CHAPTER 1

INTRODUCTION

1.1 General

Modern interconnected systems are very complex and demand careful planning, layout and operation. The introduction of HVDC and FACTS controllers in transmission networks provides both challenges and opportunities for optimum utilization of existing facilities [26]. Line compensation in AC transmission systems is usually a method of increasing load carrying capacity and control load sharing among parallel lines as well as to enhance transient stability. Line compensation in transmission lines might cause potentially subsynchronous resonance that can result in turbine-generator shaft malfunction and electrical lack of stability at oscillation frequencies below the system frequency [1, 5, 7]. That why appropriate understanding and research of SSR is to be carried out prior to installation of series capacitor compensation in power systems. The main point of concern with SSR from torsional stresses is the possibility of shaft damage. Damage can result from the long term cumulative effects associated with low amplitude torsional oscillations or the short run effects of high substantial torques. In various researches done worldwide it was found that various other situations, circumstances and parameters can also lead to an electromechanical resonance without capacitors employed being used to compensate transmission lines.

The modern power systems has the following two main characters, firstly extensive system interconnections and secondly increased dependency on FACTS devices for optimum utilization of existing resources. The modern interconnected power system is very much complex and requires proper planning, design and operation. The supply of economic and reliable electric energy is one of the major requisite for the progress of industries and consequently rises in the living standards of the people.

There are four major dynamic problems associated with the system operation. These are listed below:

1. Loss of synchronism
2. Voltage collapse
3. Low frequency oscillations
4. Subsynchronous frequency oscillations

Power system stability

Stability of power systems has been a major and continuous concern in the system operation. Under steady state or normal conditions, each of the generators connected are having same electrical speed anywhere in the system also known as synchronism of generators. Any disturbance either small or large can affect the synchronous operation of alternators. The stability of a system defined as the capability of the system to return to its normal steady state position after the transients are removed.

The disturbance can be of two types (a) small disturbance and (b) large disturbance. Small signal analysis i.e. linear equations are used for the analysis of small signal disturbances. The random or uneven changes in the load or generation are called small disturbances. Faults or loss of large loads results in voltage dip are called large disturbances and require fast action to clear out the fault.

1.2 Subsynchronous Resonance

Subsynchronous resonance is a special class of power system dynamic and stability problem, due to which turbine- generator shaft experiences torsional oscillations. These oscillations can be hazardous causing fatigue in the turbine- generator shaft which results in failure of power generation unit [7, 8].

As perdefinition of SSR is provided by the IEEE **"***Subsynchronous resonance* is a condition where the electric network exchanges energy with a turbine generator at one or more of the natural frequencies of the combined system below the synchronous frequency of the system."[6]

Any system condition during which energy is exchanged at a given subsynchronous frequency has been included in the above definition. This also includes the "natural" modes of oscillation that occur because of the inherent system characteristics, as well as "forced" modes of oscillation that are driven by a particular device or controlling scheme or controller. Networks containing transmission lines with series compensation are the most noted example of natural mode of subsynchronous operation. These lines have natural frequencies $\omega_n$that are defined by the equation (1) with their series inductance L and capacitance C combination is given in equation (1).

$$\omega_n = \sqrt{\frac{1}{LC}} = \omega_B\sqrt{\frac{X_C}{X_L}} \quad \text{----------------- (1)}$$

where ω_n is the natural frequency associated with a particular line L C product, ω_B is the system base frequency, and X_L and X_C are the inductive and capacitive reactance respectively.

The oscillations of the rotating part of the generator at subsynchronous frequency f_m results in induced voltages in the armature having components of (i) subsynchronous frequency (f_a- f_m) and (ii) super-synchronous frequency (f_a+ f_m) where f_a is the operating system frequency. This results in setting up of currents in the armature (and network) whose magnitudes and phase angles are decided by the impedances present in the network. Both current components (sub and super-synchronous) set up electromagnetic torques of the same frequencyfm. It can be shown that in general, positive damping torque occurs as a result of super-synchronous frequency while negative damping torque occurs as a result of the subsynchronous frequency. The net torque can result in negative damping if magnitudes of the subsynchronous frequency currents is large and in phase with the voltages (of subsynchronous frequency). This situation can occur when the electrical network connected to the generator armature resonates around the frequency of (f_a- f_m).

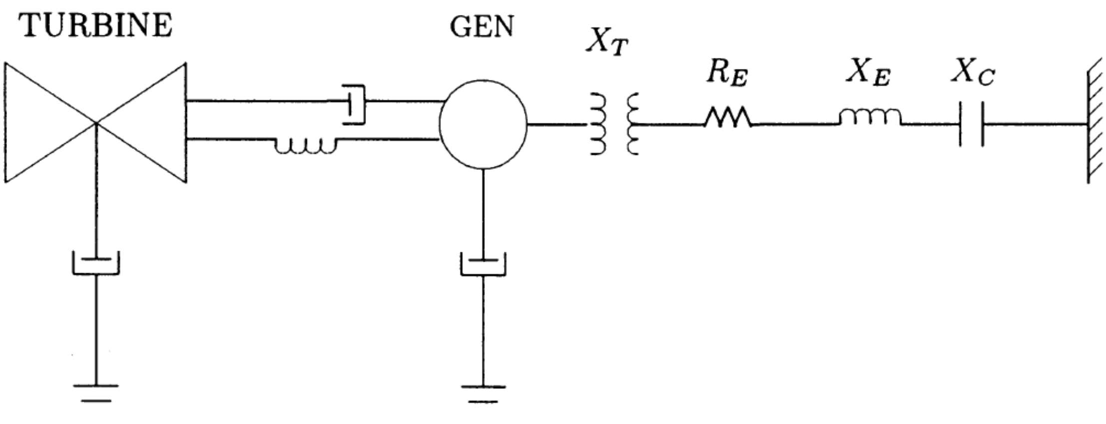

Fig 1.1 Series Compensated Power Transmission Line

The torsional modes (frequencies) of oscillations of the shaft are generally known and can be obtained from the manufacturer of the turbine-generator. The frequencies at which the network oscillates depends on many factors, such as the network switching arrangement at a particular time and the percentage of series capacitance in service. The Power system engineer needs a method for examining a large number of feasible operating conditions to determine the possibility of SSR interactions. The eigenvalue program can be one of the tool for SSR analysis. Moreover, the eigenvalue computationtrack the locus of system eigenvalues as parameters such as the series capacitance is varied to represent equipment outages. If the root locus of a given Eigenvalues approaches or crosses the imaginary axis, then a critical situation generally occurs that requires the application of one or more SSR countermeasures.

1.3 Types of SSR Interactions

There are many ways in which the system and the generator may interact with subsynchronous effects. A few interactions are given. These interactions are of more concern to power system engineer.

Induction Generator Effect
Torsional Interaction Effect
Transient Torque Effect

a.) Induction Generator Effect

Induction generator effect occurs when the generator is excited by self-excitation of the electrical power system. The resistance of the rotor to subsynchronous current is a negative resistance, as seen from the armature terminals. A positive resistance is provided by the network to these currents. However, continuous subsynchronous currents are seen when the generator's negative resistance is higher in magnitude than the positive resistance of the network at the system's natural frequencies. The general term coined for this effect is the "induction generator effect".

b.) Torsional Interaction

When the sub synchronous torque induced in the generator is close to one of the torsional natural modes of the turbine-generator shaft, torsional interactions are produced. Under this condition, oscillations in the generator rotor starts increasing and armature voltage components at both subsynchronous and super-synchronous frequencies are induced due to this motion. The induced subsynchronous frequency voltage is phased to sustain the subsynchronous torque.The inherent mechanical damping torque equal to or greater than the rotating system, the system itself will be excited. This phenomenon is called "torsional interaction."

c.) Transient Torques

The torques that occur due to system disturbances are the transient torques. These system disturbances cause sudden changes in the network, as a result of which sudden changes in currents will occur that will tend to oscillate at the natural frequencies of the network. If the transmission system is uncompensated, these dc transients are always dominant, which settles to zero with a time constant that depends on the ratio of inductance to resistance. For networks with series compensation, the transient currents will contain one or more oscillatory frequencies that will depend on the network capacitance as well as the resistance and inductance of the network.

1.2.2 Subsynchronous Resonance Analysis Tools

There are several analytical tools that have evolved for the study of SSR. The most common tools are described below briefly [27].

a. Eigenvalues analysis
b. Frequency analysis
c. Electromagnetic Transients Program (EMTP) Analysis

a. Eigenvalues analysis

Eigenvalues analysis provides additional information regarding the system performance. This type of analysis is performed with the network and the generators modelled in one linear system of differential equations. The results give both the frequencies of oscillation as well as the damping of each frequency.

Eigenvalues are described in terms of the system linear equations that are written in the following standard form.

$\dot{x}$ = Ax + Bu

Then the eigenvalues can be determined from the solutions of the matrix equation

Det [λI-A] = 0

Where the parameters λ are called the eigenvalues.

The Eigenvectors of the system matrix display the information on the relative magnitude of the response of the individual state variables in the mode represented by each state variable. Eigenvalue analysis is attractive since it provides the frequencies and the damping at each frequency for the entire system in a single calculation.

Advantages of Eigenvalue Analysis

The advantages of eigenvalue analysis are many. Some of the prominent advantages are:

- Use of the state-space equations makes it possible to utilize many other analytical tools.
- Determines all the modes of system oscillation in a only onecomputation.
- Can be arranged to study parameter sensitivities by varying parameters.
- Used to plot root loci of eigenvalue movement in response to variations.

Eigenvalue analysis also includes the computation of eigenvectors, which are often not as well understood as Eigenvalues, but are significant for analyzing the system. Very briefly, there are two types of eigenvectors, usually called the "right hand" and "left hand" eigenvectors. These quantities are used as follows:

- Right Hand Eigenvectors - show the distribution of modes of response (eigenvalues) through the state variables
- Left Hand Eigenvectors - show the relative effect of different initial conditions of the state variables on the modes of response (eigenvalues)

The right hand eigenvectors are the most useful in SSR analysis. Using these vectors, one can establish the relative magnitude of each mode's response due to each state variable. In this way, one can determine those state variables that have little or no effect on a given mode of response and, conversely, those variables that a play important role is contributing to a given response. This often tells about exactly those variables that need to be controlled in order to damp a subsynchronous oscillation on a given unit.

Disadvantages of Eigenvalue Analysis

Eigenvalue analysis is computationally intensive and is useful only for the linear problem. This type of analysis is only limited to relatively small systems, say of 500th order or less. Recent work has been done on much larger systems which requires a skilled and experienced analyst in order to be effective. Work is progressing on more general methods of solving large systems. Another difficulty of eigenvalue analysis is the general level of difficulty in writing eigenvalue computer programs.

b. Frequency Scanning [11]

Frequency scanning is a technique that has been widely used in preliminary analysis of SSR problems, and isparticularly effective in the study of induction generator effects. Thefrequency scan technique computes the equivalent resistance andinductance, seen looking into the network from a point behind the statorwinding of a particular generator. This equivalent resistance and inductance is a function of frequency. Should therebe a frequency at which the inductance is zero and the resistance negative,self-sustaining oscillations at that frequency would be expected due toinduction generator effect.

Frequency scanning is limited to the impedances seen at a particular pointin the network, usually behind the stator windings of a generator. Theprocess must be repeated for different system (switching) conditions at theterminals of each generator of interest.

c. EMTP Analysis

The Electromagnetic Transients Program (EMTP) is a program for numerical integration of the system differential equations. Unlike a transient stability program, which usually models only positive sequence quantities representing a perfectly balanced system, EMTP is a full three phase model of the system showing the transmission lines, machines, cables, and special devices such as series capacitors with complex bypass switching arrangements in a detailed manner. Moreover, nonlinear modelling of complex system components is allowed in the EMTP system. It is, therefore, well suited for analysing the transient torque SSR problems.

1.2.3. Countermeasures to Subsynchronous Resonance problems [28]

Many researchers has shown many countermeasures to SSR problems. Many papers has been discussed in the Chapter 2 in the literature section. A list of countermeasures to this problem is given below [ ]

Section 1. Filtering and Damping

Line Filter

Static Blocking Filter

Dynamic Stabiliser

Bypass Damping Filter

Excitation System damper

Section 2. Relaying and Detective Devices

Armature Current SSR relay

Torsional Motion relay

Torsional Monitor

Section 3. System Switching and Generator Tripping

Unit Switching

System Switching

Section 4. Generator and System Modifications

Generator Circuit Services reactance

Turbine Generator Modifications

Pole Face Armotissuer Windings

Static Blocking Filter

This is a three phase blocking filter constituted of L C tank circuits connected in series in per phase with step-up generator transformer. Tuning of this filter is done so that a positive resistance at frequencies which coincides with the torsional frequencies. Transient torque effects and torsional interaction are controlled using this filter.

Line Filter

A blocking filter is constituted using an appropriate inductor connected with existing series compensation capacitor in parallel. This filter blocks the subsynchronous currents at specific frequency to enter into the line section. This filter is only applicable where one frequency is involved and the origin of the problem is a single line.

Bypass Damping Filter

This is a shunt connected device, connected across to each phase series capacitor. It is designated to provide a bypass path to the subsynchronous frequency currents. This filter is designed using a series resistance connected with parallel connection of inductance and capacitance.

Dynamic Filter

It is an active filter, connected in series with generator to nullify the voltages generated due to SSR oscillations, thus preventing self-excitation due to electro mechanical interactions. The control signal is derived from the rotor motion with sufficient phase opposition voltage to override subsynchronous voltage.

Dynamic Stabiliser

This consists of thyristor controlled shunt reactors connected to isolated phase bus in order to safeguard the turbine-generator shaft. Mitigation is achieved by properly firing the thyristor switches around an operation point. This provides damping where rotor oscillations are present. This does not protect from torque problems and induction generator effects.

Excitation System damper

The output of the excitation system is modulated in order to torsional oscillations. The effectiveness can be increased by properly phase shifting and amplifying rotor oscillation signals. This is a slow acting device and hence used for relatively low level oscillations. This can’t be used for large oscillations.

Torsional Motion relay

This relay works on the principle of detection of excess mechanical stresses on the shaft and disconnecting the machine from rest of the system. The signal to the relay is proportional to the rotor speed. It is also a slow device and cannot be used for protection of SSR transients.

Armature Current SSR relay

This is used in protection from induction generator effect and torsional interaction by generator tripping for sustained oscillations. This relay senses armature current at subsynchronous frequency using two level detectors.

Torsional Monitor

This equipment is a data recording device. This continuously accesses the shaft torsional vibrations due to oscillations in the transmission network.

System Switching

Isolation of generators can be one of the mitigation techniques to SSR oscillations. This is the most effective method but it has some limitations such as reliability.

Here is the table representing the countermeasure technique and their suitability for the type of SSR problem.

Table 1.1 SSR counter Measures and their Suitability

Sl. No.	countermeasure	Induction generator effect	Torsional Interaction	Transient torque
1	Static blocking filter		✓	✓
2	Line filter		✓	✓
3	Dynamic filter		✓	
4	Dynamic stabiliser		✓	
5	Excitation system		✓	
6	Torsional motion relay		✓	
7	Armature current relay	✓	✓	
8	System switching	✓	✓	
9	Unit tripping	✓	✓	✓
10	Turbine- generator modification		✓	
11	Reactance is series with generator	✓	✓	✓
12	Pole face armotissuer winding	✓		

1.3 FACTS Devices [26]

The acronym FACTS (Flexible Alternating Current Transmission System) refers to the family of power electronic devices which are capable of enhancing system controllability and power transfer capability[ ].

FACTS devices are of different design and different combinations. The combinations are based on electrical components such as reactors and capacitors and power electronic components are thyristors. FACTS devices can be connected in series, parallel or both. The speed and flexibility of FACTS devices make them more versatile device with several advantages. Power transfer capacity enhancement, voltage stability and control, transient stability and power system oscillations damping are the few advantages. Based on design and configuration, FACTS devices can be classifies as:

- Shunt connected devices
- Series connected devices
- Series- series devices
- Shunt- series devices

A few FACTS devices are listed below:

1. Static VAR Compensator - SVC
2. Static Synchronous Compensator - STATCOM
3. Thyristor Controlled Series Capacitor - TCSC
4. Unified Power Flow Controller - UPFC
5. Static Series Synchronous Compensator - SSSC

A major concern arises with series compensator called as Subsynchronous Resonance. This is caused due to interaction between the series compensated transmission line and turbine generator shaft. This causes machine shaft to experience torsional oscillation leading to fatigue and damage. FACTS devices has been researched my many scholars for damping subsynchronous oscillations. Many are discussed in the literature chapter.

1.4. Induction Machine Damping Unit (IMDU) [1, 17, 18, 20]

An IMDU is a special high power and low energy induction machine. An IMDU can be designed with small leakage reactance and stator resistance. It is assigned to operate near synchronous speed. It is electrically connected to infinite bus and mechanically coupled with shaft of the turbine generator. The main characteristic of IMDU is that this damping method does not require any controller. An IMDU connected system is shown below:

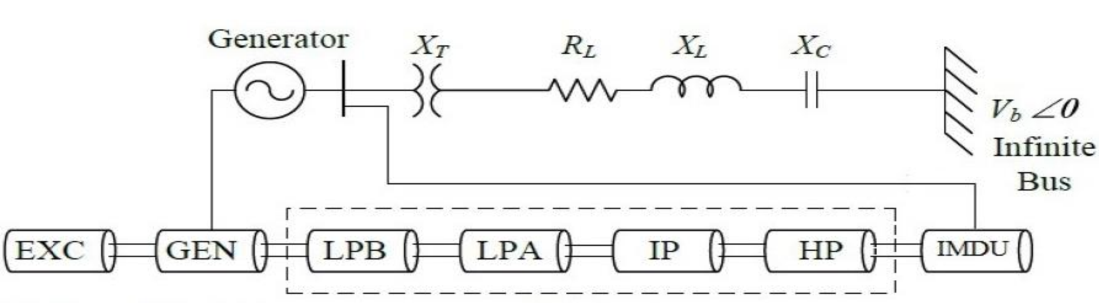

Fig1.2. IMDU connected system

The induction machine can act as motor or generator. This concept of induction machine with damping machine is used to absorb mechanical power or releases power when system is power deficient. Thus helps to damp out SSR oscillations. Motor operation is achieved when the shaft speed is found to be less than synchronous speed and works as generator when the shaft speed is more than the synchronous speed.

1.5. Objective and Scope of the thesis

Based upon the extensive review of literature the main objectives and scope of thesis are outlined below:

- To develop a suitable system model and to enhance the dynamic stability of the system using induction machine damping unit.
- To enhance and improve the dynamic performance of the series compensated power line.
- To enhance the transient stability using IMDU for dynamic operation.
- To study the subsynchronous resonance oscillations and its damping using induction machine damping unit for a wide level of series compensation.

1.1 Outline of thesis

This section describes the chapter wise summary of the work done in this thesis. Summary of each chapter is given below:

Chapter 1.describes the introduction part of the thesis. Only brief description is given about the subsynchronous oscillations, its effects and countermeasures, FACTS devices and its application to subsynchronous damping, induction machine damping unit and its role in damping rotor oscillations.

Chapter 2.presents review of literatures highlighting the dynamic, transient and SSR problems. A brief study is done on different schemes and methods applied by researchers to tackle this problem.

Chapter 3and 4.describes the modelling of generator, mechanical system, network, SVS, excitation system and IMDU. This chapter also describes the development of system model for the dynamic and transient performance of the system. IEEE type 1 excitation system is considered along with SC-TCR configuration of SVS connected at the mid-point of the transmission line. The network model is developed using limped π model.

Chapter 5.gives the detail analysis of the damping effect of Induction Machine Damping Unit (IMDU). The Eigenvalues analysis of the overall system model is discussed with and without the IMDU.

Chapter 6.a brief review of investigations carried out in this thesis and suggestion for future work are highlighted.

A detailed list of references is included in the present thesis.

CHAPTER 2

LITERATURE REVIEW

Literature Review

2.1 General

In this section many research papers, journals and books have been reviewed on emerging areas of power system dynamics and stability. As power system is a very vast topic, so the literature review is mainly focused on subsynchronous resonance, their mitigation techniques, subsynchronous analysis tools such as Eigenvalues analysis or modal analysis. Some papers are also discussed on custom power devices or FACTS devices.

2.2 Literature Survey

Narendra Kumar [1] has presented an idea for damping out SSR oscillations utilising double order SVS auxiliary controller (DOAC) in addition with continuous controlled series compensation (CCSC) and Induction Machine Damping Unit (IMDU) coupled with Turbine-Generator shaft. An application of linear dynamic model DOAC, CCSC and IMDU has been incorporated. A non-linear model has also been proposed using time domain analysis to examine the effectiveness of the proposed approach. Conclusion derived from this paper is that no controller or combination of two is effective. All the three are required for properly damping SSR oscillations. Over a wide range of demand and at various level (10% to 70%) of series compensation, SSR damping is achieved.

Narendra Kumar [17] proposed a new scheme for damping SSR known as Narendra Kumar- Subsynchronous Resonance (NK-SSR). This scheme uses the advantages of combination of reactive power and frequency (CRPF) SVS auxiliary Controller in conjunction with Induction Machine Damping Unit. The location IMDU just after the intermediate pressure (IP) turbine is found to be most effective to damp out torsional oscillations.

S. Gupta; A. Moharana; R.K. Varma [11]showed that frequency analysis can be one the potential method for analysis of Subsynchronous Resonance in wind farms having induction generators. Frequency Scanning method is based on the calculation of effective impedance when looked from the rotor side of the induction generator. SSR can be seen at realistic percentage of series compensation. On comparing result from frequency scanning method with Eigenvalues analysis, induction generator effect is more prominent in the system based on wind farm induction generators. This can be effective method for prediction of potential of SSR oscillations.

N. Kumar, S.K. Agarwal [18]. A new control strategy has been proposed in this paper. This scheme has incorporated a Proportional Integral (PI) Controller in conjunction with auxiliary control signal which is required for modulation of SVS reactive power output in accordance with locally measured signal such as active power, reactive power and voltage angle. Further damping can also be improved using IMDU. A dynamic study has been done and found that the control signals are able to keep the Eigenvalues within the stable limits.

Zhao Xueqiang; Chen Chen [2] put forward a new scheme called improved NGH Subsynchronous resonance damping scheme. This scheme added SSR detection and preferring functions. This improved scheme makes it more suitable for detection of SSR automatically on start up. This scheme makes it more economical and attractive choice of SSR related problems.

Padiyar, K.R.; Prabhu, N. [3] considered a series passive compensation and shunt active compensation connected at the midpoint of the transmission line. The objective of this paper is to examine the SSR characteristics and proposal of a new scheme auxiliary subsynchronous damping controller (SSDC) for detection and removal of torsional damping at the critical frequencies. The tuning of SSDC parameters are done to optimise the performance in the torsional frequencies range.

Kumar, N.; Kumar, S.; Jain, V.[4] developed a scheme for damping SSR by adjusting the percentage of series compensation and using FACTS controllers. Based on the case study, UPFC and SVC are most effective and SSSC is the least effective device for SSR damping. Further research is going on the UPFC optimum control parameters for SSR damping.

Lingling [10] investigated the ability of wind farm generators i.e. doubly fed induction generators (DFIG). Investigation includes design of auxiliary SSR damping controller and selection of control signals. He performed Residue-Based analysis, root locus diagram and time domain analysis for mitigating SSR.

S. Vivek, V. Selve [12] examined the potential occurrence and mitigation techniques inherited by the induction generator effects as well as by the torsional interaction in a series compensated wind power generation. STATCOM damps out SSR as well as provide the reactive power support. Shunt connected STATCOM provides positive damping to the torsional system and successfully eliminates the SSR interactions.

Shin-Muh Lee, Ching-Lien Huang [13] proposed a novel scheme utilising a superconducting magnetic energy storage (SMES). For stabilising all the SSR modes, simultaneous active power and reactive power modulation and a proportional- derivative and Integral (PID) controller is designed using the modal control theory. The effectiveness of this controller can be shown by frequency domain approach based on Eigenvalues analysis and time domain analysis.

Li Wang; San Jan Mau; Chieh Chen Chuko [14] presented a method of damping torsional mode interactions of a series compensated power system by utilising shunt reactor. For clear demonstration of the effectiveness of the scheme, SSR mode Eigenvalues under the cases of different level of loading and sensitivity analysis of shunt reactors is performed. The examination of the dynamic responses of the non-linear system model shows that PID tuned shunt reactors effectively damp out the SSR interactions and prevent the turbine- generator system from damage from torsional stresses.

Lingling Fan, Chanxia Zhu [15] performed the modal analysis of the DFIG wind farm interconnected with series compensated line. They identified the four system modes, impacts of various parameters and operating conditions and dynamic performance using modal analysis. They performed feasibility test for selection of proper SSR mitigating signal using modal analysis.

Kai Xing, George L. Kusic [16] utilised phase shifters for the analysis of SSR interactions. They used Thyristor controlled phase shifters for controlling the generator real power. This new approach control signal is based on the generator speed or modal speed deviations. This control signal is fed to the phase shifter for mitigating SSR. Phase shifter is connected at different locations and their analysis is done. This method is also the most effective SSR torsional mitigation technique.

B. L. Agrawal, R.G. Farmer [19] considered parallel turbine generators for effective damping. They performed extensive analysis and testing to verify and develop the means of determining the accurate damping of unequally loaded machine in parallel. Investigation is done to found the damping torques and load dependent mechanical damping torques, damping effect of single SVC unit and oscillating modes of parallel turbine generator units. An Eigenvalues method and EMTP method are used for the analysis purpose.

S. Puroshatthaman [20] analysed the performance of Induction machine as a damping unit. The Induction Machine Damping Unit (IMDU) is connected with the turbine- generator shaft. Eigenvalues analysis is performed on the linearized model of the system. This is done to find the optimum location of the IMDU to provide the maximum damping. Observation is made from the analysis that IMDU is a small size, high power induction machine. Rating of IMDU is about 10% of the generator rating. The IMDU effectively mitigates the peak torques in the shaft section. The torsional stress reduces by 14.8% during transients. This method is effectively possible by retrofitting the existing installation.

Zhang Xiaojin, XieXiaorong [21] put forward a multimass model with non linear modal for damping SSR. This multimass model is integrated at the Shangdu Power Plant in China. The performance is verified with electromagnetic simulations. The mechanical damping can be effectively damped using modal damping. The simulation result demonstrates that non linearmultimass modal system damping is more accurate and effective than linear average modal damping.

Adel Ridha Othman [22] demonstrated the effect of percentage of series compensation on the modes of subsynchronous resonance. Excitation modes are calculated after thee cycles, three phase to ground fault for different percentage of compensation. He made the conclusion that dangerous resonances occur if the mechanical torsional modes are in the vicinity of the zeros of the system impedance.

D. H. Baker, G. E. Boukarim, R. J. Piwko [22] studied the SSR and their mitigation methods. Turbine- generators have natural frequencies due to physical nature of the shaft elements. They identified the SSR conditions and their risk to turbine generator shaft, severity and likelihood of SSR oscillations, and adaptability of different schemes for SSR mitigation if mitigation required. SSR mitigating tools include SSR blocking filter, supplementary excitation damping control (SEDC), Thyristor controlled series Capacitor (TCSC), switching of series capacitor segments, limiting the percentage of compensation to tolerable value and torsional relays. Selection of best mitigation depends on many parameters such as amount of power, cost of mitigation equipment, operational constraints etc.

R. K. Varma [23] identified the mitigation technique of SSR by SVC using PMU. Flexible AC transmission System (FACTS) are commonly used to mitigate the oscillations in a series compensated power system. For a large interconnected system, analysing SSR is a tedious task. But with the advancement of wide area measurement WAM technology, measurement of states of large system is possible with the help of PMU. He proposed a scheme of acquisition of remote signals through PMU to damp SSR. Synchronous damping controller of SVC which is based on remote generator speed can damp out all SSR modes at all critical percentage of compensation. A midpoint connected SVC can achieve both power transfer enhancement as well as SSR mitigation.

M. Bongiorno, J. Svensson , L. Angquist [24] used a single phase voltage source controller VSC based Static Synchronous series compensator SSSC to damp out SSR oscillations. SSR damping is done by increasing the network damping at the frequencies which are harmful for turbine- generator shaft. This situation can be achieved by guiding the subsynchronous current of the grid to zero. It is shown that by injecting a small amount of voltage in the line leads to reducing the power rating of the SSSC as well as mitigating the SSR oscillations.

A. Edris [25] presented different schemes for series compensation for reducing the potential of SSR oscillations. The schemes are different combinations of capacitances and inductances. The combinations are made in such a way that their characteristic frequencies provide equal reactance at power frequency and unequal reactance for other than power frequency. The SSR oscillations drive unsymmetrical three phase currents. Different variants of compensation are series resonance compensation scheme and parallel resonance compensation scheme.

CHAPTER 3

MODELING OF SYNCHRONOUS MACHINE

3.1 Introduction

In this chapter, detail models of synchronous generator have been developed from the basic equations using phase variables and apply park transformation. The detailed mathematical model of synchronous generator used here in such a form, which can be directly utilised for dynamic stability analysis and system simulation.The synchronous generator is symmetrically represented by three symmetrically placed armature winding ‘a’, ‘b’, ‘c’, respectively for three phase, one field winding‘f’, and three damper winding ‘g’, ‘h’, and ‘k’. The detailed model is restricted to three damper winding because of the practical restrictions in finding the machine parameters. To model the eddy current effects in solid rotor, damper (amortisseur) windings are included. A set of assumptions are made to derive the basic equations of the synchronous machine.

1. The mmf is sinusoidally distributed in the air gap and the harmonics are neglected.
2. Sub transient saliency is neglected $X_d'=X_q'$.
3. Magnetic saturation and hysteresis are ignored.
4. The effects of machine damping and prime mover dynamics are small and neglected for simplicity.

3.2 Stator modelling [7, 8]

In the detail machine model of the stator of the synchronous machine is represented by current source $\mathrm{I_s}$ in parallel with inductance $\mathrm{L''_s}$ as shown in the figure. This above model simplifies the problem of interfacing the machine and network; this is required for the solution of synchronous machine equations along the network equations. The dependent current replaces the time varying coupling the stator windings and rotor windings $\mathrm{I_s}$ is a (3x1) vector and $\mathrm{L''_s}$ is a (3x3) matrix. These can be expressed as

$$\mathrm{I_s}=[\mathrm{I_a I_b I_c}]' = \mathrm{I_d}\mathrm{C} + \mathrm{I_q}S \tag{3.1}$$

Where

$$\mathrm{C^T}= \sqrt{\frac{2}{3}}\left[\cos\emptyset \quad \cos(\emptyset-\frac{2\pi}{3}) \quad \cos(\emptyset+\frac{2\pi}{3})\right] \tag{3.2}$$

$$S^T = \sqrt{\frac{2}{3}}\left[\sin\emptyset \quad \sin(\emptyset - \frac{2\pi}{3}) \quad \sin(\emptyset + \frac{2\pi}{3})\right] \tag{3.3}$$

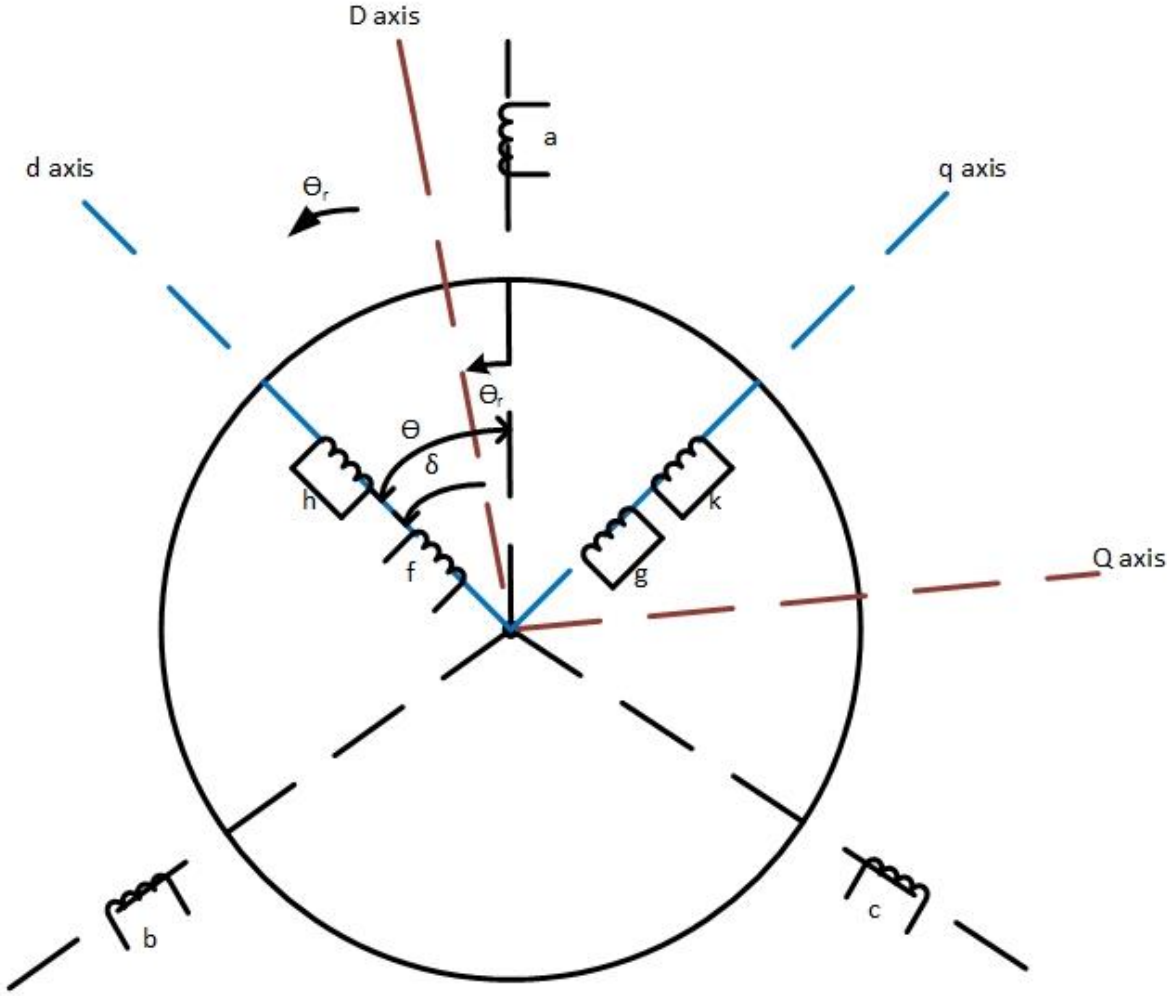

Fig 3.1 Schematic layout of windings of synchronous machine and their two axis representation

$$I_d = C_1\psi_f + C_2\psi_h \tag{3.4}$$

$$I_q = C_3\psi_g + C_4\psi_k \tag{3.5}$$

I_d and I_q dependent current sources along the d, q axis respectively.

Θ is the rotor angle.

The constants C1, C2, C3 and C4 are given in the Appendix A.

$$L''_s = \frac{L_0}{3}\begin{bmatrix}1 & 1 & 1\\ 1 & 1 & 1\\ 1 & 1 & 1\end{bmatrix} + \frac{2L_d''}{3}\begin{bmatrix}1 & \frac{-1}{2} & \frac{-1}{2}\\ \frac{-1}{2} & 1 & \frac{-1}{2}\\ \frac{-1}{2} & \frac{-1}{2} & 1\end{bmatrix} \quad (3.6)$$

Where L''_d = Sub-transient inductance of machine

L_0 = Zero sequence inductance of machine

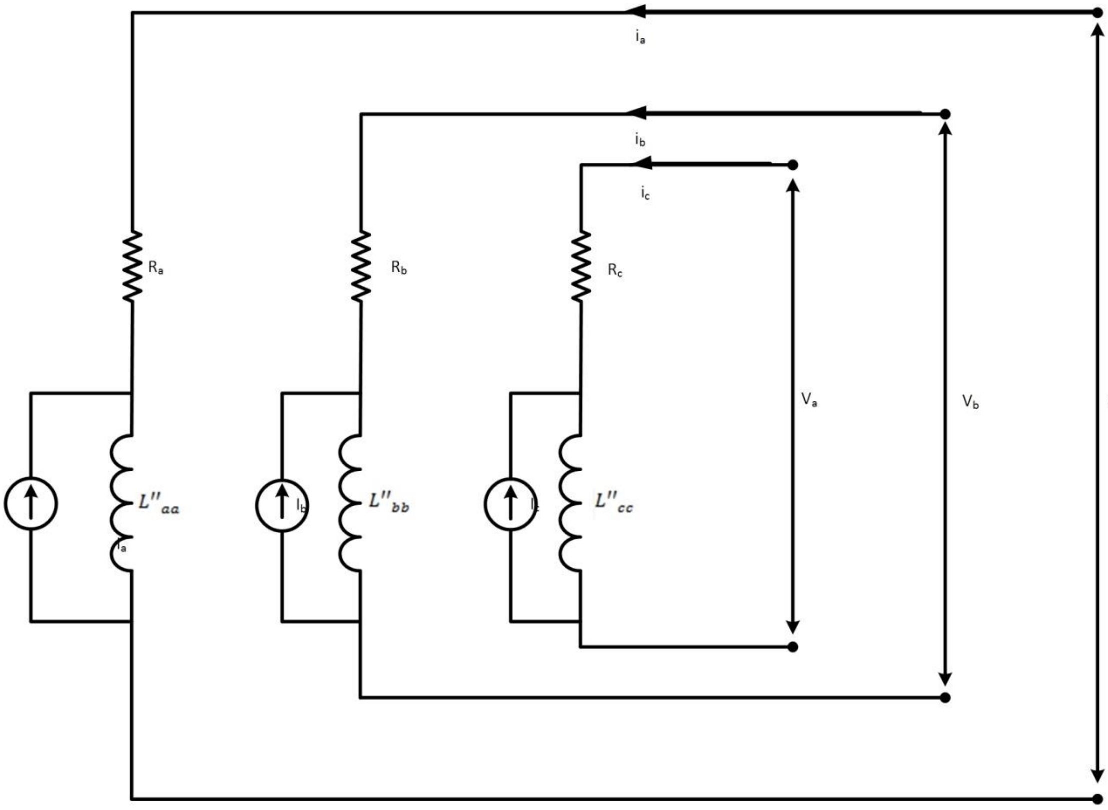

Fig 3.2 Circuit Model for the stator of Synchronous Machine

Such a representation of machine can handle symmetrical as well as unsymmetrical networks. If the external network is connected to the machine terminals is symmetrical, then a, b, c components are transformed using Clarke's Transformation to α, β, 0 components. All the three components α, β, 0 are uncoupled. This is the advantage of using this transformation. Moreover to α network is similar to the β- network as in the positive sequence network. The equivalent circuit representation consists of three mutually uncoupled meshes. Ra denotes the armature resistance. The components of armature currents correspond to the to α, β axis components. The relationship between to α, β, 0 components and a, b, c phase currents is given by the following equation.

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} \frac{\sqrt{2}}{3} & 0 & \frac{1}{\sqrt{3}} \\ \frac{-1}{\sqrt{6}} & \frac{-1}{\sqrt{2}} & \frac{1}{\sqrt{3}} \\ \frac{-1}{\sqrt{6}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} \tag{3.7}$$

$$I_\alpha = I_d \cos\theta + I_q \sin\theta \tag{3.8}$$

$$I_\beta = - I_d \sin\theta + I_q \cos\theta \tag{3.9}$$

$$I_0 = 0$$

The α axis representation of the machine stator and the α- network of the AC transmission system can be directly coupled for analysis.

The stator and rotor flux linkages are given by

$$\psi_s = [L_{ss}]i_s + [L_{sr}]i_r$$

$$\psi_r = [L_{rs}]i_s + [L_{rr}]i_r \tag{3.10}$$

Where,

L_{ss}= Stator self and mutual inductances

L_{sr}= stator to rotor inductances

L_{rs}= rotor to stator inductances

L_{rr}= rotor self and mutual inductances

$[i_s]^T = [i_a i_b i_c]$

$[\psi_s]^T = [\psi_a \psi_b \psi_c]$

$[i_r]^T = [i_f i_h i_g i_k]$

$[\psi_r]^T = [\psi_f \psi_h \psi_g \psi_k]$ (3.11)

The dependent current sources in α, β frame reference are defined as

$I_\alpha = I_d \cos\theta + I_q \sin\theta$

$I_\beta = - I_d \sin\theta + I_q \cos\theta$ (3.12)

3.3 Flux Linkage Equations [7, 8]

The rotor flux linkages are defined by the following equations:

$\dot{\psi}_f = a_1\psi_f + a_2\psi_h + b_1V_f + b_2 i_d$

$\dot{\psi}_h = a_3\psi_f + a_4\psi_h + b_3 i_d$

$\dot{\psi}_g = a_5\psi_g + a_6\psi_k + b_4 i_q$

$\dot{\psi}_k = a_7\psi_g + a_8\psi_k + b_5 i_q$ (3.13)

The constants a_1 to a_8 and b_1 to b_5 are given in the Appendix A. i_d and i_q are the d-q axis components of the machine phase currents and are defined by the equations given below:

$$i_d = \sqrt{\frac{2}{3}}\left[i_a \cos\emptyset \quad i_b \cos(\emptyset - \frac{2\pi}{3}) \quad i_c \cos(\emptyset + \frac{2\pi}{3})\right]$$

$$i_q = \sqrt{\frac{2}{3}}\left[i_a \sin\emptyset \quad i_b \sin(\emptyset - \frac{2\pi}{3}) \quad i_c \sin(\emptyset + \frac{2\pi}{3})\right] \quad (3.14)$$

It is noted that the currents i_d and i_q are defined with respect to machine or rotor reference. These currents are transformed to D- Q reference frame to have a common axis of representation with SVS and AC network, which is rotating at synchronous speed ω_0.

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} cos\delta & sin\delta \\ -sin\delta & cos\delta \end{bmatrix} \begin{bmatrix} i_D \\ i_Q \end{bmatrix} \quad (3.15)$$

Where i_D and i_Q are the components of the machine armature current along the D- axis and the Q- axis respectively. Substituting equation (2.15) in equation (2.13) and after linearizing the resultant equations, we will the following equation.

Using the above two equations, the state equation can be derived

$$\begin{bmatrix}\Delta\dot{\psi}_f\\ \Delta\dot{\psi}_h\\ \Delta\dot{\psi}_g\\ \Delta\dot{\psi}_k\end{bmatrix} = \begin{bmatrix}a_1 & a_2 & 0 & 0\\ a_3 & a_4 & 0 & 0\\ 0 & 0 & a_5 & a_6\\ 0 & 0 & a_7 & a_8\end{bmatrix}\begin{bmatrix}\Delta\psi_f\\ \Delta\psi_h\\ \Delta\psi_g\\ \Delta\psi_k\end{bmatrix} + \begin{bmatrix}-b_2 i_{q0} & 0\\ -b_3 i_{q0} & 0\\ b_4 i_{d0} & 0\\ b_5 i_{d0} & 0\end{bmatrix}\begin{bmatrix}\Delta\delta\\ \Delta\omega\end{bmatrix} +$$

$$\begin{bmatrix}b_1\\ 0\\ 0\\ 0\end{bmatrix}\begin{bmatrix}\Delta V_f\end{bmatrix} + \begin{bmatrix}b_2\cos\delta & -b_2 sin\delta\\ b_3 cos\delta & -b_3 sin\delta\\ b_4 sin\delta & b_4 cos\delta\\ b_5 sin\delta & b_5 cos\delta\end{bmatrix}\begin{bmatrix}\Delta I_D\\ \Delta I_Q\end{bmatrix} \tag{3.16}$$

The output equations of rotor sub system is developed by using the relation between i_d and i_q and rotor flux linkages.

$I_d = C_1\psi_f + C_2\psi_h$

$I_q = C_3\psi_g + C_4\psi_k$ (3.17)

$I_d$andI_q are transformed to D-Q axis components using the relation

$$\begin{bmatrix}I_D\\ I_Q\end{bmatrix} = \begin{bmatrix}\cos\delta & \sin\delta\\ -\sin\delta & \cos\delta\end{bmatrix}\begin{bmatrix}I_d\\ I_q\end{bmatrix} \tag{3.18}$$

Using the above two equations state equation can be written as:

$$\begin{bmatrix}\Delta I_D\\ \Delta I_Q\end{bmatrix} = \begin{bmatrix}C_1\cos\delta & C_2\cos\delta & C_3\sin\delta & C_4\sin\delta\\ -C_1\sin\delta & -C_2\sin\delta & C_3\cos\delta & C_4\cos\delta\end{bmatrix}\begin{bmatrix}\Delta\psi_f\\ \Delta\psi_h\\ \Delta\psi_g\\ \Delta\psi_k\end{bmatrix} + \begin{bmatrix}\Delta I_{Q0} & 0\\ -\Delta I_{D0} & 0\end{bmatrix}\begin{bmatrix}\Delta\delta\\ \Delta\omega\end{bmatrix} \tag{3.19}$$

Where

$\Delta I_{Q0} = -(C_1\psi_f + C_2\psi_h)\sin\delta + (C_3\psi_g + C_4\psi_k)\cos\delta$

$\Delta I_{D0} = (C_1\psi_f + C_2\psi_h)\cos\delta + (C_3\psi_g + C_4\psi_k)\sin\delta$ (3.20)

Now ,

$I_D = X\cos\delta + Y\sin\delta$

$I_Q = -X\sin\delta + Y\cos\delta$ (3.21)

Where, $X = (C_1\psi_f + C_2\psi_h)$

$Y = (C_3\psi_g + C_4\psi_k)$

On differentiating the above equation and the differential equations can be written in matrix form as:

$$\begin{bmatrix}\Delta\dot{I}_D\\ \Delta\dot{I}_Q\end{bmatrix} =$$

$$\begin{bmatrix}(c_1a_1+c_2a_3)\cos\delta & (c_1a_2+c_2a_4)\cos\delta & (c_3a_5+c_4a_7)\sin\delta & (c_3a_6+c_4a_8)\sin\delta\\ -(c_1a_1+c_2a_3)\sin\delta & -(c_1a_2+c_2a_4)\sin\delta & (c_3a_5+c_4a_7)\cos\delta & (c_3a_6+c_4a_8)\cos\delta\end{bmatrix}\begin{bmatrix}\Delta\psi_f\\ \Delta\psi_h\\ \Delta\psi_g\\ \Delta\psi_k\end{bmatrix}$$

$$+\begin{bmatrix}(c_1b_2+c_2b_3)\cos^2\delta + (c_3b_4+c_4a_5)\sin^2\delta & -\sin\delta\cos\delta\,(c_1b_2+c_2b_3) + \sin\delta\cos\delta\,(c_3b_4+c_4a_5)\\ -\sin\delta\cos\delta\,(c_1b_2+c_2b_3) + \sin\delta\cos\delta\,(c_3b_4+c_4a_5) & (c_1b_2+c_2b_3)\sin^2\delta + (c_3b_4+c_4a_5)\cos^2\delta\end{bmatrix}\begin{bmatrix}\Delta I_D\\ \Delta I_Q\end{bmatrix}$$

$$+\begin{bmatrix}-\cos\delta(C_1\psi_f + C_2\psi_h) - \sin\delta\,(C_3\psi_g + C_4\psi_k) - \sin\delta(C_1\dot{\psi}_f + C_2\dot{\psi}_h) + \cos\delta\,(C_3\dot{\psi}_g + C_4\dot{\psi}_k) - (c_1b_2+c_2b_3)\sin\delta\,(i_D\cos\delta - i_Q\sin\delta) + (c_3b_4+c_4a_5)\cos\delta\,(i_D\sin\delta + i_Q\cos\delta) & 0\\ \sin\delta(C_1\psi_f + C_2\psi_h) - \cos\delta\,(C_3\psi_g + C_4\psi_k) - \cos\delta(C_1\dot{\psi}_f + C_2\dot{\psi}_h) - \sin\delta\,(C_3\dot{\psi}_g + C_4\dot{\psi}_k) - (c_1b_2+c_2b_3)\cos\delta\,(i_D\cos\delta - i_Q\sin\delta) - (c_3b_4+c_4a_5)\sin\delta\,(i_D\sin\delta + i_Q\cos\delta) & 0\end{bmatrix}\begin{bmatrix}\Delta\delta\\ \Delta\omega\end{bmatrix} +$$

$$\begin{bmatrix}c_1b_1cos\delta\\ -c_1b_1sin\delta\end{bmatrix}[\Delta V_F] \qquad (3.22)$$

3.4 State Equations of Generator

The state space equations of rotor circuit is given as

$\dot{X}_R = [A_R]\,X_R + [B_{R1}]U_{R1} + [B_{R2}]U_{R2} + [B_{R3}]U_{R3}$

$\dot{Y}_{R1} = [C_{R1}]X_R + [D_{R1}]U_{R1}$

$\dot{Y}_{R2} = [C_{R2}]X_R + [D_{R2}]U_{R1} + [D_{R3}]U_{R2} + [D_{R4}]U_{R3}$ (3.23)

3.5 Modelling of Generator Mechanical System

The rotor angle is expressed as

$$\theta = \omega_0 t + \delta \tag{3.24}$$

on differentiating we get,

$$\frac{d\theta}{dt} = \frac{d\delta}{dt} + \omega_0 \tag{3.25}$$

This is can be written as

$$\dot{\Delta}\delta = \Delta\omega \tag{3.26}$$

The swing equation is given by

$$\frac{d\theta}{dt} = \frac{\omega_0}{2H}\{-D\omega + T_m - T_e\} \tag{3.27}$$

The torque equation is

$$T_e = - X_d''(i_d I_q - i_q i_d) \tag{3.28}$$

Transforming d – q axis components into D- Q axis components, we get

$$\dot{\Delta}\omega = \frac{\omega_0}{2H}[-D\Delta\omega +- X_d''(i_D \Delta I_Q + I_Q \Delta i_D - i_Q \Delta I_D - I_D \Delta i_Q)] \tag{3.29}$$

Equation 14 and equation 17 is written in matrix form as

$$\begin{bmatrix} \dot{\Delta}\delta \\ \dot{\Delta}\omega \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & \frac{-D\omega_0}{2H} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta\omega \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ \frac{\omega_0 X_d'' I_Q}{2H} & \frac{-\omega_0 X_d'' I_D}{2H} \end{bmatrix} \begin{bmatrix} \Delta i_D \\ \Delta i_Q \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ \frac{-\omega_0 X_d'' i_Q}{2H} & \frac{\omega_0 X_d'' i_D}{2H} \end{bmatrix} \begin{bmatrix} \Delta I_D \\ \Delta I_Q \end{bmatrix} \tag{3.30}$$

And

$$\begin{bmatrix} \dot{\Delta}\delta \\ \dot{\Delta}\omega \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & \frac{-D\omega_0}{2H} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta\omega \end{bmatrix} \tag{3.31}$$

3.6 State Equations of Synchronous Machine

Equation 3.22 and equation 3.31 can written in simplified form as

$[\dot{X}_m] = [A_m][X_m] + [B_{m1}][U_{m1}] + [B_{m2}][U_{m2}]$

$[Y_m] = [C_m][X_m]$ (3.32)

Chapter 4

Modelling of Excitation System, Network, SVS, Mechanical System, IMDU

4.1 Modelling of Excitation System [7, 8]

4.1.1 Introduction

The Excitation system is the arrangement for providing the current required by the field winding of a synchronous machine to produce the rated terminal voltage at the terminals. The basic blocks that are included in the excitation system are shown in Fig. 3.1.

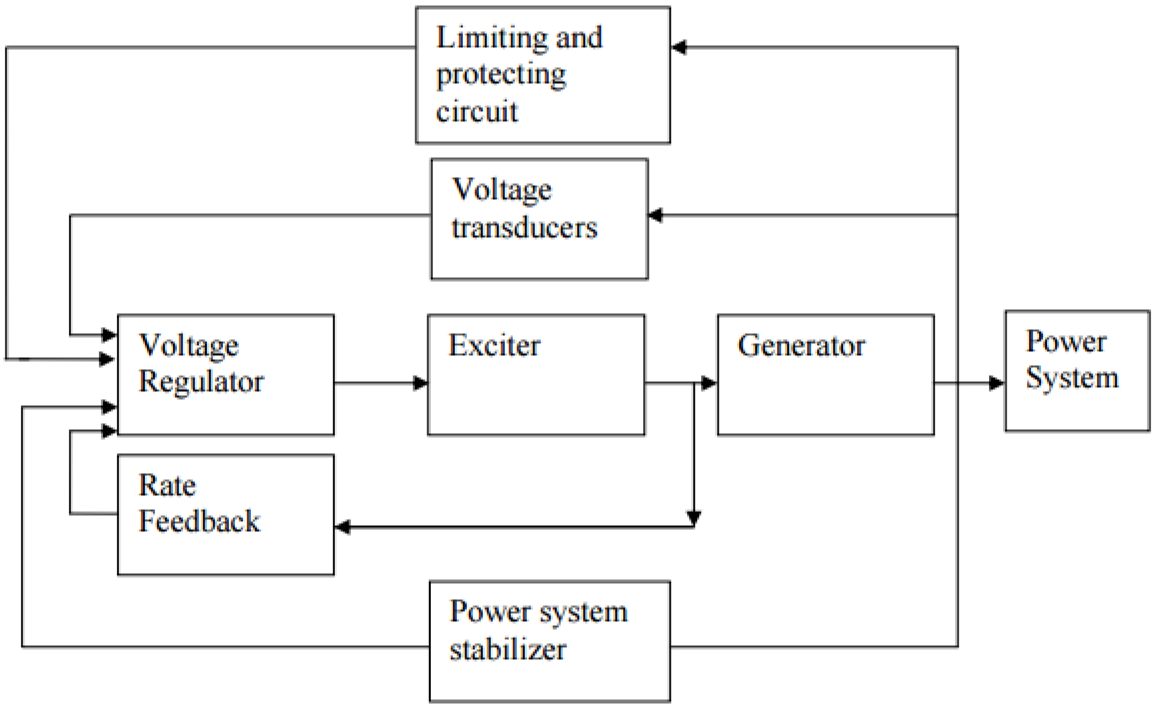

Fig. 4.1 Excitation System block diagram

Exciter can be basically of three types DC exciter, AC exciter and Static exciter.

DC exciter: In this type of exciter a separately or self-excited DC generator driven by a motor or connected to the same shaft as that of the main generator rotor is used. In case of separately excited DC generator the field winding of the DC generator is energised through a permanent magnet AC generator, the three-phase out of which is converted to DC through rectifiers.

4.1.2 IEEE Type- 1 Excitation System

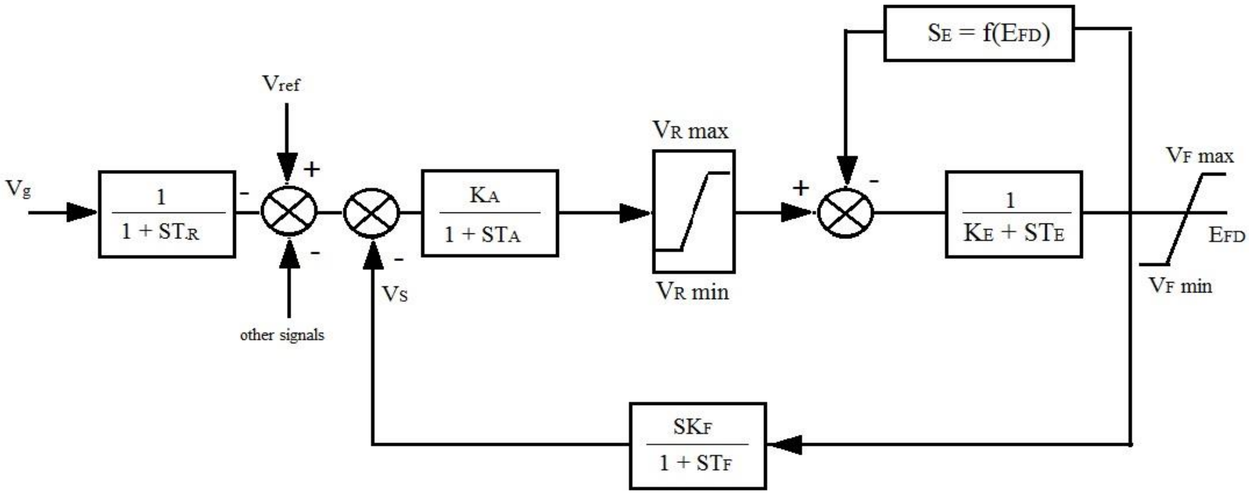

Fig 4.2 IEEE Type- 1 Excitation System

4.1.3 State Equations

From the IEEE Type – 1 Excitation model, the following differential equation can be derived

$$\dot{V}_f = \frac{-V_f(k_E + S_E)}{T_E} + \frac{V_r}{T_E} \tag{4.1}$$

$$\dot{V}_s = \frac{-SK_F(k_E + S_E)V_f}{T_E T_E} - \frac{V_r}{T_F} + \frac{SK_F}{T_E T_F} \tag{4.2}$$

$$\dot{V}_r = \frac{V_{ref}K_A}{T_A} - \frac{V_g K_A}{T_A} - \frac{V_s K_A}{T_A} - \frac{V_r}{T_A} \tag{4.3}$$

$$\begin{bmatrix} \Delta\dot{V}_f \\ \Delta\dot{V}_s \\ \Delta\dot{V}_r \end{bmatrix} = \begin{bmatrix} \frac{-(k_E + S_E)}{T_E} & 0 & \frac{1}{T_E} \\ \frac{-K_F(k_E + S_E)}{T_E T_E} & -\frac{1}{T_F} & \frac{K_F}{T_E T_F} \\ 0 & \frac{-K_A}{T_A} & \frac{-1}{T_A} \end{bmatrix} \begin{bmatrix} \Delta V_f \\ \Delta V_s \\ \Delta V_r \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \frac{-K_A}{T_A} \end{bmatrix} [\Delta V_g] \tag{4.4}$$

$$[\Delta\dot{V}_f] = \begin{bmatrix} \frac{-(k_E + S_E)}{T_E} & 0 & \frac{1}{T_E} \end{bmatrix} \begin{bmatrix} \Delta V_f \\ \Delta V_s \\ \Delta V_r \end{bmatrix} \tag{4.5}$$

The equations 24 and equation 25 are the state equations of IEEE Type- 1 Excitation system.

$$[\dot{X}_E] = [A_E][X_E] + [B_E][U_E]$$

$$[Y_E] = [C_E][X_E] \tag{4.6}$$

4.2 Modelling of Network

4.2.1 Introduction

The network model is assumed to be a single lumped π circuit transmission line. The charging capacitance of the line is combined with the fixed capacitor of the SVS. The equivalent circuit of the synchronous machine is also included in the network model. Assumption is made that the network components are symmetrical. Hence, the network can be replace by its α- axis representation circuit model which is identically same as positive sequence network. The sending end transformer and receiving end transformer are represented by their leakage impedances. The magnetising components as well as shunt conductance of the line are neglected. $I_\alpha$is the α axis component of the dependent current source as described in the stator circuit model of synchronous machine.

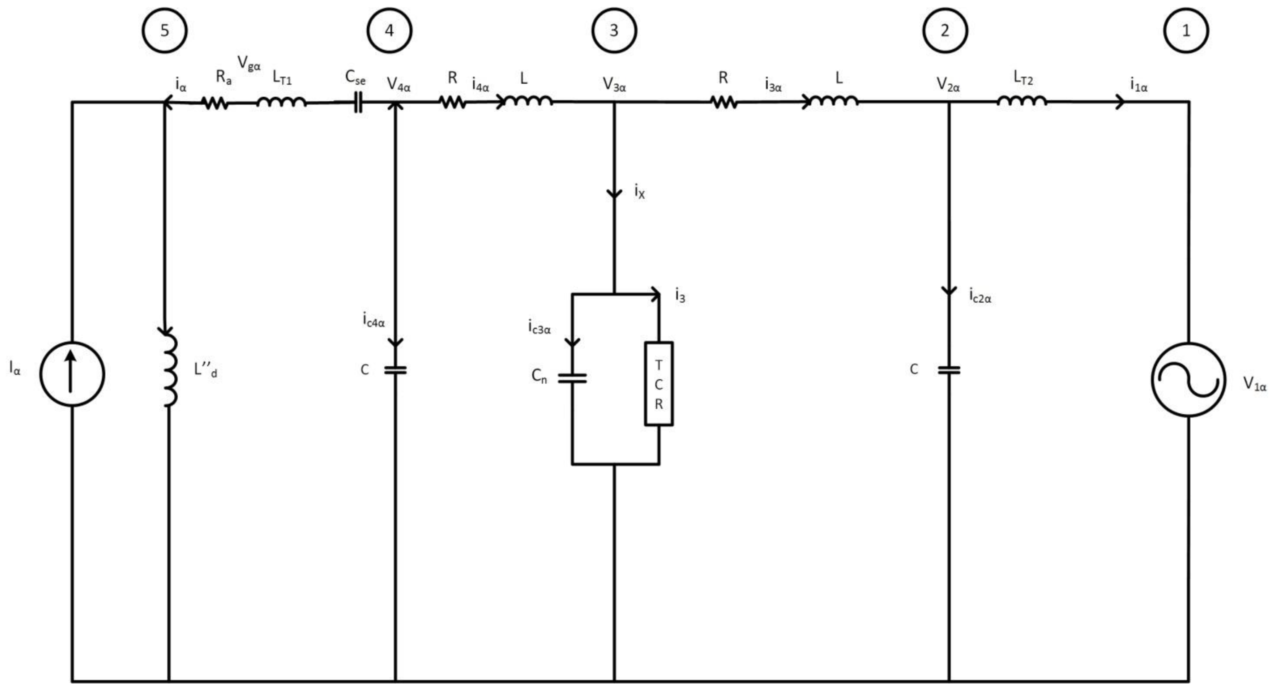

Fig. 4.3 α – axis Representation of Series compensated Network

4.2.2 Differential Equations

The differential equations governing the network are given below:

$$\frac{di_{1\alpha}}{dt} = \frac{1}{L_{T2}}(V_{2\alpha}) - \frac{1}{L_{T2}}(V_{2\alpha}) \tag{4.7}$$

$$\frac{di_{2\alpha}}{dt} = \frac{1}{L}(V_{3\alpha}) - \frac{1}{L}(V_{2\alpha}) - \frac{R}{L}(i_{2\alpha}) \tag{4.8}$$

$$\frac{di_{4\alpha}}{dt} = \frac{1}{L}(V_{4\alpha}) - \frac{1}{L}(V_{3\alpha}) - \frac{R}{L}(i_{4\alpha}) \tag{4.9}$$

$$\frac{di_{\alpha}}{dt} = \frac{R_a}{L_A}(i_\alpha) + \frac{1}{L_A}(V_{4\alpha}) - \frac{L''d}{L\,A}\left(\frac{di_\alpha}{dt}\right) - \frac{1}{L}(V_{5\alpha}) \tag{4.10}$$

$$\frac{dV_{2\alpha}}{dt} = \frac{1}{C}(i_{2\alpha}) - \frac{1}{C}(i_{1\alpha}) \tag{4.11}$$

$$\frac{dV_{3\alpha}}{dt} = \frac{-1}{C_n}(i_{2\alpha}) - \frac{1}{C_n}(i_{3\alpha}) + \frac{1}{C_n}(i_{4\alpha}) \tag{4.12}$$

$$\frac{dV_{4\alpha}}{dt} = \frac{-1}{C}(i_{\alpha}) - \frac{1}{C}(i_{4\alpha}) \tag{4.13}$$

$$\frac{dV_{5\alpha}}{dt} = \frac{1}{C_{se}}(i_{\alpha}) \tag{4.14}$$

Where $C_n = C + C_{FC}$, $L_A = L_{T1} + L''_d$, $L_1 = L + L_A$, $L_2 = L + L_{T2}$ and $R_1 = R + R_a$

Similarly the equations for β- network can be derived.

Similarly the equations for β- network can be derived.

The equations of α- β network can be transformed to synchronous rotating D- Q frame using Kron's transformation and are subsequently linearized. Since the infinite bus voltage is constant and is given as $\Delta V_{1D} = \Delta V_{1Q} = 0$.

4.2.3 State Equations

The state equation of the network model is finally obtained as follows:

$$
\begin{bmatrix} \Delta\dot{i}_{1D} \\ \Delta\dot{i}_{2D} \\ \Delta\dot{i}_{4D} \\ \Delta\dot{i}_{D} \\ \Delta\dot{V}_{2D} \\ \Delta\dot{V}_{3D} \\ \Delta\dot{V}_{4D} \\ \Delta\dot{V}_{5D} \\ \Delta\dot{i}_{1Q} \\ \Delta\dot{i}_{2Q} \\ \Delta\dot{i}_{4Q} \\ \Delta\dot{i}_{Q} \\ \Delta\dot{V}_{2Q} \\ \Delta\dot{V}_{3Q} \\ \Delta\dot{V}_{4Q} \\ \Delta\dot{V}_{5Q} \end{bmatrix} =
$$

$$
\begin{bmatrix}
0 & 0 & 0 & 0 & \frac{1}{L_{T2}} & 0 & 0 & 0 & \omega_0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{-R}{L} & 0 & 0 & \frac{-1}{L} & \frac{1}{L} & 0 & 0 & 0 & \omega_0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & \frac{-R}{L} & 0 & 0 & \frac{-1}{L} & \frac{1}{L} & 0 & 0 & 0 & \omega_0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{-R_a}{L_A} & 0 & 0 & \frac{1}{L_A} & \frac{-1}{L_A} & 0 & 0 & 0 & \omega_0 & 0 & 0 & 0 & 0 \\
\frac{-1}{C} & \frac{1}{C} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \omega_0 & 0 & 0 & 0 \\
0 & \frac{-1}{C_n} & \frac{1}{C_n} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \omega_0 & 0 & 0 \\
0 & 0 & \frac{-1}{C} & \frac{-1}{C_n} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \omega_0 & 0 \\
0 & 0 & 0 & \frac{1}{C_{se}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \omega_0 \\
\omega_0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{L_{T2}} & 0 & 0 & 0 \\
0 & \omega_0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{-R}{L} & 0 & 0 & \frac{-1}{L} & \frac{1}{L} & 0 & 0 \\
0 & 0 & \omega_0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{-R}{L} & 0 & 0 & \frac{-1}{L} & \frac{1}{L} & 0 \\
0 & 0 & 0 & \omega_0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{-R_a}{L_A} & 0 & 0 & \frac{1}{L_A} & \frac{-1}{L_A} \\
0 & 0 & 0 & 0 & \omega_0 & 0 & 0 & 0 & \frac{-1}{C} & \frac{1}{C} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & \omega_0 & 0 & 0 & 0 & \frac{-1}{C_n}n & \frac{1}{C_n} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \omega_0 & 0 & 0 & 0 & \frac{1}{C} & \frac{-1}{C} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & \omega_0 & 0 & 0 & 0 & \frac{1}{C_{se}} & 0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix} \Delta i_{1D} \\ \Delta i_{2D} \\ \Delta i_{4D} \\ \Delta i_{D} \\ \Delta V_{2D} \\ \Delta V_{3D} \\ \Delta V_{4D} \\ \Delta V_{5D} \\ \Delta i_{1Q} \\ \Delta i_{2Q} \\ \Delta i_{4Q} \\ \Delta i_{Q} \\ \Delta V_{2Q} \\ \Delta V_{3Q} \\ \Delta V_{4Q} \\ \Delta V_{5Q} \end{bmatrix} +
$$

$$
\begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ \frac{-1}{C_n} & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & \frac{-1}{C_n} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta i_{3D} \\ \Delta i_{3Q} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ -\omega_0 \frac{L''_d}{L_A} & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & -\omega_0 \frac{L''_d}{L_A} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta I_D \\ \Delta I_Q \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ \frac{-L''_d}{L_A} & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & \frac{L''_d}{L_A} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta I_D \\ \Delta I_Q \end{bmatrix} \qquad (4.15)
$$

4.3 Static VAR System (SVS) Modelling

4.3.1 Introduction

The SVS is an integrated system of static electronic and electrical components such as reactors, capacitors, transformers and switches, which are configured to provide rapid and continuously controllable shunt reactive power compensation. In some SVS configurations TCR, TCT, TST etc, the variation of reactive power is attained through active control. In other configurations, the control is entirely passive control and results obtained from inherent characteristic of the static elements used in the system. Static VAR system utilizes the thyristor control of reactive power because of its increased employment for power transfer applications.

The phase voltage are measured by PTs by measuring device which comprises of a rectifier and a low pass filter with time constant T_m. A low voltage DC signal is the output of the measuring device and is compared with the reference input V_{ref} . An error signal is generated from the difference of these two signals and error signal is fed to the regulator. Susceptance reference B_{ref} is the output of the voltage regulator for the svs. Any variation in the error signal causes an opposite change in thyristor controlled reactor’s effective susceptance. The susceptance reference from the regulator goes to the gate pulse generation block which is incorporated to issue appropriate firing pulses for the SVS valves in order to meet the reactive power requirement. The gate pulse generation block also has a synchronising block to which ensures the synchronism between the system voltage and the switching timing of the control pulses of the thyristor.

4.3.2 State Equations

A linearized model of SVS control system is considered here for the study of dynamic performance. A proportional- integral PI controller is assumed to be as voltage regulator.

The salient features is the modelling of TCR transients. The basic equations associated with the SVS modelling are derived and their state equation representation is shown below:

Where Quality Factor = Q = $\frac{\omega_0 L_s}{R_s}$

And B = $\frac{1}{\omega_0 L_s}$

L_s and R_s are the inductance and resistance of TCR respectively.

$$K_{VD} = \frac{V_{3D0}}{V_{30}}$$

$$K_{VQ} = \frac{V_{3Q0}}{V_{30}}$$

$$K_{iD} = \frac{I_{3D0}}{i_{30}}$$

$$K_{iQ} = \frac{i_{3Q0}}{i_{30}} \qquad (4.16)$$

$$\begin{bmatrix} \Delta\dot{i}_{3D} \\ \Delta\dot{i}_{3Q} \\ \dot{Z}_1 \\ \dot{Z}_2 \\ \dot{Z}_3 \\ \Delta\dot{B} \end{bmatrix} = \begin{bmatrix} \frac{-R_S}{L_S} & -\omega_0 & 0 & 0 & 0 & \omega_0 V_{3D0} \\ 0 & \frac{-R_S}{L_S} & 0 & 0 & 0 & \omega_0 V_{3Q0} \\ 0 & 0 & 0 & -1 & 0 & 0 \\ \frac{-K_D K_{iD}}{T_M} & \frac{-K_D K_{iQ}}{T_M} & 0 & \frac{-1}{T_M} & 0 & 0 \\ 0 & 0 & \frac{-K_I}{T_S} & \frac{-K_P}{T_S} & \frac{-1}{T_S} & 0 \\ 0 & 0 & 0 & 0 & \frac{-1}{T_D} & \frac{-1}{T_D} \end{bmatrix} \begin{bmatrix} \Delta i_{3D} \\ \Delta i_{3Q} \\ Z_1 \\ Z_2 \\ Z_3 \\ \Delta B \end{bmatrix} + \begin{bmatrix} \frac{1}{L_S} & 0 \\ 0 & \frac{1}{L_S} \\ 0 & 0 \\ \frac{K_{VD}}{T_M} & \frac{K_{VQ}}{T_M} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta V_{3D} \\ \Delta V_{3Q} \end{bmatrix} +$$

$$\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \frac{-R_S}{L_S} \\ 0 \end{bmatrix} [\Delta V_{ref}] + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \frac{-R_S}{L_S} \\ 0 \end{bmatrix} [\Delta V_F] \qquad (4.17)$$

$$\begin{bmatrix} \Delta\dot{i}_{3D} \\ \Delta\dot{i}_{3Q} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta i_{3D} \\ \Delta i_{3Q} \\ Z_1 \\ Z_2 \\ Z_3 \\ \Delta B \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta V_{3D} \\ \Delta V_{3Q} \end{bmatrix} \tag{4.18}$$

The state equations can be represented in the form as given below:

$$\dot{X}_s = [A_s]X_S + [B_{s1}]U_{s1} + [B_{s2}]U_{s2} + [B_{s3}]U_{s3}$$

$$Y_s = [C_s]X_s + [D_s]U_{s1} \tag{4.19}$$

$$X_S = \begin{bmatrix} \Delta i_{3D} \\ \Delta i_{3Q} \\ Z_1 \\ Z_2 \\ Z_3 \\ \Delta B \end{bmatrix};$$

$$U_{s1} = \begin{bmatrix} \Delta V_{3D} \\ \Delta V_{3Q} \end{bmatrix};$$

$$U_{s2} = [\Delta V_{ref}];$$

$$U_{s3} = [\Delta V_F];$$

$$Y_s = \begin{bmatrix} \Delta\dot{i}_{3D} \\ \Delta\dot{i}_{3Q} \end{bmatrix}$$

4.4 Mechanical System modelling

4.4.1 Introduction

The rotor of turbine generator unit is a complex mechanical system made of several rotors of different sizes, with the system mechanical shaft section and coupling. The multi- resonant model or modal mechanical model can be used for the modelling of mechanical system. The multi- resonant model is considered here, which is represented as a linear multi mass spring dashpot arrangement. Each of these major rotating mass is modelled as represented by its inertia where an each shunt element is modelled as rotating spring with negligible mass with stiffness expressed by its spring constant. The turbine generator is a six mass model.

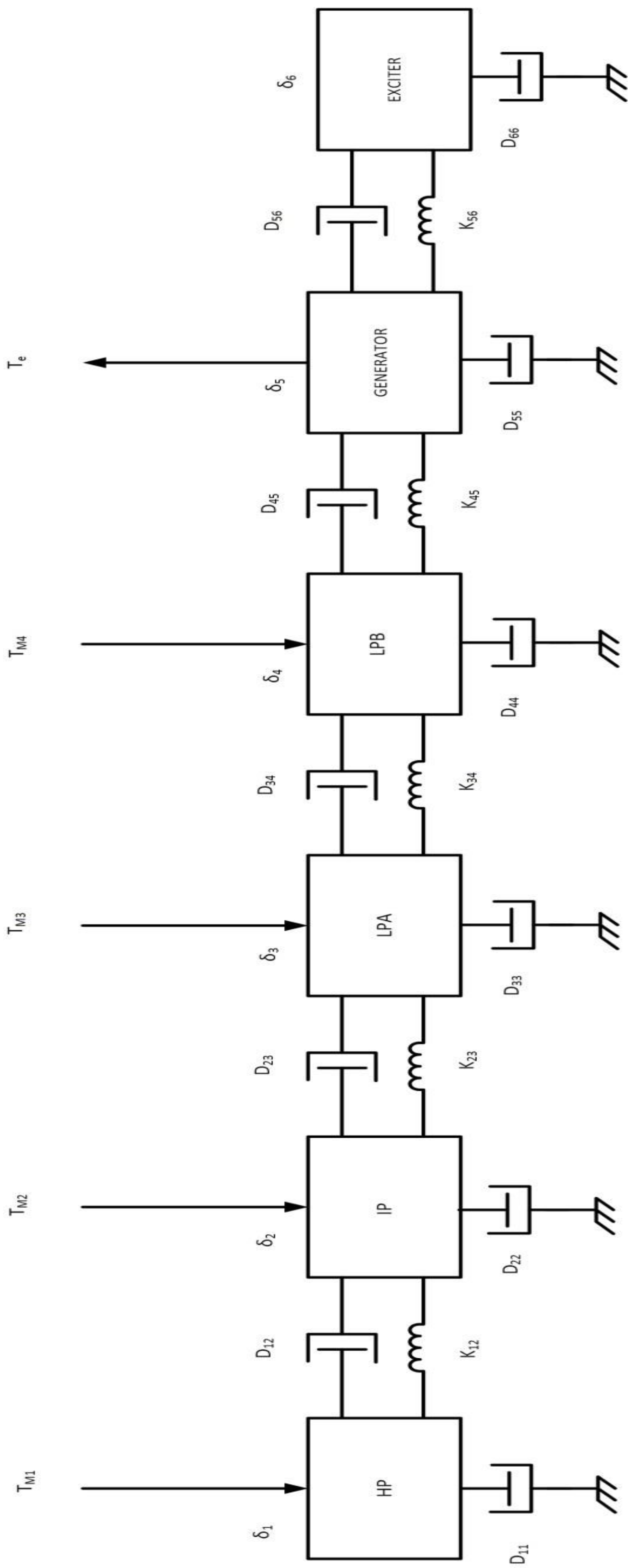

Fig 4.4 Six Spring – Mass model to Turbine Generator Shaft

Electrical analogous modelling of the mechanical system using electrical equivalent circuit of the system is given below:

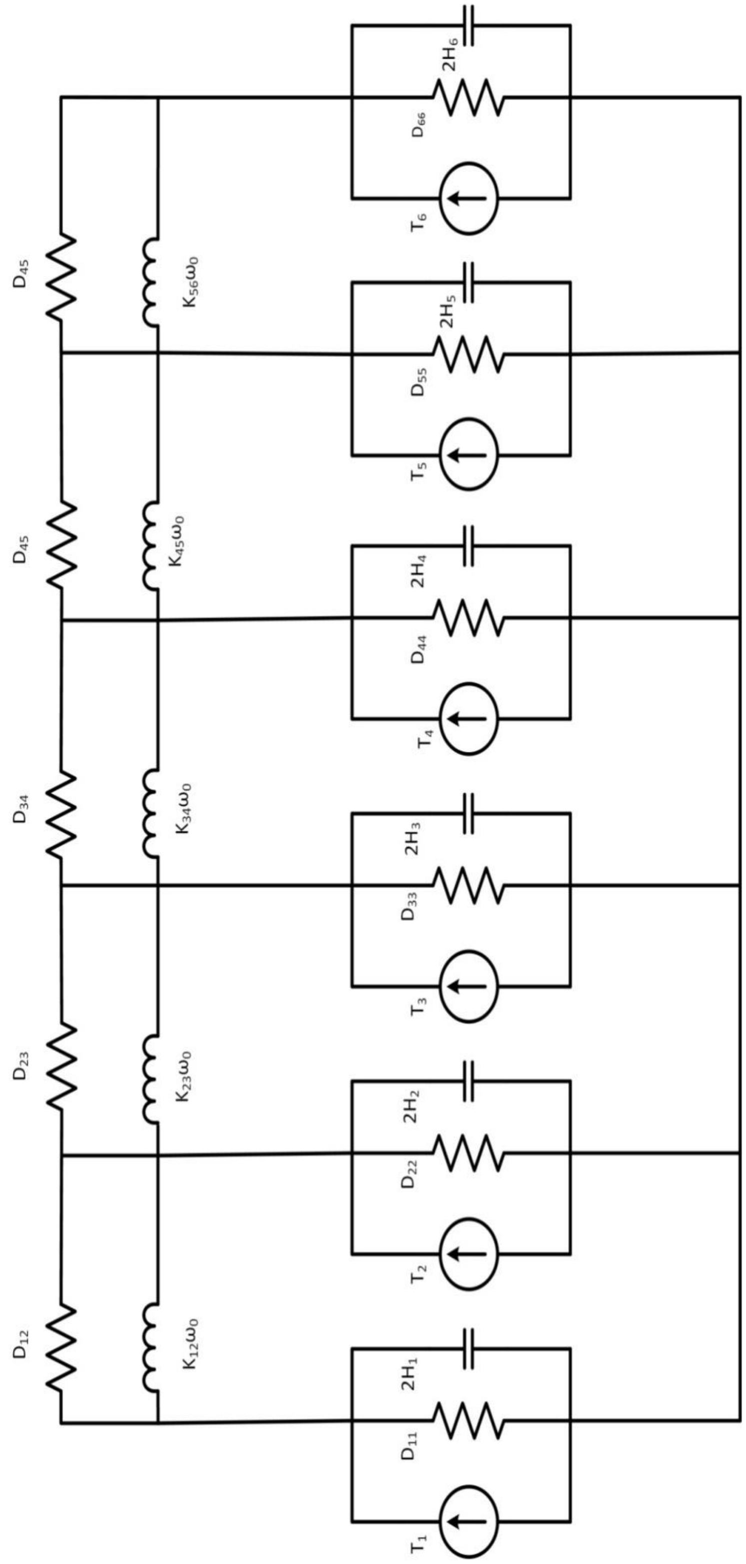

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Fig 4.5 Electrical Analogous of Six Spring Mass Turbine Generator Model

The differential equations representing the multi- mass model are given as:

$$\dot{\omega}_1=\frac{1}{M_1}[-(D_{11}+ D_{12})\omega_1 + D_{12}\omega_{12} - K_{12}(\delta_1 - \delta_2) + T_{M1}] \quad (4.20)$$

$$\dot{\omega}_2=\frac{1}{M_2}[D_{12}\omega_1 - (D_{12} + D_{22} + D_{23})\omega_2 + D_{23}\omega_3 - K_{12}(\delta_2 - \delta_1) + T_{M2}] \quad (4.21)$$

$$\dot{\omega}_3= \frac{1}{M_3}[D_{23}\omega_2 - (D_{23} + D_{33} + D_{34})\omega_3 + D_{34}\omega_4 - K_{23}(\delta_3 - \delta_2) - K_{34}(\delta_3 - \delta_4) + + T_{M3}] \quad (4.22)$$

$$\dot{\omega}_4 = \frac{1}{M_4}[D_{34}\omega_3 - (D_{34} + D_{44} + D_{45})\omega_3 + D_{34}\omega_4 - K_{34}(\delta_4 - \delta_3) - K_{45}(\delta_4 - \delta_5) + + T_{M4}] \quad (4.23)$$

$$\dot{\omega}_5=\frac{1}{M_5}[D_{45}\omega_4 - (D_{45} + D_{55} + D_{56})\omega_5 + D_{56}\omega_6 - K_{45}(\delta_5 - \delta_4) - K_{56}(\delta_5 - \delta_6) - T_e] \quad (3.23)$$

$$\dot{\omega}_6 =\frac{1}{M_6} [D_{56}\omega_5 - (D_{56} + D_{66})\omega_6 + K_{56}(\delta_6 - \delta_5)] \quad (4.24)$$

$$T_e = X''_d(i_D I_Q - i_Q I_D) \quad (4.25)$$

On linearizing these equations and writing in the state space equation form

$$\dot{X}_M = [A_M]X_M + [B_M]U_M \quad (4.26)$$

Where $X_M= [\Delta\delta_1\Delta\delta_2\Delta\delta_3\Delta\delta_4\Delta\delta_5\Delta\delta_6\Delta\omega_1\Delta\omega_2\Delta\omega_3\Delta\omega_4\Delta\omega_5\Delta\omega_6]^T$

$U_M=[\Delta T_{M1}\Delta T_{M2}\Delta T_{M3}\Delta T_{M4}\Delta T_{M5} - \Delta T_e]^T$

Since the governor system involves large time constants, so

$$\Delta T_{M1} = \Delta T_{M2} = \Delta T_{M3} = \Delta T_{M4} = 0$$

and ΔT_e = $-[X''_d(\Delta i_D I_{Q0} + i_{D0}\Delta I_Q - \Delta i_Q I_{D0} - i_{Q0}\Delta I_D]$ (4.27)

$$\dot{X}_M = [A_M]X_M + [B_{M1}]U_{M1} + [B_{M2}]U_{M2} \quad (4.28)$$

Where $U_{M1} = [\Delta I_D \ \Delta I_Q]^T$

$U_{M2} = [\Delta i_D \ \Delta i_Q]^T$

Matrices A_M, B_M, B_{M1}, and B_{M2} are given in the appendix. The output equation of the mechanical system constitutes of angular velocity and position of the generator mass. Hence the output equation of the mechanical system will be

$$Y_M = [C_M]X_M \quad (4.29)$$

Where $Y_M = [\Delta\delta_5 \ \Delta\omega_5]^T$

$\Delta\delta$ and $\Delta\omega$ are the incremental changes in the generator rotor angle and the angular speed respectively.

4.5 Modelling of Induction Machine Damping Unit

The torque of the induction machine in per unit is given by the equation

$$T_{im1} = \frac{3S}{\omega_0 r'_2[1+(Sx'_2/r'_2)2]} \qquad (4.30)$$

Where S = $(\omega_0 - \omega_1)/\omega_0$

S is called slip of the induction machine

ω_0 is synchronous speed

ω_1 is rotor speed

The mechanical equations governing the HP turbine coupled with induction machine is given as

$$M_1\dot{\omega}_1 = -(D_{11} + D_{12})\omega_1 + D_{12}\omega_2 - K_{12}(\delta_1 - \delta_2) + T_{M1} + T_{im1}$$

$$\Delta T_{im1} = \frac{3}{\omega_0 r'_2}\left[\frac{[1+(Sx'_2/r'_2)2]^2 - 2S\,(Sx'_2/r'_2)2)}{[1+(Sx'_2/r'_2)2]}\right]\Delta S \qquad (4.31)$$

Where $\Delta S = (\frac{-\Delta\omega_1}{\omega_0})$

At the normal operating point S = 0;

Thus from the above equation the mechanical system [$-(D_{11} + D_{12})/M_1$] is modified as $[-(D_{11} + D_{12})/M_1 - (3/\omega_0^2 * r'_2)]$

Higher sensitivity is required for the efficient damping of SSR oscillations.

r'_2 should me minimum so that r'_2/x'_2 is minimum.

4.6 Development of system model

The state equation and output equations of the different subsystems are combined resulting into state equations of overall system. The various subsystem models are so derived that inputs to any system is are directly obtained as output of the other systems. Fig 4.5 shows the interconnection of different subsystems considering the network transients.

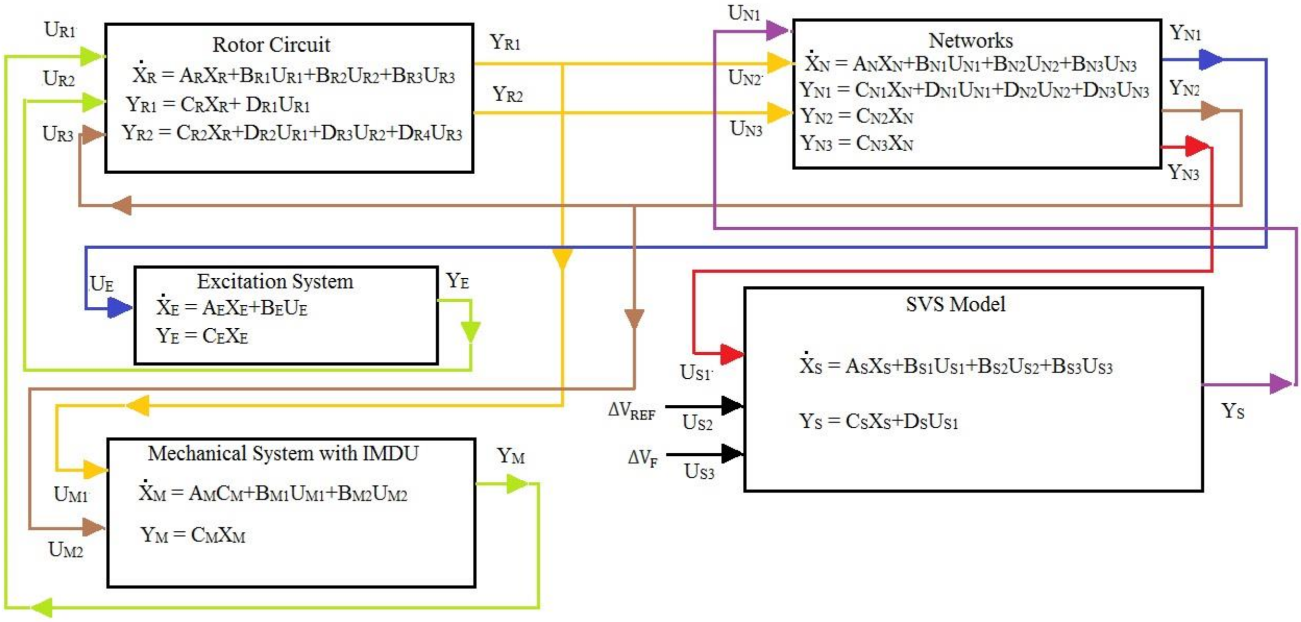

Fig 4.6 Interconnection of Various Subsystems in Overall System Model

The system matrix is given by:

A_R	$B_{R1}C_M$	$B_{R2}C_E$	$B_{R3}C_{N2}$	0
$B_{M1}C_{R1}$	$A_M+B_{M1}D_{R1}C_M$	0	$B_{M2}C_{N2}$	0
$B_ED_{N2}C_{R1}$ + $B_ED_{N3}C_{R2}$	$B_ED_{N2}D_{R1}C_M$ + $B_ED_{N3}D_{R2}C_M$	A_E + $B_ED_{N3}D_{R3}C_E$	B_EC_{N1} $+B_ED_{N1}D_SC_{N3}$ $+B_ED_{N3}D_{R4}C_{N2}$	0
$B_{N2}C_{R1}$ + $B_{N3}C_{R2}$	$B_{N2}D_{R1}C_M$ + $B_{N3}D_{R2}C_M$	$B_{N3}D_{R3}$	A_N $+B_{N1}D_SC_{N3}$ $+B_{N3}D_{R4}C_{N2}$	$B_{N1}C_S$
0	0	0	$B_{S1}C_{N3}$	A_S

The overall system model can be developed as follows:

$X = [A]X + [B]\Delta V_{ref}$

Where $X=[X_R\ X_M\ X_E\ X_N\ X_S]$ and $B=[0\ 0\ 0\ 0\ B_{S2}]$

The overall dimension of the system matrix is 41X41 with network is represented as the lumped π configuration.

Chapter 5

RESULTS AND DISCUSSION

5.1 Case Study

The IEEE First Benchmark Model is used for the analysis purpose. The system considered consists of two synchronous generators which is represented by a single unit of 1110 MVA, at 22 KV supplying power to infinite bus at 400 KV through a 600 Kms long transmission line. The system data and turbine generator spring mass system data are given in the Appendix B. About 25% compensating capacitor is installed at the sending end of the transmission line.

Table 5.4 given below shows the Eigenvalues with power generation PG = 800 MW without the induction machine damping unit. There are six torsional modes. These modes are listed in the table 5.4. torsional modes are those whose frequency is less than 314 rad/sec, differently we can say less than 50 Hz. These modes are more dominant and can be dangerous for the turbine generator shaft. The torsional modes 5, 4, 1 and 0 are unstable modes as they have positive real part. The real part of these modes must be made negative to efficiently remove the oscillations. The mechanical rotor mode has the frequency of 4.917 rad/sec.

Table 5.5 presents the Eigenvalues of the system matrix with IMDU located at the different locations in the turbine generator shaft. Discussion on various Eigenvalues is discussed below under the following cases;

Table 5.1 Load Flow Study at PG = 800 MW

Bus	Voltage pu	Delta (Degree)	Real Power (pu)	Reactive Power (pu)
1 Infinite Bus	1.0	0.0	-7.26	1.31
2 Gen Bus	1.05	63.22	-8.0	0.7393
3 SVS Bus	1.05	31.55	0.0	-2.74

Table 5.1 Load Flow Study at PG = 500 MW

Bus	Voltage pu	Delta (Degree)	Real Power (pu)	Reactive Power (pu)
1	1.0	0.0	-0.471	-0.018
2	1.05	38.92	5.0	-0.38
3	1.05	19.59	0.0	-0.0751

Table 5.1 Load Flow Study at PG = 200 MW

Bus	Voltage pu	Delta (Degree)	Real Power (pu)	Reactive Power (pu)
1	1.0	0.0	-1.95	-1.10
2	1.05	15.45	2.0	-0.84
3	1.05	7.81	0.0	1.32

TABLE 5.4

System Eigenvalues without any Damping Scheme/ Controller

Sl no.	Eigenvalues at PG=800 MW	Comments
1	0.00 ± 298.1006i	Torsional Mode #5
2	0.0879 ± 202.7272i	Torsional Mode #4
3	-0.0047 ± 160.5245i	Torsional Mode #3
4	-0.0027 ± 126.9697i	Torsional Mode #2
5	0.0042 ± 98.7432i	Torsional Mode #1
6	0.1827 ± 4.917i	Torsional Mode #0
7	-0.8766 ± 0.9191i	
8	-38.6339	
9	-33.2575	
10	-3.0433	
11	-25.7412 ± 24.1061i	
12	-3.2722 ± 3499.09i	
13	-3.2743 ± 2871.08i	
14	-13.2884 ± 2495.3i	
15	-14.9278 ± 1867.3i	
16	-12.6906 ± 1137.9i	
17	-18.9107 ± 510.13i	
18	-12.9192 ± 443.94i	
19	-5.0833 ± 311.455i	
20	-10.3875 ± 190.85i	
21	-49.9113 ±74.545i	
22	-545.2881 ± 74.43i	

Table 5.5 Eigenvalues with IMDU connected at various locations

Before HP	In between HP - IP	In between IP -LPA	In between LPA - LPB	In between LPB - GEN
-0.0106 ± 298.1006i	-0.0289 ± 298.1008i	-0.002 ± 298.1007i	0.00 ± 298.1007i	0.00 ± 298.1006i
0.0853 ± 202.7272i	0.0890 ± 202.7272i	0.0842 ± 202.7272i	0.0785 ± 202.7272i	0.0828 ± 202.7272i
-0.0247 ± 160.5245i	-0.0155 ± 160.5245i	-0.0167 ± 160.5245i	-0.0161 ± 160.5245i	-0.0159 ± 160.5245i
-0.0040 ± 126.9697i	-0.0035 ± 126.9697i	-0.0032 ± 126.9697i	-0.0043 ± 126.9697i	-0.0041 ± 126.9697i
0.00152 ± 98.7432i	0.0017 ± 98.7432i	-0.0011 ± 98.7432i	0.0038 ± 98.7432i	-0.0005 ± 98.7432i
0.1420 ± 4.917i	0.129 ± 4.917i	0.027 ± 4.917i	0.0227 ± 4.917i	0.0260 ± 4.917i
-0.8766 ± 0.9191i	-0.8765 ± 0.9191i	-0.8766 ± 0.9191i	-0.8768 ± 0.9191i	-0.8769 ± 0.9191i
-38.6339	-38.6338	-38.6338	-38.6337	-38.6338
-33.2575	-33.2575	-33.2575	-33.2578	-33.2576
-3.0433	-3.0433	-3.0433	-3.0433	-3.0433
-25.7412 ± 24.1061i	-25.7412 ± 24.1061i	-25.7412 ± 24.1061i	-25.7412 ± 24.1061i	-25.7412 ± 24.1061i
-3.2721 ± 3499.09i	-3.2722 ± 3499.09i	-3.2720 ± 3499.09i	-3.2723 ± 3499.09i	-3.2721 ± 3499.09i
-3.2743 ± 2871.08i	-3.2741 ± 2871.08i	-3.2742 ± 2871.08i	-3.2743 ± 2871.08i	-3.2743 ± 2871.08i
-13.2884 ± 2495.3i	-13.2885 ± 2495.3i	-13.2885 ± 2495.3i	-13.2884 ± 2495.3i	-13.2883 ± 2495.3i
-14.9275 ± 1867.3i	-14.9276 ± 1867.3i	-14.9278 ± 1867.3i	-14.9275 ± 1867.3i	-14.9278 ± 1867.3i
-12.6906 ± 1137.9i	-12.6906 ± 1137.9i	-12.6906 ± 1137.9i	-12.6906 ± 1137.9i	-12.6906 ± 1137.9i
-18.9107 ± 510.13i	-18.9107 ± 510.13i	-18.9107 ± 510.13i	-18.9107 ± 510.13i	-18.9107 ± 510.13i
-12.9192 ± 443.94i	-12.9192 ± 443.94i	-12.9192 ± 443.94i	-12.9192 ± 443.94i	-12.9192 ± 443.94i
-5.0833 ± 311.455i	-5.0833 ± 311.455i	-5.0833 ± 311.455i	-5.0833 ± 311.455i	-5.0833 ± 311.455i
-10.3875 ± 190.85i	-10.3875 ± 190.85i	-10.3875 ± 190.85i	-10.3875 ± 190.85i	-10.3875 ± 190.85i
-49.9113 ±74.545i	-49.9113 ±74.545i	-49.9115 ±74.545i	-49.9115 ±74.545i	-49.9113 ±74.544i

-545.2881 ± 74.43i	-545.2881 ± 74.43i	-545.2881 ± 74.43i	-545.2881 ± 74.43i	-545.2881 ± 74.43i

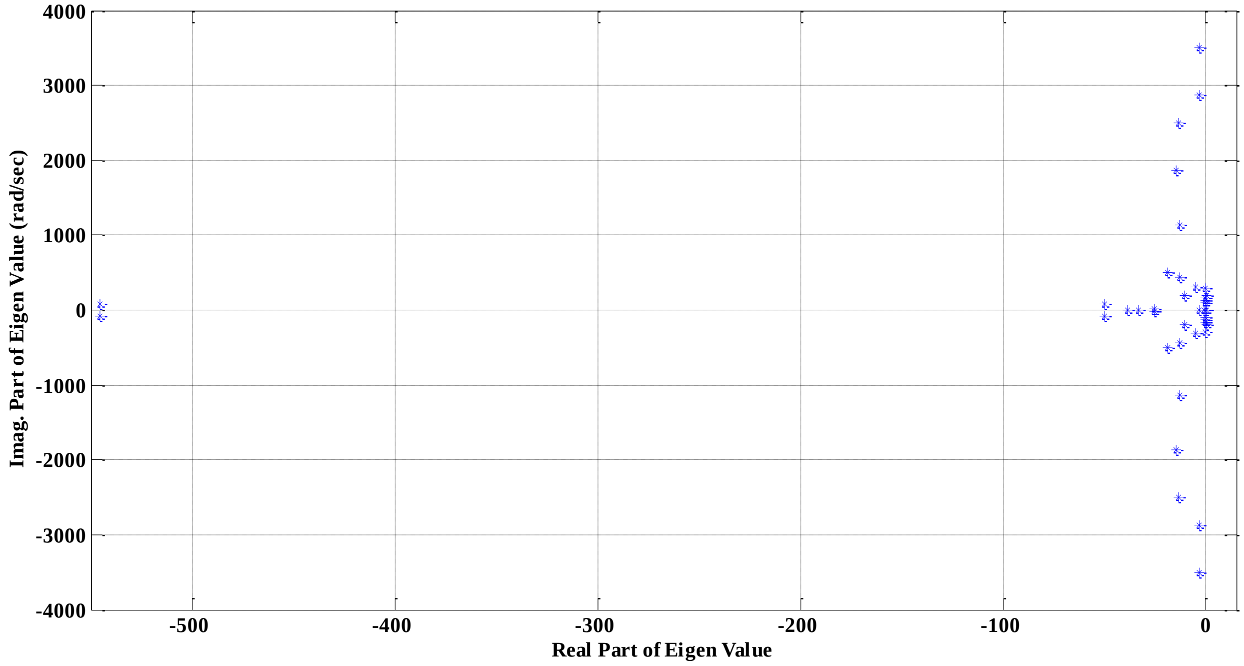

Fig 5.1 Eigenvalues of System Matrix Without IMDU

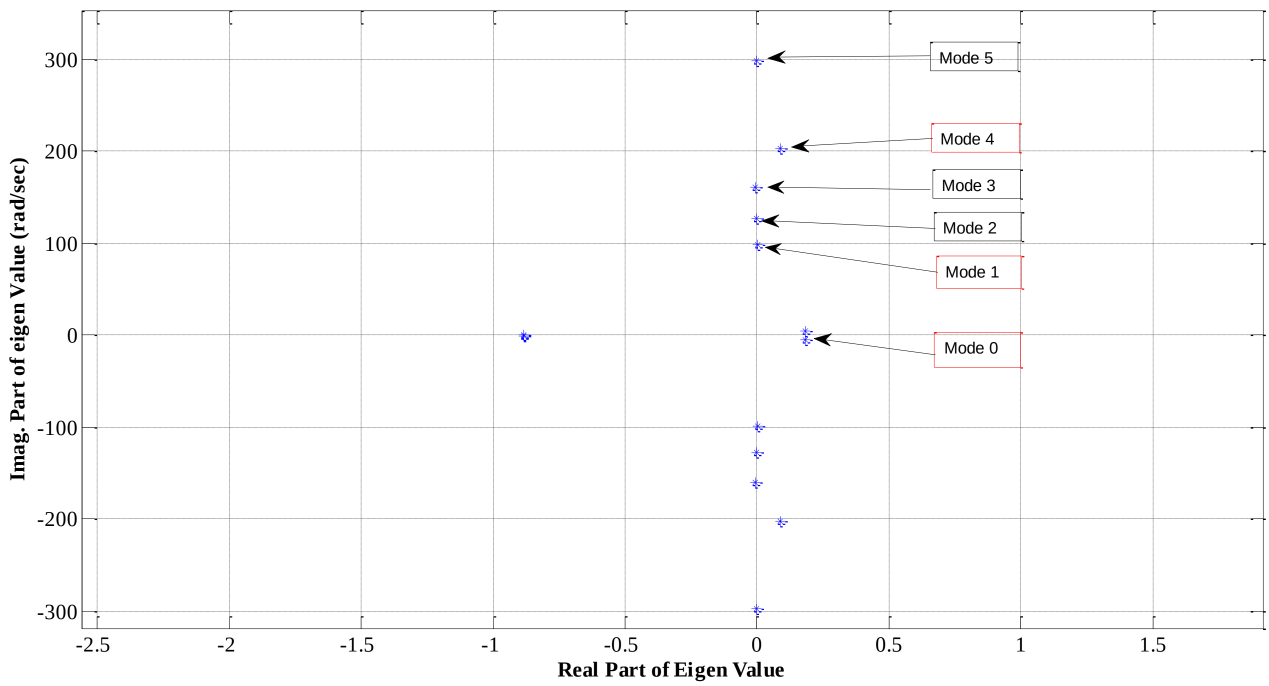

Fig 5.2 Stable and Unstable Modes of System without IMDU

Stable Modes 5, 3 and 2; Unstable Modes 4, 1 and 0

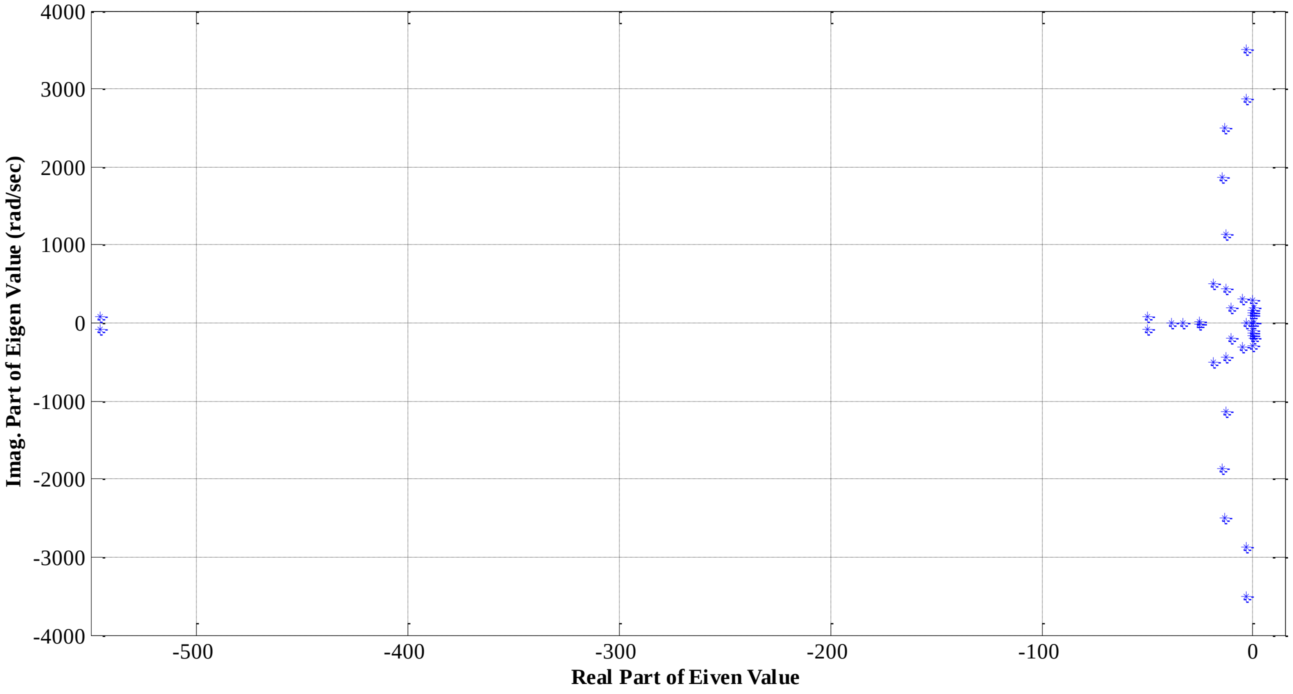

Fig 5.3 Eigenvalues of System with IMDU installed before HP Turbine

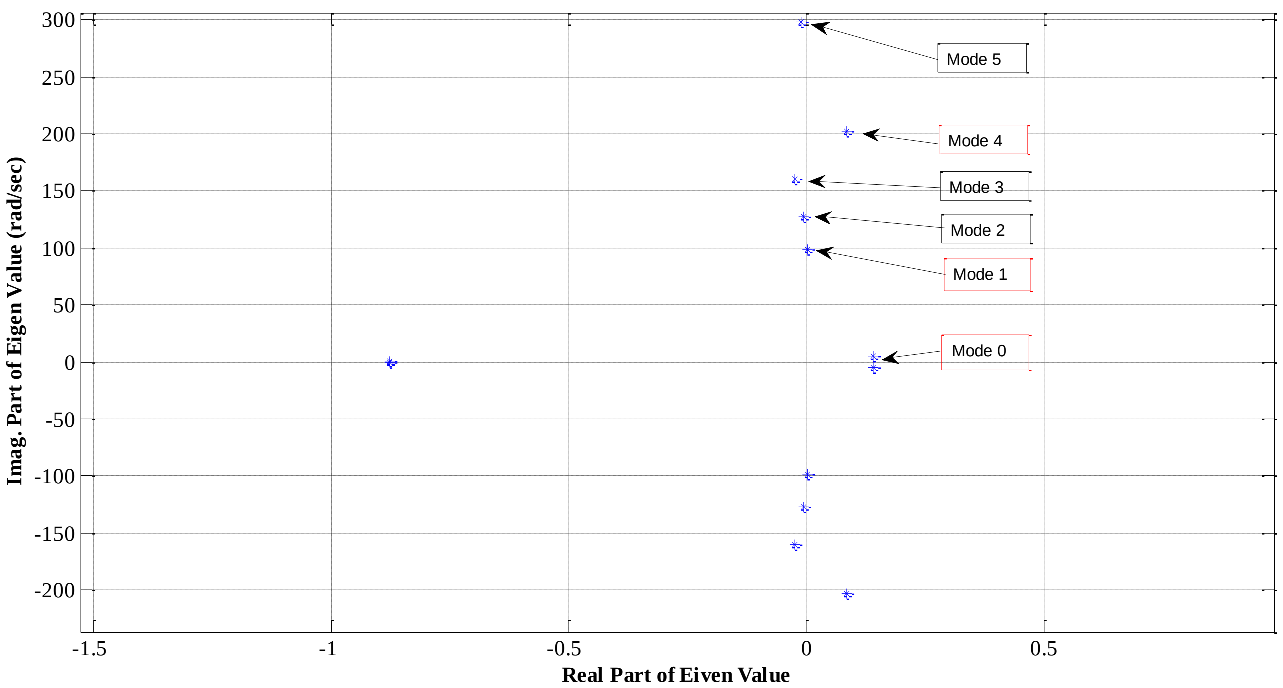

Fig 5.4 Stable and Unstable Modes with IMDU before HP Turbine

Stable Modes 5, 3 and 2; Unstable Modes 4, 1 and 0

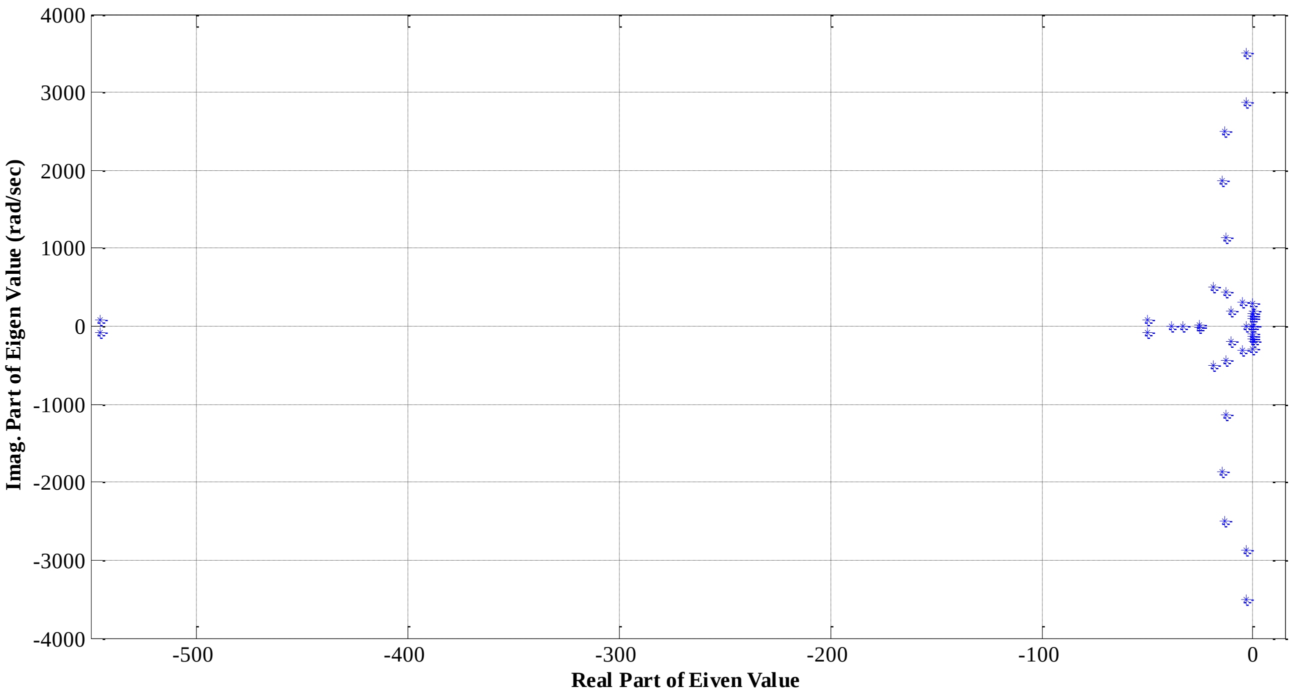

Fig 5.5 Eigenvalues of System with IMDU installed after HP Turbine

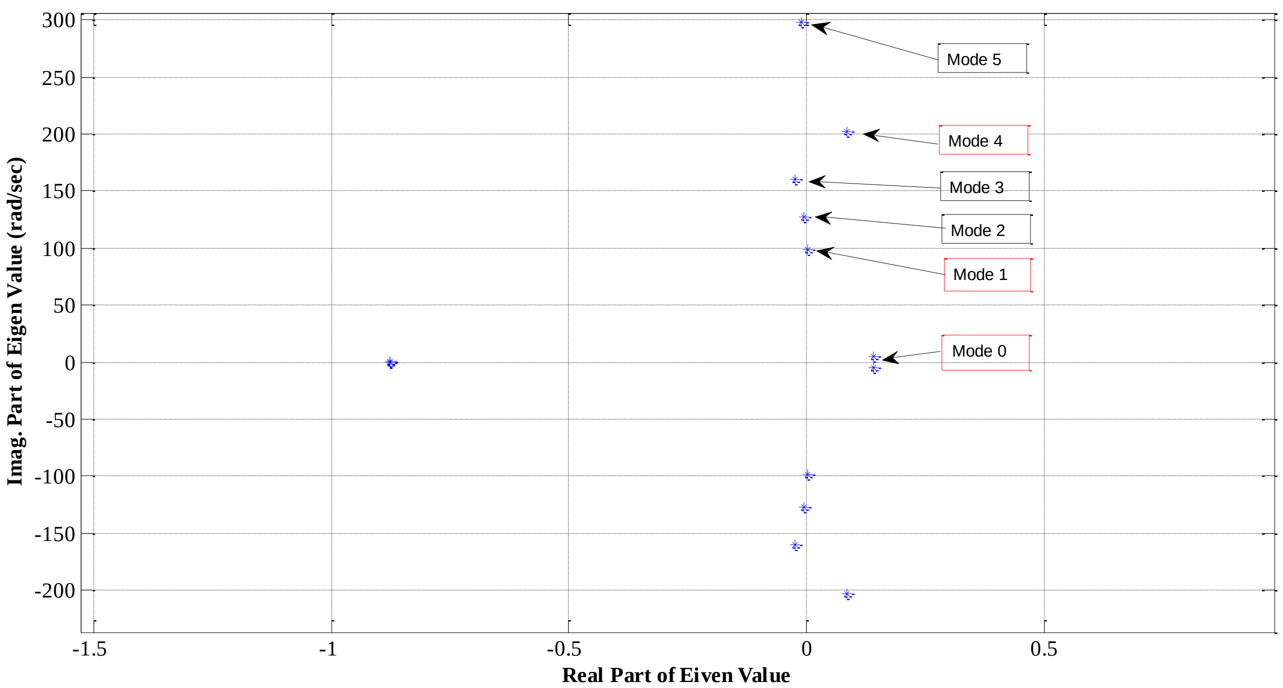

Fig 5.6 Stable and Unstable Modes with IMDU after HP Turbine

Stable Modes 5, 3 and2; Unstable Modes 4, 1 and 0

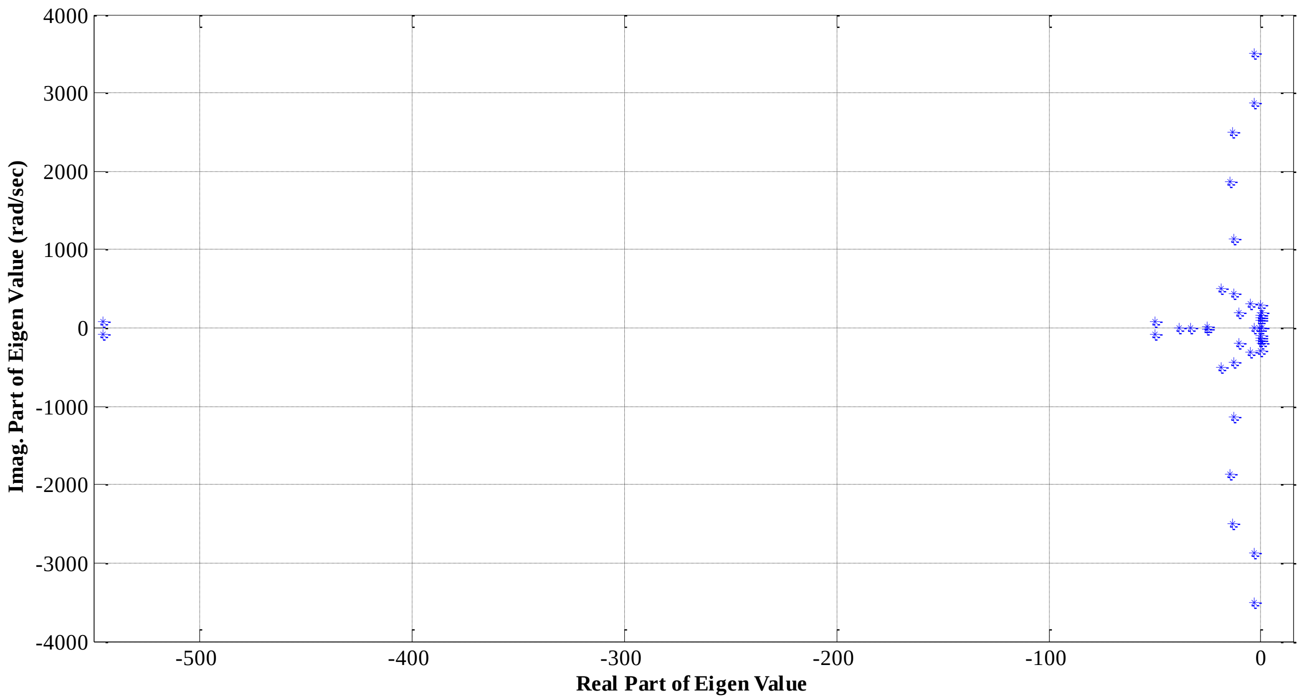

Fig 5.7 Eigenvalues of System with IMDU installed in between IP and LPA turbine

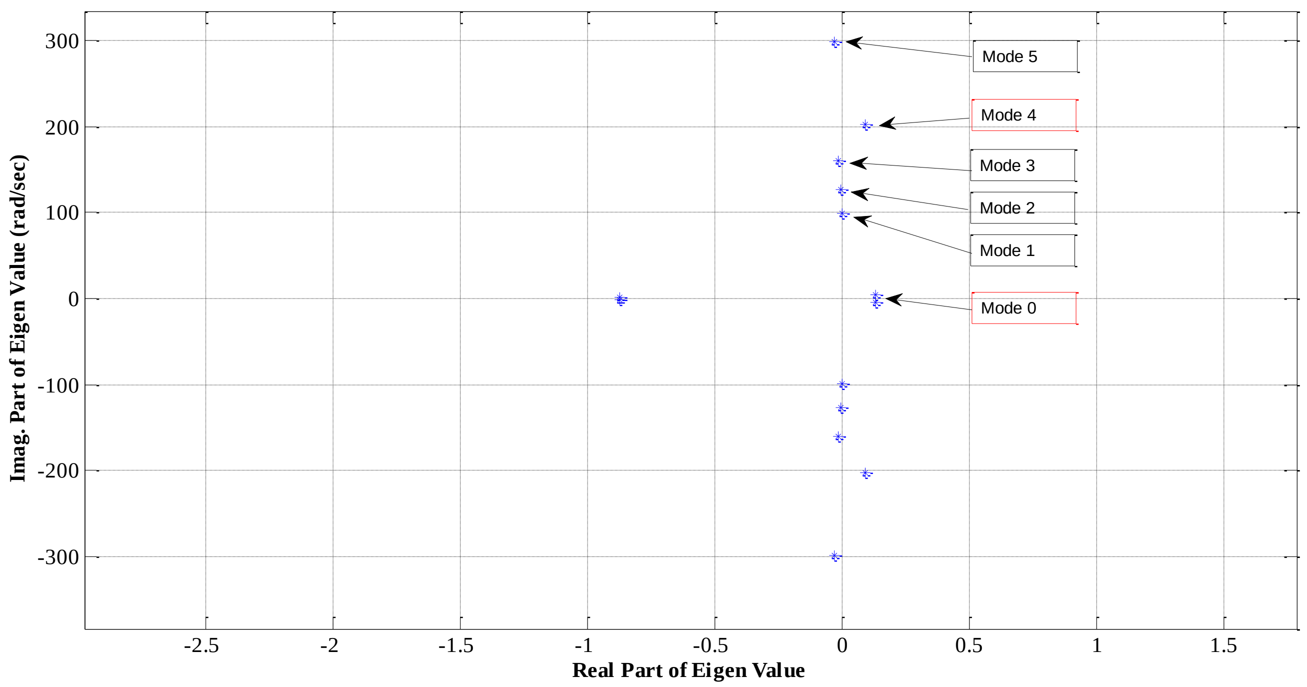

Fig 5.8 Stable and Unstable Modes with IMDU in between IP and LPA Turbine

Stable Modes 5, 3, 2 and 1; Unstable Modes 4 and 0

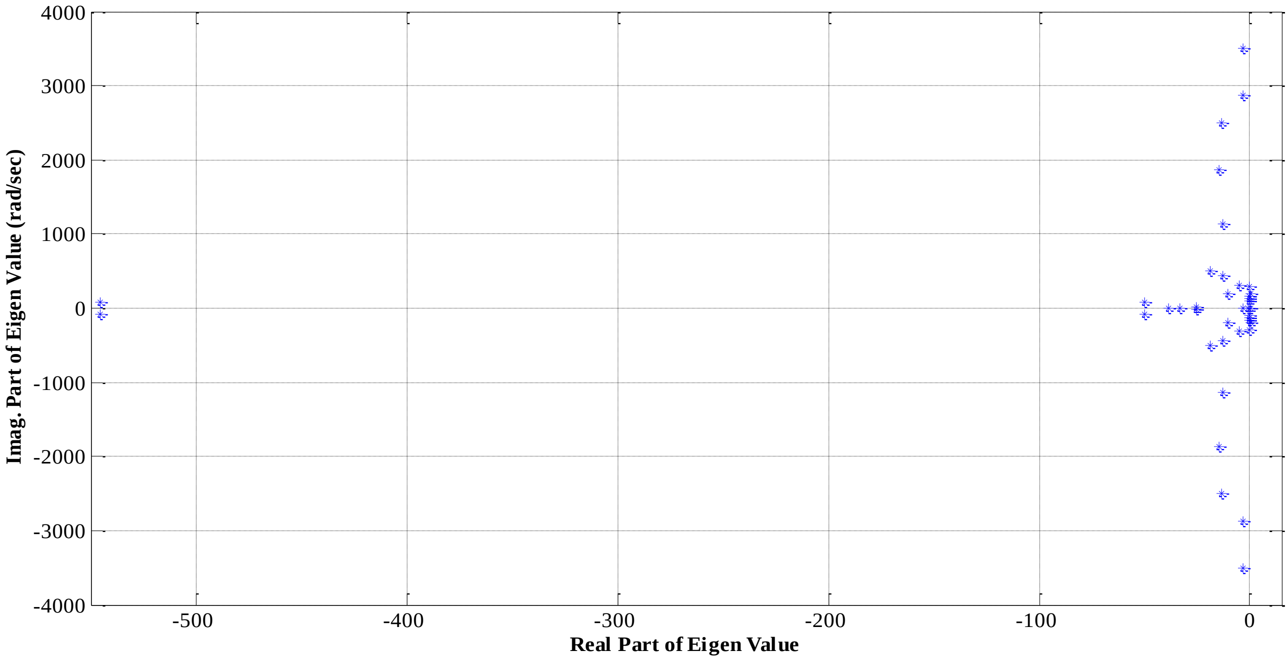

Fig 5.9 Eigenvalues of System Matrix with IMDU in between LPA and LPB

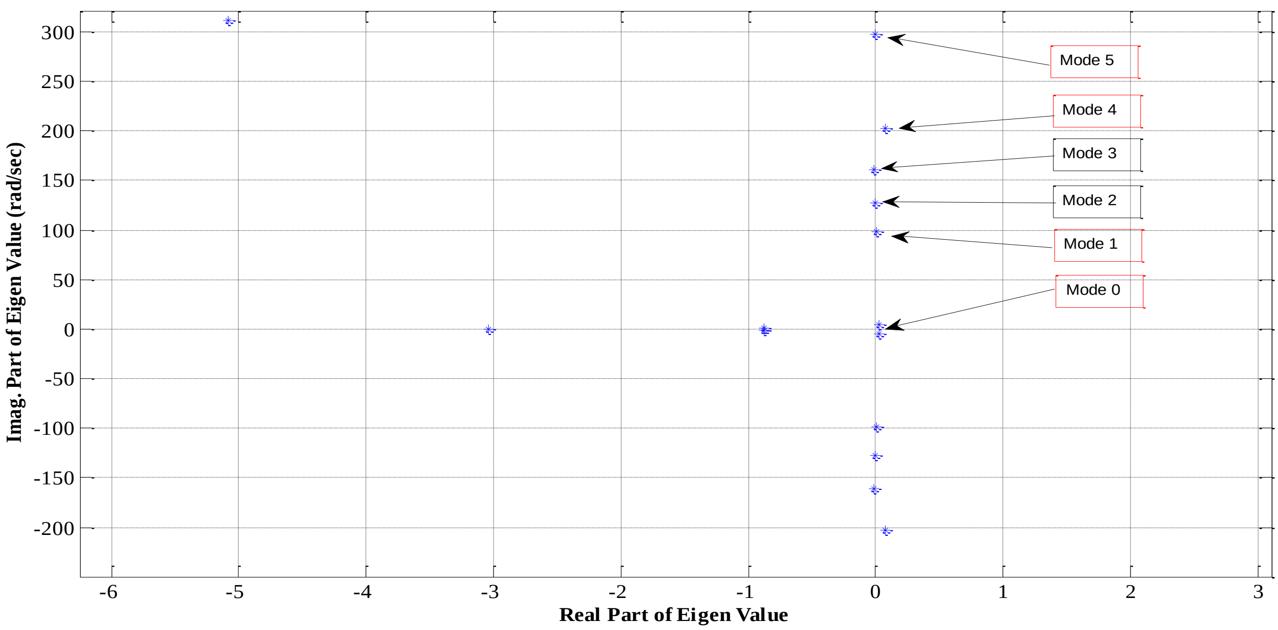

Fig. 5.10 Stable and Unstable Modes with IMDU in between LPA and LPB

Stable Modes 4 and 2; Unstable Modes 5, 4, 1 and 0

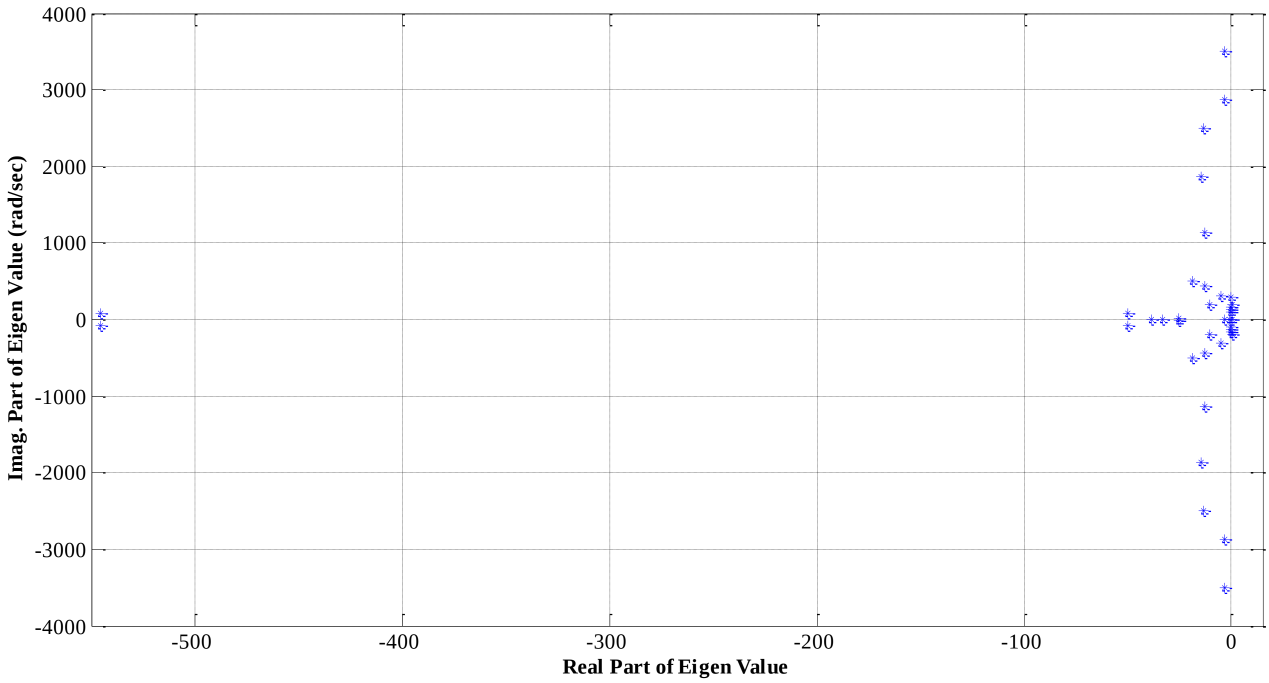

Fig 5.11 Eigenvalues of System Matrix with IMDU in between LPB and Generator

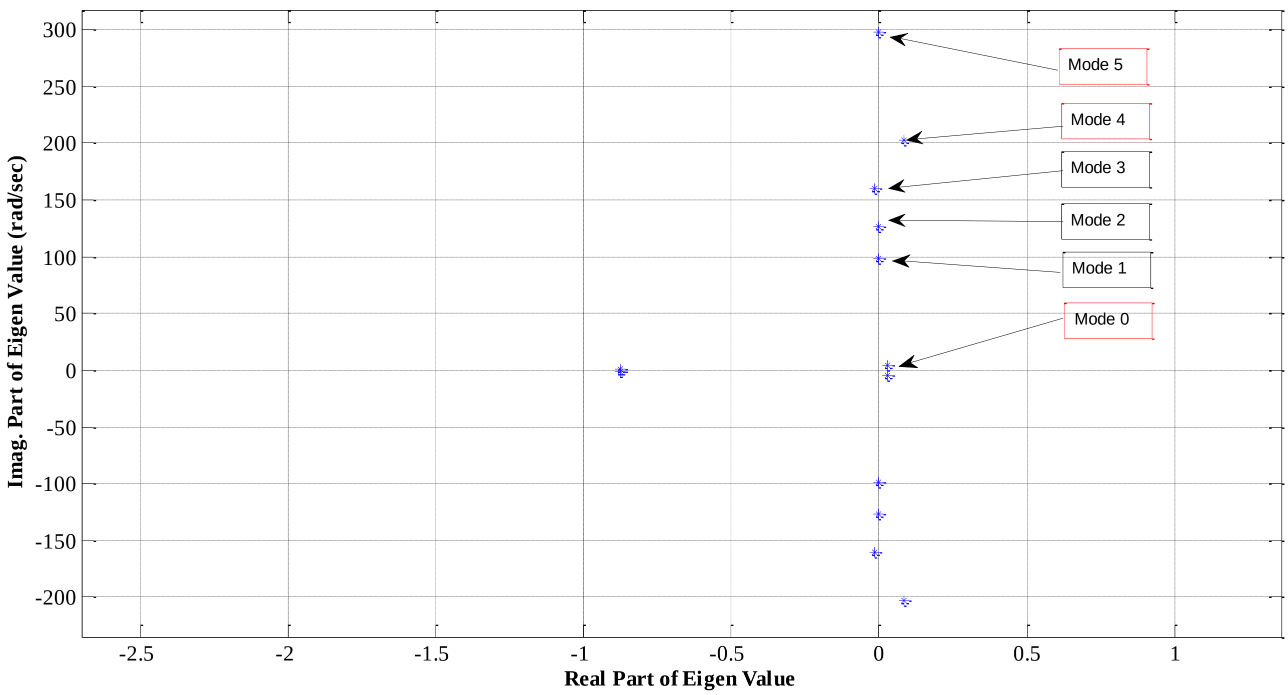

Fig. 5.12 Stable and Unstable Modes with IMDU in between LPB and Generator

Stable Modes 3, 2 and 1; Unstable Modes 5, 4 and 0

CHAPTER 6

CONCLUSION AND FUTURE SCOPE

5.1 Conclusion

This thesis presents an application of Induction machine as a damping device for the Subsynchronous oscillations causing turbine generator shaft fatigue and breakdown. Eigenvalues value analysis is performed on the IEEE First Benchmark Model.

The Eigenvalues are computed for the system with and without Induction Machine Damping Unit. The complete Eigenvalues analysis has been performed for the IEEE first benchmark model with the described damping scheme. The IMDU is connected at the different locations on the six spring mass turbine generator shaft. When IMDU is not connected to the system then, there are three unstable modes 4, 1 and 0 shown in table 5.1 and Fig 5.1. When IMDU is connected before the HP turbine still there are three unstable modes 4, 1 and 0. At the IMDU location between HP and IP turbine, modes 4, 1 and 0 are unstable. But when the IMDU is located after IP and before LPA turbine, the number of unstable modes reduces. The unstable modes are 4 and 0. IMDU at the LPA turbine has modes 5, 4 1 and 0 as unstable modes. At the IMDU location between LPB and Generator, the unstable modes are 5, 4 and 0.

On completely analysing the unstable modes at the different IMDU locations, the IMDU at the location between IP and LPA turbine has only two unstable modes 4 and 0. Hence it is the most effective IMDU location. IMDU at this location can only be placed if there is a new power plant Installation. This is a disadvantage if this scheme is implemented at the older power plants. Retrofitting is only possible if the IMDU is located at end of the turbine generator shaft.

6.2 Future Scope

In this thesis only IMDU has been used and analysed. In future this damping scheme is to be analysed in time domain and to be verified with the Eigenvalues analysis result. The IEEE first benchmark model can be demonstrated with IMDU in conjunction with other FACTS devices such as SVS, STATCOM, TCSC etc.

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APPENDIX

System Base Quantities

Base Voltage = 400 KV

Base MVA = 100 MVA

Frequency = 50 Hz

Generator data:

1110MVA, 22kV, R_a= 0.0036, X_L = 0.21

T'_{do} = 6.66,

T'_{qo} = 0.44,

T''_{do} =0.032,

T''_{qo} = 0.057,

X_d = 1.933,

X_q = 1.743,

X'_d = 0.467,

X'_q = 1.144,

X''_d = 0.312,

X''_q = 0.312

IEEE type 1 excitation system:

TR=0, TA=0.02, TE=1.0, TF=1.0s, KA=400, KE=1.0; KF=0.06 p.u.

V_{fmax}=3.9, V_{fmin}=0, V_{rmax}=7.3, V_{rmin}= -7.3

Transformer data:

R_T=0, X_T=0.15 p.u. (generator base)

Transmission line data:

Voltage 400KV, Length 600km,

Resistance R=0.034 ohm/ km,

Reactance X=0.325 ohm / km

Susceptance B_c=3.7µ mho / km

SVS data (Six-pulse operation)

Q = 100, T_M=2.4, T_S=5, T_D = 1.667ms, K_I= 1200, K_P = 0.5, K_D = 0.01

Q_L = 100 MVAr, Q_C = 300 MVAr

Torsional spring-mass system data

Mass	Shaft	Inertia H (sec)	Spring Constant (pu torque/ radian)
HP		0.1033586	
	HP – IP		25.772
IP		0.1731106	
	IP – LPA		46.635
LPA		0.9553691	
	LPA – LPB		69.478
LPB		0.983790	
	LPB – GEN		94.605
GENERATOR		0.9663006	
	GEN - EXCITER		3.768

EXCITER		0.0380697	

All self and mutual damping constants are assumed to zero.

Parameters of IMDU:

r'_2 = 3.6x 10-4, p.u.,

x'_2 = 0.32646 p.u.