STUDY OF FORCED OSCILLATIONS IN TWO AREA POWER SYSTEM

A DISSERTATION
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OF

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IN
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Submitted by:

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I **Vertika Jain**, Roll No. **2K16/PSY/21** student of M.Tech (**Power System**), hereby declare that the project Dissertation titled **"STUDY OF FORCED OSCILLATIONS IN TWO AREA POWER SYSTEM"** which is submitted by me to the Department of Electrical Engineering under the supervision of Dr. S.T. Nagarajan(Professor) and Dr. Rachna Garg(Professor), Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

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CERTIFICATE

I hereby certify that the Project Dissertation titled **"STUDY OF FORCED OSCILLATIONS IN TWO AREA POWER SYSTEM"** which is submitted by **Vertika Jain**, Roll No. **2K16/PSY/21** student of M.Tech (**Power System**) to the Department of Electrical Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the student under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

Place: Delhi
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ABSTRACT

The demand for electricity is increasing day by day leading to integration of renewable energy and increasing stability problems in the power grid. In today's scenario, small signal stability has been become an area of great interest for the researchers in dealing with stability problems of the power grid. The approach to study poorly damped low frequency oscillations for electromechanical modes is based on two different methods: Modal analysis method in power system depends upon linearized equations of system model, and Measurement based methods that are useful for monitoring power system oscillations in real time from Phasor measurement Units (PMU). Ring down analysis and ambient data analysis are the two different approaches under the measurement based method. Ring down analysis is preferred for sudden large disturbance when subjected in power system, whereas ambient analysis is observed when the power system is subjected for small continuous random fluctuations in loads and its operation is considered when it is in Quasi-Steady state. In the recent past years, with increased installation of PMUs in power grids, modal analysis techniques which are based on real time measurement data from the PMU is a preferred method for stability analysis of power system.

Apart from natural electromechanical modes which are operated by load variations in power system the electromechanical modes can be excited by forced oscillations from apparent mechanism serving as from cyclic loads or mechanical aspects of generators. They can have adverse effects on system by resonance, named as forced resonance oscillations. When the forced oscillation frequency is close to system mode frequency or Inter area mode whichever poorly damped at location for which Inter area mode is associated, system oscillations at much higher value, as compare to source can appear leading to collapse of the system.

This dissertation studies a recent event in power system installation during summer season of 2013 reported several instances for the damping level of 0.37Hz, inter area mode of western power grid obtain below 3% for several hours. The present work deals with the study about forced oscillations in power system with the popular Kundur's two area test system. The test system consists of 12 buses illustrates WECC transmission system for simulation and its transient stability and its long term dynamics. Here dissertation gives a complete description of modelling a forced oscillation from

governor of generator in two area system leading to Interarea resonance in the tie lines. Further, this work compares the PMU based measurement techniques of ring down method: Prony Analysis method and ambient method: Frequency domain decomposition (FDD) method to detect the presence of forced oscillation in power system

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CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

For any power system operations and for its reliability it is necessary to have knowledge and estimation of electromechanical oscillation at low frequency. For reliable operation of such mode estimation we have two different methods:

i. Using a power system model
ii. Linearization of equations at point of operation about an equilibrium [4] or using mode estimation method for determination [5] [6].

Block processing and recursive method are the two different approaches for the measurement phenomenon.

In Block processing methods for the mode estimation it uses a specified size time window and for new estimation autonomously window is continuously updated,

In Recursive methods, for every new sample estimated modes are updated or by combining the previous estimation and the new sample of a specified size estimated modes are updated. Ring down and ambient data are the two different forms of measurement data. For any power system response to sudden change or disturbance its measurement is **ring-down data** such as tripping of line or outage of generator which consequentially results in excitation of oscillatory modes. For any power system operating in quasi-steady state condition whereas the system input is from small continuous random oscillations in loads and other system fluctuations which are assumed to be white noise is measurement based of **ambient data**. The algorithms which are quite useful that applied on ambient data as they act as non-intrusive measurement and ambient data is well known existing through Wide Area Measurement Systems-(WAMS) [5] [6]. So far, various methods have been developed by researchers [7]. In block processing methods to identify modes in frequency domain, Frequency Domain Decomposition (FDD) [6] has been established for power system mode estimation. As block processing methods to identify modes in time domain describes Modified Extended Yule Walker (MEYW)

[8]. Similarly in time domain to estimate mode frequency and damping another method have been developed is Subspace identification method [9]-[12]. To overcome the drawbacks of block processing methods recursive methods have been developed as Robust RLS [13] and Regularized Robust RLS [14] based on recursive identification of ARMA blocks. Its speed of computation of data by updating the previous estimation through the new sampled data with its factor is its main advantage and it uses less memory for storing the data [13].

1.2 POWER SYSTEM OSCILLATIONS CLASSIFIED BY INTERACTION CHARACTERSTICS

Various types of sub synchronous frequency oscillations have been analyzed in electric power utilities (Kundur, 1994):

- Local plant mode oscillations
- Inter-Area mode oscillations
- Torsional mode oscillations
- Control mode oscillations

Oscillations associated with the units of generating station with respect to the entire power system and these are commonly associated oscillations and are known as **Local plant mode oscillation** [3]. These types of variations originate by action of Automatic voltage regulators of generating units operating at high output and providing into the weak transmission networks; this problem is more prominent with high response excitation systems. These types of oscillation have typically range about 1 to 2 Hz. By using the supplementary control of excitation system in form of PSS (Power System Stabilizers) adequate damping can be promptly establish and can be well defined by these systems.

Oscillations associated with one part of the machine with respect to the other parts of the machine are known as the **Inter-Area mode oscillation** [3]. These types of oscillations are affected by two or more groups of closely coupled machines being interconnected by weak tie lines. These types of oscillation have typically range about 0.1 to 1 Hz. Nature of the inter-area modes of oscillation are more complex as compare to other modes of oscillations like the characteristics of local plant modes.

Oscillations linked with the rotational components of turbine generator are known as **Torsional mode oscillation** [3]. Due to interactions with generating unit and prime mover controls there have been several mode of instability of torsional mode:

Excitation control of torsional mode oscillation was first analyzed in 1969 during the application of power system stabilizers at Lambton generating station in Ontario on a 555MVA fossil fired unit. On the generator side of the shaft was found to excite the minimum torsional (Hz) for the speed measurement by PSS which uses the stabilizing signal.

Oscillations linked with the controls of generating units and other equipment of the power system are knows as Control mode oscillations [3]. Inadequately tuned control of excitation system, SVC, prime movers and HVDC converters are the main reason for the cause of disturbances or instability of control modes.

1.3 POWER SYSTEM STABILITY

Ability of an electric power system to regain state of equilibrium, when subjected to a physical disturbance, for a given initial operating conditions, so that practically entire system remains unimpaired when most of the variables of system are bounded in known as the power system stability[1].

1.4 STABILITY CLASSIFICATION

Power system stability classification is based on the following considerations [2]:

i. Depends upon physical nature of resulting mode of instability that was indicated by main system components in which the disturbance or instability can be observed.
ii. Depends upon the size of disturbance evaluate which regulate the method of calculation and prediction of stability.
iii. Depends upon the system processes and in order to evaluate stability time span needed be taken into consideration.

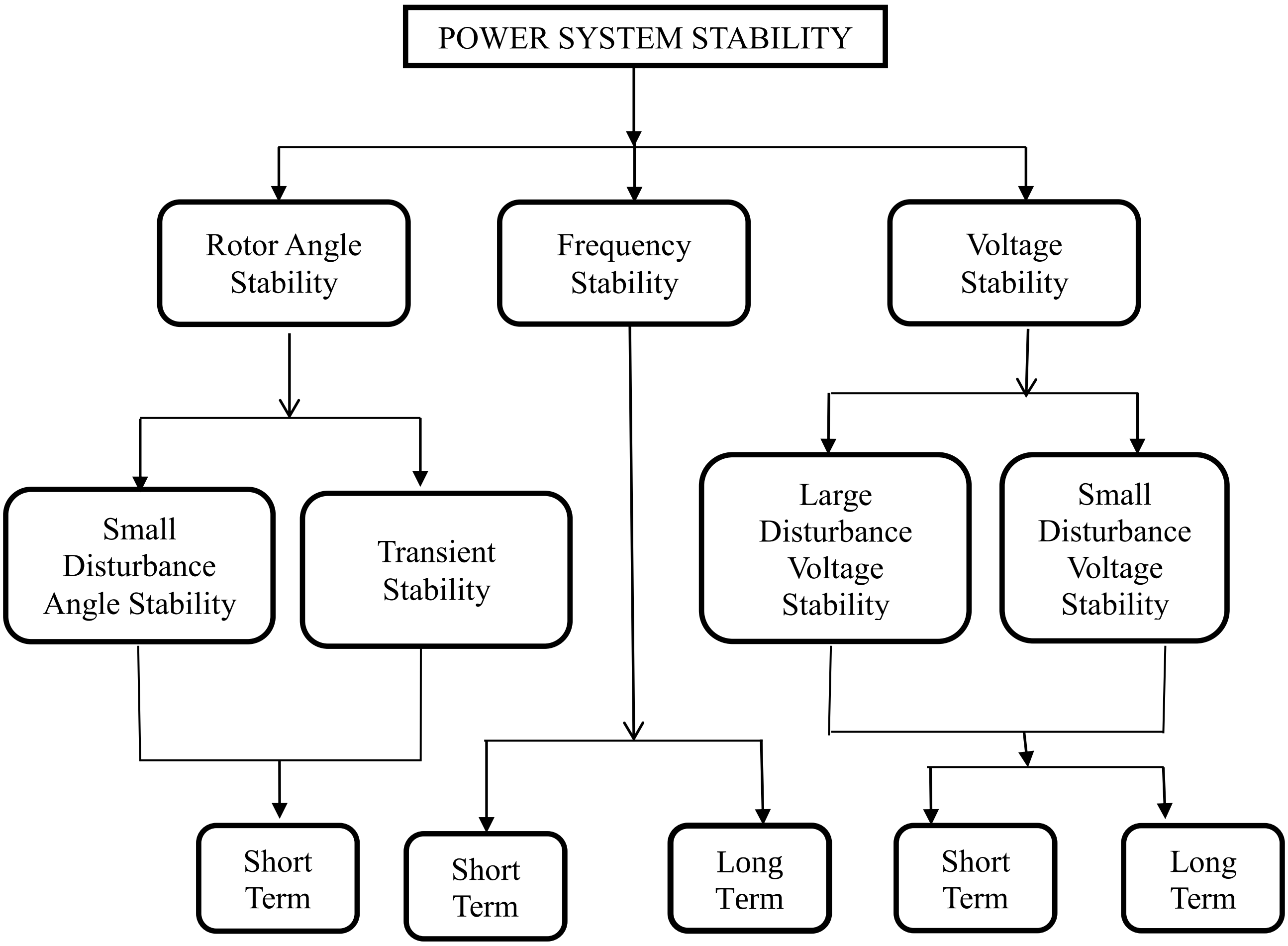


Figure 1-1 Stability Classification

1.4.1 Rotor Angle Stability

In an interconnected system ability of a synchronous generator to persist synchronism after being subjected to disturbances. For a machine to maintain equilibrium between electromagnetic torque and mechanical torque for the steady sate condition its ability of each synchronous machine in the system for a constant speed. This type of disturbances occurs in form of swings of the generator rotor which leads to loss of synchronism. Rotor angle instability includes the study of electromechanical oscillation built-in power systems. In this method power output of synchronous machine changes as there rotor angle varies its main fundamental factor for this instability. If any system loose synchronism this equilibrium varies then the law of motion says of a rotating body then the rotors of a machine will accelerate or decelerate. For any instant one generator runs with more speed as compare to the other generator than the angular position of the slower machine will increase. As a result load of the slower machine will transfer to the machine running at higher speed as depending upon the power angle relationship. Hence the angular separation and the speed difference are reduced. For an increase of angular separation beyond any certain limit results in decrease of power transfer so that the angular separation can further increases [2].

These issues can disturbance caused due to change in electromagnetic torque can be overcome by these two components

Synchronizing-Torque component, which is in phase with rotor angle variation.

- Damping-Torque component, which is in phase with speed variation.

Synchronous machine stability depend upon the existence of both the components of torque, for insufficient synchronous torque leads to non-oscillatory or aperiodic unstable system and for insufficient damping torque component leads to oscillatory unstable system.

1.4.1.1 Small Disturbance Rotor Angle Stability

Small disturbance voltage or rotor angle variations are the causes for Small disturbance stability. For considering the linearized system these disturbances are sufficiently small. Small incremental load variations, small control variations etc. are the main causes for small disturbances. Disturbances due to faults or short circuits do not come under this category. System equations are linearized within permissible limit for the purpose of analysis for which the system disturbances are considered small [4], [15], [16].

- For any system small disturbance rotor angle stability depend upon the initial operating state. There are two forms of instability: i) Lack of synchronizing torque give rise to increase in rotor angle from an aperiodic or nonoscillatory mode. ii) Due to insufficient damping torque oscillations of rotor with increase amplitude.

- In today's scenario of power systems, due to insufficient damping of oscillations leads to small disturbance rotor angle stability. Issues like aperiodic stability can be remove by use of voltage regulators acting continuously, these types of issues can still occur when subjected to field current limiters with constant excitation.
- Small disturbance rotor angle stability issues could be local or else could be global in nature. Oscillations associated with rotor angle for small section of power system in comparison to the entire system is known as Local plant mode oscillations. Strength of power system transmission as recognize by power plant, generator excitation, control systems depend upon the damping of oscillations. Issues related with widespread effects and interaction among large group of generators is considered to be Global problems. It includes oscillation associated with large group of generators in one area with the group of generators of other area. These types of oscillation are called **Interarea mode oscillations**. They have complex load characteristics as compare to other mode of oscillations and differ from local mode oscillations.
- In small disturbance stability studies time frame is of order 10-20seconds for an oscillation.

1.4.1.2 Transient Stability or Large Disturbance Rotor Angle Stability

These types of stability are associated with large system oscillations or system with major disturbances. To maintain synchronism for these types of oscillation when associated with severe disturbances is known as transient stability or large disturbance rotor angle stability.

Transient stability depends upon the factors like severity of the disturbances and its initial operating conditions. Lack of synchronizing torque leads to aperiodic angular separation in these types of instability as a result of it indicates its first swing instability. However for large power systems in relation with single mode may not fall as first swing.

- In large disturbance stability studies time frame is of order 3-5seconds and for very large systems it may extend upto 10-20seconds.

1.4.2 Voltage Stability

When a system is subjected to disturbance, to maintain stability at all buses of power system at given initial operating conditions is known as Voltage Stability. It depends upon the ability of a power system to maintain equilibrium at a given load and load demand of power system. An effect of voltage instability leads to amount of load loss within an area, fall off transmission lines and protective system elements make of cascading outages. From these types of outages or initial operating conditions that disrupt field current limit leads to loose synchronism of generators of that area in power system [17].

Rotor angle instability leads to continuous drop in bus voltages. As we have seen rapid drop in two groups of machine voltages about 180° of rotor angle leads to loss of synchronism of machines in between the points of network near to electrical center [4]. Typically, protective systems recover the voltage levels depending upon the post separation conditions and separation of two groups of machines. If such a condition does not appear then oscillation of voltages varies from high and low values near the electrical center as a result of it "pole slips" repeated between groups of two machines, in comparison when rotor angle stability is not a problem then sustained drop of voltage associated with voltage instability affect load.

As the term voltage collapse generally used, which is a process of sequence of events with voltage instability give rise to blackouts or fluctuating voltages in part of power system [4] [18] [19]. When transformer tap changer attain their boost limit including intended and/or unintended tripping of load. Rest of the load approaches to be voltage sensitive, for which the associated demand at normal voltage does not carry out.

The driving force is usually the loads for voltage instability; respond to disturbances, by the adjustment of motor slip action tends to restore the power consume by the loads. As the reactive power consumption increase leads to decrease in voltage reduction due to which stress on high voltage network increases because of restored loads. Decay in voltage causing voltage instability appears when load dynamics try to bring back power consumption beyond the capacity of transmission network and connected generation [4] [18] [19]. A considerable amount of voltage drop occur when power flow of active and reactive power is the major factor for voltage instability of transmission network through inductive reactance; this also limits transfer of transmission network power and voltage support. When generators with the field current or armature current hits time overloading capability limits transfer of power and voltage support. When reactive power increases beyond the certain capability due to increase in load leads to cause of voltage instability. A continuous drop of bus voltages leads to the risk of overvoltages and one of system may experience this effect of instability. It gives rise to the capacitive behavior of network in addition to under excitation limiters restrict generators from absorbing excess reactive power and/or from synchronous compensators. In this case instability is linked with the incapability of combined generation, transmission network to act over some load level. For restoring these load power, tap changing of transformers leads to *long term voltage instability*.

Voltage stability issue may also be observed for applications like long distance or back-to-back at the terminals of the HVDC links [20] [21]. They are usually connected from HVDC links to weak connected AC systems and may exist at rectifier or inverter stations. They are also linked from load characteristics of reactive power under adverse conditions, on these types of issues HVDC link control method plays very significant role since active and reactive power at the junction of AC/DC are determined by the controls. If the transmission system loading increases from its certain capacity, this leads to increase in voltage instability. This process is comparatively faster as the time frame is of order one second or below. As voltage instability is also linked with tap changer control of transformers which is again a slow phenomenon [20]. HVDC technology development leads to significantly increase the limits for stable system operation as compared for HVDC links for line commutated converters within the limits.

Due to voltage instability issues give rise to uncontrolled overvoltage for the synchronous machines with self excitation. This can happen if capacitive load is too large of synchronous machine. As in the case of capacitive loads as in this it can initiate at open ended high voltage transmission lines, shunt filters as well as filter banks at HVDC stations.

Similarly voltage stability is classified into following subcategories as in rotor angle stability:

1.4.2.1 Large disturbance voltage stability

The ability of a system to provide steady state voltages for subsequent large disturbances like as fault of systems, generation loss or circuit contingencies. Large disturbance voltage stability determines system and load characteristics as well as interaction of continuous and discrete system control and protection. For the observation of these type of disturbances give rise to nonlinear response examination of power system for period of time to capture the interaction and performance of such devices like motors, under load tap changing of transformers, field current, current limiters of generators. The time of frame of interest may vary from few seconds to ten minutes time window.

1.4.2.2 Small disturbance voltage stability

The ability of a system to maintain steady state voltages for a small change or incremental change in load of a system is a form of small disturbance voltage stability. At an instant of time these type of stability influences the characteristics of continuous controls, loads, discrete controls. This type of stability is useful in determining the variation in system voltage due to small changes in the system load. For relevant assumptions equation of system for analysis can be linearized through allowing computation of sensitive information for identifying the factors depending upon the stability.

As for voltage stability time frame of interest is from few seconds to ten minutes of window. Therefore, it can be further divided into short term voltage stability and long term voltage stability.

- *Short term voltage stability*: It has the tendency of component of fast acting loads like electronically controlled loads, induction motor, HVDC converters. This type of system can be solved by differential equations and they have study period of time of few seconds as in rotor angle stability.

- *Long term voltage stability*: It includes slower acting equipments like transformer tap changer, thermostatically controlled loads and current limiters of generator. This type of system requires long term simulations for calculation of performance of system dynamics [22] [23] [24]. In this case stability is analyzed by the output outage component, rather than initial disturbance of equipment.

1.4.3 Frequency Stability

It is the capability of power system to control steady frequency subsequent severe system upset occurs between generator and load overloading. It also depends upon the capability to control/restore equilibrium between the system load and generation, with minimum loss of load. Tripping of generating units or loads occurs due to sustained frequency swings causing instability or oscillations in the system.

Severe system disturbances results in form of frequency of large excursions, voltage, flow of power and many other variables of system and by invoking controls, action of processes and protections which are designed in transient stability of conventional type or study of voltage stability. As there are conditions such as boiler dynamics as well as triggered for severe system conditions due to which system may be work slowly as volts/Hertz tripping of generators for protection. For large interconnected systems these type of situation are linked as large power systems are divided into subsystems as in islands. Still stability is an issue whether an island will reach the equilibrium state of system with minimum loss of load. Therefore, determination of system response depends upon the overall system response rather than overall relative motion of machines as in islands. Generally, stability problems related to system frequency are linked from responses of equipment inability, lack of organization of control and protection devices. Such issues are elaborate in references [25]-[28].

At the same time frequency excursions all the equipment operating characteristics will operate for fraction of seconds equivalent to response of devices as in under frequency load shielding and control of generators and its protection. From Figure1 frequency stability is further classified as short term frequency stability and long term frequency stability. *Short term stability* can be explained through an example of island formation as under generated with lack of load shielding under frequency so that frequency of a system decays rapidly arising the situations like *blackout* within few seconds of an island [25]. *Long term stability* can be explained as when control of speed of steam turbines causes instability in the system due to frequency variations. The time of frame of interests for instability is from ten seconds to few minutes.

1.5 FORCED OSCILLATION IN POWER SYSTEM

The oscillation in power system has been classified into two categories i.e. free oscillations and forced oscillations. There are many algorithms that have been developed to estimate free oscillation modes in power system. Forced Oscillation is a phenomenon in power system that has been rarely seemed in the literature for the last 40years. There have been many methods recommended to detect forced oscillations and their source location. Further, forced oscillation has negative impact on estimation of its mode and its mode shape with the conditions for which they are accounted for. However to improve the reliability of power system it is necessary to differentiate between forced oscillations and free oscillations. Forced oscillations associates with system responses to external periodic perturbation. PSS (Power system stabilizer) is simple and low-cost technique to overcome oscillation by increasing damping ratio. With the operation of PMU (Phasor Measurement Unit) data, it is quite possible to monitor and record dynamic behavior of system. As one of the method for estimation of forced oscillations was proposed in 1966 [31]. It can be produced by external periodic disturbance or by mistuned generator controller. Forced oscillations are recorded as a sinusoidal signal that is originated at generator sites. The resonance between the forced oscillation and the electromechanical modes can lead to system breakdown. Sustained oscillations are imposed in power system when the system forced oscillation occurs around well damped mode. To estimate forced oscillations one should study the sources of forced oscillations in large and isolated systems. To identify these possible sources of forced oscillations help to obtain more reliable systems in power systems. Therefore, to improve the stability and reliability, locating and detecting the forced oscillations is an important aspect. Also amplitude, phase, and frequency these parameters are important parameters to analyze forced oscillations.

1.6 DISSERTATION ORGANISATION

In the first part of the dissertation (chapter 2) describes the concept of resonance and its effect in Kundur two area power system. In the next part (chapter 3) describes the fundamental description of a DIgSILENT PowerFactory. Also the basic features related to the creating of new power system are described. A detailed description of the components for the modeling of the test system. In the next part (chapter 4) of the dissertation it describes how load flow calculations have been performed in PowerFactory, also the options related to the visualization of results. Also gives a brief description about the controllers for the dynamic analysis, transient simulations and the basic study regarding the modal analysis and its stability of the system. In the last section (chapter 5) describes about the various methods and techniques that can be implemented. And then conclusion and its future scope.

CHAPTER 2

RESONANCE IN POWER SYSTEM FROM FORCED OSCILLATIONS

2.1 RESONANCE IN POWER SYSTEMS FROM FORCED OSCILLATIONS

Apart from natural electro-mechanical modes which be there excited from load variations, over and above from that forced-oscillations from external mechanism can be made into power systems such as from cyclic loads or mechanical aspects of the generators [30][31]. Natural modes of estimation are affected by the presence of forced-oscillations from some methods based on measurement estimation [32]. They can have adverse effects on generators produce by resonance among forced-oscillations. Due to widespread nature resonance in power system as forced-oscillations are more liable to inter area modes. When the system frequency is nearby system mode frequency and inter area mode is poorly damped at a location where inter area mode is associated, oscillations at much higher value as compare to source can appear leading to resonance in system. As in Western American power system can be seen in inter area modes at frequency of 0.22Hz and 0.37Hz. Therefore, when system frequency is 0.37Hz then the system is poorly damped which could be a major issue, as in western grid frequency is close to 0.37Hz in forced oscillations. This dissertation study a recent event in western American power system installation during summer season of 2013 reported several instances for the damping level of 0.37Hz, north-south inter area mode of western power grid was below 3% for several hours. A recent event in china was observed in 2005 reports 140MW tie line oscillations in which resonance appear between inter area mode and forced oscillations. Another event that took place in northern and eastern India on 30 and 31 July 2012 and that was the most severe blackout takes take and over 300 million people were affected. As it was estimated the 32 gigawatts of the generating capacity was completely cut out. It was also estimated that 27% of the energy that was generated was lost in transmission whereas 9% of peak supply was falls short of demand. The nation suffers the outage that last for 10 hours, it was the largest blackout on 31 July in the history.

2.2 BASIC CONCEPT OF FORCED OSCILLATIONS

In inter area oscillation mode corresponding to the damping ratio, the recognized oscillations doesn't have relationship with the poorly damped oscillation mode whereas they have the nature very close to forced oscillations. A process of forced oscillations which are identical to the concept i.e. proposed in physics is known as Resonance. The fundamental concept of forced oscillation has been briefly studied as follows:

- Conventional Forced Oscillation Mechanism: On single machine infinite bus system, a sinusoidal disturbance of $F_0 \sin\omega t$ is used for the analysis and in per unit system linearized rotor motion equation is given as:

$$T_J \frac{d^2 \Delta\delta}{dt^2} + D \frac{d\Delta\delta}{dt} + K_s \Delta\delta = F_0 \sin\omega t \qquad (1)$$

  Where TJ is the inertia constant, D is the damping coefficient whereas K_S is the torque coefficient of the synchronous generator; δ is the rotor angle of the synchronous machine.

  Therefore rotor angle forced oscillation can be expressed as:

$$\Delta\delta = \frac{\frac{Fo}{Ks}}{\sqrt{(1-v^2)^2 + (2\zeta v)^2}} \sin(\omega t - \phi) \qquad (2)$$

  Where $v = \frac{\omega}{\omega_0}$ and is known as frequency ratio; ζ is the damping ratio which is given as $\zeta = \frac{D}{2\omega_0 T^J}$; and ϕ is the phase difference.

  From equation-2 implies that forced frequency is equal to the system frequency when amplitude is maximum of the forced oscillation when forced frequency is equivalent to natural frequency. Under this condition for small ζ i.e. system with weak damping may give rise to forced-oscillation of high amplitude even for small cyclic disturbance, which is dangerous for power system.

  The typical forced-oscillation process shown above is the relation between forced oscillations and single frequency excitation system. It is absolutely different in real power grid of china to the observed inter area mode oscillations.

  As the active power changes with the variation in the random amplitude and small frequency band from recorded oscillations of dynamics as if these oscillations has been produce through random excitation. Time domain analysis of power system dynamics depends upon conventional mechanism. Therefore, conventional forced oscillation limits the study of observed inter area mode oscillations.

General Forced Oscillation Mechanism: The random excitation observed in frequency domain causes GFO mechanism due to forced oscillation, as time domain properties of random excitation and forced oscillation are mostly very complex. The result of this mechanism verified by simulation in 10 generator, 39 bus system. Therefore, GFO mechanism is considered for the study of oscillation observed in power grid. On the basis linear system theory, linearized power system can be designed as:

$$S_y(f) = |H(f)|^2 S_u(f) \quad (3)$$

Where H(f) is frequency domain transfer function of linear system; $S_u(f)$ is the PSD of stationary input random process; whereas $S_y(f)$ is the PSD of output of random stationary process. PSD defines how at different frequencies power of the signal is distributed. Whereas for higher order system it is problem to get the exact value of $|H(f)|^2$. To solve this issue we make use of equation (3) as it makes qualitative analysis despite of quantitative analysis. The frequency domain property of system output depends upon the input random excitation and on the squared amplitude frequency property of the transfer function.

2.3 CONCEPT OF RESONANCE

As the concept of resonance is prominent in physics. It is a tendency of a system at some frequencies to oscillate with the higher amplitude than the others [29]. System operating at natural frequencies of system for undamped or poorly damped modes will undergo resonance when subjected to external forced oscillation. The destructive behavior of resonance is strongly identified in power system in the conditions of subsynchronous resonance [33] that originate from opposing interactions from modes of electrical and mechanical torsional behavior. As in Eastern American power system sustained oscillations with higher amplitude as 280 MW were detect in June 1992 and were continue for more than 30 minutes. Issues like power quality causes problem due to oscillations in the system as they can easily damage costly power grid component.

As detecting the existence of forced oscillation and system mode interaction with it this is a challenging issue. As with the increase number of phase measurement units (PMUs) installed, i.e. easy to detect forced-oscillations and to find or analyze resonance using frame work of measurement. Some of the primary methods of detecting and locating forced-oscillations; it could be seen in [34]. This dissertation studies the effects of resonance when happen due to the effect of forced oscillations such as local vs inter area mode. This dissertation accomplishes the major analysis of interaction of forced oscillations and system mode in the context of modal properties, transient analysis of the Two Area Kundur power-system.

2.4 RESONANCE THEORY FROM PHYSICS

Resonance is a process in which the system oscillates with higher amplitude for specific frequencies for the vibrating system or for system which derives external force. When the amplitude of the response of the system is relatively maximum for a frequency then these types of frequencies are known as resonant frequencies. At these resonant frequencies, due to storage of vibrational energy small periodic force has the ability to generate large amplitude oscillations.

The phenomenon of resonance occurs between two or more various modes have the capability to store and transfer energy easily. Although, there are various losses which varies from cycle to cycle and is known as damping. When there is no forced oscillation then these resonant frequencies is almost equal to natural frequencies then the damping of the system is small [29].

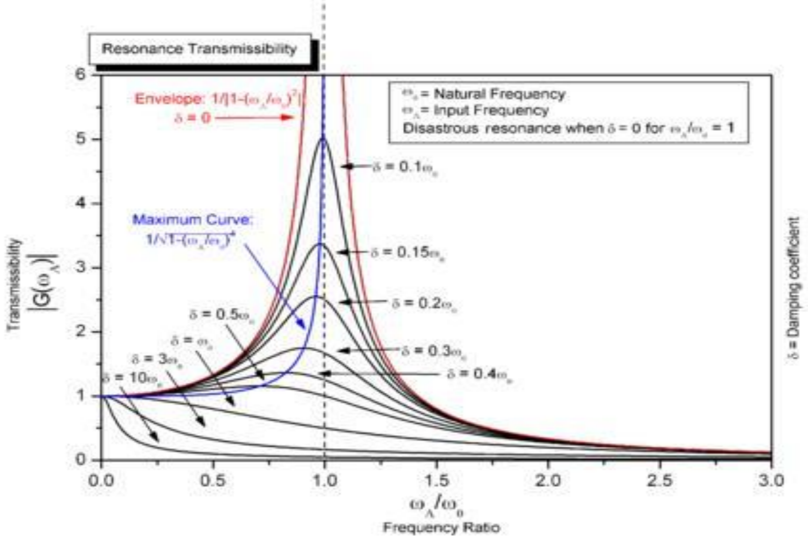


Figure 2-1 Concept of Resonance

According to the concept of physics in reference to resonance [35]. Let us consider a mass spring system as shown in figure 2-2 for an undamped forced oscillation of $F_o \cos\omega t$. From Newton's law it concludes that:

$$mX + bX + KX = F_o \cos\omega t \qquad (1)$$

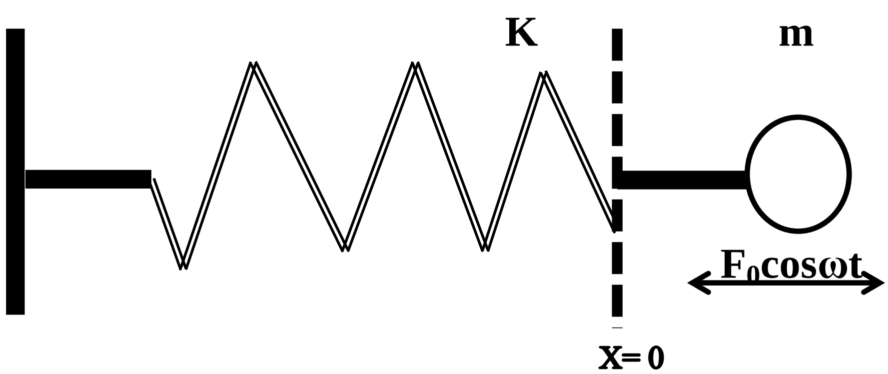


Figure 2-2 Undamped Forced oscillation Mass Spring System

whereas system damping γ and system natural frequency ω_o are:

$$\omega_o^2 = \frac{K}{m}, \ \gamma = \frac{b}{m} \qquad (2)$$

Damping ratio is given by $\zeta = \frac{\gamma}{2\omega_0}$, rewrite equation (1) in complex plane and replacing equation (2) we get,

$$Z + \gamma Z + \omega_0^2 Z = \frac{Fo}{m} e^{j\omega t} \quad (3)$$

The solution of equation (3) is given as:

$$Z = Ae^{j(\omega t-\delta)} \quad (4)$$

Replacing equation (4) in (3) we solve the equations for A and δ and is given as:

$$\begin{cases} A = \dfrac{\frac{Fo}{m}}{\sqrt{(\omega_0^2 - \omega^2)^2 + (\omega\gamma)^2}} \\ \tan\delta = \dfrac{\omega\gamma}{(\omega_0^2 - \omega^2)^2} \end{cases} \quad (5)$$

Where δ is phase difference for the forced-oscillation and A is the amplitude of oscillation. Resonance condition arises when amplitude A is at its peak value. From Equation (5) for an undamped system i.e. $\gamma = 0$ while forced frequency one and the same to natural frequency i.e. $\omega = \omega_0$ then resonance occurs due to which amplitude of oscillation becomes infinity. Whereas for damped system i.e. $\gamma = 0$ then amplitude will have some finite value from equation (5) and the amplitude becomes maximum at a frequency ω_{max} which is smaller than ω_0.

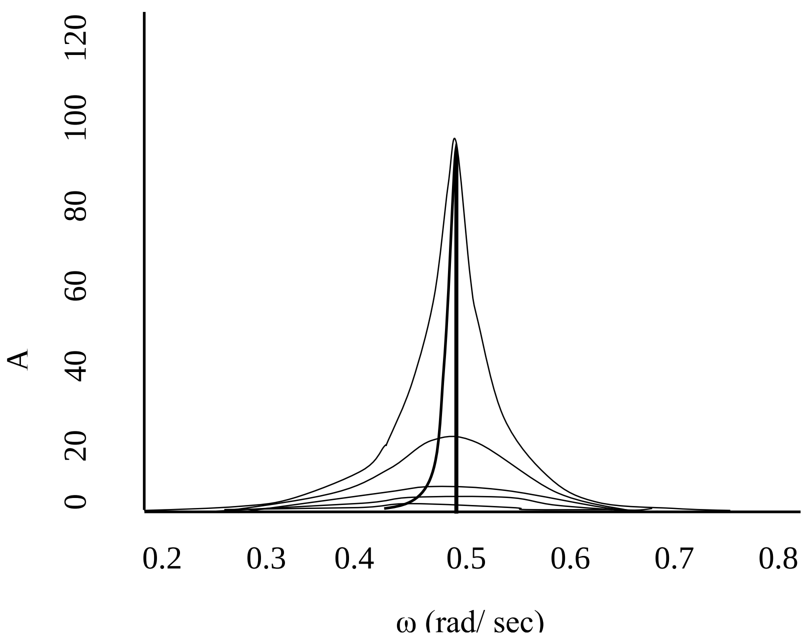


Figure 2-3 Oscillation amplitude for system with different damping levels

There can be three possible conditions:

$$\begin{cases} \omega \to 0\,, A = \dfrac{F_0}{K}\ \delta \to 0 \\ \omega \to \omega_0\,, A = \dfrac{F_0}{K}\ \delta \to \dfrac{\pi}{2} \\ \omega \to \infty\,,\ A = 0\ \delta \to \pi \end{cases} \quad (6)$$

Figure 2-3 shows the different damping level of forced oscillation which varies the amplitude A. The lowest damping system $\zeta = 2\%$ has the highest peak and with lowest damping system $\zeta = 27\%$ shows the lowest peak. Therefore the graph clearly shows that for poorly damped system the effect of resonance can be overlooked.

2.5 RESONANCE IN KUNDUR TEST POWER SYSTEM

This dissertation works on the two area Kundur investigating system [4] that provides as standard investigating case in [36]. In this system 10 MW mechanical sustained oscillation is induced by a small generator at bus 4 of Kundur test system which is associated at bus 10 of the system as shown in Figure 2-4. The location of the forced-oscillation can change to alternative buses as per requirement of the system or for analysis of the system.

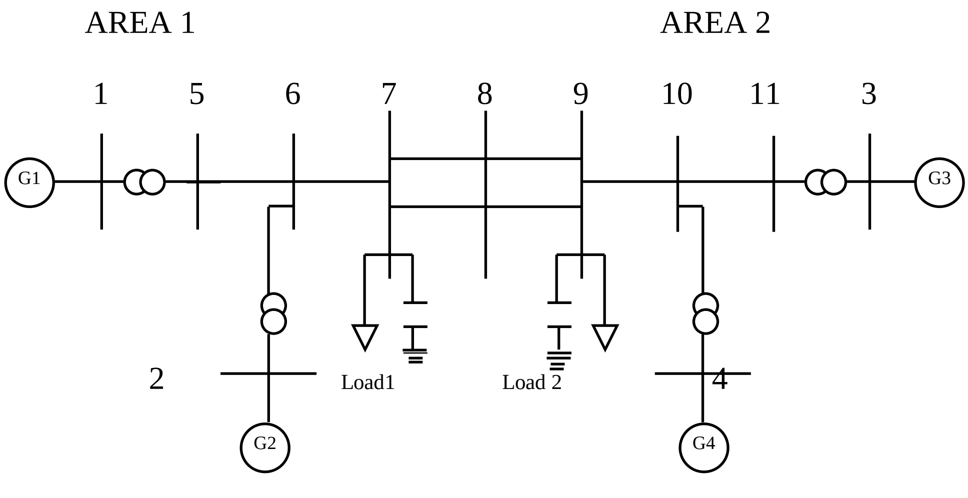


Figure 2-4 One-Line diagram of modified Kundur two area power system

In procedure simulate the random load variation 1% of the loads are modeled at buses 7 and 9. Simulated measurement of the system of forced oscillation at different modes for different combination is estimated by modal analysis, transient analysis and by calculating its Eigen values by DIgSILENT power factory. And further results estimated through prony method and analysis is done through FDD method in MATLAB.

The objectives are enclosing in this section in two forms:

- To identify how and when resonance can occur from forced-oscillations.
- To analyze how well system can detect and locate source of forced-oscillation.

CHAPTER 3

OVERVIEW OF DIgSILENT POWER FACTORY

3.1 WORKING WITH DIgSILENT POWER FACTORY

DIgSILENT is the graphical domain, it is a software tool used for constructing single line diagrams of the power system models. In building the single line diagram elements can be chosen by dragging from the Drawing Toolbox (figure 3-1) in the main graphical domain.

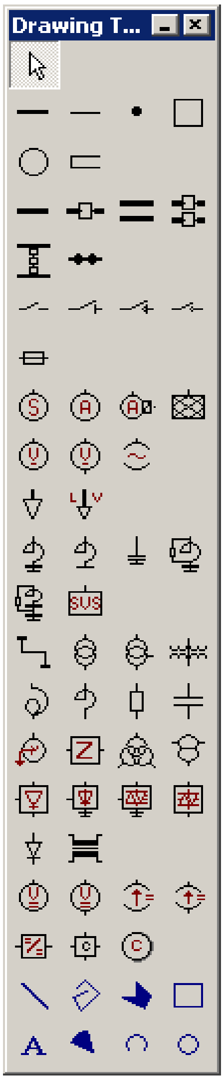


Figure 3-1 Drawing Tool Box Window

This drawing toolbox window can only be used when graphic freeze mode  is off. To make the changes in the topology can be executed only when this freeze is ON of the main window of single line diagram.

The data of the model can be very easily define either by access from the main toolbar icon of the data manager (figure 3-2) or by double clicking on an object (figure 3-3).

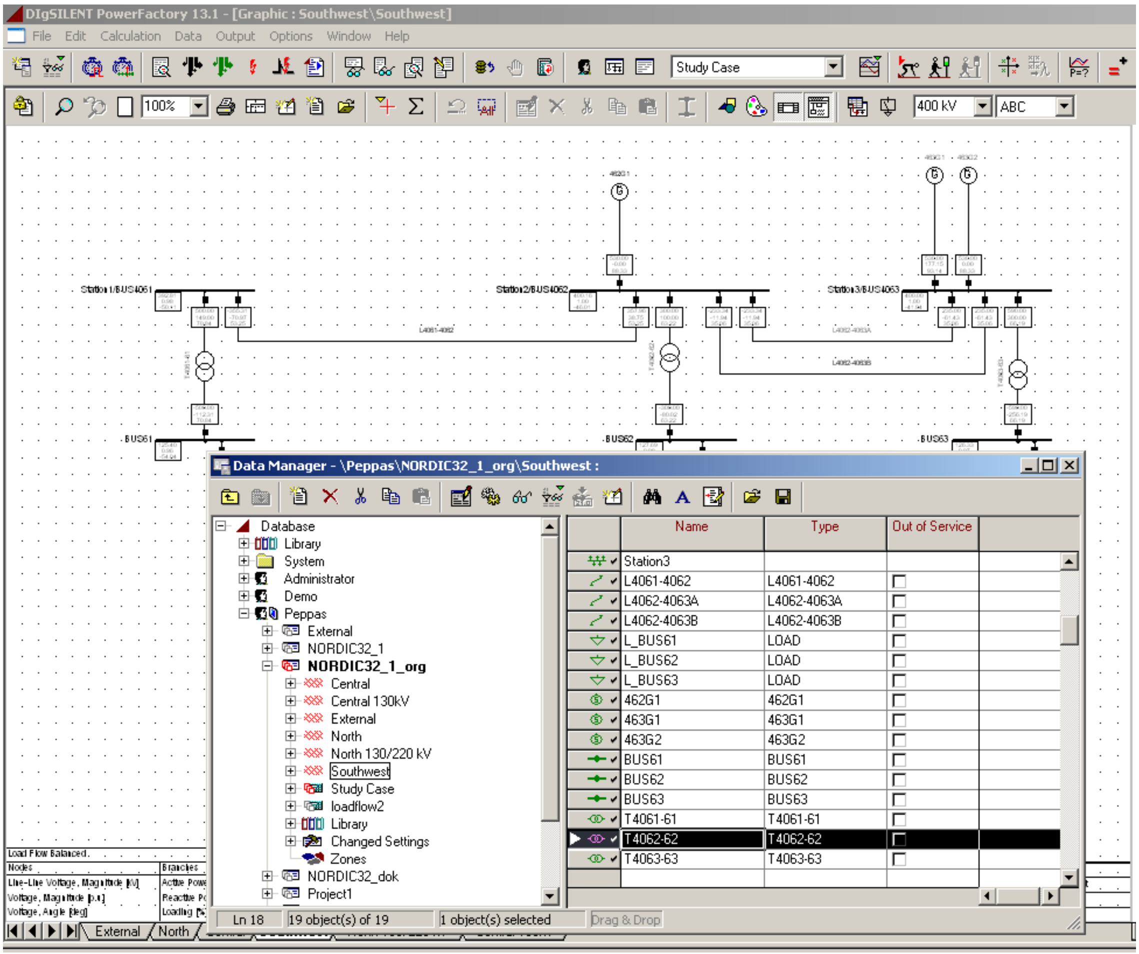


Figure 3-2 Transformer Editing Through Database Manager

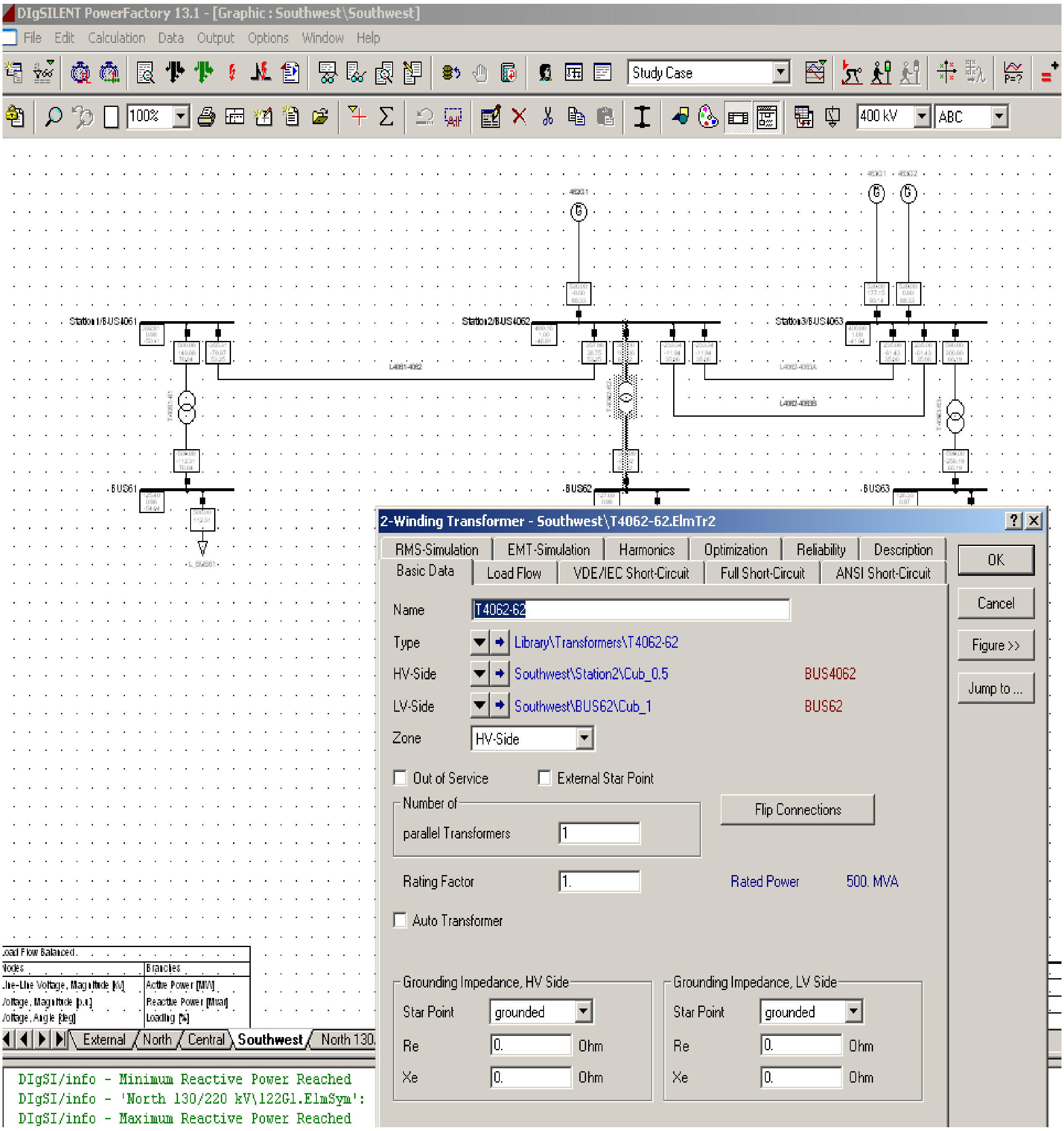


Figure 3-3 Transformer Editing

3.2 CREATING A NEW PROJECT

In the beginning for creating a new network is to describe a new project. It is done as follows:

- Open the file menu as on main menu bar.
- Select the new option

- Choose project…

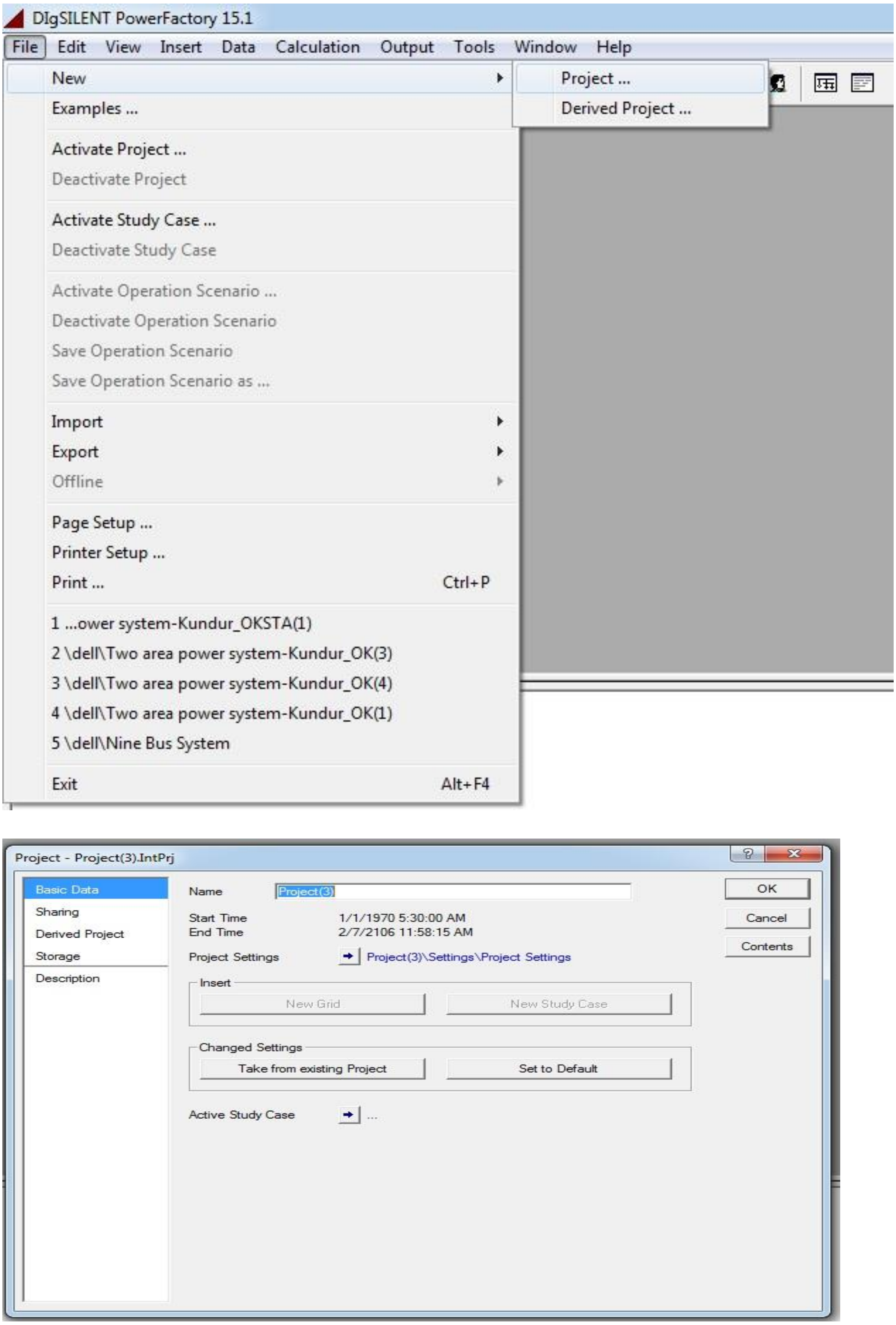


Figure 3-4 Creating New Project

- Enter the name of the project such as " Kundur Two Area Power system"
- Click the OK button
- Use of special characters is not allowed
- By selecting the Project option from the pop up dialogue and then provide a name for new system as shown in figure 3-5

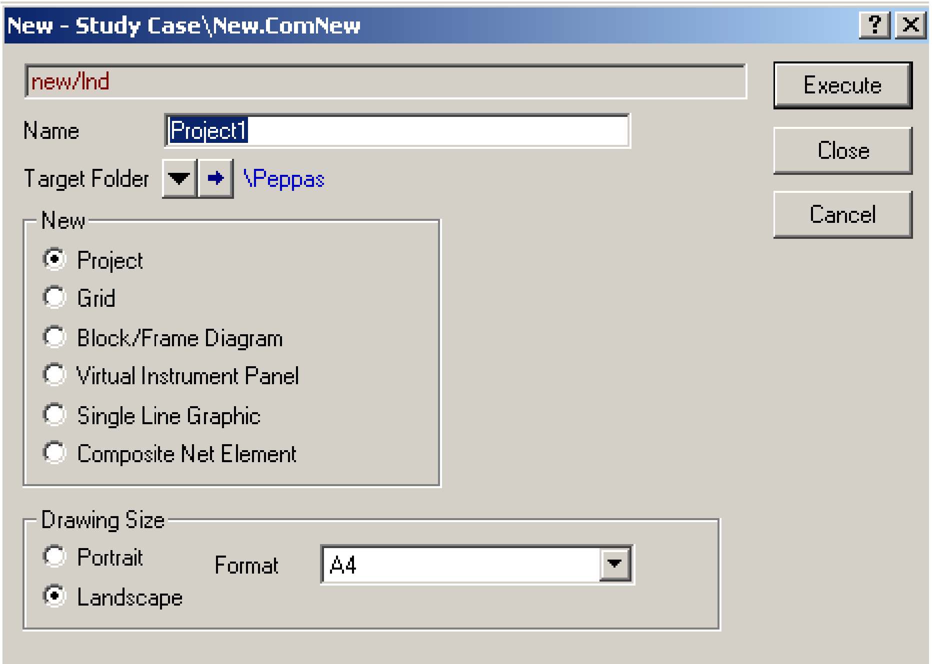


Figure 3-5 Defining a New Project

- For every project we need at least one Grid folder for which power system or subsystem is defined
- To introduce the data a dialog window of the grip pop-up

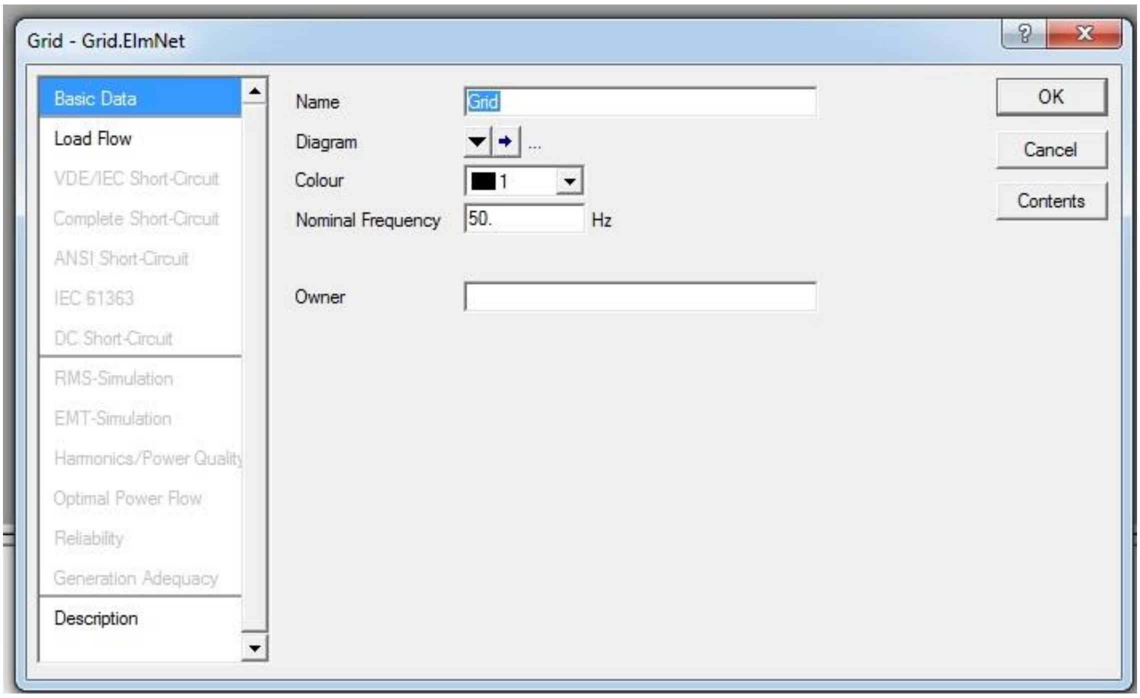


Figure 3-6 Grid Pop-Up

- A newly created project as “Kundur Two Area Power system” and its grid is created
- By selecting OK at the Grid dialogue an empty single line diagram is created with a grid called ‘External’ (figure 3-7).

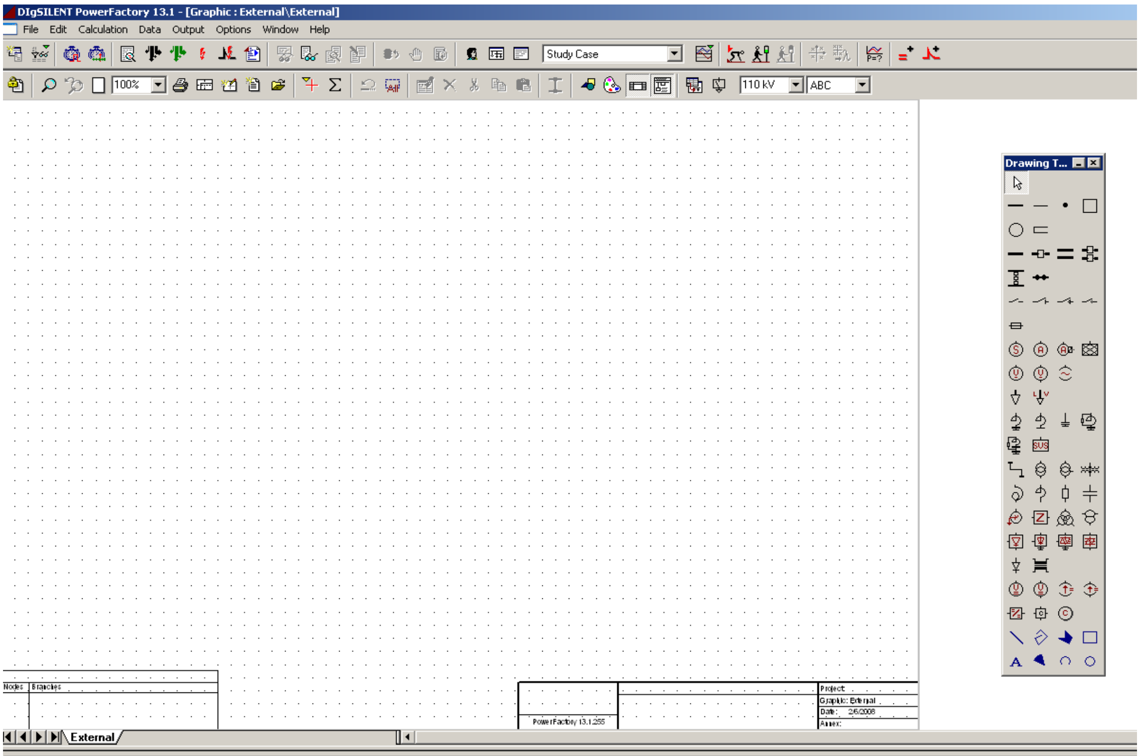


Figure 3-7 Single Line Graphic Window

- Now we can draw the single line diagram by selecting the objects as shown in figure 3-1.

3.3 CREATING AND EDITING ELEMENTS

3.3.1 Nodes Representation

For representation of node elements there are two types of elements are used: Terminals ( ) and Busbars ( ). For a terminal, node representation is the simplest form and used for the cases where neither the generators nor the transformers are connected. PowerFactory provides many options for the busbar representation like busbar, double busbar system, single busbar with tie breaker etc. (Figure 3-8) for the need of this project we make use of single busbar system and by double clicking on it a pop up dialogue box is appeared for the required data (figure 3-9 Busbar definition).

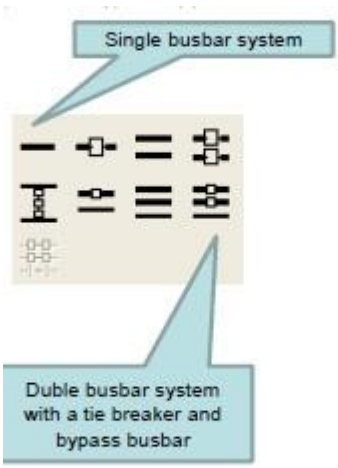
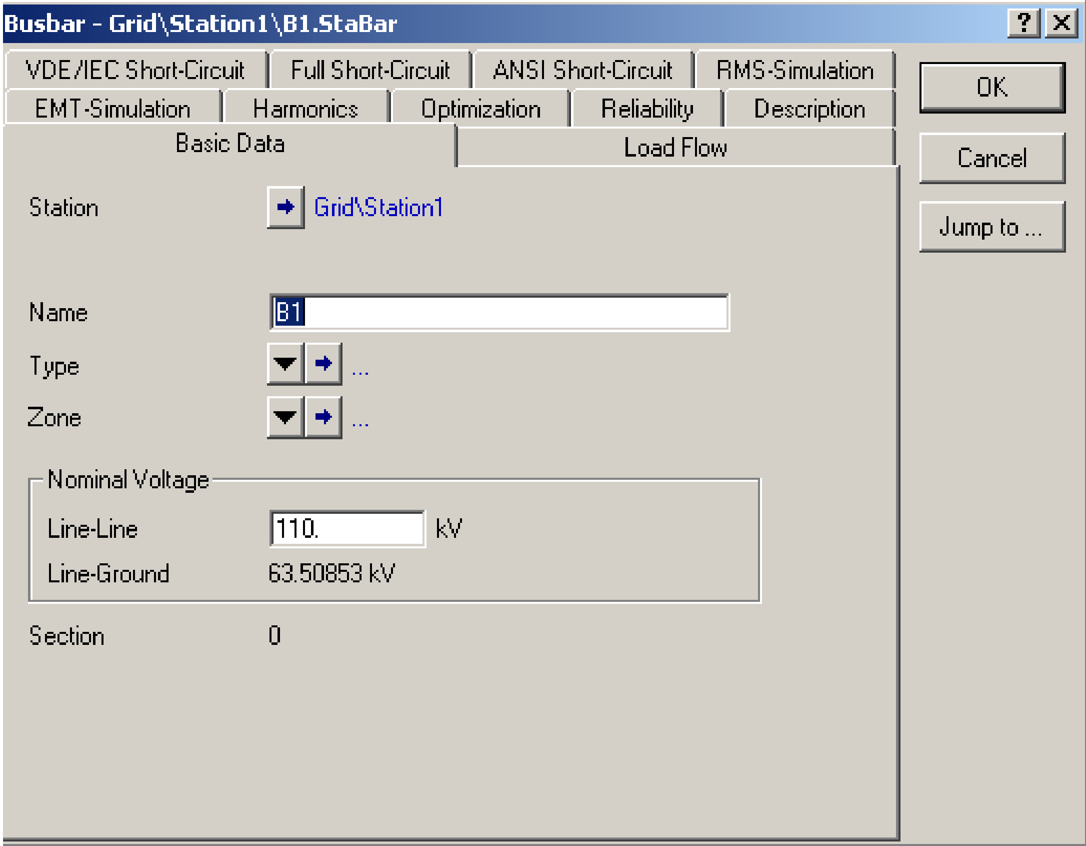


Figure 3-8 Busbar Elements

For selecting the specific type of busbar it can be selected by clicking at the button from the available types or for similar busbars a new type can be define for a system as shown in Figure 3-9 Busbar type definition.



Busbar definition

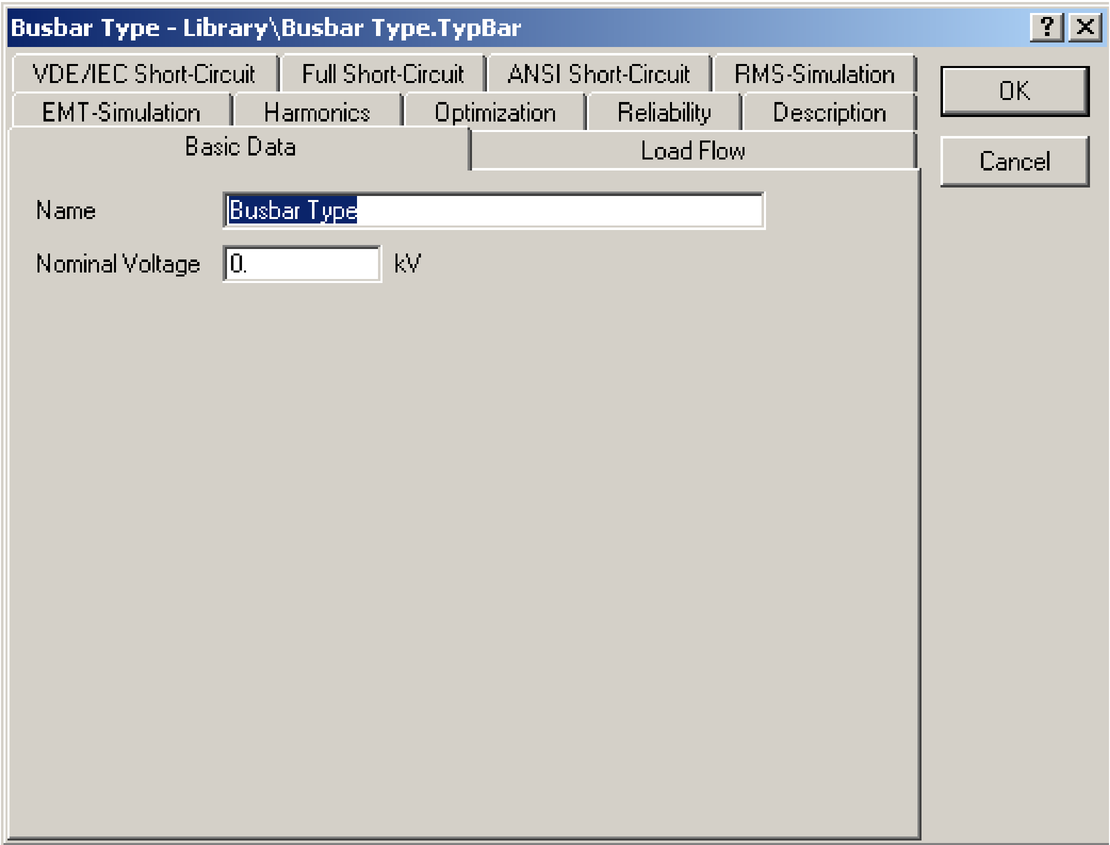


Figure 3-9 Busbar type definition

3.3.2 Line Representation

Lines in PowerFactory simply represented one-to-one connection between any two nodes. By using this icon  and by left clicking on appropriate node a connection is established between them. The line is represented by an ElmLne object from the database, after double clicking on the line it can be edited (figure 3-10). For the type of the line it needs to be defined, it can be either predefined type from the PowerFactory Library *(Select Global Type… option)* or a user defined type (*New Project Type…* option).

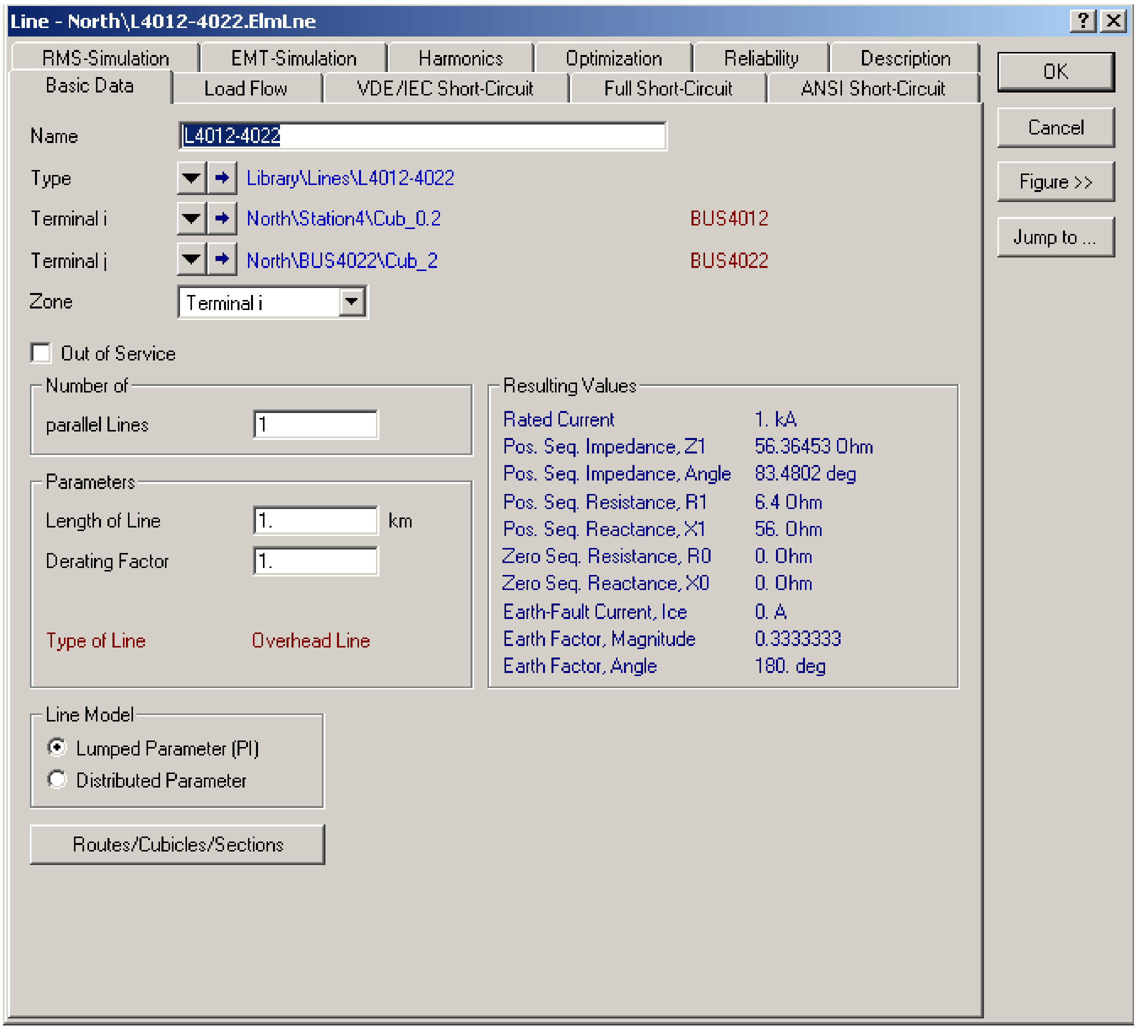


Figure 3-10 Line Definition

In this model types of new project were designed for each and every line in accordance to their characteristics, it may be nominal voltage, resistance, inductance and susceptance per km were selected for the lines according to the figure 3-11.

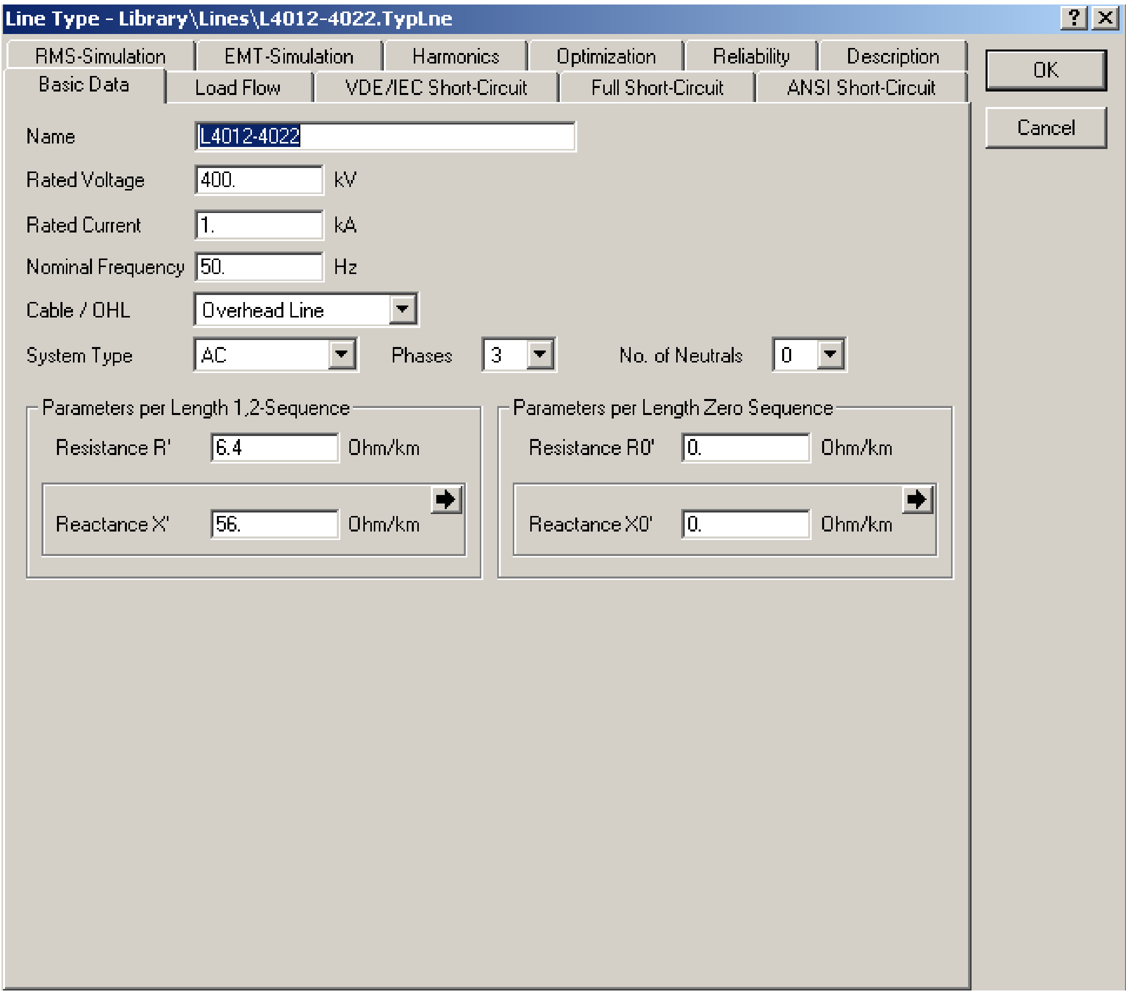


Figure 3-11 Line Type Definition

3.3.3 Load Representation

In PowerFactory Loads are selected from the drawing toolbox of the button , by dragging the button to the busbars or for the terminals for which they have to be connected. By doing so an ElmLod has been created in database which defines the load. And by double clicking on it editing of the elements or objects that have been created and information regarding the active and reactive power consumption can be done. In addition of these parameters such as voltage and frequency for a static load representation of model can be explain by selecting New project type option.

3.3.4 Synchronous Generators Representation

In PowerFactory synchronous generators are selected from the drawing toolbox of the button , by dragging the button to the busbars or for the terminals for which they have to be connected. By doing so an ElmSym has been created in database. Then the model has to edited in the following manner:

- In ElmSym object, basic data has to be define that has been created in the database. These data are related to the name of machine as if it acts as a motor or generator such as reactive power limits, mode of local voltage controller as shown in figure 3-12

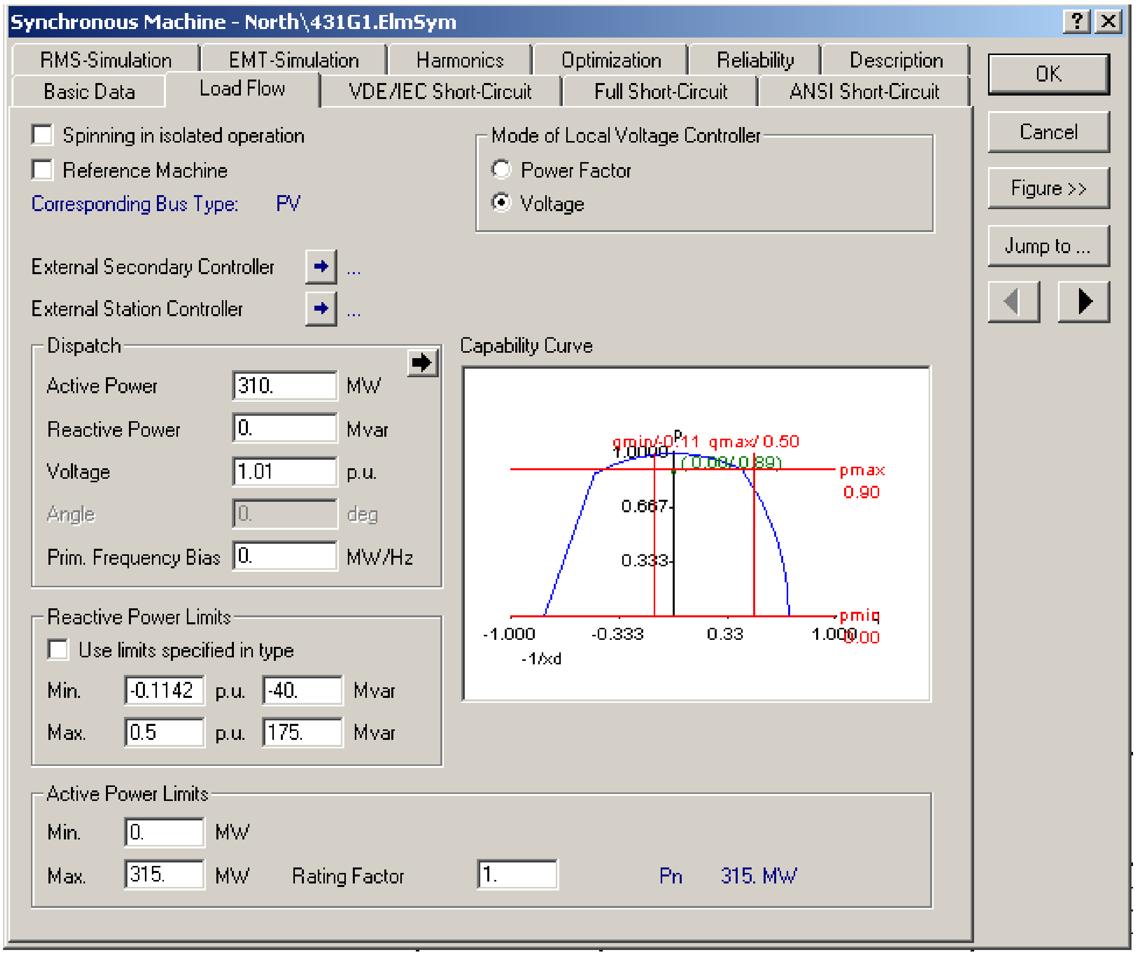


Figure 3-12 Synchronous Machine Definition

- Now we have defined the type of the generator it can be either predefined type from library of the PowerFactory or it can be user defined type. If user defined type has been selected then the information about ratings of the machine, its inertia characteristics, type of the rotor, transient reactances in addition of it transients time constants has to be provided. Figure 3-13

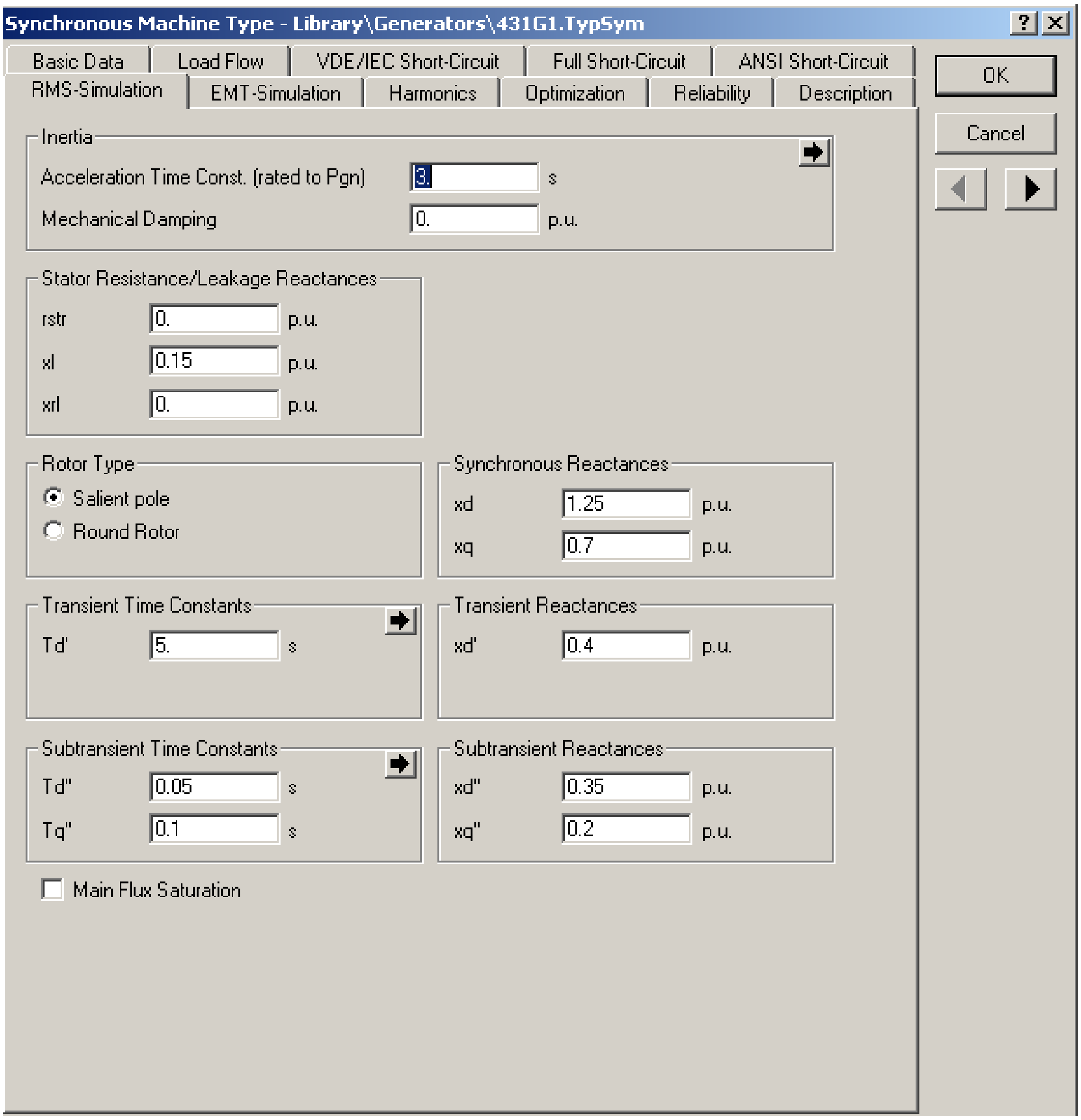
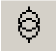
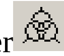
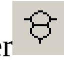


Figure 3-13 Type Definition of Synchronous Machine

3.3.5 Transformers Representation

The modeling of different types of transformers in PowerFactory incorporates such as two wing transformers , Two winding neutral transformer , Three winding transformer , Autotransformer , Boosting transformer . For the modeling two area Kundur power system two winding transformers has been used. It can be simply connected to the busbars by simply dragging it on the single line diagram and by left clicking choose the nodes. By doing so an ElmTr2 has been created in database as shown in figure 3-14. If in case connection has been wrong between low and high voltage side then an error message will occur. To solve this just flip connection button is used to reverse the connection.

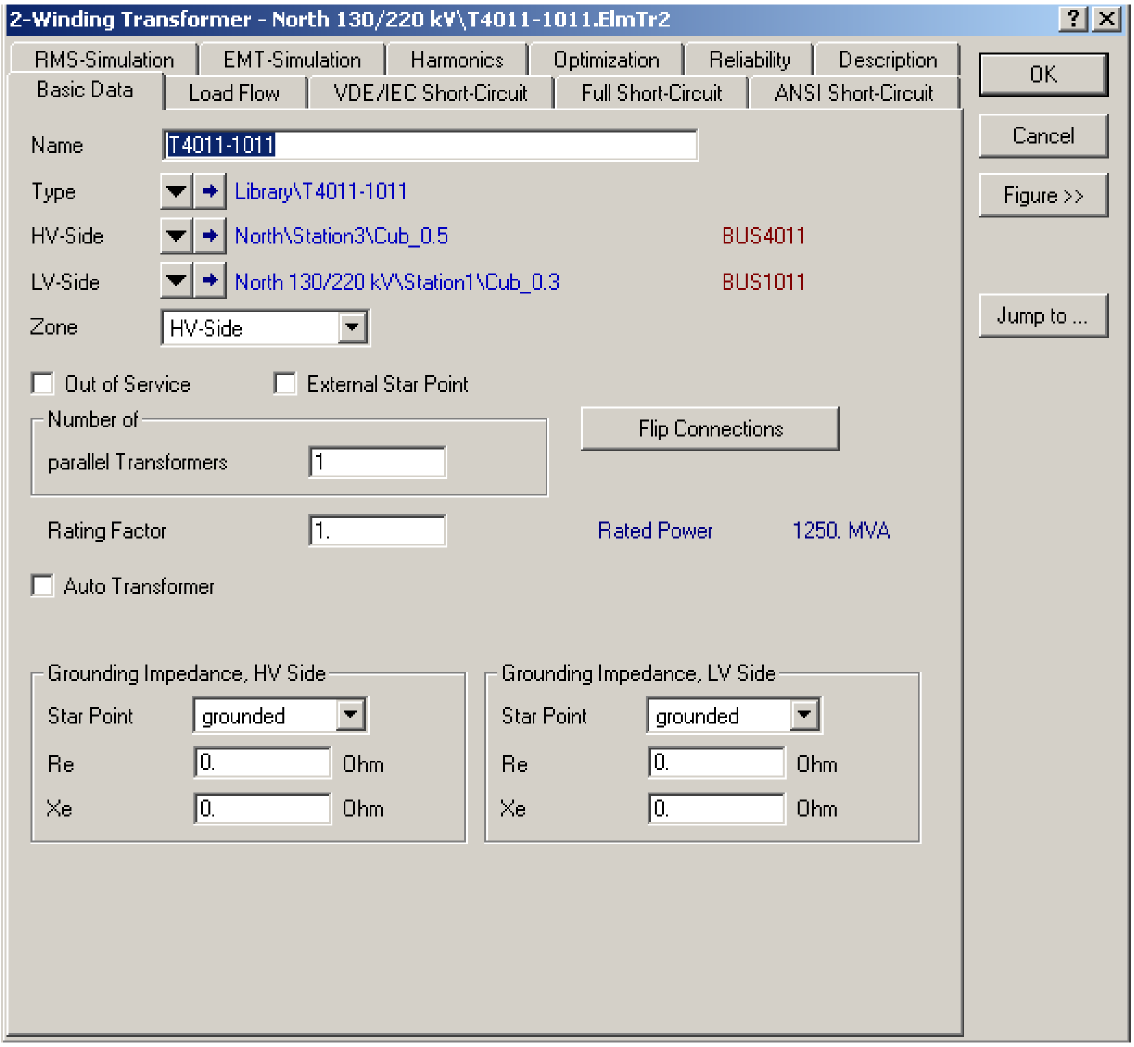
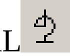


Figure 3-14 Transformer Definition

3.3.6 Shunt Impedances Representation

PowerFactory represents five type of connections like Shunt RLC , Shunt RL , Shunt C , Shunt RLCRp , Shunt RLCCRp . By doing so ElmShnt will be created in the database. As shown in Figure 3-15 elements can be edited.

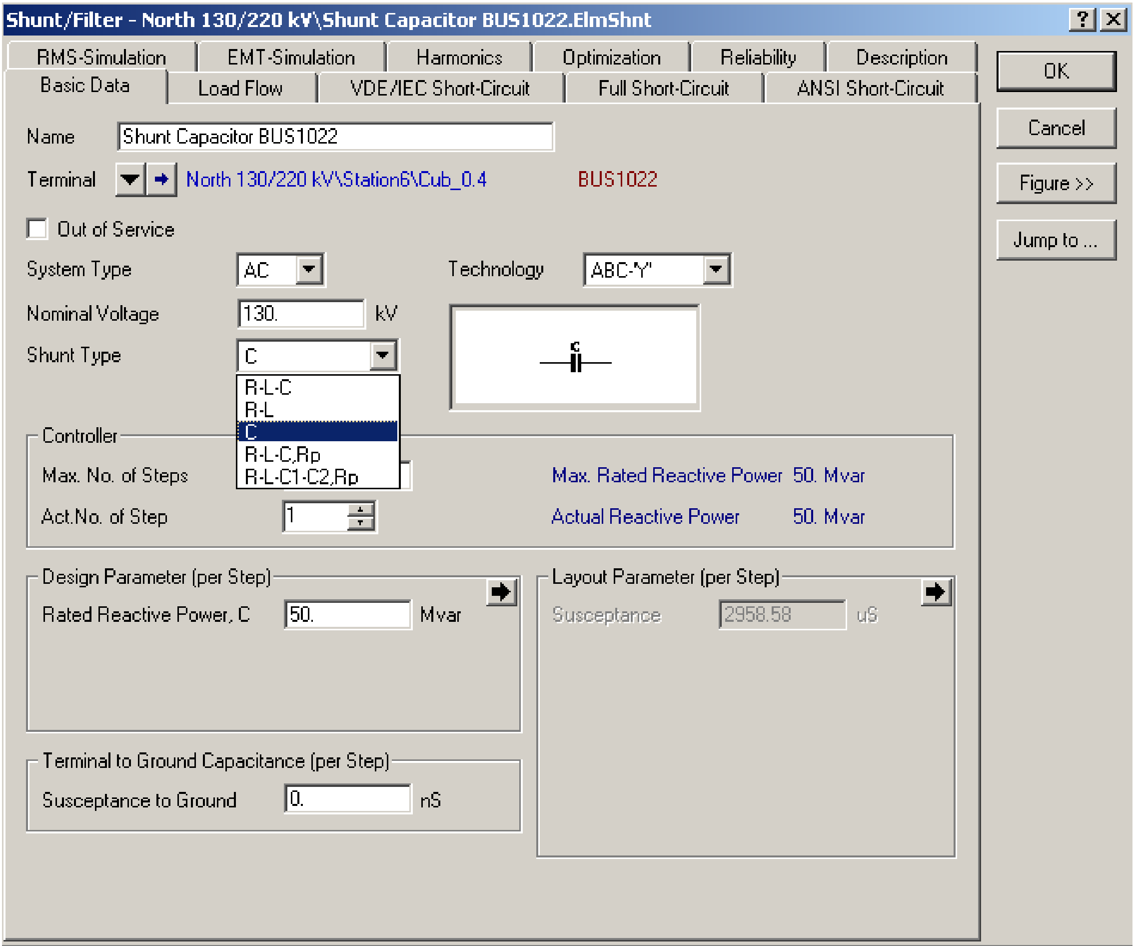


Figure 3-15 Shunt Impedance Definition

CHAPTER 4

DEVELOPING TWO AREA KUNDUR POWER SYSTEM IN DIgSILENT POWER FACTORY

4.1 INTRODUCTION: KUNDUR TEST SYSTEM

In this segment Kundur Two Area power-system [4] test case has been used for representation of two area system. At bus 4 small synchronous generator G4 of 10 MW induces a mechanical sustained oscillation through transformer 4.

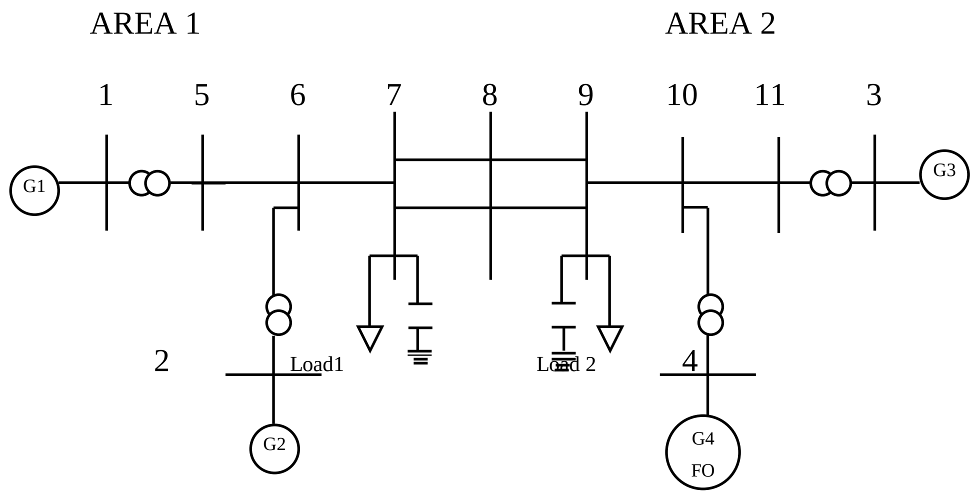


Figure 4-1 One-Line diagram of modified Kundur two area power system

It is connected to the bus 10 of Kundur Two Area Power System. This system includes four generator and three large equivalent loads connected in a meshed transmission network through transmission lines. The base MVA is 100, and system frequency is 60Hz.

The following table 4-1 shows the bus data in per unit on the bases of 100MVA and 230KV in the transmission system. In this bus1, 2 and 3 are the generation buses and bus 3 is selected as slack bus.

Table 4-1 Bus Data In p.u

Bus Number	Final Voltage (p.u)	Load (MW)	Load (MVAr)	Generation (MW)	Generation (MVAr)	Voltage Rated (kV)
1	1.03	0	0	900	393.2	20
2	1.01	0	0	900	620	20
3	1.03	0	0	375	105	20
4	1.01	0	0	700	167.2	20
5	0.98	0	0	0	0	230
6	0.92	0	0	0	0	230
7	0.87	1392.6	100	0	0	230
8	0.87	0	0	0	0	230
9	0.97	1367	100	0	0	230

The following table 4-2 shows the branch data in per unit on the bases of S_{base} = 100MVA and V_{base} = 230KVin the transmission system.

Table 4-2 Branch Data In p.u

From Bus	To Bus	Branch Resistance R	Branch Reactance X	Line Charging B
1	5	0.00000	0.52900	0.00000
2	6	0.00000	0.52900	0.00000
3	11	0.00000	0.05860	0.00000
4	10	0.00000	0.05290	0.00000
5	6	0.05290	0.5290	0.33080
6	7	0.05290	0.5290	0.33080
7	8	0.05290	0.5290	0.33080
8	9	0.05290	0.5290	0.33080
9	10	0.05290	0.5290	0.33080

4.2 MODEL OF THE SYSTEM

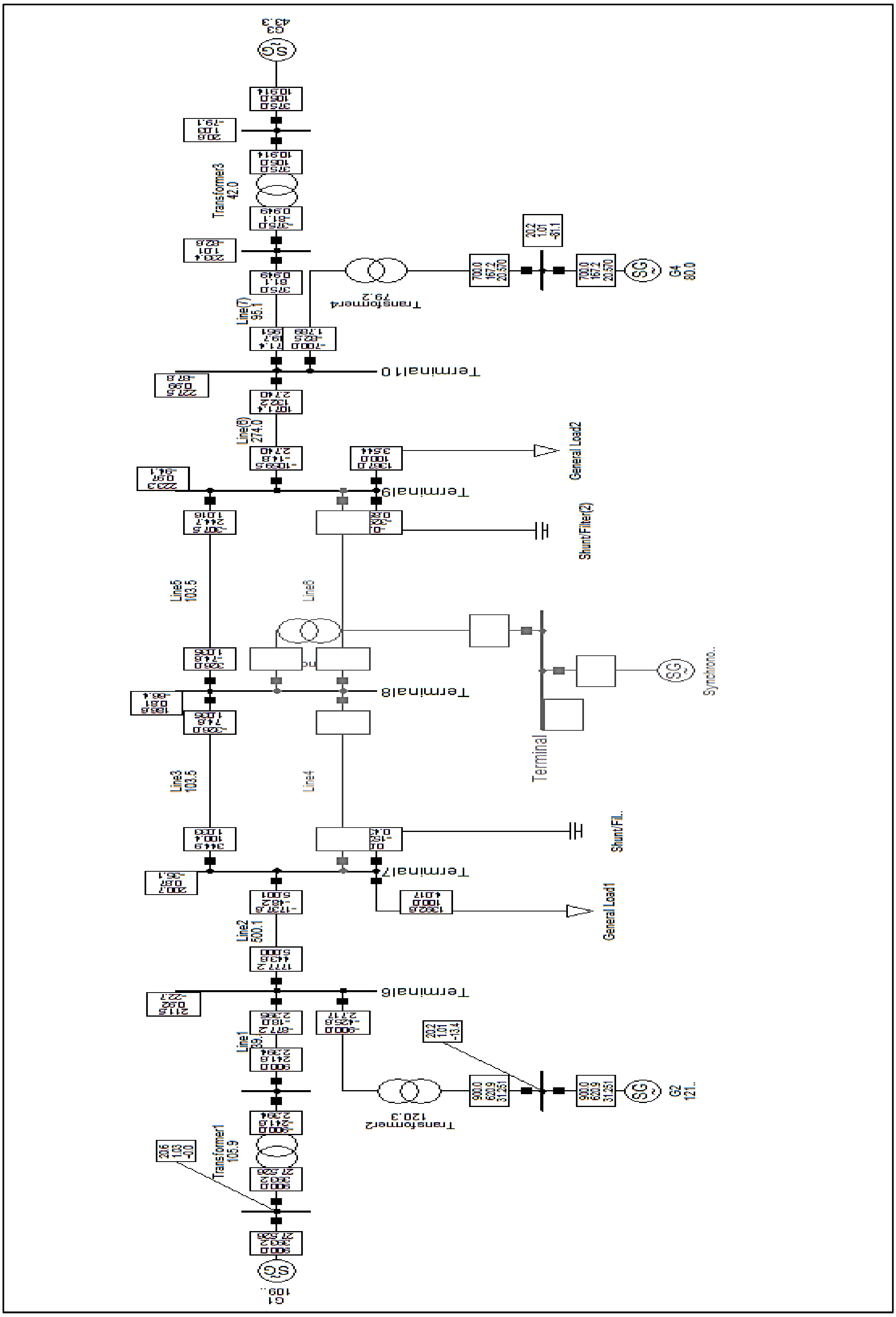


Figure 4-2 Model of the System

The system has been simulated in DIgSILENT Power Factory according to the designing mentioned in the above section. The frequency of the forced oscillations at bus 4 has been changed above and below the mode frequencies for testing the performance of the system by its load flow calculations, its transient analysis for the system stability, calculation of Eigen values and its modal analysis has been done.

4.3 LOAD FLOW CALCULATIONS:

The load flow calculation has been performed for the two area system. Load flow calculations have been done through Newton Raphson method. And it converges in 8 iterations. From table 4-3 evaluates the load flow calculation in which in describe the loading at each parameter of the grid and table 4-4 evaluates the total summary of overall grid which includes the changes in the substations, changes in the total active and reactive power changes at each terminal of the grid. Table 4-5 describes the change in parameters due to voltage interchange between the lines, its effect on the line power, its losses all the related parameters has been described in this table.
Load flow results are as follows:

Table 4-3 Total System Summary

LOAD FLOW CALCULATIONS	
AC Load Flow, Balanced, positive sequence	
Automatic Tap adjust of transformers	No
Consider Reactive Power Limits	No
Automatic Model Adaption For	No

Convergence			
Maximum Acceptable Load Flow Error For			
Nodes	1.00 KVA		
Model Equations	0.10%		
No. Of Substations	0		
No. Of 2-Winding Transformers	4		
No. Of Loads	2		
No Of BusBars	12		
No Of Shunts	2		
No. of Synchronous Machines	4		
No. Of Lines	6		
Generation	2875.00 MW	1286.19MVar	3149.59 MVA
External Infeed	0.00 MW	0.00MVar	0.00 MVA
Load P(U)	27.59.65 MW	200.00 MVar	2766.89 MVA
Load P(Un	2734.00 MW	200.00 MVar	2741.31 MVA
Load P(Un-U)	-25.65 MW	0.00 MVar	
Motor Load	0.00 MW	0.00MVar	0.00 MVA
Grid Losses	115.35 MW	1568.33 MVar	
Line Charging		-40.48 MVar	
Compensation Ind.		0.00 MVar	
Compensation Cap.		-482.14 MVar	
Installed Capacity	2880.00 MW		
Spinning Reserve	5.00 MW		
Total Power Factor:			

Generation	0.91(-)
Load/Motor	1.00/0.00(-)

Table 4-4 Complete System Report: Substations, Voltage Profiles, Grid Interchange, Area Interchange

LOAD FLOW CALCULATIONS									
AC Load Flow, Balanced, positive sequence									
Automatic Tap adjust of transformers				No					
Consider Reactive Power Limits				No					
Automatic Model Adaption For Convergence				No					
Maximum Acceptable Load Flow Error For									
Nodes				1.00 KVA					
Model Equations				0.10%					
Rated Voltage KV		BusVoltage							
KV	p.u.	KV	Deg	Active Power [MW]	Reactive Power [Mvar]	Power Factor [-]	Current [KA]	Loading [%]
Terminal 16									
230.00	0.92	211.51	-22.67					
Cub_1/ Lne	Line1			-877.24	-18.02	-1.00	2.40	239.51
Cub_2/ Lne	Line2			1777.24	443.59	0.97	5.00	500.06
Cub_2/ Tr2	Transformer2			-900.00	-425.57	-0.90	2.72	120.29
Terminal 17									
230.00	0.87	200.69	-35.14					
Cub_4/ Shnt	Shunt/ Filter(1)			0.00	-152.27	0.00	0.44	
Cub_5/ Lod	General Load1			1392.65	100.00	1.00	4.02	
Cub_1/ Lne	Line2			-1737.56	-48.15	-1.00	5.00	500.06
Cub_2/ Lne	Line3			344.91	100.43	0.96	1.03	103.50
Cub_3/ Lne	Line4							
Terminal 15									
230.00	0.98	224.78	-8.57					
Cub_1/Tr2	Transformer1			-900.00	-241.65	-0.97	2.39	105.95

Cub_2/ Lne	Line1	Line1		900.00	241.65	0.97	2.39	239.51
Terminal 11								
20.00	1.03	20.60	0.00					
Cub_2/Sym	G1			900.00	393.18	0.92	27.53	109.13
Cub_1/Tr2	Transformer1			900.00	393.18	0.92	27.53	105.95
Terminal 12								
20.00	1.01	20.20	-13.37					
Cub_2/Sym	G2			900.00	620.90	0.82	31.25	121.49
Cub_3/Tr2	Transformer2			900.00	620.90	0.82	31.25	120.29
Terminal 18								
230.00	0.81	186.57	-66.42					
Cub_1/Lne	Line3			-326.04	74.56	-0.97	1.04	103.50
Cub_2/Lne	Line4							
Cub_3/Lne	Line5			326.04	-74.56	0.97	1.04	103.50
Cub_4/Lne	Line6							
Cub_5/Tr2	2-winding Transformer							
Terminal 19								
230.00	0.97	223.29	-94.13					
Cub_4/Shnt	Shunt/ Filter(2)			0.00	-329.87	0.00	0.85	
Cub_5/Lod	General Load2			1367.00	100.00	1.00	3.54	
Cub_1/Lne	Line5							
Cub_2/Lne	Line6							
Cub_3/Lne	Line7			-1059.51	-14.79	-1.00	2.74	273.98
Terminal 110								
230.00	0.99	227.51	-87.80					
Cub_1/Lne	Line6			1071.42	132.23	0.99	2.74	273.98
Cub_2/Tr2	Transformer4			-700.00	-82.53	-0.99	2.74	273.98
Cub_3/Lne	Line7			-371.42	-49.70	0.99	0.95	95.09
Terminal 14								
20.00	1.01	20.20	-81.10					
Cub_2/Sym	G4			700.00	167.15	0.97	20.57	79.96
Cub_1/Tr2	Transformer4			700.00	167.15	0.97	20.57	79.17
Terminal 111								
230.00	1.01	233.41	-82.57					
Cub_1/Lne	Line7			375.00	81.14	0.98	0.95	95.09

Cub_1/Tr2	Transformer3			-375.00	-81.14	-0.98	0.95	42.01
Terminal 13								
20.00	1.03	20.60	-79.14					
Cub_2/Sym	G3			375.00	104.96	0.96	10.91	43.27
Cub_1/Tr2	Transformer3			375.00	104.96	0.96	10.91	42.01

	Rated Voltage	Bus Voltage			Voltage Deviation%				
	KV	p.u.	KV	deg	-10	-5	0	5	10
Terminal 16	230.00	0.920	211.51	-22.67					
Terminal17	230.00	0.873	200.69	-35.14					
Terminal15	230.00	0.977	224.78	-8.57					
Terminal11	20.00	1.030	20.60	0.00					
Terminal12	20.00	1.030	20.60	0.00					
Terminal18	230.00	0.811	186.57	-66.42					
Terminal19	230.00	0.971	223.29	-94.13					
Terminal 110	230.00	0.989	227.51	-87.80					
Terminal 14	20.00	1.010	20.20	-81.10					
Terminal 111	230.00	1.015	233.41	-82.57					
Terminal 13	20.00	1.030	20.60	-79.14					
Terminal	20.00								

Table 4-5 Complete System Report: Substations, Voltage Profiles, Grid Interchange, Area Interchange

LOAD FLOW CALCULATIONS										
AC Load Flow, Balanced, positive sequence										
Automatic Tap adjust of transformers				No						
Consider Reactive Power Limits				No						
Automatic Model Adaption For Convergence				No						
Maximum Acceptable Load Flow Error For										
Nodes				1.00 KVA						
Model Equations				0.10%						
Voltage Level	Generation	Motor Load	Load	Compensation	External Infeed	Interchange To	Power Interchange	Total Losses	Load Losses	No Load Losses
[KV]	[MW]/ [Mvar]	[MW]/ [Mvar]	[MW]/ [Mvar]	[MW]/ [Mvar]	[MW]/ [Mvar]		[MW]/ [Mvar]	[MW]/ [Mvar]	[MW]/ [Mvar]	[MW]/ [Mvar]
20.00	2875.00	0.00	0.00	0.00	0.00	230.00 KV		0.00	0.00	0.00
	1286.19	0.00	0.00	0.00	0.00			0.00	0.00	0.00
							2875.00	0.00	0.00	0.00
							1286.19	455.31	455.31	0.00
230.00	0.00	0.00	2759.65	0.00	0.00	20.00 KV		115.35	115.35	0.00
	0.00	0.00	200.00	-482.14	0.00			1113.02	1153.50	-40.48
							-2875.00	0.00	0.00	0.00
							-830.88	455.31	455.31	0.00
Total	2875.00	0.00	2759.65	0.00	0.00		0.00	115.35	115.35	0.00
	1286.19	0.00	200.00	-482.14	0.00		0.00	1568.33	1608.81	-40.48

4.4 DYNAMIC ANALYSIS

4.4.1 Controller Description:

For the analysis of dynamic behavior of the system controllers have been implemented. PowerFactory offers global library for the use of different predefined controllers such as standard IEEE models of power plants i.e. providing a wide range for dynamic regulators like governors, voltage controllers and power system stabilizers. PowerFactory control modes design concept can be summarize as follows. For a control mode designing the fundamental element is 'Model/Block definition' as it constitute specified preconfigured units or controller definition such as generators. Excitation systems, PSS and Hydro Governor are examples of Model/Block Definition described in figure 4-4, 4-5, and 4-6. In a controller model/block definition is a common definition which is not associated with particular power plant. The composite frame is a general control model which is used to define inputs and outputs of these control models. Hydro power plant schematic diagram of 'composite frame' is shown in figure 4-3. Where the forced-oscillation is injected.

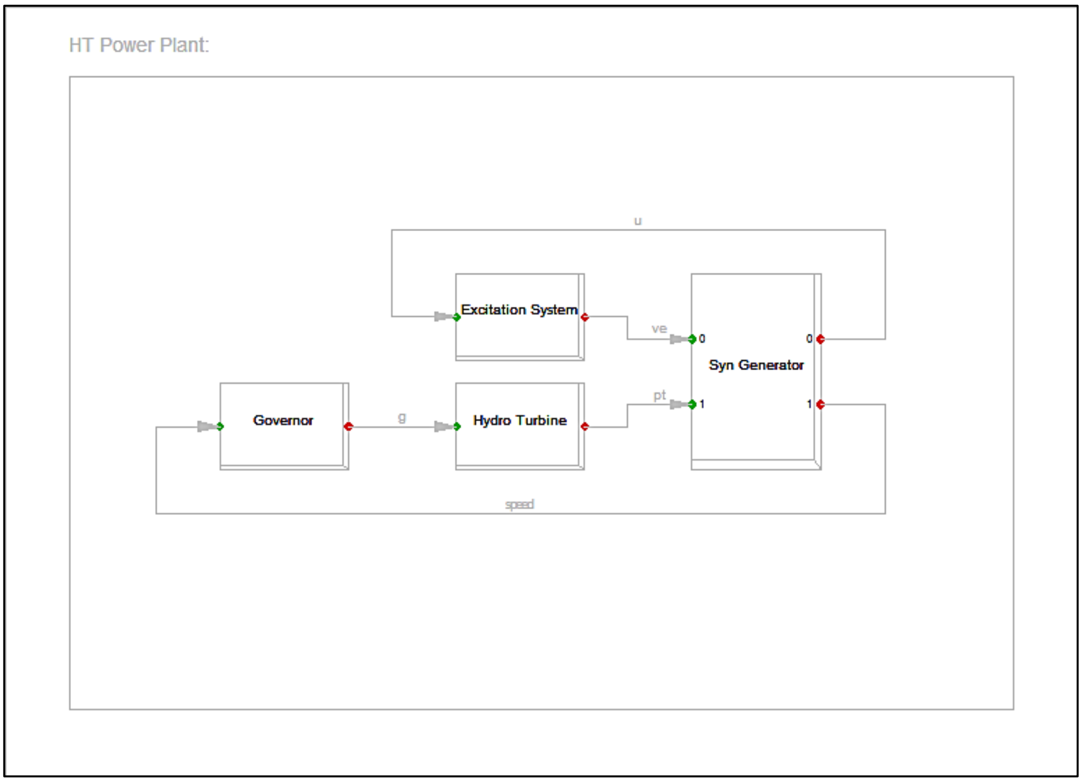


Figure 4-3 Schematic diagram of a 'Composite Frame' for a hydro power plant

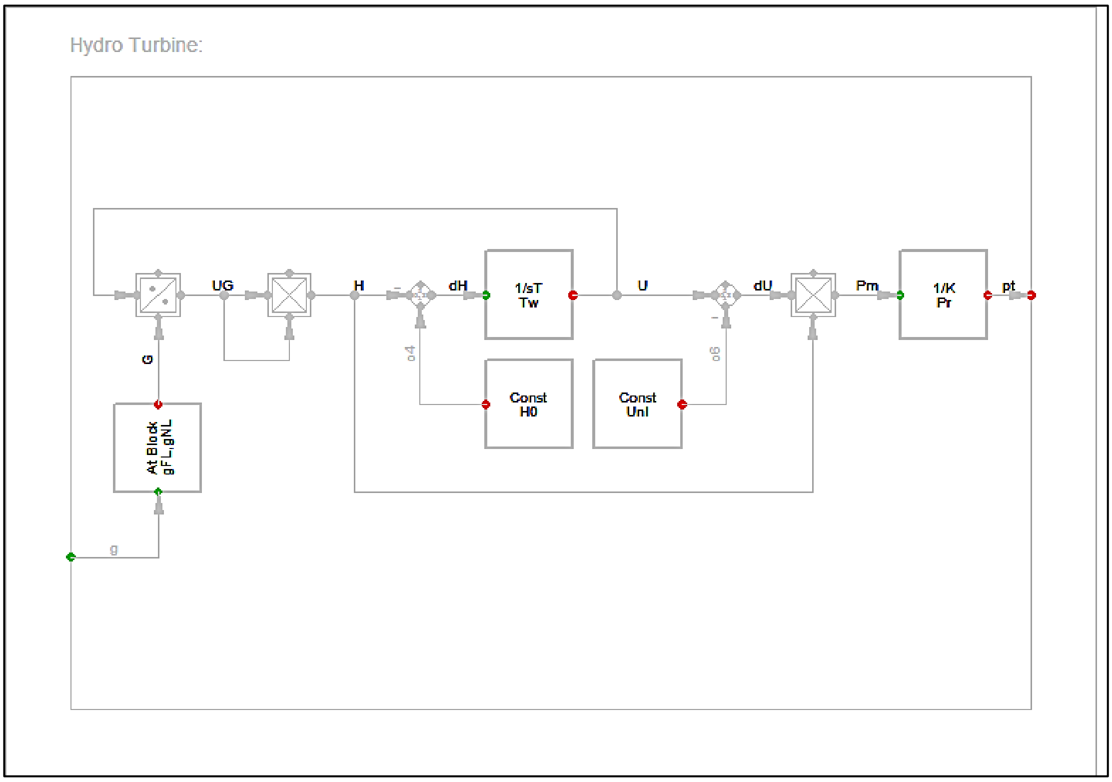


Figure 4-4 Schematic Diagram Hydro Turbine

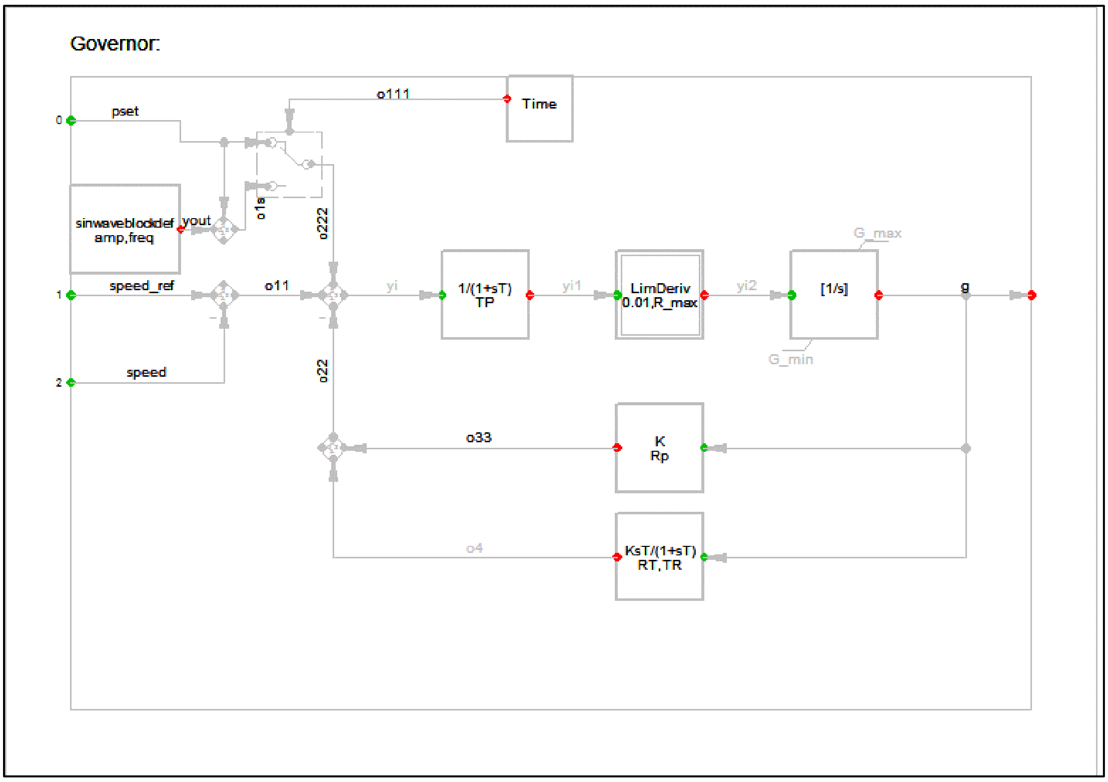


Figure 4-5 Schematic Diagram Governor

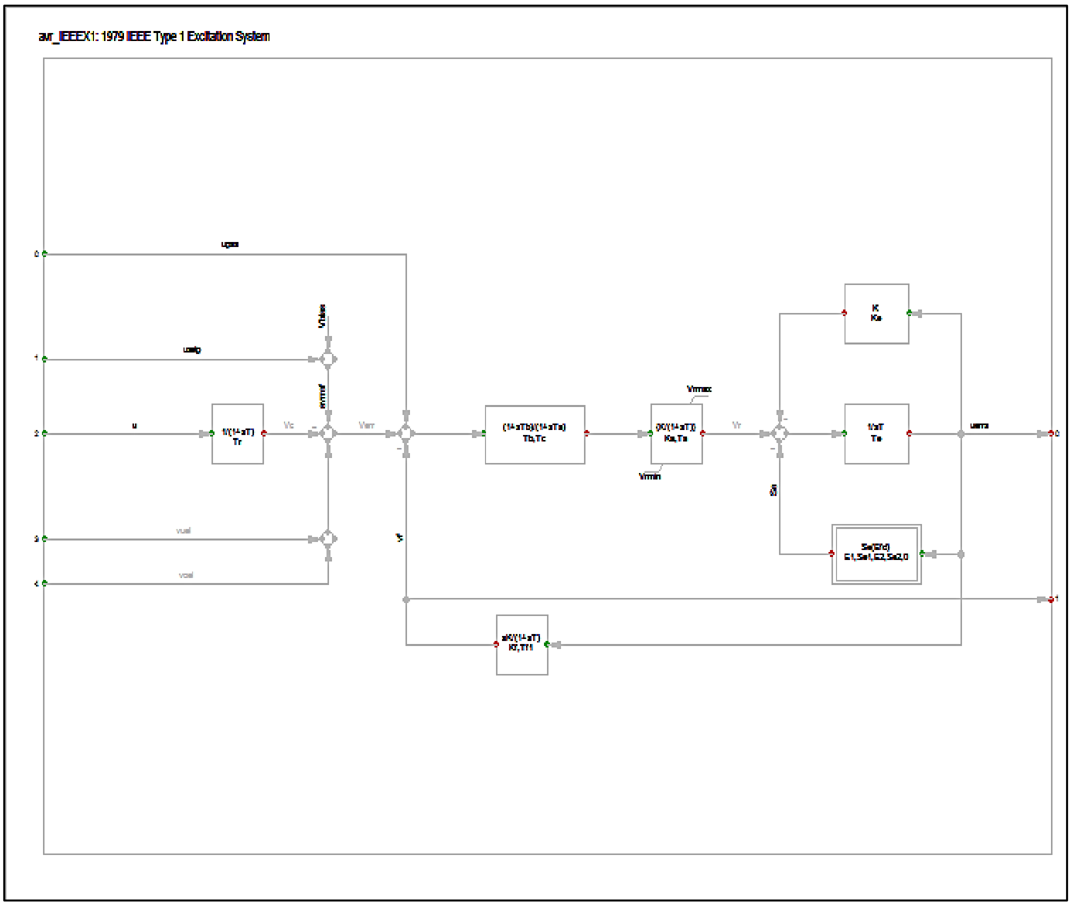


Figure 4-6 Schematic Diagram of Excitation System

4.5 SIMULATIONS AND PLOTS IN PowerFactory

4.5.1 Resonance With Inter Area Mode Forced Oscillation Output Graphs

A forced oscillation of 10 MVA at bus4 from synchronous generator G4 is injected into the bus 10 with small magnitude of generator governor oscillations. Now two Scenarios were studied in each case we have two cases as case 1 and case 2

Scenario 1: The load flow of the system was adjusted for to get a very low damping ratio of 0.01501327 for the Interarea mode of the two area system as shown in fig below. Also it can be noted from figure below that the Interarea mode is having a frequency of 0.2227072 Hz.

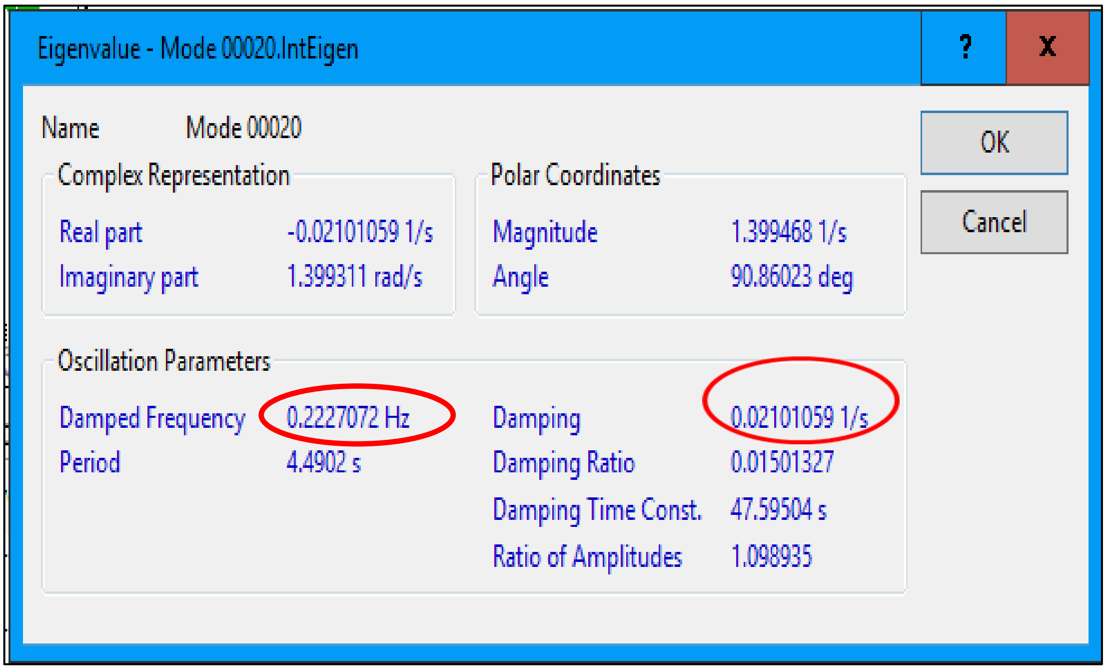


Figure 4-7 Mode 20 Eigen Value at 0.2Hz

Case 1: A forced oscillation at G4 is applied with frequency 0.2 Hz and the resulting oscillations in tie line 5 are shown in fig below.

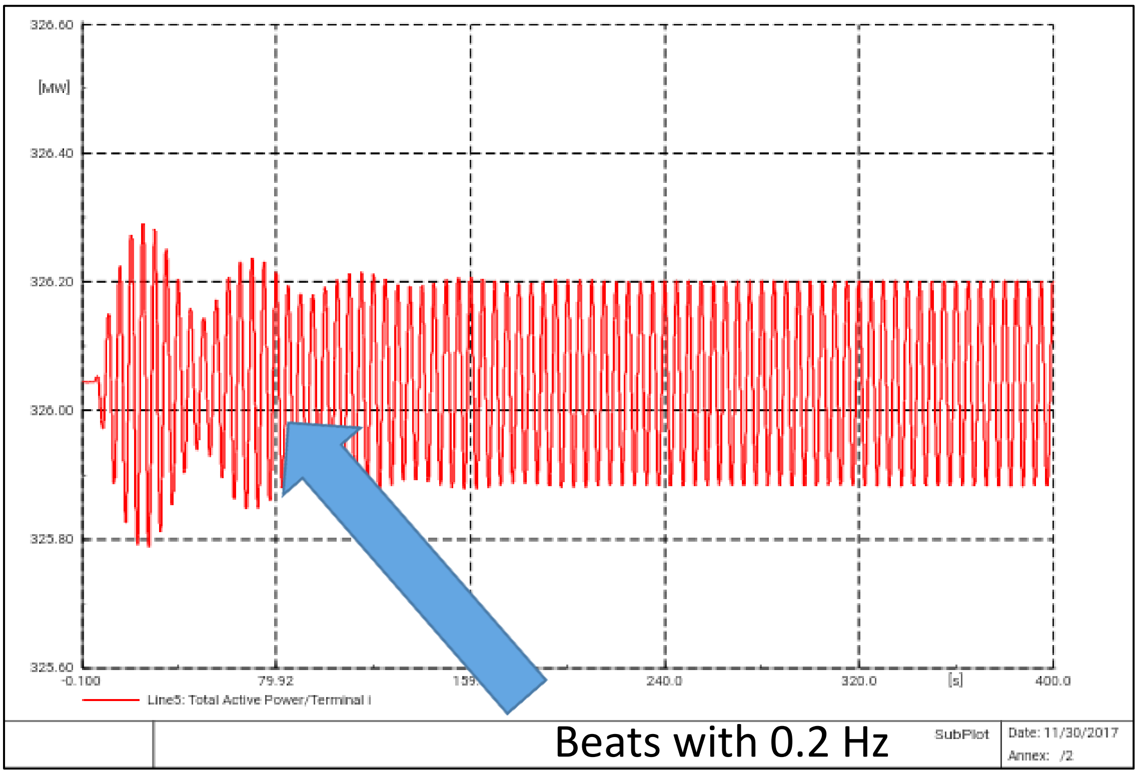


Figure 4-8 Tie Line Active Power At 0.2Hz

It can be seen form figure above that the beats are visible along with strong oscillations in the tie line power as the forced oscillation frequency of 0.2 Hz is close to the Interarea mode frequency of 0.2227072 Hz. This resembles to the beats in the resonance concept under physics.

Case2: A forced oscillation at G4 is applied with frequency 0.2227072 Hz and the resulting oscillations in tie line 5 are shown in fig below.

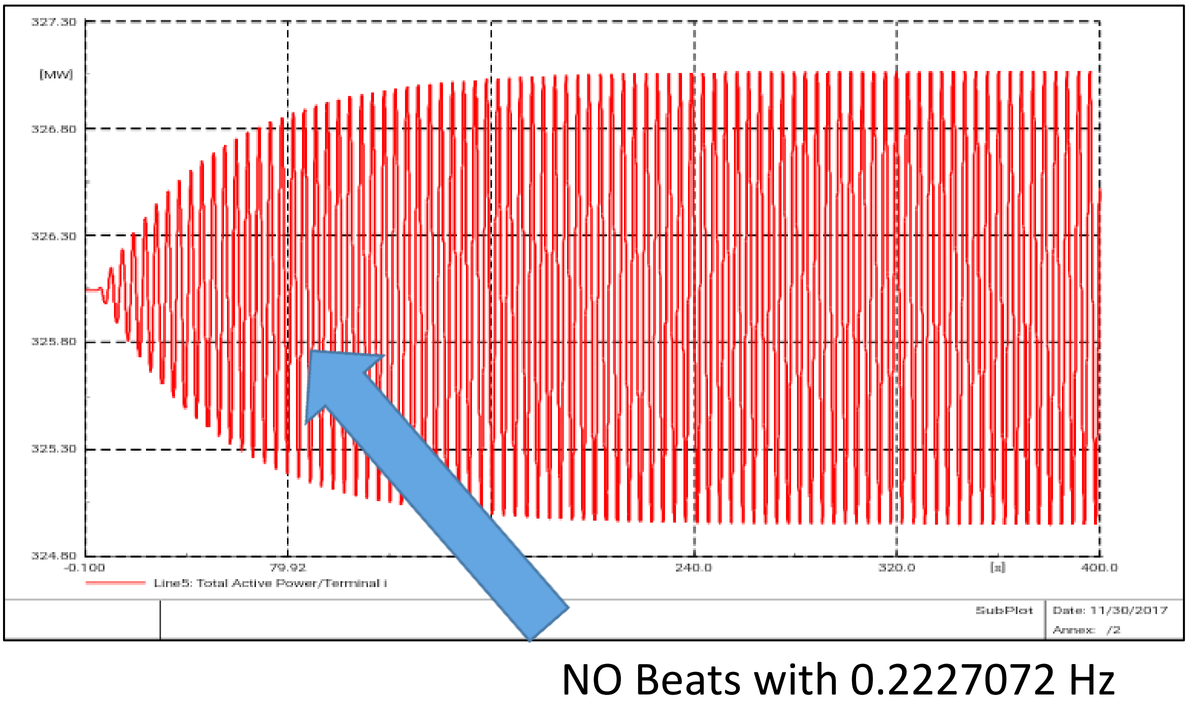


Figure 4-9 Tie Line Active Power At 0.2227072 Hz

Scenario 2: The load flow of the system was again adjusted for to get a higher damping ratio of 0.05121671 for the Interarea mode of the two area system as shown in fig below. Also it can be noted from figure below that the Interarea mode is having a frequency of 0.3458351Hz.

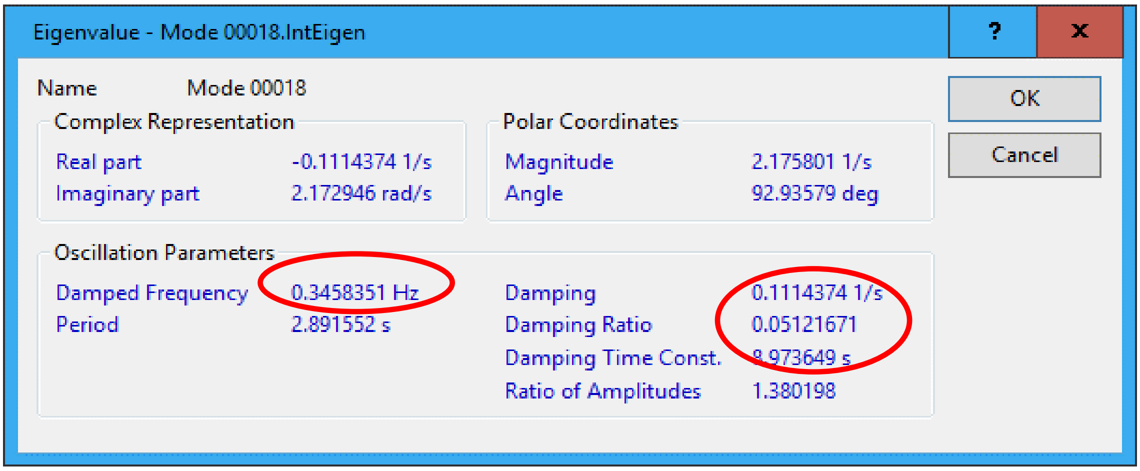


Figure 4-10 Mode 20 Eigen Value at 0.3Hz

Case 1: A forced oscillation at G4 is applied with frequency 0.3 Hz and the resulting oscillations in tie line 5 are shown in fig below.

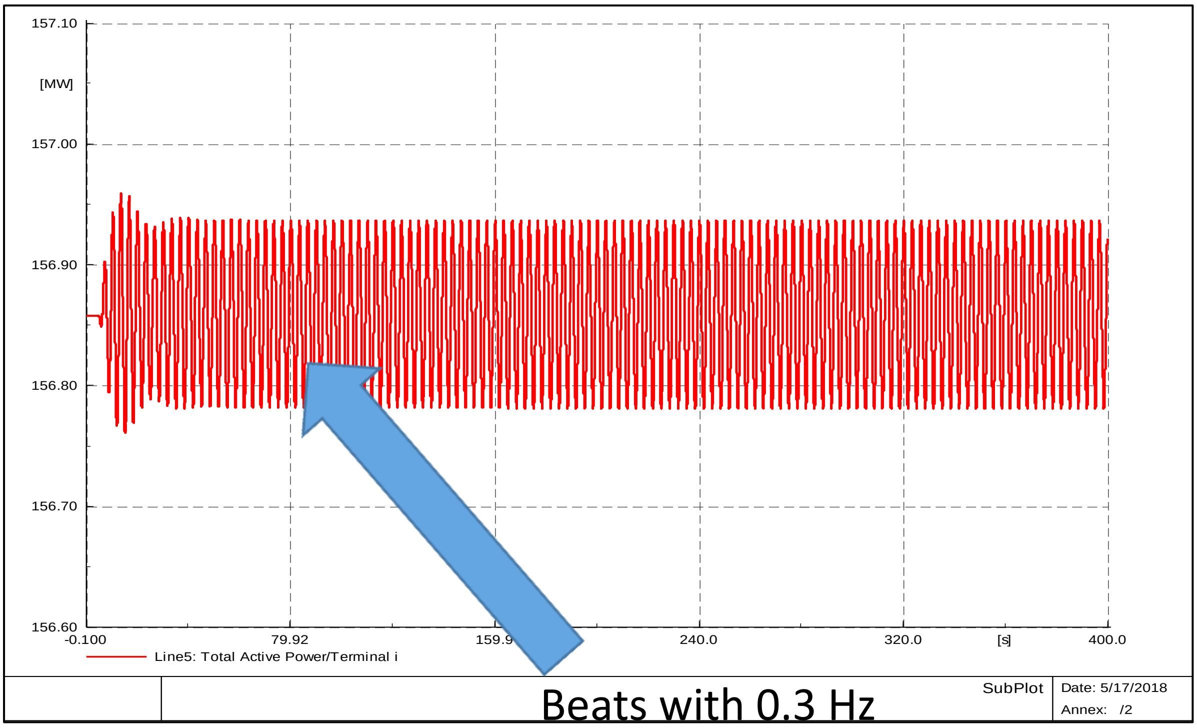


Figure 4-11 Tie Line Active Power At 0.3Hz

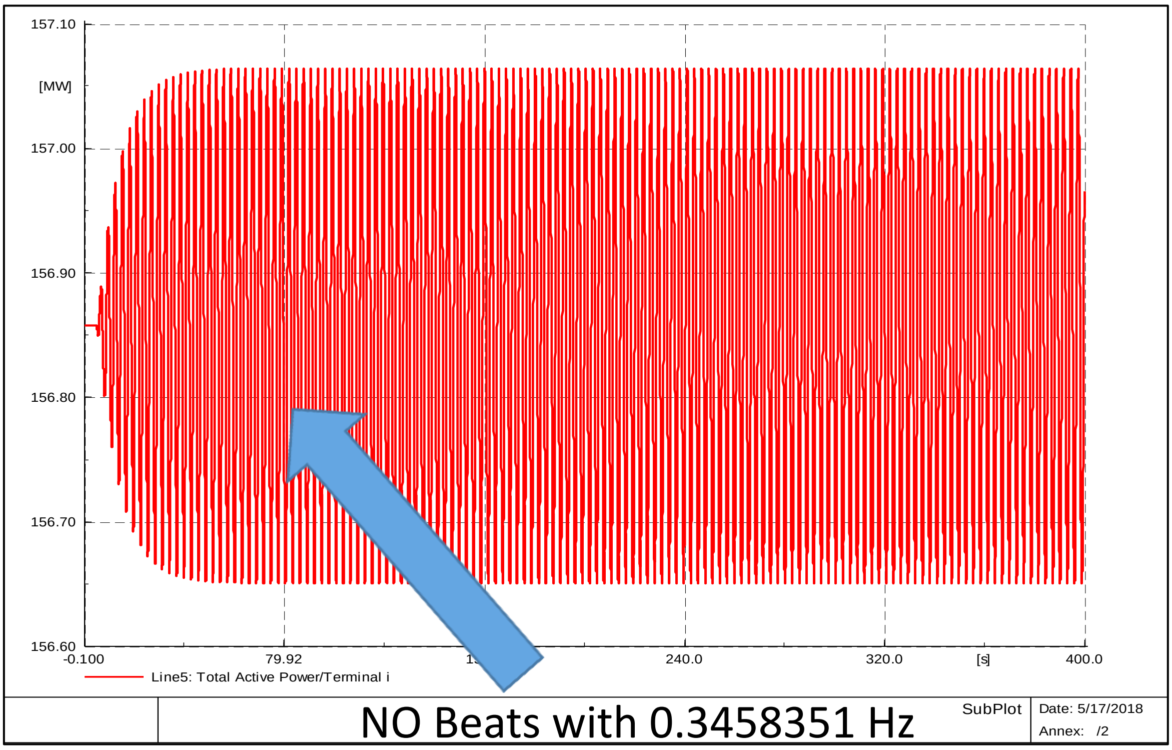


Figure 4-12 Tie Line Active Power At 0.3Hz

It can be seen form figure above that the beats are visible but subdued due to higher damping along with strong oscillations in the tie line power as the forced oscillation frequency of 0.3 Hz is close to the Interarea mode frequency of 0.3458351 Hz.

Further, the envelope shape for forced oscillation has been examined. For resonances in scenario 1 and 2 their upper envelopes without overshoot are convex in nature whereas beats are negligible as the forced component dies out rapidly the overshoots are very small in the envelope.

4.5.2 Modal Analysis

The modal analysis for two area Kundur power system reveals 28 different modes with negative real parts for stable operation of the system. Initially eigenvalues near to the real axis are presented. These eigenvalues are characterized by low frequency and sufficient damping ratio. Table 4-6 shows the values of all the 28 different modes with **0.22Hz** frequency for interarea mode. On the basis of the values eigenvalue plot, Mode phasor plot and its participation factors i.e. its controllability of a system can be viewed as shown in Fig 4-12.

Table 4-6 Mode Parameters at 0.2Hz

Mode No.	Magnitude 1/s	Damped Freq Hz	Angle deg	Damping Ratio
1	0	0	0	0
2	46.90635	7.29357109	102.31599	0.213303
3	46.90635	7.29357109	-102.31599	0.213303
4	37.94158	0	180	1
5	37.94158	0	180	1
6	35.47603	0	180	1
7	34.39755	0	180	1
8	32.9964	0	180	1
9	32.65079	0	180	1
10	26.42154	0	180	1
11	25.93187	0	180	1
12	6.07404	0.96372978	94.50362	0.078522
13	6.07404	0.96372978	-94.50362	0.078522
14	6.10888	0.96413627	97.41143	0.128993
15	6.10888	0.96413627	-97.41143	0.128993
16	5.7795	0	180	1
17	5.29859	0	180	1
18	3.8406	0.07370135	173.07473	0.992704
19	3.8406	0.07370135	-173.07473	0.992704
20	**1.39946**	**0.22270722**	**90.86022**	**0.015015**
21	**1.39946**	**0.22270722**	**90.86022**	**0.015015**
22	1.9457	0	180	1
23	0.60331	0	180	1
24	0.26124	0.00191032	177.36658	0.998943
25	0.26124	0.00191032	-177.36658	0.998943
26	0.0498	0.0034	154.59948	0.903331
27	0.0498	0.0034	-154.59948	0.903331
28	0.0003	0	180	1

For Mode 20 and 21 from above table we can see that when forced oscillation is injected the decrease the magnitude and the damping ratio is near about zero which implies system is critically damped for inter area mode oscillation.

The mode shape of this interarea mode is plotted in figure 4-11 and the following values have been obtained:

- Controllability of mode is -0.021+ 1.399* j
- Magnitude is 1.399 (1/s)
- Angle is 90.860°
- Period is 4.490 s

- Frequency is 0.223 Hz
- Damping is 0.021(1/s)
- Ratio of Amplitudes is 1.099
- Minimum Contribution is 0.100

We can see from the plot that the two pair of generators are oscillating in out of phase corresponding to the interarea mode.

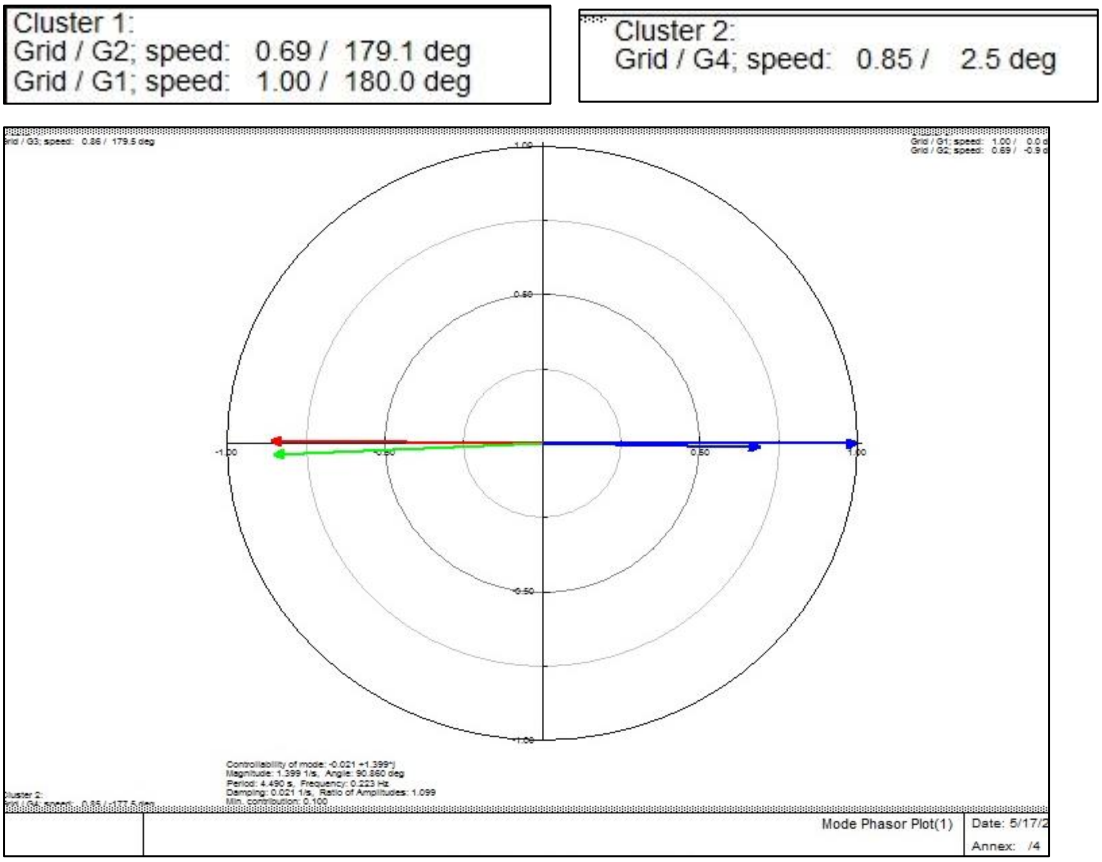


Figure 4-13 Modal Analysis at 0.2 Hz

The relative participation factor for this mode is represented as follows:

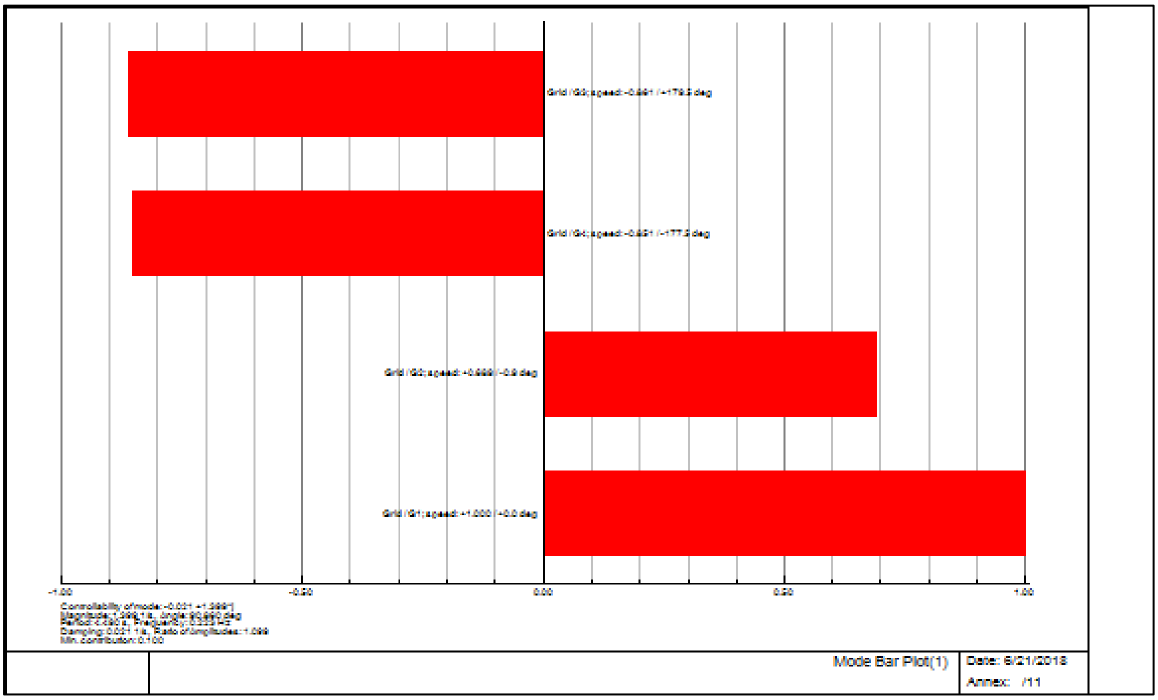


Figure 4-14 Participation Factor

Now at 0.3 Hz system mode frequency has been changed and the following values have been obtained. Table 4-7 represents all the different 28 modes values at 0.3Hz frequency.

Table 4-7 Mode Parameters at 0.3Hz

Mode No.	Magnitude 1/s	Damped Freq Hz	Angle deg	Damping Ratio
18	**3.8406**	**0.07370135**	**173.07473**	**0.992704**
19	**3.8406**	**0.07370135**	**-173.07473**	**0.992704**
20	**1.11946**	**0.35470722**	**9086022**	**0.051015**
21	**1.11946**	**0.35470722**	**9086022**	**0.051015**

From the figure 4-13 mode phasor plot is plotted and the following values have been obtained:

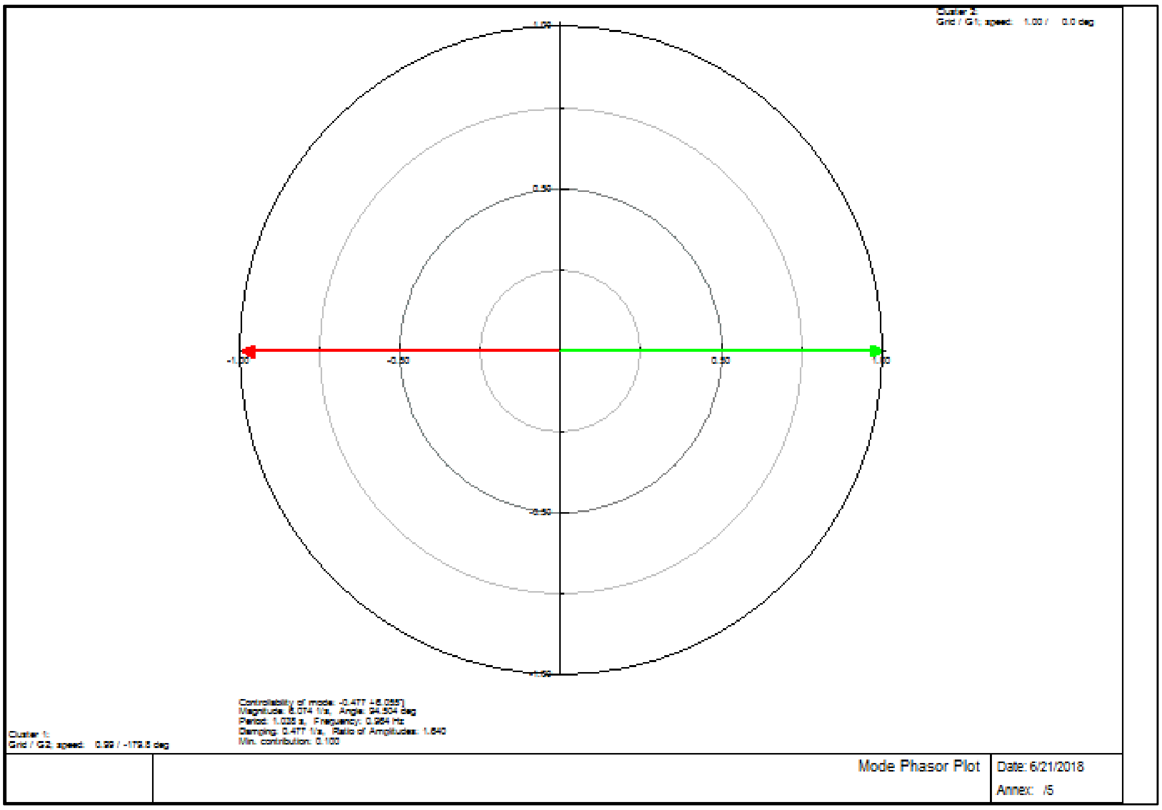


Figure 4-15 Modal Analysis at 0.3 Hz

- Controllability of mode is +0.000+0.000* j
- Magnitude is 0.000 (1/s)
- Angle is 0.000°
- Period is 0.000 s

- Frequency is 0.000 Hz
- Damping is -0.000(1/s)
- Ratio of Amplitudes is 0.000
- Minimum Contribution is 0.100

The behaviour of a system has been studied under small load variations. The basic purpose was to observe if these small variations can lead to any of above conjugate pairs of eigenvalues diagonally across of the imaginary axis representing angular instability of the system.

The relative participation factor for this mode is represented as follows:

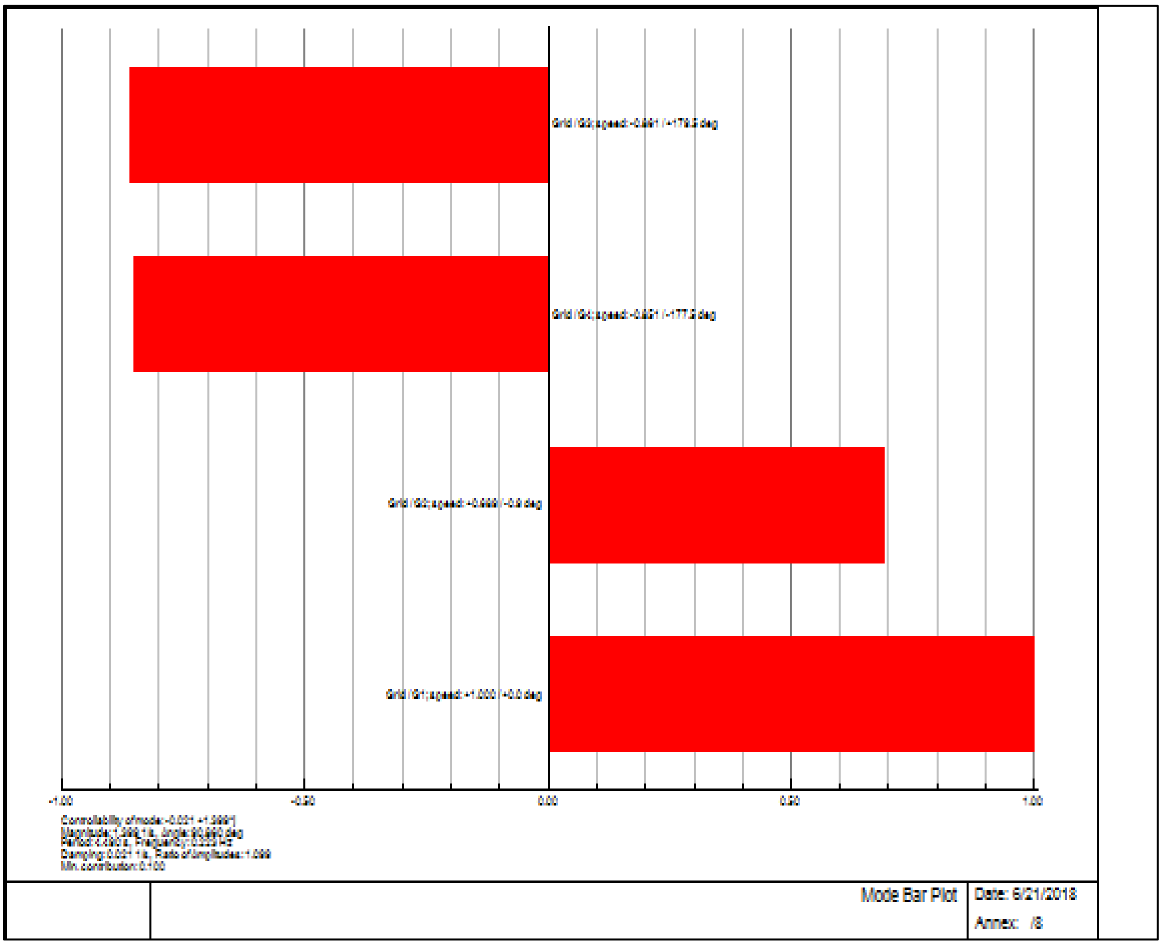


Figure 4-16 Participation Factor

CHAPTER 5

PMU BASED MEASUREMENT TECHNIQUES

PMU based measurement techniques are now widely being explored for detection of events in power system. There have been many several methods that have been introduced by researchers [7] like

- For Block Processing Methods introduces Modified Extended Yule Walker (MEYW) i.e. used to identify modes in time domain [8].
- Subspace identification method is also used for mode estimation in time domain for mode damping and frequency [9]-[12].
- Frequency Domain Decomposition [FDD] method for mode estimation in power system for frequency domain has been developed [6].

Above and beyond these block processing methods to overcome its drawbacks recursive methods have been introduced.

- Based on recursive identification for ARMA blocks have been introduced as Robust RLS [13] and Regularized Robust RLS [14].

The main advantage for using the recursive methods is its speed of computation for updating its previous estimation with the new sample data with chosen forgetting factor. Another advantage of this method they require less memory for storing the data. In this work two methods FDD and PA method has been explored as follows.

5.1 FAST FREQUENCY DOMAIN DECOMPOSITION FOR AMBIENT OSCILLATION MONITORING

Frequency Domain Decomposition (FDD) is briefly introduced. In Frequency Domain Decomposition (FDD) method, it includes two significant steps for estimating mode information. First step is for Power Spectral Density (PSD) matrix calculation, which requires auto-spectrum and cross-spectrum estimation for each discrete frequency of measured signal after Fourier transform of the matrix and the next step is PSD matrix for Singular Value Decomposition (SVD). Though, these two steps make FDD time-consuming and when the data window becomes large then its computation burden increases.

5.1.1 Structure and Procedures of Frequency Domain Decomposition

In power system recent past years all over the world synchrophasors has been widely installed. Besides this it is becoming further popular to obtain meaningful information by making use of synchrophasor measurements. On this area a lot of research is going. Frequency Domain Decomposition (FDD) introduces for system modal analysis and it is extended to synchrophasor application. In power system for dynamic analysis FDD algorithm is an important aspect to monitor damping of a system. Figure shows FDD procedures and structure.

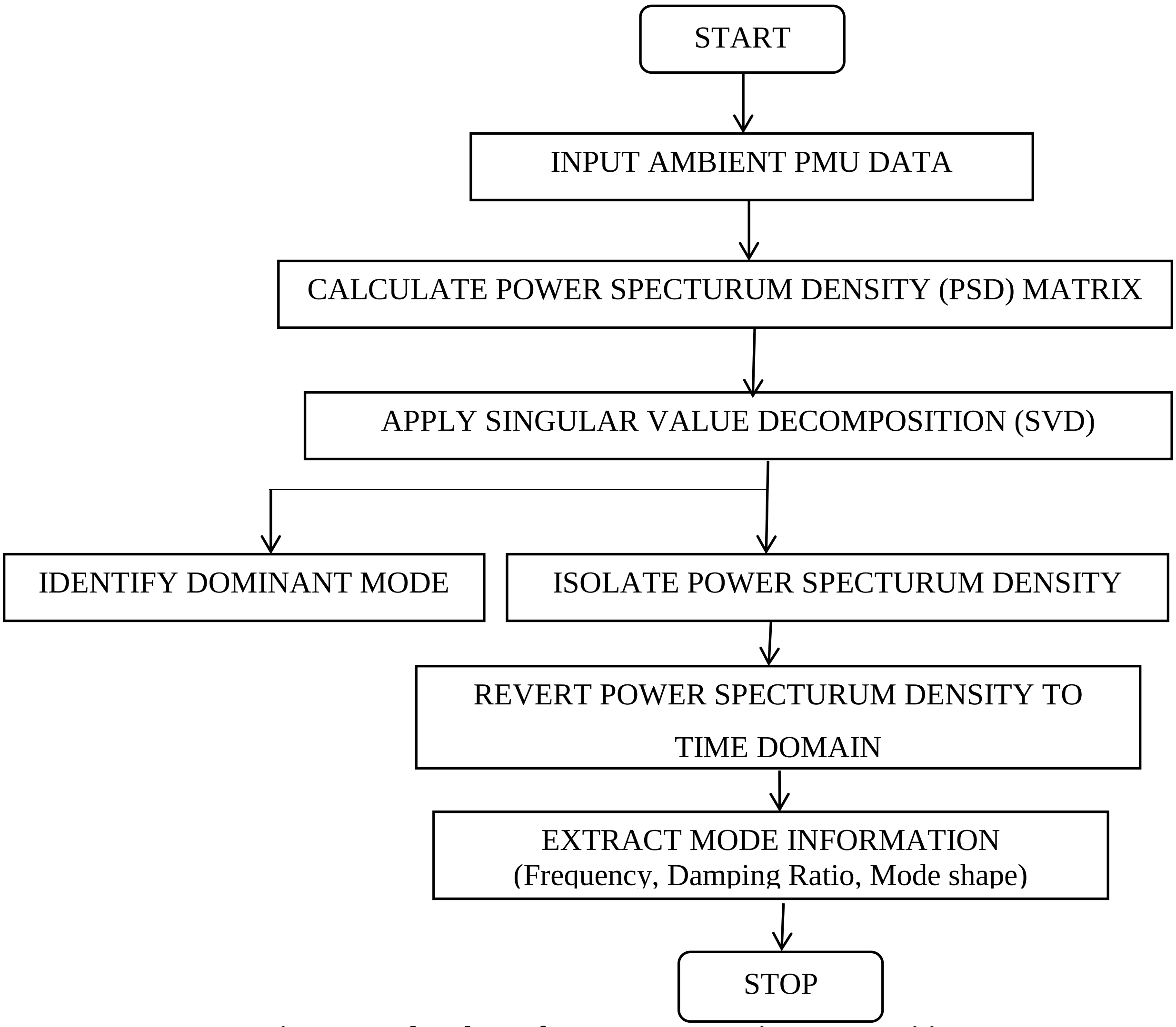


Figure 5-1 Flowchart of Frequency Domain Decomposition

5.1.2 Basic Theory of Frequency Domain Decomposition

Power system is of high-order nonlinear system. For the benefit of the system analysis it can be linearized and simplified around its equilibrium point. Its simplified state space can be written as:

$$\Delta\dot{x} = A\,\Delta x + B\,\Delta u$$
$$\Delta y = C\,\Delta x \qquad 1$$

Where Δx is the system state vector, usually rotor angle, speed of generator etc. Δu is the input vector and Δy is the output vector it can be any type of PMU measurement of a system. Coefficient matrices are A, B and C. For multi-input multi-output(MIMO) system such as linearized power system model illustrates from equation 1, therefore it shows the relationship between power spectrum density input $S_{uu}(j\omega)$ and power spectrum density output $S_{yy}(j\omega)$ represents the following equation

$$S_{yy}(j\omega) = H(j\omega)\, S_{uu}(j\omega)\, H^{*}(j\omega) \qquad 2$$

Where H is overall transfer function of system for all modes as well as all outputs besides this *subscript denotes Hermitian transpose operation. Therefore, output power spectrum density $S_{yy}(j\omega)$ is estimated through synchrophasor data by accounting auto/ cross of spectrum subsequently its Fourier transform. Whereas given analysis window (t_o, t_f), assuming F_i (ω_j) express as it fourier transform of a measured signal y_i (t_i) at $t = t_i$ whereas fourier transform at each discrete frequency $\omega = \omega_j$ of a measured signal within the frequency range (0, ω_f). Now at a specified discrete frequency it is defined as F (ω_j):

$$F(\omega_j) = (F_1(\omega_j) \ldots\ldots F_{n_y}(\omega_j)) \qquad 3$$

The PSD matrix can be find by:

$$\widehat{S}_{yy}(j\,\omega_j) = F(\omega_j)\, F^{*}(\omega_j) \qquad 4$$

Whereas diagonal elements $F_i(\omega_j)\, F_i^{*}(\omega_j)$ represents auto-spectrum and cross spectrum is estimated by off diagonal elements $F_i(\omega_j)\, F_i^{*}(\omega_j)$ ($i \neq k$).

By executing singular value decomposition (SVD) at each discrete frequency $\omega = \omega_j$ not beyond its frequency range to the output power spectrum matrix ($S_{yy}(j\omega)$) is obtained by the following equation :

$$\widehat{S}_{yy}(j\,\omega_j) = W_i\,(\omega_i)\,S_i(\omega_i)\,W_i^*\,(\omega_i)$$

$$= [w_1(\omega_i)\ \ldots\ldots\ w_{n_y}\ (\omega_i)]\begin{bmatrix} s_1(\omega_i) & & \\ & \ddots & \\ & & s_1(\omega_i) \end{bmatrix}\begin{bmatrix} w_1^*(\omega_i) \\ \vdots \\ w^*_{ny}(\omega_i) \end{bmatrix} \qquad 5$$

Hence $w_i(\omega_i)$ denotes singular vector and $S_i(\omega_i)$ denotes singular value. If near a peak frequency $\omega = \omega_i$, there is only one dominant mode would be a rank one matrix then the first singular value is considerably larger than others in a matrix. The rank of singular value matrix $S_i(\omega_i)$ is determined by number of the poorly damped modes those are excited by disturbances near $\omega = \omega_i$. Now at each discrete frequencies $\omega = \omega_i$, SVD can be applied to PSD matrix, its largest singular value versus frequency can be plotted. And therefore this plot is known as Complex Mode Indication Function (CMIF) plot.

5.1.3 Results of the two area system

In two area Kundur power system we have identified the result above to compare our results we have done the analysis in MATLAB by FDD method. By exporting the values from DIgSILENT PowerFactory and importing these results in MATLAB we have identified its mode shape and its damping frequencies. Frequency domain decomposition coding has been discussed in Appendix. Figure 5-2 shows the damping at 0.3Hz of frequency. The identified results related to the FDD method is as follows:

Identified frequencies

Mode: 1; Modal Frequency: 0.2 (Hz)

Related mode shapes

Mode shape # 1:

Damping Factor is given as: .99

So the system is found estimated to be critically stable at 0.3Hz of frequency of forced oscillations. However the expected results for forced oscillations has be undamped or zero damping. Therefore FDD method is found not suitable for detecting forced oscillations.

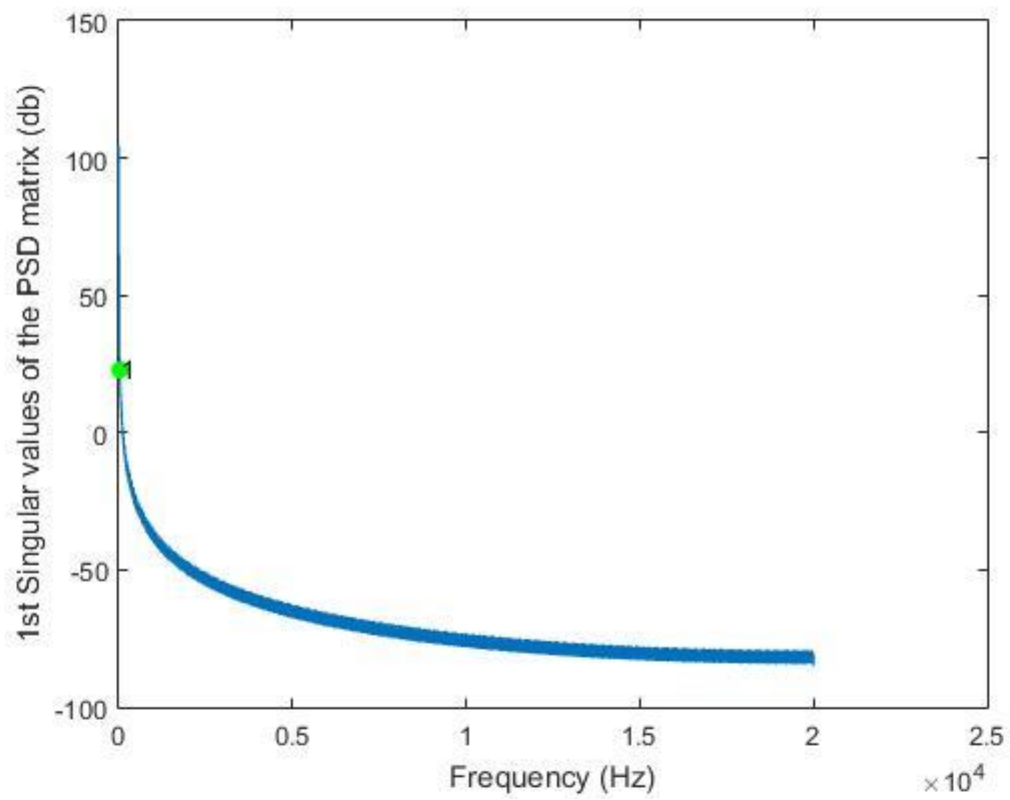


Figure 5-2 FDD Output Graph

5.2 PRONY ANALYSIS FOR AMBIENT OSCILLATION MONITORING

In 1795, Gaspard Riche, Baron de Prony[7] introduce a method for representing gas expansion behaviour in relationship with sums of damped exponentials. This method determines on the recorded samples which have first fitting exponentials to find data between equally spaced measurements, then finding the intermediate points by estimating the exponential model of system. These techniques for data modelling as linear combination of exponentials have been developed from exactly fitting damped. For a given N data samples x[1],……x[n], Prony method calculates x[n] by using p-term exponential model given as:

$$\boldsymbol{\widehat{x[n]} = \sum_{k=1}^{p} A_k \ \exp[(a_k + j2\pi f_k)(n-1)T + j\theta_k]}, \quad 1 \leq n \leq N, \qquad 1$$

Where A_k is the amplitude, T is time between samples, a_k is damping factor in second^{-1}, θ_k is sinusoidal phase in radians and f_k is frequency. However, exponentials in complex conjugate pairs must exist for real data samples, which will be change into the expression:

$$\widehat{\mathbf{x}[\mathbf{n}]} = \sum_{\mathbf{k=1}}^{\mathbf{p/2}} \mathbf{2A_k} \ \mathbf{exp}[\mathbf{a_k}(\mathbf{n}-\mathbf{1})\mathbf{T}]\mathbf{cos}[\mathbf{2\pi f_k})(\mathbf{n}-\mathbf{1})\mathbf{T}+\mathbf{j\theta_k}] \text{ , } 1\leq n \leq N, \qquad 2$$

In power systems, for analysing oscillations Prony analysis has been widely used [40-41], and characterizing systems based on their responses, from which models can be derived [6]. In addition, Prony has also been used for protection applications and tracking dynamics of measurements. However, its unique performance of preceding applications makes it different method for model validation.

5.2.1 Basic Method for Analysis

If the total number of exponential parameters is same as the data samples, then an exact fitting can be evaluate. Equation (1) can be written as

$$X[n] = \sum_{\mathbf{k=1}}^{\mathbf{p}} \mathbf{h_k} \, \mathbf{z_k^{n-1}} \qquad 3$$

Where,

$$h_k = A_k \exp(j\theta_k)$$

$$z_k = \exp\left[(a_k + j2\pi f_k)\, T\right] \qquad 4$$

as the number of samples is equal to number of complex parameters in exponentials, $\hat{x}$[n] expression of estimate could be replaced with x[n]. therefore equation 3 can be rewritten as :

$$\begin{bmatrix} z_1^0 & z_2^0 & \cdots & z_p^0 \\ z_1^1 & z_2^1 & \cdots & z_p^1 \\ \vdots & \vdots & & \vdots \\ z_1^{p-1} & z_2^{p-1} & \cdots & z_p^{p-1} \end{bmatrix} \begin{bmatrix} \boldsymbol{h_1} \\ \boldsymbol{h_2} \\ \vdots \\ \boldsymbol{h_p} \end{bmatrix} = \begin{bmatrix} \boldsymbol{x[1]} \\ \boldsymbol{x[2]} \\ \vdots \\ \boldsymbol{x[p]} \end{bmatrix} \qquad 5$$

Equation 3 is a solution to homogenous linear constant coefficient equation in order to solve this equation 5. Let us consider a polynomial ϕ (z) constitute z_k as roots:

$$\Phi(z) = \prod_{k=1}^{p}(z - z_k) \qquad 6$$

Now, the above expression is summation form by expanding it into power series:

$$\Phi\ (z) = \sum_{m=0}^{p} a[m] z^{p-m} \qquad 7$$

This expression constitutes of complex coefficients a[m] as a[0]. Now applying equation7 in equation 1 we will get p x p matrix satisfies the obtained relation:

$$\begin{bmatrix} x[p] & x[p-1] & \cdots & x[1] \\ x[p+1] & x[p] & \cdots & x[2] \\ \vdots & \vdots & & \vdots \\ x[2p-1] & x[2p-2] & \cdots & x[p] \end{bmatrix} \begin{bmatrix} a[1] \\ a[2] \\ \vdots \\ a[p] \end{bmatrix} = - \begin{bmatrix} x[p+1] \\ x[p+2] \\ \vdots \\ x[2p] \end{bmatrix} \qquad 8$$

The above matrix can now be solve to evaluate complex polynomial coefficients and can solve for the roots of z_i in equation 5. Now we can solve for sinusoidal frequency and damping.

$$a_i = \frac{\ln |z_i}{T} \text{ second}^{-1} \qquad 9$$

$$f_i = \tan^{-1} \frac{\frac{\Im\{z_i\}}{\Re\ z_i\}}}{2\pi T} \text{ Hz}$$

From z_i knowing we can find h_i parameters which is used to determine amplitude and phase components.

$A_i = [h_i]$

$$\theta_i = \tan^{-1} \frac{\Im\{z_i\}}{\Re\{z_i\}} \text{ radians} \qquad 10$$

Steps for Prony Algorithm

The strategy for obtaining a Prony solution can be summarized as follows:

Step 1: Arrange all selected elements of record into a data matrix.

Step 2: Fit the data within discrete linear prediction model, like least squares Solution.

Step 3: Find the roots of the characteristic polynomial shown in equation1 linked with model of Step 1.

Step 4: By using the roots evaluated in step 3 as complex modal frequencies for the signal then evaluate amplitude and the initial phase of each mode.

5.2.2 Results of the two area system

On the basis of our previous experience with the real time PMU data such as transient analysis Prony method is seen to be outstanding for real time ring down modal analysis.

FDD fails in our analysis as its damping ratio estimate of Interarea mode at 0.2Hz was found to be 0.9. Prony analysis technique has been applied to forced oscillation response data to find an inter-area mode forced oscillation near 0.2Hz case. Power factory has inbuilt Prony analysis engine which was used in this study. By using prony analysis damping ratio was found to be near zero as shown in Table 5-1, which satisfies the condition for undamped system.

Table 5-1 Prony Analysis

Prony - Line5 m Psum bus1	**Line5**		
Prony Frequency in Hz	**Prony Damping Ratio**	**Prony Magnitude**	**Prony Phase Angle**
	Total Active Power/Terminal in 1/s	**Total Active Power/Terminal in MW**	**Total Active Power/Terminal in degree**
-50.000001	13.690756	0	-153.89053
-41.246751	13.418404	0	-123.450874
-32.342931	12.575557	0	-92.728096
-22.941919	10.934012	0	-60.898031
-0.400688	0.012539	0.000183	137.354474
-0.19938	-0.001903	0.077639	163.031296
0	0.000001	326.042691	0.000001
0.19938	**-0.001903**	**0.077639**	**-163.027698**
0.400688	0.012539	0.000182	-137.320181
22.941919	10.934012	0	113.117461
32.342931	12.575557	0	144.947504
41.246751	13.418404	0	175.670398

CHAPTER 6

CONCLUSION AND FUTURE SCOPE

6.1 CONCLUSION

In this Dissertation, measurement based oscillation monitoring techniques were studied to make use of the PMU data available for small signal stability monitoring with respect to forced oscillations in power system. The objective is to detect the poorly damped modes that occur in system by making use of ambient data and to detect the presence of forced oscillations. All modal estimation such as frequency, mode shapes, damping ratio and energy level were estimated for forced oscillations. This work also studies the components, amplitude and envelope of forced oscillation in Two Area Kundur power system. Some important conclusions for forced oscillations in power system are:

- Forced oscillations can occur in power system due a malfunctioning of mechanical components in power system as well as power electronic components in the system.
- If the frequency of the forced oscillations injected in the power system is close to that of the system electromechanical modes, then there is a possibility of resonance in the system.
- The forced one is of the same frequency with zero damping as forced disturbance. Another one is similar as system mode modal properties.
- Forced oscillation shapes are identical as envelope. The nature of upper envelope is non-oscillatory of resonance. Similarly, the envelope of the beats is always oscillatory in nature.

In this dissertation two different methods: Frequency domain decomposition (FDD) and Prony Analysis (PA) were studied for measurement of forced oscillations in power system. The nature of the forced oscillations has been studied for Interarea modes, and also how the conditions of resonance occur. It has been found that PA method gives better estimate of forced oscillations than FDD method of estimation. Further research in this area is necessary.

6.2 FUTURE SCOPE

Future scope of work in this area includes:

- To develop methods and algorithms to detect the location of forced oscillation in the system
- Explore other signal processing techniques than the one explored in this thesis for detecting the presence of forced oscillations in the power stem.

Similarly, for studying other stability phenomenon like voltage security monitoring and two level or multi-level techniques for ring down analysis can be studied for future research. And an overall research is needed to find the sources of forced oscillation in order to avoid the danger of large blackouts and resonance in power system.

APPENDIX

MATLAB CODE FOR FREQUENCY DOMAIN DECOMPOSITION

```
function [Frq,phi]=FDD(Input,Fs)

% Frequency Domain Decomposition (FDD) algorithm for modal analysis
% This code allows you to manually select the peaks by simply drawing
a rectangle around the peaks.


% Input: the name of input file that contains time history data
% Fs: sampling frequency
% Frq: identified frequencies
% phi: identified mode shapes
% Example: [Frq,phi]=FDD('voltage.xlsx',40411);

% For detailed information about this method see: Brincker R, Zhang
LM, Andersen P. Modal identification from ambient responses using
Frequency Domain Decomposition. In: Proceedings of the 18th
International Modal Analysis Conf., USA: San Antonio, 2000.

% --------------------------------------------------------------------
-----
% Initialization
close all
% --------------------------------------------------------------------
-----
% Import time history data: Processed accelereation data must be
% arranged in a columnwise format (one column for each measurement
channel)
% Note that the acceleration data must be preprocessed (detrend,
filtered etc.).
% Read acceleration data from the excel file
Acc=xlsread(Input);
display('FDD is in progress, please wait ...')
% --------------------------------------------------------------------
-----
% Compute Power Spectral Density (PSD) matrix.
% CPSD function, with default settings, is used to compute the cross
power
% spectral density matrix. More sophisticated methods can also be
% applied for more accuracy.
for I=1:size(Acc,2)
    for J=1:size(Acc,2)
        [PSD(I,J,:),F(I,J,:)]=cpsd(Acc(:,I),Acc(:,J),[],[],[],Fs);
    end
end
Frequencies(:,1)=F(1,1,:);
% --------------------------------------------------------------------
-----
% Perform Modal Analysis (Use the Identifier function, below)
[Frq,phi,Fp,s1] = Identifier(PSD,Frequencies);
% Save results
save('IdResults.mat','phi','Fp','s1','Frequencies')
% --------------------------------------------------------------------
-----
% Print results
```

```
display('-----------------------------------------------------')
display('               Identification Results              ')
display('-----------------------------------------------------')
% Print frequencies
display('Identified frequencies')
for I=1:size(Frq,1)
    fprintf('Mode: %d; Modal Frequency: %6.4g (Hz)\n',I,Frq(I))
end
% Print Mode shapes
display('Related mode shapes')
for I=1:size(Frq,1)
    fprintf('Mode shape # %d:\n\n',I)
    disp(phi(:,I))
end

end

%% ---------------------------- subfunctions -------------------------
-----
function [Frq,phi,Fp,s1] = Identifier(PSD,F)

% Compute SVD of the PSD at each frequency
for I=1:size(PSD,3)
    [u,s,~] = svd(PSD(:,:,I));
    s1(I) = s(1);
% First eigen values
    s2(I) = s(2,2);
% Second eigen values
    ms(:,I)=u(:,1);
% Mode shape
end

% Plot first singular values of the PSD matrix
figure
hold on
plot(F,mag2db(s1))
xlabel('Frequency (Hz)')
ylabel('1st Singular values of the PSD matrix (db)')

% ---------------------------------------------------------------------
-----
% Peak selection
% a: Draw rectangles around peaks while holding left click
% b: Press "Space" key to continue peak selection
% c: Press "any other key" if you have selected a peak by mistake and
want
% to ignore it
% ---------------------------------------------------------------------
-----

Fp=[];% Frequencies related to selected peaks
NumPeaks=input('Enter the number of desired peaks:');
display('-----------------------------------------------------')
display('Peak selection procedure')
display('a: Draw rectangles around peaks while holding left click')
display('b: Press "Space" key to continue the peak selection')
display('c: Press "any other key" if you have selected a peak by
mistake and want to ignore it')
k=0;
while k~=NumPeaks
```

```
    A=getrect;
% Draw a rectangle around the peak
    [~,P1]=min(abs(F-A(1)));
    [~,P2]=min(abs(F-(A(1)+A(3))));
    [~,B]=max(s1(P1:P2));
    Max=B+P1-1;
% Frequency at the selected peak

scatter(F(Max),mag2db(s1(Max)),'MarkerEdgeColor','b','MarkerFaceColor'
,'b')          % Mark this peak
    pause;key=get(gcf,'CurrentKey');
    Fp(end+1,:)=[Max,F(Max)];
    if strcmp(key,'space')
        % Press space to continue peak selection
        k=k+1;

scatter(F(Max),mag2db(s1(Max)),'MarkerEdgeColor','g','MarkerFaceColor'
,'g')       % Mark this peak as green
    else
        % Press any other key to ignore this peak
        Fp(end,:)=[];

scatter(F(Max),mag2db(s1(Max)),'MarkerEdgeColor','r','MarkerFaceColor'
,'r')       % Mark this peak as red
    end
end
% Number selected peaks, respectively
[~,Sr]=sort(Fp(:,2));
Fp=Fp(Sr,:);
clf
plot(F,mag2db(s1))
hold on
xlabel('Frequency (Hz)')
ylabel('1st Singular values of the PSD matrix (db)')
for I=1:size(Fp,1)

scatter(Fp(I,2),mag2db(s1(Fp(I,1))),'MarkerEdgeColor','g','MarkerFaceC
olor','g')
    text(Fp(I,2), mag2db(s1(Fp(I,1)))*1.05, mat2str(I))
end
% Identified modal frequencies
Frq=Fp(:,2);
% Compute mode shapes for each selected peak
for J=1:size(Fp,1)
    [ug, ~, ~] = svd(PSD(:,:,Fp(J,1)));
    phi(:,J) = ug(:,1);
end

end
```

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