Stability Controllers

Transient stability is important from the view point of maintaining system security, that is the incidence of a fault should not lead to tripping of generating unit due to loss of synchronism and the possibility of a cascaded outage leading to system black out. There are various means and ways of improving the transient stability of a system, which try to achieve one or more of the following effects:

- Reduction in the disturbing influence by minimizing the fault severity and duration
- Increase of the restoring synchronizing forces
- Reduction of the accelerating torque through control of prime mover mechanical power
- Reduction of accelerating torque by applying artificial load.

Unlike steady state or small signal stability, which has to be continuously maintained at all times, the transient stability is a function of the disturbance. The improvement of transient stability can be achieved not only by proper system design but also from the use of control action, which is not continuous, but is initiated following a disturbance and is temporary in nature.

1.6 FACTs Controller for Transient Stability Improvement

Studies show that the primary reason for the loss of transient stability in a power system is overloading of some of the lines, as a consequence of tripping off of the other lines after faults or heavy loss of loads. By the means of flexible and rapid control over the AC transmission parameters and network topology, flexible AC transmission system (FACTs) technology can facilitate the power control, enhance the power transfer capacity, decrease the line losses and generation costs, and improve the stability and security of the power system.

After having adopted FACTs devices, the operating point of the power system in steady state can be altered to improve the transient stability significantly. This can be done by correctly changing the pattern of power flow. A lot of studies show that the reason for the loss of transient stability in a power system is that some overloads occurred in some lines while some other lines were tripped off after faults.

Recent advances in FACTs devices offer the potential for enhanced system control both during steady state operation and following system disturbances. Thyristor controlled series compensator (TCSC), the first generation of FACTs, can control the line impedance through the introduction of a thyristor controlled capacitor in series with the transmission line. Different types of FACTs controllers and TCSC controller are discussed in further sections.

1.7 Report Organization

This dissertation is organized as follows:

Chapter 1 discusses different types of power system stabilities. In this chapter transient stability is also discussed in detail. This chapter also gives details of factors influencing transient stability.

Chapter 2 gives detailed review of literature of different FACTs devices and of TCSC controller used in power system has been given.

In Chapter 3 different types of FACTs controllers and controllable parameter of FACTs devices are discussed. This chapter gives details of FACTs controllers and TCSC controller used for transient stability improvement.

In Chapter 4 TCSC controller details has been given. In this chapter detailed mathematical modeling and transfer function model of TCSC controller has been given. Basic module and different modes of TCSC controller is discussed in this chapter.

Chapter 5 discusses the multi-machine power system modeling and mathematics involved for SIMULINK modeling.

In Chapter 6, the SIMULINK model for multi-machine system and TCSC controller has been given. In this chapter complete modeling of multi-machine power system has been explained.

In Chapter 7, the simulation results are shown for multi-machine power system with TCSC controller. Simulation for different TCSC controller parameters and fault clearing time is carried out.

Chapter 8 gives conclusions and identifies scope for future research in the area of TCSC controller.

2.1 Introduction

The rapid development of power electronics technology provides exciting opportunities to development new power system equipment for better utilization of existing systems. During last decade, a number of control devices under the term "Flexible AC transmission systems (FACTs) technology" have been proposed and implemented.

A large number of papers and reports have been published on theses subjects. Books by Mathur and Varma [1], Song and Johns [2], and Hingorani and Gyugyi [3] cover the basic idea about the FACTs devices. A detailed explanation has been given for all the FACTs devices.

Kundur [4] provides a general introduction to the power system stability problem, including a discussion of the basic concepts, classification, and the definitions of related terms. Edris [5] gives the history of emergence of FACTs and the recent developments in the field.

Zhang and Ding [6] give a general overview of FACTs devices development, briefly describes the effects of FACTs devices. This paper also presents some aspects and directions need to be studied. Habur and O'Leary [7] provide definitions of the most common application of FACTS devices as well as enumerate their benefits. Generic information on the costs and benefits of FACTS devices is then provided. The paper then discusses seven applications of FACTS devices in Australia, Brazil, Indonesia, South Africa and The USA.

2.2 FACTs Devices in Power Systems

Colvara et al. [8] discuss the problem of power system stability including FACTs controllers. First, the controlled series compensation is considered in the machine against infinite bar system and its effects are taken into account by means of construction of a Lyapunov function. After the multi – machine case is considered and is shown that the single machine results apply to multi – machine systems.

Mihalic and Gabrijel [9] have used Lyapunov function to develop control strategies for the thyristor-controlled phase shifting transformers (TCPSTs). Two typical representations of TCPSTs were chosen, a quadrature boosting transformer (QBT) and a phase angle regulator (PAR). For the QBT used the proposed control law can significantly improve the large signal stability in comparison to the control law based on the traditionally used model.

Gabrijel and Mihalic [10] have described the time domain digital simulation and direct method, which employs Lyapunov energy function for the transient stability assessment of power systems with FACTs controllers. The discussion focuses on direct methods and the derivation of appropriate energy functions using FACTs devices.

Hasmani et al. [11] have proposed a nonlinear coordinated generator excitation and thyristor controlled phase sifter (TCPS) controller to enhance the transient stability of multi-machine power system. To eliminate the nonlinearities and interconnections of the multi-machine power system, a direct feedback linearization (DFL) compensator through the excitation loop is designed. Digital simulation studies were conducted on a three- machine power system to show the effectiveness of the proposed control scheme in enhancing the transient stability of the system regardless of the network parameters, operating points and fault locations.

Lo and Khan [12] have presented an application of fuzzy logic control to determine the control signal of static var compensator (SVC) for improvement of power system stability. The presented controller is based on fuzzy set theory and is called fuzzy logic controller (FLC). The proposed FLC for SVC is proved to be very effective and robust in damping power system oscillations and thereby enhancing system transient stability.

Lo and Lin [13] have developed a new control strategy for multiple controlled series compensating (CSC) devices for the enhancement of power system stability. The findings of this study indicate that the CSC control scheme based on linear theory may fail to maintain stability during a major disturbance. The proposed control strategy is capable of overcoming this weakness. This is because the inherent characteristics of the electric power system. The effectiveness of the proposed method has been demonstrated from the case study of multi - machine power system.

Sharaf et al. [14] have presented a novel, self-adjusting variable series capacitor compensation (VSrC) scheme to enhance the transient stability of an interconnected AC system. In this paper the feasibility of a simple transient stability enhancement tool using FACTS – self-controlled, error driven, error scaled VSrC is studied. The stabilizing performance of VSrC is validated and verified by digital computer simulation on a single machine infinite bus system.

Sadeghzdeh et al. [15] investigate the application of FACTs devices to increase the maximum loadability of the transmission lines, which may be constrained by a transient stability limit. Hence, the on – line fuzzy control of the super conducting magnetic energy storage (SMES) and the static synchronous series compensator (SSSC) are suggested. The fuzzy rule bases are defined and explained.

Nelson et al. [16] have studied the effect of different FACTs controllers using critical fault clearing time (CFCT) on transient stability. Specifically the study compares, the high response (HIR) generator excitation system, SVC, STATCOM, TCSC and UPFC. The study demonstrates that FACTs, in general, are more powerful than high response excitation systems in enhancing transient stability.

Overbye and Brown [17] have described the development of new techniques for analysis and control of power systems using FACTs devices during both the voltage and transient stability time frames.

Wang et al. [18] have proposed nonlinear, variable structures control theory for series capacitor control and breaking resistor control to improve the transient stability of a SMIB power system. A related simulation follows and shows that variable structure control of series capacitor and breaking resistor is effective for enhancement of power system steady state performance and transient stability.

2.3 The Role of TCSC Controller in Power systems

TCSC is an effective and economical means of solving problems of transient stability, dynamic stability, steady state stability and voltage stability in long transmission lines. Dai et al. [19] propose an improved, artificial neural network (ANN) inversion control strategy, which can linearize the controlled TCSC system into a first order integral system in a wide range. By directly controlling active power through TCSC, both goals of indirectly controlling remote generator's power angle and enhancing the system's transient stability are simultaneously reached.

Juncheng et al. [20] present a mathematical model to explain the factors affecting transient response of the TCSC. The model can give advice to the design of TCSC controller. Rules of controller parameter adjustment are discussed and the model is verified by digital simulation results.

Lei et al. [21] have presented a coordinated control scheme for excitation systems and TCSC controls for improving the stability of a transmission system, where a power plant is connected with a proper grid through long transmission lines. The proposed control scheme is developed upon nonlinear optimal variable aim strategies. The simulation is carried by the NETOMAC program system.

Xu [22] explains the steady state characteristics of the TCSC in time domain and frequency domain. Based on this, the controllable impedance range of TCSC and its thyristor controlled reactance (TCR) constraints are studied. It is shown that the key point to select the reactance of the TCR is to determine the ratio of the reactance of series capacitor to that of the TCR. The concept of impedance sensitivity factor (ISF) of the TCSC is presented and it is proved that ISF is the main factor determining the controllable impedance range of TCSC.

Rosso [23] examines the use of TCSC for stability improvement of power systems. An appropriate TCSC model for angle stability studies is used to design a simple controller based on the dynamic response of the system. The aim of this paper is to design a proper TCSC controller based on small signal and transient stability analysis so that transfer capability limits can be increased. A simplified model of the Argentinean high voltage interconnected system is used to illustrate the concept presented in this paper.

Jiang and Lei [24] have used a nonlinear control scheme for the TCSC to damp power oscillations and improve transient stability of power system. The effectiveness and robustness of the proposed linear nonlinear control scheme are demonstrated with a single machine infinite bus power system. The TCSC modeling and power system simulation are performed using the program system NETOMAC. In comparison with a conventional control scheme, significant improvements of dynamical performance in the test power system are achieved by the proposed nonlinear control strategy for the TCSC.

Li et al. [25] have proposed a method that can accurately simulate the nonlinear performance of TCSC, so that the impact of TCSC on power system stability can be more reasonably evaluated. Zhou and Liang [26] have discussed the control scheme for TCSC to enhance the transient stability and power oscillation damping. Various issues related to the control schemes for TCSC on these two functions are discussed.

Xiaolu et al. [27] have presented a fundamental frequency stability model for TCSC. The paper first analyses the factors that influence the transients of TCSC when the operation condition changes and the time domain simulations are performed. Changes in the network such as connecting a shunt resistor, inserting a series capacitor, reduction in generation, load etc. when accomplished under suitable control scheme can improve transient stability. Switching of series capacitors in a transmission line can also help to damp oscillatory power transients.

Tan and Wang [28] have proposed a robust nonlinear thyristor controlled field excitation and series power flow controller to enhance the transient stability of a single machine infinite bus power system. The design of the resulting controller is independent of the operating point. Simulation results are presented to demonstrate the effectiveness of the proposed controller for transient stability of the power system.

Padiyar and Uma [29] have given a detailed analysis and study of a discrete control strategy for TCSC to improve stability. SMIB is considered to illustrate the development of control strategy. The energy function is used in determining the switching instants. The control philosophy is later extended to multi - machine system.

Han et al. [30] have analyzed the detailed dynamics of the TCSC. The system considered is single machine connected to infinite bus through TCSC transmission line. Transient characteristics as well as steady state characteristics of the TCSC are presented using the analytical equation for three operating modes of the TCSC. The simulations are performed using the MATLAB program.

Noroozian et al. [31] examine improvement of power system dynamics by use of UPFC, TCPST and TCSC. The achieved control laws are shown to be effective both for damping of large signal and small signal disturbances and are robust with respect to loading condition, fault location and network structure.

Gjerde et al. [32] have discussed the application of FACTs for enhancing system stability in the main grid of Southern Norway. General aspect of application of FACTs in the Norwegian power system has been discussed. The result indicates that TCSC could be used to redispatch the power flow on the tie lines and prevent synchronization problems after major disturbances in the South Norwegian main grid.

Paserba et al. [33] have presented a model for TCSC, which is applicable for typical transient and oscillatory stability studies. This paper also includes a discussion on relevant information to extend the modeling detail of the TCSC for use with long – term stability analysis. McDonald et al. [34] have analyzed TCSC for the transient stability improvement. The paper also describes the mathematical modeling and high current test series for the application of TCSC controller under severe requirements.

In the next chapter operating principles of the FACTs controllers are discussed in detail.

3.1 Introduction

FACTs technology opens up new opportunities for controlling and enhancing the useable capacity of present, as well as new upgraded lines. The possibility that current through a line can be controlled at a reasonable cost enables a large potential of increasing the capacity of existing lines with longer conductors and use one of the FACTs controller to enable corresponding power to flow through such lines under normal and contingency conditions.

These opportunities arise through the ability of FACTs controllers to control the interrelated parameters that govern the operation of transmission system including series impedance, shunt impedance, current, voltage, phase angle and the damping of oscillations at various frequencies below the rated frequency.

By providing added flexibility, FACTS controllers can enable a line to carry power closer to its thermal rating. FACTs technology refers to devices that enable flexible electrical power system operation, i.e. controlled active & reactive power flow redirection in transmission paths. FACTs device offers continuous control of power flow or voltage, against daily load changes or change in network topologies.

The first generation of FACTs devices emerged some thirty years ago in the form of passive reactive elements driven by thyristor switch banks. The second generation FACTs can achieve the same, and in some cases better, results with much smaller reactive elements by using power electronics with turn off capability. Because of their fast response FACTs can also improve the stability of an electrical power system by helping critically disturbed generators to give away the excess energy gained through the acceleration during fault.

3.2 Controllable Parameters for FACTs Devices

Following are the few basic points regarding the possibilities of power flow control:

- Control of the line impedance X (e.g. with thyristor controlled series capacitor) can provide a powerful means of current control.

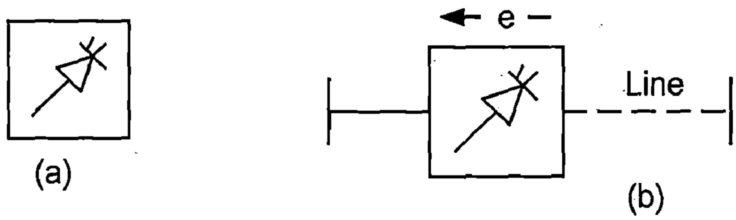
- When the angle is not large, which is often the case, control of X or the angle substantially provides the control of active power.
- Control of angle (with a phase regulator for example), which in turn controls the driving voltage, provides a powerful means of controlling the current flow and hence active power flow when the angle is not large.
- Injecting a voltage in series with the line, and perpendicular to the current flow, can increase or decrease the magnitude of current flow. Since the current flow lags the driving voltage by 90 degrees, this means injection of reactive power in series, can provide a powerful means of controlling the line current, and hence the active power when the angle is not large.
- Injecting voltage in series with the line and with any phase angle with respect to the driving voltage can control the magnitude and the phase of the line current. This means that injecting a voltage phasor with variable phase angle can provide powerful means of precisely controlling the active and reactive power flow. This requires injection of both active and reactive power in series.
- When the angle is not large, controlling magnitude of one or the other line voltages can be a very cost effective means for the control of reactive power flow through the interconnection
- Combination of the line impedance control with a series controlled and voltage regulation with a shunt controller can also provide a cost effective means to control both the active power flow and reactive power flow between the two systems.

3.3 Types of FACTs Controllers

In general FACTs controllers can be divided into four categories:

3.3.1 Series controller

The series controller could be variable impedance, such as capacitor, reactor, etc or power electronics based variable source of main frequency, sub synchronous and harmonic frequencies to serve the desired need. Figure 2.3(a) shows the general symbol of FACTs controllers. Figure 3.3(b) shows the series controller.



Figurė3.3 (a) General symbol of FACTs controller (b) Series Controller

In principle all the series controllers inject voltage in series with the line. Any other phase relationship will involve handling of real power as well. Series connected controller impacts the driving voltage and hence the current and power flow directly. Therefore, if the purpose of the application is to control the current/power flow and damp oscillations, the series controller for a given MVA size is several times more powerful than the shunt controller. SSSC, TCSC (discussed in detail in further sections) etc are the example of series controllers.

3.3.2 Shunt controller

As in the case of series controllers, the shunt controllers may be variable impedance, variable source, or a combination of these. In principle, all shunt controllers inject current into the system at the point of connection.

Figure 3.3(c) shows the shunt controller. The shunt controller is like a current source, which draws from or injects current into the line.

The shunt controller is therefore a good way to control voltage at and around the point of connection through injection of reactive current (leading or lagging), alone or a combination of active and reactive current for a more effective voltage control and damping of oscillations. One important advantage of the shunt controller is that it serves the bus node independently of the individual lines connected to the bus. STATCOM, SSG, SVC, TCR etc are the examples of shunt controllers.

3.3.3 Combined series-series controllers

This could be a combination of separate series controllers, which are controlled in a coordinated manner, in a multi-line transmission system or it could be a unified controller, in which series controller provide independent series reactive compensation for each line but also transfer real power among the line via the power link. Series-series controller is shown in figure 3.3(d). The real power transfer capability of the unified series-series controller, referred as interline power flow controller, makes it possible to balance both the real and reactive power flow in the lines and thereby maximize the utilization of the transmission system.

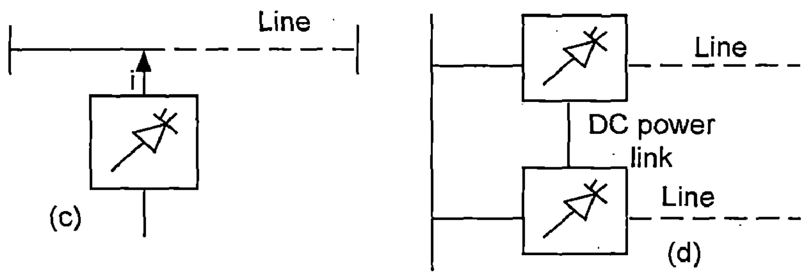


Figure 3.3 (c) Shunt controller (d) Combined series-series controller

3.3.4 Combined series-shunt controllers

Series-shunt controller is shown in figure 3.3(e). This could be a combination of separate shunt and series controllers, which are controlled in a coordinated manner, or a unified power, flow controller with series and shunt elements.

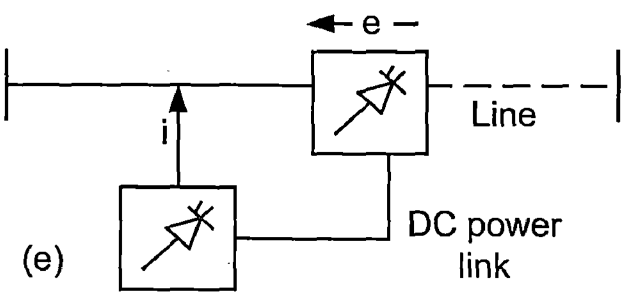


Figure 3.3 (e) Combined series-shunt controller

In principle, combined shunt and series controllers inject current into the system with the shunt part of the controller and voltage in series in the line with the series part of the controller. UPFC, TCPST are the example of shunt series controller.

3.3 Relative Importance of Different Types of Controllers

It is important to note that the series connected controller impacts the driving voltage and hence the current and power flow directly. Therefore, if the purpose of application is to control the current/power flow and damp oscillations, the series controller for a given MVA size is several times more powerful than the shunt controller.

The shunt controller on the other hand, is like a current source, which draws from or injects current into the line. The shunt controller is therefore a good way to control voltage at and around the point of connection through injection of current (leading or lagging), alone or a combination of active and reactive current for a more effective voltage control and damping voltage oscillations.

Adding or subtracting the FACTs controller voltage in series can be most cost effective way of improving the voltage profile. One important advantage of shunt controller is that it serves the bus node independently of the individual lines connected to the bus.

3.4 Advantages of FACTs Devicves

FACTs devices enable the transmission system to obtain one or more of the following benefits:

- Control of power flow as ordered. The use of control of the power flow may be to follow a contract, meet the utilities' own needs, ensure optimum power flow, ride through emergency conditions, or a combination thereof.
- Increase the loading capability of lines to their thermal capabilities, including short term and seasonal. This can be accomplished by overcoming other limitations, and sharing of power among lines according to their capability

- Increase the system security through raising the transient stability limit, limiting short circuit currents and overloads, managing cascading blackouts and damping electromechanical oscillations of power systems and machines.
- Provide secure tie line connections to neighboring utilities and regions thereby decreasing overall generation reserve requirements on both sides.
- Provide greater flexibility in siting new generation
- Upgrade of lines
- Reduce reactive power flows, thus allowing the lines to carry active power
- Reduce loop flows
- Increase utilization of lowest cost generation.
- Balancing the power flow over a wide range of operating conditions, thereby using the power system network most efficiently.
- Balancing the power flow in parallel networks operating at different voltage levels.

3.5 Application and Technical Benefits of Facts Devices

FACTs devices are required when there is a need to respond to dynamic (fast changing) network conditions. The conventional solutions are normally less expensive than FACTs devices, but limited in their dynamic behavior.

	Load Flow Control	Voltage Control	Transient Stability	Dynamic Stability	
SVC	*	* * *	*	* *	*
STATCOM	*	* * *	* *	* *	* *
TCSC	* *	*	* * *	* *	* * * Better ↓
UPFC	* * *	* * *	* *	* *	

Table 3.1 Technical benefits of FACTs devices

Table 3.1 below describes the technical benefits of the principle FACTs devices including steady state applications in addressing problems of voltage limits, loop flows, short circuit levels and sub synchronous resonance. Flexible AC Transmission system (FACTs) controllers can balance the power flow and thereby using the existing power system network most efficiently. In the next chapter the detailed mathematical model and transfer function model of TCSC controller is explained.

4.1 Introduction

Series capacitors offer certain major advantages over the shunt capacitors. With series capacitors, the reactive power increases as the square of line current, whereas with shunt capacitors, the reactive power is proportional to the square of bus voltage. For achieving same system benefits as those of series capacitors, shunt capacitors required are three to six times more reactive power rated than series capacitors. Furthermore shunt capacitors typically must be connected at the midpoint, whereas no such requirement exists for series capacitors.

TCSC is an effective and economical means of solving problems of transient stability, dynamic stability, steady state stability and voltage stability in long transmission lines. Thyristor controlled series compensator, the first generation of FACTs, can control the line impedance through the introduction of a thyristor controlled capacitor in series with the transmission line.

By flexibly and quickly adjusting the reactance of the TCSC, many relevant benefits can be achieved such as the better utilization of transmission capability, efficient power flow control, transient stability improvement, power oscillation damping, control over sub synchronous resonance (SSR), and fault current limitation.

4.2 Basic module of TCSC Controller

The basic module has a fixed series capacitor C, in parallel with a thyristor-controlled reactor, L_s as shown in figure 4.1(a). A metal oxide varistor (MOV) is connected across series capacitor to prevent the occurrence of high capacitor over voltages. MOV allows the capacitor to remain in circuit even during fault conditions and hence improves transient stability.

A circuit breaker (CB) is installed across capacitor for controlling the insertion of capacitor. If TCSC valves are required to operate in fully on mode for prolonged duration, the conduction losses are minimized by installing an ultra high speed contact (UHSC) across the valve. This offers a loss less switching operation similar to that of circuit breakers. The metallic contact is closed shortly after the thyristor is turned on, and is opened shortly before the valve is turned off. During a sudden overload of the valve, and also during fault conditions, the metallic contact is closed to minimize the stress on the valve.

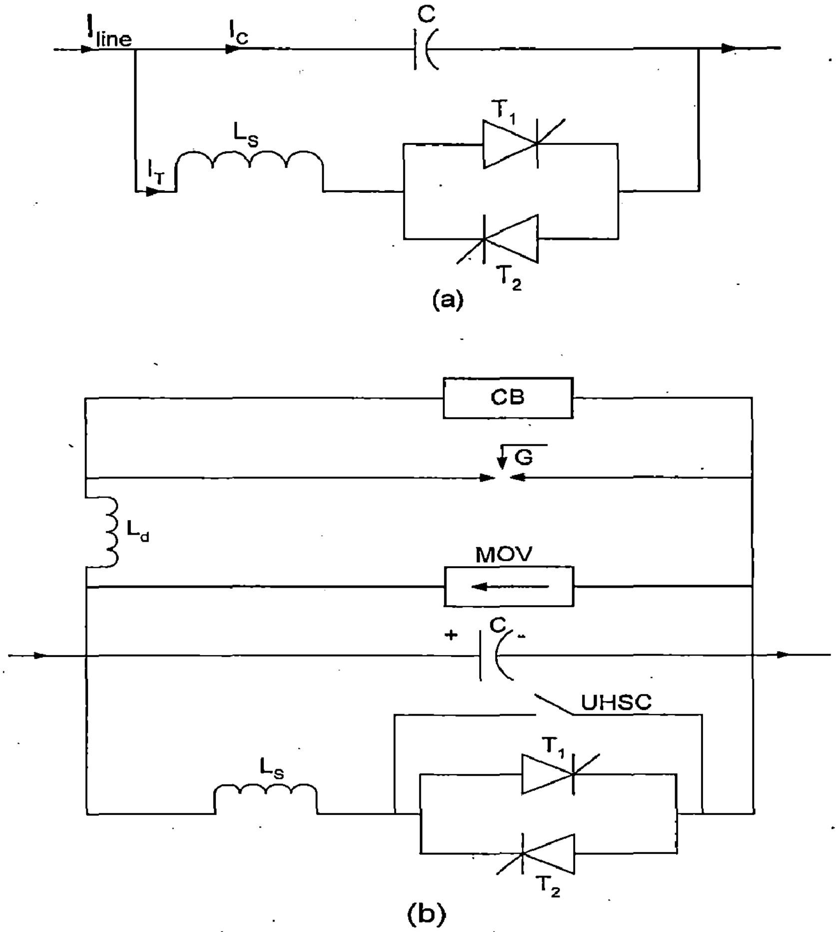


Figure 4.1 TCSC module (a) A basic module (b) a practical module

An actual TCSC system usually comprises a cascaded combination of many such TCSC modules, together with a fixed series capacitor; C_F. This fixed series capacitor is provided primarily to minimize costs.

Figure 4.2 shows the conceptual TCSC system with basic TCSC modules. The capacitors C_1, C_2,.., C_n; in different TCSC modules may have different values to provide a wider range of reactance control. The inductor in series with the anti-parallel thyristor is split into two parts to protect the thyristor valves in case of inductor short circuit.

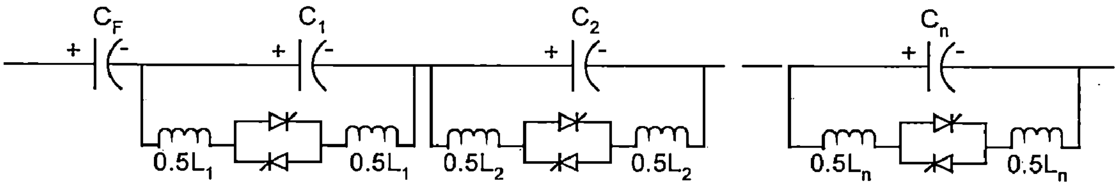


Figure 4.2 Conceptual TCSC system

4.3 Operation of TCSC Controller

A TCSC is a series controlled capacitive reactance that can provide continuous control of power on the AC line over a wide range. A simple understanding of TCSC functioning can be obtained by analyzing the behavior of a variable inductor connected in series with a fixed capacitor, as shown in figure 4.3. The equivalent impedance Z_{eq} of this LC combination can be expressed as:

$$Z_{eq} = \left(j\frac{1}{\omega C} \right) \| (j\omega L) = -j\frac{1}{\omega C - \frac{1}{\omega L}} \qquad (4.1)$$

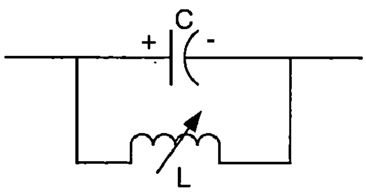


Figure 4.3 A variable inductor connected in shunt with a fixed capacitor

If $\omega C - (1/\omega L) > 0$ or $\omega L > (1/\omega C)$, the reactance of the FC is less than that of the parallel connected variable reactor and this combination provides a variable capacitive reactance. If $\omega C - 1/\omega L = 0$, a resonance develops that results in infinite capacitive impedance, this is an unacceptable condition. If $\omega C - (1/\omega L) < 0$, then the combination provides inductance above the value of fixed inductor. This situation corresponds to the inductive vernier mode of the TCSC operation, discussed in further section.

The behavior of TCSC is similar to that of the LC parallel combination. The difference is that the LC combination analysis is based on pure sinusoidal voltage and current in the circuit, where as in TCSC because of the voltage and current in the FC and thyristor controlled reactor (TCR) are not sinusoidal because of thyristor switching. The detail of TCSC working is discussed in further sections.

4.4 Modes of TCSC Operation

TCSC can operate in different modes because of the various operations of thyristor valves. There are three different modes of TCSC operation. These are discussed in detail in this section.

4.4.1 Bypassed thyristor mode

Figure 4.4 shows bypassed thyristor mode operation mode. In this mode, the thyristors are made to conduct fully with a conduction angle of 180°. Gate pulses are applied as soon as the voltage across the thyristor reaches zero and becomes positive, resulting in continuous sinusoidal flow of current through the thyristor valves. The TCSC module behaves like a parallel capacitor inductor combination.

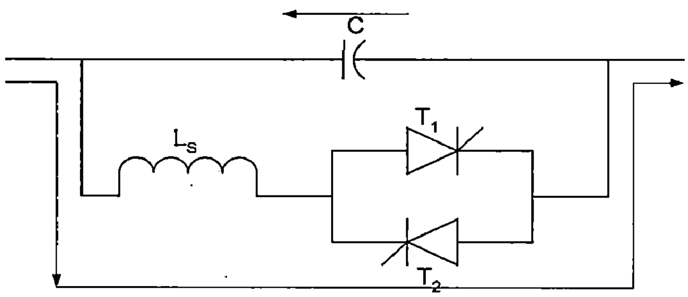


Figure 4.4 TCSC bypassed thyristor mode

4.4.2 Blocked thyristor mode

Figure 4.5 shows blocked thyristor mode operation. This mode is also known as waiting mode; in this mode the firing pulses to the thyristor valves are blocked. If the thyristors are conducting and a blocking command is given, the thyristors turn off as soon as the current through them reaches a zero crossing. Hence this behaves as fixed series capacitor, and the net TCSC reactance is capacitive.

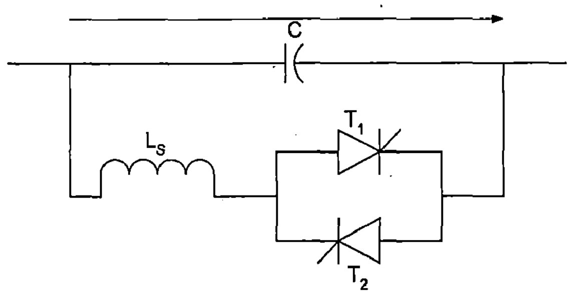


Figure 4.5 TCSC blocked thyristor mode

4.4.3 Partially conducting thyristor or vernier mode

Figure 4.6 (a) and 4.6 (b) show partially conducting thyristor or vernier mode operation. This mode allows the TCSC to behave either as a continuously controllable capacitive reactance or as a continuously controllable inductive reactance. This is achieved by varying the thyristor-pair firing angle in an appropriate range.

A variant of this mode is capacitive vernier control mode, in which the thyristors are fixed when the capacitor voltage and capacitor current have opposite polarity. This condition causes a TCR current opposite to capacitive current, thereby resulting loop current flow in the TCSC controller.

The loop current increases the voltage across the FC, effectively enhancing the equivalent capacitive reactance and series compensation level for the same value of the line current. Another variant is the inductive vernier mode, in this mode the direction of circulating current is reversed and the controller behaves as inductive impedance.

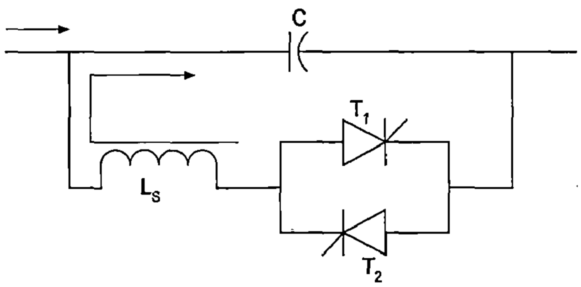


Figure 4.6 (a) TCSC partially conducting capacitive vernier mode

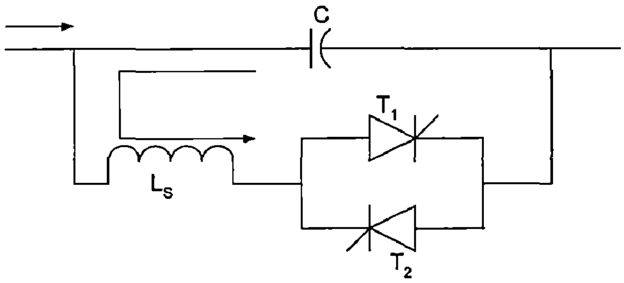


Figure 4.6 (b) TCSC partially conducting inductive vernier mode

4.5 Mathematical analysis of TCSC

Simplified TCSC circuit is shown in figure 4.7 for the analysis. Transmission line current is assumed to be the independent input variable and is represented as variable current source, $i_S(t)$. Here for the analysis the line current is assumed to be sinusoidal.

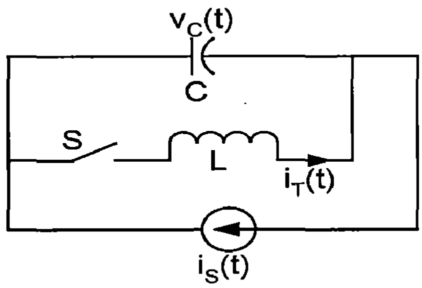


Figure 4.7 Simplified TCSC circuit

The current through the capacitor, C, is given as:

$$C\frac{dv_C}{dt} = i_S(t) - i_T(t).u \tag{4.2}$$

Where u is the switching variable.

$u = 1$, When thyristor valves are conducting or when switch S is closed.

$u = 0$, When thyristors are blocked or when switch S is open.

$i_T(t)$ is thyristor valve current and is given as

$$L\frac{di_T(t)}{dt} = v_C.u \tag{4.3}$$

and

$$i_S(t) = I_m \cos \omega t \tag{4.4}$$

Above equations can be solved by the knowledge of switching instants. For balanced TCSC operation, the thyristors are switched on twice in each cycle of line current at instants t_1 and t_3, given as

$$t_1 = -\frac{\beta}{\omega}$$

$$t_3 = \frac{\pi - \beta}{\omega}$$

Where β is the angle of advance before the forward voltage becomes zero.

i.e. $\beta = \pi - \alpha;\ \ 0 < \beta < \beta_{max}$

The firing angle α is generated using a reference signal that can be in phase with the capacitor voltage. The thyristor switch S turns off at the instants t_2 and t_4 defined as

$$t_2 = t_1 + \frac{\sigma}{\omega}$$

$$t_4 = t_3 + \frac{\sigma}{\omega}$$

Where σ is the conduction angle, which is same for positive and negative cycle of conduction.

$$\sigma = 2\beta$$

$$\text{or } \sigma = 2(\pi - \alpha) \qquad (4.5)$$

Here firing angle α, is defined as the period from the zero cross point of capacitor voltage v_c to the firing instant of the corresponding thyristor and Angle of advance β, is defined as the period from firing instant to the time when the forward voltage of the thyristor is lost.

By solving above equations the steady state thyristor current i_T can be given as

$$i_T(t) = \frac{k^2}{k^2 - 2} I_m \left(\cos\omega t - \frac{\cos\beta}{\cos k\beta} \cos\omega_r t \right); \qquad -\beta \le \omega t \le \beta \qquad (4.6)$$

Where

$$\omega_r = \frac{1}{\sqrt{LC}}$$

$$k = \frac{\omega_r}{\omega} = \sqrt{\frac{X_C}{X_P}} \qquad (4.7)$$

X_C = Nominal reactance of the fixed capacitor only.

X_P = Inductive reactance of inductor connected in parallel with fixed capacitor.

The steady state capacitor voltage at the instant $\omega t = -\beta$ is given as

$$v_{C1} = \frac{I_m X_C}{k^2 - 1}(\sin\beta - k\cos\beta\tan k\beta) \qquad (4.8)$$

At $\omega t = \beta, i_T = 0$, and capacitor voltage is

$$v_C(t) = v_{C2} = -v_{C1} \qquad (4.9)$$

The final expression for the capacitor voltage is given as

$$v_C(t) = \frac{I_m X_C}{k^2 - 1}\left(-\sin\omega t + k\frac{\cos\beta}{\cos k\beta}\sin\omega_r t\right); \qquad -\beta \le \omega t \le \beta \qquad (4.10)$$

$$v_C(t) = v_{C2} + \mathrm{Im}\,X_C(\sin\omega t - \sin\beta); \qquad \beta \le \omega t \le \pi - \beta \qquad (4.11)$$

The equivalent TCSC reactance is the ratio of V_{CF} to I_m

$$X_{TCSC} = \frac{V_{CF}}{I_m} = X_C - \frac{X_C^2}{(X_C - X_P)}\frac{2\beta + \sin 2\beta}{\pi} + \frac{4X_C^2}{(X_C - X_P)}\frac{\cos^2\beta}{(k^2 - 1)}\frac{(k\tan k\beta - \tan\beta)}{\pi} \qquad (4.12)$$

or

$$X_{TCSC} = \frac{V_{CF}}{I_m} = X_C - \frac{X_C^2}{(X_C - X_P)}\frac{\sigma + \sin\sigma}{\pi} + \frac{4X_C^2}{(X_C - X_P)}\frac{\cos^2(\sigma/2)}{(k^2 - 1)}\frac{(k\tan(k\sigma/2) - \tan(\sigma/2))}{\pi}$$

(4.13)

$$X_{pu} = \frac{X_{TCSC}}{X_C}$$

The variation of per unit TCSC reactance as a function of firing angle α for different values of X_C/X_P is described in figure 4.8. If value of X_C is changed then the maximum value of X_{TCSC} also changes and hence initial value of compensation can be changed. In figure 4.8 the value of X_C is 0.08, whereas in figure 4.9 value of X_C is 0.22.

It is clear from figures 4.8 and 4.9 that change in X_C affects X_{TCSC} variation significantly. Hence provides flexibility for compensation. Figure 4.10 shows X_{TCSC} variation for different value of X_C for constant k. It is to be noted that a parallel resonance is created between X_P and X_C at the fundamental frequency. At the resonant point, the TCSC exhibits very large impedance and results in a significant voltage drop. The resonant region is avoided by installing limits on the firing angle. TCSC is mainly used in capacitive zone.

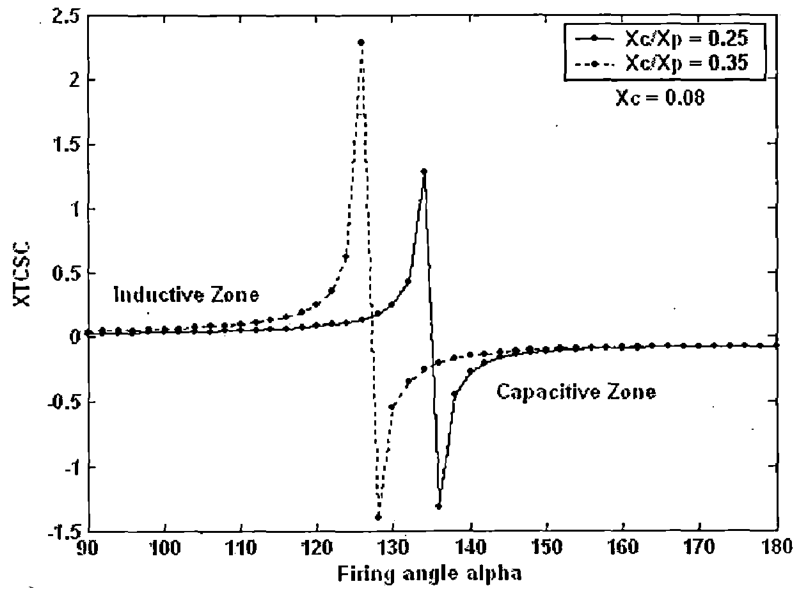


Figure 4.8 X_{TCSC} vs α for different values of k for X_C = 0.08

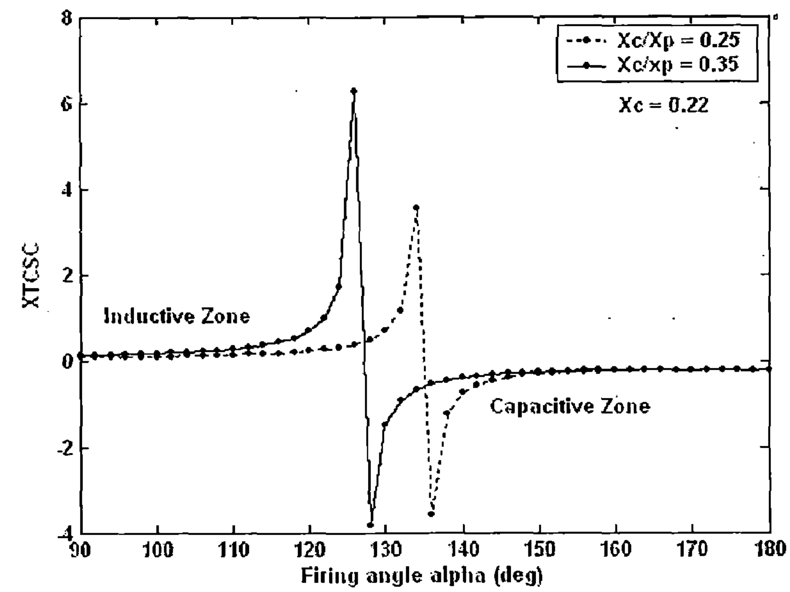


Figure 4.9 X_{TCSC} vs α for different values of k for X_C = 0.22

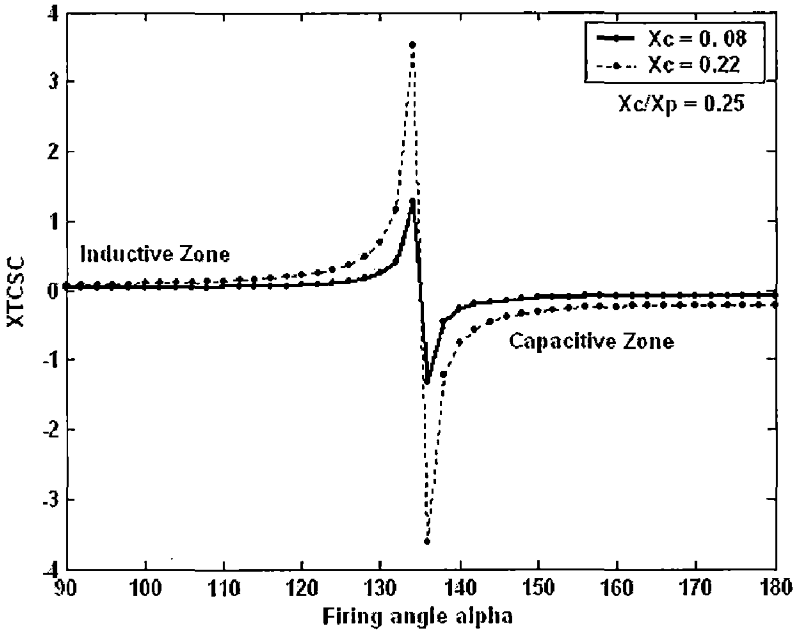


Figure 4.10 X_{TCSC} vs α for different values of X_C for $k = 2$

4.6 Transfer function model of TCSC controller

Figure 4.11 shows transfer function model of TCSC controller. TCSC controller input signal is speed deviation $\Delta\omega$ and output signal is the stabilizing signal. (i.e. deviation in conduction angle $\Delta\sigma$). It comprises of gain block, signal washout block and phase compensator block. An optimum controller can be obtained by suitable selection of time constants T_w, T_1, T_2 and gain K with some designing technique.

The signal wash out block is a high pass filter that prevents the steady changes in the speed by modifying the conduction angle. The value of washout time constant T_w should be high enough to allow signals associated with rotor oscillation to pass unchanged. T_w may be in the range of 1-20 sec. The phase lead compensator is used for the phase lag between the angular speed and the resulting electrical torque, so that the TCSC controller produces a component of electrical torque in phase with the rotor speed deviation. The gain of TCSC controller is chosen such that it provides satisfactory damping.

The effective line reactance can be given as $X_{TL} = X_{Line} - X_{CF} - X_{TCSC}(\sigma)$; Where $\sigma = \sigma_0 + \Delta\sigma$, σ_0 = initial value of conduction angle. X_{Line} is the line reactance. Change in conduction angle σ_0 changes initial compensation. The compensation may be provided only through TCSC controller (i.e. X_{TCSC}) or it may be divided in two components i.e. fixed capacitor X_{CF} with TCSC controller (X_{TCSC}). Figs 4.12 & 4.13 show both configurations respectively.

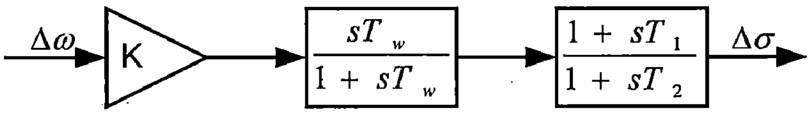


Figure 4.11 Transfer function model of TCSC controller

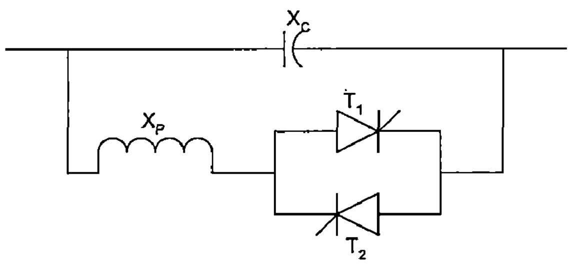


Figure 4.12 Total compensation through X_{TCSC}

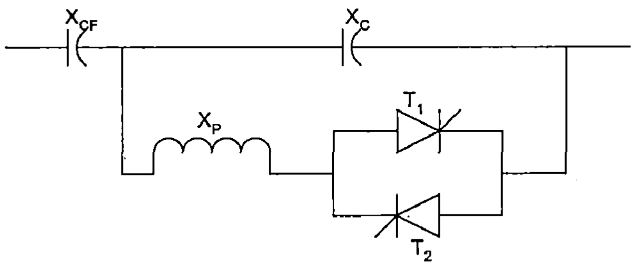


Figure 4.13 Combined compensation with series capacitor

4.7 Placement of the TCSC Controller

The placement of FACTs controllers at appropriate location is a critical issue. An optimally placed FACTs device requires a lower rating to achieve the same control objective than if it were located elsewhere. At times, the FACTs controllers may be need to be placed at non-optimal locations to minimize costs, especially when land prices and environmental concerns become important.

The following conditions generally apply when land prices and environmental concerns become important. The following conditions generally apply when considering the placement of TCSC controllers:

- The TCSC controllers should be located in lines that experience limiting power oscillations.
- The swing of voltage on each side of the TCSC controllers must be within acceptable limits.
- The control action of the TCSC controllers in one transmission path should not cause undue power swings in a parallel path. If it does, then variable series compensation may become necessary in the parallel path.
- Sometimes it may be advisable to distribute the control action between multiple TCSC controllers rather than confining the control action to one large rating TCSC controller.

For the system studied location of TCSC is decided by calculating power flow during different fault conditions, which is described in chapter 6.

In the next chapter mathematical modeling of multi-machine power system have been discussed.

5.1 Mathematical Modeling Of Multi-Machine Power System

A typical example of a multi-machine power system network is given in figure 5.1.1, which is three-machine nine-bus system with three loads. For the purpose of this study the generators are represented by the classical model and loads by constant impedances. The generator and the power system network are represented in terms of the characteristic equations under dynamic conditions. Once the Y matrix for each network condition (pre-fault, during fault and after fault) is calculated, we can eliminate all the nodes except for the internal generator nodes so as to obtain the Y matrix for the reduced network.

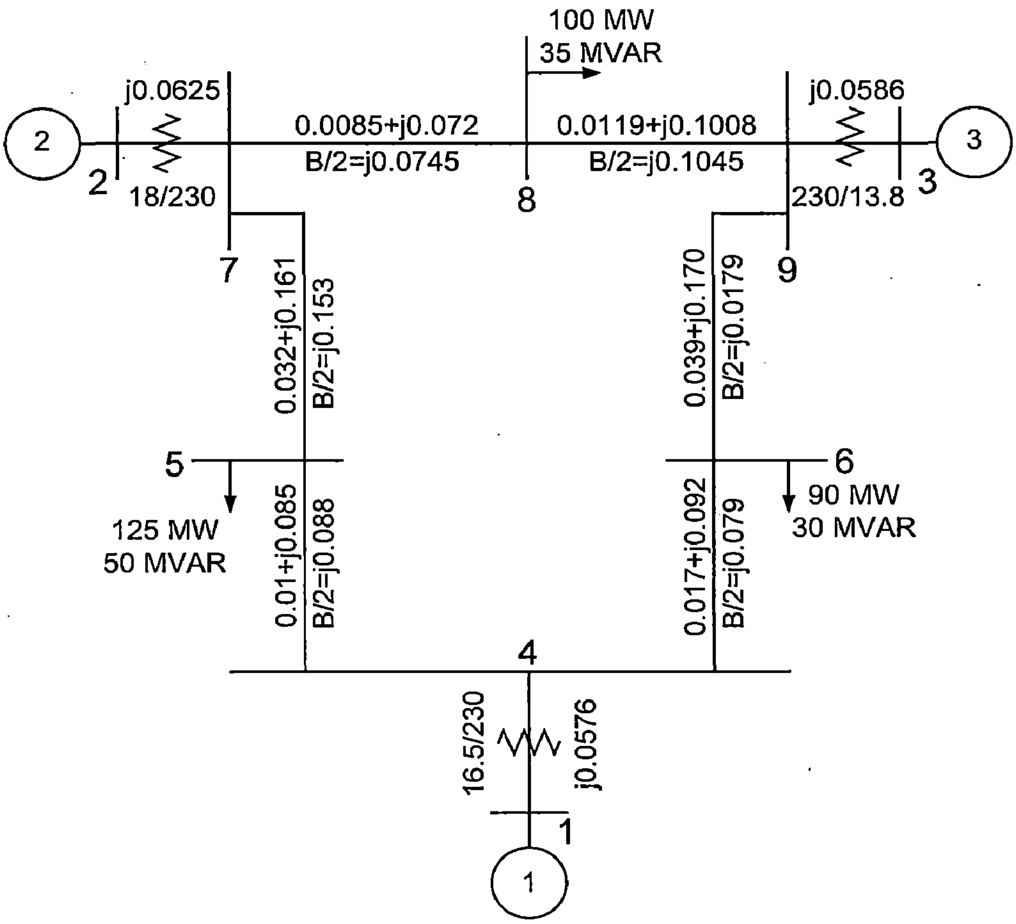


Figure 5.1.1 WSCC 3-machine, 9-bus system

The reduction can be achieved by matrix operation with the fact in mind that all the nodes have zero injection currents except for the internal generator nodes. In the power system with n generators, the nodal equation can be written as:

$$\begin{bmatrix} I_n \\ 0 \end{bmatrix} = \begin{bmatrix} Y_{nn} & Y_{nr} \\ Y_{rn} & Y_{rr} \end{bmatrix} \begin{bmatrix} V_n \\ V_r \end{bmatrix}, \tag{5.1}$$

where, the subscript 'n' is used to denote generator nodes and the subscript 'r' is used for the remaining nodes.

Expanding equation 5.1,

$I_n = Y_{nn}V_n + Y_{nr}V_r$, $0 = Y_{rn}V_n + Y_{rr}V_r$

From which we eliminate V_r to find

$$I_n = \left(Y_{nn} - Y_{nr}Y_{rr}^{-1}Y_{rn}\right)V_n \tag{5.2}$$

Thus, the desired reduced matrix can be written as follows,

$$Y_R = \left(Y_{nn} - Y_{nr}Y_{rr}^{-1}Y_{rn}\right) \tag{5.3}$$

It has dimensions (n * n) where 'n' is the number of generators. Note that the network reduction illustrated by Eqs (5.1) - (5.3) is a convenient analytical technique that can be used only when the loads are treated as constant impedances.

For the power system under study, the reduced matrices are calculated. The power into the network at node 'i', which is the electrical power output of machine 'i', is given by,

$$P_{ei} = E_i^2 G_{ii} + \sum_{\substack{j=1 \\ j \neq i}}^{n} E_i E_j Y_{ij} \cos(\theta_{ij} - \delta_i + \delta_j) \quad i = 1,2,3,\ldots\ldots n \tag{5.4}$$

where

$\overline{Y}_{ij} = Y_{ij}\angle\theta_{ij} = G_{ij} + jB_{ij}$ = Negative of the transfer admittance between nodes 'i' and 'j'.

$\overline{Y}_{ii} = Y_{ii}\angle\theta_i = G_{ii} + jB_{ii}$ = Driving point admittance of node 'i'.

The equations of motion are given by,

$$\frac{2H_i}{\omega_R}\frac{d\omega_i}{dt} + D_i\omega_i = P_{mi} - \left[E_i^2 G_{ii} + \sum_{\substack{j=1 \\ j \neq i}}^{n} E_i E_j Y_{ij} \cos(\theta_{ij} - \delta_i + \delta_j)\right] \tag{5.5}$$

$$\frac{d\delta_i}{dt} = \omega_i - \omega_R \qquad i = 1,2,3,........n \qquad (5.6)$$

It should be noted at this point that prior to the disturbance $(t = 0^-)$ $P_{mi0} = P_{ei0}$,

There by,

$$P_{ei0} = E_i^2 G_{ii0} + \sum_{\substack{j=1 \\ j \neq i}}^{n} E_i E_j Y_{ij0} \cos(\theta_{ij0} - \delta_{i0} + \delta_{j0}) \qquad (5.7)$$

The subscript '0' is used to indicate the pre-transient conditions.

As the network changes due to switching during the fault, the corresponding new values of the variables are replaced in the above equations. Figures 5.1.2 & 5.1.3 gives the Simulink representation of the characteristic equations.

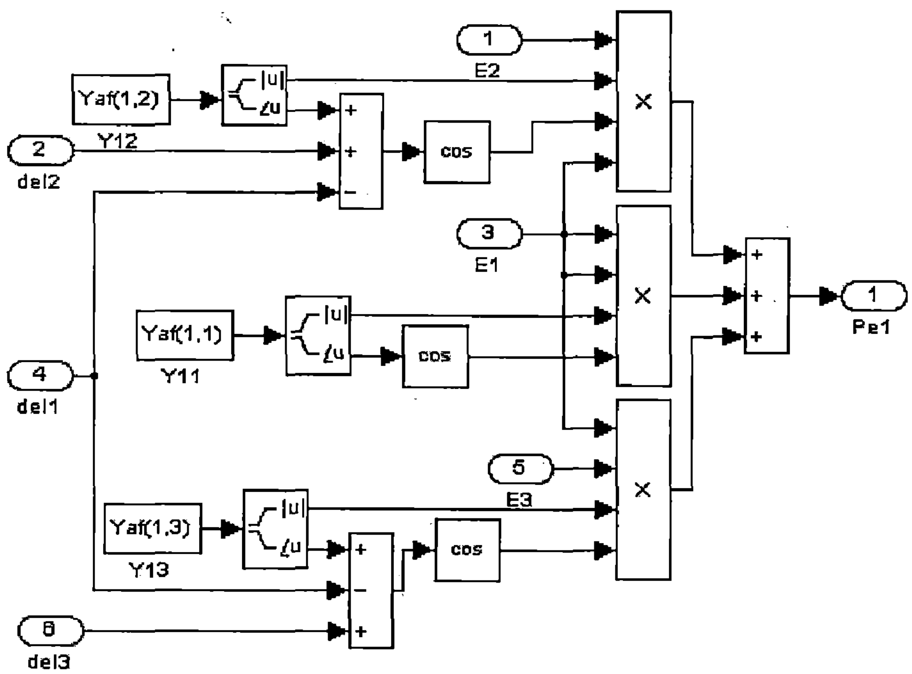


Figure 5.1.2 Computation of electrical power output of gen. # 1

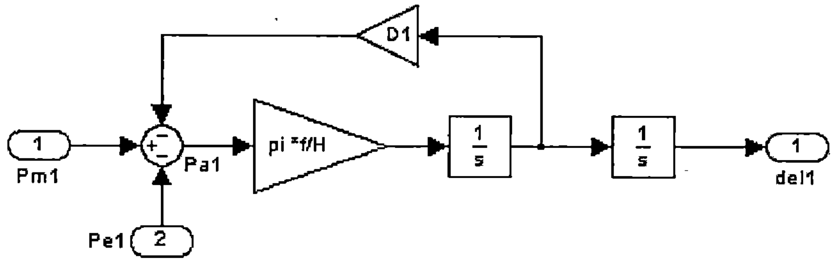


Figure 5.1.3 Representation of equation of motion of gen. # 1

In a classical system of representation the mechanical power input to the generators and the internal machine voltages are assumed to be constant. In the next chapter detailed multi-machine modeling in SIMULINK and simulation results are discussed.

5.2 Simulink Modeling of Multi-Machine Power System

The complete system has been represented in terms of SIMULINK (a software tool associated with MATLAB) blocks in a single integral model. SIMULINK is an interactive environment for modeling, analyzing and a wide variety of dynamic systems. It provides a graphical user interface for constructing block diagram model using "drag-drop" operations.

A system is configured in terms of block diagram representation from a library of standard components. A parameter within any block can be controlled from MATLAB command line or through m-file program. This is useful for transient stability study as the power system configuration differ before fault and after fault.

The 3 machine 9 bus system is taken as an example for the study as shown in figure 5.1.1. Three-phase fault near bus 7 at the end of line 5-7 is assumed and the fault is cleared in by opening line 5-7. For the analysis first reduced Y matrix is to be calculated, figure 5.2.1 below shows the SIMULINK model for the calculation of $Y_{reduced}$ according to equation (5.3). This is further utilized for the calculation of electrical power of the generator (e_1) as shown in figure 5.2.2. Similarly e_2 and e_3 are calculated.

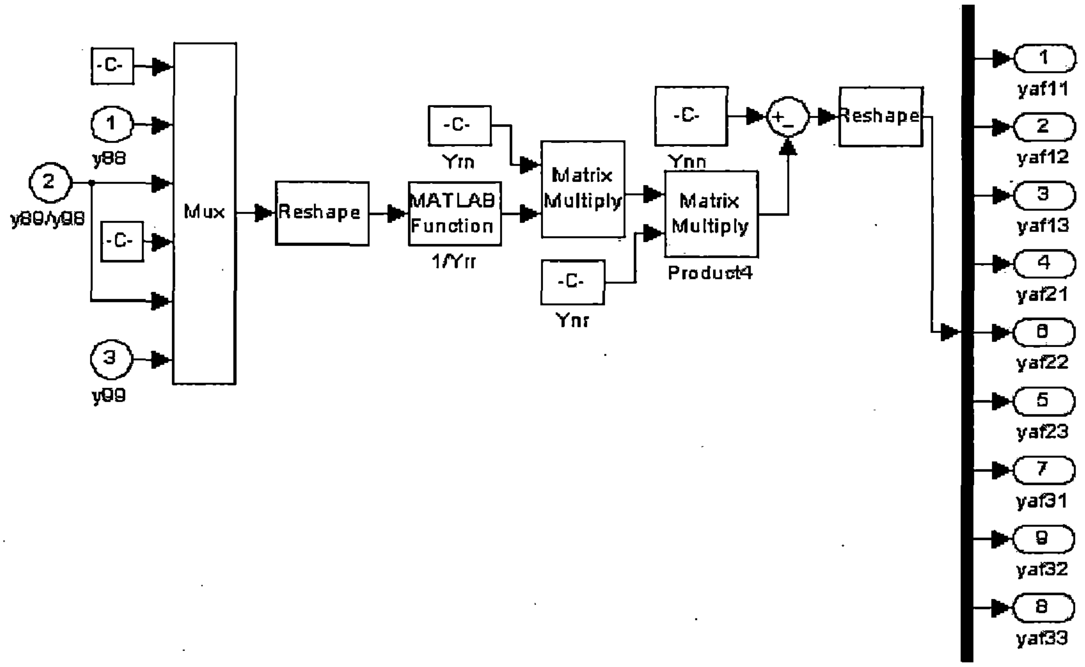


Figure 5.2.1 SIMULINK model for $Y_{reduced}$ calculation

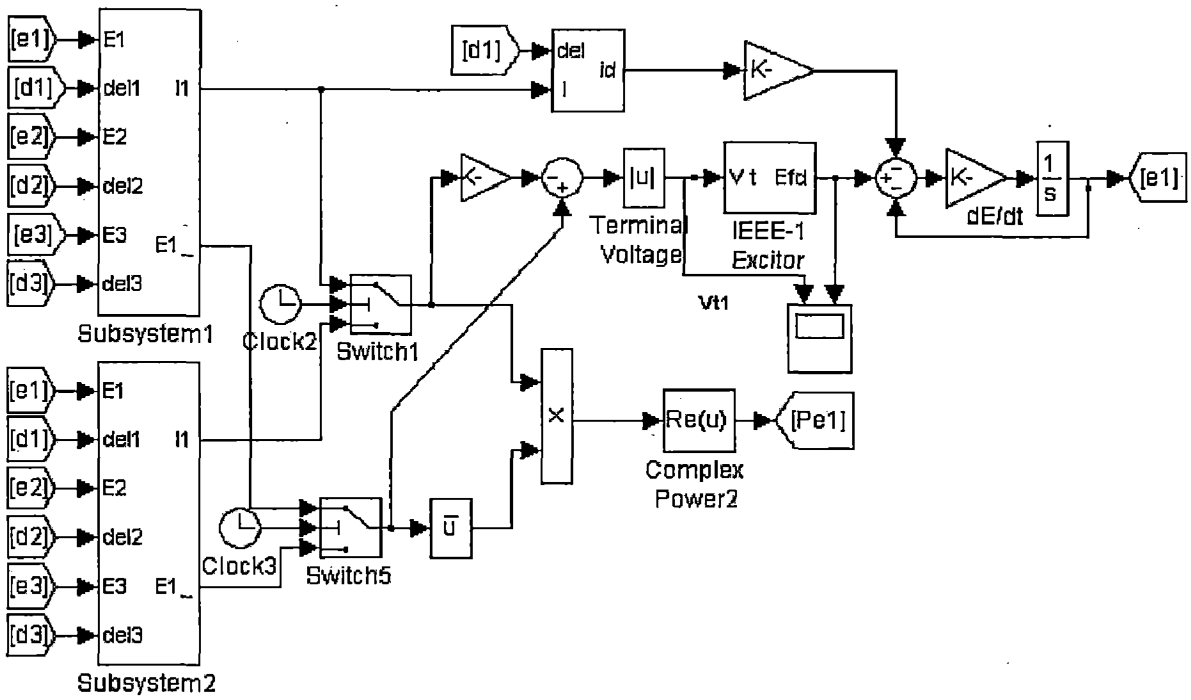


Figure 5.2.2 SIMULINK model for the calculation of electrical power (e_1) of gen. # 1(without TCSC controller)

Figure 5.2.3-5.2.5 show the SIMULINK model for the calculation of generator angles δ_1, δ_2 and δ_3 respectively.

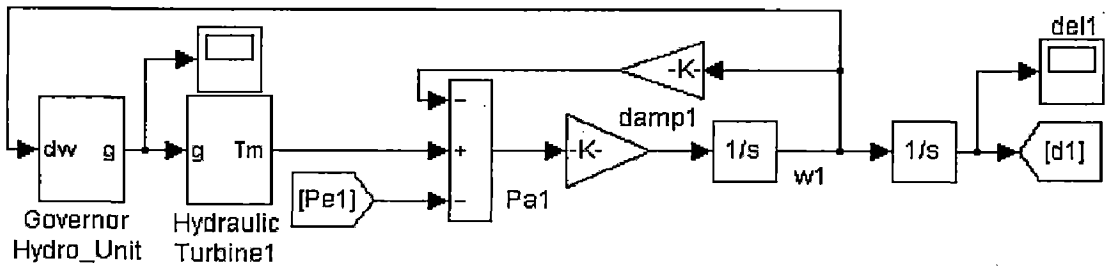


Figure 5.2.3 SIMULINK model for the calculation of rotor angle of gen.#1 (δ_1)

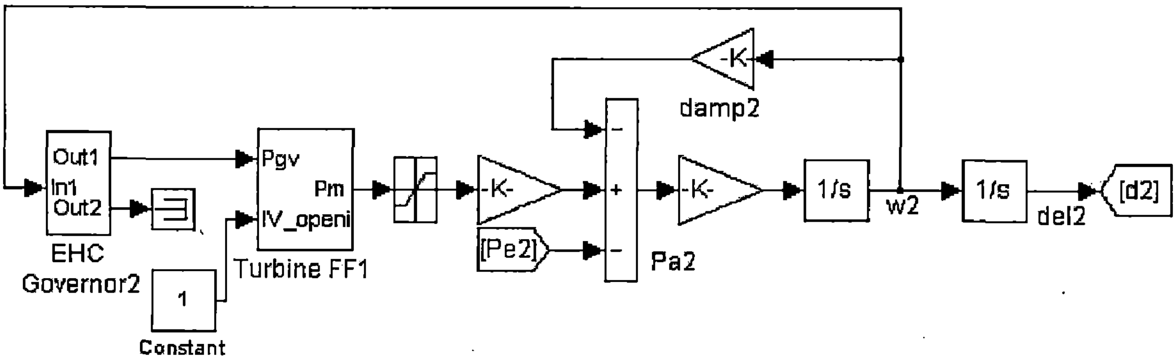


Figure 5.2.4 SIMULINK model for the calculation of rotor angle of gen. # 2 (δ_2)

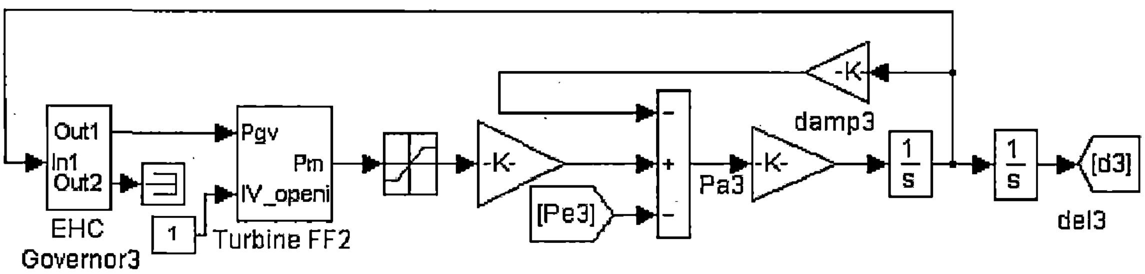


Figure 5.2.5 SIMULINK model for the calculation of rotor angle of gen. # 3 (δ_3)

After the calculation of individual rotor angles δ_{21} and δ_{31} is calculated as shown in figure 5.2.6 and 5.2.7 respectively.

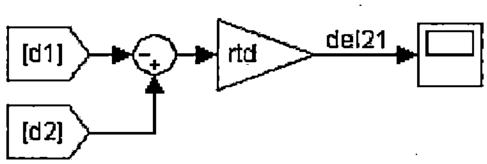


Figure 5.2.6 SIMULINK model for the calculation of δ_{21}

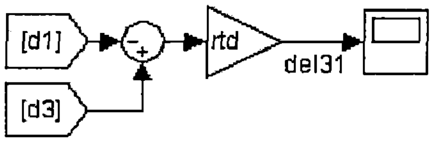


Figure 5.2.7 SIMULINK model for the calculation of δ_{31}

Figure 5.2.8 shows the SIMULINK model of the TCSC controller, which is inserted in line 8-9. From Table A.2 and A.3 it is clear that line 8-9 experiences severe changes in power flow. Hence TCSC controller is inserted in line 8-9. The input signal of the TCSC controller is variation in δ_{21} and the output is X_{TCSC}. With the help of wash out block and lag/lead compensator block the variation in δ_{21} and δ_{31} is converted to equivalent conduction angle variation $\Delta\sigma$ and then this change is converted to equivalent compensation X_{TCSC} that is to be provided for the system.

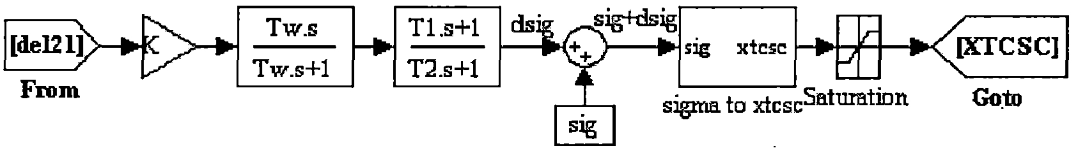


Figure 5.2.8 SIMULINK model of TCSC controller (del21 to X_{TCSC} conversion)

Figure 5.2.9 below shows the subsystem for the conversion of $\Delta\sigma$ into X_{TCSC}, according to equation 4.13.

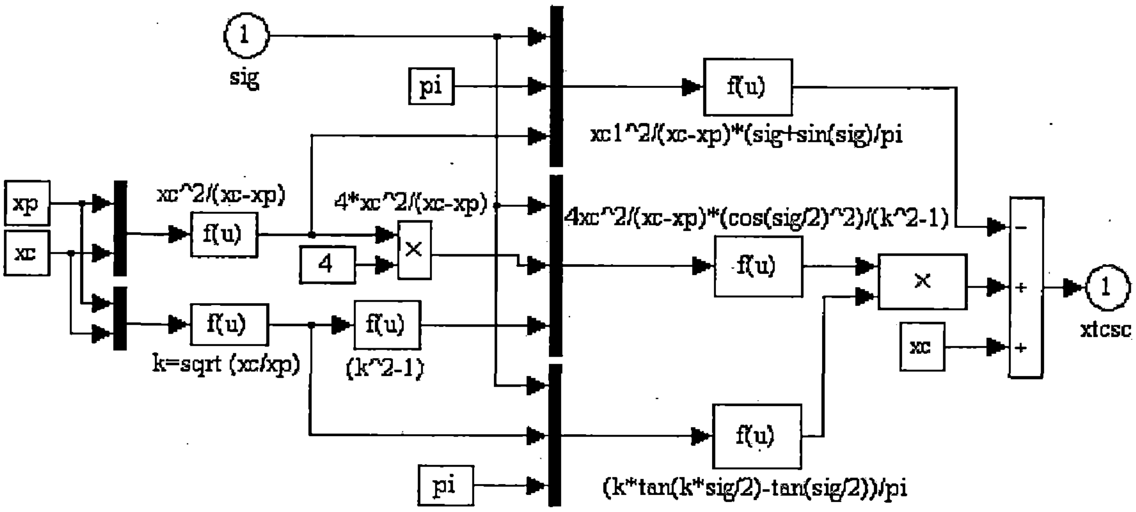


Figure5.2.9 SIMULINK model of TCSC controller subsystem sigma to X_{TCSC} conversion

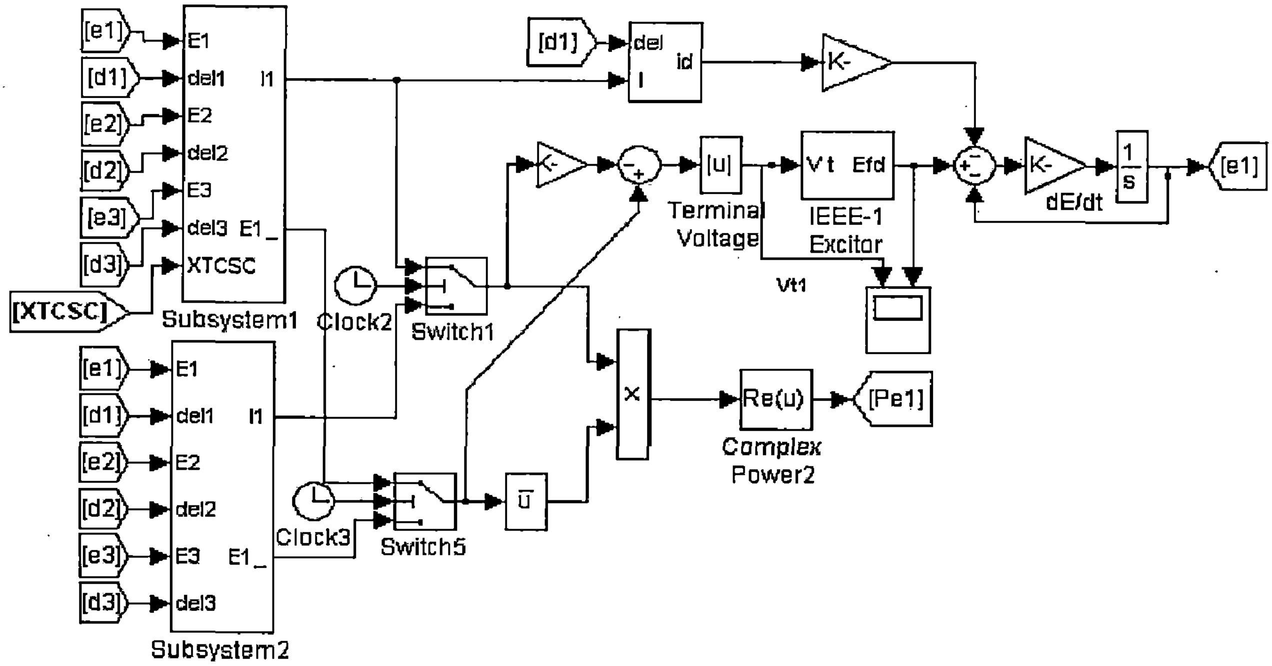


Figure 5.2.10 SIMULINK model for the calculation of electrical power (e_1) of gen.# 1(with TCSC controller)

Figure 5.2.10 shows the subsystem for the calculation of electrical power of generator # 1 with TCSC controller. Similarly e_2 and e_3 is calculated, and then new values of δ_{21} and δ_{31} is calculated accordingly. Figures 5.2.11 and 5.2.12 show the subsystem for the calculation of E_1 and I_1.

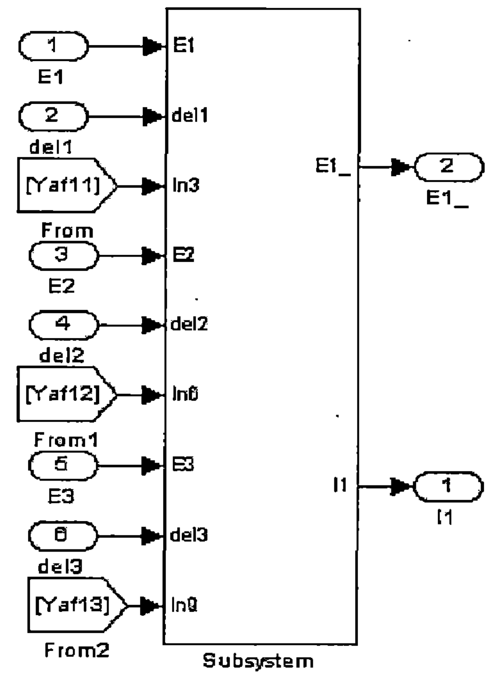


Figure 5.2.11 Subsystem for the calculation of E_1 and I_1

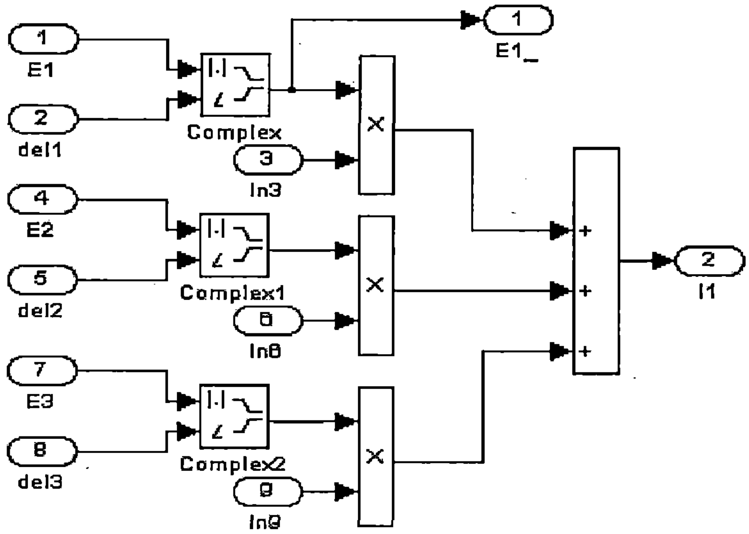


Figure 5.2.12 SIMULINK model for the calculation of E_1 and I_1

The SIMULINK model of multi-machine power system with TCSC controller is analyzed for different conditions. Figures 6.1 and 6.2 show rotor angle variation for multi-machine power system without any compensation, with conventional series compensation and with TCSC controller. Analysis shows that if compensation is provided directly then the damping is slower. But compensation is provided through TCSC controller then system attains stability at a faster rate. With conventional series compensation system oscillates more but with TCSC controller the stability is achieved at a faster rate. It can be said that for the same amount of compensation TCSC controller can provide better damping. For figure 6.1 Fault clearing time (FCT) is taken as 0.10 sec and following are the TCSC controller parameter values K = 3, T_W = 20, T_1 = 10, T_2 = 20, initial firing angle α_0 = 150°.

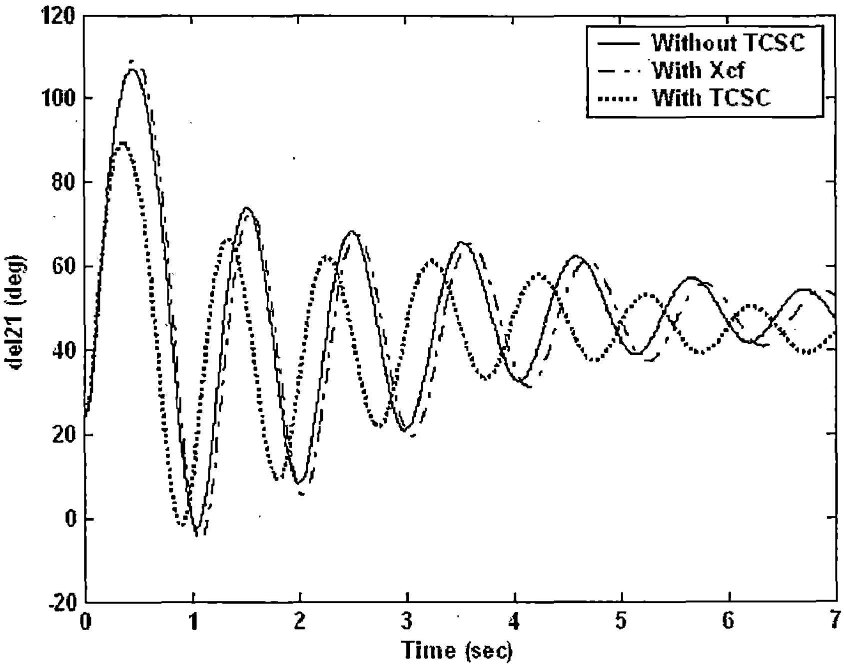


Figure 6.1 Rotor angle δ_{21} variation for different compensation

Figure 6.3 shows X_{TCSC} variation for different values of X_C at constant k. If X_C is decreased than the value of initial compensation also decreases at constant k. Another method of changing XTCSC is by changing the value of compensation ratio k and keeping X_C constant, as shown in figure 6.4. Similarly if X_C/X_P ratio is changed the TCSC controller automatically changes the value of compensation accordingly, as shown in figure 6.5.

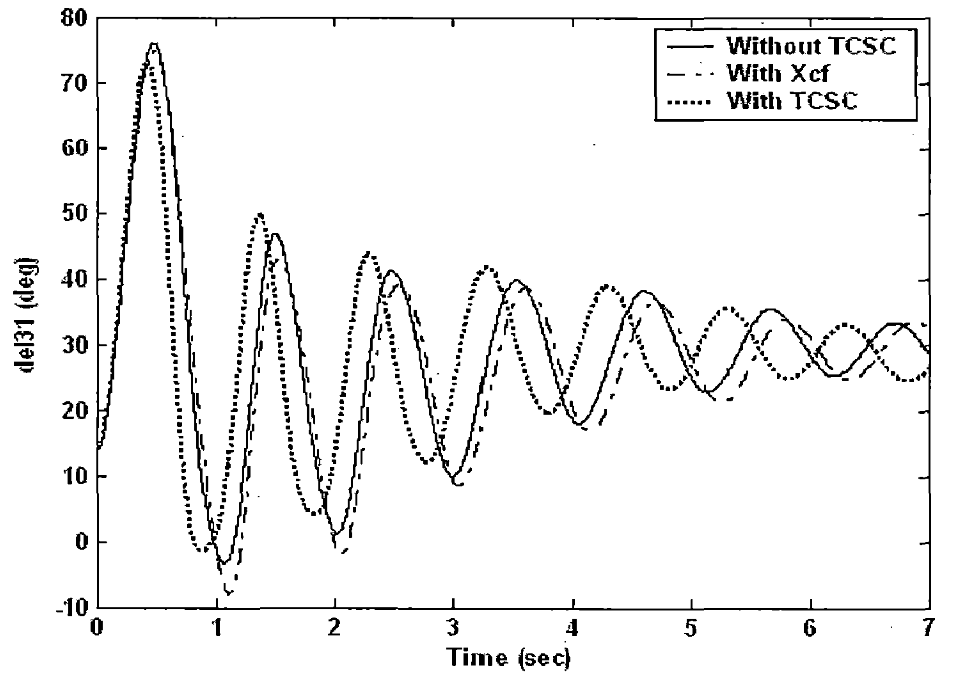


Figure 6.2 Rotor angle δ_{31} variation for different compensation

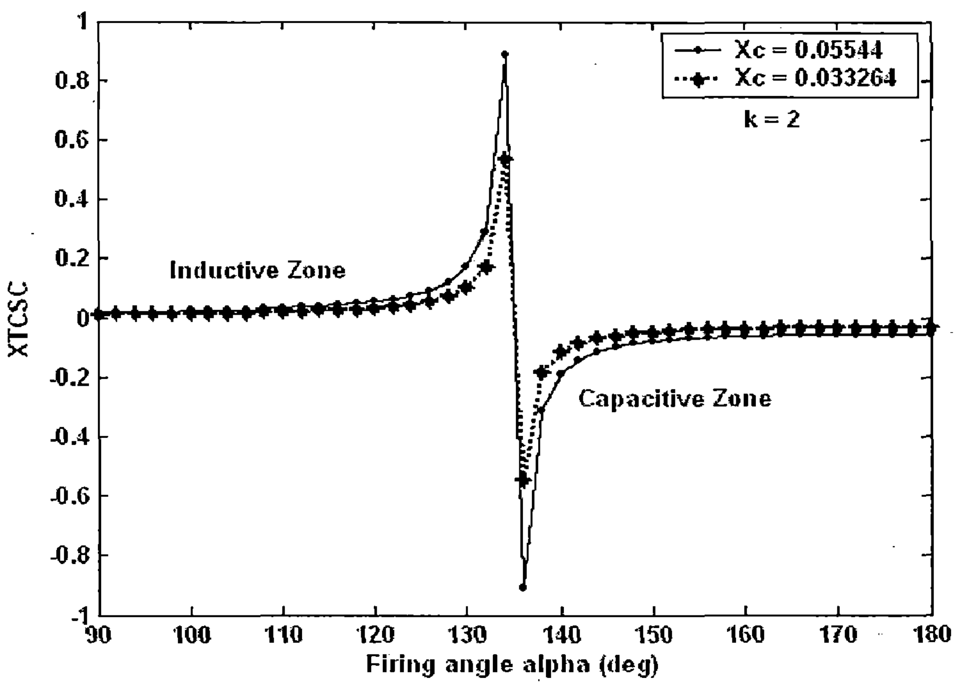


Figure 6.3 X_{TCSC} variation for different values of X_C at constant k=2

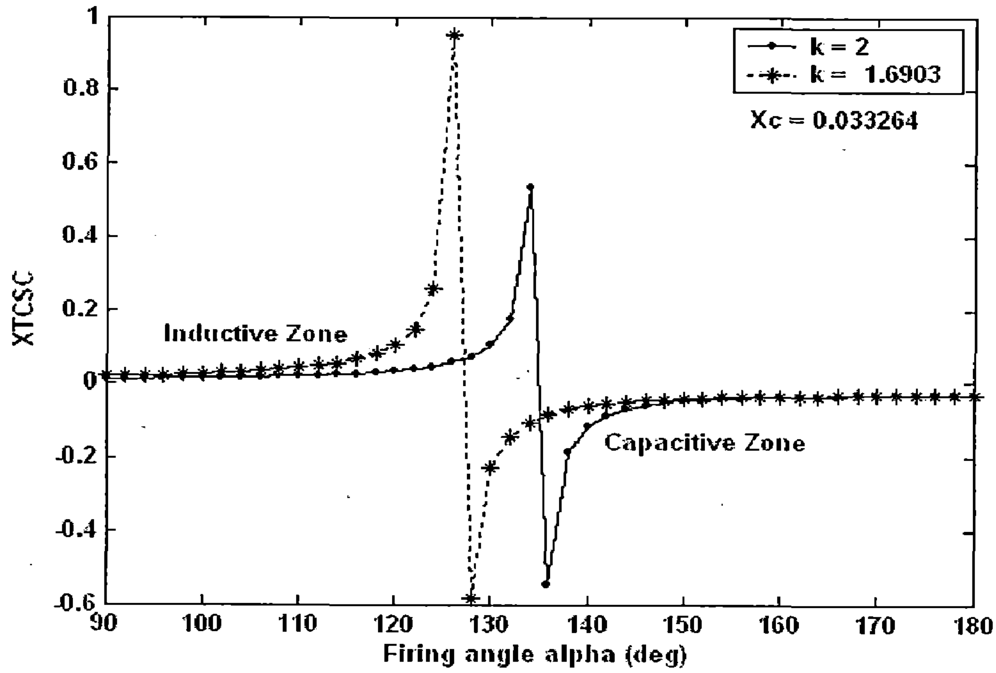


Figure 6.4 X_{TCSC} variation for different values of k at constant X_C = 0.033264

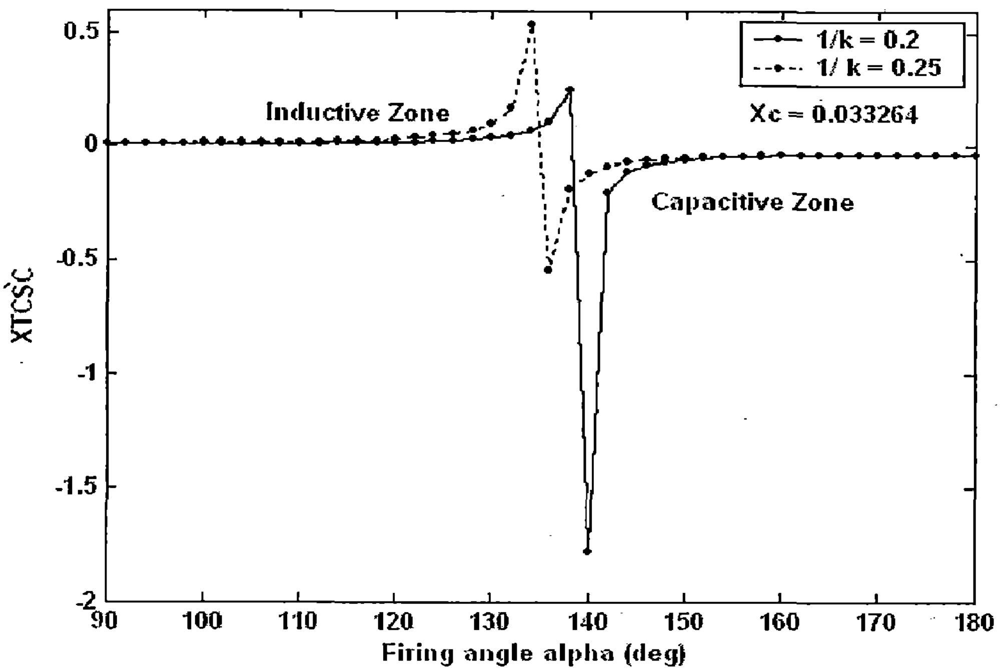


Figure 6.5 X_{TCSC} variation for different values of X_C/X_P ratio at constant X_C = 0.03326

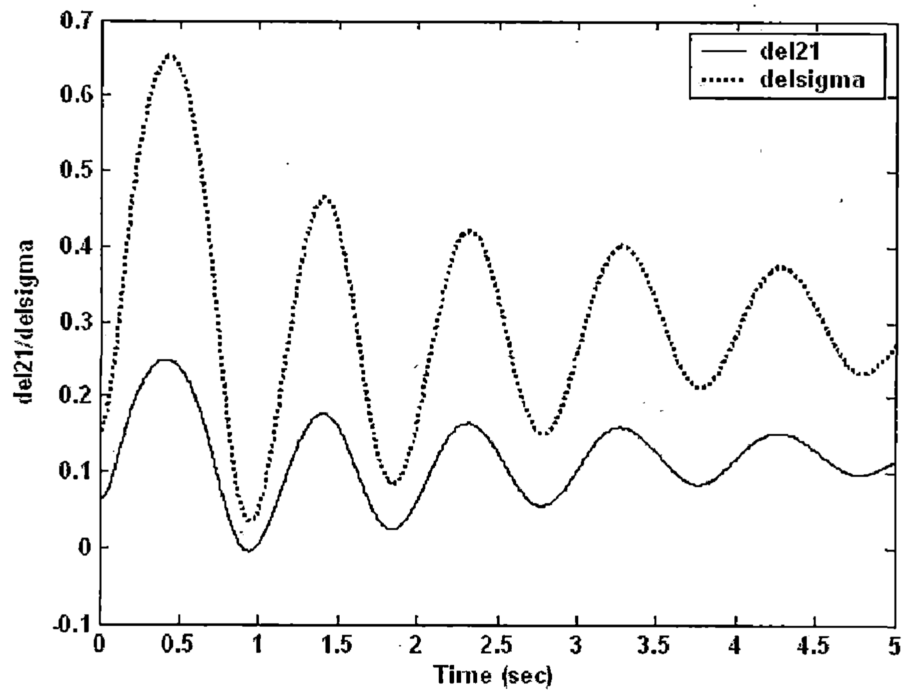


Figure 6.6 TCSC controller input (δ_{21}) vs output $\Delta\sigma$

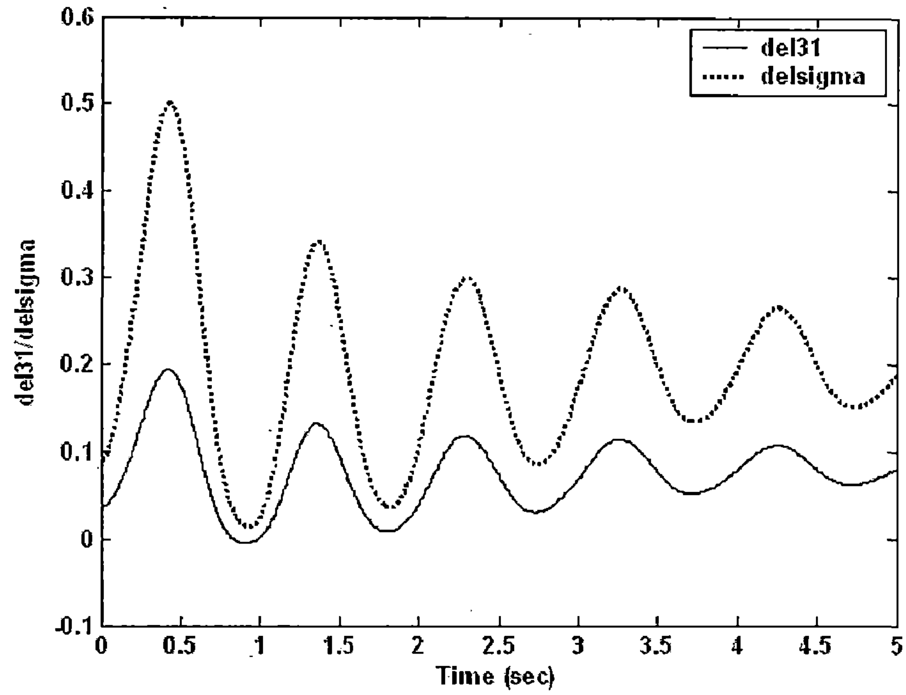


Figure 6.7 TCSC controller input (δ_{31}) vs output $\Delta\sigma$

Figures 6.6 and 6.7 show the TCSC controller input and output variation. The input to TCSC controller is the variation in δ_{21} or δ_{31}, which is converted to equivalent change in firing angle of thyristor $\Delta\sigma$. This change in firing angle decides the value of compensation automatically and hence system stability is improved. Figure 6.8 shows the X_{TCSC} variation for the corresponding variation in δ_{21}, similarly X_{TCSC} for variation in δ_{31} can be obtained.

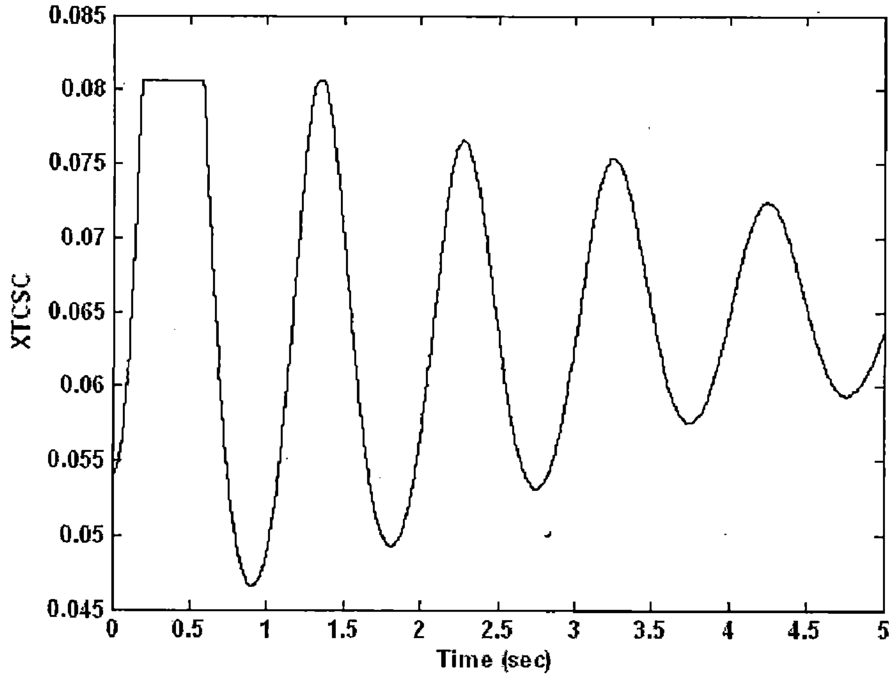


Figure 6.8 X_{TCSC} for variation in δ_{21}

Figure 6.9 and 6.10 below shows the δ_{21}, δ_{31} variation for different values of TCSC controller gain K respectively. It is clear from the figure that if K decreases then the level of compensation also decreases (shown in figure 6.11) and hence oscillation increases which may lead to instability. Similarly for other TCSC controller parameter variation the compensation changes and hence stability changes. Rotor angle variation for change in T_w, and T_2 is shown in figures 6.12 and 6.13 respectively. Figure 6.14 shows he effect of initial firing angle on compensation and stability. It is clear from the figure that if initial conduction angle decreases the system oscillations are increased which may lead to system instability. The system is analyzed for different fault clearing times (FCT) and it has been observed that TCSC controller improves the stability margin significantly. Figure 6.15 for FCT = 0.143 sec the system without TCSC controller is unstable but with TCSC controller the system gains stability. It has been observed that the system with TCSC controller is stable for FCT = 0.161 sec as shown in figure 6.16. It is clear from the figure if FCT increased the system takes time to attain stability and TCSC controller automatically decides the compensation.

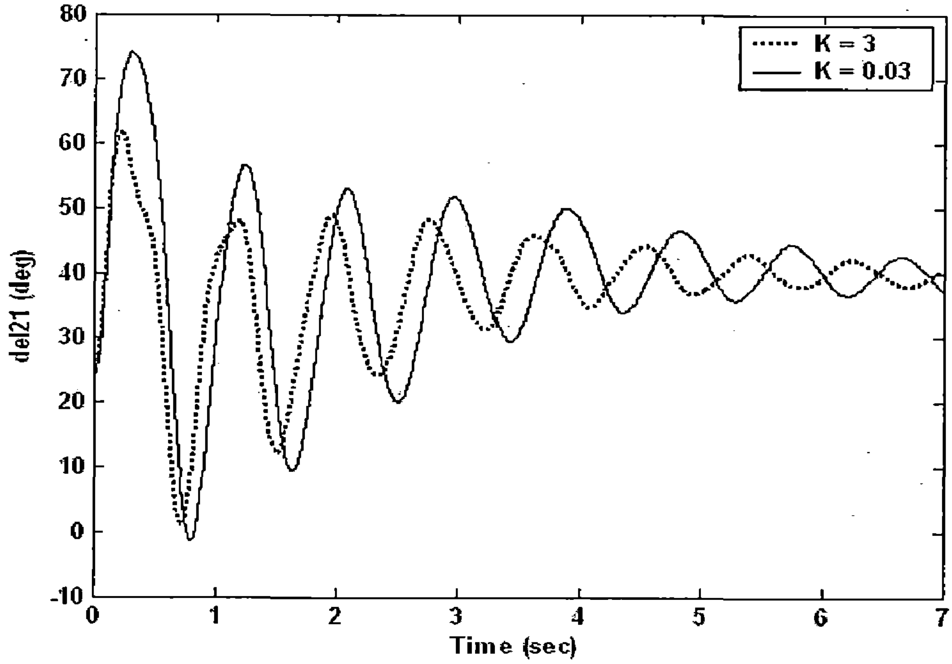


Figure 6.9 δ_{21} *variation for different values of TCSC controller gain K*

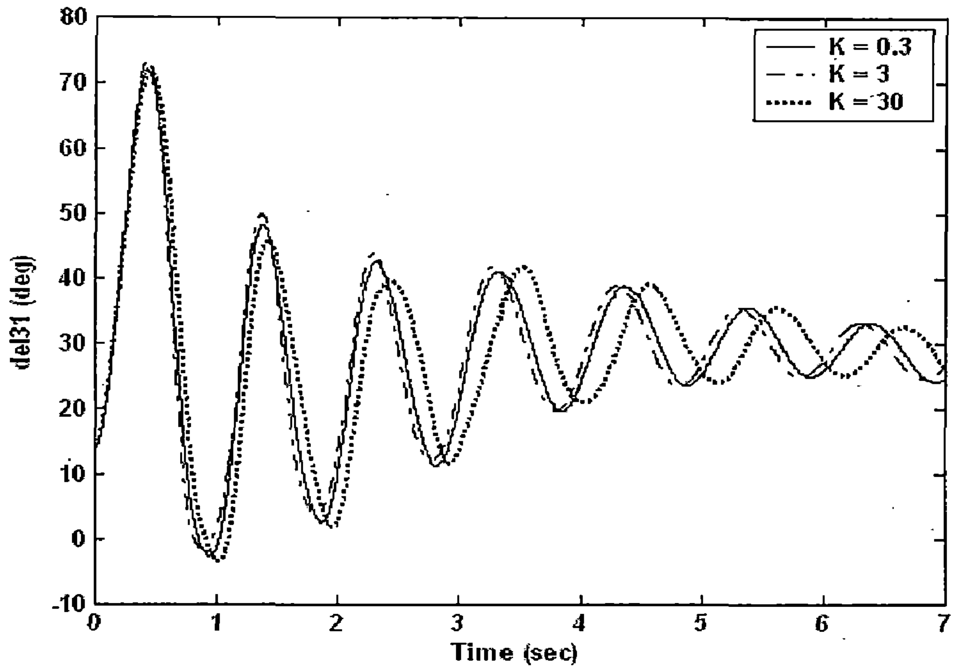


Figure 6.10 δ_{31} *variation for different values of TCSC controller gain K*

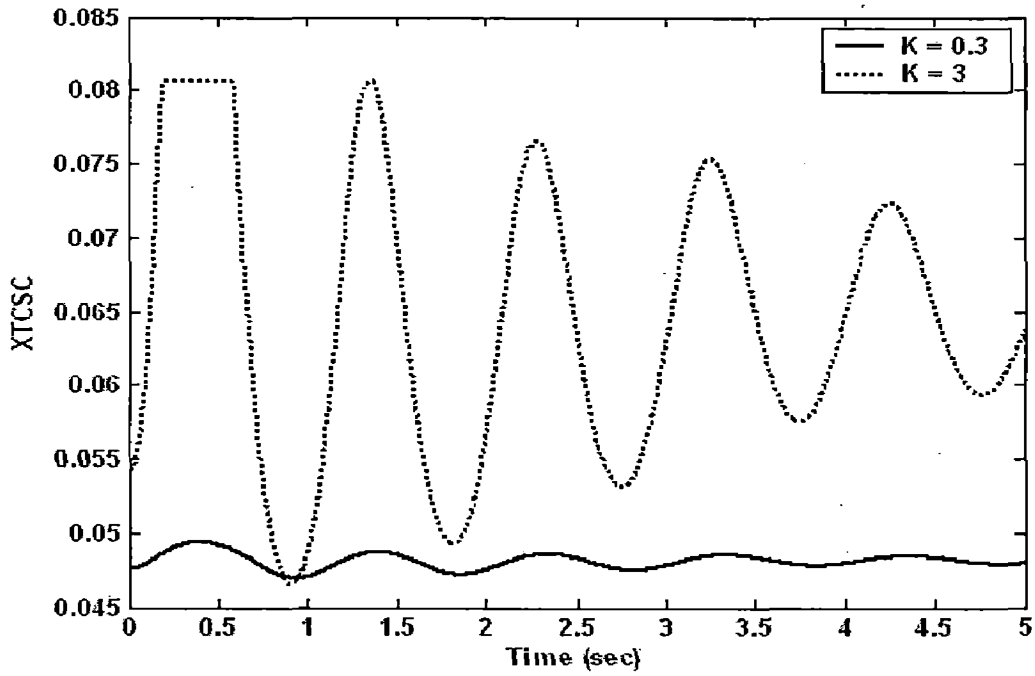


Figure 6.11 X_{TCSC} variation for different values of TCSC controller gain K

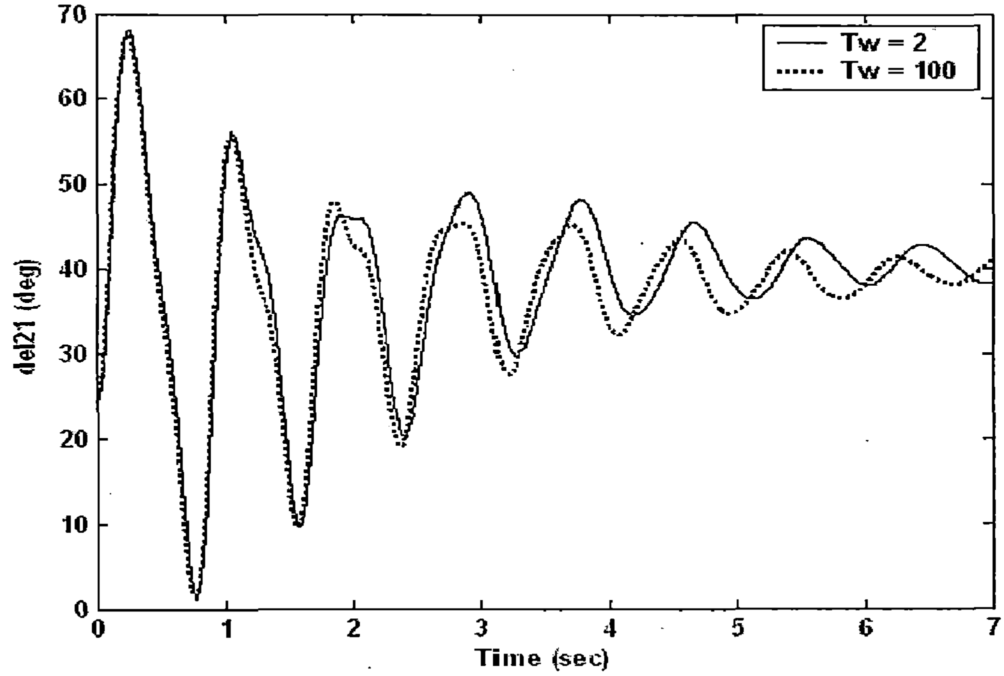


Figure 6.12 δ_{21} Variation for different values of T_w

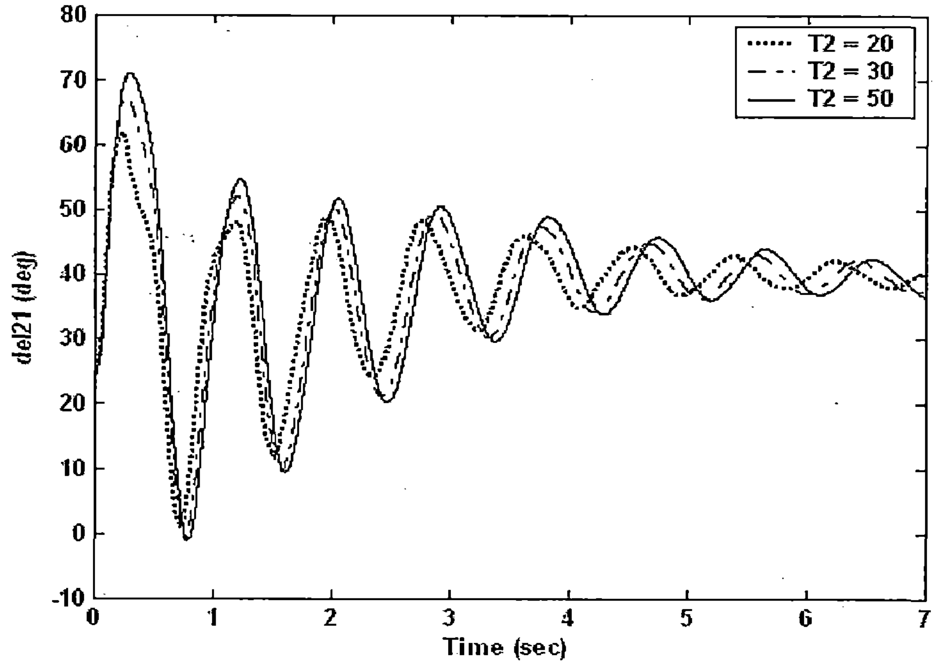


Figure 6.13 δ_{21} Variation for different values of T_2

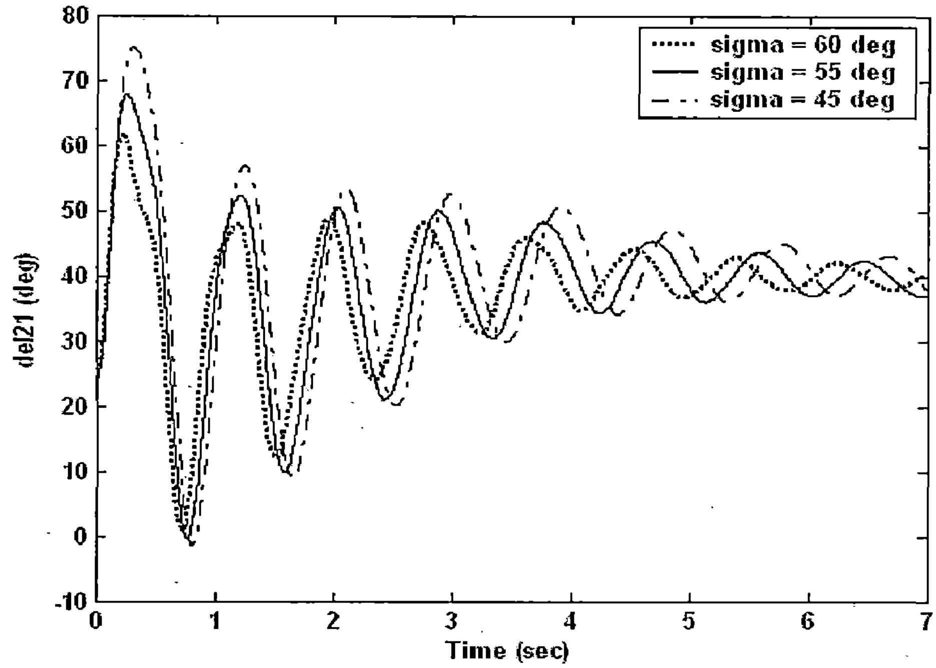


Figure 6.14 δ_{21} Variation for different values of initial conduction angle(σ_0)

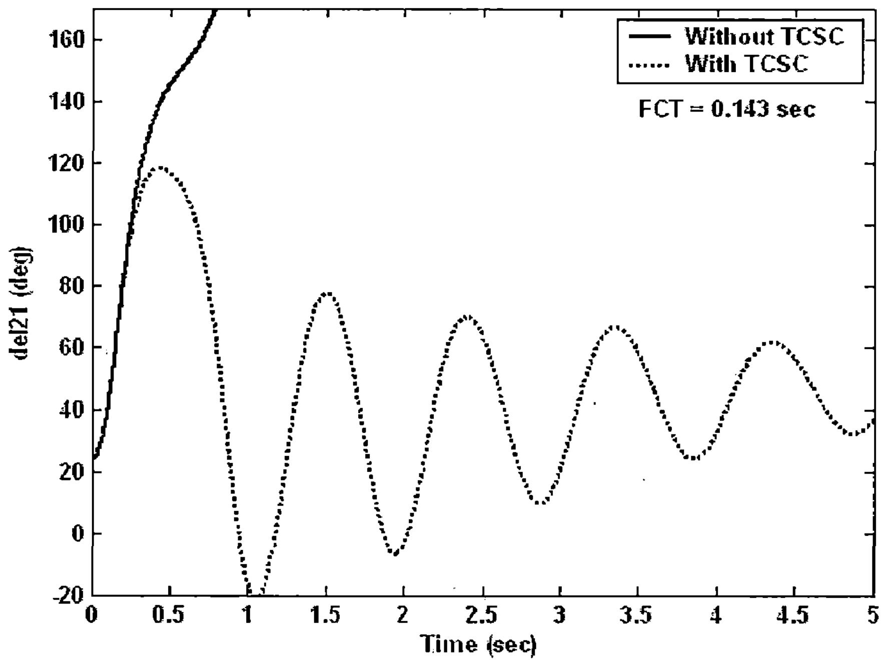


Figure 6.15 δ_{21} *Variation for critical fault clearing time (CCT), FCT = 0.143 sec*

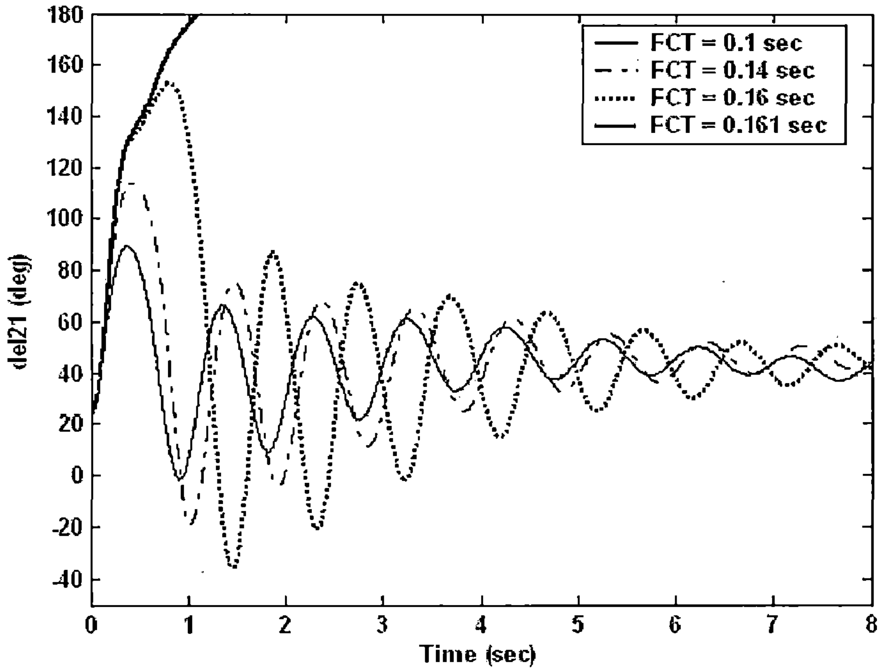


Figure 6.16 δ_{21} *Variation for different FCT with TCSC controller*

CHAPTER 7 CONCLUSIONS AND SCOPE FOR FUTURE WORK

7.1 Conclusions

TCSC controller for multi-machine power system has been designed using SIMULINK. It has been observed that TCSC controller can improve the transient stability of multi-machine power system. The results obtained shows that TCSC controller provides better damping as compared with the same amount of series compensation.

Stability of the multi-machine power system studied is affected by change in TCSC controller parameters. Results for variation in the TCSC controller parameters namely, T_2, T_W and K are shown. It is clear from the results that the variation should be within certain limits for the stability of the system.

Changing the value of initial firing angle alpha can change TCSC controller compensation. If TCSC controller enters resonance zone than the system stability is disturbed i.e. system oscillates and never attains stability.

Simulation results shows that with TCSC controller transient stability of the system studied is improved, as the system without TCSC controller is unstable but if TCSC controller is inserted the system is stable for FCT = 0.143 sec. Simulation is carried out for different set of TCSC controller parameters and it is observed that the system stability is affected. Proper value of TCSC controller parameters are obtained by trial and error for the system studied, no specific technique is used.

If this compensation is provided through conventional series capacitor then the damping is slow and oscillation persists for longer duration. The compensation can also be divided in to fixed capacitor in series with X_{TCSC} (i.e. compensation through TCSC controller). The combination provides better compensation as compared with traditional series compensation. But if compensation is provided only through TCSC then the damping is faster and system attains stability quickly.

If fault-clearing time is increased then TCSC compensation also increases and system oscillations are damped accordingly. It has been observed that a critically unstable multi-machine power system is stable if TCSC controller is used. Change in fault clearing time or change in any of TCSC controller parameter changes X_{TCSC} and hence stability changes.

If the value of parameters is beyond certain limit then system stability is affected, because any such change reflects in the calculation of X_{TCSC} by the means of causing variation in the firing angle α. If change in α is in resonance zone the system becomes unstable. Similarly if fault clearing is delayed beyond a limit then the system becomes unstable. Simulation for different fault clearing time is carried out and it is observed that the TCSC controller improves the critical fault clearing time significantly. According to the value of FCT the controller decides the required compensation and oscillations are damped accordingly.

7.2 Scope for Future Work

In the present TCSC controller for multi-machine system has been designed using SIMULINK. The presented controller is suitable only in capacitive zone. For the transition from capacitive zone to bypass mode the TCSC can be modeled with its detailed dynamics. If compensation level is changed or if the system fault is of different type then TCSC controller design need to be changed accordingly. For selection of the values of the TCSC controller parameters no proper technique has been used. A still more generic TCSC controller can be designed by using some optimization technique. This can be done by using genetic algorithm or any other optimization tool. Artificial Intelligent techniques can also be used for designing a suitable controller, robust to the system parameter variations. TCSC controller design can further be modified for the improvement of steady state stability or for voltage stability improvement. Same design can be extended for the other types of faults in multi-machine power system.

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APPENDIX

A.1 Data for multi-machine power system

Generator no.	1	2	3
Rated MVA	247.5	192	128
kV	16.5	18	13.8
H (sec)	23.64	6.4	3.01
Power Factor	1	0.85	0.85
Type	Hydro	Steam	Steam
Speed	1800r/min	3600r/min	3600r/min
Xd	0.146	0.8958	1.3125
X'd	0.0608	0.1198	0.1813
Xq	0.0969	0.8645	1.2578
X'q	0.0969	0.1969	0.25
Xl (leakage)	0.0336	0.0521	0.0742
Tdo	8.96	6	5.89
T'qo	0	0.535	0.6
Stored energy At rated speed	2364 MW-s	640 MW-s	301 MW-s

Note: Reactance values are in pu on a 100MVA base. All time constants are in seconds.

A.2 Real power flow for the multi-machine power system for fault at different lines

From bus`	To Bus	Pw(MVA)	Pf (8-9)	Pf (7-8)	Pf (9-6)	Pf (5-7)	Pf (6-4)	Pf (5-4)
1	4	46.069	46.425	55.651	52.625	58.445	46.976	49.480
2	7	190.000	190.000	190.000	190.000	190.000	190.000	190.000
3	9	85.000	85.000	85.000	85.000	85.000	85.000	85.000
4	1	-46.069	-46.425	-55.651	-52.625	-58.447	-46.976	-49.480
	5	24.768	38.746	-52.839	-38.974	127.016	46.976	**0.000**
	6	21.301	7.679	108.490	91.598	-68.569	**0.000**	49.480
5	4	-24.586	-38.460	53.553	39.442	-125.000	-46.663	**0.000**
	7	-100.414	-86.540	-178.553	-164.442	**0.000**	-78.337	-125.000
6	4	-21.207	-7.641	-106.527	90.000	69.744	**0.000**	-49.069
	9	-68.793	-82.359	16.527	**0.000**	-159.744	-90.000	-40.931
7	2	-190.000	-190.000	-190.000	-190.000	-190.000	-190.000	-190.000
	5	103.720	89.039	190.000	174.125	**0.000**	80.327	132.804
	8	86.280	100.961	**0.000**	15.875	190.000	109.673	57.196
8	7	-85.673	-100.000	**0.000**	-15.845	-186.977	-108.677	-56.904
	9	-14.327	**0.000**	-100.000	-84.155	86.977	8.677	-43.096
9	3	-85.000	-85.000	-85.000	-85.000	-85.000	-85.000	-85.000
	6	70.622	85.000	-16.352	**0.000**	170.987	93.652	41.579
	8	14.378	**0.000**	101.352	-85.000	-85.987	-8.652	43.421

P_w = real power flow without fault, P_f = power flow after fault

A.3 Ratio of Real power flow with faulted line to real power without fault for the multi-machine power system.

From bus	to Bus	Pf/ Pw (8-9)	Pf/Pw (7-8)	Pf/Pw(9-6)	Pf/Pw (5-7)	Pf/Pw (6-4)	Pf/Pw (5-4)
1	4	1.008	1.208	1.142	1.269	1.020	1.074
2	7	1.000	1.000	1.000	1.000	1.000	1.000
3	9	1.000	1.000	1.000	1.000	1.000	1.000
4	1	1.008	1.208	1.142	1.269	1.020	1.074
	5	1.564	-2.133	-1.574	5.128	1.897	**0.000**
	6	0.360	5.093	4.300	-3.219	**0.000**	2.323
5	4	1.564	-2.178	-1.604	5.084	1.898	**0.000**
	7	0.862	1.778	1.638	**0.000**	0.780	1.245
6	4	0.360	5.023	-4.244	-3.289	**0.000**	2.314
	9	1.197	-0.240	**0.000**	2.322	1.308	0.595
7	2	1.000	1.000	1.000	1.000	1.000	1.000
	5	0.858	1.832	1.679	**0.000**	0.774	1.280
	8	1.170	**0.000**	0.184	2.202	1.271	0.663
8	7	1.167	**0.000**	0.185	2.182	1.269	0.664
	9	**0.000**	6.980	5.874	-6.071	-0.606	3.008
9	3	1.000	1.000	1.000	1.000	1.000	1.000
	6	1.204	-0.232	**0.000**	2.421	1.326	0.589
	8	**0.000**	7.049	-5.912	-5.980	-0.602	3.020

P_w = real power flow without fault, P_f = power flow after fault