A STUDY ON ELECTROMECHANICAL MODE ESTIMATION OF POWER SYSTEM BY SUBSPACE IDENTIFICATION METHOD

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CERTIFICATE

I hereby certify that the Project Dissertation titled, **"A Study on Electromechanical Mode estimation of power system by Subspace identification method"** which is submitted by, Vipin Kumar, Roll No. 2K16/PSY/22 student of M.Tech Power System (PSY), under the supervision of Prof. S.T. Nagarajan and Prof. Priya Mahajan of Electrical Engineering Department, 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 our 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.

S.T. Nagarajan

Place: Delhi **Prof. S. T. NAGARAJAN**

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ABSTRACT

The thesis is focused around the study of electromechanical oscillations in the power system which are primarily responsible for instability in the power system. The analysis is carried out on two platforms – DigSILENT's Power Factory and Matlab. In this thesis, popular Kundur's two area system is considered for evaluation of system parameters, considering a three phase fault on the tie lines. Modal analysis of a system is gaining popularity in the analysis of system's eigen values, that are interpolated to obtain modes present in the system. The two platforms involved are communicated via comma separated values (.csv) files.

Power factory is used in this analysis of two area system. A two area model is implemented consisting of four generators and eleven bus system. Phasor simulation is executed on the model for the three phase fault, thus obtaining graphs of the simulation for tie-line power, rotors speed, and rotor angle with respect to time. Moreover the simulation is extended by taking modal analysis of the current system in operation. Modal properties of the system depicts the behaviour of the system oscillations, the system properties thus obtained shows the system under consideration is stable.

Matlab utilizes the fact that the system under consideration is a linear discrete time system. It explores the concepts of linear algebra for the evaluation of system modal properties by subspace identification method. Matlab is used for study of the two area system undergoing a transient by Subspace identification (SSI) and Recursive adaptive subspace identification (RASSI) method. RASSI method is recursive method that is applied for the continuous monitoring of the system modal properties with the synchrophasor data.

A comparison of these methods has been carried out in this work.

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ABBREVIATIONS

PSS	Power System Stabilizer
AVR	Automatic Voltage Regulator
SSI	Subspace Identification
RASSI	Recursive Adaptive Subspace Identification
SVD	Singular Value Decomposition
GOI	Government of India
LTI	Linear time invariant

LIST OF SYMBOLS

A	System state matrix
C	System Output matrix
B	System Input matrix
x_{k+1}	Future state value
x_k	Present state value
y_k	Present output state
w_k	Process noise
v_k	Measurement noise
H, Ĥ	Co-variance matrix
O, Ô	Observability matirx
ϕ_m	Model Mode Shape matrix
ϕ_s	System Mode Shape matrix

Chapter 1
Introduction

India is having an electric utility sector as one national grid with installation capacity of 344.00 GW as on June 2018[1]. Renewable sources have constituted nearly 33.23% of installed capacity. The country is having an electricity consumption of nearly 1,122 kWh per capita during financial year 2016-17. At world level, India is securing as a third largest producer as well as third largest consumer of electricity. Agriculture sector has reached a record highest of (17.89%) consumption of electric energy in FY 2015-16 among all countries.

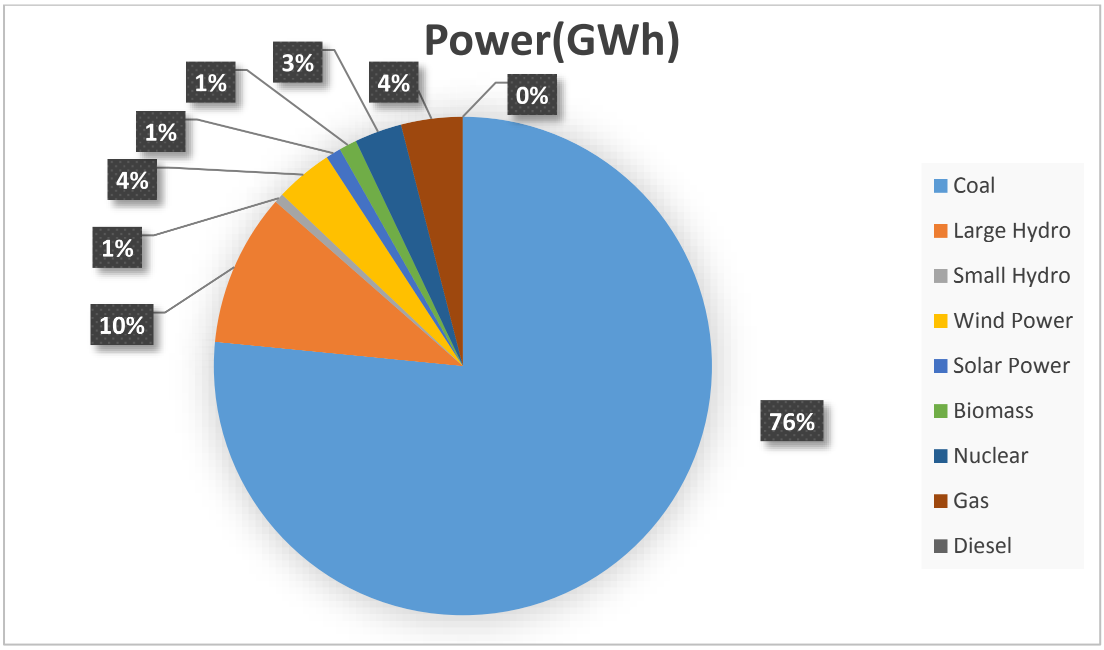


Figure 1.1 Electricity generation by different sources for FY 2016-17

India is lacking adequate infrastructure to supply electricity despite having surplus power generation capacity. The GOI has launched "Power for All" scheme for the people in the country to address the lack of enormous electric supply. Inspite of the fact, the government is investing for an increased venture of renewable energy. Power sector of India is mostly governed by fossil fuels, primarily coal, which in comparison to last year produced about three quarters of total electricity. The GOI has prepared a National Electricity Plan (NEP) of 2018 which states that the nation do have plenty of power plants of non-renewable type for until year 2027, with nearby commissioning of approximately 50 GW power plants under construction and also accomplishing a total capacity of 275 GW renewable power.

1.1 General

Power-system provides a vital importance in our daily life. Modern day requires huge amount of energy for use in industry, commerce, agriculture, transportation, communication, domestic households etc. Electrical power cannot be conveniently stored in large quantities. Thus means that the entire generation at any instant must be met by the energy demand. Power-system must fulfil reliability of supply, supplying electrical energy of good quality & providing economic generation and transmission at all environmental conditions possible. Moreover, the power-system is a highly non-linear system that operates in a constantly varying conditions: changing loads, generator outputs and operating parameters that change continuously.

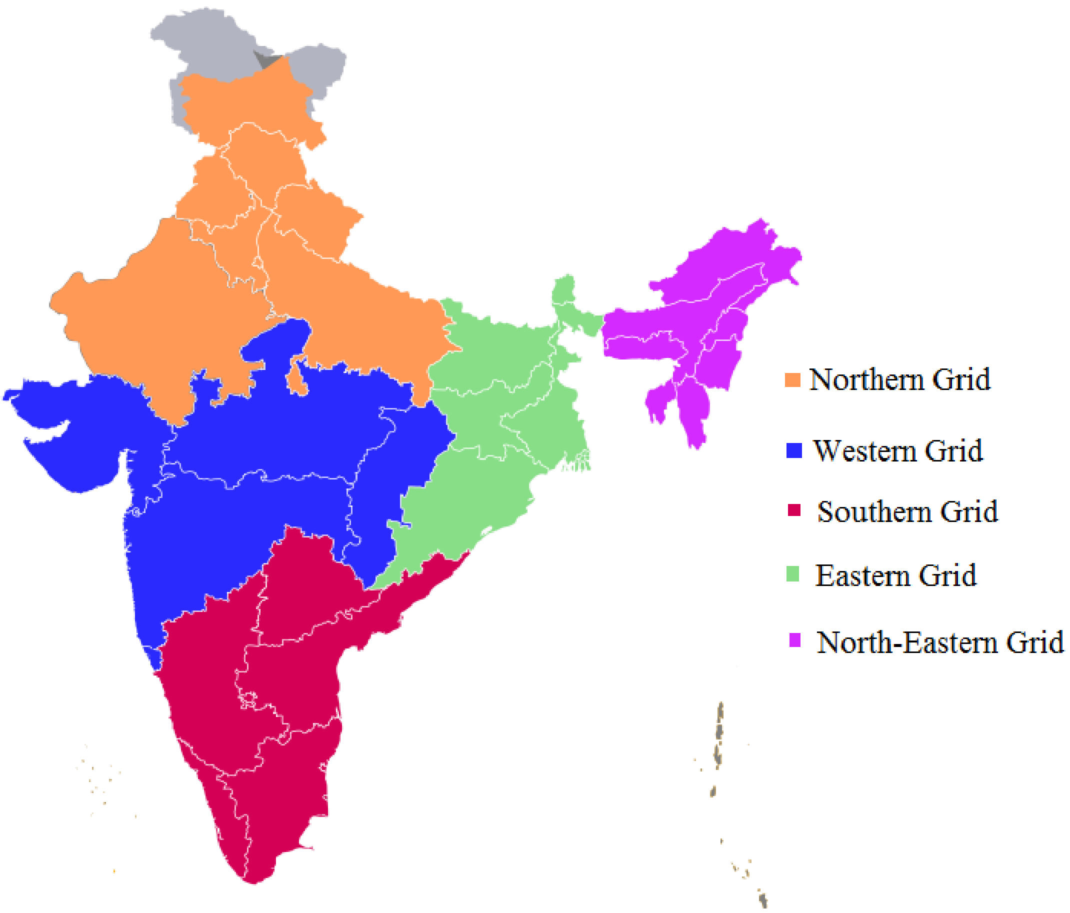


Figure 1.2 The national grid constituting 5 regional power grids.

India is having a single wide-area synchronous grid that covers entire country. The spread of HV transmission lines is approximated to 416 km^2 in entire area of the country. The area has HT (230 kV and above) transmission lines is nearly equal to 322,000 km in length and HV (132 and above) transmission lines nearly 700,000 km. The transmission lines above 400 V have a length of 10,558,177 km [1]. The power-system operates with large number of sub-stations along with a vast network of hv transmission lines with low demand factor, which is not competence in meeting the peak load of electricity demand. Comprehensive studied exploring engineering concepts are required to be implicated and evolving system inadequacies to make smart grid that can provide a maximising utility of transmission infrastructure.

The July 2012 a major blackout, that affected the northern region of the country, was among the largest power grid failure in Indian history. The introduction of Availability Based Tariff (ABT) has brought satisfactory stability for power transmission in the Indian transmission grids. Nevertheless, having additional surplus power in power grid is not a convenient solution to the problem moreover, it is becoming outdated. India's Aggregate Transmission and Commercial (ATC) concord losses of nearly 21% in FY 2017-18.

Power-system stability have been identified as an essential issues for operation of power-system since 1920s [3]. Several major blackouts have been reported by power-system instability that have showed the significance of stability phenomenon [5]. Over the couple of decades, transient instability in most of the systems was considered as the dominant stability problem, and presently it is been in focus for the ample of the industry’s attention related in concerning power-system stability. As evolution of power-systems is going at a fast rate through continuous growth in inter-connections, using new controls and technologies, and with the increased inter-connection operation has made the system operate under extremely stressed conditions, thus causing different forms of instability in the system to have emerged i.e. for example, frequency stability, inter area oscillations and voltage stability are becoming greatest concerns than in the immediate past. With the concern, the need to analyze the hard facts of power-system stability by consistent use of methodology for developing power-system design and operating criteria. Study procedures and standard analytical tools are in continuous development in the present for analyzing instability concern.

Modal analysis is the process for evaluation of dynamic properties of the system in the frequency domain. Mode shapes demonstrate the eigenvectors that describe the relative displacement of two or more elements in a system. With the advancement of digital computing, the analysis of the signals in frequency domain allows us to use various implementation methods. These methods provide a better understanding for the system stability by mode shapes. Modal analysis thus allow us to know the mode shapes involved in the stability of the power-system under a transient disturbance. Mode shapes gives eigen vectors that are responsible for causing the instability in the system.

1.2 Power-System Stability: Definition

Power-system engineering practitioners have commonly agreed for the definition of power-system stability as mentioned by P.Kundur [2] and is as defined as

"Power-system stability is the ability of an electrical power-system, for a given initial operating conditions, to regain the state of operating equilibrium after system being subjected to a physical disturbances, with most of the system variables bounded so that practically the entire system remains intact."

During system operating under normal conditions, all generators of the system operate at a common equilibrium point. After undergoing a disturbance, developed in the system, the equilibrium is disturbed thus all generators responding to the disturbance. The generators respond to the changes in the system to attain the equilibrium again, and the stability of the system is restored.

1.3 Motivation

Stability concerns about the ability for a power-system to recover from disturbances, both large and small, and settling to a state of acceptable equilibrium. Randomly occurring changes in load conditions, faults that results in subsection tripping and random changes in values of regulating controllers, are some examples of disturbances. With the large growing power-system the stability issues are at a great concern.

Linear algebra provides a wide concept in the state-space modelling of the system by exploring the wide area of vectors, matrices and planes. Mode estimation is realised with the projection of vectors, thus providing the mode vectors for the specific eigen value for the system. Subspace algorithm are effective methods for the estimation of modes of a system from wide area measurement of ambient data. They have relatively simple technique of implementation for selection of order of the system. With the recursive implementation of the data the computational burden for calculation of the SVD of large-dimensional matrix is overcome. Also adaptive switching allows us to give fast accurate online estimation of modes damping and damped frequency.

1.4 Dissection of thesis

The thesis report is outlined as follows.

Chapter 1 is an Introduction giving a brief study of the project

Chapter 2 deals with the Literature review of the work proposed in the thesis. It gives the consent of the work proposed on previous research works.

Chapter 3 describes Electromechanical Modes in details exploring the types and their involvement in stability of the power-system.

Chapter 4 describes implementation of model in **DigSILENT** (power factory) to obtain the real time system values.

Chapter 5 describes implementation of Modal Analysis in **MATLAB** that assimilate the mathematical rigor of linear algebra.

Chapter 6 describes the review of results that provide information concerning stability of dynamic systems in operation and practical results in connections of the model analysis done in MATLAB.

Chapter 7 describes the conclusion drawn and future scope of work.

1.5 Conclusion

In this chapter a brief about power-system stability and mode shapes is discussed. Modes are responsible for the stability of the system, modes shapes entirely trace the characteristics of the system dynamics. The chapter also provide a quick look of the topics structured in the thesis/dissertation.

Chapter 2
Literature Review

2.1 Introduction

The chapter imparts a concise literature review of "Estimation of modes in a power-system for stability analysis". For the presented work, extensive surveying of previous significant research work has been done in context of blackout for small-signal stability. Based on the work done for thesis, the prime emphasis of this literature review is on the following points:

i. Stability Analysis of power-systems
ii. Study of oscillations
iii. State-space modelling
iv. Modes and stability relation

2.2 Stability Analysis of power-system [5]-[8]

Stability in power-system is recognised as the important issue for power-system operation since many major blackouts have been caused. Stability evaluation is a vital aspect for the reliability and continuity of power between generation and distribution in power-system. Certain blackout make an understanding the issues of stability:

Gregory S. Vassell (1965) [5] reported the northeast blackout happened in year 1965. It was a major breakdown that almost spanned for 13hrs of no power supply across the region. The major reason behind the blackout was tripping of the heavily loaded 230kV transmission line, thus generating large surge across the power-system under operation and causing a catastrophic failure of the entire system.

S. Arash Nezam Sarmadi et al.(2016) [6] deliberates the oscillations event in western American power-system occurred on November 29, 2005, when a 20 MW forced oscillation injected in Alberta leads to 200 MW oscillations on inter-tie lines of California-Oregon. The synchro- phasor data shows that the large amplitude in tie-line oscillations that were caused by a resonance between forced oscillations and 0.25 Hz inter-area mode of western system.

Loi Lei Lai et al. (2013) [7] discussed about Indian blackouts occurred at July end. A report developed by the enquiry committee, which was formed by the Ministry of Power, showed the blackout of grid was primarily because of the weak transmission system which suffered from multiple outages. The problem simulated in power factory, the solution to the cause is applying more stable AVRs in the generators and HVDC and HV AC should be well-coordinated to reduce power-system instability.

C. Cañizares et al.(2016) [8] summarizes six benchmark systems for the control and analysis of the electro-mechanical oscillations of the power-systems as recommended by the IEEE for stability analysis. The benchmark systems are chosen for particular characteristics that leads to designing of control system problems, in relevance for the research organizations.

2.3 Study of oscillation [9]-[16]

Most of the stability concerns with the study of oscillations in the power system. The study of oscillation make a perspective idea of how different area under common operation behave for a common disturbances. Following research work has been extensively analyzed and studied for the work:

M. Klein et al. (1991) [9] presented an approach to study the nature of inter-area oscillations in power-systems. They discussed the effects of the system structure, generator modelling, types of excitation and system loads. The study involves stability of both small-signal and transient, for determination of characteristics of the system.

Aaron F. Snyder et al. (1998) [10] explains oscillations of low frequency are harmful for the objectives of transferring maximum power & getting optimal power-system security. The problem can be rectified by addition of the PSS to the AVR on the generators in the power-system. The use of additional stabilizer provides a damping provided by a means to reduce the hindering effects caused of the power-system oscillations. The addition of remote feedback controller into the generator has improved damping of the low frequency inter-area oscillation developed in the two-area system.

R. Kuiava et al. (2008) [11] explains that with the increase in the number of small generators connected to grid, the distribution networks are source of problems related to electro-mechanical oscillations. The paper also showed that a significant impact on the power quality across the grid is also seen due to the presence of sustained oscillations in the response of these systems. A conventionally designed PSS has the capability of considerably enhancing the damping of the oscillations thus mitigating issues of power quality due to the potential adverse effects of the electro-mechanical oscillation.

W. Du et al. (2009) [12] presented a comprehensive survey on power-system oscillation stability and controlling them using FACTS devices. The paper initially covers the problem and then analysis of power-system oscillation, focusing damping torque analysis and modal analysis. Thereafter an analysis of study on damping power-system oscillation for controllability of oscillations. Lastly the paper analyses the applications of FACTS for enhancing oscillation damping and stability.

Ammar Ajamal et al. (2015) [13] explains the unstable or poorly damped modes of inter-area oscillations are undesirable as they results in inefficient operation of power systems, moreover can results in power system tripping or major blackouts. In the paper, a robust PSS is developed, based on PMU signals to certify reasonable damping of inter-area oscillations that results in enhancing of power-system stability. Results of time-domain transient simulation and modal analysis shows that inter-area oscillations damping was significantly improved with the modelled PSSs.

2.4 State-space Modeling [17]-[20]

State-space modelling is done for the extensive study of power system oscillations, evaluating modes in any power system. Modes of a system are eigen values of the state system matrix.

Maryam Dehghani et al. (2008) [17] explains hierarchical model for parameter identification of large-scale power systems. The method uses the theoretical relations between machine parameters and the other network elements to find the state-space model of the system. The hierarchical structure consists of two levels. In the first level, the local subsystem parameters are estimated using online measurements. In the second level, the interacting parameters are identified by the transfer some information from each subsystem.

M. Karrari et al. (2004) [18] proposed a method to determination of physical parameters of a synchronous generator using an online measurement of the terminal voltage, electrical power, and field voltage, following a gradual variation of the rotor angle, and the field voltage maintaining the equivalent steady-state operating condition. The method is based on the information that the synchronous generator is composed of well defined linear and nonlinear model structures.

Nelson Martins (1986) [19] explains eigenvalue and frequency response methods are fundamental tools for implication in the analysis of small-signal stability of multi-machine in any power-systems. One algorithm evaluates eigenvectors and eigenvalues of a large power-system, while other gives the frequency response of the transfer functions.

2.5 Modes and Stability Relation [23]-[29]

Electromechanical modes are parameters for the evaluation of stability in any power system. Modes are having an damped frequency and damping ratio, modes with low damping ratio often responsible the instability of power system.

K. A. Salunkhe et al. (2016) [23] explains despite the use of devices like power swing damping controllers and generator excitation systems, in many power-systems a poorly damped or undamped swings are occasionally observed. Reasonably because of the inability of the controllers to filter a large variety of swing modes and operating conditions. Online eigen value analysis of the system model, assuming linear, can be used for suggest corrective actions. The paper developed a scheme for evaluation of combined measurement and model based approach for power swing damping valuation and control. Information of Mode-shape is emphasised to correlate the modes observed in linearized model and measurements. Once a low-damped mode is correctly identified, various effective and robust control actions for improving the damping can be estimated.

Vedran S. Perić et al. (2016) [24] formulates an optimality criterion that can be used in ambient mode estimators for the selection of synchrophasor signals. The paper proposed a procedure to rank synchrophasor signals in accordance to their ability to estimate parameters of the critical mode with lowest variance. They highlights the fact that mode estimation is an important synchrophasor applications. Operational changes in the power-system to cause for a change signals that contain the most information about these modes.

Jiawei Ning et al. (2015) [25] proposed a two-level distributed architecture, for ambient estimation of modes of inter-area and local modes from large number of PMU measurements. The architecture greatly reduced the communication burden. In present scenario of oscillation monitoring methodologies, the majority of the algorithmic computations is performed locally at the substation level. Modal estimation evaluated at substation are sent to the large control center where they are grouped, combined , and analyzed to extract system modal properties of inter-area and local modes.

L. Wang et al. (1989) [26] outsource the two sparsity based techniques, eigenvalue techniques and modified Amoldi method, for large power-systems to be analysed for the small-signal stability analysis. Methods does not require any initial guess of eigenvalues and have reliable convergence characteristics. A specific group of eigenvalues are calculated using the method based on the algorithm. The results shows that sparsity matrices are appropriate for the eigen analysis of large power-systems.

Lalit Kumar et al. (2017) [27] presented the studied Northern Regional Power Grid (NRPG) of India for local PSS control for system. Eigenvalue analysis suggests one inter-area mode is poorly damped. The modified residue approach suggests for the locations of two local PSS. The design the compensating blocks of local PSSs, a key step in PSSs design, are modelled using the characteristics of the generators.

S. A. Nezam Sarmadi et al. (2014) [28] explains methods based on measurement for estimating electromechanical modes of low-frequency to identify modal properties of power-system oscillations. The paper proposes a recursive adaptive stochastic subspace identification algorithm for online monitoring of power-system modes using synchrophasor data. It portrays both the accuracy of subspace identification and the fast computational capability of the recursive methods.

Guoping Liu et al. (2007) [29] enlightens with the growing application of synchro phasors or PMU's for the power grid, system can be observed in real-time. With the real time data the modal information as well as the mode shape for electro-magnetic oscillations can be extracted, while they are in still under process of developing in the real power-system. The algorithms use three signal processing engines for the evaluation of modes. The algorithms can identify negatively damped or poorly damped oscillations due to intra-area, local, or inter-area electromechanical oscillatory modes.

2.6 Conclusion

In this chapter provides the literature survey of the extensive work on the power-system stability. The chapter shows the stability is a foremost concern of power-system and is evaluated with the modes. The modes are evaluated by the eigen values of the system state-space matrix. Lastly, Literature review provides knowledge in gaining the fundamental concepts of the system and also present the overview of the research work done so far.

Chapter 3
Power-system Oscillations and Modelling

A study of electromechanical oscillations of the power-system about an operating point for the system subjected to sufficiently small order of disturbance which does not trigger non-linearity in the system behaviour is termed as small-signal rotor angle stability analysis. The study is essentially concerned with the ability to maintain synchronism of the power-system under small disturbances. The disturbances developed are considered of sufficiently smaller magnitude so that system equations can be linearized at the operating point.

A power-system cannot be operated with a small-signal instability for a given operating condition, thus, for the satisfactory operation of power-systems small-signal stability is a necessity. The study mainly comprises the sufficiency of damping of all modes, which are associated with a system as such the power transfer is not inhibited. It is pretended that such a dynamic system is when disturbed from its steady state condition, the system variables trace out a flow, referred to as trajectories. The trajectories often exhibit oscillatory nature or monotonic behaviour. For the stable system, the developed trajectories should remain in limits and converge to obtain as acceptable operating point.

3.1 Power-system Oscillations [29-32]

When large number of generator working in parallel to deliver a common loads, the power-system oscillations are produced in a system. In a power-system with large no of synchronous machines produce torques, which depends on the rotors relative angular displacement of the generator. The torque (also known as synchronizing torque) maintain synchronism of the generators. The synchronizing torques and moment of inertia of generator rotor makes the angular displacement among the generators, for which generators using the transmission lines oscillate for the disturbance. Under such conditions, the generators work as solid rigid bodies that exchange energy between them by oscillating with respect to one-another. If the system have small-signal instability, oscillations grow in magnitude over the span of time, eventually responsible for outages of power-system. Furthermore, a power-system is always in a continuous random disturbances subjected to changes in the form of generation demand or load variation or controller setting changes. Hence the system never settles to a steady state operating point for any given point of time. Thus for the system stability having adequate damping of all system oscillations is critical.

In an over stressed system, a small magnitude of synchronizing torque and a relatively low damping may be defined constrain of the system operation for limiting power transfer. Furthermore predicting oscillation boundaries and thus managing them, becomes extremely difficult.

3.2 Classification of Power-system Oscillations

For a convenience of the analysis, the oscillations associated with a power system is classified as.

1. Swing mode oscillations.
2. Control mode oscillations.
3. Torsional mode oscillations.

3.2.1 Swing Mode Oscillations

The mode is also termed as electro-mechanical mode. The electro-mechanical modes for an n generator system, associated with the generator rotors are (n-1) modes. In this mode, the generator rotor is having a high association, where the two coherent group generators oscillate against each other, in which among the groups have an approximate phase difference of 180º. There also exists is a zero mode or rigid body mode, primarily associated with the movement of the center of inertia where all rotor of generators acts as a single rigid rotor. It is not necessary that, all modes involve all generators. The type of swing mode depends upon the location of generators in the system. The oscillation modes are further grouped into four categories:

1) Local machine-system oscillations.

2) Interunit mode oscillations.

3) Local mode oscillations.

4) Interarea mode oscillations.

1) Local Machine system oscillations: When one or more synchronous machines at a power station are found to be swinging together against a reasonably load center or large power-system at a frequencies ranging between 0.7 Hz to 2 Hz. Since the oscillations are localized at a small part of the power-system or one station, the term local is used.

2) Interunit mode oscillations: The oscillations typically developed at a power plant, when two or more synchronous generators are seen swinging against each-other, typically for frequencies ranging from 1.5 Hz up to 3 Hz.

3) Local mode oscillations: The oscillations typically produced in close vicinity of power plants for which the generator within an area having coherent groups swings against each-other. The oscillation frequencies of the mode covers frequencies ranging from 0.8 up to 1.8 Hz.

4) Interarea mode oscillations: The oscillations typically produced when in a power system, combinations of synchronous machines on one area are found swinging against generators on another area. The oscillations produced are of a relatively inferior frequencies than local machine modes, typically ranging between 0.1 to 0.6 Hz. The inter-area modes generally have effects over large area moreover control of these modes are difficult.

3.2.2 Control Mode Oscillations:

These modes are produced because of the other control devices connected to the generators and generating units. The usual causes of instability of these modes involve speed governors, static var compensators, poorly tuned exciters, and HVDC converters.

3.2.3 Torsional Mode Oscillations:

The oscillations developed due to the relative angular motion of a unit i.e. between the rotating elements (exciter, synchronous machine, and turbine), along with the frequency range between 4Hz and above. This natural damping of the mechanical system is very small. The modulated output power of excitation system, and modulated power of synchronous machine for the recurred changes in generator field voltage acts as a source of torque for inducing torsional oscillations with the excitation system.

Out of these modes, interarea mode are identified as universal small-signal stability concerns that are triggered because of interactions between huge number of generators and following widespread effects.

3.3 Methods of Analysis of Small-Signal Stability [31]

1. Eigen-value analysis.
2. Frequency response and residue based analysis.
3. Synchronizing and damping torque analysis.
4. Time-domain solution analysis.

3.3.1 Eigen-value Analysis [19]

Eigen-values: For a non-trivial solution to the equation, the eigen-value for any matrix A is given by the value of the λ (scalar parameter)

$$A\underline{u} = \lambda\underline{u} \qquad (3.3..1)$$

where A is an (n x n) input matrix and $\underline{u}$ is (n x 1) vector referred to as eigenvector.

$$(A - \lambda I)\ \underline{u} = 0 \qquad (3.3.2)$$

where I is an identity matrix of dimension (n x n).
For a non-trivial solution,

$$\det (A - \lambda I) = 0 \qquad (3.3.3)$$

Equation 2.3.3is also referred as the characteristic equation. For the n solutions of parameter $\lambda = \lambda_1, \lambda_2, \ldots, \lambda_n$ are referred to as the eigenvalues of A. The eigenvalues of a matrix can be real or complex. In general, $\lambda_i = \sigma_i + j\omega_i$, where σ_i is termed to as neper frequency in neper/s, and ω_i is termed to as radian angular frequency in rad/s.
Eigenvectors:
Eigen vectors are the n element column vector $\underline{u}_i$, for any eigenvalue λ_i, which satisfies equation 3.3.1 is called the right eigenvector of A for λ_i, Therefore we have

$$A\underline{u}_i = \lambda_i\underline{u}_i \qquad i = 1, 2, \ldots, n \qquad (3.3.4)$$

The eigen vector $\underline{u}_i$ is of the form

$$\underline{u}_i = \begin{bmatrix} u_{1i} \\ u_{2i} \\ \vdots \\ u_{ni} \end{bmatrix}$$

Similarly, for the n element row vector v_j that satisfies

$$\underline{v}_j A = \lambda_j \underline{v}_j \qquad j = 1, 2, \ldots, n \qquad (3.3.5)$$

is called the left eigenvector of matrix A for eigenvalue λ_j , and is of the form

$$\underline{v}_j = [v_{j1} \quad v_{j2} \quad \cdots \quad v_{jn}]$$

The left and right eigenvector are orthogonal corresponding to different eigenvalues. In other words,

$$\underline{v}_j \, \underline{u}_i = 0 \tag{3.3.6}$$

3.4 Eigen values and Stability

For any mode corresponding to an eigen-value (λ_i), the time dependent characteristic is given by $e^{\lambda_i t}$. Therefore, the study of eigenvalues reviles the stability of the system as follows.

1. A mode having a real eigen-value is a non-oscillatory mode. A negative real eigenvalue is identified as decaying mode. The larger is real part in magnitude, the higher is the decay. Thus, aperiodic monotonic instability of the mode is represented by a positive real eigen-value.

2. Complex eigenvalues corresponds to an oscillatory mode and always occur in conjugate pairs. The real part of eigenvalues provides damping, whereas imaginary part is responsible for the frequency of oscillation. Complex eigenvalues are specified as,

$$\lambda = \sigma \pm j\omega \tag{3.3.7}$$

The oscillation frequency in Hz is given by

$$f = \frac{\omega}{2\pi} \tag{3.3.8}$$

The damping ratio is given by

$$\zeta = \frac{\sigma}{\sqrt{\sigma^2 + \omega^2}} \tag{3.3.9}$$

The damping ratio ζ determines the rate at which the amplitude of the oscillation decays. The amplitude decays with a time constant of $\frac{1}{|\sigma|}$. Otherwise, the amplitude decays at rate $\frac{1}{e}$ or 37% of the initial amplitude in $\frac{f}{|\sigma|}$ seconds or in $\left(\frac{1}{2\pi}\frac{\sqrt{1-\zeta^2}}{\zeta}\right)$ cycles of oscillations. The dynamic performance of the system is evaluated by the small-signal stability analysis by calculating the eigen-values and eigen-vectors of the system-state matrix for a power system model considering it be linear.

For the satisfactory operation of power-system, it is mandate that all modes or all eigenvalues are stable. Moreover, it is preferred in a system, electro-mechanical oscillations are damped out.

3.5 System Modelling and Identification

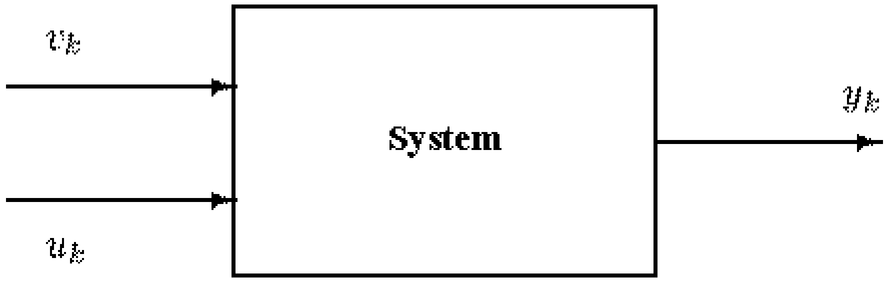


Figure 3.1 A simple dynamic system model

The figure shows the dynamic model of the system with deterministic inputs u_k, disturbances v_k, and outputs y_k. The system parameters are considered vectors and k is the discrete time-index. The user can control input u_k but not v_k. The input as well as output signals are measured to provide valuable information for the system.

A dynamic model, shown in Figure 3.1, depicts mostly all physical, technical or industrial phenomena governed. Differential for continuous time or difference for discrete time equations are used to define such system-models. Equations describes the dynamic nature of the system behaviour as a function of time. Mathematical models are studied for monitoring, simulation, prediction, analysis, control system designs, optimization, fault detection, etc. Lastly, modelling is used for the control and feedback.

Fundamentally, there are two ways for a dynamic system to be mathematical modelled. Physicists are having concern in models governed by physical laws that carefully explain the basic important mechanisms of perceived phenomena. The necessary mathematical tool is nonlinear partial differential equations.

For engineers however, on the other hand are not really involved in the accurate model, but models of engineering applications. With this viewpoint, a mathematical model is just an initial step for systems global design. The modelling quality is achieved by the serving its ultimate goal. In divergence with physicists, engineers are ready for compromise complexity of model versus exactness.

In the modeling dynamical systems, experiments on a system are performed with suitable numerical data designated to the constraints so as to fit parameterized model. In this method, system identification is done for the analysis of electro-mechanical modes to determine the stability. Finally in validation step, the model worked data which is not used in system experiment.

3.6 System Identification: A new Generation Approach [34-36]

First of all, the state-space models are of central importance for determination of system stability, which are developed by subspace identification algorithms. Later the approach of subspace identification algorithms is discussed that highlights improvements of subspace identification algorithms compared to persisting "classical" approaches.

3.6.1. State-Space Models: Engineering approach

The model is restricted to LTI, discrete-time, state-space models that can synthesize most of the industrial processes are accurately as described by this approach. Mathematically, the models are described by the difference equations as follows:

$$\begin{aligned} x_{k+1} &= Ax_k + Bu_k + w_k \\ y_k &= Cx_k + Du_k + v_k \end{aligned} \tag{3.6.1}$$

with

$$E\left[\begin{pmatrix} w_p \\ v_p \end{pmatrix}\begin{pmatrix} w_p^T & v_p^T \end{pmatrix}\right] = \begin{pmatrix} Q & S \\ S^T & R \end{pmatrix}\delta_{pq} \geq 0 \tag{3.6.2}$$

The model comprises,

vectors: The input vector $u_k \in \mathbb{R}^m$ and output vector $y_k \in \mathbb{R}^l$ are the measurements for any time instant k, containing of respectively the m inputs and l outputs of the process. The state vector $x_k \in \mathbb{R}^n$ of the process at discrete time instant k and contains the numerical values of n states. $v_k \in \mathbb{R}^l$ and $w_k \in \mathbb{R}^n$ are unmeasurable vector signals. It is assumed that they are zero mean, stationary, white noise vector sequences.

matrices: $A \in \mathbb{R}^{nxn}$ represents the dynamical system matrix that describes the dynamics of the system behaviour. $B \in \mathbb{R}^{nxm}$ represents input matrix that signifies the linear transformation of the deterministic inputs which influence the next state. $C \in \mathbb{R}^{lxn}$ represents output matrix which describes the perception of output which is transferred from the internal state in the measurements y_k. The matrix $D \in \mathbb{R}^{lxm}$ is reffered as direct feedthrough.

The matrices $Q \in \mathbb{R}^{nxn}$, $S \in \mathbb{R}^{nxl}$ and $R \in \mathbb{R}^{lxl}$ represents covariance matrices of the two noise sequences w_k and v_k. The observability of the matrix pair {A,C} implies that all modes in the system are observed in the output y_k and can be identified. Also, controllability of the matrix pair $\{A, [B\ Q^{1/2}]\}$ infers that all the system modes are excited by either the stochastic input w_k or deterministic input u_k.

A system is shown in Figure 3.2.

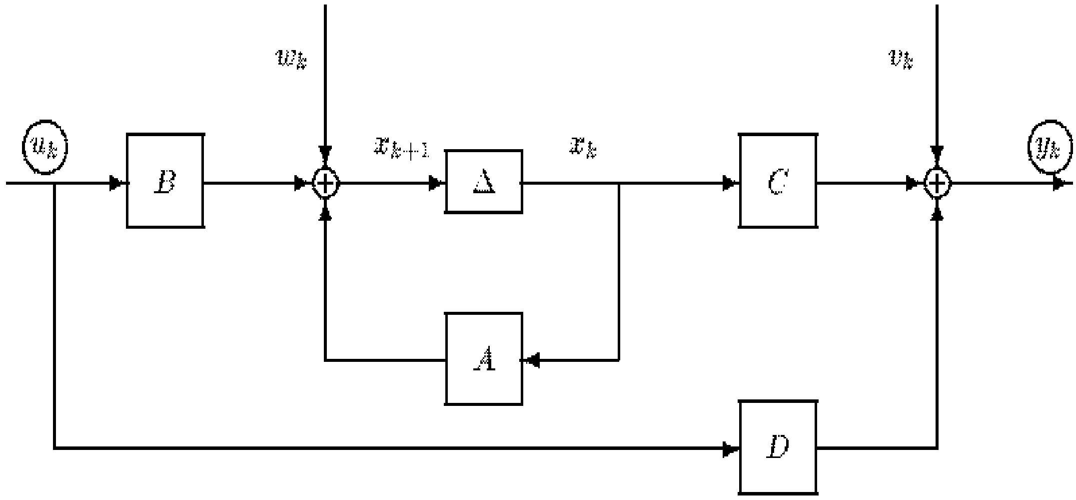


Figure 3.2 Detailed dynamic model of system.

The model is restricted to finite dimensional LTI systems to be evaluated. The input u_k and output y_k vector signals are measured while v_k, w_k are unknown disturbance signals. The symbol Δ represents a delay. Dynamics of the system is represented by the inherent feedback via the matrix A.

- First of all, for MIMO systems, the modelling can only be done using state-space representation which is appropriate to work with in computer aided control system design. State-space modelling have the capability of effectively computing most optimal controllers.

- All the dynamics of the system are collected in one matrix A, in other words, the eigenvalues of the A describes all the measured distinct modes of the system that are observed.
- A crucial point of linearity is explained by the reason that most of the industrial processes are very well estimated by a finite dimensional linear systems and by taking high order (n) the complex behaviour can also be involved. In case nonlinearities, two measures are possible: Either by recursively updating of the model by using identifying a time-varying system or by possibly is provided by (mild) nonlinearities which can be incorporated in the control design, and do not matter.

3.6.2. Working of SSI Algorithms

SSI algorithms are based on concepts from linear algebra, statistics, and system theory, which is replicated in the following table:

System	Geometry	Algorithm
High order state sequence	Projection (orthogonal or oblique)	QR-decomposition
Low order state sequence	Determine finite (Generalized) dimensional subspace	SVD
System matrices	Linear relations	Least squares

Table 3.1 Subspace identification algorithm with order complexities

The main theoretical innovations of SSI are:

The dynamics of the states of the system are highlighted for the perspective of system identification, whereas “classical” techniques are mainly centred around input output structure. The introduction of the state in the field of identification area have evolved since development the analysis of dynamical systems and in control system theory. As a consequence, if the system states are known, the identification problem becomes a linear problem contained in unknown system matrices.

The interpretation of SSI algorithms is that the method provisionally linearize the problem, but becomes highly non-linear optimization problem when written in methods of prediction error. Also, another view involves SSI algorithms rather than identifying input-output models, they identify as input-state-output models.

3.6.3. Subspace Identification: A Brief [37,46]

The field of mathematical engineering involving system identification has been started some 15 years ago. The innovations in SSI methods are

Parametrizations: The subspace identification algorithms uses state-space technique and the order of the system as the only parameter. However, minimal parametrizations are having many problems as:

- The results obtained can be extremely sensitive to small perturbations.
- Overlapping parametrizations becomes necessary.
- In practice, minimal state-space models are really feasible.

The subspace identification approach require only the order of the model that is user-specified which can be determined by inspection of certain singular values. The subspace thus does not suffer from inconveniences.

Convergence: Subspace identification algorithms, when applied correctly, are quite fast, irreverent to the fact that SSI use QR and SVD decomposition techniques. As a matter of fact, compared to the “classical” identification methods, they are fast because they are not iterative. Moreover, algorithms from concepts of numerical linear algebra, numerical analysis is guaranteed precisely.

Model reduction: With the computer aided control system design environment, developing the models is our main interest lies in using linear system theories, and controller complexity is proportional to the order of system. One is always persuaded to obtain models having minimum low order as possible. The model reduction can be directly obtained in subspace identification, directly from input-output data without computing the need for high order model.

3.7 Geometric Tool [38]

The geometric concepts are employed for SSI algorithms are based on: the matrices are assumed as $A \in \mathbb{R}^{mxl}$, $B \in \mathbb{R}^{nxl}$ and $C \in \mathbb{R}^{pxl}$. The vector coordinates in the ambient space of l-dimension, are the elements of a row of one of the given considered matrices. The basis for a linear vector space in the ambient space is defined by the rows of the matrix A, B, C. The geometric operations are easily implemented using the QR decomposition technique.

3.7.1. Orthogonal projections

Suppose the projection of row-space of any matrix over the row-space of the matrix $B \in \mathbb{R}^{nxl}$ is denoted by operator Π_B, it is defined as:

$$\Pi_B \stackrel{\text{def}}{=} B^T.(BB^T)^{\dagger}.B \tag{3.7.1}$$

where $[S]^{\dagger}$ denotes the Moore-Penrose pseudo-inverse of the matrix [S]. A/**B** is used as a script for the projection of the row-space of the matrix $A \in \mathbb{R}^{mxl}$ on the row-space of the matrix B:

$$\begin{aligned} A/B &\stackrel{\text{def}}{=} A.\Pi_B \\ &= AB^T.(BB^T)^{\dagger}.B \end{aligned} \tag{3.7.2}$$

Figure 1.8 shows interpolation of the operator projection in the ambient l-dimensional space as indicated. The orthogonal projection is implemented using QR decomposition which is a natural numerical tool for the projection.

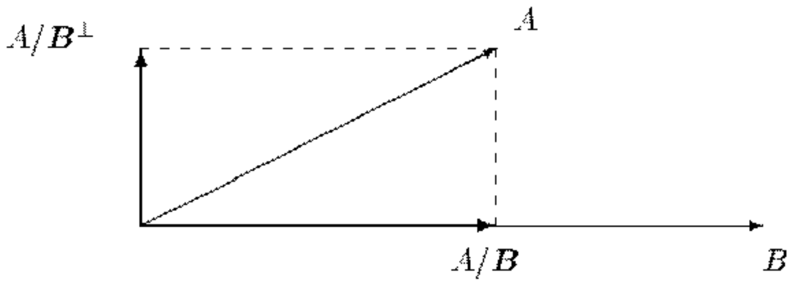


Figure 3.3 Interpolation of the orthogonal-projection in the l-dimensional space.

The geometric operator $\Pi_{B^{\perp}}$ represents the projection of the row-space of matrix A over the orthogonal complement of the row-space of the matrix B:

$$A/\boldsymbol{B}^{\perp} \stackrel{\text{def}}{=} A.\Pi_{B^{\perp}} \tag{3.7.3}$$

3.7.2. Oblique projections

Decomposition of vector A may also be obtained using linear combinations of two non-orthogonal matrix B and matrix C along with their orthogonal complements. Illustrated in Figure 3.4. The implementation of projection is as follows:

$$\mathrm{A} = \mathrm{L}_B.\mathrm{B} + \mathrm{L}_C.\mathrm{C} + L_{\mathrm{B}^{\perp}.\mathrm{C}^{\perp}}.\begin{pmatrix}\mathrm{B} \\ C\end{pmatrix}^{\perp} \tag{3.7.4}$$

The matrix $L_C.C$ is represented as the oblique projection of the row-space of A along the row-space of B over the row-space of C:

$$A/_B\boldsymbol{C} \stackrel{\text{def}}{=} L_C.C \tag{3.7.5}$$

Statistically, the orthogonal-projection of the row-space of A over the combined row-space of B and C is evaluated as:

$$A\Big/\begin{pmatrix} C \\ B \end{pmatrix} = A(C^T \quad B^T).\begin{pmatrix} CC^T & CB^T \\ BC^T & BB^T \end{pmatrix}^{\dagger}.\begin{pmatrix} C \\ B \end{pmatrix} \tag{3.7.6}$$

The oblique projection can also be defined by decomposing equation 3.7.6 over the row-spaces of B and C:

Definition: The oblique projection of the row-space of A ∊ $\mathbb{R}^{mxl}$ along the row-space of B ∊ $\mathbb{R}^{nxl}$ on the row-space of C ∊ $\mathbb{R}^{pxl}$ is defined as:

$$A/_BC \stackrel{\text{def}}{=} A(C^T \quad B^T).\left[\begin{pmatrix} CC^T & CB^T \\ BC^T & BB^T \end{pmatrix}^{\dagger}\right]_{first\ r\ columns}.C \tag{3.7.7}$$

The oblique projection are having some properties as:

$$B/_BC = 0 \tag{3.7.8}$$

$$C/_BC = 0 \tag{3.7.9}$$

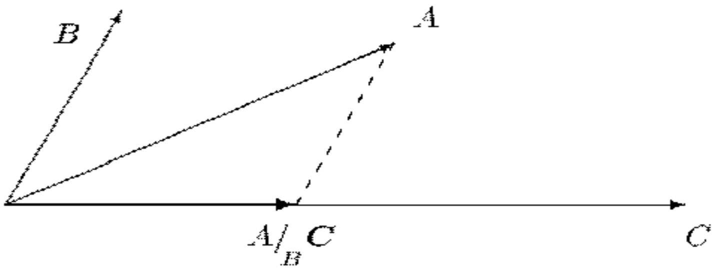


Figure 3.4 Interpolation of oblique-projection in the l-dimensional space.

3.7.3. Principal angles and directions

As pictorially illustrated in Figure 3.5, the principal angles between two subspaces are the angles between two vectors. Suppose matrices A ∊ $\mathbb{R}^{mxl}$ and B ∊ $\mathbb{R}^{nxl}$ having unit vectors a_1 ∊ row-space of A also, b_1 ∊ row-space of B. The first principal angle Θ_1 is the minimum of the angle between a_1 and b_1. The unit-vectors a_1 and b_1 are the first principal directions and Θ_1 is the first principal angle. Now taking another set of unit vector a_2 orthogonal to a_1 ∊ row-space of A and b_2 orthogonal to b_1 ∊ row-space of B and decreasing the angle Θ_2 among them for the second principal directions and angle. Minimum of (m, n) angles should be found by the same procedure.

Definition 1

The principal angles $\Theta_1 \leq \Theta_2 \leq \ldots \leq \pi/2$ defined between the row-spaces of matrix A ∈ $\mathbb{R}^{mxl}$ and matrix B ∈ $\mathbb{R}^{nxl}$ and the equivalent principal directions given by a_i ∈ row-space of A and b_i ∈ row-space of B are stated as follows:

$$\cos \Theta_k = \max a^T .b \text{ (a ∈ row-space A and b ∈ row-space B)} = a_k^T . b_k \tag{3.7.10}$$

subject to $\|a\| = \|b\| = 1$ and for k > 1 , $a^T.a_i = 0$ for i = 1,…, k-1 and $b^T.b_i = 0$ for i = 1,…, k-1.

Definition 2

Given two matrices A ∈ $\mathbb{R}^{mxl}$ and B ∈ $\mathbb{R}^{nxl}$ and the SVD:

$$A^T.(AA^T)^{\dagger}.AB^T.(BB^T)^{\dagger}.B = USV^T \tag{3.7.11}$$

The principal directions can be obtained among the row-spaces of matrixes A and B by the rows of evaluated matrixes U^T and V^T. The singular values are obtained by the cosines of the principal angles. The principal angles and directions are represented as:

$$[\boldsymbol{A}\sphericalangle B] \stackrel{\text{def}}{=} U^T,$$
$$[A\sphericalangle \boldsymbol{B}] \stackrel{\text{def}}{=} V^T,$$
$$[A\sphericalangle B] \stackrel{\text{def}}{=} S,$$

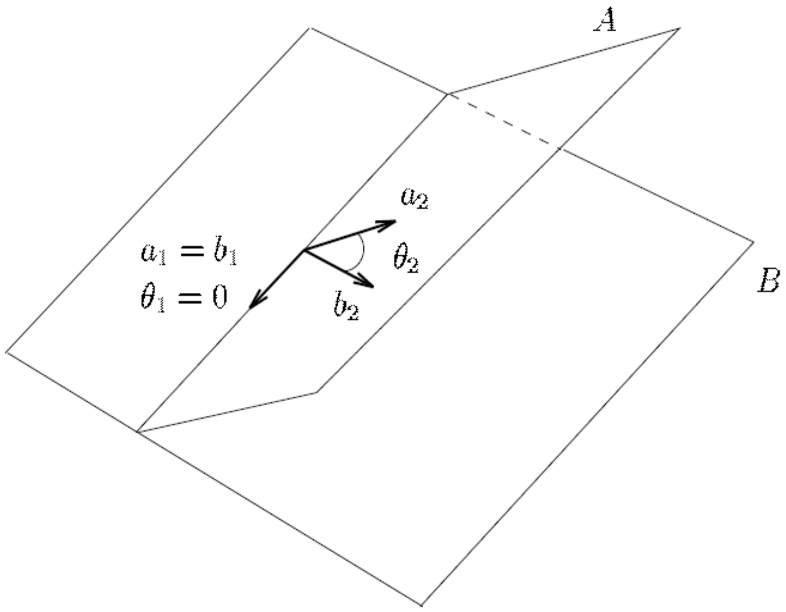


Figure 3.5 Interpolation of principal angles and directions in the l-dimensional space.

3.8 Conclusion

This chapter presents understanding of the basic concepts of power-system oscillations and its types. The chapter also provides the method of modelling of the power-system in state-space. Thus process of evaluating the system matrices by eigen values analysis. Subspace algorithm is a new approach in eigen value analysis, exploring the system matrices with the geometric tools like orthogonal and oblique projections. Projecting the vectors helps the system to develop fast approach towards the convergence for solution of any problem.

Chapter 4
MODELLING IN POWER FACTORY

Power Factory is a highly designated software application for power-system analysis in analysing generation, transmission and distribution. The power factory have full range of functionality from highly advanced and sophisticated applications involving distributed generation, performance monitoring, and real-time simulation for system supervision and testing.

4.1. Power Factory Basic Functions [51]

Load Flow Analysis

Power Factory perform a range of methods of load flow calculations, involving Newton-Raphson technique for AC systems for balanced and unbalanced systems and a linear DC method. The implemented technique exhibit excellent stability and convergence.

Short-Circuit Analysis

Power Factory provides short circuit calculations for single and multiple faults, with a number of reporting options. It determines the short circuit currents with the required algorithms and high precision, without considering the assumptions or simplifications required in standard fault analysis.

RMS/EMT Simulation

The RMS simulation tool in Power Factory is used to analyse transients under both balanced and unbalanced conditions, incorporating a simulation scan feature.

Also, an EMT simulation kernel required for solving transient power system problems such as lightning, sub-synchronous resonance problems, inrush currents, or switching and temporary over-voltages.

Load Flow Sensitivities

Load Flow Sensitivities are required to know the critical point of a system, also how the changes in system conditions responsible that affect critical point. Sensitivity Analysis tool accomplishes calculation of static voltage stability for identifying strong and weak parts of the network.

Power Equipment Models

Power Factory is available with a comprehensive suite of power equipment models and libraries, to enable the modelling of all network elements, along with controllers and protection devices.

Results and Reporting

Results and other data can be presented to the user in a variety of ways, including inbuilt spreadsheet or text reports and configurable presentation of results on graphics or in tabular format. Interactive plots can also be easily generated and customised.

4.2. Two Area Model [30]

The two area system comprises of two fully symmetrical areas connected together. Each area is equipped with two identical round rotor generators making in total of four generators. The system consists of eleven buses connected to two load centres. The model was precisely designed for the study low frequency electro-mechanical oscillations in large inter-connected power-systems. Regardless of its small size, it impersonates very closely the behaviour of distinctive power-systems in real operation. The model under analysis is considered as the benchmark model for analysis of small-signal stability problem in power-systems.

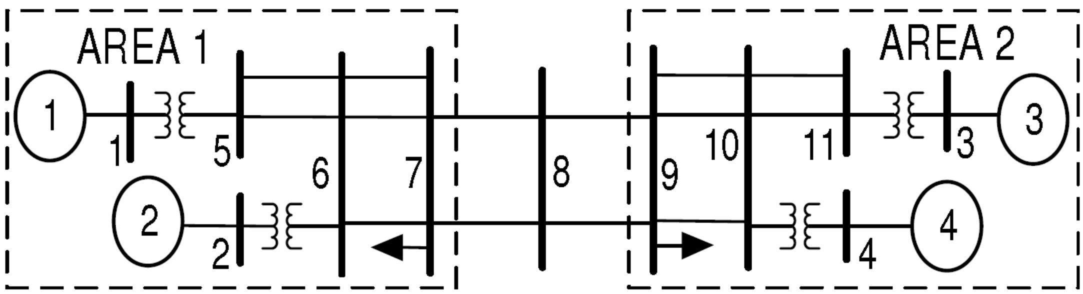


Figure 4.1 Single line diagram of two-area system

Due to its symmetric structure and power flow conditions, the two local modes related to two areas can have identical frequencies. The inter area oscillation between two areas have a lower frequency than the local modes. This benchmark model showed that well designed PSSs effectively damp inter area as well as local electromechanical modes simultaneously.

4.1.1. Load Flow Basic Data [30]

Power factory performs a Newton Raphson iteration method on the given model to solve the load flow analysis. For the load flow calculation the data for the entire model is mapped taken as follows:

Bus Data

Buses are electrical conductors that are maintained at a specific voltage and capable of carrying a high current, used to make a common connection between several circuits of the system.

The following table show the bus data in per unit on the bases of 900 MVA and 230kV.

Bus Number	Bus Type	Final Voltage (pu)	Load (MW)	Load (MVAr)	Generation (MW)	Generation (MVAr)	Rated Voltage (kV)
1	1	1.03	0	0	700	185	20
2	3	1.01	0	0	700	235	20
3	3	1.03	0	0	700	176	20
4	3	1.01	0	0	700	202	20
5	2	1	0	0	0	0	230
6	2	1	0	0	0	0	230
7	2	1	967	100	0	0	230
8	2	1	0	0	0	0	230
9	2	1	1767	100	0	0	230
10	2	1	0	0	0	0	230
11	2	1	0	0	0	0	230

1 = slack bus, 2 =Load (P-Q) bus, 3 = Generation (P-V) bus

Table 4.1 Bus data for load flow study

Generator Data

There are four synchronous generator connected to the model. Generators are source of power for the load flow to occur, they have an electromechanical conversion process that converts mechanical energy to electrical energy. The generators have assumed to have star connected winding.

The generator connected to the model are having the following data:

	Gen 1	Gen 2	Gen 3	Gen 4
MVA rating	900	900	900	900
Active Power (kW)	700	700	700	700
Reactive Power (kVAr)	185	235	176	202
Voltage (pu)	1.03	1.01	1.03	1.01
Voltage (kV)	20	20	20	20
Power factor	0.8	0.8	0.8	0.8

Table 4.2 Generator data for load flow study

Transmission Line Data

Transmission line are used to transmit large amount of power over a long distances, usually from an energy source to different load centres located at remote distances.
Power factory requires the data expressed in real units

The following table show the line data in per unit on the bases of 900 MVA and 230kV.

From Bus	To Bus	Distance (km)	Resistance (Ohm/km)	Reactance (Ohm/km)	Line Charging (µS/km)
5	6	25	0.0529	0.529	3.308
6	7	10	0.0529	0.529	3.308
7	8	110	0.0529	0.529	3.308
7	8	110	0.0529	0.529	3.308
8	9	110	0.0529	0.529	3.308
8	9	110	0.0529	0.529	3.308
9	10	10	0.0529	0.529	3.308
10	11	25	0.0529	0.529	3.308

Table 4.3 Line data for load flow study

Transformer Data

Transformers are used to supply power at high voltages as the transmission losses are reduced. The transformers connected are having low winding star connected and high winding as delta connected. The transformers belong to the same phasor group for operation.

The following table show the transformer data

	TF 1	TF 2	TF 3	TF 4
Type	Y-Δ	Y-Δ	Y-Δ	Y-Δ
MVA rating	900	900	900	900
Primary Voltage(kV)	20	20	20	20
Secondary Voltage (kV)	230	230	230	230

Table 4.4 Transformer data for load flow study

Load Data

Loads are connected to the system at the bus 7 and bus 9.

The following table show the load data & shunt filter data

	Real Power (kW)	Reactive Power (kVAr)
Load A	967	100
Load B	1767	100
Filter 1	0	-184
Filter 2	0	-330

Table 4.5 Load and Shunt filter data for load flow study

4.1.2. RMS/EMT Transient Data

Transient analysis evaluates a response of system under operation over a period of time. The transient analysis has an accuracy, which of is dependent on the size of time steps, steps added up together for the complete simulation time. With the increment in time is by one predetermined time step, the parameters are evaluated based on the initial calculated values.

Afterwards, transient-stability for the system is analyzed using simulated a three phase short circuit fault near the 50% of the transmission line connecting bus 7 and bus 8 at t=1 s. The fault is developed at Line 7-8, the fault-clearing time of the circuit breaker (0.01 s) is analyzed for the performance of the system.

The following table show the generator transient data

	Gen 1	Gen 2	Gen 3	Gen 4
Inertia Constant, H	6.5	6.5	6.125	6.125
r_{str}	0.0025	0.0025	0.0025	0.0025
x_l	0.2	0.2	0.2	0.2
x_d	1.8	1.8	1.8	1.8
x_q	1.7	1.7	1.7	1.7
T_{d0}’	8	8	8	8
T_{q0}’	0.4	0.4	0.4	0.4
x_d’	0.3	0.3	0.3	0.3
x_q’	0.55	0.55	0.55	0.55
T_{d0}’’	0.03	0.03	0.03	0.03
T_{q0}’’	0.05	0.05	0.05	0.05
x_d’’	0.25	0.25	0.25	0.25
x_q’’	0.25	0.25	0.25	0.25

Table 4.6 Generator data for RMS transient study

4.3. Performing transient simulation

The process of transient analysis involves following steps:

1. Calculation of initial variables

   The internal variables and the internal operation status of connected machines, other controllers and other transient analysis that produce the time domain simulation is calculated based on a load flow calculation.

2. Defining an event (short circuit in our case)

   A short circuit event is created on transmission line between bus 7 and bus 8 at t =1 sec. The fault is also cleared by creating another event at t = 1.01 sec of time.

3. Defining result variables

Certain result parameters at buses and generators are evaluated like active power, rotor angle and rotor speed.

4. Defining output graph

   By creating virtual instrument panel, the specific output graphs are analyzed and plotted as a function of time for the particular simulation time.

5. Executing simulation

   The final simulation step, executing the model to assimilated the results and graphs.

4.4. Simulation Results

The developed system has been modelled & simulated as shown in Appendix using DigSILENT's power factory software. All the parameters have been designed using the above mentioned values for the load flow analysis of the model. The load flow simulation results are obtained as mentioned underneath.

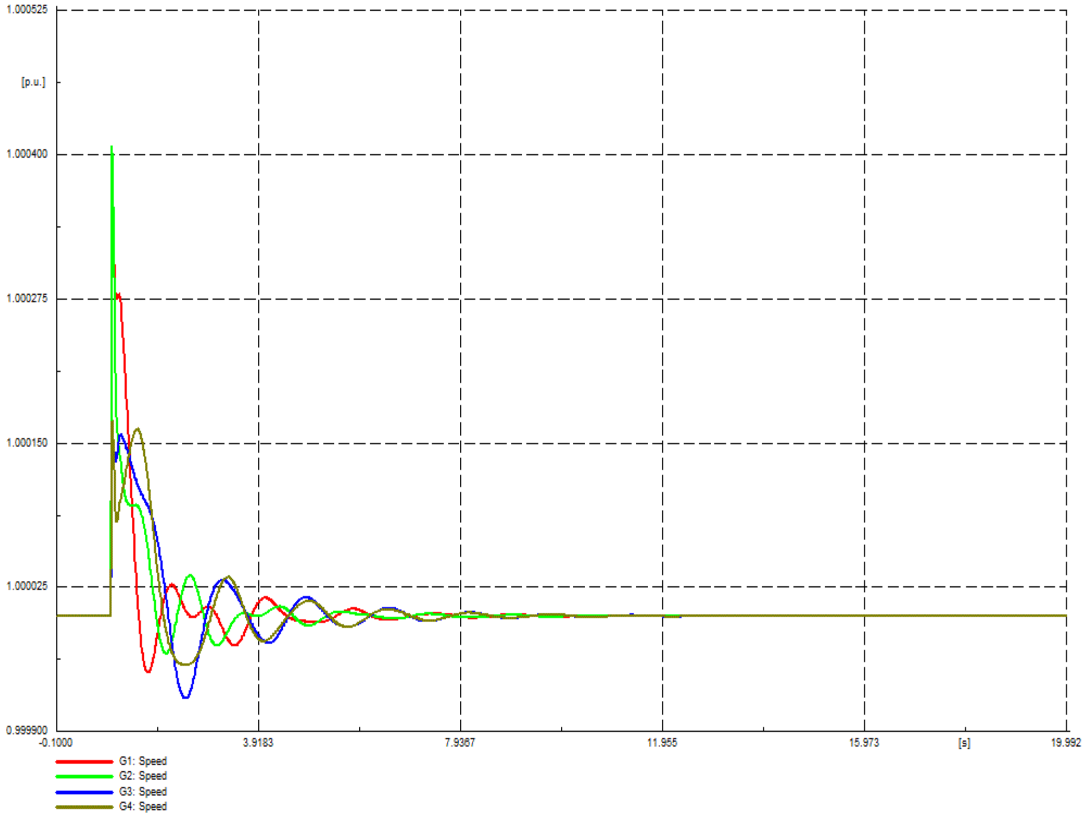


Figure 4.2 Graph of generator speed for two-area system

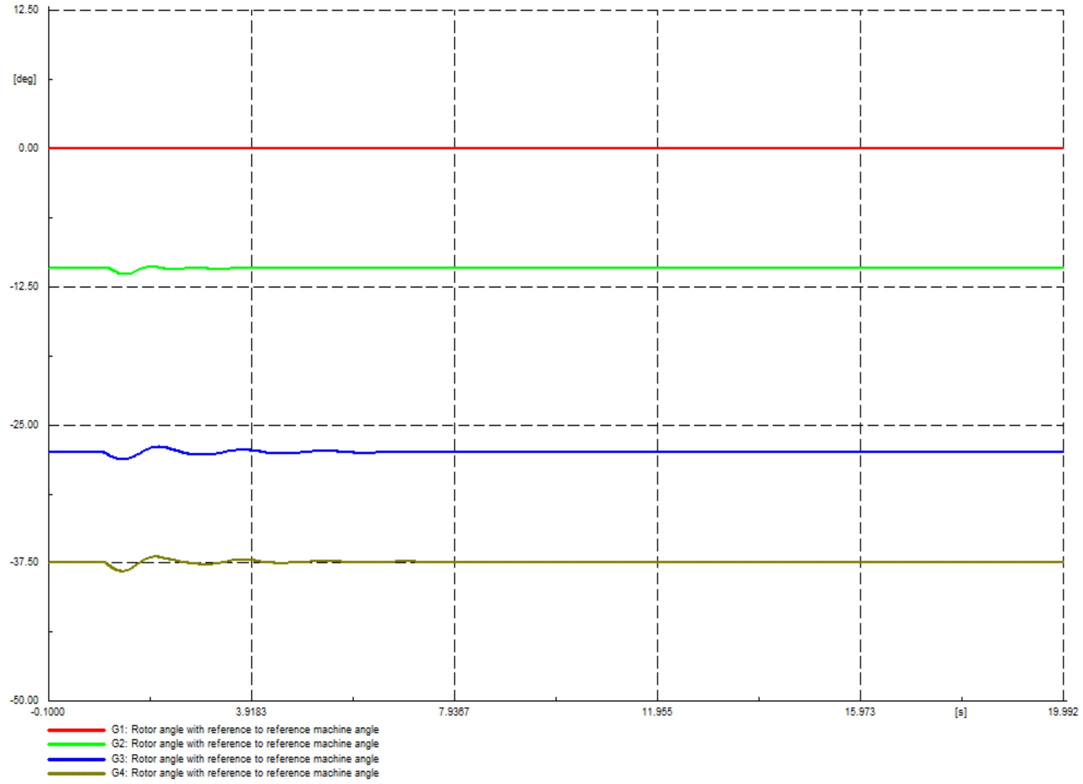


Figure 4.3 Graph of generator rotor angle for two-area system

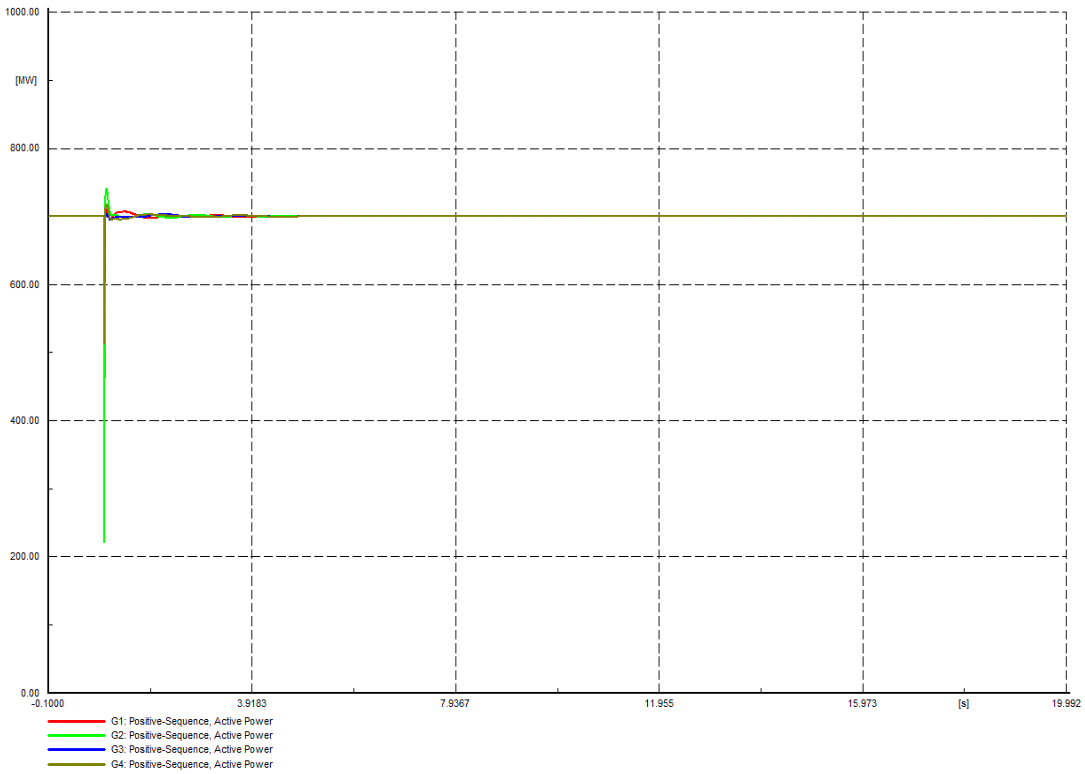


Figure 4.4 Graph of generator Active power for two-area system

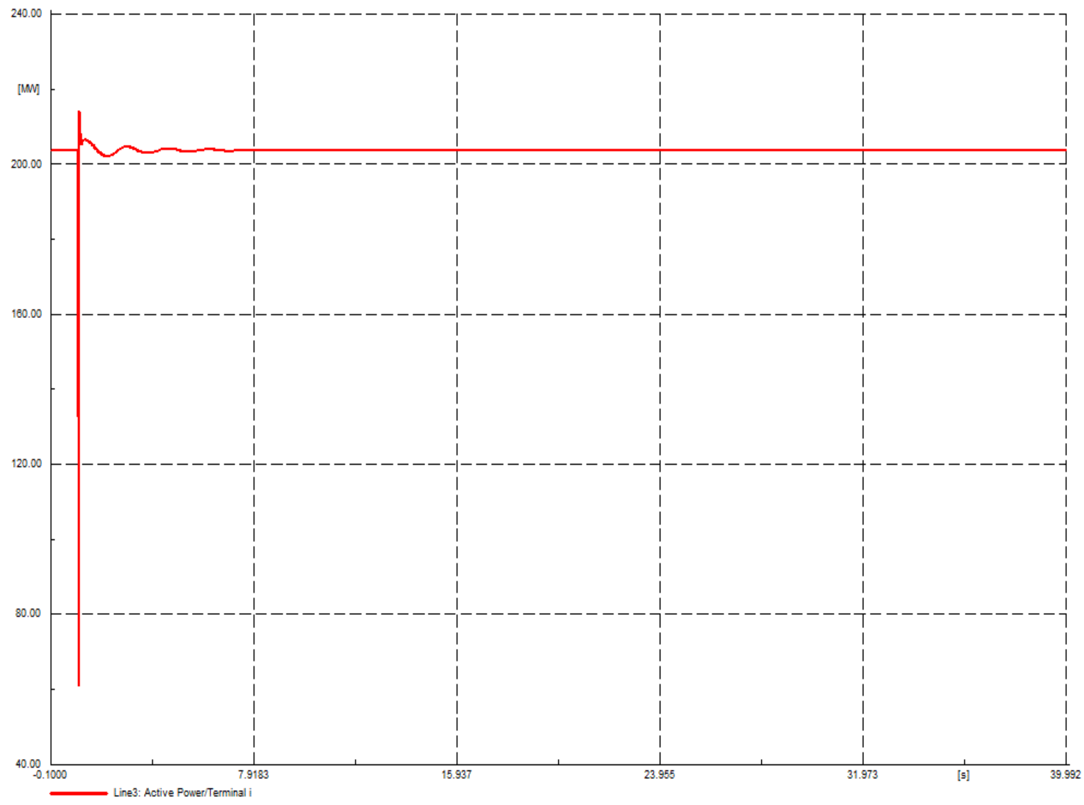


Figure 4.5 Graph of Tie line power at line 3 for two-area system

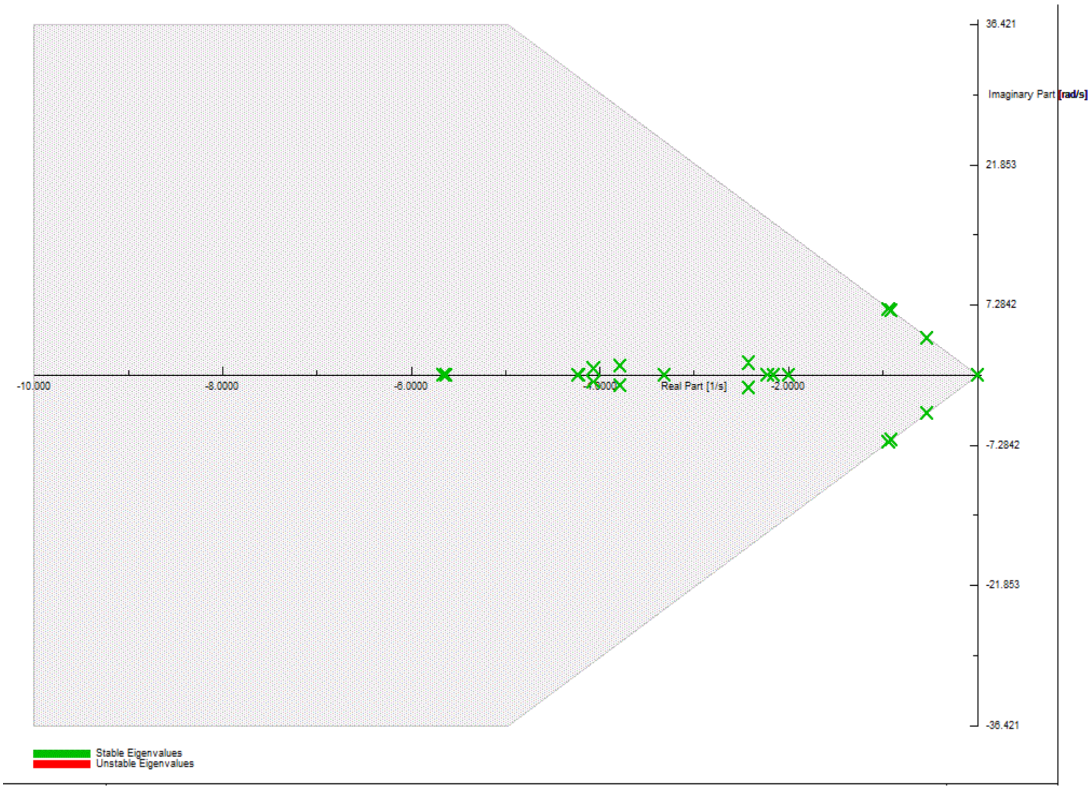


Figure 4.6 All eigen value of two-area system

Eigenvalues			Magnitude	Angle	Damped Frequency	Damping ratio
eig no	eigvalr in 1/s	eigvali in rad/s	in 1/s	in degree	in Hz	
1	0	0	0	0	0	0
2	-132.604174	0	132.604174	180	0	1
3	-130.379075	0	130.379075	180	0	1
4	-123.836334	0	123.836334	180	0	1
5	-123.557568	0	123.557568	180	0	1
6	-79.526175	0	79.526175	180	0	1
7	-79.694853	0	79.694853	180	0	1
8	-76.369204	0	76.369204	180	0	1
9	-75.565377	0	75.565377	180	0	1
10	-19.790094	36.394949	41.427529	-118.504375	5.795374	0.477704
11	-19.790094	-36.394949	41.427529	118.504375	5.795374	0.477704
12	-21.49259	33.481765	39.786430	-122.668122	5.331491	0.540199
13	-21.49259	-33.481765	39.786430	122.668122	5.331491	0.540199
14	-25.336342	24.712688	35.392756	-135.691455	3.935141	0.715862
15	-25.336342	-24.712688	35.392756	135.691455	3.935141	0.715862
16	-25.434138	24.349178	35.210479	-136.226295	3.877258	0.722346
17	-25.434138	-24.349178	35.210479	136.226295	3.877258	0.722346
18	-32.380146	0	32.380146	180	0	1
19	-32.453943	0	32.453943	180	0	1
20	-26.322777	0	26.322777	180	0	1
21	-27.124635	0	27.124635	180	0	1
22	-0.921738	6.702179	6.765265	-97.788980	1.067226	0.136246
23	-0.921738	-6.702179	6.765265	97.788980	1.067226	0.136246
24	-0.930811	6.918047	6.980386	-97.621263	1.101600	0.133347
25	-0.930811	-6.918047	6.980386	97.621263	1.101600	0.133347
26	-0.534124	3.871593	3.908263	-97.813263	0.616496	0.136665
27	-0.534124	-3.871593	3.908263	97.813263	0.616496	0.136665
28	-10.089231	0	10.089231	180	0	1
29	-10.091872	0	10.091872	180	0	1
30	-10.121693	0	10.121693	180	0	1
31	-10.133566	0	10.133566	180	0	1
32	-2.429222	1.30188	2.756086	-151.797747	0.207306	0.881403
33	-2.429222	-1.30188	2.756086	151.797747	0.207306	0.881403
34	-2.22274	0	2.222740	180	0	1
35	-2.176278	0	2.176278	180	0	1
36	-5.636888	0	5.636888	180	0	1
37	-5.663651	0	5.663651	180	0	1
38	-3.792118	1.01187	3.924798	-165.051998	0.161126	0.966194
39	-3.792118	-1.01187	3.924798	165.051998	0.161126	0.966194
40	-4.071381	0.694156	4.130133	-170.319404	0.110534	0.985775
41	-4.071381	-0.694156	4.130133	170.319404	0.110534	0.985775

Eigenvalues			Magnitude	Angle	Damped Frequency	Damping ratio
eig no	eigvalr in 1/s	eigvali in rad/s	in 1/s	in degree	in Hz	
42	-3.343628	0	3.343628	180	0	1
43	-4.233364	0	4.233364	180	0	1
44	-4.240239	0	4.240239	180	0	1
45	-1000000	0	1000000	180	0	1
46	-2	0	2	180	0	1
47	-20	0	20	180	0	1
48	-1000000	0	1000000	180	0	1
49	-2	0	2	180	0	1
50	-20	0	20	180	0	1
51	-1000000	0	1000000	180	0	1
52	-2	0	2	180	0	1
53	-20	0	20	180	0	1
54	-1000000	0	1000000	180	0	1
55	-2	0	2	180	0	1
56	-20	0	20	180	0	1

Table 4.7 All eigen values (Modes) of the system

Eigenvalues			Magnitude	Angle	Damped Frequency	Damping ratio
Mode No.	real in 1/s	Imaginary in rad/s	in 1/s	in degree	in Hz	
22	-0.921738	6.702179	6.765265	-97.788980	1.067226	0.136246
24	-0.930811	6.918047	6.980386	-97.621263	1.101600	0.133347
26	-0.534124	3.871593	3.908263	-97.813263	0.616496	0.136665

Table 4.8 Oscillatory eigen values (Modes) of the system

4.5. Conclusion

This chapter presents understanding of the two area model, also performing a transient analysis and modal analysis by the power factory. This chapter provides the data required by the power factory for the load flow analysis and RMS transient analysis. The transient analysis performed on the model provides the graph files after simulation of the two area system undergoing a three phase short circuit. The transient behaviour of the real power-system under simulation in obtained for the analysis in .csv files.

Chapter 5
MODAL ANALYSIS

Modal analysis is performed to compute eigen value properties of any system. Over the years modified methods being developed by various researchers for the calculation of modes of the power system. For oscillatory stability studies, the modal analysis calculates the eigenvalues and eigenvectors that is at most powerful tool. Traditionally, linearized dynamic models are used for evaluating mode shapes. For large power systems, exact dynamic models are difficult to create. Therefore, mode shape estimation methods based on measurement are employed by various researchers. Measurement data is grouped into three distinctive categories:

- Ambient data are the set of the measurement data reserved during the conditions when a power-system is at equilibrium state and the only small-amplitude disturbance is produced from random load changes.
- Ringdown data resembles measurement data of responses corresponding to biger disturbances resulting from line tripping or faults as a consequence oscillations are observed.
- Probing data is obtained when the system is intentionally injected with a low-level pseudo-random noise to test the system performance.

5.1. Introduction

The modal analysis is carried by following methods

5.1.1. Block-processing approaches

5.1.2.1. MYW and MYWS methods [41]

This methods calculates the coefficients for polynomial equation in AR model using YW method. For methods of block processing, the modified extended Yule-Walker is employed for identification of modes of the system in time-domain. Method using frequency domain decomposition are developed which are frequency based analysis of power system for mode estimation, the method is based on wavelet transforms. Method involving Subspace identification is used to evaluate frequency and mode damping.

5.1.2.2. N4SID Algorithm [43]

Mode estimation using N4SID is another approach of that is a outstanding method of system state-space subspace identification. The popularity of subspace methods is primarily for the reason of easy applicability and numerical easiness of the procedure which is employed in the algorithms, and for control purposes, the system is conveniently represented in state-space form. Moreover the method, have other advantages like easy selection of order or ability for handling huge data set, marks it suitable for estimation. Recently recursive methods have shown dominance over the block processing methods, because block processing methods have some limitations. Employing recursive identification several methods like Robust RLS, ARMA method, and regularized robust RLS are developed.

5.1.2. **Online approaches**

Model techniques developed are as follows:

5.1.2.1. Transfer function Method

Transfer function (TF) based approach, the relationship between TFs and mode shapes is employed to compute mode shape once a TF is recognized from the state variables. The causality of the identified TF model may not certain, or for a discrete model structure, models can be considered non causal. The accuracy of the identified TF model results in the accuracy of mode shape estimation.

5.1.2.2. Prony method [46][47]

Oscillation mode parameter identification involving Prony method most widely used algorithm, the principle of the method involves fitting the analytical signal to a linear combination of exponential terms. The Prony method introduced for identifying the problem on ring down data and was effectively resolved. Prony analysis is an extension of Fourier analysis of the given signal by directly estimating the damping, relative phase, and frequency of modal components. However, the availability the ring down data is not definite, and that it is unfeasible to perform analysis on a large disturbance, limits the methods.

5.1.2.3. Selective Modal Analysis (SMA) [48][49]

The method is a physically inspired structure involved for understanding, analyzing and simplifying complicated LTI models of dynamic systems. The technique focus on selected portions of the behaviour and structure of the system in efficient and accurate manner. The relevant part of the system is singled out for the dynamics of interest in direct manner while the other is collapsed in the way which leaves the dynamic behaviour and selected structure unharmed.

5.1.2.4. Subspace Identification [34]-[36]

The SSI method is based on the description of the power system dynamics using a general state-space structure, where the system dynamics is represented by the state-matrices A, B, C, and D for any system. The mathematical relations is basis for system modelling in making of the non-linear model of a power system, lately assuming model to linearize around a stable operating point. Eigen analysis for any system generates the system state matrix with evaluation of the modes.

5.2. Modal analysis using Matlab

The scale of power system, with the interconnection of power grids, is becoming larger and larger. With the upcoming situation, gaining the accurate data for modes and mode shapes at any instant is becoming typical and also more essential. The methods of obtaining mode data and their respective mode shapes are further classified in two categories: methods of identifying utilizing measurements and methods centred on precise mathematical models.

Primarily, the limitation of mathematical model to define the behaviour of a power system dynamics. Secondly, expansion of power system intensely increase the computational burden of the method. Thirdly, variations always observed in a continuous manner, the method of mathematical modelling does not timely retain the variations in power-system.

The modal analysis use in a multivariable approach for an ideal representation of system. It can also be used for estimation in existence of load variations of non-Gaussian nature. The problems related to system identification during the formation

- Finding estimates of the system matrices and the system order. The transform using a modal decomposition is done for investigating different modes for modal frequency and damping.
- Damping estimation based on spectral independent component analysis.

The method involves of two different steps:

(i) a multivariate analysis using a mode selection step for the estimation of their frequencies and detection of the presence of inter-area modes.

(ii) estimating the system response by the estimation of the mode damping.

Among the methods developed, stochastic subspace method is best effective algorithms in system identification field. A simplification of non-linear power system into a linear, continuous time-invariant differential system while evaluating the electro-mechanical characteristics. The practical measurements must be taken in the form of continuous time train of pulses for the system to be represented with linear-time-invariant discrete system. The SSI uses mathematical tool of SVD on the system state matrix for identifying mode shapes.

The order selection technique while using subspace identification is a relatively simple moreover they are better for handling system dynamic and large data changes. The main deficiency in using the method is SVD of a large-dimensional matrix that requires high computational burden, which is difficult to implement at times in applications.

The work proposes a stochastic subspace identification technique (SSI) having adaptive and recursive method, which recursively updates the estimations at each instant to overcome the problem of heavy computational burden of SVD. Therefore, the method provides two advantages over SSI- effective estimation ability of recursive methods along with the ease of implementation of subspace algorithms.

Also, the estimation more responsive under conditions of poor damping or smoother during condition of good damping with the forgetting factor having adaptive selection method when desired. The algorithm of adaptive switching is proposed in the implementation procedure that allows resourceful tracing of dominant modes damping levels gradual variations and from abrupt changes in system conditions.

5.3. Modelling SSI [28]

During the ambient condition, power system operates with small deviation in loads. These variations are supposed as Gaussian white-noise signals and SSI may be implemented for estimating the dynamic behaviour of the system.

Considering nth order linear discrete system as described by equation (3.6.1)

$$\mathrm{x_{k+1}} = \mathrm{Ax_k} + \mathrm{Bu_k} + \mathrm{w_k}$$
$$\mathrm{y_k} = \mathrm{Cx_k} + \mathrm{Du_k} + \mathrm{v_k}$$

where $w_k$is the process noise, v_k is the measurement noise, $y_k \in \Re^{lxl}$ and $x_k \in \Re^{lxl}$. The noises are stationary, zero mean Gaussian noises.

In accordance to dynamic theory of power system for small-signal analysis, small changes in the power-system are assumed to be defined by the differential equations obtained from the non-linear differential algebraic equations after linearizing for an operating point.

The SSI method, can be achieved by two dissimilar ways on the basis of aspects of implementation: the stochastic subspace based on covariance (Cov-SSI) & the stochastic subspace based on data-driven (data-SSI). Foremost operates on the output covariance, rearmost operates directly on output data.

The covariance matrix is defined as

$$H = \begin{bmatrix} R_0 & R_1 & \cdots \\ R_1 & R_2 & \cdots \\ \cdots & \cdots & \cdots \end{bmatrix} \qquad 5.3.1$$

where $R_i \equiv \epsilon\{y_k y_{k-i}^T\}$ and $\epsilon\{0\}$ represents the projected value. Also,

$$R_i = CA^iG \qquad 5.3.2$$

Let O and C be observability and controllability matrices,

then we have

$$H = \begin{bmatrix} C \\ CA \\ CA^2 \\ \cdots \end{bmatrix} [G \quad AG \quad A^2G \quad \cdots] = OC \qquad 5.3.3$$

Ideally covariance matrix H is stated for infinite values but in real world it is difficult having an infinite size matrix, therefore estimation of finite sized H for set of measured covariances $\hat{R}_0 \ldots \hat{R}_{2i}$ is used as follows:

$$\hat{H} = \begin{bmatrix} \hat{R}_0 & \hat{R}_1 & \cdots & \hat{R}_I \\ \hat{R}_1 & \hat{R}_2 & \cdots & \hat{R}_{I+1} \\ \cdots & \cdots & \cdots & \cdots \\ \hat{R}_I & \hat{R}_{I+1} & \cdots & \hat{R}_{2I} \end{bmatrix} \qquad 5.3.4$$

For many applications $\hat{H}$ is evaluated readily by two output sets defined over a length of data-window

$$y_k^+ \equiv \begin{bmatrix} y_k \\ y_{k+1} \\ \cdots \\ y_{k+I} \end{bmatrix} \quad y_k^- \equiv \begin{bmatrix} y_k \\ y_{k-1} \\ \cdots \\ y_{k-I} \end{bmatrix} \qquad 5.3.5$$

The data-window length is 2 x I. then $\hat{H}$ evaluated using:

$$\hat{H} = \frac{1}{p} \sum_k y_k^+ \, y_k^{-T} \qquad 5.3.6$$

Where k coves the entire range of data and normalization parameter p, is set as 1. Since modal properties of the system remains same after multiplying a constant by $\hat{H}$.

The state matrix A and henceforth system modes can be evaluated once the extended observability matrix is calculated. A finite sized observability matrix $\hat{O}$ (beside O) is evaluated from SVD of $\hat{H}$ for largest 'n' singular values and n represents order of system. Taking SVD of $\hat{H}$, we get

$$\hat{H} = USV^T = [U_1 \quad U_2] \begin{bmatrix} S_1 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V_1^T \\ V_2^T \end{bmatrix} \qquad 5.3.7$$

where U represents left-singular vector, S represents diagonal matrix comprising singular values and V represents right-singular vector. Matrix $S_1 \in \Re^{nxn}$ comprises 'n' singular-values that are dominant. The extended observability matrix is calculated as

$$\hat{O} = U_1 \times S_1^{½} \qquad 5.3.8$$

The form of the observability matrix is

$$\hat{O} = \begin{bmatrix} C \\ CA \\ \cdots \\ CA^n \end{bmatrix} \epsilon \, \Re^{(n+1)l \times n} \qquad 5.3.9$$

Let $\underline{\hat{O}}$ and $\overline{\hat{O}}$ are defined as the matrix Ô without the last row and without the first rows, the system state matrix Â and system output matrix Ĉ evaluated as:

$$\hat{A} = \overline{\hat{O}}^{\dagger} \underline{\hat{O}} \ , \hat{C} = \hat{O}(1{:}\, l, :) \qquad 5.3.10$$

where $o^{\dagger}$ represents the pseudo-inverse of the matrix o. Mode frequency and damping is deduced from eigenvalue analysis of the matrix Â involving transformation from discrete to continuous:

$$\hat{A}_c = \frac{1}{T_S} \log \hat{A} \ , \quad \hat{C}_c = \hat{C} \qquad 5.3.11$$

where T_s represents sampling time.

Right eigenvectors of $\hat{A}_c$ obtained represents mode shapes of the system, nevertheless the estimated mode shapes by algorithm are of the model. The system mode shape are evaluated by multiplication by $\hat{C}_c$

$$\phi_i^s = \hat{C}_c \times \phi_i^m \qquad 5.3.12$$

where ϕ_i^m and ϕ_i^s are the mode-shapes of model and system for i^{th} mode.

5.4. Modelling RSSI

The SSI method developed above is exclusive of recursion of parameters and is similar to a block-processing method that provides an autonomous approximation for each separate data window.

For obtaining an online estimation of the model, the initial estimation done in the similar as the non-recursive SSI method with designated data window length. After calculating the initial covariance matrix H by above SSI method, H will be recursively updated using next sets of observed values. For inculcating the recursion of H, old values must disremembered with each iteration by multiplying H with μ, known as forgetting factor.

The updated covariance matrix is calculated as

$$\hat{H}_t = \mu \hat{H}_{t-1} + y_t^+ y_t^{-T} \qquad 5.4.1$$

In order to make the recursion faster, Ô is updated directly without considering SVD in each iteration

$$W(t) = \hat{H}_t \left[W^T(t-1)\hat{H}_t\right]^{\dagger} \qquad 5.4.2$$

$$\ddot{\omega}_{t-1} = W^T(t-1)\hat{H}_{t-1} \qquad 5.4.3$$

$$P(t-1) = [\ddot{\omega}_{t-1}\ddot{\omega}_{t-1}^T]^{\dagger} \qquad 5.4.4$$

$$w(t) = \ddot{\omega}_{t-1} y_t^- \quad \in \Re^{n \times 1} \qquad 5.4.5$$

$$h(t) = W^T(t-1)y_t^+ \quad \in \Re^{n\times 1} \tag{5.4.6}$$

$$\phi^2(t) = [w(t) \quad h(t)] \quad \in \Re^{n\times 2} \tag{5.4.7}$$

$$\mu^2\Lambda(t) = \begin{bmatrix} -y_t^{-T} y_t^- & \mu \\ \mu & 0 \end{bmatrix} \in \Re^{2\times 2} \tag{5.4.8}$$

$$K(t) = [\mu^2\Lambda(t) + \phi^T(t)P(t-1)\phi(t)]^{-1} \times \phi^T(t)P(t-1) \ \in \Re^{2\times n} \tag{5.4.9}$$

$$\mathrm{v(t)} = [\hat{\mathrm{H}}_{t-1}y_t^- \quad y_t^+] \in \Re^{lI\times 2} \tag{5.4.10}$$

$$P(t) = \frac{1}{\mu^2}[P(t-1) - P(t-1)\phi(t)K(t)\ ] \in \Re^{2\times n} \tag{5.4.11}$$

$$w(t) = \mu w(t-1) + h(t)y_t^{-T} \in \Re^{n\times lI} \tag{5.4.12}$$

$$\hat{\mathrm{H}}_t = \mu\hat{\mathrm{H}}_{t-1} + y_t^+ y_t^{-T} \in \Re^{lI\times lI} \tag{5.4.13}$$

$$W(t) = W(t-1) + [v(t) - W(t-1)\phi(t)]K(t) \in \Re^{lI\times n} \tag{5.4.14}$$

The final observability matrix evaluated as

$$\hat{\mathrm{O}}_t = W(t) \tag{5.4.15}$$

Mode estimation is done using equations (5.4.15) and (5.3.8)–(5.3.12).

5.5. Modelling RASSI

Forgetting factor μ is having a value slightly smaller than unity. With the forgetting factor more close to unity, higher stress on past modal histories, thus opposing to the update for new information. The smoother estimation is obtained with higher forgetting factor as the relationship indicates. With smooth estimation, tracking changes in mode values becomes slower. Sometimes in power systems, there is a need for tracing several modes concurrently and properties of the mode can change irrespective of each other. Henceforth, the method of adaptive switching is compatible tool for each mode detection and application in power-system. It is based on the principles stated as:

1) Generally when the mode damping is small, the estimation are more accurate because the modes are better excited as oscillation damps slowly. As the poorly damped modes are having higher mode energy.
2) During lower damping, a more responsive estimator is required for tracing the development of modes.

With the developed adaptive SSI method, dual estimations are performed simultaneously over the time with high and low forgetting factors. The foremost is done for smooth estimation while rearmost for fast estimation. With the two estimates λ_1 and

λ_2 for each mode, the final estimate λ_A of RASSI be is selected from either of established modes by the logic provided shown:

$$\lambda_A = \begin{cases} \lambda_{1,} & if\ \xi_2 > \xi_T\ and\ T_o > T'' \\ & if\ \xi_2 < \xi_T\ and\ T_u < T' \\ \lambda_2 & if\ \xi_2 < \xi_T\ and\ T_u > T' \\ & if\ \xi_2 > \xi_T\ and\ T_o > T'' \end{cases} \tag{5.5.1}$$

where λ_A represents final estimated mode, λ_1 and λ_2 are the other two estimates for mode for slow and fast tracking capabilities respectively. ξ_2 is the value of damping ratio for fast estimator and ξ_A be threshold damping ratio. T_u and T_v are the total time durations for estimated damping ratio of fast estimator that stays continuously below and over the damping ratio threshold, respectively.

Finally, T´ and T´´ are defined as follows:

$$T' = T_{u\,max}$$

$$T'' = \begin{cases} T_u\,, & if\ T_u < T_{o\,max} \\ T_{o\,max}\,, & if\ T_u < T_{o\,max} \end{cases} \tag{5.5.2}$$

where $T_{u\ max}$ and $T_{o\ max}$ are two tuneable constraints which specify the maximum transient time deliberated when the threshold damping reached.

5.6. Conclusion

The following Chapter provides a brief summary of the methods developed for the modal analysis of the power system. The chapter provides in depth knowledge of the subspace algorithm developed for the analysis of the system and the RASSI technique developed for the online estimation of modes of the power system.

Chapter 6
REVIEW OF RESULTS

6.1. Introduction

Modal Method is developed for the analysis of small-signal stability problem for the system. Real power system is established is fabricated using power factory, a transient RMS is performed on the model with a three-phase short-circuit on 50% of the transmission line in between bus 7 and bus 8. The fault is created at t = 1 sec and subsequently removed at t = 1.01 sec at natural zero. The results of simulation are exported in (.csv) file for the analysis in Matlab. The RASSI method is implemented for the evaluation of modal parameters of the system.

6.2. Results from matlab

Results are evaluated for modal analysis using tie line power. The following results are obtained from modal analysis by SSI and RASSI method.

Singular values of the system

ss =
 1.0e+03 *
7.5524
0.9388
0.0616
0.037
0.001
0.0009
0.0001
0
0

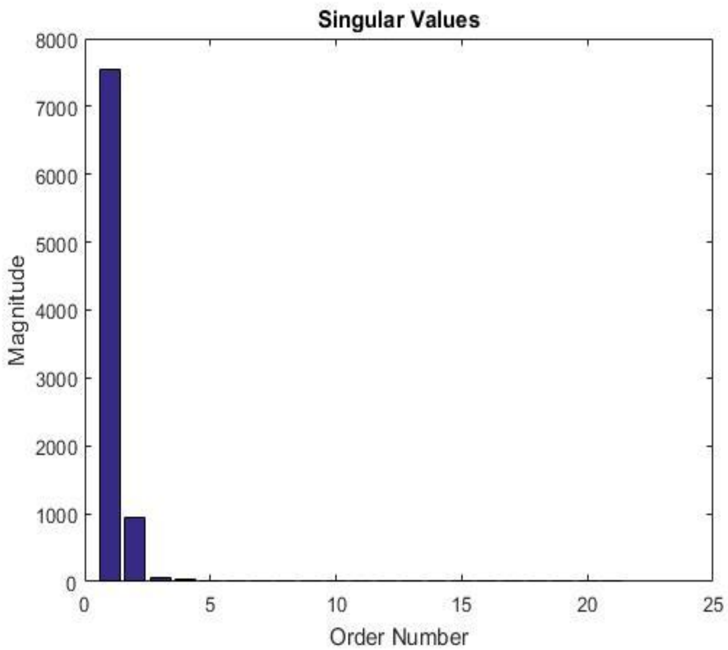


Figure 6.1 Singular value plot

Order of the system = No of Singular values =7

Mode shapes of the system using SSI method

ith Mode Shape of System
phi_i_s =
-16.5862 - 0.4096i -18.7522 + 3.2507i 0.9889 + 4.6264i 2.4509 - 2.4693i
7.1512 - 4.3640i 5.0492 - 2.6607i 6.1577 - 5.7975i

Mode shapes of the system using RASSI method

ith Mode Shape of System
phi_i_s =
-0.0032 - 0.0005i 0.0090 + 0.0159i 0.0110 + 0.0053i -0.0141 + 0.0029i
-0.0087 + 0.0105i -0.0088 + 0.0125i 0.0145 + 0.0231i

6.3. Comparison of results

Based on the analysis, the following results are evaluated:

Based on tie-line power	
SSI Method	**RASSI Method**
Mode Shape 1=	Mode Shape 1=
-16.5862 - 0.4096i	-0.0032 - 0.0005i
Damp_rat =	Damp_rat =
0.9997	0.9871
Osc_freq =	Osc_freq =
0.0652	8.19E-05
Mode Shape 2=	Mode Shape 2=
-18.7522 + 3.2507i	0.0090 + 0.0159i
Damp_rat =	Damp_rat =
0.9853	0.4922
Osc_freq =	Osc_freq =
0.5174	0.0025
Mode Shape 3=	Mode Shape 3=
0.9889 + 4.6264i	0.0110 + 0.0053i
Damp_rat =	Damp_rat =
-0.209	0.9002
Osc_freq =	Osc_freq =
0.7363	8.44E-04
Mode Shape 4=	Mode Shape 4=
2.4509 - 2.4693i	-0.0141 + 0.0029i
Damp_rat =	Damp_rat =
-0.7045	0.9798
Osc_freq =	Osc_freq =
0.393	4.58E-04

Mode Shape 5=	Mode Shape 5=
7.1512 - 4.3640i	-0.0087 + 0.0105i
Damp_rat =	Damp_rat =
-0.8536	0.6404
Osc_freq =	Osc_freq =
0.6945	0.0017
Mode Shape 6=	Mode Shape 6=
5.0492 - 2.6607i	-0.0088 + 0.0125i
Damp_rat =	Damp_rat =
-0.8847	0.5767
Osc_freq =	Osc_freq =
0.4235	0.002
Mode Shape 7=	Mode Shape 7=
6.1577 - 5.7975i	0.0145 + 0.0231i
Damp_rat =	Damp_rat =
-0.7281	0.5308
Osc_freq =	Osc_freq =
0.9227	0.0037
time =	time =
30.0653	28.9703

Table 6.1 Comparision of Modes Data

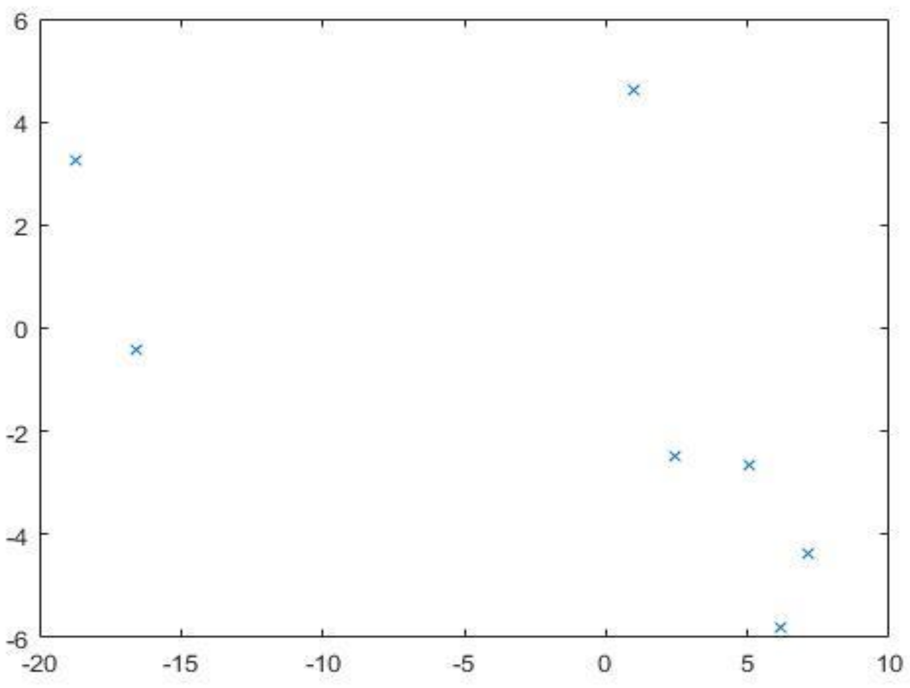


Figure 6.2 Mode shape plot by SSI method

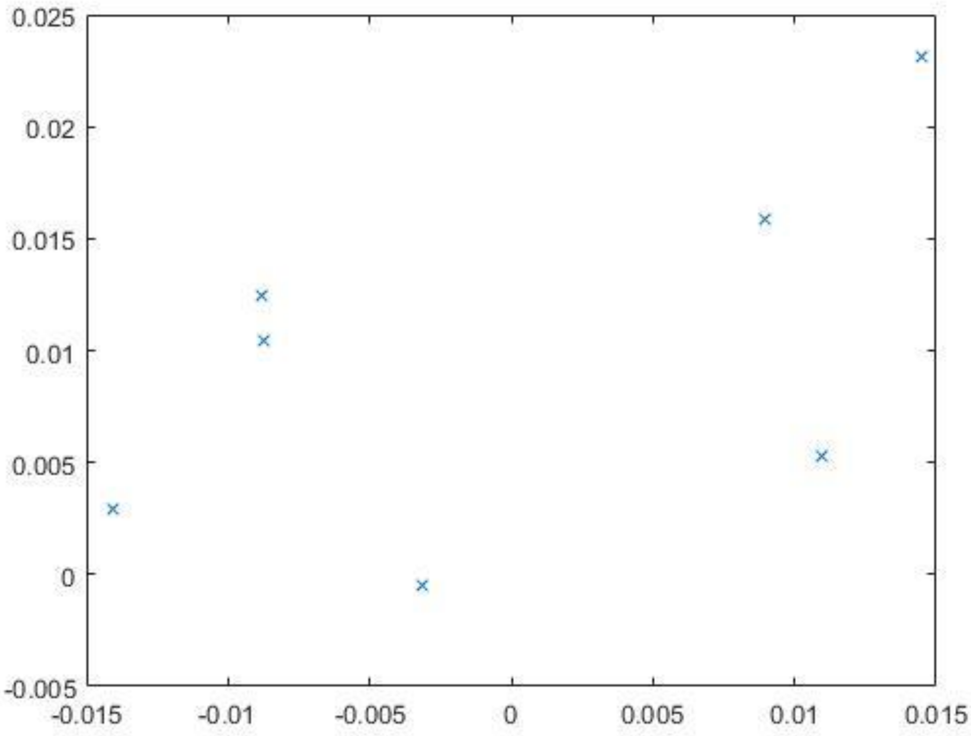


Figure 6.3 Mode shape plot by RASSI method

With the above observation, it can be seen that the RASSI method is having more no of modes toward left half plane than SSI method. Mode estimation done by SSI is a not convenient due to the fact the system properties keeps changing with change in time. RASSI on the other hand, evaluates the mode parameters at the instant, also for any sudden change in the behaviour of the system the system response in predicted fast.

6.4. Conclusion

The RASSI method developed provides an online estimation of the modal properties of the system, on calculation of tie line power at transmission line between bus 7 and bus 8. The computational procedure of RASSI is fast than the computational procedure of SSI algorithm. Moreover the SSI algorithm is less accurate than RASSI method having a low forgetting factor.

Chapter 7
CONCLUSION AND FUTURE WORK

7.1. Conclusion

Basic analyses including transient (RMS) and Modal analysis were carried out using DigSILENT's power factory, includes load flow calculations, transient stability for the three phase fault in 3 and modal analysis/eigenvalues calculation on two area system. Transient stability analyses is an important considerations during the planning, design and operation of modern power systems.

RASSI method has the following benefits:

- The method developed is comparatively fast recursive approach for a short initialization of data window that works with small refresh rates. With the small refresh rates, damping changes can be tracked with a fast rates, which helps associating damping changes with system changes for a better evaluation of root cause mode identification. Moreover, fast refresh rate are required for fast tracking, they also plays an important role in analysis for automatic control action.
- The method is successfully implemented and is able to adapt effectively for each mode thus finding the damping levels.
- The method provides fast transient response for estimations concurred in transient conditions as well as steady state performance with minor standard deviations in the estimations.

7.2. Future Scope

In this thesis, we have considered a three phase fault on transmission line between bus 7 and bus 8, the model can be tested at different fault location for the transient analysis of the system thus understanding the concepts of modes of oscillation.

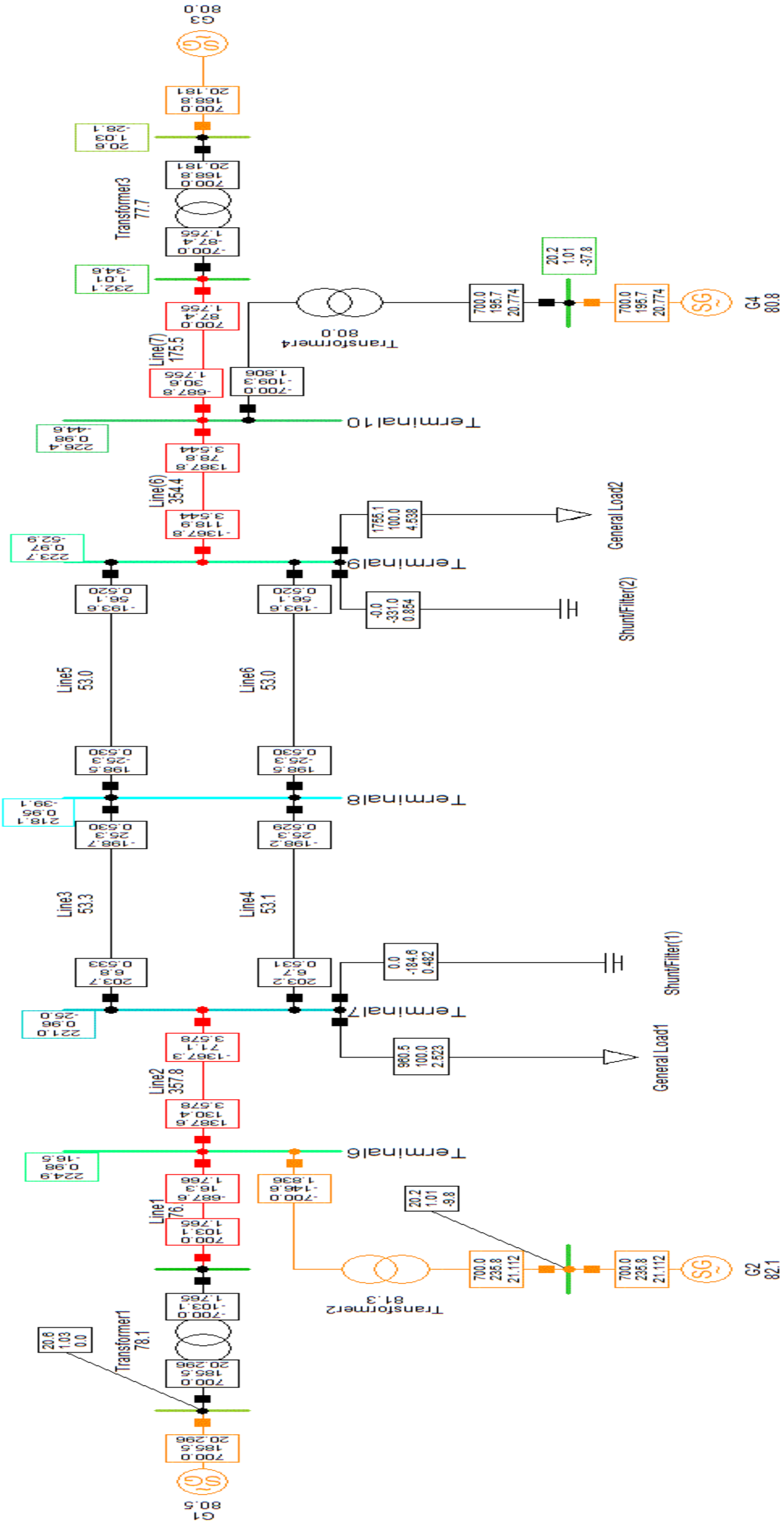
Further research can be done on methods for improving switching logic algorithm between multiple engines with two different forgetting factors. Further we have restricted ourselves for the analysis on single output function, the model presented is a multi-dimensional approach, the response for a multi-dimensional model would be studied.

The proposed methodology need to be tested in real-field applications. Also, ambient modal estimation for handling of random noise required to be studied.

APPENDICES

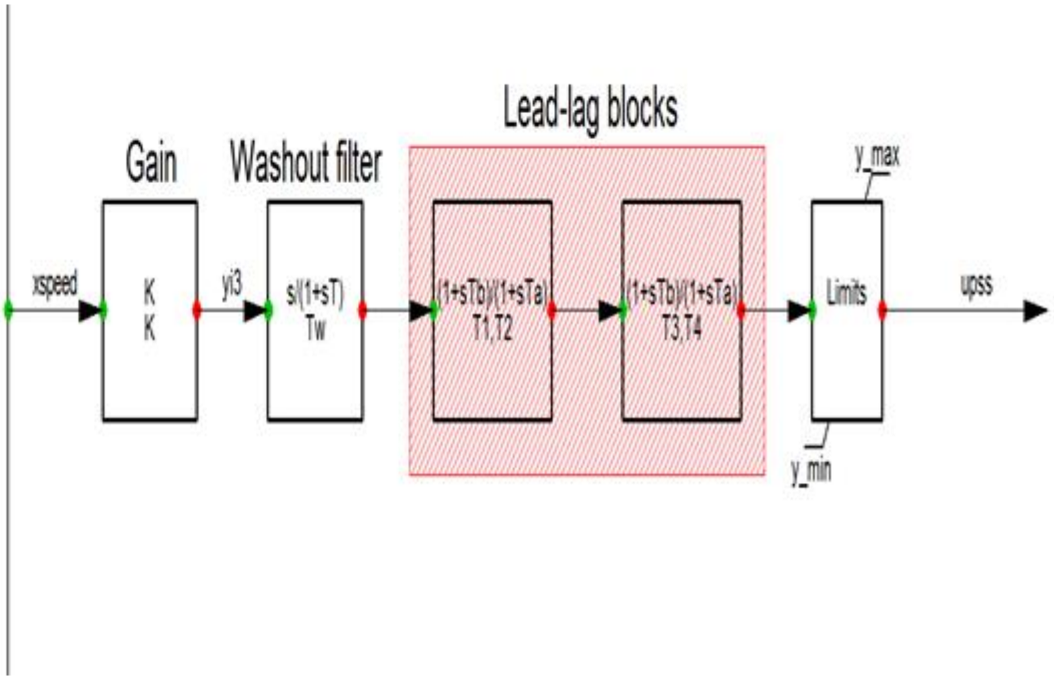
Appendix I	Power factory simulation model of two area system
Appendix II	Power system stabilizer (model) developed in power factory
Appendix III	Modal plots of oscillatory modes for different system parameters
Appendix IV	Mode Bar Plots of oscillatory modes for different parameters
Appendix V	Matlab Coding

APPENDIX I : Power Factory Simulation



```
----------------------------------------------------------------------------------------------------------------------
| Load Flow Calculation                                                                              Busbars/Terminals |
----------------------------------------------------------------------------------------------------------------------
|     AC Load Flow, balanced, positive sequence               |     Automatic Model Adaptation for Convergence         No        |
|     Automatic Tap Adjust of Transformers          No        |     Max. Acceptable Load Flow Error for                          |
|     Consider Reactive Power Limits                No        |        Nodes                                           1.00 kVA  |
|                                                             |        Model Equations                                 0.10 %    |
----------------------------------------------------------------------------------------------------------------------
----------------------------------------------------------------------------------------------------------------------
| Grid: Grid                System Stage: Grid            | Study Case: Study Case               | Annex:             / 1  |
----------------------------------------------------------------------------------------------------------------------
|          rated                              Active Reactive Power                  |                                  |
|         Voltage      Bus-voltage            Power   Power  Factor Current Loading|          Additional Data           |
|           [kV]  [p.u.]     [kV]    [deg]    [MW]   [Mvar]    [-]    [kA]    [%]  |                                  |
----------------------------------------------------------------------------------------------------------------------
|Terminal6                                                                           |                                  |
|        230.00    0.98  224.97  -16.55                                              |                                  |
|    Cub_1  /Lne       Line1              -687.64    16.72  -1.00     1.77  176.52 |Pv:  12364.42 kW   cLod:  4.31 Mvar L:   25.00 km|
|    Cub_2  /Lne       Line2              1387.64   128.75   1.00     3.58  357.65 |Pv:  20300.84 kW   cLod:  1.65 Mvar L:   10.00 km|
|    Cub_5  /Tr2       Transformer2       -700.00  -145.47  -0.98     1.83   81.21 |Tap:     0.00      Min:       0      Max:      0  |
|                                                                                    |                                  |
|Terminal7                                                                           |                                  |
|        230.00    0.96  221.04  -24.96                                              |                                  |
|    Cub_4  /Shnt      Shunt/Filter(1)       0.00  -184.72   0.00     0.48          |                                  |
|    Cub_5  /Lod       General Load1       966.98   100.00   0.99     2.54          |P10:    967.00 MW   Q10: 100.00 Mvar             |
|    Cub_1  /Lne       Line2             -1367.33    72.61  -1.00     3.58  357.65 |Pv:  20300.84 kW   cLod:  1.65 Mvar L:   10.00 km|
|    Cub_2  /Lne       Line3               200.44     6.09   1.00     0.52   52.38 |Pv:   4788.62 kW   cLod: 17.47 Mvar L:  110.00 km|
|    Cub_3  /Lne       Line4               199.91     6.01   1.00     0.52   52.24 |Pv:   4786.32 kW   cLod: 17.55 Mvar L:  110.00 km|
|                                                                                    |                                  |
|Terminal5                                                                           |                                  |
|        230.00    1.01  231.49   -6.46                                              |                                  |
|    Cub_1  /Tr2       Transformer1       -700.00  -102.62  -0.99     1.76   78.10 |Tap:     0.00      Min:       0      Max:      0  |
|    Cub_2  /Lne       Line1               700.00   102.62   0.99     1.76  176.52 |Pv:  12364.42 kW   cLod:  4.31 Mvar L:   25.00 km|
|                                                                                    |                                  |
|Terminal1                                                                           |                                  |
|         20.00    1.03   20.60    0.00                                              |                                  |
|    Cub_2  /Sym       G1                  700.00   184.97   0.97    20.29   80.45 |Typ:    SL                                      |
|    Cub_1  /Tr2       Transformer1        700.00   184.97   0.97    20.29   78.10 |Tap:     0.00      Min:       0      Max:      0  |
|                                                                                    |                                  |
----------------------------------------------------------------------------------------------------------------------
```

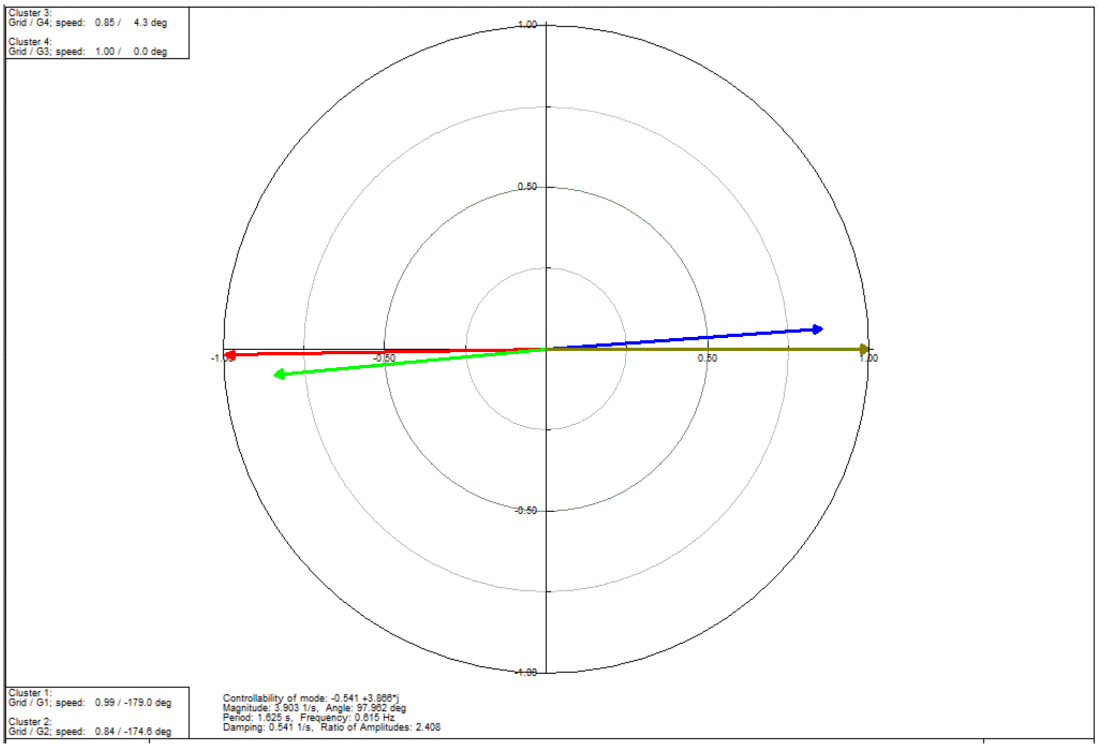
Load Flow Calculations of two-area system



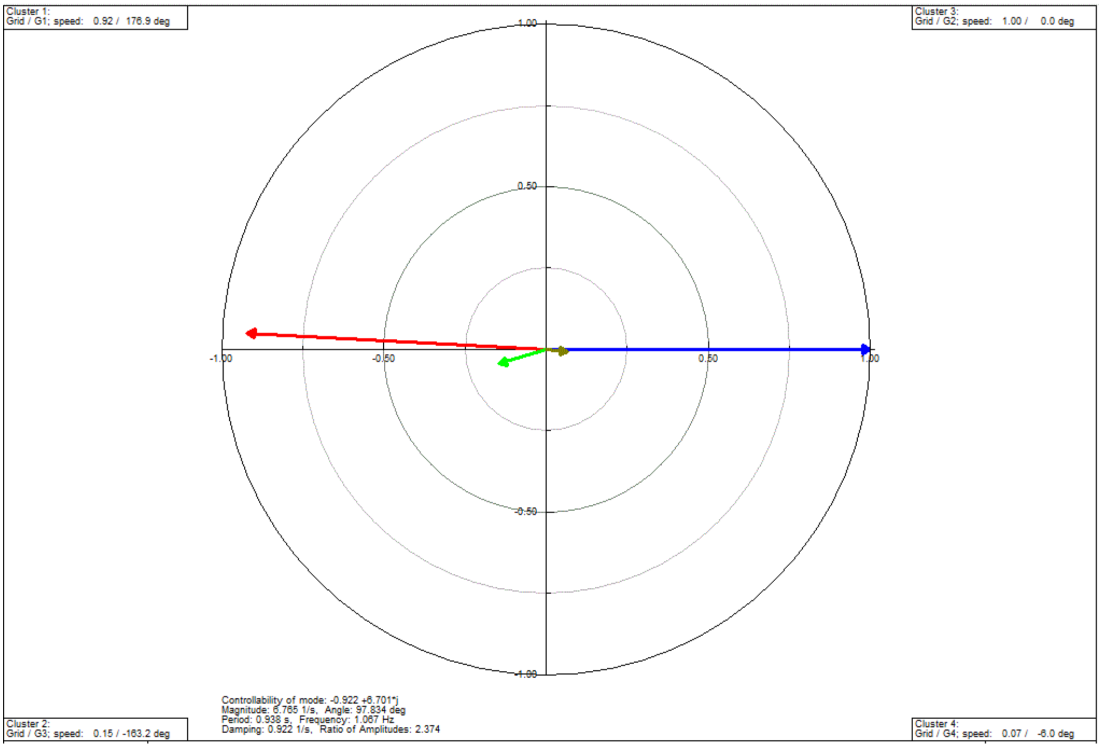
PSS Model developed in power factory

Parameter	Vaule
K	50
T1	0.5
T2	0.5
T3	0.05
T4	0.05
Tw	0
y_min	0
y_max	0

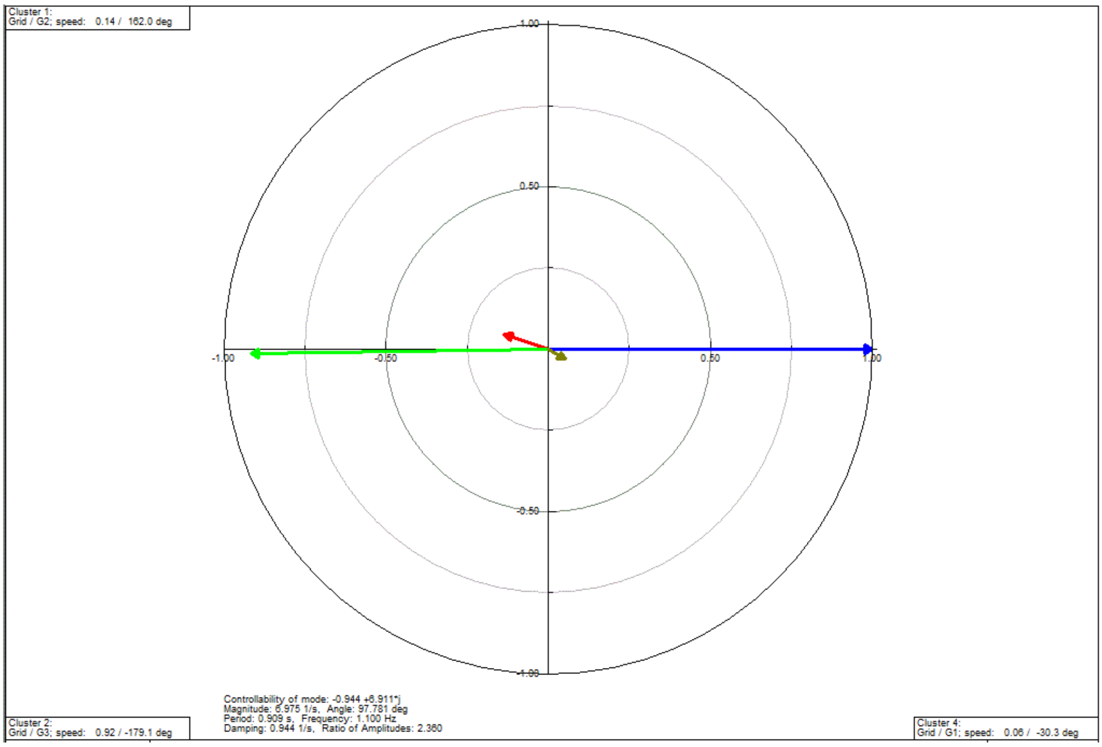
PSS parameters develoved in power factory



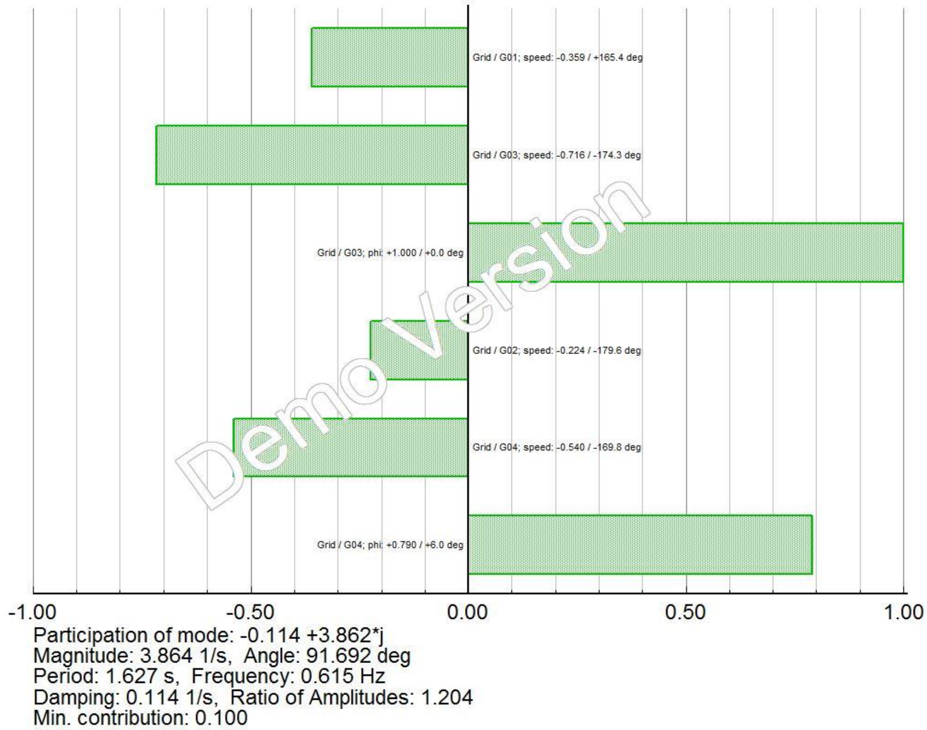
Mode plot for 0.61 Hz for generator rotor speed



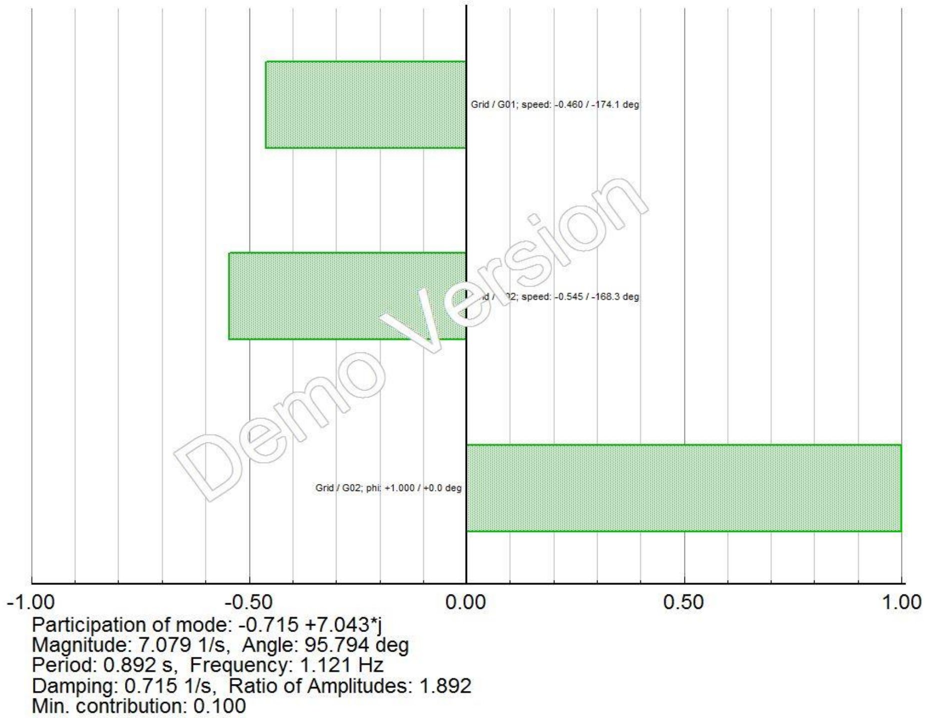
Mode plot for 1.067 Hz for generator rotor speed



Mode plot for 1.10 Hz for generator rotor speed



Mode Bar Plot of 0.61 Hz showing minimum contribution



Mode Bar Plot of 1.21 Hz showing minimum contribution

MATLAB CODING

```
%--------------------RASSI Optimization algorithm--------------------
% This procedure is used for analysis for Kundur's Two Area system.
% For solv1ing this problem two platforms are employed :
% Matlab(Mathworks)and DIgSILENT (PowerFactory).
%-DIgSILENT - real power system and controller modeling;
%-Matlab    - Coding of RASSI method;

%   Consider a multivariable fourth order system A,W,C,V
%   which is driven by white noise and generates an output y:
%
%               x_{k+1} = A x_k + W_k
%                y_k    = C x_k + V_k
%              cov(e_k) = R
% y_k = Output Matrix of (lX1) dimesnion
% x_k = Input Matrix of (nX1) dimesnion
% W_k is the process noise, V_k is measurement noise

% Variable initialization
clear all; clc; %Clear the workspace and the command window
I = 20;          % data window size of the algorithm

% Accessing the communication .csv files in Matlab
y3 = load('Tie_power1.csv'); % output loaded from .csv files(Normal
case)

y = y3(:,3); %for Tie line power

% DATA WINDOW LENGTH = 2*win
[r1,c1] = size(y); % l(in paper)=c1, l(in paper)=r1

% Implementation for Stochastic Subspace identification(SSI)
disp('                  SUBSPACE IDENTIFICATION ')
tic %Start the watch

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                  SSI ALGORITHM                  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%5%%%%%%%%%%%%%%%%

% ******************************************
% STEP 1: Evaluating covariance matrix Hcap
% ******************************************
Hcap_s = zeros(I+1);
yplus =[]; yminus=[]; Hcapall=[];
disp('Covariance Matrix = Hcap');
for k1 = I : (r1-(2*I+1))                   % k1 = 1 : r1

    k1;
    % Evaluating Hval_k,yplus_k,yminus_k
    [Hval_k,yplus_k,yminus_k] = Covar_mat(y, I, k1-I);
    [Hcap_s] = [Hcap_s] + [Hval_k];

    % storing previous values
    [yplus] = [yplus , yplus_k];
```

```
    [yminus] = [yminus , yminus_k];
    [Hcapall] = [Hcapall, Hcap_s];

end

Hcap_s

% ***********************************************
%     STEP 2: Evaluating SVD of Hcap
% ***********************************************
disp('Performing SVD...');
[U,S,V] = svd(Hcap_s);

% Eigen Values
ss = diag(S);
U_Hcap = U; V_Hcap = V; S_Hcap = S; ss
clear U V S

disp('No. of dominant Eigen values() = order =  ');

% ****************************************************
% STEP 3: Determine the order from the singular values
% ****************************************************
% loop for halt program to input ORDER.
n = [];
if (length(n) == 0)
    max_order = I+1; %max. order that can be estimated
    figure(1);hold off;
    xx = []; yy = [];
    bar_out = bar([1:max_order],ss);
    xx = bar_out.XData;
    yy = bar_out.YData;
    title('Singular Values');
    xlabel('Order Number');ylabel('Magnitude');
    n = 0;
end

if (n==0)
    while ((n < 1) | (n > max_order))
        n = input('      System order ? ');
        if (n == []);n = -1;end
    end
end

% *****************************************************
% STEP 4: Evaluating Extended Observability Matrix Ocap
% *****************************************************
% Extended observability matrix
disp('Extended Observability Matrix = Ocap');
n;
U1 = U_Hcap(:,1:n);         % extraction of submatrix of U
U2 = U_Hcap(:,n+1:I);       % extraction of submatrix of U
S1 = S_Hcap(1:n,1:n);       % extraction of submatrix of S
[m1,n1]=size(S1);
for i1=1:m1
    for j1=1:n1
        S1(i1,j1)=sqrt(S1(i1,j1));  % taking square root of values
    end
end

S2=S1;
```

```
[Ocap] = [U1]*[S2]       % extended observability matrix
[m2,n2]=size(Ocap);

Ocapup = Ocap(2:m2,:);
Ocapdw = Ocap(1:(m2-1),:);
Ocapup; Ocapdw;

%Moore-Penrose pseudo inverse calculation
% Aleft =(inv(A'*A))*A'
% Aright =A'*(inv(A*A'))
disp('Evaluating Moore-Penrose pseudo inverse');
Ocapdw_lt = (inv(Ocapdw'*Ocapdw))*Ocapdw';
[m3,n3]=size(Ocapdw_lt);
Ocapdw_rt = Ocapdw'*(inv(Ocapdw*Ocapdw'));
[m4,n4]=size(Ocapdw_rt);

% ****************************************************
%             STEP 5: Evaluating Acap and Ccap
% ****************************************************
disp('Discrete System Matrix = Acap');
Acap = Ocapdw_lt*Ocapup
disp('Discrete Output Matrix = Ccap');
Ccap = Ocap(1:c1,:)

Acap1 = Acap; Ts = 0.01;
[m5,n5]=size(Acap1);
for i2=1:m5
    for j2=1:n5
        Acap1(i2,j2)=log(Acap1(i2,j2))/Ts;  % taking log of values
    end
end
Acap1;

% Continous time system matrices
disp('Cotinous System Matrix = Acap');
Acap_c = Acap1
disp('Cotinous Output Matrix = Ccap');
Ccap_c = Ccap


% ****************************************************
%       STEP 6: Evaluating Modes and Mode shapes
% ****************************************************
% Mode shapes are right Eigen vectors of Acap_c
[V,D,W] = eig(Acap_c);
V_Acap_c = V;  % column are right eigen vectors
D_Acap_c = D;  % Diagonal matrix of eigen values of A.
W_Acap_c = W;  % column are left eigen vectors
clear V D W

disp('ith Mode Shape of Model');
phi_i_m = V_Acap_c  % ith Mode shapes of Model
disp('ith Mode Shape of System');
phi_i_s = Ccap_c*phi_i_m  % ith Mode shapes of system
figure(4); grid on
plot(phi_i_s,'x')

% ****************************************************
% STEP 7: Evaluating damping and oscillation frequency
% ****************************************************
ss1 = phi_i_s(:,1:n);
```

```
for zz = 1:n

Shape = ss1(:,zz)
Z1 = real(Shape);
Z2 = imag(Shape);
Zmag = sqrt((Z1^2)+(Z2^2));
Damp_rat = (-Z1/Zmag)
Osc_freq = abs(Z2/(2*pi))
nat_osc_freq = Osc_freq/(sqrt(1-Damp_rat^2));

end

%H = tf(1, conv([1, s1],[1, s2]),0.01)
%damp(H)

save SSI;
toc; %Stop watch
time = toc %Computation time



%%%%%%%%%%%%%%%%%%%%%%%%
%    RASSI ALGORITHM   %
%%%%%%%%%%%%%%%%%%%%%%%%

disp('      RECURSIVE ADAPTIVE SUBSPACE IDENTIFICATION ')
% Variable initialization
I = I;              % window size of the algorithm
mu = 0.8;                % forgetting factor
w_t_1 = 0;               % initial value of weight
Hcap_t_1 = []; Hcapall_t = [];

tic %Start the watch
% ******************************************
% STEP 1: Updating covariance matrix Hcap_t
% ******************************************
    disp('Step 1');

    [ Hval_0,yplus_0,yminus_0 ] = Covar_mat( y, I, 20);

    for iter = I : (r1-(2*I+1))
    %disp('Evaluating next Hcap_t');
    ins_t = iter;

    Hcap_ini = Hcap_s; % UPDATE !!!
    if(length(Hcap_t_1)==0)
        Hcap_t_1 = Hcap_ini;
    else
        ((ins_t-I)*(I+1)-(I)):((ins_t-I)*(I+1));
        Hcap_t_1 = Hcapall_t(:,((ins_t-I)*(I+1)-(I)):((ins_t-
I)*(I+1)));
    end
    [r12,c12] = size(Hcap_t_1);

    Hval_t = yplus(:,(ins_t-I+1))*yminus(:,(ins_t-I+1))';
    [r13,c13] = size(Hval_t);
    [ Hcap1 ] = mu.*[ Hcap_t_1 ] + [ Hval_t ];
    Hcap_t_1 = Hcap1;
    Hcap_t = Hcap1;
    [Hcapall_t] = [Hcapall_t, Hcap_t];    % past values
```

```
end

% ******************************************
%      Step 2: Obtaining Initial Values
% ******************************************
    disp('Step 2');
    W_t_1 = U1;
    Hcap_t_1 = Hcap_s;
    %Hcapall_t(:,((ins_t-win+1)*win-(win-1)):((ins_t-win+1)*win));
    [wcap_t_1] = [W_t_1]'*[Hcap_t_1];
    P1 = [wcap_t_1*wcap_t_1'];
    %Moore-Penrose pseudo inverse calculation
    % Aleft =(inv(A'*A))*A'
    P_t_1 = (inv(P1'*P1))*P1';

% ******************************************
%       Step 3: Evaluating parameters
% ******************************************
    disp('Step 3');
    % initial weight
    %    in iterartion
    ins_t = 0;
    [w1a_t] = [];
    [P_ta] = [];
    [Wa] = [];
    [Ocapa] = [];
    wcapa = wcap_t_1;
    [Damp_all] = [];
    [Osc_f_all] = [];

for ins_t = I : (r1-(2*I+1))

    [P_ta] = [P_ta, P_t_1];
    ytminus = yminus(:,ins_t-I+1);
    ytplus = yplus(:,ins_t-I+1);
    [m5,n5] = size(ytminus);

    ins_t;
    w1_t = wcap_t_1*ytminus;                        %(nX1)
    [w1a_t] = [w1a_t, w1_t];                        %with present value
    h_t = W_t_1'*ytplus;                            %(nX1)
    AB = [ w1_t, h_t ];                             %(nX2)
    [phi_t] = sqrt(AB);                             %(nX2)
    MU = mu*ones(1);
    ZE = zeros(1);
    mu_kai_t = [-(ytminus'*ytminus), MU; MU', ZE];    %(2X2)
    kai_t = mu_kai_t/(mu^2);
    K_t = (inv([mu_kai_t + (phi_t'*P_t_1*phi_t)]))*(phi_t'*P_t_1);

    v_t =[Hcap_t_1*ytminus, ytplus];                     %(winX2)
    P_t1 = [ P_t_1 - P_t_1*phi_t*K_t ];
    P_t = P_t1/(mu^2);                                   %(nXn)

    wcap_t = mu*wcap_t_1 + h_t*ytminus';                %(nXwin)
    [wcapa] = [wcapa, wcap_t];                          %with past value
    Hcap_t = mu*Hcap_t_1 + ytplus*ytminus';             %(winXwin)
    [W_t] = [W_t_1] + [v_t - W_t_1*phi_t]*[K_t];        %(winXn)
    Ocap_t = W_t;
    [Ocapa] = [Ocapa, Ocap_t];
```

```
    % Updating previous values with new values
    [Wa] = [Wa, W_t_1];
    [W_t_1] = [W_t];
    [wcap_t_1] = [wcap_t];
    [P_t_1] = [P_t];
    [Hcap_t_1] = [Hcap_t];
end
    [m6,n6] = size(Ocapa);
    Ocap_f = Ocapa(:,(n6-n+1):(n6));
%    m2 = 0; n2 = 0;
%     [m2,n2]=size(Ocap_f);


    Ocapup = Ocap_f(2:m2,:);
    Ocapdw = Ocap_f(1:(m2-1),:);

    %Moore-Penrose pseudo inverse calculation
    % Aleft =(inv(A'*A))*A'
    % Aright =A'*(inv(A*A'))
    Ocapdw_lt = (inv(Ocapdw'*Ocapdw))*Ocapdw';
    [m3,n3]=size(Ocapdw_lt);
    Ocapdw_rt = Ocapdw'*(inv(Ocapdw*Ocapdw'));
    [m4,n4]=size(Ocapdw_rt);

    disp('Discrete System Matrix = Acap');
    Acap = Ocapdw_lt*Ocapup
    disp('Discrete Output Matrix = Ccap');
    Ccap = Ocap_f(1:c1,:)

    Acap1 = Acap; Ts =0.01;
    [m5,n5]=size(Acap1);

    % taking square root of values
    for i2=1:m5
        for j2=1:n5
            Acap1(i2,j2)=log(Acap1(i2,j2))/Ts;
        end
    end
    Acap1;

    % Continous time system matrices
    disp('Cotinous System Matrix = Acap');
    Acap_c = Acap1
    disp('Cotinous Output Matrix = Ccap');
    Ccap_c = Ccap

    % Mode shapes are right Eigen vectors of Acap_c

    [V,D,W] = eig(Acap_c);
    V_Acap = V;  % column are right eigen vectors
    D_Acap = D;  % Diagonal matrix of eigen values of A.
    W_Acap = W;  % column are left eigen vectors
    clear V D W

    disp('ith Mode Shape of Model');
    phi_i_m = V_Acap  % ith Mode shapes of Model
    disp('ith Mode Shape of System');
    phi_i_s = Ccap_c*phi_i_m  % ith Mode shapes of system

    figure(5); grid on
```

```
    plot(phi_i_s,'x')
    A_t = Acap;
    C_t = Ccap;

    % *****************************************************
    %     Evaluating damping and oscillation frequency
    % *****************************************************
    ss1 = phi_i_s(:,1:n);
    max_damp_rat = 0;
    [Damp1] = [];
    [Osc1] = [];
    for zz = 1:n
        Shape = ss1(:,zz)
        Z1 = real(Shape);
        Z2 = imag(Shape);
        Zmag = sqrt((Z1^2)+(Z2^2));
        Damp_rat = abs(-Z1/Zmag)
        Osc_freq = abs(Z2/(2*pi))
        nat_osc_freq = Osc_freq/(sqrt(1-Damp_rat^2));

        [Damp1] = [Damp1; Damp_rat];
        [Osc1] = [Osc1; Osc_freq];
    end
    [Damp_all] = [Damp_all, Damp1];
    [Osc_f_all] = [Osc_f_all, Osc1];

%end

save RSSI;
toc; %Stop watch
time = toc %Computation time
```

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