STUDY OF SUBSYNCHRONOUS RESONANCE AND ITS COUNTERMEASURE USING STATIC VAR COMPENSATOR

A THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

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In
Electrical Engineering

By

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CERTIFICATE

This is to certify that the thesis entitled **" Study of subsynchronous resonsnce and its countermeasures using static VAR compensator"** submitted by **Shweta Agarwal (Roll no.:10602013)** and **Suchitra Singh (Roll no.: 10602049)** in the partial fulfilment of the requirement for the degree of **Bachelor of Technology in Electrical Engineering,** National Institute of Technology, Rourkela, is an authentic work carried out by them under my supervision.

To the best of my knowledge the matter embodied in the thesis has not been submitted to any other university/institute for the award of any degree or diploma.

Prof P.C.Panda
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CHAPTER 1

INTRODUCTION

INTRODUCTION

1.1 BASIC STRUCTURE OF POWER SYSTEMS

In this modern age, due to the overgrowing demand of electrical energy, the size and complexity of power systems is growing equally. The main components of an electrical power system comprise of generating stations, transmission lines and distribution systems apart from various other controlling equipment. The generating stations comprising of turbines and generators convert the mechanical energy in the form of water pressure or steam pressure to electrical energy. Generated electrical energy is then transmitted to the distribution stations through the transmission network. The transmission lines also help in connecting one power system to the other for various reasons. It forms a power transmission link between the load centres and the generating stations, which may be situated large distances apart due to various technical and economical considerations.

1.2 TRANSMISSION LINES

In a power system the transmission line plays an important role in transmitting electrical energy from the generating stations to the load centres. In other words they may be viewed as the arteries of the power system with the generating station being the heart. Again it is learnt that a huge percentage of the total investment of a power system is spent in erecting the transmission system. The availability of a well developed, high capacity transmission system makes it economic and feasible to transmit large blocks of electrical energy over long distances. It would be definitely better, if the same amount of electrical energy is transmitted over a transmission line having lesser installation cost or the power transmission capability of an existing transmission line is increased.

All the transmission lines have both resistance and reactance (both inductive and capacitive).The resistance is dependent on the material from which the conductor is made off. It also depends on the length of the line and area of cross section of the conductor. The inductance is due to the fact that the conductor is surrounded by the magnetic lines of force. A capacitance is also available in the line due to other current carrying conductors and the ground.

Thus a transmission line can be represented by the various parameters like resistance, inductive reactance, shunt capacitance and shunt conductance. The shunt conductance which is mostly due to leakage currents over the insulators is almost always neglected in power transmission lines. Out of these parameters the inductive reactance of the line is the most predominant one.

In a power system, where alternators are connected to the transmission lines, the power transfer takes place as per the equation given below:

$P= [V_1][V_2]/X. \sin \alpha$

Hence from the above equation it can be concluded that the power transfer can be increased by

1. Increasing V_1 and V_2 i.e sending and receiving end voltages.
2. Increasing α i.e the load angle, or
3. Decreasing X i.e reactance of the transmission line.

But the problems associated with 1 and 2 are as follows:

By increasing the voltage levels the problems of providing the necessary switch gears and insulators increases. At the same time the cost of transmission tower increases. For α, we cannot increase it to a value as we wish because the problem of stability comes. The value of α is kept within certain range.

Therefore the only possibility left is by decreasing the value of X i.e the total reactance of the line. It can be done by inserting a series capacitor in the line. Hence the value of total reactance becomes:

$X= X_e – X_c$

1.3 <u>SERIES CAPACITOR COMPENSATED SYSTEM</u>

The basic difference between the series capacitor compensated systems and uncompensated systems is that the frequency components of the transient torque (following a disturbance) can vary throughout the range between 0 to 120 Hz. For these systems the transient torque associated with the positive sequence component of the resonant electrical frequency current is in the range 0 to 60 Hz, which is below the rotor frequency (60 Hz) and is called subsynchronous torque and that associated with the negative sequence component of the resonant electrical frequency current is in the range 60 to 120 Hz and is called supersynchronous torque. This broad spectrum of frequency indicates that under certain system conditions it may be possible to directly excite the natural frequencies of the mechanical systems.

1.4 MECHANICAL SYSTEM

The rotor of a turbo-generator is a very complex mechanical system. The generator rotor is connected to the last turbine of a group of turbines and the exciter is connected to the rotor at the end. The various sections are coupled together with the help of interconnecting shafts. The rotor of a turbo-generator may exceed 150 feet in total length and may weigh several hundred tons. There are also a number of smaller components such as turbine blades, rotor coils, retaining rings, blowers, pumps and excitation system components that are included in the complete assembly. This system possesses an infinite number of modes of torsional oscillations.

1.5 CAUSES OF SHAFT DAMAGE

When a massive turbo-generator unit as discussed above is connected to a power system, system switching events such as fault occurrence, fault clearance, incorrect synchronising and reclosing and live switching which generally occurs independent of subsynchronous resonance conditions will have the effect on turbo-generator shafts. In particular high speed reclosing is a practice that deserves special concern with respect to the possible shaft damage. Such events consequently decay the fatigue life of the shafts. But the two incidents of turbo-generator shaft failure, which occurred at Mohave, brought a new concept in this field. On both the occasions the failures were attributed to torsional shaft oscillations resulting from subsynchronous resonant conditions, which exist in a system using series capacitor compensated transmission line.

1.6 SUBSYNCHRONOUS RESONANCE (SSR)

Resonance is defined, for physical systems in general, as the relatively large selective response of an object or system that vibrates in step (in phase) with an externally applied force . Resonance for electrical systems is defined as the enhancement of the response of a physical system to a periodic excitation when the excitation frequency is equal to a natural frequency of the system. Resonance, therefore, implies a periodic phenomena such as vibration, and two oscillators, one driven at or near its resonant frequency and the other driving as an externally applied force.

Subsynchronous resonance is an electric power system 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. Due to the interaction between the electrical power system and turbo-generator mechanical system, the subsynchronous oscillations can be sustained and amplified.

In general the series capacitor compensated transmission system is more complex and will result in many sub synchronous frequencies (f_{er}). Each of these frequencies are definable by an equation similar to the equation given above with the appropriate change in data.

$$f_{er} = f_o \sqrt{\frac{X_C}{X'' + X_E + X_T}}$$

$$f_r = f_o \pm f_{er}$$

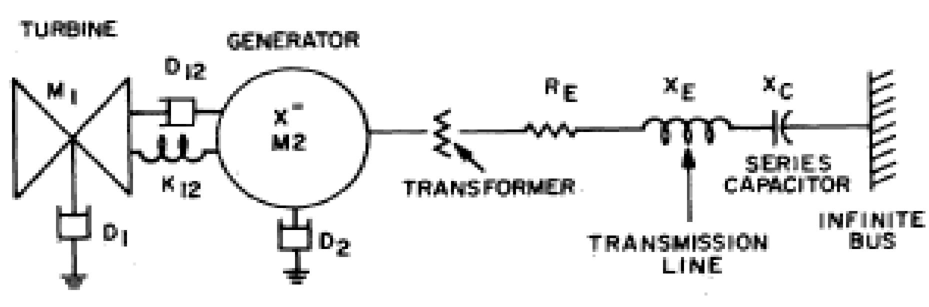


Figure 1. Turbine-Generator with Compensated Transmission

f_{er} =electrical system resonant frequency

f_o= synchronous frequency

X”= sub transient reactance of the generator

X_E= inductive reactance of transmission line

X_t=leakage reactance of transformer

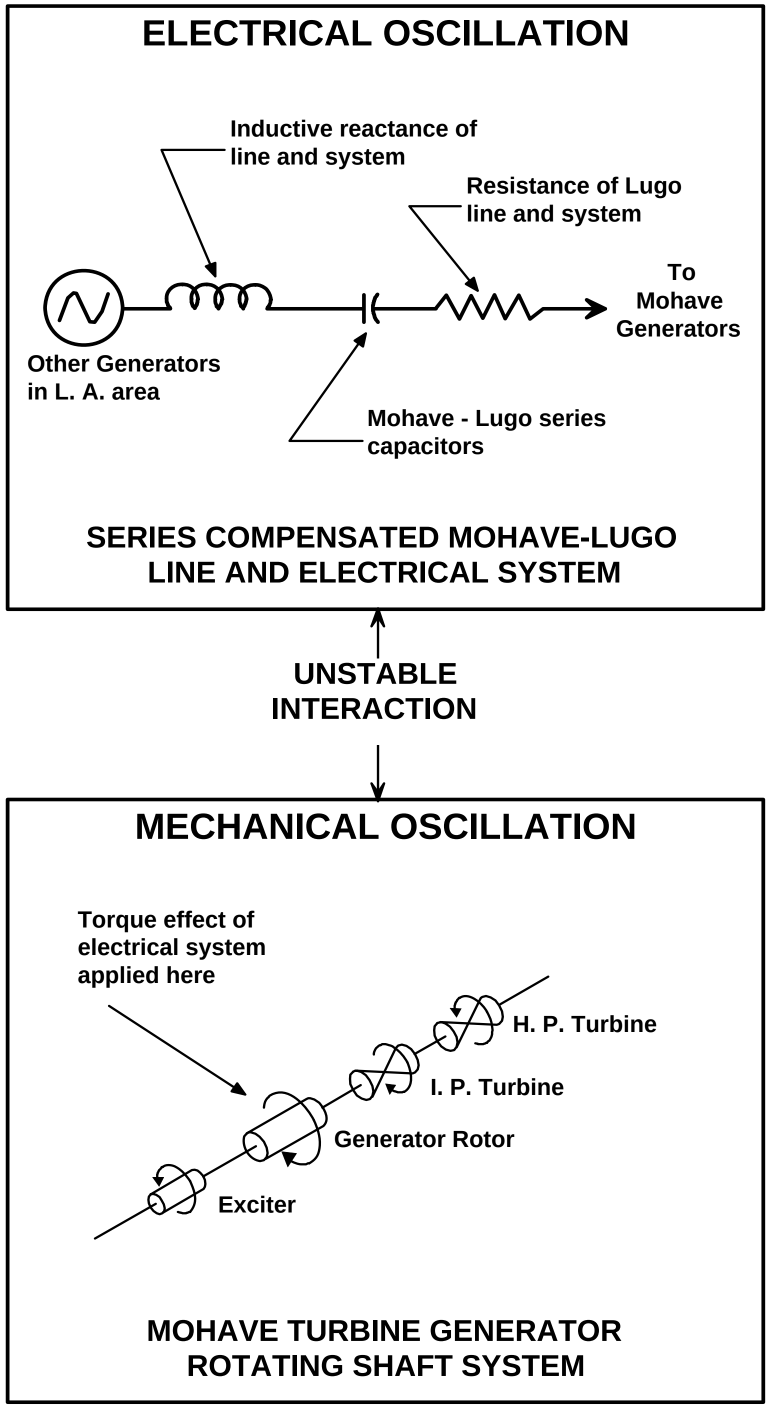
f_r=induced rotor current frequency

Currents of resonant frequency (f_{er}) in the electrical system give rise to rotor current of frequency f_r as indicated in the equation given below.

$f_r = f_0 \pm f_{er}$

A balanced three phase set of armature currents at resonant frequency produces a rotating magnetic field in the synchronous machine. The time distribution of the phase currents together with the space distribution of the armature winding causes rotation at an angular frequency of $2\pi f_{er}$. The frequency of rotor body currents induced by this field is governed by the relative velocity between the armature field and the rotor. Positive sequence components of stator current produce rotor current at sub synchronous frequency $f_r = f_0 - f_{er}$. Negative sequence components of the stator current produce rotor current at super-synchronous frequency $f_r = f_0 + f_{er}$. .

As the rotor magnetic field overtakes the more slowly rotating subsynchronous mmf in the armature, it produces a sub-synchronous torque having a frequency which is the difference



<u>SUBSYNCHRONOUS RESONANCE</u>

between the electrical frequency corresponding rotor average speed (f_0) and the electrical subsynchronous frequency (f_{er}). The sub-synchronous electrical frequency and sub-synchronous torque frequency (f_0 - f_{er}) are said to be complimentary because they add to unity, when expressed in per unit synchronous frequency (f_0).

1.6.1 SELF EXCITATION

In a power system employing series capacitor compensated transmission line, the electrical sub-synchronous currents entering the generator terminals produces sub-synchronous terminal voltage components. These voltage components may sustain the currents to produce the effect that is called self excitation. There are two types of self excitation: one involving electrical dynamics and the other involving both electrical and mechanical turbine generator dynamics, accordingly to resonance phenomena can be classified into two categories:

1. Induction generator effect
2. Torsional interaction

a. Induction generator effect:

Self excitation of the electrical system alone is caused by induction generator effect. Because the rotor circuits are turning more rapidly than the rotating mmf caused by the sub-synchronous armature currents, the rotor resistance to sub-synchronous currents viewed from the armature terminals is negative. When this negative resistance exceeds the sum of the armature and network resistance at a resonant frequency, there will be self excitation.

b. Torsional interaction:

Generator rotor oscillations at a torsional mode frequency (f_n) induce armature voltage component of subsynchronous and super-synchronous frequency(f_{en}). The armature voltage frequency component are related to the torsional made frequency by the equation

$f_{en} = f_0 \pm f_n$

When f_{en} is close to f_{er}, the subsynchronous frequency voltage is phased to sustain the sunsynchornous torque. If the component of sub-synchronous torque in phase with rotor velocity deviation equals or exceeds the inherent mechanical damping torque of the rotating system, the system will become self excited. This interplay between the electrical and mechanical system is called torsional interaction.

Combined Effect of Torsional Interaction and Induction Generator Effect:

It is important to recognize that induction generator effect and torsional interaction are not mutually exclusive and will co-exist, but are often separated for ease of analysis. Torsional interaction generally dominates when the subsynchronous torque frequency (fo - fer) is close to one of the torsional modes. Induction generator effect generally dominates when the subsynchronous torque frequency (f_0 - f_{er}) is separated from the torsional frequency. There is no clear cut criteria to indicate which type of self-excitation dominates and, in fact, both effects may be significant.

1.6.2 SHAFT TORQUE AMPLIFICATION:

When the transmission system contains series capacitor, it is possible that the complement of the electrical network natural frequency may align closely with one of the torsional natural frequencies. If this is the case, torques may be induced in the shafts following a system disturbance which are much larger than those developed as a result of three phase fault in an uncompensated system. This is due to the resonance effect and the fact that the torisonal mode damping in a turbine generator rotor system has been observed to be extremely low. This effect is again referred to as shaft torque amplification.

Most often, the shaft response is not sinusoidal with a single frequency component, but contains contributions from the same peak torque level the torsional fatigue life consumption will be significantly lower for a multimode response in comparison to a single mode response.

1.6.3 FATIGUE DAMAGE:

In this context it would be purposeful to have a basic idea about fatigue damage. It is defined as the process of progressive localized permanent structural change occurring in a material subject to conditions which produce fluctuating stresses and strains at some points and which may culminate in cracks of complete fracture after a sufficient number of fluctuations.

Transient disturbances that can occur either on uncompensated or series capacitor compensated transmission network can remove fatigue life from turbine generator shafts. In applications where the complete fracture or separation of a component would result in a serious secondary damage, it is common to define 100% fatigue life expenditure as the initiation of a crack, rather than gross failure. Clearly the integrity of turbine generator shaft system falls in this category.

Fatigue is a cumulative process. It is not until all the fatigue life is used up that an observable defect such a crack will be obtained. Hence, for example, if a shaft system is inspected and no cracks are identified following a severe torsional duty, as the majority of the shaft fatigue life may have been consumed. A few relatively minor disturbances in the future may then initiate a crack and possible gross failure.

High cycle fatigue, damage due to a large number of low amplitude fluctuations, is characterized by elastic deformation. **Low cycle fatigue**, damage due to a small number of large amplitude fluctuations, involves local plastic deformation in regions such as keyways, fillets, etc. For elastic deformations the structure will return to its initial dimensions when the loading is removed. Conversely, deformations which contain plastic components will not return to zero upon removal of the load. The **fatigue life N** of a component is the number of stress or strain cycles of a specified character or magnitude that can be withstood before failure of a specified nature occurs. The **S-N Diagram** is a plot of cyclic stress amplitude against the number of cycles to failure. The **fatigue limit**, sometimes called the endurance limit, is the limiting value of the median fatigue strength as the number of cycles (N) becomes very large. Hence stress cycles below the fatigue limit are considered to result in negligible fatigue life consumption.

1.6.4 TORSIONAL NATURAL FREQUENCIES AND MODE SHAPE:

When a fault occurs, the whole power system gets disturbed. Following this disturbance, the turbine generator rotor masses will oscillates relative to one another at one or more of the turbine mechanical natural frequencies or torsional mode frequencies, which depends upon the nature of the disturbance and the system conditions. When the mechanical system oscillates under steady state conditions at one of the natural frequencies, the relative amplitude and phase of the individual turbine generator rotor elements are fixed and are called the mode shapes of torsional motion. The notion of mode shape in this context is defined for the mechanical system acting alone in the absence of damping. This mode shape often displayed graphically is an Eigen vector of rotational displacement and/or rotational velocity of the rotor inertial elements, when the system is represented mathematically.

The torsional modes involving shaft twists are commonly numbered sequentially according to mode frequency and number of phase reversals in the mode shape. Thus mode-1 has the lowest mode frequency and only one phase reversal in the mode shape. More generally mode-'n' has the nth lowest frequency and a mode shape with 'n' phase reversals. The maximum number of modes is one less than the number of inertial elements in the spring mass model.

1.6.5 DAMPING AND DECREMENT FACTOR:

Damping is nothing but the process of restricting the oscillations in a system. Torsional mode damping quantifies the rate of decay of torsional oscillations at a torsional mode frequency and can be expressed in several ways. The most easily measured quantity is the ratio of successive peaks of oscillations: the natural logarithm of this ratio is known as the logarithmic decrement or log-dec δ. For slow decay, the log-dec is approximately equal to the fraction of decay per cycle. An alternative measure is the time in seconds for the envelope of decay to decrease to the fraction 1/e of its value from an earlier point in the time. This measure is the time constant is defined as the decrement factor (σ_n) and is equal to the mode frequency in hertz multiplied by the log-dec.

Damping measured by test includes the combined effect of both the mechanical as well as the electrical system damping. In the course of system studies mechanical and electrical system damping are normally represented separately. Several factors affect the apparent damping of the torsional modes of vibration. These factors can be conveniently grouped based on their origin being either mechanical or electrical.

The damping of mechanical origin is associated with the dissipative force of windage bearing friction and hysteresis loss. The damping due to steam forces on the turbine blades is suspected to be the dominant influence that causes increased damping with load. These components of damping are small and are generally load dependent and vibration amplitude dependent. The collective damping effects of mechanical origin are represented by σ_m , the decrement factor of mechanical system modes acting alone.

The damping contribution of electrical origin are associated with incremental I^2R loss per unit of generator velocity produced in the transmission lines, synchronous machine armature windings, field winding and rotor body surface. These loss components are particularly frequency sensitive and to some extent amplitude sensitive due to magnetic hysteresis and saturation. Collectively the damping elements of electrical origin are represented by σ_e, the decrement factor of the torsional mechanical modes in the absence of mechanical damping. The electrical damping σ is load and system reactance dependent and is related to the effective rotor resistance. For small amplitude oscillations the modal damping is given by $\sigma = \sigma_m + \sigma_e$.

In the presence of series capacitor compensation a negative damping component may be produced due to torsional interaction.

1.6.6 MATHEMATICAL MODELS:

The analysis of self excitation or transient shaft torque caused by disturbances in the system requires mathematical modelling of the torsional mechanical system. Investigation of the SSR torsional interaction problems can be performed using one of two methods: "all-modes method" and "modal method’’. In the "allmodes" method, the generator shaft is represented by all of its masses. The machine rotor impedance is taken constant for all modes. This method shows the trend of all the modes and gives a qualitative picture for their behaviour". The "modal" method uses an equivalent mass-spring model to represent a single mechanical mode of oscillation. A different value of rotor impedance is used with each mode to reflect the effect of the corresponding resonant electrical frequency. Although widely utilized, the "modal method" can be highly misleading for this application, since it overlooks the coupling between the different torsional modes.

A complete representation would require the solution of the elastic behaviour of the whole turbine generator. A frequently used mechanical representation called a spring mass model allows computation of rotor motion with torque applied to individual masses as inputs.

As a computational aid it has been found desirable here to construct a completer spring mass model of the whole system raking their individual inertia and spring constant based on the rated KVA. The torque equations of the spring mass model are seen to be ‘N’ second order differential equations of motion for an ‘N’ mass model coupled to one another by the spring elements.

1.7 COUNTERMEASURES TO SUB-SYNCHRONOUS RESONANCE PROBLEM:

As discussed earlier, a series capacitor compensated transmission line will help to have the optimum/ economical power transfer. The cost of constructing another line for the transfer of same amount o additional power that the series capacitor compensated line can carry will be much higher as compared to the cost of additional equipments to be installed to counter act the subsynchronous resonance problem.

The analysis of subsynchronnous resonance in series capacitor compensated power transmission system is a complex technical problem. When such an analysis reveals either unstable system operating condition or an unacceptable risk of equipment damage during system disturbance, measures to resolve the problems must be implemented. These measures may include modification to the transmission system, restrictive operating criteria and/or the addition of equipments designed to counteract the problems. For many long distance transmission systems series compensation including the required corrective measures is the most economical alternative.

1.8 STATIC REACTIVE COMPENSATING SYSTEMS

In the previous section, one type of reactor compensation for countering subsynchronous resonance problem was mentioned as a dynamic filter, which uses thyristors to modulate the current through a parallel connected reactor in response to speed variations. The advent of high speed, high current switching thyristors has brought a new concept in designing reactive compensators for optimum system performance. The improvements achieved in providing these static VAR compensators are as follows:

1. Damping is provided for SSR oscillations.
2. Due to increased damping provided, the dynamic system stability is improved.
3. Load power factor can be improved thereby increasing the efficiency of transmission.
4. Transient stability is improved.
5. The fast dynamic response of SVC's have offered a replacement to synchronous condensers.

The use of series capacitors in transmission lines to increase the power transfer capability may cause subsynchronous resonance oscillations between the electrical and mechanical system which may result in a serious damage to the generating unit. Subsynchronous resonance is thus an additional problem to be considered when planning future power system addition. Again the increased benefits derived of higher levels of series compensations must be weighted against the additional expenditure to reliably control the subsynchronous problems. The aim of subsynchronous resonance analysis should be for:

1. Developing and testing equipment to provide safe operation of generators under subsynchronous resonance conditions.
2. Developing and testing subsynchronous resonance relays, that will provide protection from transient disturbances

1.9 SOME HINTS ABOUT SVS

Thyristor controlled static shunt VAR systems(SVS) are finding wider use in both industrial and transmission system applications. In high power industrial applications, static reactive VAR systems are well established means of reactive power control, especially for reduction of voltage fluctuations caused by inductive loads such as asynchronous motors, arc furnaces etc. These systems are being applied to power transmission systems to provide better voltage regulation, reactive power support, improve damping and an increase in system stability.

1.9.1 BASIC FUNCTIONS OF SVS:

The following basic requirements of a power transmission system can be performed by static VAR systems:

- Maintaining the system voltage profile under dynamic load conditions such as line switching or load rejection.
- Improving the power transfer capability of the system, therby increasing the dynamic and transient stability of the system.
- Suppression of power systems oscillations thereby improving the system damping.
- Suppression of voltage fluctuations caused by disturbing loads such as rolling mills, arc furnaces and single phase traction loads.
- Controlling the reactive power flow and thereby minimising the system losses.
- Limiting the voltage rise at the AC bus of a HVDC terminal on load rejection or converter blocking.

1.9.2 THE REQUIREMENTS OF A SVS

- Control range
- Control based on various signals: ΔV, ΔQ, $f(\Delta V, \Delta Q, \Delta P, \Delta f, \Delta W)$
- High speed of response
- Low losses and high efficiency
- Minimal generation of harmonics
- Low maintenance requirements
- Compatibility with unbalanced system or operation

1.9.3 ADVANTAGES OF SVS:

The controllable static VAR system has many advantages which are summarised as follows:

- Fast response between two/three cycles
- Control the reactive power of each phase independent of other phases.
- No rotating parts, so no inertial problems and little maintenance expenditure.

CHAPTER 2

SYSTEM MODELLING FOR SSR STUDY

SYSTEM MODELLING FOR SSR STUDY

2.1 INTRODUCTION TO SYSTEM MODELLING

In recent years due to the overgrowing size and complexity of power systems, the nature of system stability problems has changed a lot. Hence it demands a more accurate engineering analysis of the system stability problems. To meet the adverse situations, now there is a trend towards the use of control systems associated with the excitation system, the prime movers and the transmission system to improve the stability margin of the power system. This emphasis on analysis necessarily requires system and equipment models which should adequately represent their behaviour more accurately.

The present interest in power system modelling was developed just over four decades ago. Various electrical and electro-mechanical analysers had been employed upto that time, but the most promising was shown to be the purely electrical network analyser. In this analyser, the system resistance, reactance and capacitance were represented directly by similar elements. The synchronous machines were simulated by an alternating voltage variable in both magnitude and phase and connected in series with an inductance and resistance.

Improvements were made in the basic network analyser model by adding more complicated machine representation based on park’s equation, in which analogue computing techniques were used for the solution of the machine differential equations. The complex hybrid analogue computer/network analyser was a development of this. Micro machines provide the most satisfactory solution to some problems in which qualitative results are demanded. They enable extensive experimentations which would ideally be performed on an actual system to be undertaken under laboratory conditions with no risk to expensive plant. Disadvantages of this method of analysis are:

1. The constants of the model cannot be adjusted to correspond exactly to those of the system.
2. The time required to set up a system can be fairly large.
3. The number of machines which can be represented is limited to a few in number.

Digital computers were employed initially to replace the network analyser. Much interest centred on the effective solution of the active and reactive power distribution or load flow problem.

2.2 MATHEMATICAL MODEL OF MECHANICAL SYSTEM:

The arrangement of the various turbine sections, generator and exciter in the mechanical system is shown in figure- . The turbine sections are as follows:

- High Pressure Turbine (HP)
- Intermediate Pressure Turbine (IP)
- Low Pressure Turbine – A (LPA)
- Low Pressure Turbine – B (LPB)

The various turbine sections can be mathematically represented by an equivalent mass spring system with their inertia, spring constant and damping. The mechanical system of the generator and exciter can be represented in a similar fashion. Inertia is expressed in terms of inertia constant H based on rated KVA. The simple second order torque equation in this system of units is:

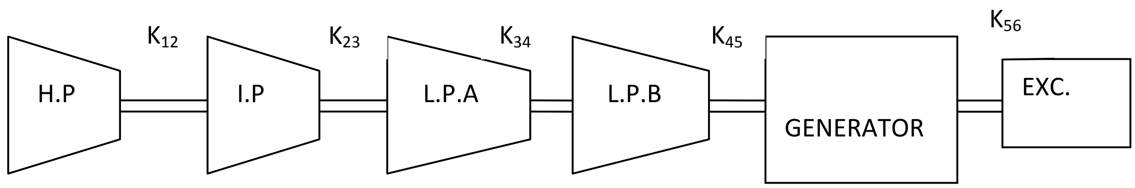
$T = 2H/Wb.\delta'' + D\delta' + K\delta$

Here in the torque equation ,$T = T_{mechanical} - T_{electrical}$

$= T_m - T_e$

All the mathematical representations of the system are done in per unit. The base torque is that required at synchronous speed to deliver mechanical power in kilowatts equal to the rated (base) KVA value. The spring constant K is given in per unit where base spring constant is defined as base torque divided by base angle. The steady state mechanical torque is apportioned among the four turbine sections HP, IP, LPA, LPB respectively as follows 30%, 26%, 22% and 22%. The exciter steady state torque is assumed to be zero.

ROTOR MECHANICAL ARRANGEMENT



'A' MATRIX FOR MECHANICAL SYSTEM:

0	0	0	0	0	0	1	0	0	0	0	0
0	0	0	0	0	0	0	1	0	0	0	0
0	0	0	0	0	0	0	0	1	0	0	0
0	0	0	0	0	0	0	0	0	1	0	0
0	0	0	0	0	0	0	0	0	0	1	0
0	0	0	0	0	0	0	0	0	0	0	1
-K12/J1	K12/J1	0	0	0	0	-(D12+D11)/J1	D12/J1	0	0	0	0
K12/J2	-(K12+K23)/J2	K23/J2	0	0	0	D12/J2	-(D22+D12+D23)/J2	D23/J2	0	0	0
0	K23/J3	-(K34+K23)/J3	K34/J3	0	0	0	D23/J3	-(D33+D34+D23)/J3	D34/J3	0	0
0	0	K34/J4	-(K34+K45)/J4	K45/J4	0	0	0	D34/J4	-(D34+D44+D45)/J4	D45/J4	0
0	0	0	K45/J5	-(K45+K56)/J5	K56/J5	0	0	0	D45/J5	-(D55+D45+D56)/J5	D56/J5
0	0	0	0	K56/J6	-K56/J6	0	0	0	0	D56/J6	-(D56+D66)/J6

SYSTEM DATA

GENERATOR IMPEDANCES AND TIME CONSTANTS

X_d= 1.79 p.u

T_{do}'= 4.3 sec

X_d'= 0.169 p.u

T_{do}''= 0.032 sec

X_d''= 0.135 p.u

T_{qo}'= 0.85 sec

X_q= 1.71 p.u

T_{qo}''= 0.05 sec

S_q'=0.228 p.u

R_a= 0.0o

X_q''= 0.200 p.u

ROTOR SPRING-MASS PARAMETERS

H_1= 0.092897 sec

K_{12}= 19.303 p.u(Torque/rad)

H_2= 0.155589 sec

K_{23}= 34.929 p.u(Torque/rad)

H_3= 0.858670 sec

K_{34}= 52.038 p.u(Torque/rad)

H_4= 0.884215 sec

K_{45}= 70.858 p.u(Torque/rad)

H_5= 0.868495 sec

K_{56}= 2.822 p.u(Torque/rad)

H_6= 0.0342165 sec

TRANSMISSION LINE PARAMETERS

X_t= 0.14 p.u

R_t =0.01 p.u

X_e= 0.56 p.u

R_e= 0.02 p.u

X_c= variable

TURBINE STEADY STATE TORQUE DISTRIBUTION

T_{hp}= 30%

T_{lpa} = 22%

T_{ip}=26%

T_{lpb}= 22%

T_{exc}= 0

2.3 MATHEMATICAL MODEL OF SYNCHRONOUS GENERATOR

In developing equations of a synchronous machine, the following assumptions are made:

- The stator windings are sinusoidally distributed along the air gap as far as the mutual effects with the rotor are considered.
- The stator slots cause no appreciable variation of the rotor inductances with rotor position.
- Magnetic hysteresis is negligible.
- Magnetic saturation effects are negligible.

The stator circuit consists of three phase armature windings carrying alternating currents. The rotor circuit comprises of field winding carrying direct current. For purpose of analysis the currents in the rotor winding may be assumed to flow in two sets of closed circuits: one set whose flux is in line with that of the field along the d-axis and the other set whose flux is at right angles to the field axis or along the q-axis.

$[V] = [Z_m][I] + [L][pI]$

Where $[V] = \begin{bmatrix} V_d \\ V_q \\ V_f \\ V_{kd} \\ V_{kq} \end{bmatrix}$

$[i] = \begin{bmatrix} i_d \\ i_q \\ i_f \\ i_{kd} \\ i_{kq} \end{bmatrix}$

$[Z_m]$=

$R_a + w_f (L_q – L_d) \sin\theta. \cos\theta$	$w_r (L_q + L_d) - w_f (L_d \cos^2\theta + L_q \sin^2\theta)$	$- w_r L_{md} \sin\theta$	$- w_r L_{md} \sin\theta$	$w_r L_{mq} \cos\theta$
$w_f (L_d \sin^2\theta + L_q \cos^2\theta) – w_r(L_q + L_d)$	$R_a + w_f (L_d – L_q) \sin\theta. \cos\theta$	$- w_r L_{md} \cos\theta$	$- w_r L_{md} \cos\theta$	$w_r L_{mq} \sin\theta$
$-(w_f - w_r) L_{md} \sin\theta$	$-(w_f - w_r) L_{md} \cos\theta$	R_{fd}	0	0
$-(w_f - w_r) L_{md} \sin\theta$	$-(w_f - w_r) L_{md} \cos\theta$	0	R_{kd}	0
$(w_f - w_r) L_{mq} \cos\theta$	$-(w_f - w_r) L_{mq} \sin\theta$	0	0	R_{kq}

[L]=

$L_d \cos^2\theta + L_q \sin^2\theta$	$(L_q – L_d) \sin\theta. \cos\theta$	$L_{md} \cos\theta$	$L_{md} \cos\theta$	$L_{mq} \sin\theta$
$(L_q – L_d) \sin\theta. \cos\theta$	$L_d \sin^2\theta + L_q \cos^2\theta$	$-L_{md} \sin\theta$	$-L_{md} \sin\theta$	$L_{mq} \cos\theta$
$L_{md} \cos\theta$	$-L_{md} \sin\theta$	L_{fd}	L_{md}	0
$L_{md} \cos\theta$	$-L_{md} \sin\theta$	L_{md}	L_{kd}	0
$L_{mq} \sin\theta$	$L_{mq} \cos\theta$	0	0	L_{kq}

Final differential equation of synchronous generator sub-transient model are :

$P\Delta e_d' = (X_q - X_q')/T_{qo}'\ \Delta I_q - 1/T_{qo}\Delta\ e_d'$

$P\Delta e_q' = -(X_q - X_q')/\ T_{qo}'\Delta I_d - 1/\ T_{qo}\Delta e_q'$

$P\Delta e_d'' = (1/T_{qo}'')\Delta e_d' + (X_q' - X_q'')/\ T_{qo}''\Delta I_q - 1/\ T_{qo}''\Delta e_d''$

$P\Delta e_q'' = (1/T_{do}'')\Delta e_q' - (X_d - X_d'')/\ T_{do}''\Delta Id - 1/\ T_{do}''\Delta e_q''$

The analysis of synchronous machine equations in terms of dq0 variables is considerably simpler than in terms of phase quantities, for the following reasons:

- The dynamic performance equations have constant inductances.
- For balanced conditions, zero sequence quantities disappear.
- For balanced steady state operation, the stator quantities have constant values. For other modes of operation they vary with time.
- The parameters associated with d- and q-axis may be directly measured from terminal tests.

2.4 MATHEMATICAL MODEL OF ELECTRICAL NETWORK

The electrical network configuration adopted for this work is a simple radial RLC circuit. The circuit parameters expressed in per unit on the generator MVA rating at 60 Hz corresponds to the Navajo- Mccullough line. The reactance is proportional to frequency and resistances are constant. The current in the network changes from that of the machine current when the SVC is connected. Hence two sets of network equations are to be framed to take care of the two models. One set deals with the system without SVC and the other set deals with the system with SVC.

Voltage equations of transmission line:

$V_d = R_e\ I_d + (X_e/W_0)PI_d - (X_e\ /\ W_0)(W - W_0)I_q - (W/\ W_0)\ X_e\ I_q + V_{cd} + |V_b|\ \sin\alpha$

$V_q = R_e\ I_q + (X_e/W_0)PI_q + (X_e\ /W_0)(W - W_0)I_d + (W/\ W_0)\ X_e I_d + V_{cq} + |V_b|\ \cos\alpha$

Current equations of transmission line:

$I_d = CPV_{cd} - CV_{cq}(W - W_0) - WCV_{cq}$

$I_q = CPV_{cq} + CV_{cd}(W - W_0) – WCV_{cd}$

On linearization:

$P\Delta V_{cd} = W_0 X_c \Delta I_d + (2W - W_0) \Delta V_{cq} + 2V_{cq} \Delta W$

$P\Delta V_{cq} = W_0 X_c \Delta I_q + (2W - W_0) \Delta V_{cd} + 2V_{cd} \Delta W$

2.5 STATIC VAR COMPENSATOR

The dynamic filter which uses thyristors to modulate the current through a shunt connected reactor can be used to countermeasure the SSR problem. The capacitive reactance part is assumed to be fixed and reactance part is taken as variable one by making use of the thyristor switching.

In this study the SVC unit is assumed to be connected to the generator bus terminals all the time. The thyristor phase controlled reactor is represented by an inertia less voltage source behind affixed reactance Xs. The magnitude of Es is controlled by the controller of the SVC. This type of SVC provides only reactive power and has negligible amount of MW loss.

2.6 MATHEMATICAL MODEL OF SVC

The SVC is mathematically represented in the model by writing down the differential equations relating to its inductive reactance and capacitive reactance part. The preliminary differential equations of the inductor and capacitor of the SVC are as follows:

2.7 MATHEMATICAL MODEL OF FIELD CONTROL

The field excitation control system of a synchronous machine is provided to meet the reactive power demand of the system under small disturbance conditions. The field regulator helps in recovering the system from output voltage fluctuations following a minor disturbance. In the formation of the model , maximum and minimum limits are imposed on the regulator itself and account is taken of saturation on the rotating exciter output voltage.

CHAPTER-3

EIGEN VALUE AND TRANSIENT STABILITY ANALYSIS

3.1 EIGEN VALUE ANALYSIS

To study the small signal performance with and without SVC, the system differential equations are linearised about on initial operating point and the system in both the cases is represented in the state space form:

$$[\Delta X] = [A]\ [\Delta X]$$

Where [ΔX] represents the state vector

and [A] represents the system matrix.

The elements of the system matrix are obtained from the co-efficient of the linearised system equations. In this work, the 6^{th} order model of the synchronous machine is taken since it has got certain advantages over the 5^{th} order model. Hence the system without SVC has 20 states consisting of 12^{th} order mass-spring system, 4^{th} order model for generator starter and transmission line and 4^{th} order model for rotor windings. The system with SVC has 28 states consisting of 12^{th} order mass-spring system, 6^{th} order model for generator starter and transmission line, 4^{th} order model for generator rotor windings, 4^{th} order model for SVC and 2^{nd} order model for field and SVC controller.

Although a six mass-spring system has got five distinct modes, only four out of the six are predominant modes. These models are mainly responsible for the instability of the system having series capacitor compensated transmission line, depending on the series compensation level. The modal frequencies of these modes are found out by simply considering the 12^{th} order mechanical system alone and doing the necessary analysis. The mechanical damping at the moment is taken to be zero.

For a large and complicated system the Eigen value analysis is the best method available for the stability studies. The nature of the Eigen values of the system matrix indicates the stability of the system from which the system matrix is formed. The Eigen values of the matrix 'A' are the roots of the characteristic equation:

$$|\lambda I - A| = 0$$

The real part of the Eigen values reflects the stability of the system.

3.1.1 <u>Modal frequencies of the modes</u>

By performing the Eigen value analysis on the 12*12 matrix 'A', which is obtained by considering the mechanical system alone gives the modal frequencies of the modes of the system in the imaginary parts of the Eigen values. The modal frequencies of these modes found from analysis are as follows:

Mode-1 = 15.7 Hz

Mode-2 = 20.2 Hz

Mode-3 = 25.5 Hz

Mode-4 = 32.3 Hz

The real parts of the Eigen values are found to be zero. By considering a small positive value of damping constant D for all six masses, the real parts of the Eigen values become negative, which indicates stability of the system.

3.1.2 <u>Torsional modes characteristics (Without SVC)</u>

Torsional modes characteristics problems will be induced in the system only by the above mentioned four modes. To get a clear view of the effectiveness of various mode depending on the series compensation level it is shown graphically. Tests are conducted on the 20^{th} order linearised model (without SVC) at various levels of capacitor compensation. The initial conditions are calculated in the computer program itself. When the generator is delivering P_o = 0.9 p.u. power factor. The terminal voltage of the generator or the rotor bus voltage to which the generator is connected is taken as reference and kept at 1.0 p.u. Once the initial conditions are found out, they are substituted in the matrix elements in the program itself to get the system matrix 'A'. Then by varying the series capacitor compensation level (X_c) in percentage of line reactance (X_e) the Eigen values are found out by using the eigen value subroutine. The results are shown precisely in table-2. By a number of trail runs it is found that the peak of the various modes occurs at the following compensation level.

Mode	4	3	2	1
X_c / X_e(%)	26.4	40.71	54.28	67.14
X_c (p.u.)	0.185	0.285	0.380	0.470
W(rad/s)	202.1	160.1	126.8	98.2
f(Hz)	32.2	25.5	20.2	15.6

The torsional mode characteristics are drawn by plotting the real parts of the eigen values corresponding to the modes versus the percentage of X_c / X_e and is presented in figure-10.

It is equally important to note the variation in the electrical system oscillation mode. With no line series capacitor compensation, the electrical system oscillation model occurs at the synchronous frequency (377 rad/sec). By changing the line series capacitor compensation level the eigen value corresponding to the system electrical mode is found to be changed. The electrical mode characteristics are obtained by plotting the real part of the Eigen values corresponding to the electrical mode versus percentage of X_c/X_e. It is also found that as the series compensation level increases, oscillation frequency of electrical mode approaches and passes those of the torsional mode frequencies of the mechanical system. SSR is denoted when a resonance of the electrical mode nears or coincides with one of the torsional modes. Afterall the modes have passed and at about 90% or more level of capacitor compensation the electrical system mode starts to show its own instability which is indicated by the presence of positive real part of Eigen value corresponding to the electrical mode.

3.1.3 Damping of undamped modes using SVC

For this project a SVC is adopted to damp out the undamped modes. Hence the system matrix ‘A’ is found out from the 28-linearised differential equations as discussed earlier, after incorporating the SVC to the power system and taking the various practical values of K_C, T_C, K_W, K_F, T_F, B_C, B_L. Now this system can give various damping levels to the undamped modes from which the optimum level for particular series compensation can be found out by a number of trail runs. Mechanical damping is assumed to be zero. In this way although all the torsional modes are damped out still some eigen values are left with positive real parts at supersynchronous frequency. So effort is made to make the whole system eigen values negative and hence assuring the system stability. For that purpose a small mechanical damping of 0.01/0.1 is taken for the system since all the systems have inherent damping.

3.2 TRANSIENT STABILITY PERFORMANCE

Unlike the eigen value analysis in which a linearised system mode is used, computer simulated dynamic performance tests are performed on the nonlinear system model itself. The non-linear system model is described by a set of 20 differential equations for the system without SVC and a set of 28 differential equations for the system with SVC.

3.2.1 Observation of Torsional Oscillations

A pulsated disturbance of 20% of actual value for 0.2 second is assumed for the test at various conditions. Typical response of the system at 50% capacitor compensation level is observed. The system is subjected to a mechanical as well as an electrical disturbance of the above specification at different time. The mechanical disturbance is assumed to take place by an increase in steam pressure of 20% to the HP turbine for 0.2 second. But the electrical disturbance is assumed to take place temporarily at the generator bus by a sudden collapse of the voltage by 20% for 0.2 second.

The above faulty conditions are applied to the system nonlinear model without SVC. Typical responses of the system variables are plotted against time. The response of the system without SVC has an unstable tendency and continuously growing oscillatory intermediate shaft torques. The phenomena of torsional oscillations are also observed by the frequent reversal of the intermediate shaft torque about the operating point. The response curves are shown in the graphs given below.

3.2.2 Damping of torsional oscillations (with SVC)

The same faults are applied to the system non-linear model with SVC to study the response of the system under such conditions. The results show, that the system tries to oscillate following the disturbance but subsequently stabilised within 2-3 seconds. From that nonlinear system dynamic simulation, it can be observed that the SVC is very much effective in damping the torsional oscillations. Following the fault the SVC starts to excite from its initial state and supplies the reactive power demand there by damping the oscillations and finally comes back to its previous state once again as the oscillation is suppressed. The typical response curves are shown in graphs given below for the mechanical and electrical fault respectively with one to one correspondence to the system without SVC. All the response curve in both the cases are shown for a capacitor compensation of 50% and the generator is delivering Pg = 0.9 p.u. at 0.9 power factor. Since all the systems have inherent damping, a mechanical damping of 0.01 p.u. is taken for all masses to improve the response of the system.

SVC capacitor:

$PV_d = W_0/B_c\, I_d - W_0/B_c\, I_{nd} - W_0/B_c\, I_{ld} + V_q\,(2W-W_0)$

$PV_q = W_0/B_c\, I_q - W_0/B_c\, I_{nq} - W_0/B_c\, I_{lq} + V_d\,(2W-W_0)$

SVC inductor:

$PI_{ld} = W_0\,(B_c - B_s)\, V_d + (2W-W_0)\, I_{lq}$

$PI_{lq} = W_0\,(B_c - B_s)\, V_q + (2W-W_0)\, I_{ld}$

RESULTS

EIGEN VALUE ANALYSIS OF MECHANICAL SYSTEM

1.0e+002 *

0.0000 + 2.9818i

0.0000 - 2.9818i

-0.0000 + 2.0285i

-0.0000 - 2.0285i

-0.0000 + 1.6052i

-0.0000 - 1.6052i

-0.0000 + 1.2681i

-0.0000 - 1.2681i

-0.0000 + 0.9871i

-0.0000 - 0.9871i

0.0000 + 0.0456i

0.0000 - 0.0456i

EIGEN VALUE ANALYSIS OF THE MECHANICAL SYSTEM(D=.001)

The eigen values are:

-0.0069 + 2.9818i

-0.0069 - 2.9818i

-0.0016 + 2.0285i

-0.0016 - 2.0285i

-0.0063 + 1.6051i

-0.0063 - 1.6051i

-0.0247 + 1.2677i

-0.0247 - 1.2677i

-0.0056 + 0.9872i

-0.0056 - 0.9872i

0.0039 + 0.6790i

-0.0039 – 0.6790i

EIGEN VALUE ANALYSIS OF THE SYSTEM WITHOUT SVC AT PC=40.71%

WO=377.00

PF=0.90

PC=40.71

PO=0.900

QO=0.4359

XC=0.2850

THETA=0.4510

DELTA= 1.1497

EDDD= 0.5840

EQDD=0.8746

EDD= 0.5732

EQD= 0.9059

VCD= 0.1102

VCQ=-0.2628

VB= 0.8703

The eigen values are

1.0e+002 *

-0.2500 + 3.4587i

0.2500 – 3.4587i

-0.1453 + 4.9074i

-0.1453 - 4.9074i

0.0015 + 2.9818i

0.0015 - 2.9818i

0.0005 + 1.9686i

0.0005 - 1.9686i

0.0066 + 1.7779i

0.0066 - 1.7779i

0.0029 + 1.5604i

0.0029 - 1.5604i

0.0005 + 1.2571i

0.0005 - 1.2571i

0.0008 + 0.7965i

0.0008 - 0.7965i

-0.9124 + 0.3675i

-0.9124 – 0.3675i

-0.5110 + 0.3384i

-0.5110 - 0.3384i

-0.0098 + 0.0086i

-0.0098 - 0.0086i

EIGEN VALUE ANALYSIS OF THE SYSTEM WITH SVC AT PC=40.71%

WO=377.00

PF=0.90

PC=40.71

PO=0.900

QO=0.4359

XC=0.2850

DELTA= 1.1964

EDDD= 0.5840

EQDD=0.8746

EDD= 0.5732

EQD= 0.9059

VB= 0.7735

VF= 2.4008

BS=0.2500

The eigen values are

-5.1456 – 0.0000i

-1.4467 - 3.2069i

-1.6358 + 0.0000i

-1.4467 + 3.2069i

-1.4467 + 3.2069i

-17.2313+0.0000i

-32.9714+0.0000i

-33.3928-14.6402i

-33.3928+14.6402i

-53.9221 + 0.0000i

-28.9234-122.0517i

-67.2549-106.0001i

-5.8163 - 160.3983i

-28.9234+122.0517i

-67.2549+106.0001i

-5.8163 + 160.3983i

11.7918 - 201.2496i

-11.7918+201.2496i

-66.7381-285.9112i

-1.9102 - 374.5915i

-66.7381+285.9110i

-1.9102 + 374.5915i

-6.4150 - 593.2465i

-52.1130+ 562.1400i

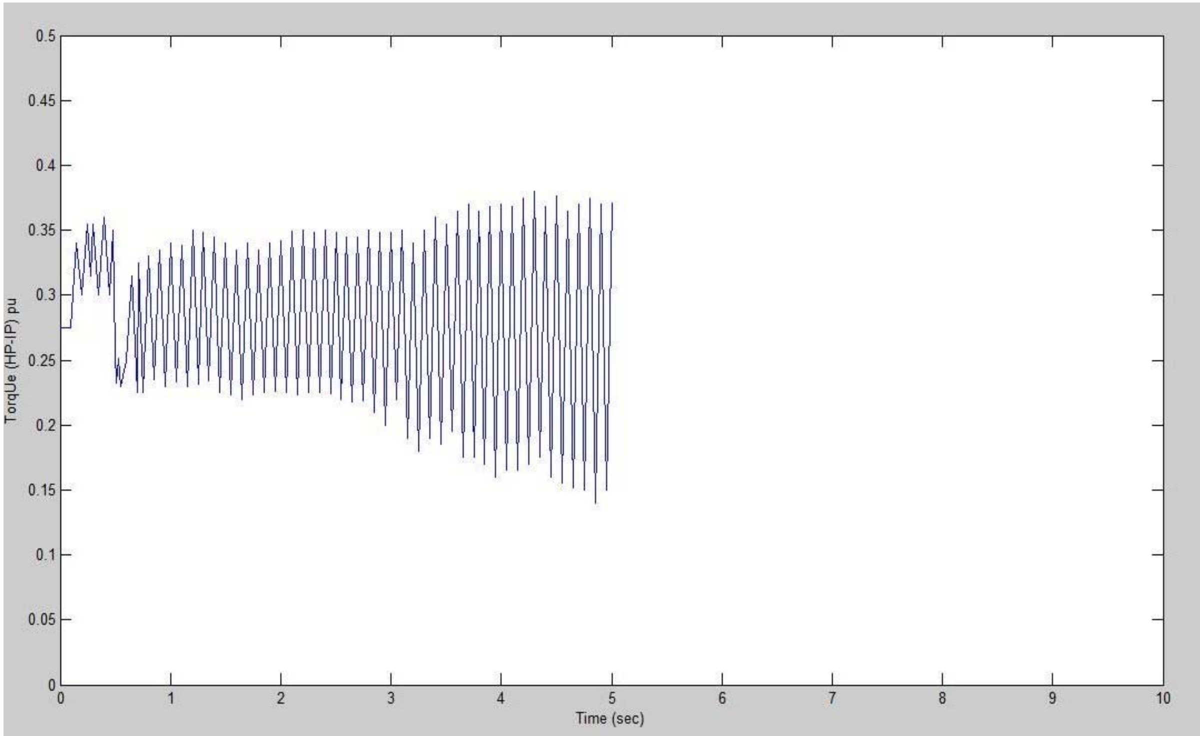
-6.4150 + 593.2465i

-1.8183 -1102.5782i

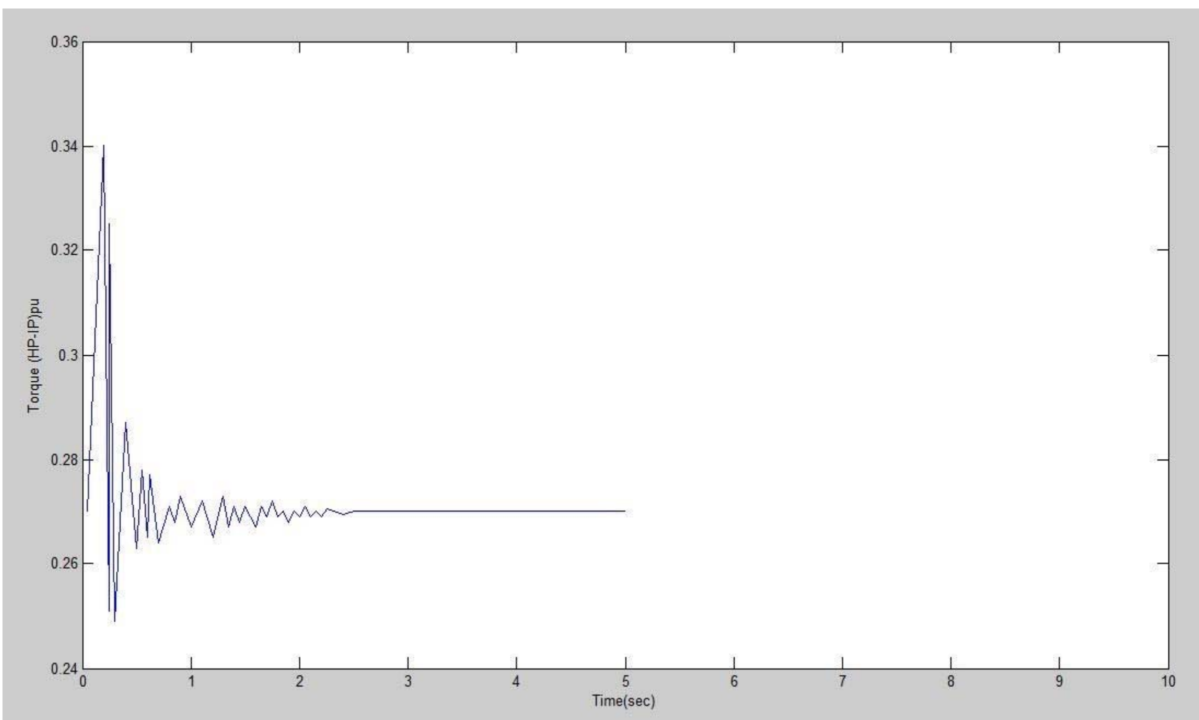
-1.8183+1102.5782i

-2.2642 -1890.7434i

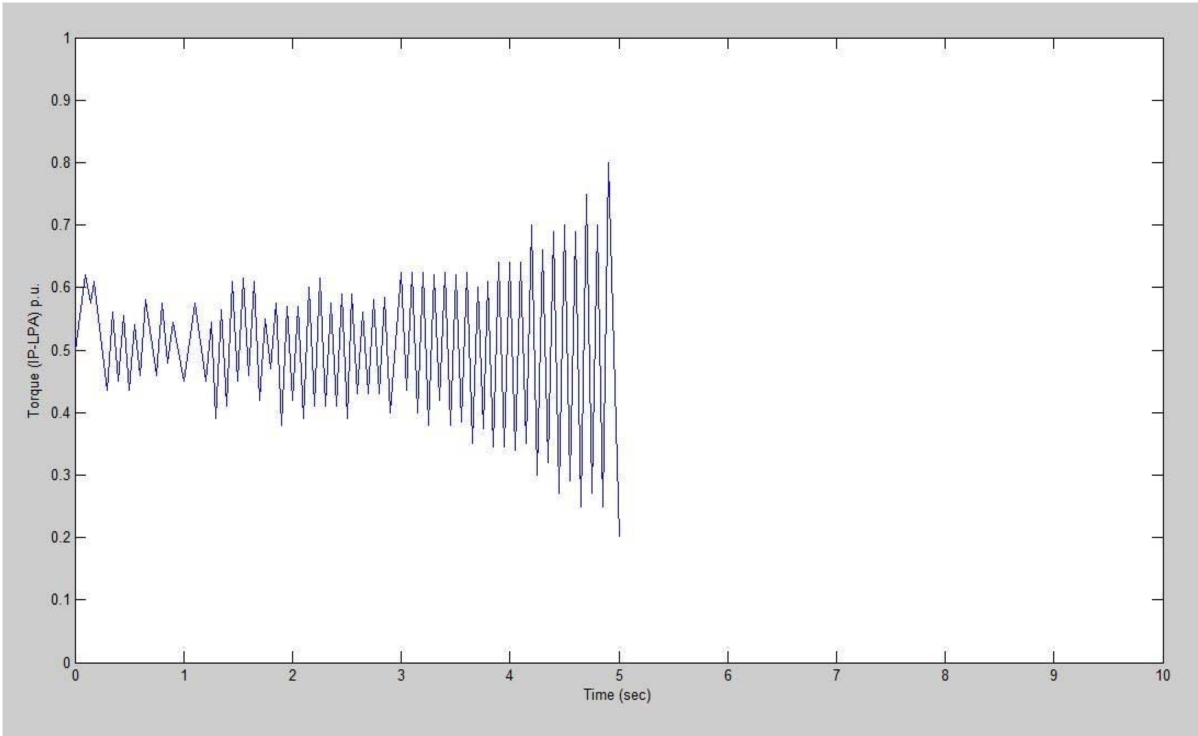
-.2642 + 1890.7434i



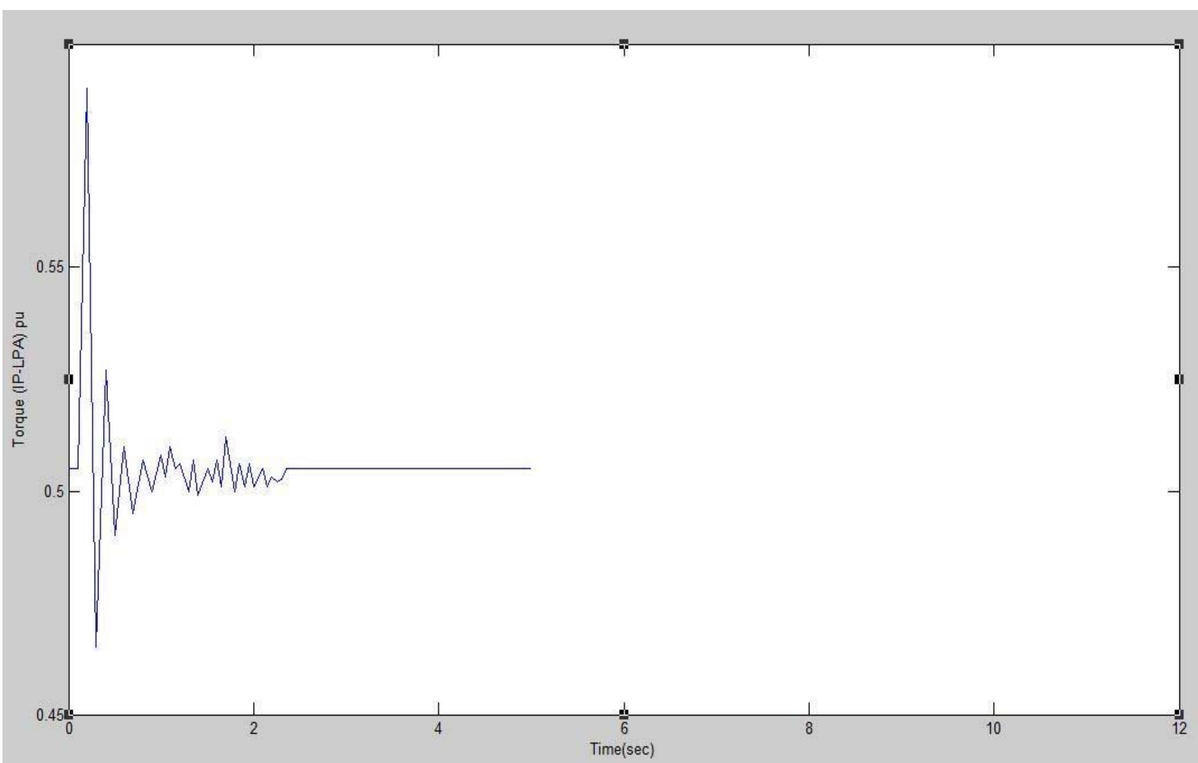
Torsional oscillations of the mass-spring system without control, PC = 50% (Mechanical fault)



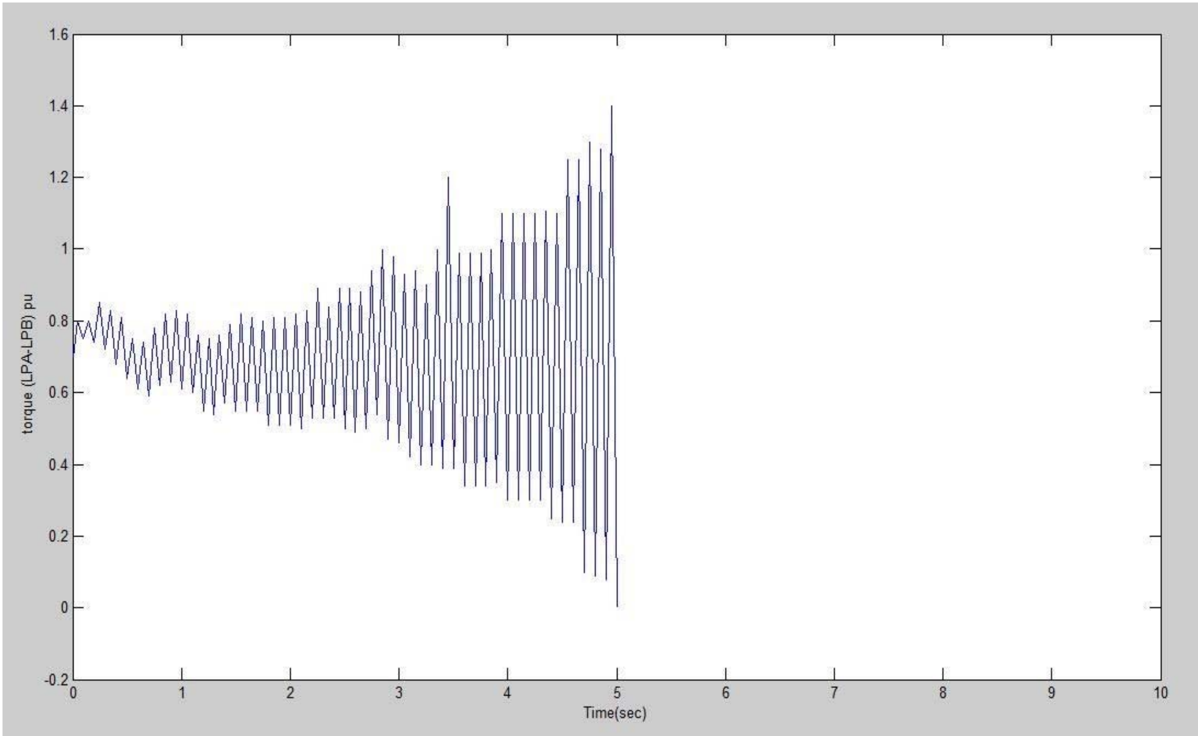
Torsional oscillations of the mass-spring system with SVC control (mechanical fault)



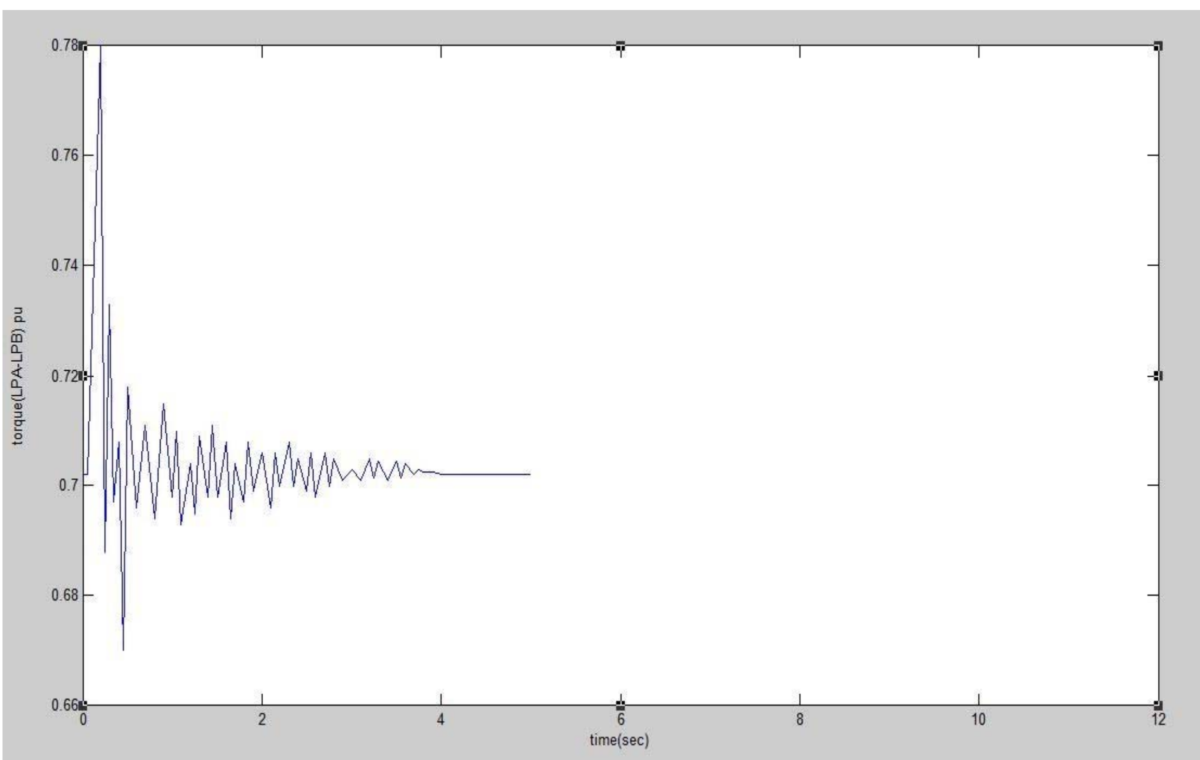
Torsional oscillations of the Mass-spring system without control, PC = 50% (Mechanical fault)



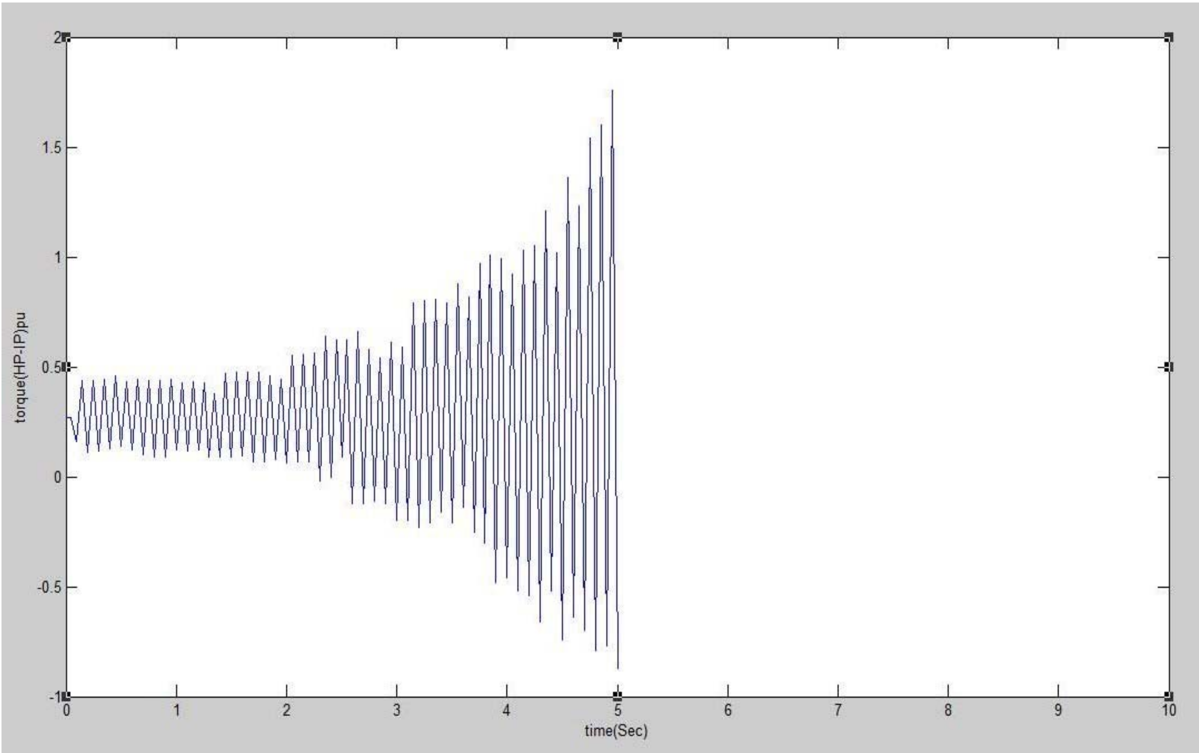
Torsional oscillations of the mass-spring system with SVC control,PC = 50% (Mechanical fault)



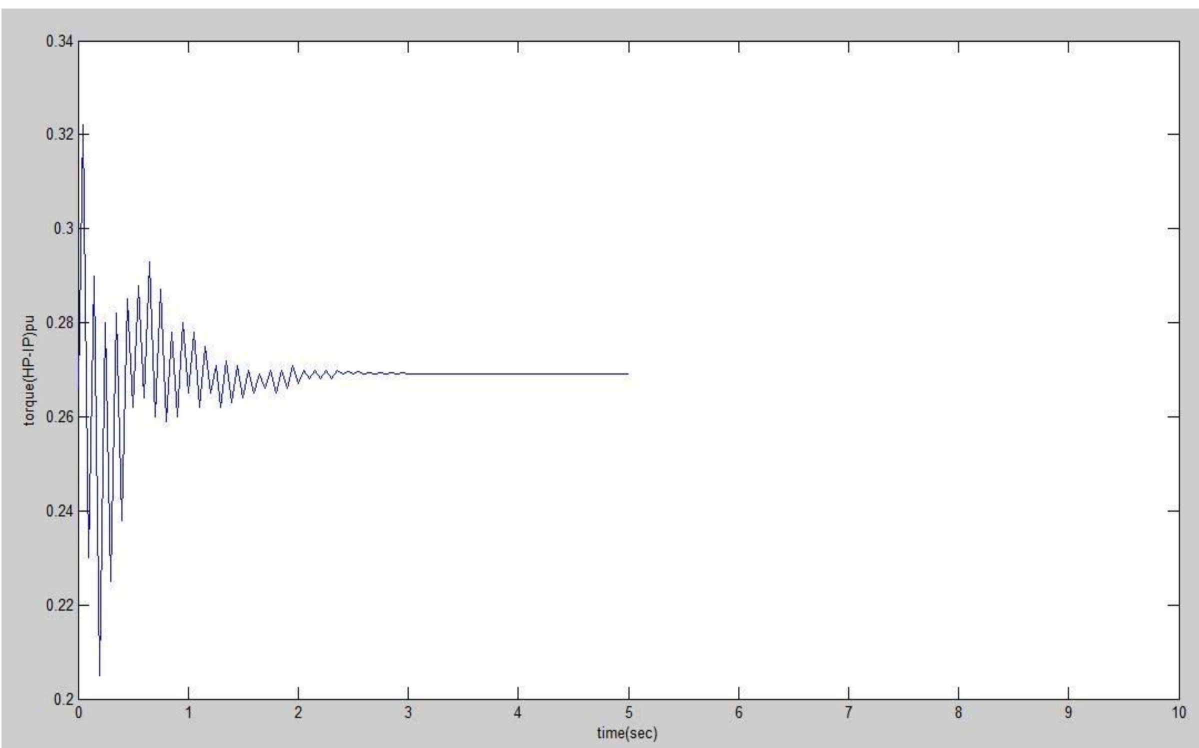
Torsional oscillations of the mass-spring system without control, PC=50% (Mechanical fault)



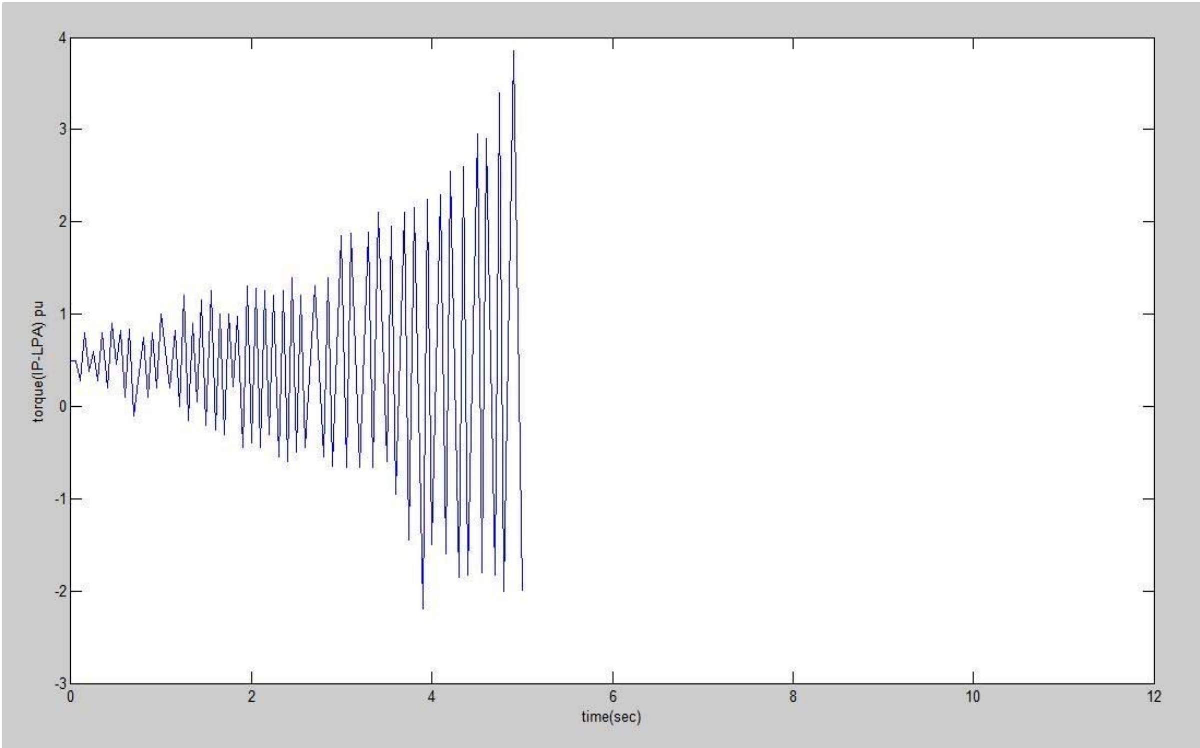
Torsional oscillations of the mass-spring system with SVC ,PC=50% (Mechanical fault)



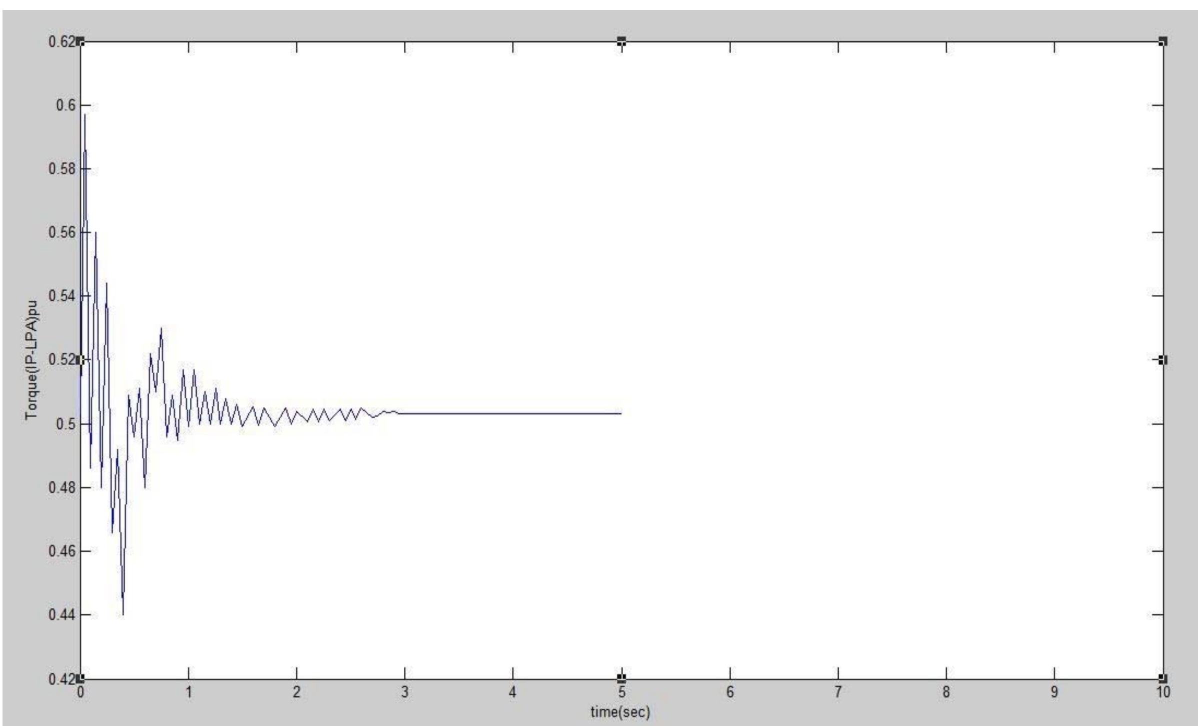
Torsional oscillations of the mass-spring system without SVC,PC=50% (Electrical fault)



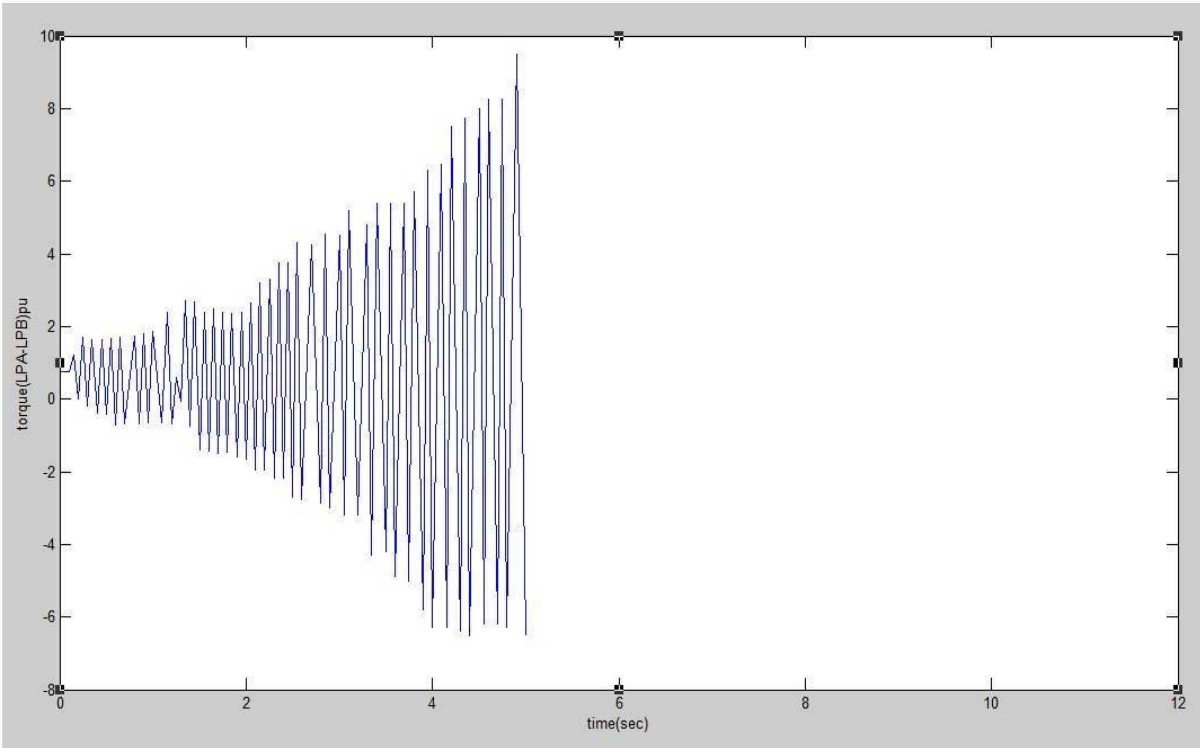
Torsional oscillations of the mass-spring system with SVC,PC=50% (Electrical fault)



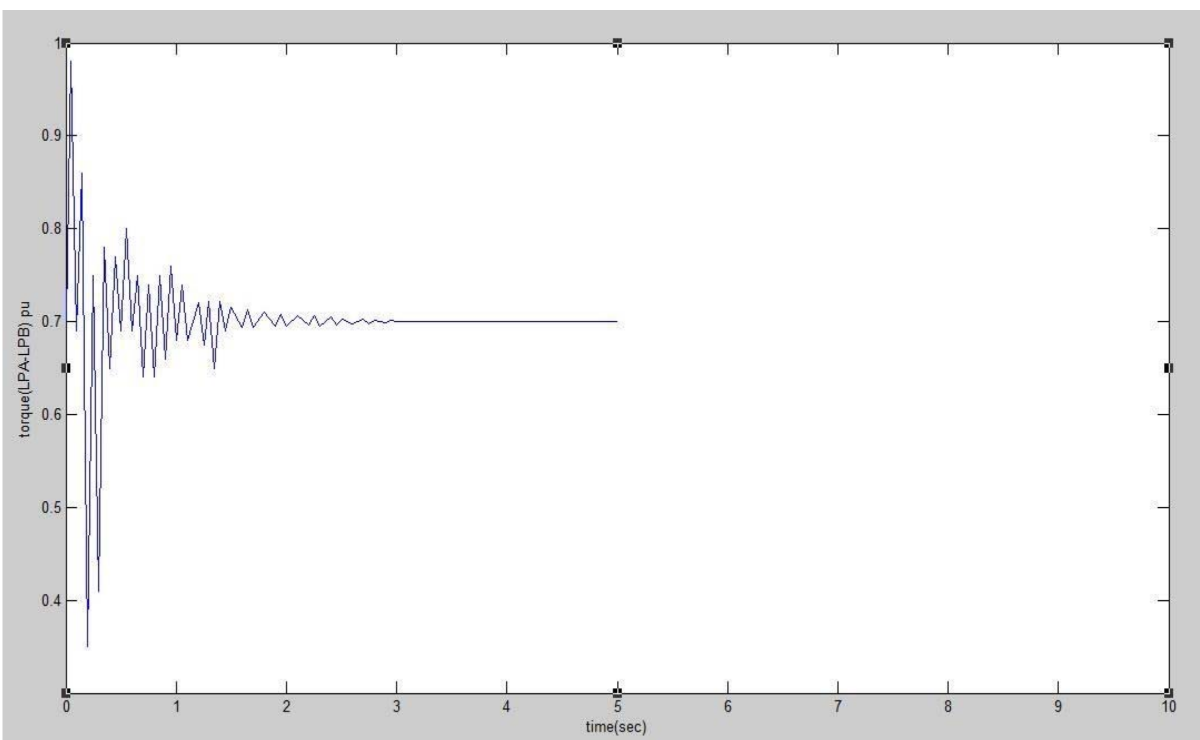
Torsional oscillations of the mass-spring system without SVC,PC=50% (Electrical fault)



Torsional oscillations of the mass-spring system with SVC ,PU=50% (Electrical fault)



Torsional oscillations of the mass-spring system without SVC,PU=50% (Electrical fault)



Torsional oscillations of the mass-spring system with SVC, PC=50% (Electrical fault)

CHAPTER 4

DISCUSSION AND CONCLUSIONS

DISCUSSION AND CONCLUSION

Due to the overgrowing demand of electric power utility it is felt necessary to supply the consumer with his demand of power at a lesser cost. The cost of power supplied to the consumer takes into account the initial investment and the running cost of the whole power system. Out of these initial investments the installation cost of the transmission system requires a huge percentage of the total investment. Hence it is felt necessary to transmit large amounts of power on a transmission line from its usual capacity. Efforts on this area brought the solution to compensate the inductive reactance of the line by a series capacitor thereby increasing the power transfer capability. Subsequent implementation of this idea brought into light a new phenomenon called subsynchronous resonance, which poses a threat to the fatigue life of the rotor shaft.

Subsynchronous resonance is nothing but the result of an interaction between the electrical power system and turbine generator mechanical system. Series compensated transmission line is the main source of such adverse effect. Hence counter measures are suggested to damp out such torsional oscillations which occur in series capacitor compensated power systems following a system disturbance.

To study the torsional oscillation problems and further to suggest countermeasures of such problems it needs an accurate system modelling. In this study a SVC is adopted to damp out the torsional oscillations of the power systems. The system is modelled without and with SVC to observe the phenomena of torsional interaction and subsequently how it is damped out by the SVC. All modes method of system modelling is adopted for the study with the data taken from the First Benchmark Model. The mechanical system is represented by a six mass-spring model, generator by a subtransient machine model and transmission line by a simple radial RLC circuit.

Eigen value analysis is done first, by taking the linearised model of the system around the steady state operating point. The torsional mode characteristics of the system are found out for different capacitor compensation level. The variation of electrical modal characteristics is also observed. Further an Eigen value analysis is performed on the linearised system model having a SVC. It is found that the SVC can effectively damp out the oscillating modes. But at that time it is observed that some of the eigen values have positive real parts at super synchronous frequency. So to place all the eigen values of the system in the negative half of the s-plane a very small mechanical damping of 0.1 p.u. is taken for all masses. It is also in agreement with the practical case that all systems have inherent damping. At various level of series compensation the values of the peaks don't observed to vary appreciably with varied load condition.

Next a pulsated torque disturbance and a temporary electrical disturbance of 20% for 0.2 seconds each is chosen for the test. The result shows that the system without SVC is highly unstable with growing shaft torque oscillations where as the system with SVC has stable operation within 2 to 3 seconds.

Again a major electrixal as well as a mechanical disturbance of 0.2 sec is applied separately to each model once for electrical disturbance and next for mechanical disturbance. Here also the system without SVC is highly unstable with growing oscillation of shaft torques. But the system with SVC ensures stable operation within 5 second by damping out the torsional oscillations. For the transient performance studies with SVC a very small mechanical damping of 0.01 p.u. is taken for all the masses to improve the response of the system. It is also in agreement with the practical cases. Since all the systems have some inherent damping.

A more accurate model of the whole system should be simulated for further studies which should adequately represent the system for better system study. An adaptively tuned SVS controller may be designed which will be more effective in damping the torsional oscillations.

By performing the Eigen value analysis on the 12*12 matrix 'A', which is obtained by considering the mechanical system alone gives the modal frequencies of the modes of the system in the imaginary parts of the Eigen values. The real parts of the Eigen values are found to be zero. By considering a small positive value of damping constant D for all six masses, the real parts of the Eigen values become negative, which indicates stability of the system.

The electrical mode characteristics are obtained by plotting the real part of the Eigen values corresponding to the electrical mode versus percentage of X_c/X_e. It is also found that as the series compensation level increases, oscillation frequency of electrical mode approaches and passes those of the torsional mode frequencies of the mechanical system.

Afterall the modes have passed and at about 90% or more level of capacitor compensation the electrical system mode starts to show its own instability which is indicated by the presence of positive real part of Eigen value corresponding to the electrical mode.

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