Chapter I

INTRODUCTION

The need for transmitting large blocks of power over long transmission lines is rapidly becoming the major problem facing utility engineers today. The corresponding increase of the complexity of power systems coupled with the growth in the size of synchronous generators cause some apprehension as to their stability limits. Various measures have been applied to increase such limits. These include reducing the reactance of transformers, increasing the number of parallel lines, the adoption of bundled conductors and series capacitor compensation.

Previous work indicated the possibility of the occurrence of low frequency self- excited oscillations of synchronous machines when they are connected to series capacitor compensated transmission lines. It has been shown that a high ratio of line resistance to reactance reduces the machine damping torque, and that the compensation of the line reactance by means of series capacitors which can increases the effective value of x/r ratio.

Series capacitors have been extensively used as a very effective means of increasing power transfer capability of transmission system, and improving transient and steady state stability limits of a power system. This is due to partially compensating the reactance of the transmission lines. Damage can result from the long term cumulative effects of low amplitude torsional oscillations (or) the short term effects of high amplitude torques. Typically hydro units have mechanical parameters that are less prone to SSR problems than thermal units. However, the application of series capacitors may lead to the phenomenon of subsynchronous resonance.

Growth of electric power transmission facilities is restricted despite the fact that bulk power transfers and use of transmission systems by third parties are increasing. Transmission bottlenecks, non-uniform utilization of facilities and unwanted parallel path or loop flows are not uncommon. Transmission system expansion is needed, but not easily accomplished. Factors that contribute to this situation include a variety of environmental, land-use and regulatory requirements. As a result, the utility industry is facing the challenge of the efficient utilization of the existing AC transmission lines.

FACTS controllers are power electronic based controllers which can influence transmission system voltage, currents, impedances and/or phase angle rapidly. Thus, such controllers can improve the security of a power system by enhancing its steady state and transient stability or by damping the sub-synchronous resonance oscillations. FACTS application studies require an understanding of the individual FACTS controllers as well as openness to the application of novel approaches. Series capacitive compensation has long been used as a means to increase the power transfer capability of a transmission line by reducing the inductive reactance of the line. This, however, may lead to sub-synchronous resonance (SSR).

Damping SSR oscillations has been a topic of great interest and research. Early strategies suggested dissipating the energy during resonance in resistor banks [2]. Countermeasures utilizing TCSC, NGH schemes [3–5], phase shifters [6], excitation controllers, and static VAR compensators [7] have been extensively researched through the years. Numerous modeling techniques and improvements on these schemes have also been given [8-9]. The use of stored magnetic energy has been published in [10–12].

The concept of the SSSC(static synchronous series capacitor)as a countermeasure to SSR was devised in [13]. These papers stated the possibility of damping SSR using an SSSC in conjunction with additional control for static VAR systems.

A system similar to the IEEE First Benchmark Model (FBM) [16] was utilized in these papers for SSSC. In this paper, we use an SSSC [44,45] to eliminate SSR or improving synchronizing power coefficient. Addition of SSSC in series compensated power system provides superior performance and characteristics reduction of the MVAR rating of the SSSC is an added advantage of the combination high value of capacitive reactance can cause torsional interaction. The main contributions of this report include putting forward the possibility of damping SSR with coupled to the electrical network. The IEEE First Benchmark Models for subsynchronous studies is used to conduct Eigenvalues analyses and time domain simulations. Time domain simulation studies were conducted with SSSC. Simulations to study large transients were conducted. The synchronizing coefficient between masses was varied, and its effects on SSR mitigation and transient stability were observed.

The inclusion of STATCOM does not change the SSR characteristics of network significantly. By using type 2 controller for 2 level VSC based STATCOM we are able to damp SSR up to some extend but not significantly .Application of this concept to the IEEE first bench mark model proved that STATCOM ,provided at the generator terminal and equipped with voltage controller damp the torsional oscillation. By connecting an auxiliary speed deviation is effective in damping the torsional oscillation at all compensated level.

SSR PHENOMENON:-

Subsynchronous resonance is a phenomenon associated with the energy exchanged between the turbine-generator mechanical and electrical systems. A number of mechanical masses of the turbine-generator shaft (e.g. turbine stages and generator) oscillate at some frequencies known as torsional oscillations which are characterized by their mechanical properties like spring constants and mass inertia. The frequencies of these oscillations range from 10 to 55 Hz for 60 Hz system [17].

The oscillation of the generator rotor at a natural mechanical frequency 'f_m' results in voltages induced in the armature having components of:

(i) Sub-synchronous frequency (f_0 - f_m).

(ii) Super-synchronous frequency (f_0 + f_m).

Where 'f_0' is the operating frequency. These voltages setup currents in the armature (and network), whose magnitudes and phase angles depend on the network impedances. The super-synchronous frequency currents result in positive damping torque while the sub-synchronous frequency results in negative damping torque [18]. If the series capacitive compensated electrical network has a torsional frequency around (f_0 - f_m), the torsional oscillation will amplify, resulting in a shaft fatigue or damage. This kind of interaction between the series capacitor and the turbine-generator shaft system is known as "Sub-synchronous Resonance" or "SSR" [1].

1.1 Definition of SSR:-

The IEEE definition of subsynchronous oscillation is [1]:

"Subsynchronous oscillation is an electric power system condition where the electric network exchanges significant energy with a turbine-generator at one or more of the natural frequencies of the combined system below the synchronous frequency of the system following a disturbance from equilibrium".

Electrical power generation involves interaction between the electrical and mechanical energies coupled through the generator. It follows that any change in the electric power system results in a corresponding reaction/response from the mechanical system and vice versa. Slow-changing load translates to a slow-changing mechanical torque on the rotor shaft, which in turn is matched by a slow-changing rotor angle to new steady-state angle between the rotor and the stator along with adjustment in the mechanical power input to the rotor through the turbines. Major disturbances such as faults and fault clearing result in large transient torques on the mechanical system and corresponding transient twisting of the rotor shaft couplings between turbines and generator.

A typical rotor of a large turbine-generator consists of several rotating masses, turbine stages, a generator, and often a rotor of a rotating exciter as shown in Figure 1.1. The rotor masses and coupling shafts form a spring-mass system which has intrinsic modes of torsional natural frequencies which are always below the synchronous frequency [19]. There are generally modes of torsional oscillations for an *6*-mass-spring system, in addition to a zero mode by which the entire mass-spring system oscillates as a rigid body. The mechanical damping for the torsional vibration is always low but positive, which is mainly due to friction,

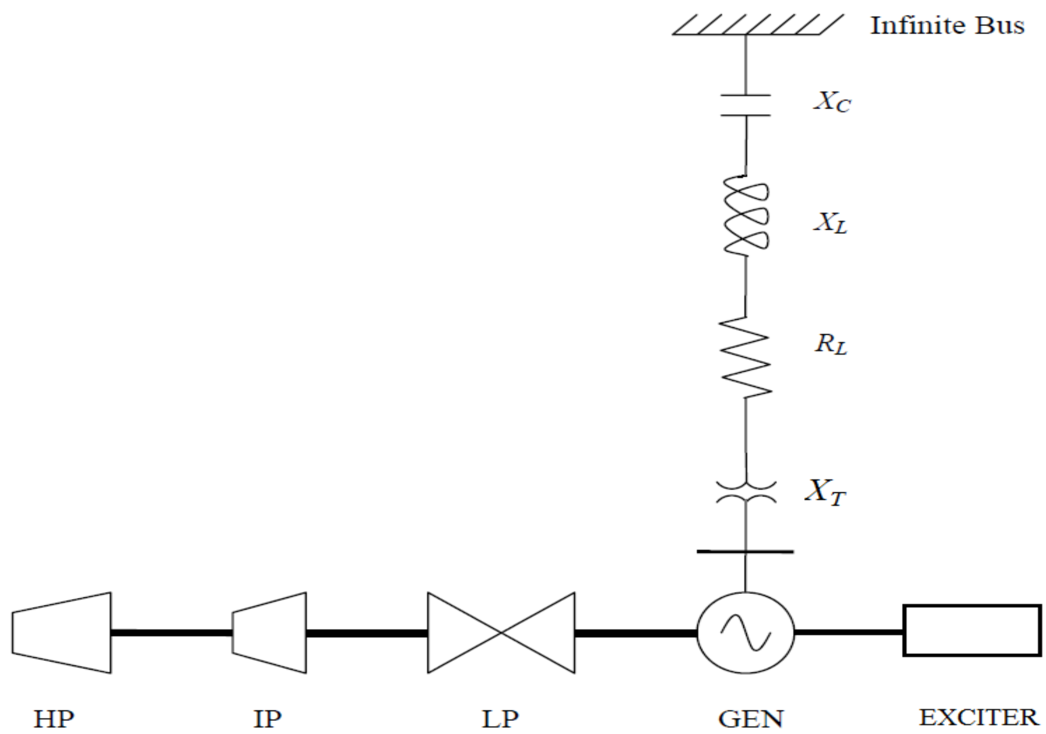


Figure 1.1 A schematic diagram of a series compensated single machine infinite bus system.

A single machine infinite bus system with the series capacitor compensated transmission line shown above in Figure 1.1 will have a resonance frequency f_e given by [18].

$$f_e = f_0\sqrt{\frac{X_C}{X'' + X_L + X_T}} = f_0\sqrt{\frac{X_C}{X_{tot}}} \tag{1.1}$$

where 'f_0' is system nominal frequency, X'' is sub-transient reactance of the generator, X_T is transformer leakage reactance, X_L is transmission line inductive reactance, R_L is total transmission line resistance and X_C is the capacitive reactance. The compensation level k = X_C / X_L is always less than unity as $X_C < X_L$. It is more likely that the electrical resonant frequency is close to one of the compliments of torsional oscillation frequency (i.e. f_0 - f_m) exciting the torsional mode of oscillation. In such a condition, the electrical damping of the system becomes negative and sub-synchronous oscillations can build up from a very small disturbance. To avoid this problem, the series compensation level can be selected such that its value does not lie near one of the compliments of torsional oscillation frequency. However, this is very difficult to achieve as the value of X_{tot} depends on the continuous changing system configuration due to planned and unplanned line switching.

1.2 Impact of Phase Imbalance on SSR

The coupling between the electrical and mechanical sides in a synchronous generator occurs through an interaction between the driving mechanical torque and a developed electromagnetic torque. The electromagnetic torque is developed by the interaction of the machine currents with the magnetic fields, namely the interaction of the armature currents with the rotor magnetic field and the interaction of the rotor currents with the armature magnetic field. The three-phase currents in the armature windings have their full capability of developing interacting electromagnetic torque when they are balanced in the time and space domains. In this balanced condition, the three-phase currents create a circular rotating magnetic field of a constant amplitude and speed. Unbalanced currents [20] on the other hand create an elliptical rotating field which has a time varying amplitude and speed. The elliptical field however is equivalent to a circular rotating field component, and a pulsating field component of comparatively lower magnitude. This means that phase imbalance weakens the electromechanical coupling and as a result reduces the energy exchange between the turbine-generator electrical and mechanical sides.

1.3 Types of SSR Interactions

There are two types of SSR interactions [18]:

1.3.1. Self excitation or steady state SSR

The subsynchronous frequency current entering the generator terminals produces subsynchronous frequency terminal voltage components. These voltage components may sustain the currents to produce self excitation. There are two types of self excitation:

1.3.1.1. Induction generator effect

The electrical resonance due to the series capacitor compensated transmission line creates a revolving field on the generator stator corresponding to the resonant frequency. For the highly compensated transmission line, the electrical resonance frequency f_e will be less than system nominal frequency f_0 and the resonant current drawn by the electrical network causes a rotating field at subsynchronous frequency. Since the generator rotor is rotating at synchronous frequency the synchronous machine behaves like an induction generator with respect to the sub synchronously rotating field. The slip of the machine viewed as an induction generator is given by the relation:

$$s = (f_e - f_0)/f_e < 0, \qquad \text{For } f_e < f_0 \tag{1.2}$$

As the slip is negative, the equivalent resistance viewed from the armature terminals is negative and when this magnitude of the negative resistance exceeds the sum of the armature and network resistance at a resonant frequency, there will be a self excitation.

1.3.1.2. Torsional Interaction

The generator rotor torsional oscillation frequency f_m induces armature voltage components at the frequencies given by:

$$f_{em} = f_0 \pm f_m \tag{1.3}$$

When the sub-synchronous frequency component of f_{em} coincides or is very close to an electric resonance frequency f_e of the generator and transmission system, the torsional oscillation and electrical resonance will be mutually excited resulting in SSR. In such a case, the electrical resonance acts as a negative damping to the torsional oscillation and the torsional oscillation acts as a negative resistance to the electrical resonance.

1.3.2. Transient Torques or Transient SSR

Transient torques are those that result from system disturbances. System disturbances cause sudden changes in the network, resulting in sudden changes in the currents that will tend to oscillate at the natural frequencies of the network. In a transmission system without series capacitors, these transients decay to zero with a time constant that depends on the ratio of inductance to resistance. For the series capacitor compensated transmission line, the transient torque contains many components including unidirectional, exponentially decaying and oscillatory torques from subsynchronous to multiples (typically second harmonic) of the network frequency. Due to the SSR phenomenon, the subsynchronous frequency component of torque can have a large amplitude immediately following large disturbances, although it may decay eventually [18]. Such large amplitude subsynchronous torque degrades the shaft life and is cumulative in nature.

1.4 SSR Analysis Tools

The SSR phenomenon involves energy exchange between mechanical and electrical systems. Therefore, the detailed representation of both electromechanical dynamics of the generating units and the electromagnetic dynamics of the transmission network is required for the analysis of SSR. There are several methods available for the study of SSR and some commonly used methods are described in brief in this section.

1.4.1. Frequency Scanning

This technique computes the equivalent resistance and inductance seen from the stator winding of the generator to the network as a function of frequency. If there is a frequency at which the inductance is zero and the resistance is negative, self sustaining oscillations would be expected due to the induction generator effect. This method is particularly suited for preliminary analysis of SSR problems.

1.4.2. Eigenvalues Analysis

This is performed with the network and the generator modeled by a system of linear simultaneous differential equations. The results provide both the natural frequencies of oscillation as well as the damping of each frequency. This technique thus will be used for conducting the small-signal analysis to provide a comprehensive understanding of the various aspects of the SSR phenomenon. The performance of a dynamic system such as the power system may be described by a set of *n* first-order nonlinear ordinary differential equations, which may be liberalized in the following standard expression:

$$\Delta \dot{X} = A\Delta X + B\Delta U \tag{1.4}$$

where

Δ --- prefix to denote a small deviation about the initial operating point

ΔX --- the state vector

ΔU --- the input vector

A --- the state matrix

B --- the control or input matrix

The stability of the system is given by the eigenvalues of matrix A as follows:

1. A real eigenvalue is associated with a non-oscillatory mode. A negative real eigenvalue represents a decaying mode. The larger its absolute value, the fast is the decay. A positive real eigenvalue represents aperiodic instability.
2. Complex eigenvalues always occur as conjugate pairs, and each pair corresponds to an oscillatory mode. The real part of the eigenvalues represents the damping and the imaginary part represents the frequency of oscillation. A negative real component represents a damped oscillation. On the other hand, a positive real component represents an oscillation with an increasing amplitude.

Therefore, the negativeness of the real part of all eigenvalues assures the system stability. The more negative the real part, the sooner the response of the associated mode dies.

CHAPTER -II

LITERATURE REVIEW

INTRODUCTION 2.1 :-

Series capacitors have been extensively used as a very effective means of increasing power transfer capability of transmission system, and improving transient and steady state stability limits of a power system. This is due to partially compensating the reactance of the transmission lines. The dynamic behavior of power system is quite complex and a good understanding is essential for proper system planning and secure operation.

The chapters presents a comprehensive review about the device used for damping Subsynchronous phenomenon (SSR) by using series and shunt devices. Static synchronous series compensator is used as a series device and STATCOM is used as a shunt device recent advances in the field of emerging new technology, known as FLEXIBLE AC TRANSMISSION SYSTEM.

Subsynchronous resonance (SSR) in series compensated power system is a phenomenon implying an undesirable energy exchange between electrical and mechanical sides of turbine generator sets at a frequency below resonant frequency .
Since the discovery in 1970 that SSR was the main cause of shaft failure at Mohave power plant in Southern Naveda, extensive research and development of effective SSR mitigating measures [15,52,53,54]. Among these SSSC and STATCOM has gained importance in recent years.

D.H. Baker et al.[40] provided an overview of subsynchronous resonance (SSR) and impact of series compensation on SSR. Analysis methods to evaluate SSR risk were described including SSR stability analysis and transient torque analysis. Technical methods for mitigating SSR problems and the solution methods range from simple method techniques to avoid SSR to complex solutions involving sophisticated combination of mitigating equipments were provided.

A.E. Hammed and M. EL. Sadek [41] presented a new concept for controlling SSR by using SVC device which is a shunt compensated device. It based on using model speeds as feedback signals, was presented. The analytical results were verified by detailed digital computer simulation study.

S.M. Sadeghzadeh et al.[42] investigated the application of FACTS devices to increase the maximum loadability of the transmission line which may be constrained by a transient stability limit, .the online control fuzzy control of the superconducting magnetic energy storage (SMES) and the static synchronous series compensator(SSSC) were suggested .The effect of control loop time delay on the performance of the controller was also presented.

H.F.Wang [43] investigated the damping control function of a series compensated SSSC installed in power system the lineralized model of SSSC is integrated into power system is established and method to design the SSSC controller was proposed .In this paper infinite power system was studied. He proposed a SSSC controller to damp power system oscillations. By SSSC SSR can be damped effectively.

G.N. Pillani and Arindam Ghosh [44] demonstrated the application of SSSC in combination with fixed capacitor to avoid torsional mode instability. In this paper, a static synchronous series compensator(SSSC), along with a fixed capacitor, is used to avoid torsional mode instability in a series compensated transmission system. A 48-step harmonic neutralized inverter is used for the realization of the SSSC. The system under consideration is the IEEE first benchmark model on SSR analysis. The system stability is studied both through eigenvalue analysis and EMTDC/PSCAD simulation studies. It is shown that the combination of the SSSC and the fixed capacitor improves the synchronizing power coefficient. The presence of the fixed capacitor ensures increased damping of small signal oscillations.

G. N. Pilani and H.O. Gupta [45] presented the analysis of series compensated power system with a static synchronous series compensator (SSSC).The objective was to investigate the SSR characteristics of the compensated system. A five level diode clamped voltage source inverter (VSI) with fundamental switching frequency is applied as SSSC. The SSR characteristics were study through eigenvalue analysis.

I. Ngamrov et al. [46] proposed a robust design method of lead/lag controller equipped SSSC. The optimal parameters of controller were obtained by using Tabu Search Algorithm.(TSA).The proposed controller was used in an interconnected power system to stabilize frequency oscillations.

A.H. M. RAHIM and S.A.AL.B aiyat et al .[47] developed a robust controller for providing damping to power system transients through STATCOM devices.

M.M Farsangi et al. [48] proposed a method to select to select the input signals for both single and multiple flexible ac transmission (FACTS DEVICES) in small and large power systems. Different input and output controllability analyses were used to access the most appropriate input signals (stabilizing signals) for the static VAR compensator(SVC), the static synchronous compensator (SSSC) for achieving good damping of inter area oscillations.

Ni Yixin et. el. [49] designed fuzzy controllers for FLEXIBLE AC TRANSMISSION SYSTEM (FACTS DEVICES),in interconnected power systems two typical FACTS devices are STATCOM and UPSC were used an example to show that FACTS devices are used to improve interconnected power system dynamic behavior.

Sidharta Panda, R.N. Pante and A. Wahdwani [50] dealt with determining the optimal location of shunt FACTS devices for a long transmission line with predefined direction of real power flow so that maximum improvement in its transient stability performance is achieved by them. The validity of the midpoint location of shunt FACTS devices was verified with different FACTS devices namely static VAR compensator (SVC) and static synchronous compensator (STATCOM) using actual line model a two area test was used to show the effectiveness of off center location of shunt FACTS devices. From simulation results it was observed that the fact devices was placed slightly off center towards sending end give better performance in improving transient stability. The result also show that optimal location of shunt devices depends on line loading and also depend on system initial operating conditions.

K.R.PADIYAR and NAGESH PRABHU [51] investigated the subsynchronous resonance (SSR) characteristics of a series compensated system with a static synchronous series compensator (SSSC) as a part of total compensation. The IEEE First Benchmark Model is used for the analysis of damping SSR by adding SSSC. The active series compensator was provided by a three level twelve pulse SSSC. The modeling and control details of three level voltage souse converter (VSC) based SSSC were discussed. The analysis of SSR with SSSC was carried out based on frequency domain method, eigenvalue analysis and time domain analysis.

B.K.Keshavan and N Prabhu [52] did the damping of subsynchronous oscillation using STATCOM which is provided in the transmission line. The effectiveness of auxiliary signal designed as computed internal angle (CIA) which modulates the voltage reference of STATCOM is investigated. The auxiliary signal CIA is synthesized by local measurement of voltage and line current at the STATCOM bus. The IEEE second benchmark model was considered for study .The analyses of SSR was carried out using Eigenvalue analyses and the results were validated by transient simulation using mat lab SIMULINK. They also developed a new control signal named as computed internal voltage (CIV) to compute the internal voltage of the remotely located generator utilizing locally measurable transmission line current signals STATCOM bus voltage. It was demonstrated that the system was effectively damped under SSR condition.

2.2: CONCLUSION

In the present chapter comprehensive review of the development in the area of series and shunt compensated device like static synchronous series compensator and STATCOM has been presented. The emphasis is on the recent advances taken place in this area. It is observed that SSSC and STATCOM are finding increasing application in the modern power system. A FLEXIBLE AC TRANSMISSION is emerging as an advanced technology for the efficient utilization of existing power systems .

In the early stage of power system development, both steady state and transient stability problems challenged system planners . The development of fast acting static exciters and electronic voltage regulators overcame to large extent the transient stability and steady state problems (caused by slow shift in the generator rotor motion as the loading was increased).

Over the last few years, the problem of slow frequency oscillations have assumed importance. The frequency of oscillation in the range of 0.2 to 2.0 Hz. The lower the frequency, the more widespread are the oscillations (also called inter area oscillations).Another problem faced by modern power system is the problem of voltage collapse or voltage instability which is a manifestation of steady state instability. Historically steady state instability has been associated with angle instability and slow loss of synchronism among generators the slow collapse of voltage at load buses under high loading conditions and reactive power limitation is a recent phenomenon.

Power system bottlenecks are faced in countries with large generation reserves. The economic and environmental factors necessitate generation sites at remote location and wheeling of power through existing networks. The operational problem faced in such cases require detailed analysis of dynamic behavior of power system and development of suitable controllers to overcome the problem. For damping subsynchronous resonance phenomenon various FACTS devices are available such as SVC, STATCOM, SSSC, TCSC, UPSC . In this project we are using one series and one shunt device static synchronous compensator (SSSC) and static compensator (STATCOM) for SSR analysis.

Chapter -III

SMALL-SIGNAL ANALYSIS OF SUBSYNCHRONOUS RESONANCE PHENOMENON

3.1 Introduction

The differential and algebraic equations which describe the dynamic performance of the synchronous machine and the transmission network are in general nonlinear. For the purpose of stability analysis, these equations may be linearized by assuming that a disturbance is considered to be small. Small-signal analysis using linear techniques provides valuable information about the inherent dynamic characteristics of the power system and assists in its design.

This chapter presents an analytical method useful in the study of small-signal analysis of subsynchronous resonance (SSR) establishes a literalized model for the power system, and performs the analysis of the SSR using the eigenvalue technique. By studying the small-signal stability of the power system, the engineer will be able to find countermeasures to damp all subsynchronous torsional oscillations.

3.2 IEEE First Benchmark Model Small Signal Analysis

The IEEE First Benchmark Model (FBM) [16] is developed by IEEE Subsynchronous Resonance Task Force for testing the various kinds of subsynchronous resonance countermeasures.

This system, shown in Figure 1.1, consists of a single series-capacitor compensated transmission line connecting a large turbine-generator to a large system. The shaft system of the turbine-generator unit consists of a high-pressure turbine (HP), an intermediate-pressure turbine (IP), two low pressure turbines (LPA & LPB), the generator rotor (GEN), and its rotating exciter (EXC).

This model offers various kinds of SSR problems and is chosen as a test system for testing the proposed SSR mitigation methods in this research work.

The schematic diagram of the FBM system is shown in Figure 3.1. The system mechanical and electrical data are given in Appendix B.

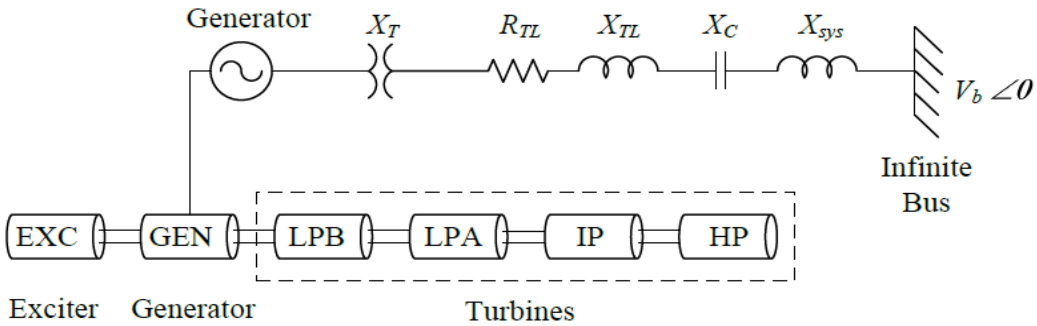


figure 3.1 The IEEE First Benchmark Model schematic diagram.

3.3 Power System Modeling

The nonlinear differential equations of the system under study are derived by developing individually the mathematical models which represent the various components of the system. The eigenvalue analysis gives information of both resonant frequency and damping at that frequency. So to understand the effect of series compensation, a detailed mathematical model of the whole system is developed for eigenvalue analysis. First individual mathematical models describing the synchronous generator, turbine-generator mechanical system, and electric network are presented. Then all the equations are combined in a standard form for the computation of the eigenvalues.

3.3.1 Synchronous Machine Modeling

A conventional synchronous machine schematic diagram is shown in Figure 3.2 [21]. The model shows three-phase armature windings on the stator (*a, b,* and *c*). The rotor of the machine carries the field winding *fd* and damper windings. The damper windings are represented by equivalent damper circuits in the direct axis (*d*-axis) and quadrature axis (*q*-axis): *h* on *d*-axis, and *g* and *k* on *q*-axis.

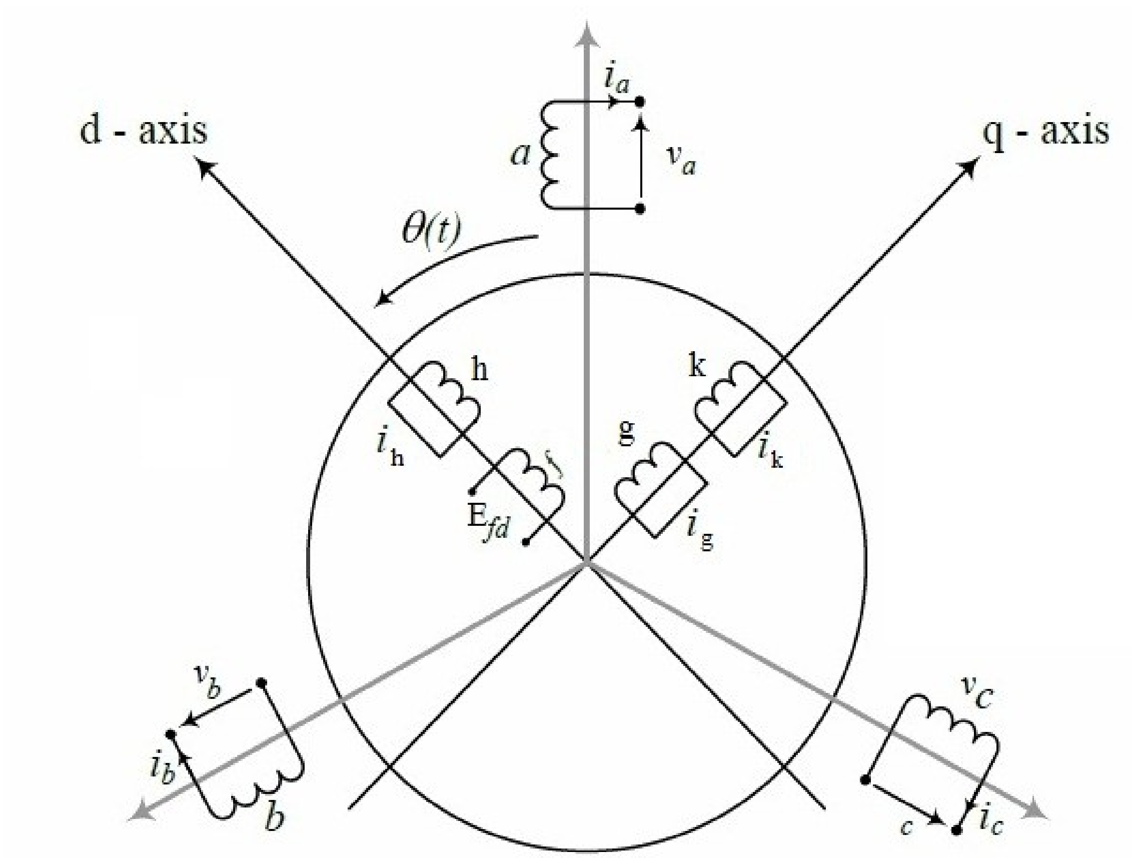


Figure 3.2 Schematic diagram of a conventional synchronous machine.

a,b,c	:	Stator windings
v_a,v_b,v_c	:	Stator three-phase winding voltages.
i_a,i_b,i_c	:	Stator three-phase winding currents.
f	:	Field winding.
E_{fd}	:	Field voltage.
h	:	d – axis damper winding.
g	:	First q – axis damper winding.
k	:	Second q – axis damper winding.
θ(t)	:	The electrical angle (in *rad*) by which *d* – axis leads magnetic axis *of phase a* winding.

Note: We will use Model 1.1(22) (Field circuit with one equivalent damper on q-axis) published By IEEE task force, of synchronous machine for modeling.

The electrical dynamic equations of the synchronous machine (model 1.1) are developed by writing equations of the coupled circuits and presented below [18,21]:

- ***Stator Equations:***

$$v_d = -\frac{1}{\omega_B}\frac{d\Psi_d}{dt} - (1+S_m)\Psi_q - R_a i_d \tag{3.1}$$

$$v_q = -\frac{1}{\omega_B}\frac{d\Psi_q}{dt} - (1+S_m)\Psi_d - R_a i_q \tag{3.2}$$

- ***Rotor Equations:***

$$\frac{dE_d'}{dt} = \frac{1}{T_{qo}'}\left[-E_d' - (x_q - x_q')i_q\right] \tag{3.3}$$

$$\frac{dE_q'}{dt} = \frac{1}{T_{do}'}\left[-E_q' + (x_d - x_d')i_d + E_{fd}\right] \tag{3.4}$$

Where

$$i_d = \frac{\Psi_d - E_q'}{x_d'} \quad \text{and} \quad i_q = \frac{\Psi_q + E_d'}{x_q'} \tag{3.5 and 3.6}$$

Stator Flux Linkage Equations:

$$\Psi_d = x_d i_d + x_{ad} i_f \tag{3.7}$$

$$\Psi_q = x_q i_q + x_{aq} i_g \tag{3.8}$$

- ***Rotor Flux linkage Equations:***

$$\Psi_f = x_{ad} i_d + x_f i_f \tag{3.9}$$

$$\Psi_g = x_{aq} i_q + x_g i_g \tag{3.10}$$

- ***Air-gap Torque Equation***

$$T_e = \Psi_d i_q - \Psi_q i_d \tag{3.11}$$

Linearizing and rearranging Eq.3.1 to 3.6 and expressed as a set of first order differential equations as(18):

$$\frac{d\Delta x_e}{dt} = [A_e]\Delta x_e + [B_{e1}]\Delta u_e + [B_{e2}]E_{fd} \tag{3.12}$$

And

$$\Delta y_e = [C_e]\Delta x_e \tag{3.13}$$

Where

$$\left[\Delta \dot{x}_e\right]^t = \left[\Delta\dot{\Psi}_d \quad \Delta\dot{\Psi}_q \quad \Delta\dot{E}_d' \quad \Delta\dot{E}_q'\right]$$

$$\left[\Delta x_e\right]^t = \left[\Delta\Psi_d \quad \Delta\Psi_q \quad \Delta E_d' \quad \Delta E_q'\right]$$

$$\left[\Delta u_e\right]^t = \left[\Delta v_D \quad \Delta v_Q\right]$$

$$\left[\Delta y_e\right]^t = \left[\Delta i_D \quad \Delta i_Q\right]$$

$$[A_e] = \begin{bmatrix} -\frac{\omega_B R_a}{x_d'} & -\omega_B & 0 & \frac{\omega_B R_a}{x_d'} \\ \omega_B & -\frac{\omega_B R_a}{x_{q'}} & -\frac{\omega_B R_a}{x_q'} & 0 \\ 0 & -\frac{1}{T_{qo}'}\left(\frac{x_q}{x_q'} - 1\right) & -\frac{1}{T_{qo}'}\left(\frac{x_q}{x_q'}\right) & 0 \\ \frac{1}{T_{do}'}\left(\frac{x_d}{x_d'} - 1\right) & 0 & 0 & -\frac{1}{T_{do}'}\left(\frac{x_d}{x_d'}\right) \end{bmatrix}$$

$$[B_{e1}] = \begin{bmatrix} -\omega_B \cos\delta & \omega_B \sin\delta & 0 & 0 \\ -\omega_B \sin\delta & -\omega_B \cos\delta & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$[B_{e2}]^t = \begin{bmatrix} 0 & 0 & 0 & \dfrac{1}{T_{do}'} \end{bmatrix}$$

$$[C_e] = \begin{bmatrix} \dfrac{\cos\delta}{x_d'} & \dfrac{\sin\delta}{x_q'} & \dfrac{\sin\delta}{x_q'} & -\dfrac{\cos\delta}{x_d'} \\ -\dfrac{\sin\delta}{x_d'} & \dfrac{\cos\delta}{x_q'} & \dfrac{\cos\delta}{x_q'} & \dfrac{\sin\delta}{x_d'} \end{bmatrix}$$

3.3.2 Modeling of Turbine Generator Mechanical System

The turbine-generator mechanical system consists of six masses; high-pressure turbine (HP), intermediate-pressure turbine (IP), low pressure turbine A (LPA) and low pressure turbine B (LPB), an exciter (EXC), and a generator (GEN) coupled to a common shaft as shown in Figure 3.3. The mechanical properties of the masses and shaft sections are given in Appendix B. The turbine masses, generator rotor and exciter are considered as lumped masses (rigid body) connected to each other via mass less springs. The mathematical expressions describing the dynamics of the system are developed considering the lumped multi-mass model.

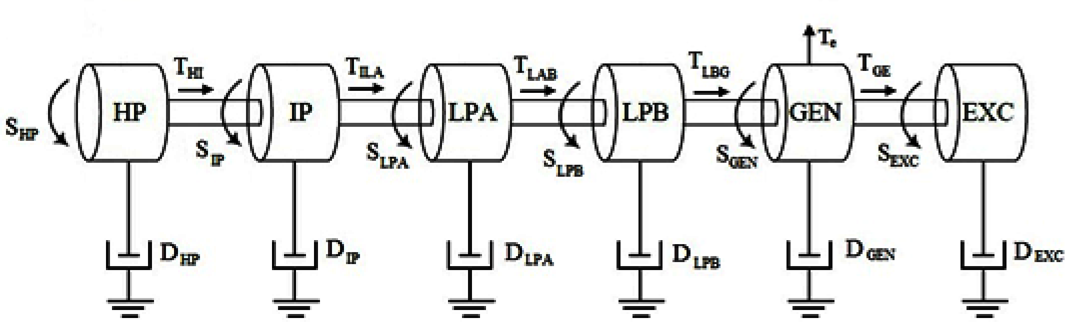


Figure 3.3 Mechanical structure of six mass FBM system.

Note: In the mechanical system we have considered *S* and *T* as state variable.

The mechanical system state space equations are(18)

$$\dot{\delta}_{GEN} = S_{GEN}\,\omega_B \tag{3.14}$$

$$\dot{S}_{EXC} = -\frac{D_{EXC}}{2H_{EXC}}S_{EXC} + \frac{T_{GE}}{2H_{EXC}} \tag{3.15}$$

$$\dot{T}_{GE} = K_{GE}\left(S_{GEN} - S_{EXC}\right) \tag{3.16}$$

$$\dot{S}_{GEN} = -\frac{D_{GEN}}{2H_{GEN}}S_{GEN} + \frac{1}{2H_{GEN}}\left(T_{LBG} - T_{GE}\right) - \frac{1}{2H_{GEN}}T_e \tag{3.17}$$

$$\dot{T}_{LBG} = K_{LBG}\left(S_{LPB} - S_{GEN}\right) \tag{3.18}$$

$$\dot{S}_{LPB} = -\frac{D_{LPB}}{2H_{LPB}}S_{LPB} + \frac{1}{2H_{LPB}}\left(T_{LAB} - T_{LBG}\right) \tag{3.19}$$

$$\dot{T}_{LAB} = K_{LAB}\left(S_{LPA} - S_{LPB}\right) \tag{3.20}$$

$$\dot{S}_{LPA} = -\frac{D_{LPA}}{2H_{LPA}}S_{LPA} + \frac{1}{2H_{LPA}}\left(T_{ILA} - T_{LAB}\right) \tag{3.21}$$

$$\dot{T}_{ILA} = K_{ILA}\left(S_{IP} - S_{LPA}\right) \tag{3.22}$$

$$\dot{S}_{IP} = -\frac{D_{IP}}{2H_{IP}}S_{IP} + \frac{1}{2H_{IP}}\left(T_{HI} - T_{ILA}\right) \tag{3.23}$$

$$\dot{T}_{HI} = K_{HI}\left(S_{HP} - S_{IP}\right) \tag{3.24}$$

$$\dot{S}_{HP} = -\frac{D_{HP}}{2H_{HP}}S_{HP} - \frac{T_{HI}}{2H_{HP}} \tag{3.25}$$

Linearizing and rearranging Equation (3.14-3.25), the overall shaft equations can be given by the following matrix equation

$$\Delta\dot{x}_m = \left[A_m\right]\Delta x_m + \left[B_{m1}\right]\Delta T_e \tag{3.26}$$

$$\Delta y_m = \left[C_m\right]\Delta x_m \tag{3.27}$$

Where:

$$\left[\dot{\Delta x}_m\right]^t = \left[\dot{\delta}_{GEN} \quad \dot{S}_{EXC} \quad \dot{T}_{GE} \quad \dot{S}_{GEN} \quad \dot{T}_{LBG} \quad \dot{S}_{LPB} \quad \dot{T}_{LAB} \quad \dot{S}_{LPA} \quad \dot{T}_{ILA} \quad \dot{S}_{IP} \quad \dot{T}_{HI} \quad \dot{S}_{HP}\right]$$

$$\left[\Delta x_m\right]^t = \left[\delta_{GEN} \quad S_{EXC} \quad T_{GE} \quad S_{GEN} \quad T_{LBG} \quad S_{LPB} \quad T_{LAB} \quad S_{LPA} \quad T_{ILA} \quad S_{IP} \quad T_{HI} \quad S_{HP}\right]$$

$$\left[\Delta y_m\right]^t = \left[\Delta\delta_{GEN} \quad \Delta S_{GEN}\right]$$

$$\left[B_{m1}\right] = \begin{bmatrix} 0 \\ 0 \\ 0 \\ -\dfrac{1}{2H_{GEN}} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$\left[C_m\right] = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Now in Eq. 3.11, putting values of ψ_d and ψ_q from 3.7,3.8 and on Linearizing T_e we get:

$$\left[\Delta T_e\right] = \left[C_{me}\right]\Delta x_e \qquad (3.28)$$

Where

$$[C_{me}]^t = \begin{bmatrix} \frac{(x_d'-x_q')}{x_d' x_q'}\Psi_{qo} + \frac{E_{do}'}{x_q'} \\ \frac{(x_d'-x_q')}{x_d' x_q'}\Psi_{do} + \frac{E_{qo}'}{x_d'} \\ \frac{\Psi_{do}}{x_q'} \\ \frac{\Psi_{qo}}{x_d'} \end{bmatrix}$$

From Eq. 3.28 and 3.26

$$\dot{\Delta x}_m = [B_{m1} C_{me}]\Delta x_e + [A_m]\Delta x_m \tag{3.29}$$

3.3.3 Synchronous M/C Mechanical and Electrical System Combined equation

Modified electrical system equations are

$$\dot{\Delta x}_e = [A_e]\Delta x_e + [B_{e1}]\Delta u_e + [B_{e2}]E_{fd} + [B_{e3}]\Delta y_m \tag{3.30}$$

From Eq. 3.27

$$\dot{\Delta x}_e = [A_e]\Delta x_e + [B_{e3} C_m]\Delta x_m + [B_{e1}]\Delta u_e + [B_{e2}]E_{fd} \tag{3.31}$$

Combining Eq. 3.31 and 3.29

$$\dot{\Delta x}_G = [A_G]\Delta x_G + [B_{G1}]\Delta u_e + [B_{G2}]E_{fd} \tag{3.32}$$

Where;

$$\left[\dot{\Delta x}_G\right]^t = \left[\dot{\Delta x}_e \quad \dot{\Delta x}_m\right]$$

$$\left[\Delta x_G\right]^t = \left[\Delta x_e \quad \Delta x_m\right]$$

$$[B_{e3}] = \begin{bmatrix} \omega_B v_{qo} & -\omega_B \Psi_{qo} \\ -\omega_B v_{do} & \omega_B \Psi_{do} \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

$$[A_G] = \begin{bmatrix} [A_e] & [B_{e3} C_m] \\ [B_{m1} C_{me}] & [A_m] \end{bmatrix}$$

$$[B_{G1}] = \begin{bmatrix} B_{e1} \\ 0 \end{bmatrix}$$

$$[B_{G2}] = \begin{bmatrix} B_{e2} \\ 0 \end{bmatrix}$$

And also modified output equation:

$$\Delta y_G = [C_e]\Delta x_e + [C_{em}]\Delta y_m \tag{3.33}$$

From Eq. 3.27

$$\Delta y_G = [C_e]\Delta x_e + [C_{em} C_m]\Delta x_m \tag{3.34}$$

$$\Delta y_G = [C_G]\Delta x_G \tag{3.35}$$

Where:

$$[\Delta y_G] = \begin{bmatrix} \Delta i_D \\ \Delta i_Q \end{bmatrix}$$

$$[C_G] = [[C_E] \quad [C_{em} C_m]]$$

$$[C_{em}] = [P_{em}]\begin{bmatrix} x_{eo} & 0 \end{bmatrix}$$

$$[P_{em}] = \left[\frac{\Delta C_e}{\Delta \delta}\right] = \begin{bmatrix} -\dfrac{\sin\delta}{x_d'} & \dfrac{\cos\delta}{x_q'} & \dfrac{\cos\delta}{x_q'} & \dfrac{\sin\delta}{x_d'} \\ -\dfrac{\cos\delta}{x_d'} & -\dfrac{\sin\delta}{x_q'} & -\dfrac{\sin\delta}{x_q'} & \dfrac{\cos\delta}{x_d'} \end{bmatrix}$$

$$\left[x_{eo}\right]^t = \begin{bmatrix} \Psi_{do} & \Psi_{qo} & E_{do}' & E_{qo}' \end{bmatrix}$$

So final combined electrical and mechanical equations are

$$\Delta \dot{x}_G = [A_G]\Delta x_G + [B_{G1}]\Delta u_e + [B_{G2}]E_{fd} \qquad 3.36$$

$$\Delta y_G = [C_G]\Delta x_G \qquad 3.37$$

3.3.4 Modeling of the Transmission Line

A series capacitor-compensated transmission line may be represented by the *RLC* circuit(18) shown in Figure 3.4.

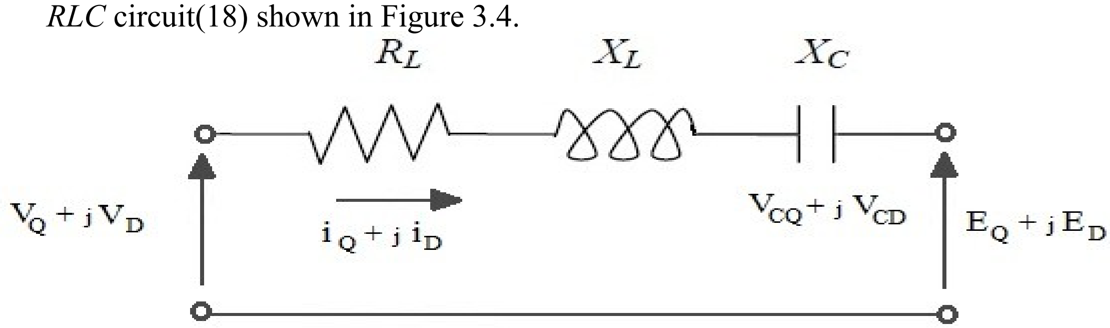


Figure 3.4 A series capacitor-compensated transmission line.

Note: We will take voltage across capacitor as state variable.

The differential equations for the circuit elements, after applying Park's transformation, can be expressed in the d-q reference frame as following

The voltage across the capacitor(18):

$$\begin{bmatrix} \Delta\dot{V}_{CD} \\ \Delta\dot{V}_{CQ} \end{bmatrix} = \begin{bmatrix} 0 & -\omega_B \\ \omega_B & 0 \end{bmatrix} \begin{bmatrix} \Delta V_{CD} \\ \Delta V_{CQ} \end{bmatrix} + \begin{bmatrix} \omega_B X_C & 0 \\ 0 & \omega_B X_C \end{bmatrix} \begin{bmatrix} \Delta i_D \\ \Delta i_Q \end{bmatrix}$$

The above equations can be represented in state space model as:

$$\Delta\dot{x}_N = [A_N]\Delta x_N + [B_{N1}]\Delta u_{N1} + [B_{N2}]\Delta u_{N2} \qquad 3.38$$

Where:

$$[\Delta\dot{x}_N]^t = \begin{bmatrix} \Delta\dot{V}_{CD} & \Delta\dot{V}_{CQ} \end{bmatrix}$$

$$[U_{N1}] = \begin{bmatrix} i_D \\ i_Q \end{bmatrix}$$

$$[U_{N2}] = \begin{bmatrix} E_D \\ E_Q \end{bmatrix}$$

$$[A_N] = \begin{bmatrix} 0 & -\omega_B \\ \omega_B & 0 \end{bmatrix}$$

$$[B_{N1}] = \begin{bmatrix} \omega_B X_C & 0 \\ 0 & \omega_B X_C \end{bmatrix}$$

$$[B_{N2}] = [0]$$

3.3.5 Combined Generator and Transmission Line Modeling

The combined system equations can be obtain after eliminating the variables u_e and $u_{N1.}$

Since $u_{N1} = y_G = [C_G]x_G$ 3.39

And the expression for u_e depends upon the network.

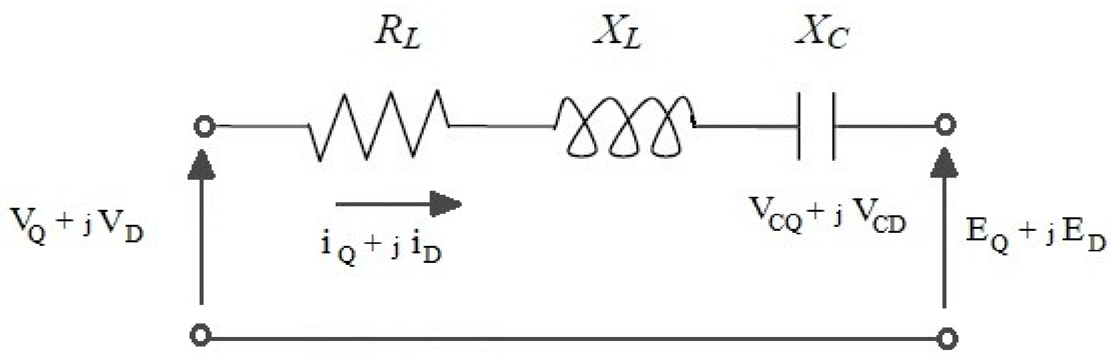


Figure 3.5 Network Diagram

For the network as shown in figure we have

$$V_D = E_D + V_{CD} + R i_D + \frac{X_L}{\omega_B} \dot{i}_D + X_L i_Q \qquad 3.40$$

$$V_Q = E_Q + V_{CQ} + R i_Q + \frac{X_L}{\omega_B} \dot{i}_Q + X_L i_D \qquad 3.41$$

From equation 3.40, 3.41, 3.32 and 3.35 and on Linearizing we have

$$\Delta u_e = [H]\left[\Delta x_N + [F_1]\Delta x_G + \frac{X_L}{\omega_B}[C_G B_{G2}]\Delta E_{fd} + \Delta u_{N2} \right] \qquad 3.42$$

Where:

$$[H] = \left\{ I - \frac{X_L}{\omega_B}[C_G B_{G1}] \right\}^{-1}$$

***I** is a unit matrix.*

$$[F_1] = [F C_G] + \frac{X_L}{\omega_B}[C_G A_G]$$

$$[F] = \begin{bmatrix} R & X_L \\ -X_L & R \end{bmatrix}$$

From Equation 3.36 and 3.42, the final System equations are:

$$\Delta \dot{x}_T = [A_T]\Delta x_T + [B_{T1}]\Delta E_{fd} + [B_{T2}]\Delta u_{N2} \qquad 3.43$$

Where:

$$\left[\dot{\Delta x}_T\right]^t = \left[\dot{\Delta x}_G \quad \dot{\Delta x}_N\right]$$

$$\left[\Delta x_T\right]^t = \left[\Delta x_G \quad \Delta x_N\right]$$

$$\left[A_T\right] = \begin{bmatrix} [A_G]+[B_{G1}HF_1] & [B_{G1}H] \\ [B_{N1}C_G] & [A_N] \end{bmatrix}$$

$$\left[B_{T1}\right] = \begin{bmatrix} [B_{G2}]+\frac{X_L}{\omega_B}[B_{G1}HC_GB_{G2}] \\ 0 \end{bmatrix}$$

$$\left[B_{T2}\right] = \begin{bmatrix} [B_{G1}H] \\ [B_{N2}] \end{bmatrix}$$

3.3.6 EIGEN value analysis of IEEE First Benchmark Model

The above system is simulated with the help of MATLAB. The Network parameter are based on generator base of 892.4 MVA are given in Appendix B .The Synchronous M/C data are given in Appendix B. The shaft inertia and spring constant are given in Appendix B. There are six inertia corresponding to six rotors-four turbines, generator and rotating exciter.

The generator is assumed to be operated at no load(P_G=0, Q_G=0). The infinite bus voltage is assumed to be 1.0 pu. The AVR is neglected in the study. The nominal value of series compensation is assumed to be 70% (X_C=0.35 pu). Damping is assumed to zero.

Table 3.1 Eigenvalues of the combined system

Sr. No.	Machine Model(1.1) P=0,Q=0	Comments
1	-1.4521 + j10.264 -1.4521 - j10.264	Torsional Mode #0
2	0.022651 + j99.626 0.022651 - j99.626	Torsional Mode #1
3	0.026317 + j127.14 0.026317 – j127.14	Torsional Mode #2
4	0.041363 + j160.35 0.041363 - j160.35	Torsional Mode #3
5	0.0024116 + j202.86 0.0024116 - j202.86	Torsional Mode #4
6	2.9973e-007 + j298.18 2.9973e-007 - j298.18	Torsional Mode #5
7	-3.3952 + j141.24 -3.3952 - j141.24	Network Mode #1
8	-4.4198 + j612.42 -4.4198 - j612.42	Network Mode #2
9	-0.95897	
10	-1.2155	

It is obvious from the Table 3-1 that when the electrical network subsynchronous resonance frequency is near to one of the torsional modes , the corresponding torsional mode is destabilized.

3.3.6(A)RESULTS WHEN NO COMPENSATING DEVICE CONNECTED TO IT:-

Time Domain Analysis

The above IEEE FBM was studied for small signal stability in time domain with the help of MATLAB model was made and it was given step input to it . We feed the value of A ,B,C,D matrix in it and got the corresponding results.

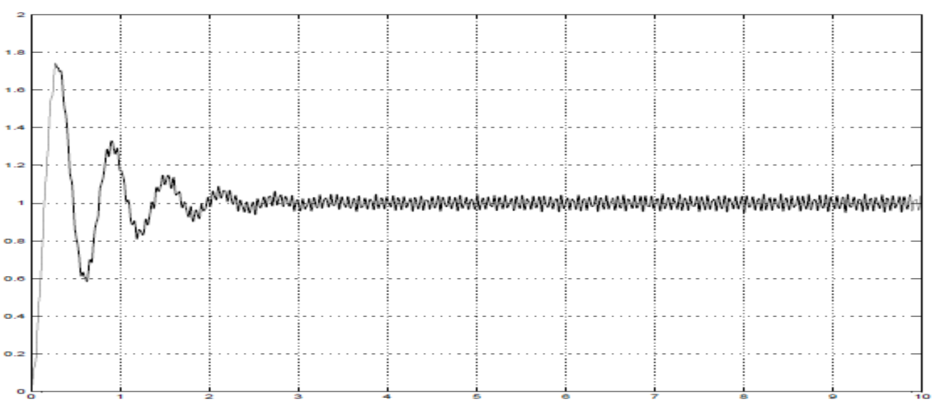
Field winding voltage $\mathbf{E_{fd} = 1}$

Voltage across D axis $\mathbf{V_{cd} = 1}$

Voltage across Q axis $\mathbf{V_{cq} = 1}$

And following observations were obtained (till 10 seconds) :

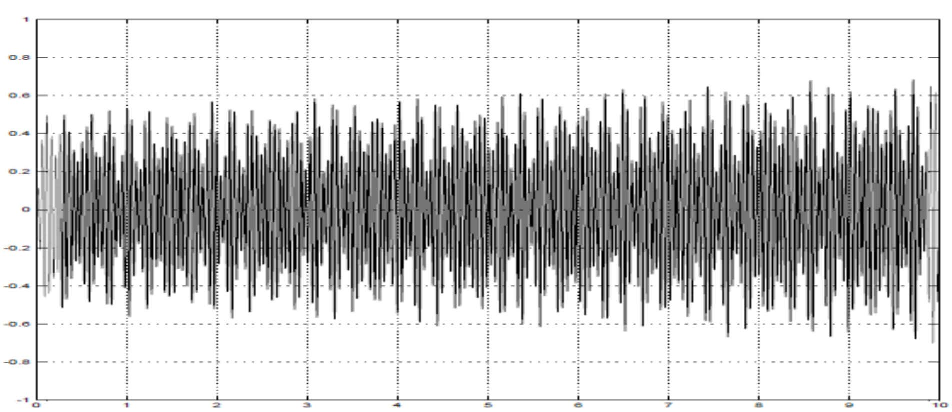
δ_{GEN}



Time, s

Figure 3.6 Variation of torque angle with time (X_C=0.35)

T_{GE}



Time, s

Figure 3.7 Variation of torque at GE shaft with time (X_C=0.35)

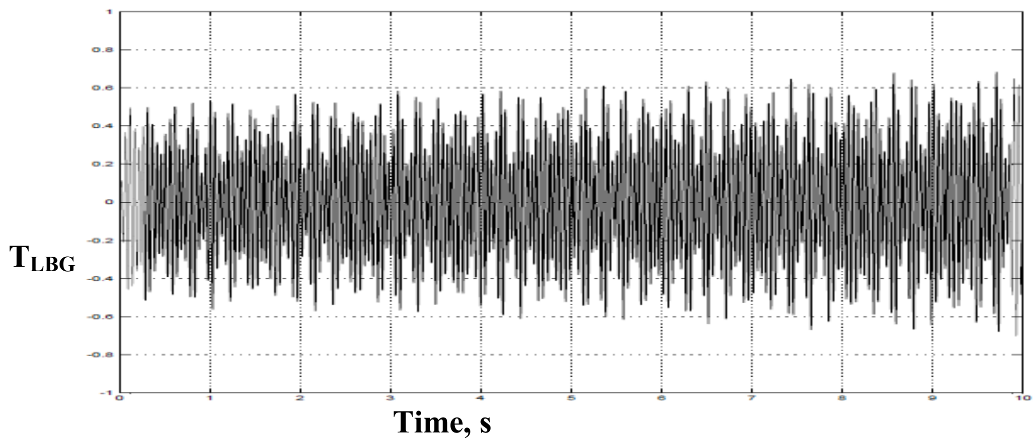


Figure 3.8 Variation of torque at LBG shaft with time (X_C=0.35)

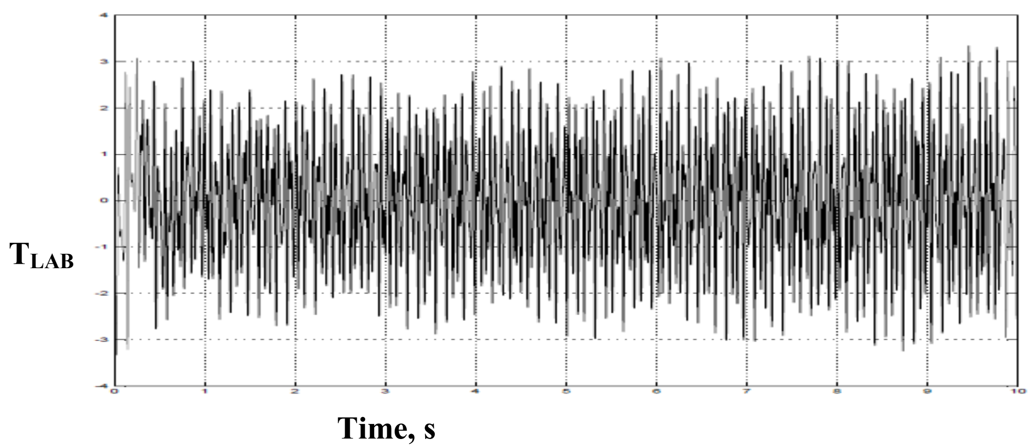


Figure 3.9 Variation of torque at LAB shaft with time (X_C=0.35)

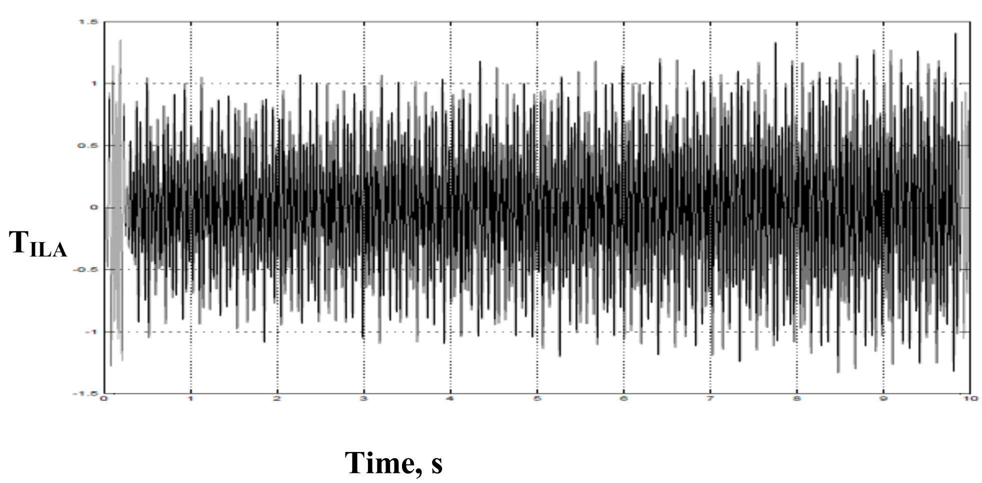
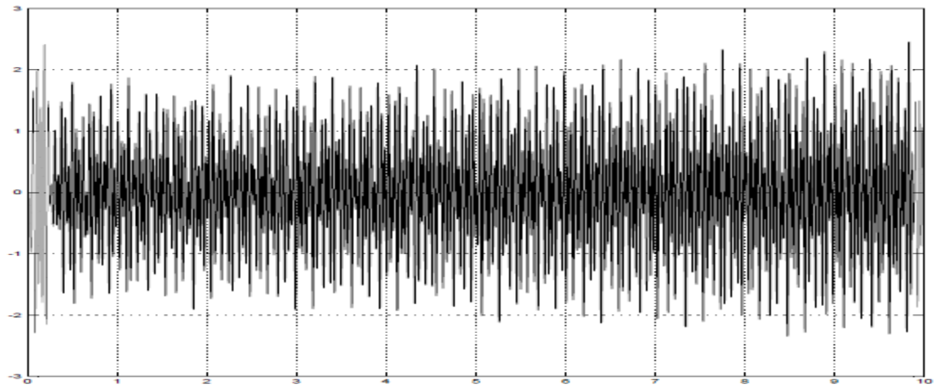


Figure 3.10 Variation of torque at ILA shaft with time (X_C=0.35)

T_{HI}



Time, s

Figure 3.11 Variation of torque at HI shaft with time (X_C=0.35)

3.4 Summary

This chapter presented the investigations of the subsynchronous resonance phenomenon under small disturbances. These investigations are conducted on the IEEE first benchmark model which consists of a large turbine-generator connecting to an infinite bus system through a series capacitor compensated transmission line.

The analysis was performed by modeling the individual systems (synchronous generator, electric network, and turbine-generator mechanical system) separately. The dynamic equations are linearized and combined in a single expression. These set of linearized equations were grouped and mathematically manipulated in order to obtain the overall system model in a state-space form.

It is observed that the mechanical system exhibits five modes of torsional oscillations. In many cases, reducing the compensation level can solve the torsional interaction problem, but is not an economic solution.

The analysis shows that the FBM system is suitable for testing the robustness of the proposed technique.

Chapter- IV

DAMPING SUBSYNCHRONOUS RESONANCE USING SSSC (STATIC SYNCHRONOUS SERIES COMPENSATOR)

4.1 Introduction:

The problem of torsional oscillations occurs because of imbalance in active power (a difference between turbine input and generator output) during rotor swing, but only few work has been reported for handling this problem through active power control, because it become very costly for system. A Static Synchronous Series Compensator (SSSC) is a series connected FACTS device. It uses a voltage-source converter to inject series voltage at the fundamental frequency. The output of the VSC can be controlled in amplitude as well as in phase by controlling the injected voltage phase angle, SSSC can be used as a reactive power or a real power compensating device based on its energy storage [1, 27-29]. For example if the injected series voltage leads or lags the transmission line current, then reactive power either absorbed or generated would be exchanged. On the other hand if the injected voltage is in phase with the line current then real power would be exchanged. In the case of reactive power compensation the injected series voltage decreases the effective transmission line reactance and therefore increases the real power transfer along the line. The SSSC is a more beneficial controller than the TCSC because of its ability to not only modulate the line reactance but also the line resistance in consonance with the power swings. It thereby imparts more damping to the generators that contribute to the power oscillations [30].

4.2 Principle of Operation

The basic operating principle of the SSSC can be explained with reference to the

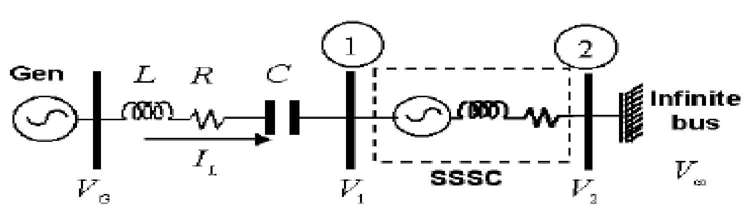


Fig.4.1.(a)SSSC connected to transmission line

conventional series capacitive compensation as shown in Figure 5.1. The phasor diagram shows that the series capacitor presents a lagging quadrature voltage with respect to the line current which opposes the leading voltage across the inductance of the transmission line. Thus, the series capacitive compensation works by increasing the voltage.

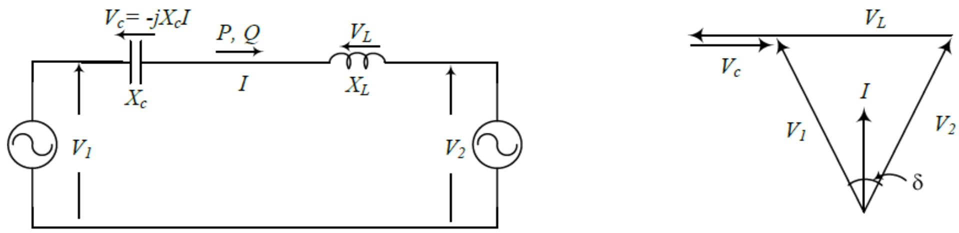


Fig. 4.1:A basic two machine system with a series capacitor compensated line and associated phasor diagram

Vinj=Vc=-jXcI=-jKXI **4.1.**

Where

Vc = voltage across capacitor

I=line current

XL=voltage across inductor

K=Degree of series compensation.

In a similar manner, the same steady-state power transmission can be established if the series compensation is provided by a synchronous ac voltage-source as shown in Figure 4.2, whose output precisely matches the voltage of the series capacitor.

By making the output voltage of the static synchronous voltage-source a function of the line current as shown in Eq. (4.1), the same compensation provided by the series capacitor can be accomplished. However, in contrast to the real series capacitor, the static voltage-source is able to maintain a constant compensating voltage in the presence of a variable line current or control the amplitude of the injected compensating voltage independent of the amplitude of the line current.

For the normal capacitive compensation, the output voltage lags the line current by 90 degree. The output voltage of a VSC can be readily reversed by simple control action to make it lead or lag the line current by 90 degree. Figure 4.2(b) shows the phasor diagram when the VSC output voltage is lagging the line current by 90 degree and is acting as a capacitor while Figure 4.2(d) shows the VSC output voltage leading the line current by 90 degree and giving an inductive effect. Figure 4.2(c) shows no compensation mode of operation of the SSSC and at this condition, the output voltage is zero where is the magnitude of the injected compensating voltage (Vij), is the control parameter and *I* is the magnitude of the line current.

$$\overrightarrow{V_{inj}} = \pm jV_{inj}(\zeta)\frac{\vec{I}}{I} \quad (4.2)$$

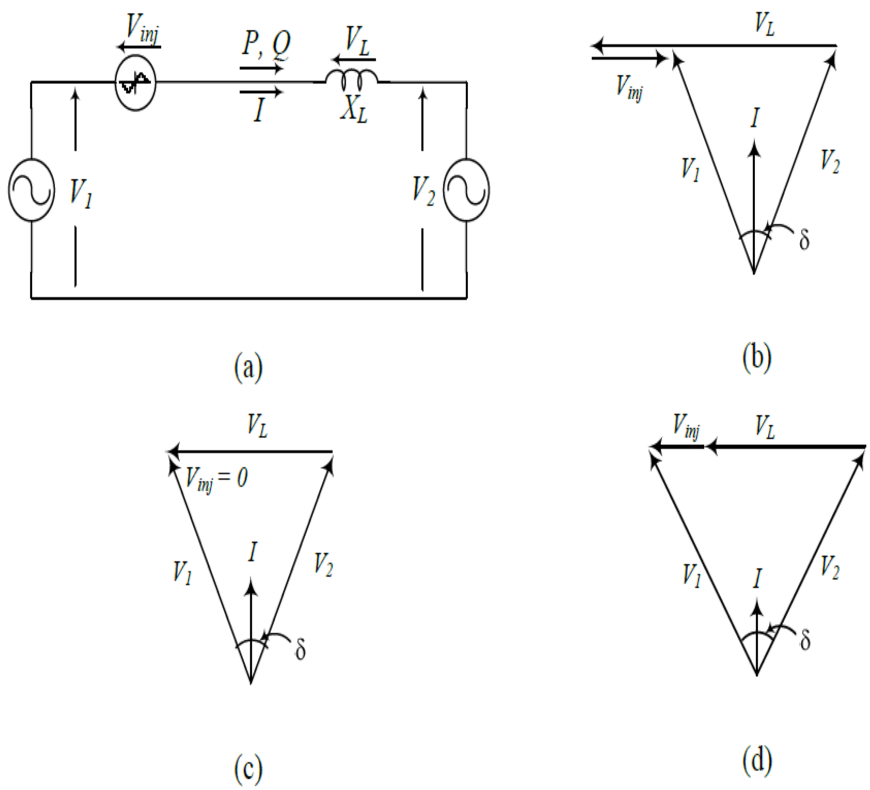


FIG.4.2. **A SSSC operation (a) in a two bus system and phasor diagrams of (b) capacitive compensation, (c) no compensation, and (d) inductive compensation modes**.

connected to the transmission line. The SSSC has a GTO based power converter, controller, dc storage, and coupling transformer. The controller circuit gets local variable inputs like line current, bus voltage and controller parameters.

4.3 Modeling of SSSC for Damping Subsynchronous Resonance Oscillations

Modeling of the SSSC is done by MATLAB coding program. It has been shown that if the subsynchronous oscillations drive unsymmetrical phase currents, the developed electromagnetic torque will be lower than what it would be if the three-phase currents are symmetrical . The unsymmetrical current results in a lower coupling strength between the mechanical and the electrical system at asynchronous oscillations. Therefore, the energy exchange between the electrical and the mechanical systems at **subsynchronous oscillations** will be suppressed, thus avoiding the build-up of torsional stresses on the generator shaft system under **subsynchronous resonance** conditions.

Unbalanced operation of the electrical system is achieved by operating the SSSC in an unbalanced mode. The unbalanced operation of the electrical system for a short period of time decreases coupling between the electrical and mechanical systems and eventually suppresses the subsynchronous .

The inverter configuration of SSSC [6, 7] used here consists of a 48-step inverter and magnetic circuit, which contains 18 single-phase three winding transformers and six single-phase two winding transformers [6 , 7]. In Fig. 4(a), is the voltage injected by SSSC. The series inductance accounts for the leakage of the interfacing transformer and transformers in the magnetic structure of the inverter, while represents the conduction losses of the inverter and transformer. In the dc side shown in Fig. 4(b), is the voltage across the dc capacitor that has a value of , the resistance in shunt with the dc capacitor represents the switching losses, and is the current through the inverter as seen by the dc side.

The fundamental component of phase-a of the inverter output voltage is

$$v_{ia} = \sigma \frac{16\sqrt{3}V_{DC}Sin(\alpha + \theta_f)}{\pi} \qquad 4.3$$

Where

σ is the turn ratio of the interfacing transformer ,w is fundamental frequency, and θ_f is phase displacement of inverter voltage with respect to reference bus .

Normalized per unit equations of the SSSC in DQ frame are

$$\frac{d}{dt}\begin{bmatrix} i_{ld} \\ i_{lq} \\ v_{dc} \end{bmatrix} = \begin{bmatrix} -\frac{WR_R}{X_R} & -W & -\rho_1 Sin\theta_f \\ W & -\frac{WR_R}{X_R} & -\rho_1 Cos\theta_f \\ \rho_2 Sin\theta_f & \rho_2 Cos\theta_f & -\frac{WX_{DC}}{R_{DC}} \end{bmatrix}\begin{bmatrix} i_{ld} \\ i_{lq} \\ v_{dc} \end{bmatrix} + \begin{bmatrix} \frac{W}{X_R} & 0 & 0 \\ 0 & \frac{W}{X_R} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\begin{bmatrix} v_{TD} \\ v_{TQ} \\ 0 \end{bmatrix} \tag{4.4}$$

$X_R = WL_R$

$X_{DC} = \frac{1}{WC_{DC}}$

$\rho 1 = \sqrt{3}W / X_R$

$\rho 2 = \sqrt{3}WX_{DC}$

literalizing SSSC Equations can be written as

$$\Delta \dot{x}_{N2} = [AN2]\Delta x_{N2} + [BN2]\Delta Y_G + [B_C]\Delta\theta_F \tag{4.5}$$

$$\Delta v_1 = -\frac{X_R}{W}\Delta \dot{Y}_G + [F2]\Delta Y_G + [F_{S2}]\Delta X_{N2} + [F_C]\Delta\theta_F + \Delta e_2 \tag{4.6}$$

$$\triangle X_{N2} = \triangle V_{dc}$$

$$\triangle e_2^T = \left[\triangle V_{\alpha D} \quad \triangle V_{\alpha Q} \right]$$

$$\left[A_{N2} \right] = -wX_{dc} / R_{dc}$$

$$\left[B_{N2} \right] = \sqrt{3} wX_{dc} \left[Sin\theta_{f0} \quad Cos\theta_{f0} \right]$$

$$\left[B_C \right] = \sqrt{3} wX_{dc} \left(i_{D0} Cos\theta_{f0} - i_{D0} Sin\theta_{f0} \right)$$

$$F_2 = \begin{bmatrix} R_R & X_R \\ -X_R & R_R \end{bmatrix}$$

$$\left[F_{S2} \right]^T = \left[\sqrt{3} Sin\theta_{f0} \quad \sqrt{3} Cos\theta_{f0} \right]$$

$$\left[F_c \right] = \sqrt{3} v_{dc0} \left(Cos\theta_{f0} - Sin\theta_{f0} \right)$$

$$\triangle \dot{x}_n = \left[A_N \right] \triangle x_N + \left[B_N \right] \triangle y_G + \left[B_c \right] \triangle \theta_f$$

$$\triangle u_G = \frac{X}{w} \triangle \dot{y}_G + \left[F_S \right] \triangle x_N + \left[F \right] \triangle y_G + \left[F_c \right] \triangle e_2 \qquad 4.7,4.8$$

Note that combining above equation the net overall equation is given above are equation of SSSC.

COMBINED SYSYTEM MODEL EQUATION:-

Combining the generator and network models we get the overall system equation

$$\dot{X} = Ax + Bu$$

Where $x^t = \left[\triangle x_G \quad \triangle x_N \right]$ and $u = \triangle \theta_f$

$$A = \begin{bmatrix} \left\{ A_G + B_G H \left(FC_G + \frac{X_T C_G A_G}{w_B} \right) \right\} & B_G H F_S \\ B_N C_G & A_N \end{bmatrix} \qquad 4.9$$

$$B^T = \left[B_G H F_C \quad B_C \right] \text{ and } H = \left\{ I - \frac{X_L}{w_B} [C_G][B_G] \right\}^{-1} \qquad 4.10$$

TABLE 5 .1:EIGEN VALUE RESULT WHEN SSSC IS CONNECTED TO IT

MODES	CAPACITOR+SSSC
SUPERSYNCHRONOUS	-4.3400 + j502.79 -4.3400 – j502.79
SUBSYN1	-3.9400+ j250.13 -3.9000– j250.13
MODE0	-0.4000 + j8.40 -0.4000 – j8.40
MODE1	-0.1500 + j99.13 -0.1500 – j99.13
MODE2	-0.6600 + j127.02 -0.6600 – j127.02
MODE3	-0.6600 + j160.63 -0.6600 – j160.63
MODE4	-0.0300 + j203.04 -0.0300– j203.04
MODE5	-0.1800 + j298.18 -0.1800 – j298.18

4.3.1.AFTER INSTALLING SSSC THE RESULTS ARE

Time Domain Analysis

The above Model was studied for small signal stability in time domain with the help of MATLAB.

SIMULINK model was made and it was given step input as(for 10 sec:

$E_{fd} = 1$; $V_{cd} = 1$; $V_{cq} = 1$

And following observations were obtained:

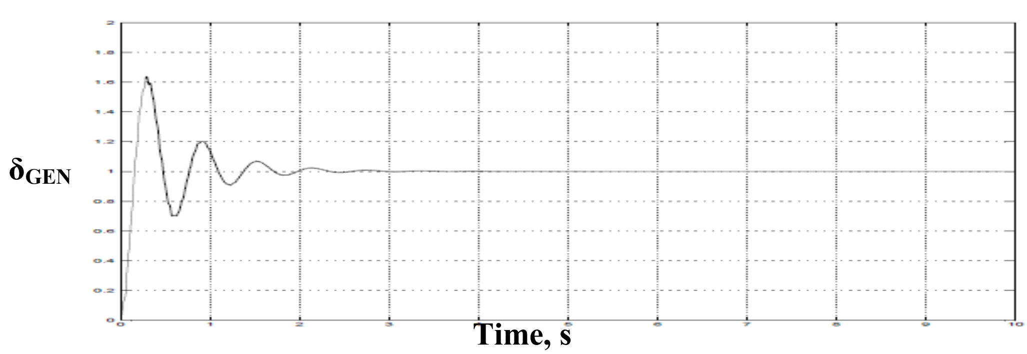


Figure 5.3 Variation of torque angle with time (with SSSC)

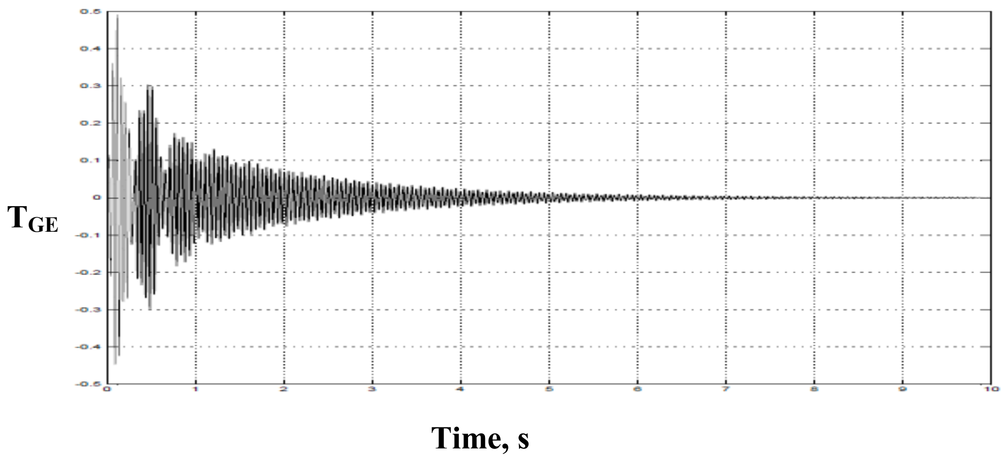


Figure 5.4 Variation of torque at GE shaft with time (with SSSC)

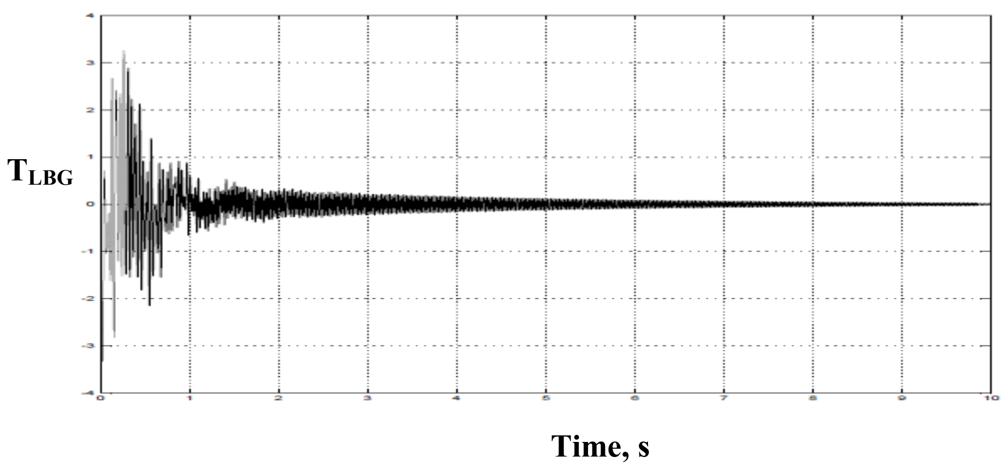


Figure 5.5 Variation of torque at LBG shaft with time (with SSSC)

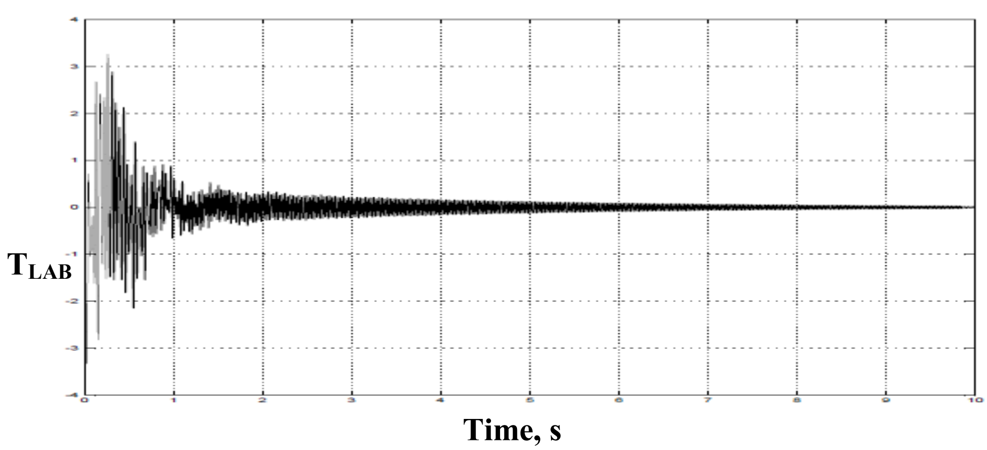
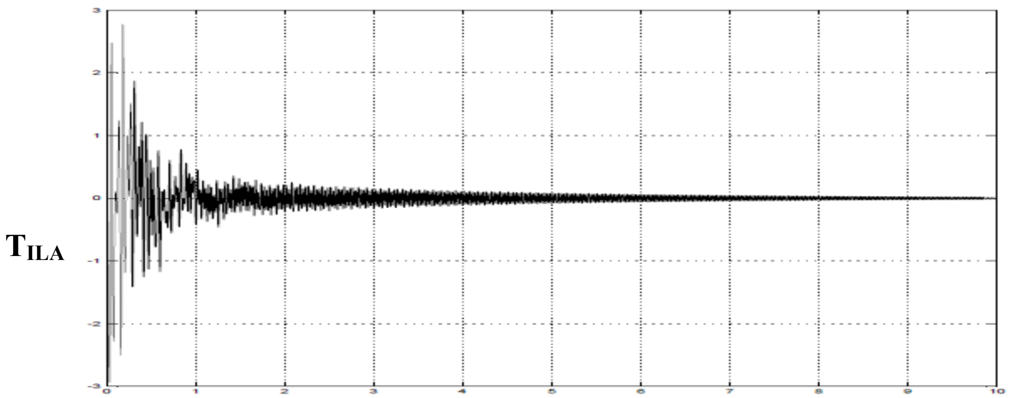
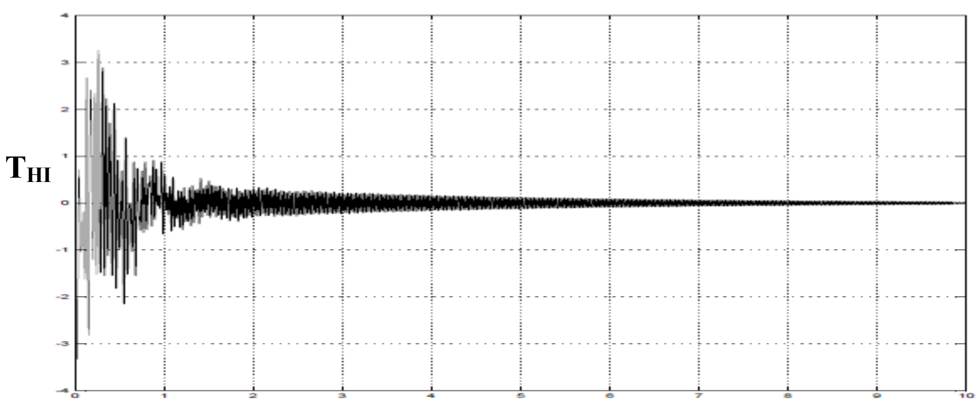


Figure 5.6 Variation of torque at LAB shaft with time (with SSSC)



Time, s

Figure 4.5 Variation of torque at ILA shaft with time (with SSSC)



Time, s

Figure 4.5 Variation of torque at HI shaft with time (with SSSC)

5.4: Summary

Addition of an SSSC in a series compensated power system provides superior performance characteristics and application flexibility not achievable by conventional series capacitors. The voltage source nature of the SSSC can stabilize the unstable torsional modes of a fixed capacitor compensated transmission system as it increases the damping of the torsional and network modes. The presence of series capacitor increases the synchronizing power coefficient. It also improves the small signal stability of power system. Reduction of the MVAR rating of the SSSC is an added advantage of the combination. As SSSC can exchange both active and reactive power so it makes possible to control reactive and resistive line drops and maintain a effective x/r ratio for series compensation High values of capacitive reactance can cause torsional interaction. An auxiliary controller that modulates the output of the PI controller can stabilize the torsional modes. Thus, with the combination of the SSSC and damping controller, the amount of fixed compensation can be increased without endangering the system stability.

CHAPTER -V

DAMPING SUBSYNCHRONOUS RESONANCE USING A STATIC SYNCHRONOUS COMPENSATOR

5.1 **INTRODUCTION**:-

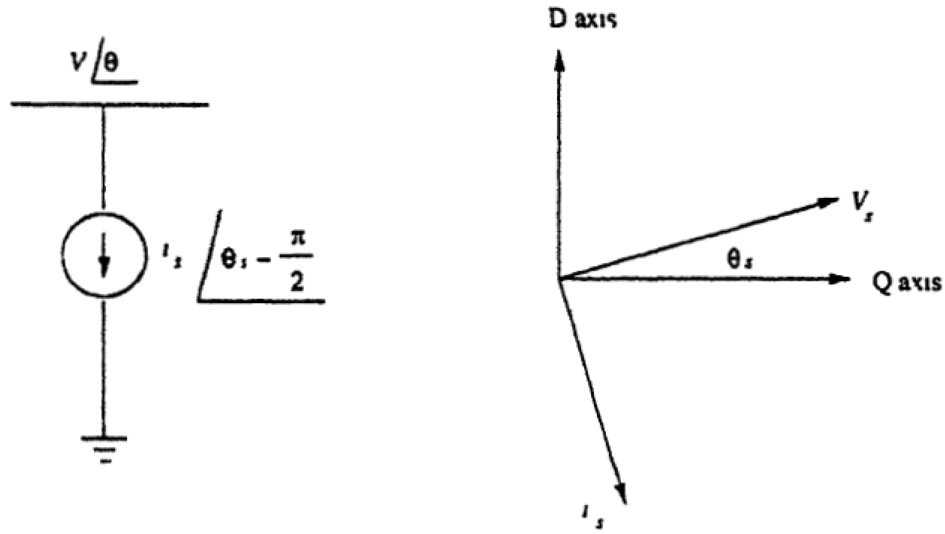


FIG 5.1:-Equivalent Circuit Representation of STATCOM.

A Static Synchronous Compensator (STATCOM) [54] is a shunt connected device that is capable of generating or absorbing reactive power and in which the output can be varied to control specific parameters of an electric power system. It is in general, a solid-state switching converter that is capable of generating or absorbing independently controllable real and reactive power at its output terminals when it is fed from an energy source or energy-storage device at its input terminals. The STATCOM considered here is a GTO (gate turn off) based voltage-source converter which, from a given input of dc voltage, produces a set of three- phase ac output voltages each in phase with and coupled to the corresponding ac system voltage through a relatively small tie reactance (0.1–0.15 p.u.) generally provided by coupling transformer leakage output voltage amplitude and phase angle can be controlled by controlling the GTOs firing angle. The operating principle is similar to the synchronous condenser but its operating speed is much faster because of the lack of mechanical rotating components. In contrast to the synchronous condenser, the STATCOM [50] reactive current output is independent of the bus voltages.

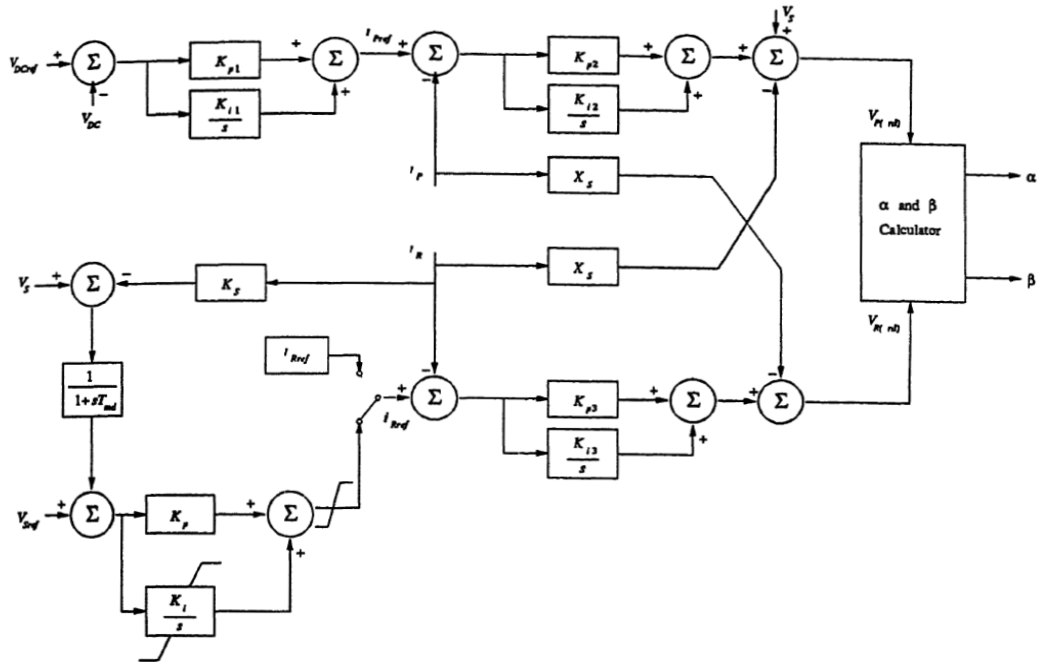


Fig 5.2 Type 1 controller for 3 level VSC based STATCOM.

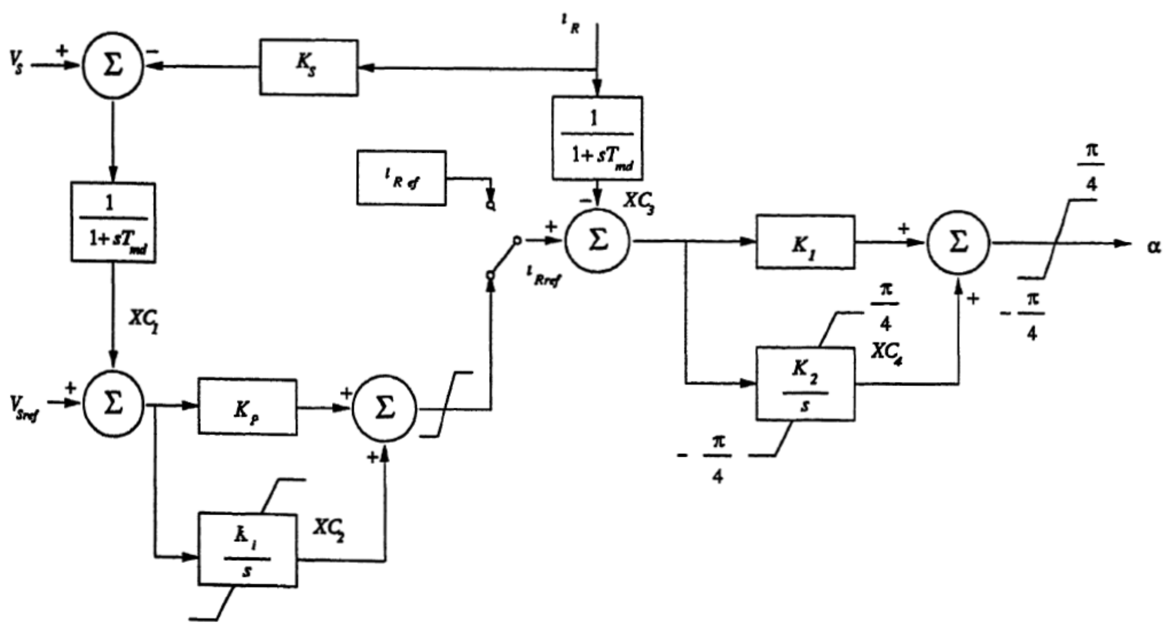


FIG 5.3 :-TYPE-2 controller for 2 level VSC based STATCOM .

In this project, TYPE-2 controller for 2 level VSC based STATCOM controller was used. A STATCOM can improve power system performance such as: dynamic voltage control in transmission and distribution systems, damping of power system oscillations, voltage flicker control and control of reactive power and active power if needed in the connected line.

5.2:- PRINCIPLE OF OPERATION:-

The basic operating principle [50] of reactive power generation by a voltage-source converter based STATCOM can be explained with the help of the schematic diagram of the STATCOM shown in fig 5.1. From the dc input voltage source, provided by a charged capacitor or battery, the converter produces a set of controllable three-phase output voltages. Each phase output voltage is in phase with and coupled to the corresponding ac system phase voltage via a coupling transformer.

If Vpcc is the bus voltage at which the STATCOM is connected, and Vs is the STATCOM output voltage, then considering a system with two voltage sources coupled by the transformer leakage reactance X , real and reactive power flow can be written as

$$P = \frac{V_{PCC} V_S Sin\delta}{X_T} \qquad 5.1$$

$$Q = \frac{\left| V_{PCC} - V_S Cos\delta \right| V_{PCC}}{X_T} \qquad 5.2$$

where is the phase angle between V and Vpcc. Eqs. (5.1) and (5.2) reveal the fact that the operation of a STATCOM for absorbing and generating reactive power can be done by controlling the magnitude of STATCOM voltage. There are three possibilities of operation:

i. Case I : if , reactive power is generated.

ii.Case II : if , reactive power is absorbed.

iii.Case III: if , no exchange of reactive power occurs.

Along with reactive power compensation, adjusting the phase shift between the converter output voltage and the ac system voltage (i.e. controlling) can control the real power exchange between the converter and the ac system. A small amount of real power is needed, however, supply the losses in the magnetic and switching circuits and dc capacitor losses. A detailed schematic diagram of a STATCOM connected to the ac system grid is shown in Figure 5.4.

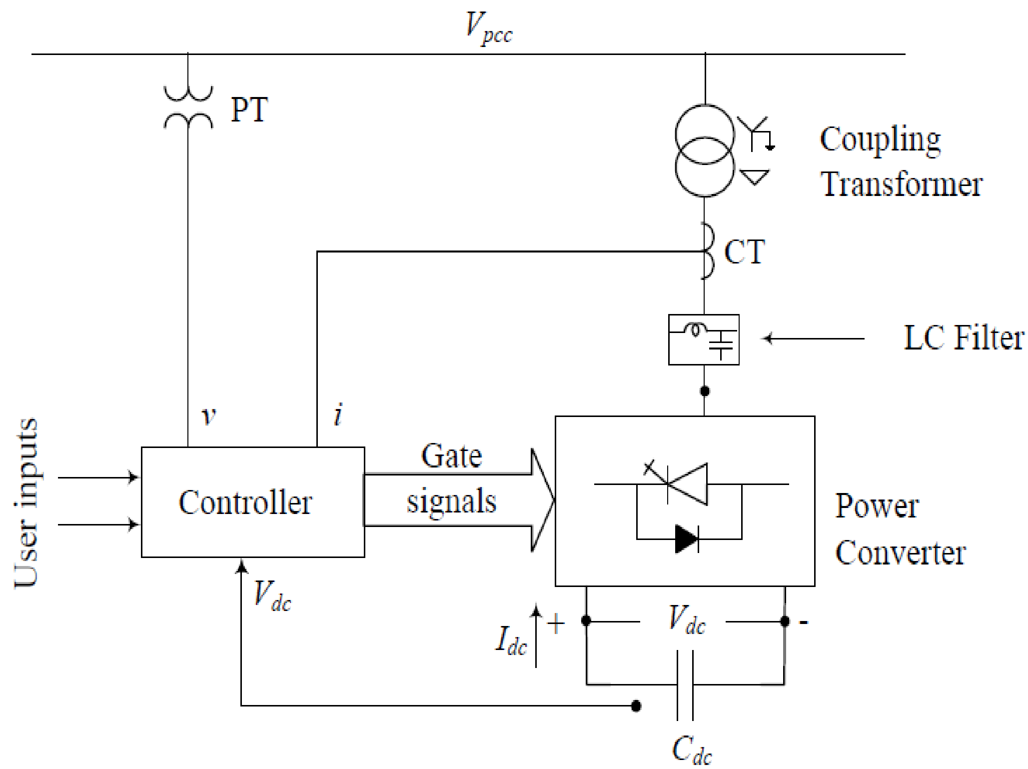


Fig 5.4: **STATCOM Schematic Diagram**

The operation of the STATCOM is controlled as desired by using a controller. The controller takes inputs like system variables (voltages and currents), user inputs Such as controller gain settings, reference values etc. and dc capacitor voltage and generates appropriate gate switching signals required for the power converter. The output of the converter is filtered using a low pass LC filter tuned near the carrier frequency and coupled to the ac grid through a three-phase coupling transformer. Potential transformer (PT) and current transformer (CT) are used to sense the system voltages and currents. The transformer leakage reactance acts as a coupling inductor.

5.3 STATCOM IMPLEMENTATION IN THE IEEE FIRST BENCHMARK MODEL

The developed STATCOM model is incorporated in the IEEE First Benchmark Model for the validation of the proposed method as shown in Figure 5.5 .For this purpose, a STATCOM is assumed to be installed in the test system at a fractional distance M of the length of the transmission line from bus A. STATCOM is placed near the generator terminal.

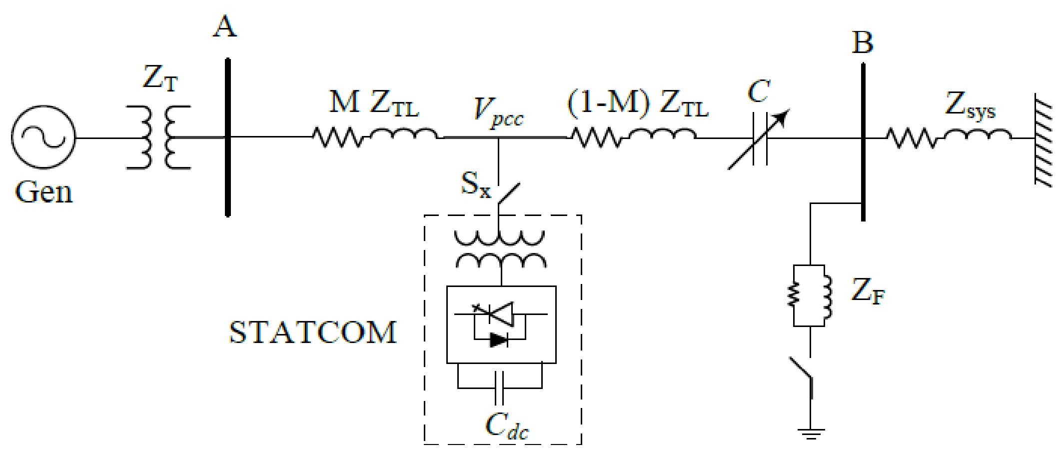


Fig 5.5: STATCOM Implementation In IEEE First Bench Mark Model

Table 5.1 :-To Study Electrical Parameter Of First Benchmark Model For Simulation Study

Base MVA	892.4 MVA
Base voltage	500 kV
Real power at infinite bus	0.89 p.u.
Reactive power at infinite bus	0.06 p.u.
Terminal voltage at infinite bus	$1.00\angle 0^0$ p.u.
System frequency	60 Hz

5.2: TABLE OF EIGEN VALUE ANALYSIS USING STATCOM.

-0.0079+621.4i -0.0079-621.4i	Super synchronous network mode
-0.0002+101.1i -0.0002+101.1i	Sub synchronous network mode
-0.0005+16.3i -0.0005-16.3i	Torsional mode 0
0.0000+98.7i 0.0000+98.7i	Torsional mode 1
-0.0000+127.2i -0.0000+127.2i	Torsional mode 2
-0.000+160.5i -0.000-160.5i	Torsional mode 3
0.002+202.2i 0.002+202.2i	Torsional mode 4
-0.0000+298.2i -0.0000+298.2i	Torsional mode 5

Here we see from table that that most of Eigen values are negative but some positive frequency components are also present. So STATCOM which is a shunt device not as much effective as compare to series devices.

5.4.2 APPLICATION OF STATCOM

The STATCOM has the following applications in controlling power system dynamics.

- Damping of power system oscillations
- Damping of sub synchronous oscillations
- Balanced loading of individual phases
- Reactive compensationof AC-DC converters and HVDC links
- Improvement of transient stability margin
- Improvement of steady-state power transfer capacity
- Reduction of temporary over-voltages
- Effective voltages regulation and control
- Reduction of rapid voltages fluctuations

5.4: CONCLUSION:-

In this chapter using STATCOM to damp the subsynchronous oscillation in addition to controlling the voltage in power system has been proposed. The inclusion of STATCOM does not change the SSR characteristics of network significantly. By using type 2 controller for 2 level VSC based STATCOM we are able to damp SSR up to some extend but not significantly. Application of this concept to the IEEE first bench mark model proved that STATCOM provided at the generator terminal and equipped with voltage controller not damp the torsional oscillation effectively. But by adding an auxiliary controller to it we can damp the SSR (subsynchronous resonance) up to some extent.

NOTE:-All the equation of STATCOM and Type 2, level 2 controller given in APPENDIX D.

CHAPTER-VI

COMPARISION OF DAMPING SUBSYNCHRONOUS RESONANCE USING SSSC AND STATCOM:-

By using an appropriate method for the shunt compensation of reactive power, the transmission steady state power is increased and the voltage profile along with the transmission line is controlled. The **STATCOM** is one example of a shunt compensation device of the Flexible AC Transmission Systems (FACTS) family. It is a static synchronous generator which is used for shunt compensation of reactive power and its inductive or capacitive current can be controlled independently of the system AC voltage.

The static Synchronous Series Compensator (**SSSC**) is a series device of the FACTS family that uses power electronics to control the power flow and to improve the power oscillation damping on power grids. When an SSSC injects an alternating voltage leading the line current, it emulates an inductive reactance as well as capacitive reactance in series with the transmission line causing the power flow as well as the line current to decrease as the level of compensation increases. At this time the SSSC is considered to operate in inductive mode. At this time the SSSC is considered to be operating in a capacitive mode. Therefore, the SSSC can apply rapid changes in system parameters such as the line impedance and the line currents.

The FACTS devices increases power handling capacity of the line and improves transient stability as well as damping performance of the power system. The static synchronous compensators (STATCOM) consists of shunt connected voltage source converter through coupling transformer with the transmission line . STATCOM can control voltage magnitude and, to a small extent, the phase angle in a very short time and therefore, has little ability to improve the system damping as well as voltage profile of the System. The Static Synchronous Series Compensator (SSSC) consist of series connected voltage source converter with coupling transformer in series with the transmission line. SSSC can inject a voltage with controllable magnitude and phase angle at the line frequency and found to be more capable of handling power flow control improvements of transient stability and damping of oscillations etc.

The shunt connected VSC is STATCOM injects an almost sinusoidal current of variable magnitude and in quadrature with the line voltage, at the point of connection. The series connected VSC is SSSC injects an almost sinusoidal voltage of variable magnitude and in quadrature with the line current. When the STATCOM and the SSSC operates as standalone controllers with open dc link switch they exchange almost exclusively reactive power at their terminals. The exchange power at the terminals of SSSC can be reactive as well as real. It was found that a SSSC in phase imbalanced mode for damping the SSR oscillation is more effective compared to a STATCOM.

1) As SSSC can exchange both active and reactive power so it makes possible to control reactive and resistive line drops and maintain a effective x/r ratio for series compensation.
2) Reduction in MVAR rating of SSSC is an added advantage for suppressing SSR. SSSC is a series FACTS device, which could be used to completely replace traditional series capacitor with even more flexibility of series compensation.
3) By including STATCOM in series compensated transmission line we do not change the SSR characteristics of network significantly.
4) STATCOM can control the line reactive power and by adding an auxiliary speed controller in STATCOM we can control SSR also effectively. This paper provides comparative study of damping SSR by using FACTS Devices SSSC and STATCOM which is series and shunt device respectively
5) It is found that SSSC a series FACTS device is more effective in damping SSR in comparison the STATCOM which is a shunt FACTS device.

.

Chapter- VII

MAIN CONCLUSIONS AND FUTURE SCOPE OF WORK

8.1. MAIN CONCLUSION

Eigenvalues studies and time domain simulations conducted on the IEEE First Benchmark Model show the damping benefits on SSR of SSSC and STATCOM coupled to transmission line. The major findings of the study are as follows:

Addition of an SSSC in a series compensated power system provides superior performance characteristics and application flexibility not achievable by conventional series capacitors. The voltage source nature of the SSSC can stabilize the unstable torsional modes of a fixed capacitor compensated transmission system as it increases the damping of the torsional and network modes. The presence of series capacitor increases the synchronizing power coefficient. It also improves the small signal stability of power system. Reduction of the MVAR rating of the SSSC is an added advantage of the combination. High values of capacitive reactance can cause torsional interaction. An auxiliary controller that modulates the output of the PI controller can stabilize the torsional modes. Thus, with the combination of the SSSC and damping controller the amount of fixed compensation can be increased without endangering the system stability

In this we have studied the characteristics of a transmission line compensated by series capacitor with the STATCOM provided at the generator terminal of the transmission line. In this we used type two level two controller. Instability of torsional modes is possible if the complement of the network resonant frequency matches with any of the torsional mode of the mechanical system The tools for the study are Damping torque analysis using simplified and detailed D-Q models of two level three level STATCOM. Eigenvalue analysis with detailed D-Q models of two level and three level model of STATCOM. Transient simulation with detailed D-Q model and three phase model of STATCOM(considering switching action).Find out the eigen values by installing STATCOM in first benchmark model to damp the subsynchronous resonance(SSR) in power system.

FUTURE SCOPE OF WORK:-

1. Various factors such as system configuration, system parameter and rating of device (As in any dynamical system investigations the result can be affected by rating of STATCOM and SSSC).

2. As a future work further studies can be carried out by applying the proposed scheme to the real compensated power system for choice of most suitable parameter for study.

3. Various problems that are arise due to unbalance in short period of time can also be investigated SSSC can be further investigated as economic alternatives of series compensation .

4. As in whole work we used the IEEE first bench mark model .for further study we can use IEEE second benchmark model also.

5. For damping SSR we can use another FACTS device also like UPSC,SVC,IPFC etc. These devices are further used for dynamic and transient performance of the power system.

6. Economic comparative study can be made for efficient FACTS controller for enhancement of power transfer capability, loss reductions voltage stability enhancement and damping sub synchronous resonance to find out the most economic FACTS controller.

7. Damping of SSR using STATCOM and SSSC can be done on SIMULINK also. Along with Eigenvalue analysis we can also see the result using simulation also.

8.STATCOM used for damping SSR is not as much effective device. By inserting frequency controlling we can further improve the damping of SSR using STATCOM by adding a auxiliary speed controller device in it.

REFERENCES

[1] IEEE Subsynchronous Resonance Working Group, “Terms, definitions and symbols for subsynchronous oscillations,” *IEEE Trans. Power App. Syst.*, vol. PAS-104, no. 6,pp. 1326–1334, Jun. 1985.

[2] O. Wasynczuk, “Damping shaft torsional oscillations using a dynamically controlled resistor bank,” *IEEE Trans. Power App. Syst.*, vol. PAS-100, no. 7, pp. 3340–3349, Jul. 1981.

[3] E. Gustafson, A. Aberg, and K. J. Astrom, “Subsynchronous resonance. A controller for active damping,” in *Proc. 4th IEEE Conf. Control Applications*, Sep. 1995, pp. 389–394.

[4] N. Kakimoto and A. Phongphanphanee, “Subsynchronous resonance damping Control of thyristor-controlled series capacitor,” *IEEE Power Eng. Rev.*, vol. 22, no. 9, p. 63,Sep. 2002.

[5] H. Sugimoto, M. Goto, W. Kai, Y. Yokomizu, and T. Matsumura, “Comparative studies of subsynchronous resonance damping schemes,” in *Proc. Int. Conf. Power System Technology*, Oct. 2002,vol. 3, pp. 1472–1476.

[6] M. R. Iravani and R. M. Mathur, “Damping subsynchronous oscillations in power systems using a static phase-shifter,” *IEEE Trans. Power Syst.*, vol. 1, no. 2, pp. 76– 82, May 1986.

[7] L.Wang and Y. Y. Hsu, “Damping of subsynchronous resonance using excitation controllers and static VAr compensations: A comparative study,” *IEEE Trans. Energy Convers.*, vol. 3, no. 1, pp. 6–13, Mar. 1988.

[8] B. K. Perkins and M. R. Iravani, “Dynamic modeling of a TCSC with application to SSR analysis,” *IEEE Trans. Power Syst.*, vol. 12, no. 4,pp. 1619–1625, Nov. 1997.

[9] X. Zhao and C. Chen, "Damping subsynchronous resonance using an improved NGH SSR damping scheme," in *Proc. IEEE Power Eng. Soc. Summer Meeting*, Jul. 1999, vol. 2, pp. 780–785.

[10] W. Li, L. Shin-Muh, and H. Ching-Lien, "Damping subsynchronous resonance Using superconducting magnetic energy storage unit," *IEEE Trans. Energy Convers.*, vol. 9, no. 4, pp. 770–777, Dec. 1994.

[11] A. H. M. A. Rahim, A. M. Mohammad, and M. R. Khan, "Control of subsynchronous resonant modes in a series compensated system through superconducting magnetic energy storage units," *IEEE Trans. Energy Convers.*, vol. 11, no. 1, pp. 175–180, Mar. 1996.

[12] O.Wasynczuk, "Damping subsynchronous resonance using energy storage," *IEEE Trans. Power App. Syst.*, vol. PAS-101, no. 4, pp. 905–914, Apr. 1982.

[13] S. K. Gupta, A. K. Gupta, and N. Kumar, "Damping subsynchronous resonance in power systems," *Proc. Inst. Elect. Eng., Gen., Transm.,Distrib.*, vol. 149, no. 6, pp. 679–688, Nov. 2002.

[14] K. Narendra, "Damping SSR in a series compensated power system," in *Proc. IEEE Power India Conf.*, 2006, p. 7.

[15] IEEE Subsynchronous Resonance Task Force, "First benchmark model for Computer simulation of sub synchronous resonance," *IEEE Trans. Power App. Syst.*, vol. PAS-96, no. 5, pp. 1565–1572, Sep. 1977.

[16] D. Walker, C. Bowler, R. Jackson, and D. Hodges, "Results of sub synchronous resonance test at Mohave," *IEEE Transactions on Power Apparatus and Systems*, vol94, no. 5, pp. 1878–1889, 1975.

[17] K. R. Padiyar, Power System Dynamics stability and control, BS Publication, second Edition,2008.

[18] G. Pillai, A. Ghosh, and A. Joshi, “Torsional interaction studies on a power system compensated by SSSC and fixed capacitor,” *IEEE Transactions on Power Delivery*, vol. 18, no. 3, pp. 988–993, 2003.

[19] A. A. Edris, “Subsynchronous resonance countermeasure using phase imbalance,”*IEEE Transactions on Power Systems*, vol. 8, no. 4, pp. 1438–1447, 1993.

[20] P.Kundur,”Power system stability and control”, *New York: McGraw-Hill*, 1994.

[21] IEEE Task Force,”Current usage and suggested practices in power system stability Simulations for synchronous machines”, *IEEE Trans. On Energy Conversion,* Vol. EC-1,No.1, 1986, pp. 77-93

[22] “Flexible AC Transmission Systems (FACTS),” *Electrical Power Research Institute Rep*., Number EL-6943, Sept. 1991.

[23] K.-H. Chu and C. Pollock, “PWM-controlled series compensation with low harmonic distortion,” in *Proc. Inst. Elect. Eng.—Gen., Transm. Dist.*, vol. 144, 1997, pp. 555–560.

[24] A. Ghosh and G. Ledwich, “Modeling and control of thyristor-controlled series compensators,” in *Proc. Inst. Elect. Eng.-Gen., Transm. Dist.*, vol. 142, 1995, pp. 297–304.

[25] L.Gyugyi, C. D. Schauder, and K. K. Sen, “Static synchronous series Compensator:A solid-state approach to the series compensation of transmission lines,” *IEEE Trans. Power Delivery*, vol. 12, pp. 406–417, Jan. 1997.

[26] K. K. Sen, “SSSC—Static synchronous series compensator: Theory, modeling and application,” *IEEE Trans. Power Delivery*, vol. 13, pp

[27] N. G. Hingorani, L. Gyugyi, “Understanding FACTS: concepts and technology of flexible AC transmission systems”, *New York: IEEE Press*, 2000.

[28] J. Butler and C. Concordia, “Analysis of series capacitor application problems,” *IEEE Transactions* , vol. 56, pp. 975–988, 1937.

[29] D. Walker, C. Bowler, R. Jackson, and D. Hodges, “Results of subsynchronous resonance test at Mohave,” *IEEE Transactions on Power Apparatus and Systems* , vol. 94, no. 5, pp. 1878–1889, 1975.

[30] M. H. Rashid, Power electronics: circuits, devices, and applications, 3rd ed., Pear son/Prentice Hall, 2004.

[31] N. Raju, N. Raju, S. Venkata, and V. Sastry, “The use of decoupled converter s to optimize the power electronics of shunt and series ac system controllers,” *IEEE Transactions on Power Delivery* , vol. 12, no. 2, pp. 895–900, 1997.

[32] J. Vithayathil, C. Taylor , M. Klinger, and W. Mittelstadt, “Case studies of conventional and novel methods of reactive power control on an ac transmission system,” ser. *CIGRE paper, Paris, France*, 1988, pp. 38 – 02.

[33] L. Gyugyi, “Unified power -flow control concept for flexible ac transmission systems,” *IEEE Proceedings- Generation, Transmission and Distribution,* vol. 139, no. 4, pp. 323–331, 1992.

[34] K. R. Padiyar, Analysis of Subsynchronous Resonance in Power Systems, Kluwer Academic Publishers, 1999.

[35] *IEEE Subsynchronous Resonance Working Group*, “Terms, definitions and symbols for subsynchronous oscillations,”

[36] K. Patil, J. Senthil, J. Jiang, and R. Mathur, “Application of STATCOM for damping torsional oscillations in series compensated ac systems,” IEEE Transaction on Energy Conversion , vol. 13, no. 3, pp. 237–243, 1998.

[37] Abbey, C., Khodabakhchian, B., and Céza Joós, “Three-level inverter based STATCOM,”EMTP-RV document , 2005.

[38] H. A. Shinzo Tamai, “Control performance of single-phase STATCOM and BtB by three-level inverters,”*Electrical Engineering in Japan*, vol. 157, no. , pp. 54–62, 2006.

[39] J. Salaet, A. Gilabert, J. Bordonau, S. Alepuz, A. Cano, and L. Gimeno, “Nonlinear control of neutral point in three-level single-phase converter by means of switching redundant states,” Electronics Letters , vol. 42, no. 5, pp. 304–306, 2006.

[40] Baker D.H. , Boukarim G.E, D`Aquila and Piwko R.J.,”subsynchronous resonance studies and mitigating methods for series capacitor applications”, Proceedings of the Inaugural IEEE conference and Exposition in Africa,july 2005, pp. 386-392.

[41] Hammed A.E. ,”Application of thyristor control VAR compensator for damping subsynchronous oscillations in power syatems,”IEEE Trans. On PAS ,Vol. PAS-103,No.,1Jan 1984.

[42] Sadeghzadeh S.M., Ehsan M.,Said N.H. Feuillet R., “Improvement of transient stability limit in power system transmission line using Fuzzy control control of

FACT devices “,*IEEE Transmission on power systems*,Vol.13,issue 3,August 1998,pp. 917-922.

[43] Wang H.F. ,”Static synchronous series compensator to damp power system oscillations”,*Electrical power system research* ,Vol. 54 ,2000,pp. 133-119.

[44] Pilani G.N., Ghosh A.,Jhoshi A.,”Torsional oscillation Studies in an SSSC compensated power systems”, *Electrical power system research* ,Vol. 55 ,2000,pp. 57-64.

[45] Pilani G.N.,Gupta H.O.,”Analysis of subsynchronous resonance with five level diode –clamped VSI based SSSC,” *proceeding on energy and power system* Vol.468,2005.

[46] Ngamrow I.,Kongprawechhon W.,”A robust controller design of SSSC for stabilization of frequency oscillations” *in interconnected power system research* ,Vol. 67, 2003,pp. 161-176.

[47] Frsangi M.M.,Song Y.H., Lee K.Y.,”Choice of FACT Device control inputs for damping interarea oscillations”, *IEEE Transactions on power system*,vol.19,issue 2,oct.1998,pp.1135-1143.

[48] Yixin Ni, Mak Lai On ,Huang Zhenyu ,Chen Shousun ,Zheng Baolin, “Fuzzy logic damping controller for FACTS devices in interconnected power systems”, *IEEE international Symposium on circuits and systems* ,Vol. 5, June 1999 ,pp.591-594.

[49] Panda S.,Patel R.N. and Wadhwani A.,”Optimal location of shunt devices in longtransmission line to improve transient stability”*CIGRE* ,September 2005,pp.177-189.

[50] Nagesh Prabhu ," Analysis of Subsynchronous Resonance with Voltage Source Converter based FACTS and HVDC Controllers", PhD thesis, Indian Institute of Science, Bangalore, September 2004.

[51] Fouad A.A. and Khu,K.T.,"Subsynchronous resonance zones in the IEEE Benchmark power system ",*IEEE TRANS on PAS* ,Vol. PAS-97,pp 754-762,may/june 1978.

[52] IEEE committee report ,"First supplement to a bibliography for the study of subsynchronous resonance between rotating machines and power systems ", *IEEE TRANS on PAS ,Vol. PAS*-98,pp 1872-1875 ,Nov./Dec. 1979.

[53] IEEE SSR working group "Countermeasures to subsynchronous resonance problems," *IEEE Trans on PAS* ,Vol. PAS-99 ,pp 1810-1818 ,Sep/Oct 1979.

[54] Padiyar K.R. and Prabhu Nagesh "Design and performance evaluation of subsynchronous damping controller with STATCOM",*IEEE transaction on power delivery,Vol.21 No.3,July 2006.*

[55] Padiyar K. R. and Prabhu N.,"Analysis of subsynchronous oscillation with three level twelve pulse based SSSC ",*Conference on convergent Technologies TENCON* ,Vol. 1,Oct. 2003,pp.76-80.

[56] Keshavan B. K and Prabhu N.,"Damping of sunsynchronous oscillation by switched series capacitor ",*IEEE Transaction on power system apparatus and systems,* Vol..99 ,No. 6,pp. 81-88,1979.

APPENDIX A

A.1:- Load Flow Program In MATLAB

To calculate the initial condition.

```
clc
P=0;
R=0;
Q=0;
phi0=acos(0.9);
Eb=1+j*0;
Xe=0.35;Xq=1.710;Xd=1.79;X1d=0.169;X1q=0.228;
Pt=P/cos(phi0);
Q=Pt*sin(phi0)
S=P+j*Q;
Ia0=S/Eb;
Vt0=Eb+(Ia0*(R+j*Xe));
theta0=angle(Vt0);
Eq0=Vt0+j*Xq*Ia0;
delta0=angle(Eq0);

Id0=-1*abs(Ia0)*sin(delta0-phi0)
Iq0=abs(Ia0)*cos(delta0-phi0)

Efd0=abs(Eq0)-(Xd-Xq)*Id0
E1q0=Efd0+(Xd-X1d)*Id0
E1d0=-(Xq-X1q)*Iq0

Vd0=-1*abs(Vt0)*sin(delta0-theta0)
Vq0=abs(Vt0)*cos(delta0-theta0)

sied0=(X1d*Id0)+E1q0
sieq0=(X1q*Iq0)-E1d0
```

APPENDIX B

SYSTEM DATA

B.1 Electrical Parameters

Table B-1. Network impedances, (in per unit, base: 892.4MVA, 500 kV)

Parameter	Positive Sequence	Zero Sequence
R_L	0.02	0.50
X_T	0.14	0.14
X_L	0.50	1.56
X_{sys}	0.06	0.06
X_C	0.35	0.35

Table B-2. Synchronous machine parameters, (in per unit, base: 892.4MVA, 26 kV)

B.2 Mechanical Parameters

Reactance	Value, p.u.	Time Constant	Value, *second*
x_d	1.790	T_{do}'	4.300
x_d'	0.169	T_{do}''	0.032
x_d''	0.135	T_{qo}'	0.850
x_q	1.710	T_{qo}''	0.050
x_q'	0.228		
x_q''	0.200		

Table B-3. Shaft inertia and spring constants

Mass	**Shaft**	**Inertia M** (Seconds)	**Spring constant *K*** (p.u./rad)
EXC		0.0342165	
	GEN-EXC		2.822
GEN		0.868495	
	LPB-GEN		70.858
LPB		0.884215	
	LPA-LPB		52.038
LPA		0.858670	
	IP-LPA		34.929
IP		0.155589	
	HP-IP		19.303
HP		0.092897	

Parameter for STATCOM:-

Kp=.1, Ki=-100,ks=.15
Irmax=.1681,Irmin= -.1681,
K1=.175, K2=3.5,
bc=0.2984,
K=4.341607527
Xc=.35 ,Xl=.7,
Ra=.02,R=0.002,Rp=299.66
Tmd=3.5;alpha=2.94,dethas=1.95

APPENDIX C

Load Flow Program In MATLAB

To calculate the initial condition using SSSC

```
clc
P=0.7;
R=0;
Q=0;
phi0=acos(0.9);
Eb=1+j*0;
Xe=0.35;Xq=1.710;Xd=1.79;X1d=0.169;X1q=0.228;
Pt=P/cos(phi0);
Q=Pt*sin(phi0)
S=P+j*Q;
Ia0=S/Eb;
Vt0=Eb+(Ia0*(R+j*Xe));
theta0=angle(Vt0);
Eq0=Vt0+j*Xq*Ia0;
delta0=angle(Eq0);
Id0=-1*abs(Ia0)*sin(delta0-phi0)
Iq0=abs(Ia0)*cos(delta0-phi0)

Efd0=abs(Eq0)-(Xd-Xq)*Id0
E1q0=Efd0+(Xd-X1d)*Id0
E1d0=-(Xq-X1q)*Iq0

Vd0=-1*abs(Vt0)*sin(delta0-theta0)
Vq0=abs(Vt0)*cos(delta0-theta0)

sied0=(X1d*Id0)+E1q0
sieq0=(X1q*Iq0)-E1d0
```

APPENDIX D:-

TYPE 2 CONTROLLER EQUATIONS USED IN STATCOM:-

$$\triangle X_{SC} = [A_{SC}]\triangle X_{SC} + \left[B_{Sc}^{i}\right]\begin{bmatrix}\triangle i_{SD}\\ \triangle i_{SQ}\end{bmatrix} + \left[B_{SE}^{V}\right]\triangle U_{SE} \qquad 1$$

$$\triangle \alpha = [C_{SC}]\triangle X_{SC} \qquad 2$$

$$\triangle X_{SC} = [\triangle XC1 \quad \triangle XC2 \quad \triangle XC3 \quad \triangle XC4]^{t} \qquad 3$$

$$[A_{SC}] = \begin{bmatrix} -\dfrac{1}{T_{md}} & 0 & 0 & 0 \\ -K_I & 0 & 0 & 0 \\ 0 & 0 & -\dfrac{1}{T_{md}} & 0 \\ -K_P K_2 & K_2 & -K_2 & 0 \end{bmatrix} \qquad 4$$

$$\left[B_{SC}^{I}\right] = \begin{bmatrix} \dfrac{K_S v_{QS}}{V_S T_{md}} & -\dfrac{K_S v_{SD}}{V_S T_{md}} \\ 0 & 0 \\ \dfrac{-v_{SQ}}{V_S T_{md}} & \dfrac{v_{SD}}{V_S T_{md}} \\ 0 & 0 \end{bmatrix} \qquad 5$$

$$\left[B_{SC}^{V}\right] = \begin{bmatrix} \dfrac{v_{SD}}{V_S T_{md}} - \dfrac{K_S C_2}{T_{md}} & \dfrac{v_{SQ}}{V_S T_{md}} - \dfrac{K_S C_3}{T_{md}} \\ 0 & 0 \\ \dfrac{C_2}{T_{md}} & \dfrac{C_3}{T_{md}} \\ 0 & 0 \end{bmatrix} \qquad 6$$

$$\begin{bmatrix} i_{SD} \\ i_{SQ} \end{bmatrix} = [C_{SE}]\triangle X_{SE} \qquad 7$$

$$C_2 = \frac{i_{SQ}}{V_S} - \frac{i_R v_{SD}}{{V_S}^2}$$ 8

$$C_3 = \frac{i_{SD}}{V_S} - \frac{i_R v_{SQ}}{{V_S}^2}$$ 9

$$\left[C_{SE}\right] = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$ 10

$$\left[A_{ST}\right] = \begin{bmatrix} A_{SE} & B^{C}{}_{SE}C_{SC} \\ B^{I}{}_{SC}C_{SE} & A_{SC} \end{bmatrix}$$ 11

$$\left[B_{ST}\right] = \begin{bmatrix} B_{SE}^{V} \\ B_{SC}^{V} \end{bmatrix}$$ 12

$$\left[B_{ST}\right] = \begin{bmatrix} B_{SE}^{V} \\ B_{SC}^{V} \end{bmatrix}$$ 13

$$\left[C_{ST}\right] = \left[C_{SE} \quad [0]\right]$$ 14

$$\left[D_{ST}\right] = [0]$$ 15

With detailed model of type-1 and type-2 STATCOM Equation:-

$$\left[\triangle X_{ST}\right] = \left[A_{ST}\right]\triangle X_{ST} + \left[B_{ST}\right]\begin{bmatrix} v_{SD} \\ v_{SQ} \end{bmatrix}$$ 16

$$\begin{bmatrix} i_{SD} \\ i_{SQ} \end{bmatrix} = \left[C_{ST}\right]\triangle X_{ST} + \left[D_{ST}\right]\begin{bmatrix} \triangle V_{SD} \\ \triangle V_{SQ} \end{bmatrix}$$ 17

$$\left[Y_S\right]=\left[C_{ST}\right]\left[sI-A_{ST}\right]^{-1}\left[B_{ST}\right]+\left[D_{ST}\right] \qquad 18$$

TYPE -2 STATCOM EQUATION:-

$$\triangle X_{SC}=\left[A_{SC}\right]\triangle X_{SC}+\left[B^{i}_{Sc}\right]\begin{bmatrix}\triangle i_{SD}\\ \triangle i_{SQ}\end{bmatrix}+\left[B^{V}_{SE}\right]\triangle U_{SE} \qquad 19$$

$$\left[A_{SE}\right]=\begin{bmatrix}-\frac{R_S W_B}{X_S} & -W_0 & -\frac{W_B K Sin(\alpha+\theta_s)}{X_S}\\ W_0 & -\frac{R_S W_B}{X_S} & -\frac{W_B K Cos(\alpha+\theta_s)}{X_S}\\ \frac{W_B K Sin(\alpha+\theta_s)}{b_c} & \frac{W_B K Cos(\alpha+\theta_s)}{b_c} & -\frac{W_B}{b_c R_p}\end{bmatrix} \qquad 20$$

$$\left[A_{SE}\right]=\begin{bmatrix}\frac{W_B}{X_S} & 0\\ 0 & \frac{W_B}{X_S}\\ 0 & 0\end{bmatrix} \qquad 21$$

$$\left[B^{V}_{SE}\right]=\begin{bmatrix}\frac{W_B}{X_S}\left[1-\frac{K v_{dc} Cos(\alpha+\theta_s) vsq}{Vs^2}\right] & \frac{W_B K v_{dc} Cos(\alpha+\theta_s) v_{SD}}{X_S Vs^2}\\ \frac{W_B K v_{dc} Sin(\alpha+\theta_s) v_{SQ}}{X_S Vs^2} & \frac{W_B}{X_S}\left[1-\frac{K v_{dc} Sin(\alpha+\theta_s) v_{SD}}{Vs^2}\right]\\ -\frac{W_B K_{c1} vsq}{b_c Vs^2} & \frac{W_B K_{c1} v_{SD}}{b_c Vs^2}\end{bmatrix} \qquad 22$$

SIMPLIFIED MODEL OF STATCOM EQUATION:-

$$V_S = \sqrt{v_{SQ}^2 + v_{SD}^2}$$

$$\Delta V_s = \frac{v_{SQ}\Delta V_{SQ}}{V_S} + \frac{v_{SD}\Delta V_{SD}}{V_S}$$

$$\frac{di_{sa}}{dt} = -\frac{W_B}{X_S}\left[R_S i_{sa} + v^i{}_{sa} - v_{sa}\right]$$

$$\frac{di_{sc}}{dt} = -\frac{W_B}{X_S}\left[R_S i_{sc} + v^i{}_{sc} - v_{sc}\right]$$

$$\frac{di_{sb}}{dt} = -\frac{W_B}{X_S}\left[R_S i_{sb} + v^i{}_{sb} - v_{sb}\right]$$

$$\frac{di_{sc}}{dt} = -\frac{W_B}{X_S}\left[R_S i_{sc} + v^i{}_{sc} - v_{sc}\right]$$

$$\Delta V_s = Cos\theta_s \vartriangle v_{SQ} + Sin\theta_s \vartriangle v_{SD}$$

$$\frac{dv_{dc}}{dt} = -\frac{W_B}{b_c}\left[\frac{v_{dc}}{R_P} + i_{dc}\right]$$

$$\frac{di_{sd}}{dt} = -\frac{R_S W_B}{X_S} i_{sd} - W_0 i_{sq} + \frac{W_B}{X_S}\left[v_{sd} - v^i{}_{sd}\right]$$

$$\frac{di_{sq}}{dt} = -\frac{R_S W_B}{X_S} i_{sq} + W_0 i_{sd} + \frac{W_B}{X_S}\left[v_{sq} - v^i{}_{sq}\right]$$

$$\frac{dv_{dc}}{dt} = -\frac{W_B i_{dc}}{b_c} - \frac{W_B v_{dc}}{b_c R_B}$$

$$v^i{}_{sd} = K v_{dc} Sin(\alpha + \theta_s)$$

$$v^i{}_{sq} = K v_{dc} Cos(\alpha + \theta_s)$$

$$K = \frac{2\sqrt{6}}{\pi}$$

$$\theta_s = Tan^{-1}\frac{v_{sd}}{v_{sq}}$$

$$V_S = \sqrt{v_{SQ}^2 + v_{SD}^2}$$

$$\frac{di_{sd}}{dt} = -\frac{R_S W_B}{X_S} i_{sd} - W_0 i_{sq} - \frac{W_B K v_{dc} Sin(\alpha + \theta_s)}{X_S} + \frac{W_B v_{SD}}{X_S}$$

$$\frac{di_{SQ}}{dt} = -\frac{R_S W_B}{X_S} i_{SQ} - W_0 i_{SD} - \frac{W_B K v_{dc} Cos(\alpha + \theta_s)}{X_S} + \frac{W_B v_{SQ}}{X_S}$$

FINAL MECHANICAL MATRIX OF FIRST BENCHMARK MODEL

$$[A_m] = \begin{bmatrix}
0 & 0 & 0 & \omega_B & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -\frac{D_{EXC}}{2H_{EXC}} & \frac{1}{2H_{EXC}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -K_{GE} & 0 & K_{GE} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & -\frac{1}{2H_{GEN}} & -\frac{D_{GEN}}{2H_{GEN}} & \frac{1}{2H_{GEN}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & -K_{LBG} & 0 & K_{LBG} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & -\frac{1}{2H_{LPB}} & -\frac{D_{LPB}}{2H_{LPB}} & \frac{1}{2H_{LPB}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & -K_{LAB} & 0 & K_{LAB} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{2H_{LPA}} & -\frac{D_{LPA}}{2H_{LPA}} & \frac{1}{2H_{LPA}} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & -K_{ILA} & 0 & K_{ILA} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{2H_{IP}} & -\frac{D_{IP}}{2H_{IP}} & \frac{1}{2H_{IP}} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -K_{HI} & 0 & K_{HI} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{2H_{HP}} & -\frac{D_{HP}}{2H_{HP}} & \frac{1}{2H_{HP}} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -K_{PI} & 0 & K_{HI} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{2H_{IM}} & -\frac{D_{IM}}{2H_{IM}}
\end{bmatrix}$$