MATLAB MODELLING FOR ANALYZING SMALL SIGNAL STABILITY OF MULTIMACHINE LARGE SCALE POWER SYSTEM

A THESIS SUBMITTED TOWARDS PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE DEGREE OF MASTER OF TECHNOLOGY

MASTER OF TECHNOLOGY

IN

ENERGY SCIENCE AND TECHNOLOGY

FACULTY OF INTERDISCIPLINARY STUDIES,LAW MANAGEMENT (FISLAM)
COURSES ARE AFFILIATED TO
FACULTY OF ENGINEERING AND TECHNOLOGY
JADAVPUR UNIVERSITY

UNDER SUPERVISION OF

Dr. RATAN MANDAL

JADAVPUR UNIVERSITY

SUBMMITTED BY

AVIK DAS

ROLL NO: M4ENR19016

SCHOOL OF ENERGY STUDIES
JADAVPUR UNIVERSITY
KOLKATA 700032
INDIA

2019

CERTIFICATE FOR RECOMMENDATION

This is to certify that the thesis entitled **MATLAB MODELLING FOR ANALYZING SMALL SIGNAL STABILITY OF MULTIMACHINE LARGE SCALE POWER SYSTEM**, which is being submitted by **Avik Das** in partial fulfilment of the requirements for the award of the degree of **Master of Energy Studies** at the School of Energy Studies and Application, Jadavpur University, Kolkata700032, during the academic year 2018-2019, is the record of the student's own work carried out by him under our supervision.

Thesis Guide

Dr. Ratan Mandal

Professor, School of Energy Studies
Jadavpur University
Kolkata

Director

Dr. Ratan Mandal

Professor, School of Energy Studies
Jadavpur University
Kolkata

Prof. Pankaj Kumar Roy

Dean of Faculty of Interdisciplinary Studies, Law and Management

Jadavpur University
Kolkata

CERTIFICATE FOR APPROVAL

The foregoing thesis entitled **MATLAB MODELLING FOR ANALYZING SMALL SIGNAL STABILITY OF MULTIMACHINE LARGE SCALE POWER SYSTEM** is hereby approved as a creditable study of an engineering subject carried out and presented in a satisfactory manner to warrant its acceptance as a prerequisite for the degree of **Master of Energy Studies** at the School of Energy Studies and Application, Jadavpur University, Kolkata 700032, for which it has been submitted. It is understood that by this approval the undersigned do not necessarily endorse or approve any statement made, opinion expressed, or conclusion drawn there in but approve the thesis only for the purpose for which it is submitted.

COMMITTEE ON FINAL EXAMINATION
FOR EVALUATION OF THESIS

____

____

____

____

DECLARATION OF ORIGINALITY & COMPLIANCE OF ACADEMIC ETHICS

It is hereby declared that the thesis entitled **MATLAB MODELLING FOR ANALYZING SMALL SIGNAL STABILITY OF MULTIMACHINE LARGE SCALE POWER SYSTEM** contains literature survey and original research work by the undersigned candidate, as part of his degree of **Master of Energy Studies** at the School of Energy Studies and Application,Jadavpur University, Kolkata700032.
All information in this document has been obtained and presented in accordance with academic rules and ethical conduct.
It is also declared that all materials and results, not original to this work have been fully cited and referred throughout this thesis, according to rules of ethical conduct.

Name: AVIK DAS

Registration Number: 119693 of 12-13

Examination Roll Number: M4ENR19016

Dated:

(Signature)

ACKNOWLEDGEMENT

I have immense pleasure in expressing my profound gratitude and sincere thanks to my respected thesis advisors **Prof. Ratan Mondal** for his valuable guidance, constant encouragement, useful suggestions, keen interest and timely help in completing this thesis successfully. It has been an excellent opportunity for me to work under his supervision.

I am also expressing my gratitude towards **Prof. Tushar Jash** for his guidance.

I also thankfully acknowledge the assistance received from all the research scholar of Department of Energy Studies for their sincere, spontaneous and active support during the preparation of this work.

I would like to specially thank **all my friends** for their constant motivation and support without which this report would not have been materialized.

My thanks also to technical and non technical staffs in the laboratory who helped me kindly.

Further, I also take this opportunity to thank all the teachers who taught me and shared their knowledge with me. I must express my heartiest thanks to my friends and seniors at Jadavpur University.

Abstract

The main objective of this paper is to study the nature of inter-area oscillations in power systems. Small signal stability refers to the ability of a power system to maintain synchronism under small disturbances. Instability may arise in two forms increase of rotor angle due to lack of sufficient synchronization torque and rotor oscillations of increasing amplitude due to lack of sufficient damping torque. To study small signal stability analysis synchronous machine model, transmission line model and two area system model and the dynamic state matrix eigenvalues and eigen vectors are constructed and the small signal stability analysis done with the developed algorithm. The 11 bus systems are considered here for study of oscillations. The effects of the system structure, generator modelling, excitation type, and system loads are dis-cussed in detail. In the study, a 11 bus 4 machine 2 area standard system has been modeled in Matlab environment to get the eigenvalue analysis of the system and parallely the same system has been simulated in PSAT software. Then a comparison has been put up between those results. This paper showed any multi-machine system stability can be easily analyzed by the algorithm presented almost accurately.

Contents

List of Figures

Chapter 1

INTRODUCTION

Power systems have evolved from the original central generating station concept to a modern highly interconnected system with improved technologies affecting each part of the system separately. The techniques for analysis of power systems have been affected most drastically by the maturity of digital computing. Compared to other disciplines within electrical engineering, the foundations of the analysis are often hidden in assumptions and methods that have resulted from years of experience and cleverness. On the one hand, we have a host of techniques and models mixed with the art of power engineering and, at the other extreme, we have sophisticated control systems requiring rigorous system theory. It is necessary to strike a balance between these two extremes so that theoretically sound engineering solutions can be obtained. The purpose of this thesis is to seek such a middle ground in the area of dynamic analysis. The challenge of modeling and simulation lies in the need to capture (with minimal size and complexity) the ”objective” These phenomena must be understood before effective simulation can be performed.

The subject of power system dynamics and stability is clearly an extremely broad topic with a long history and volumes of published literature. There are many ways to divide and categorize this subject for both education and research. While a substantial amount of information about the dynamic behavior of power systems can be gained through experience working with and testing individual pieces of equipment, the complex problems and operating practices of large interconnected systems can be better understood if this experience is coupled with a mathematical model.

Scaled-model systems such as transient network analyzers have a value in providing a physical feeling for the dynamic response of power systems, but they are limited to small sizes and are not flexible enough to accommodate complex issues. While analog simulation techniques have a place in the study of system dynamics, capability and flexibility have made digital simulation the primary method for analysis.

There are several main divisions in the study of power system dynamics and stability [23]. F. P. deMello classified dynamic processes into three categories:

1. Electrical machine and system dynamics
2. System governing and generation control
3. Prime-mover energy supply dynamics and control

In the same reference, C. Concordia and R. P. Schulz classify dynamic studies according to four concepts:

1. The time of the system condition: past, present, or future
2. The time range of the study: microsecond through hourly response
3. The nature of the system under study: new station, new line, etc.
4. The technical scope of the study: fault analysis, load shedding, subsynchronous resonance, etc.

All of these classifications share a common thread: They emphasize that the system is not in steady state and that many models for various com- ponents must be used in varying degrees of detail to allow efficient and practical analysis.

The first half of this thesis is thus devoted to the subject of modeling, and the second half is devoted to the use of interconnected models for common dynamic studies. Neither subject receives an exhaustive treatment; rather, fundamental concepts are presented as a foundation for probing deeper into the vast number of important and interesting dynamic phenomena in power systems.

Moreover , modern electrical power systems have grown to a large complexity due to increasing interconnections, installation of large generating units and extra-high volt-age tie-lines etc.
The system response to such disturbances involves large excursions of generator rotor angles, power flows, bus voltages, and other system variables. It is important that, while steady-state stability is a function only of operating conditions.

Small signal stability is the ability of the system to maintain synchronism under small disturbances which occur continually on the system due to small variations in loads and generation or other small disturbances on the system. A disturbance is considered to be small if the equations that represent the dynamic performance of the system can be linearized for the purpose of analysis function of both the operating conditions and the disturbance.

To analyze any system firstly a mathematical modelling is needed. To model any system all the components of the system has to be modelled separately and then bringing them all altogether to a combined nature. Similarly for power system Multimachine problem all the components meas the synchronous machine, the load , transmission line, load flow analysis, the DSRs all has to be modelled separately first.

For synchronous machine modelling, There is probably more literature on synchronous machines than on any other device in electrical engineering. Unfortunately, this vast amount of material often makes the subject complex and confusing. In addition, most of the work on reduced-order modeling is based primarily on physical intu- ition, practical experience, and years of experimentation. The evolution of dynamic analysis has caused some problems in notation as it relates to com- mon symbols that eventually require data from manufacturers. This text uses the conventions and notations of [16], which essentially follows those of many publications on synchronous machines [4][28][29][3][33][36][12].

When the notation differs significantly from these and other conventions, notes are given to clarify any possible misunderstanding. The topics of time constants and machine inductances are examples of such notations. While some documents define time constants and inductances in terms of physical experiments, this text uses fixed expressions in terms of model parameters. Since there can be a considerable difference in numerical values, it is important to always verify the meaning of symbols when obtaining data. This is most effectively done by comparing the model in which a parameter appears with the test or calculation that was performed to produce the data.

In many cases, the parameter values are provided from design data based on the same expressions given in this text. In some cases, the parameter values are provided from standard tests that may not precisely relate to the expressions given in this text.

In this case, there is normally a procedure to convert the values into consistent data [21]. The original Parkâ$^{\text{TM}}$s transformation is used together with the âœx ad â per unit system [5], [30] . This results in a reciprocal transformed per-unit model where 1.0 per-unit excitation results in rated open-circuit voltage for a linear magnetic system. Even with this standard choice, there is enough freedom in scaling to produce various model structures that appear different [20]. These issues are discussed further in later sections.

When comes the matter of small signal stability, we consider linearized analysis of multimachine power systems that is necessary for the study of both steady-state and voltage stability. In many cases, instability and eventual loss of synchronism are initiated by some spurious disturbance in the system resulting in oscillatory behavior that, if not damped, may eventually build up. This is very much a function of the operating condition of the power system. Oscillations, even if undamped at low frequencies, are undesirable because they limit power transfers on transmission lines and, in some cases, induce stress in the mechanical shaft. The source of inter-area oscillations is difficult to diagnose. Extensive research has been done in both of these areas. In recent years, there has been considerable interest in dynamic voltage collapse. As regional transfers vary over a wide range due to restructuring and open transmission access, certain parts of the system may face increased loading conditions.

Earlier, this phenomenon was analyzed purely on the basis of static considerations, i.e., load-flow equations. In this chapter, we develop a comprehensive dynamic model to study both low-frequency oscillations and voltage stability using a two-axis model with IEEE-Type I exciter, as well as the flux-decay model with a high-gain fast exciter. Both the electromechanical oscillations and their damping, as well as dynamic voltage stability, are discussed. The electromechanical oscillation is of two types:

1. Local mode, typically in the 1 to 3-Hz range between a remotely located power station and the rest of the system.

2. Inter-area oscillations in the range of less than 1 Hz.

Two kinds of analysis are possible:

1. A multimachine linearized analysis that computes the eigenvalues and also finds those machines that contribute to a particular eigenvalue (both local and inter-area oscillations can be studied in such a framework).

2. A single-machine infinite-bus system case that investigates only local oscillations.

Dynamic voltage stability is analyzed by monitoring the eigenvalues of the linearized system as a power system is progressively loaded. Instability occurs when a pair of complex eigenvalues cross to the right-half plane. This is referred to as dynamic voltage instability. Mathematically, it is called Hopf bifurcation.

Also discussed in this thesis is the role of a power system stabilizer that stabilizes a machine with respect to the local mode of oscillation. A brief review of the approaches to the design of the stabilizers is given. For detailed design procedures, it is necessary to refer to the literature. References P . Kundur. and [34] are the basic works in this area.

In this thesis a new method for algorithm to analyze the two area four generator system is investigated. Stability studies for power system planning, operation and control rely immensely on computer based power system simulation tools. Simulation tools use mathematical models that predict the dynamic performance of the system. It is crucial that these power system models be modeled accurately to predict the actual performance of the system.

Chapter 2

Literature Review

Small-signal rotor angle stability analysis mainly deals with a study of electromechanical oscillations-related performance of the system about an operating point when the system is subjected to sufficiently small magnitude of disturbance that will not trigger non-linear behaviour of the system. Thus, this study is mainly concerned with the ability of the power system to maintain synchronism under small disturbances. The disturbances are considered to be sufficiently small that linearization of system equations is possible for analysis purposes. This permits linear system theory to be applied for system analysis even though the system is inherently non-linear.

A power system at a given operating condition may be large disturbance unstable, still such a system can be operated, though unsecurely. However, if the system is small-signal unstable at a given operating condition, it cannot be operated. Therefore, small-signal stability is a fundamental requirement for the satisfactory operation of power systems. Such a study mainly involves the verification of sufficiency of damping of all modes associated with a system so that power transfer is not constrained.

It is known that when a dynamic system such as power system is perturbed from its steady state condition, the system variables trace out a flow, referred to as trajectories. These trajectories may exhibit oscillatory or monotonic behaviour. For the system to be stable, these trajectories must remain bounded and converge to an acceptable operating point.

If we want the power system oscillations, A study of power system oscillations is of interest in a system where more than one generator is working in parallel to deliver a common load. In small systems, there may be only tens of generators and in large systems there may be thousands of generators working in parallel. In such a situation synchronous machines produce torques that depend on the relative angular displacement of their rotors. These torques act to keep the generators in synchronism (synchronizing torque), thus, if the angular displacement between generators increases, an electrical torque is produced that tries to reduce that angular displacement. It is as though the generators were connected by torsional spring, and just as in spring mass system where a restraining force due to spring action against moment of mass, results in oscillations, the moment of inertia of rotors and synchronizing torques cause the angular displacement of the generators to oscillate following the occurrence of a disturbance when it is operating under steady state. Under these conditions, the generators behave as rigid bodies and oscillate with respect to one another using the electrical transmission path between them to exchange energy. If a system is small-signal unstable, oscillations can grow in magnitude over the span of many seconds and, can eventually result in outages of major portions of the power system. Further, a power system is continuously subjected to random disturbances in the form of load or generation changes/changes in controller settings. Hence it never settles to a steady state at any given point of time. Therefore having adequate damping of all system oscillations is critical to system stability and therefore, to system security and reliability.

In a well designed and operated system, these oscillations of the rotor angle dis- placement decay and settle to a value that will not constraint power flow through the transmission network. Such a system is said to be small-signal stable. In the following circumstances, the system may be small-signal unstable [35] [7] [10]

1. Use of high gain fast-acting exciters.
2. Heavy power transfer over long transmission lines from remote generating plants.
3. Power transfer over weak ties between systems which may result due to line outages.
4. Inadequate tuning of controls of equipment such as generator excitation systems, HVDC converters, static var compensators.
5. Adverse interaction of electrical and mechanical systems causing instabilities of torsional mode oscillations.

In an over stressed system, a relatively low inherent damping and a small magnitude of synchronous torque coefficient may constrain the system operation by limiting power transfer. Further, in such cases, predicting oscillation boundaries and therefore to manage them, becomes increasingly difficult.

Power system stabilizer (PSS) is a cost effective way of improving the damping of elec- tromechanical oscillations of rotors and in turn it improves the power transfer capability of transmission lines. It provides the damping by modulating the voltage reference of exciter control so as to develop a component of electrical torque in phase with the rotor speed deviations. The location of PSS in a power system is depicted in the following figure.

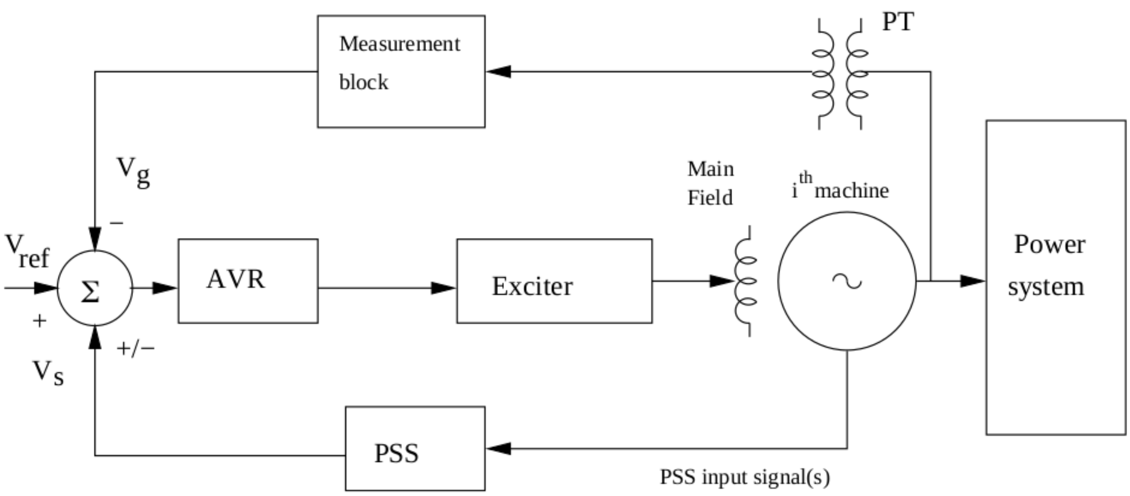

Figure 2.1: Location of PSS in a power system.

Such a way of producing damping torque is the most cost-effective method of enhancing the small-signal stability of power systems, in comparison to FACTS-based controllers [10] The necessary power application is brought about in the normal process of torque development mechanism in the generator. Generally, PSS is installed to improve damping of local modes which is destabilized by the use of a high gain fast acting exciter. However, by judiciously placing power system stabilizers in a system, and with appropriate tuning of PSS parameters, it is possible to even improve the damping of inter area modes. While designing a PSS to produce damping torque in a desired frequency range, care must be taken to see that the PSS does not destabilize the other oscillatory modes, for example, torsional modes . Another important criterion in designing a PSS is to provide additional damping torque without affecting the synchronizing torque at critical oscillation frequencies, so that the inter-tie power transfer is not constrained.

As per IEEE standards 421.5 - 1992 , the following are the two main categories of PSS:

1. Single input power system stabilizer: It is known that in order to modify a mode of oscillation by feedback, the chosen input must excite the mode and it must be visible in the chosen output. Thus, for this kind of PSS design, commonly used input signals are shaft speed, terminal bus frequency and electrical power output.

2. Dual input power system stabilizer: In this kind of PSS design, a combination of signals such as speed and electrical power output are used.

Previously Power system stabilizers (PSS) were not introduced to the system for better stability. The idea was firstly introduced by simulation results[15] , designed to illustrate the influence of PSS on inter-area and local oscillations in interconnected power systems are reported. It is shown that the PSS location and the voltage characteristics of the system loads are significant factors in the ability of a PSS to increase the damping of inter-area oscillations. It is also shown that an interaction between modes in two distinct parts of a power system is possible, due to resonance, and that this might cause distortions in mode shape and participation factors.

Paper[31] presents the detailed formulation for the analysis of multimachine systems taking into account the generator dynamics and considering active power and reactive current as output variables. The accuracy of prediction of voltage instability using the reduced formulation is investigated through the case study of a 10 machine 39 bus system. The effects of exciter gain and time constant are also examined and the results are presented. In addition, the effect of static var compensator (SVC) is also analysed through eigenvalue analysis. The results are also validated by system simulation. It showed that the voltage instability ,caused by the instability of the exciter mode can be due to Hopf bifurcation which occurs at increased load. Application of SVC has the effect of avoiding voltage instability and hence voltage collapse by stabilising the exciter modes. At high exciter gains, although SVC helps in stabilising the exciter modes, the system remains unstable as few of the swing modes remain unstable.

Paper[27] deals with damping of inter-area and local electromechanical oscillation modes using controllable se- ries capacitor (CSC) and controllable shunt capacitor (SVC). The impacts of SVC and CSC on the structure of the system closed loop matrix are investigated. A numerical ex- ample is provided to support the analytical findings. This paper provides an insight and understanding in the basic characteristics of damping effects of the studied devices. The insight is obtained by the study of a simple power system which exhibits both inter-area and local power swings. The understandings and findings can be tabulated as i) Contribution of a controllable series capacitor (CSC) to damping of local modes is always positive. ii) Damping of local modes by a controllable shunt capacitor (SVC) is sensitive to the distribution of power among the machines; under some loading conditions local modes might be excited. iii) CSC exhibits more effective damping than SVC for inter-area modes.

The need for a correct representation of electrical loads in stability studies was emphasized in [14]. Several series of load-voltage tests performed on the Southern California Edison Company system are described. The test results are summarized and used as the basis for individual bus load representation. This paper has showed that in normal operation good speed governors are essential to preserve frequency stability and to permit the successful operation of automatic power-frequency control. On the other side, they have also shown that they cannot be expected to contribute to the damping of oscillations among paralleled generators. During emergencies the action of speed governors must be taken into account in order to predict system behaviour and appropriate relay settings and must be allowed to take action to prevent excessive frequency deviations.

A physical interpretation of two state feedback controllers for damping power system electromechanical oscillations was presented in [8]. They have been developed by ElectricitÃ© de France (EDF). The first one is called the desensitized four loop regulator (DFLR) and it is designed to damp local electromechanical oscillations. It is a robust controller which offers good performance despite the variations of the generator operating conditions. The second controller is called the extended desensitized four loop regulator (EDFLR) and it is designed to address both local and interarea oscillations. The physical interpretation is accomplished converting the state feedback scheme to the standard structure formed by an automatic voltage regulator (AVR) plus a power system stabilizer (PSS). Two widely used PSS design methods based on eigenvalue sensitivities and frequency response are reviewed to obtain the interpretation. The DFLR can be interpreted as a controller which provides the suitable phase compensation according to these two PSS design methods over a wider frequency range. The EDFLR can be interpreted as a controller which maximizes its robustness under uncertainties at both PSS output and the input of the plant.

Paper[1] presents a small-signal model and analysis of a current-controlled, voltage-regulated three-phase voltage-source inverter for uninterruptible power supplies (UPS). Using perturbation and small signal analysis techniques, linear steady-state and dynamic models of the UPS system in the rotating frame of reference are derived. The small-signal model is used to study the effects of various feedback variables on the dynamic performance of the UPS system. Experimental results are provided to validate the analytical models. The results show that the models accurately represent the UPS system. In addition, the analytical approach has the advantage that transfer functions between the inverter output variables and the modulating signal can be derived and used to assess the behaviour of the system using classical control techniques.
Paper[11] presents the latest comprehensive literature review of AC and DC microgrid (MG) systems in connection with distributed generation (DG) units using renewable energy sources (RESs), energy storage systems (ESS) and loads. A survey on the alternative DG units' configurations in the low voltage AC (LVAC) and DC (LVDC) distribution networks with several applications of microgrid systems in the viewpoint of the current and the future consumer equipments energy market is extensively discussed. Based on the economical, technical and environmental benefits of the renewable energy related DG units, a thorough comparison between the two types of microgrid systems is provided. The paper also investigates the feasibility, control and energy management strategies of the two microgrid systems relying on the most current research works. Finally, the generalized relay tripping currents are derived and the protection strategies in microgrid systems are addressed in detail. From this literature survey, it can be revealed that the AC and DC microgrid systems with multiconverter devices are intrinsically potential for the future energy systems to achieve reliability, efficiency and quality power supply.

A systematic approach to small-signal modelling of a micro-grid system that includes conventional (rotating machine) and electronically interfaced distributed resource (DR) units is presented in [13]. The proposed approach incorporates fundamental frequency deviations in the overall system model and provides a methodology for the analysis of autonomous micro-grid, which inherently is more prone to frequency changes than the conventional utility grid. The model represents (i) electromechanical dynamics of the synchronous machine including the exciter and the governor systems, (ii) dynamics of the voltage-sourced converter and its real/reactive power controllers and (iii) the network dynamics. The model is intended for the controller design/optimisation, evaluation of angle/voltage stability, investigation of torsional dynamics, controller interactions of electronically interfaced DR units and low-frequency power quality issues. Typical results from application of the proposed modelling approach to a study system are presented. The results are qualitatively verified on the basis of the comparison with those obtained from time-domain simulation in the PSCAD/EMTDC environment.

Machine drive modelling can be obtained from [17]. Modelling of converters used for grid integration for renewable sources can be obtained from [9].

Paper[22] investigates some aspects of stability in microgrids. There are different types of microgrid applications. The system structure and the control topology vary depending on the application and so does the aspect of stability in a microgrid. This paper briefly encompasses the stability aspects of remote, utility connected and facility microgrids depending on the modes of operation, control topology, types of micro sources and network parameters. The small signal, transient and the voltage stability aspects in each type of the microgrid are discussed along with scope of improvements. With a brief review of the existing microgrid control methods in the literature and different industry solutions, this paper sets up an initial platform for different types of microgrids stability assessment. Various generalized stability improvement methods are demonstrated for different types of microgrids. The conventional stability study of microgrids presented in this paper facilitates an organized way to plan the micro source operation, microgrid controller design, islanding procedure, frequency control and the load shedding criteria. The stability investigations are presented with different control methods, eigen value analysis and time domain simulations to justify different claims.

Growth of distributed generation has led to distribution systems with a mixture of rotating machine generators and inverter interfaced generators. The stability of such networks needs to be studied through the analysis of state-space models, and so suitable models of inverters are needed to complement the well-established models of rotating machines. As machine model[19] include features such as automatic voltage regulators and wash-out functions, the inverter model also includes phase-locking functions and internal control loops. The model for voltage source inverters with an internal current control loop, an outer power regulation loop, a measurement of average power and a phase-locked loop has been developed. The model is presented in detail and is formed with a state-vector, similar to that used for rotating machines. The model includes nonlinear terms but can be linearised about an operating point. The state-space model is verified against a component-level time-step simulation in Simulink/PLECS.

At present, robust analysis is an important issue for designing controllers in inverter-based distributed generation systems. In these systems, the fluctuation of DC voltage level from renewable resources (e.g., fuel cells, solar cells, wind turbines) and loading conditions cause system uncertainties and disturbances. To enhance the robust performance of the DG systems, a new class of inverter controller is required to achieve both robustness and performance of entire systems. In this paper[26], the proposed technique applies Genetic Algorithms (GA) to determine the optimal controller parameters so that stability margin of the controlled system is maximized. In addition, the structure of (Proportional-Integral-Derivative) PID with first order derivation filter is selected as the final controller to realize a practical robust controller. As results indicated, stability margin of the proposed controller is better than that of the reduced order controller designed by Hankel Norm model reduction. The proposed technique, hence, offers a robust controller with a guaranteed stability margin; also it is practically feasible to be implemented.

The analysis of the small-signal stability of conventional power systems is well established, but for inverter based microgrids there is a need to establish how circuit and control features give rise to particular oscillatory modes and which of these have poor damping. This paper[32] develops the modeling and analysis of autonomous operation of inverter-based microgrids. Each sub-module is modeled in state-space form and all are combined together on a common reference frame. The model captures the detail of the control loops of the inverter but not the switching action. Some inverter modes are found at relatively high frequency and so a full dynamic model of the network (rather than an algebraic impedance model) is used. The complete model is linearized around an operating point and the resulting system matrix is used to derive the eigenvalues. The eigenvalues (termed "modes") indicate the frequency and damping of oscillatory components in the transient response. A sensitivity analysis is also presented which helps identifying the origin of each of the modes and identify possible feedback signals for design of controllers to improve the system stability. With experience it is possible to simplify the model (reduce the order) if particular modes are not of interest as is the case with synchronous machine models. Experimental results from a microgrid of three 10-kW inverters are used to verify the results obtained from the model.

Microgrid is an aggregation of distributed generators (DGs) and energy storage systems (ESS) through corresponding power interface, such as synchronous generators, asynchronous generators and power electronic devices. Without the support from the public grid, the control and management of an autonomous microgrid is more complex due to its poor equivalent system inertia. To investigate microgrid dynamic stability, a small-signal model[37] of a typical microgrid containing asynchronous generator based wind turbine, synchronous diesel generator, power electronic based energy storage and power network is proposed in this paper. The small-signal model of each of the subsystem is established respectively and then the global model is set up in a global reference axil frame. Eigenvalues distributions of the microgrid system under certain steady operating status are identified to indicate the damping of the oscillatory terms and its effect on system stability margin. Eigenvalues loci analysis is also presented which helps identifying the relationship among the dynamic stability, system configuration and operation status, such as the variation of intermittent generations and ESS with different control strategies. The results obtained from the model and eigenvalues analysis are verified through simulations and experiments on a study microgrid system.

The complete-order modelling of state-space representations of synchronous and induction generators for wind turbine applications is presented[38]. Fully equivalent models with different state variables, suitable for different control schemes, are given. The state-space representations provide a convenient, compact and elegant way to assess the induction and synchronous generator-based wind turbines, with information readily available for stability, controllability and observability analyses. Simulation results of the featured representations are assessed. As an example, the control of a doubly-fed induction generator-based wind turbine is included.

Mathematical modeling of synchronous and induction generators for wind turbines using state-space representations is presented [39]. Emphasis is given to those models suitable for control schemes of variable-speed wind turbines and their application for different power system studies. The state-space representations provide a convenient way to assess different configurations of fixed and variable-speed wind turbines based on synchronous and induction generators. The modeling approach here presented allows both transient and small-signal stability analysis. As a case study, the performance of fixed and variable-speed wind turbines under faults and voltage sags is assessed. The state-space models are used to investigate the capability of different wind turbine technologies to satisfy Grid Code requirements. An eigenanalysis is included to show the flexibility of the models.

Implementation of power electronic devices has introduced novel challenges in microgrid (MG) operation and control; and hence the condition of power electronic devices should be monitored for stable operation of the entire grid.Paper[18] presents detailed small signal model of the MG based upon Renewable Energy Resources (RESs), focusing on the dynamic behavior of power electronic devices and associated controllers. Variations on inverter modulation indices and boost converter duty cycles were applied to observe small signal stability performance of the MG. Eigenvalues and participation factor analysis were presented to identify weak modes and stability margin. Analysis of eigenvalue loci shows motion of low frequency loci toward the right-half complex plane as the parameters of power electronic devices varied. More severe oscillatory behavior was experienced when fluctuation occurred at the gridside inverter, which indicates fast degradation of damping and stability margin. The presented work contributes to help utilities in designing stable MG for seamless integration of renewable energy into power system.

The modeling and analysis of the impact of Solar Photovoltaic (PV) on the small signal stability of power system are explored. The analysis[2] provides explanations of the impact of the closedloop control on the power system stability. Two system models, Single Solar Infinite Bus (SSIB) system and solar connected multi- machine system are considered. In model of PV, module variable are algebraic that is, they change instantaneously and the modeled dynamics are those of the power converter controller. The discussion considers maximum power point tracking, dc link voltage and current controller. In case of SSIB sensitivity to different weather conditions such as irradiance, temperature is studied. Also sensitivity to different power system conditions such as voltage variation, reactive power support from solar is studied. In multi-machine case impact of different active and reactive power injection levels is analyzed. The observations and conclusions obtained from eigenvalue, participation factor analysis suggest that even though the PV generation system dynamic do not participate into low frequency oscillation modes, its control can influence small signal damping depending based on its location in the system.

Inverter-based distributed generators (DGs) based on renewable sources are widely used in microgrids. Most of these sources operate in droop control mode for efficient load sharing. Higher droop is desired in these systems to improve dynamic power sharing, however, such systems suffer from stability issues. Stability margin of a system having different combinations of inverter and synchronous generator-based sources is compared in this work[6]. A microgrid is modelled here with three DGs on a standard 13 bus system using state space approach. The study showed that lack of stability of inverters restricts the use of higher droop gains, resulting in poor powersharing dynamics. A droop control is proposed to improve transient response and stability margin in such cases. The results are validated with time domain simulations using Simulink in MATLAB environment.

The analysis of the small-signal stability of conventional power systems is well established, but for inverter based microgrids there is a need to establish how circuit and control features give rise to particular oscillatory modes and which of these have poor damping. Paper[24] develops the modeling and analysis of autonomous operation of inverter-based microgrids. Each sub-module is modeled in state-space form and all are combined together on a common reference frame. The model captures the detail of the control loops of the inverter but not the switching action. Someinvertermodes are found at relativelyhigh frequency and so a full dynamic model of the network (rather than an algebraic impedance model) is used. The complete model is linearized around an operating point and the resulting system matrix is used to derive the eigenvalues. The eigenvalues (termed âœmodesâ) indicate the frequency and damping of oscillatory components in the transient response. A sensitivity analysis is also presented which helps identifying the origin of each of the modes and identify possible feedback signals for design of controllers to improve the system stability. With experience it is possible to simplify the model (reduce the order) if particular modes are not of interest as is the case with synchronous machine models. Experimental results from a microgrid of three 10-kW inverters are used to verify the results obtained from the model.

Paper[24] describes the modeling and small signal analysis of a grid connected doubly-fed induction generator (DFIG). Different models are formulated and compared with each other for different assumptions (two or one-mass drive train, with or without stator transients). The models are developed from the basic flux linkage, voltage and torque equations. Eigenvalues and participation factor analysis of the linearized models are carried out to relate the DFIG electromechanical modes to its relevant state variables.

Paper[25] focuses on the super/subsynchronous operation of the doubly fed induction generator (DFIG) system. The impact of a damping controller on the different modes of operation for the DFIG-based wind generation system is investigated. The coordinated tuning of the damping controller to enhance the damping of the oscillatory modes using bacteria foraging techniqueis presented. The results from eigenvalue analysis are presented to elucidate the effectiveness of the tuned damping controller in the DFIG system. The robustness issue of the damping controller is

also investigated.
Whereas paper[1] presents a small-signal model and analysis of a current-controlled, voltage-regulated three-phase voltage-source inverter for uninterruptible power supplies (UPS). Using perturbation and small- signal analysis techniques, linear steady-state and dy- namic models of the UPS system in the rotating frame of reference are derived. The small-signal model is used to study the effects of various feedback variables on the dynamic performance of the UPS system. Experimental results are provided to validate the analytical models.

2.1 Research Gap

There are till date many softwares to analyze the small signal stability. Like PSAT there is a many simulation softwares too. But all those are not accurate and also bulky. I have shown in the result section of my thesis, PSAT also have error in calculation. But till date PSAT is the most used and authentic software made for this type of analysis. I have tried to present here a new software to simulate such power systems with a new algorithm.

2.2 Aims Objective

Till date there are many software to analyze the multi machine stability. But most of them are not close to the standard values. I have presented a simple algorithm to analyze considering the load model only by its active and reactive powers. The ratings of the active and reactive power of each and every component is most important. So very consciously I have put the limits during calculation. I have also presented a universally applicable flow-chart to any kind of power system with conventional sources to analyze stability. To take the perfection my results has been compared with standard PSAT results.

Chapter 3

System Description and Modelling

A well known 4 machine, 11 bus power system has been used to demonstrate the modal analysis of a power system. The standard system[25] is taken for analysis. The ratings of each component is given in the appendix section.

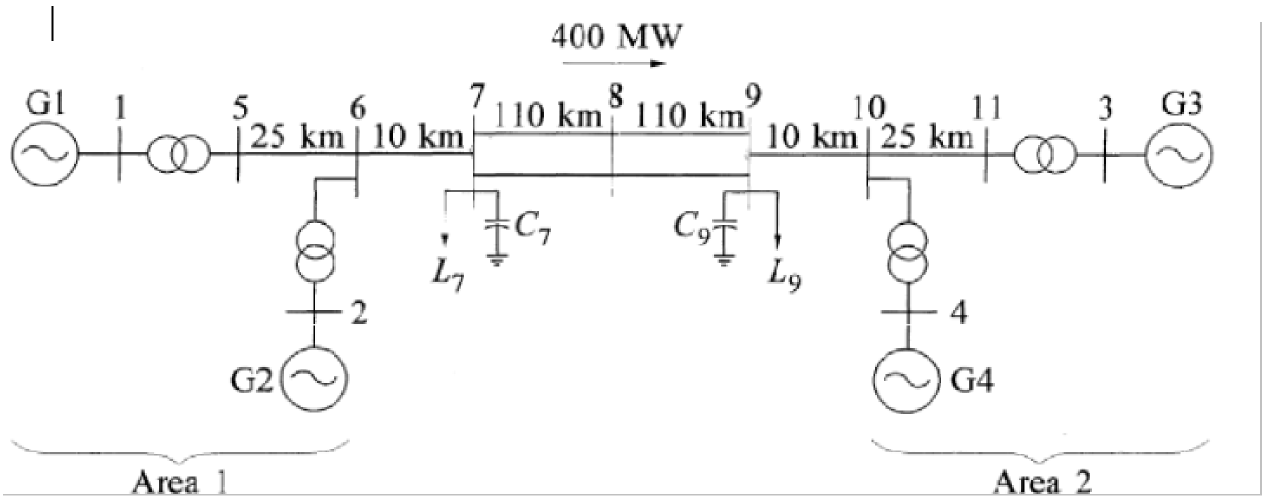

Figure 3.1: IEEE 11 bus 2 area system

3.1 Synchronous Machine Model

The synchronous generators are modelled as classical machines with delta and omega as state variables. The generator is represented by the Norton equivalent for network solution. The admittance of the generator is included in the main diagonals of Y matrix.

$$J\frac{d\omega}{dt} = T_m - T_e \quad (1)$$

$$\frac{d\delta}{dt} = \omega - \omega_0 \quad (2)$$

3.2 Transmission Line Model (Short Line)

A transmission line is modeled as a short line. It consists of a series impedance comprised of a resistance R and reactance X between the terminal nodes.

3.3 Load Model

The loads are modeled as a constant admittance in transient stability studies.

3.4 Introduction of Two-Area System

The machines are considered to be TYPE 2B Model. The system contains eleven buses and two areas, connected by a weak tie between bus 7 and 9. Totally two loads are applied to the system at bus 7 and 9. Two shunt capacitor are also connected to bus 7 and 9 as shown in the figure 1 below.

The system has the fundamental frequency 60 Hz. The system comprises two similar areas connected by a weak tie3. Each area consists of two generators, each having a rating of 900 MVA and 20 kV.

We will perform:

- Power-flow calculation
- Linear Analysis and Modal Analysis
- Time-domain simulation.

The left half of the system is identified as area 1 and the right half is identified as area 2. The saturation of the synchronous machines are not identical.

This chapter describes the methodology for incorporation of the model for small-signal analysis of single machine-infinite bus and multi-machine configurations. This is followed by relevant results obtained for these configurations.

Chapter 4

Small Signal Stability

Small Signal Stability is the ability of the power system to maintain Synchronism under small perturbations. Such perturbations occur continuously on the system because of small variations in load and generation where the system continuously adjusts itself to changing conditions. Restoring forces acting on the machine help them to maintain stable conditions. The system must be able to operate satisfactory under these conditions and successfully supply the maximum load. The âœSmall Signalâ disturbances are considered suffiently small for linearization of system equations to be permissible for the purpose of analysis.

The most common form of synchronism, monotonically, in the first few seconds following the fault due to lack of synchronizing torque and damping torque. The stability of the following types of oscillations is of concern. Local modes are associated with the oscillations of generating units at a particular station with respect to the rest of system. These oscillations are localized in a small part of the power system. Inter area modes are associated with the oscillations of many machines in one part of the system against machines in the other parts.

4.1 State Equation

For a classical model of the synchronous machine the states are incremental changes in rotor speed and angle. In our analysis the super bar notation on the per unit quantities are dropped out. The state equations for the SMIB system shown in the Figure are given by

$$\begin{bmatrix} \Delta\dot{\omega} \\ \Delta\dot{\delta} \end{bmatrix} = \begin{bmatrix} \frac{-K_D}{2H} & \frac{-K_S}{2H} \\ \omega_0 & 0 \end{bmatrix} \begin{bmatrix} \Delta\omega \\ \Delta\delta \end{bmatrix} + \begin{bmatrix} \frac{1}{2H} \\ 0 \end{bmatrix} \Delta T_m \qquad (3)$$

This is the form of $\dot{X} = Ax + Bu$. The elements of the state matrix A are seen to be dependent on the system parameters KD, H, XT and the initial operating condition represented by the values of E1 and Î´0. Where, del omega is in per unit del delta is in radians The synchronizing torque coefficient is given by

$$K_S = \frac{|E'||V_\infty|}{(X_d' + X_{tr} + X_{line})} \cos\delta \qquad (4)$$

4.2 Multimachine Model

The base system is symmetric; it consists of two identical areas connected through a relatively weak tie. Each area including two generating units with equal outputs. The full symmetry of the base system clarifies the effect that various factors have on the inter-area mode. Dynamic data for the generator and excitation systems used in the study are given in Appendix. In setting up the various power flows used in the studies, capacitors were added as necessary to ensure that the systems voltage profile was satisfactory.

The electro-mechanical modes of oscillation are present in this system; two inter-area modes, one in each area, and one inter area low frequency mode, in which the generating units in one area oscillate against those in other area.

Our experience with large inter connected systems confirms some of the results of our studies using the small system, and we are confident that the general conclusions drawn from our work, will apply to large systems. The following equations pertain to the fourmachine system.

4.3 State Space Model

Our aim in this section is to derive the equations for multi machine system that represent the dynamics of the machine and the controller in the state space form.The right hand side of the differential equations for the machine and the controllers will contain algebraic variables such as current, voltage or power and incremental changes in them should be eliminated to obtain the equations in state variables canonical form. Once the equations in the state variables canonical form are obtained, we can apply eigen value technique to access stability.

Assumptions:

- The machines are considered to be classical (no controllers)
- Damping ignored
- Loads are assumed as constant admittances Preparation:

The initial conditions for delta , omega and voltages are obtained from load flow and the past history terms for delta and omega are obtained from the initial conditions.

$$\begin{bmatrix} \dot{\Delta\omega} \\ \dot{\Delta\delta} \\ \Delta\dot{E}'_q \\ \Delta\dot{E}'_d \\ \Delta\dot{E}''_q \\ \Delta\dot{E}''_d \end{bmatrix} = \begin{bmatrix} \frac{-K_D}{2H} & \Delta T_e & 0 & 0 & 0 & 0 \\ \omega_s & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{T'_{d0}} & -\frac{1}{T'_{d0}} & 0 & 0 & 0 \\ 0 & \frac{1}{T'_{q0}} & 0 - \frac{1}{T'_{q0}} & 0 & 0 & 0 \\ 0 & \frac{1}{T'_{d0}} & 0 & 0 & -\frac{1}{T'_{q0}} & 0 \\ 0 & \frac{1}{T'_{d0}} & 0 & 0 & 0 & -\frac{1}{T'_{q0}} \end{bmatrix} \begin{bmatrix} \Delta\omega \\ \Delta\delta \\ \Delta E'_q \\ \Delta E'_d \\ \Delta E'_d \\ \Delta E''_d \end{bmatrix} + \begin{bmatrix} \overline{\Delta T}_m \\ 0 \\ \frac{1}{T'_{d0}} \Delta E_{FD} \\ \frac{1}{T'_{q0}} \Delta E_{FD} \\ \frac{1}{T'_{d0}} \Delta E_{FD} \\ \frac{1}{T'_{q0}} \Delta E_{FD} \end{bmatrix} \quad (5)$$

4.4 Multi-Machine Small Signal Stability Algorithm for Type 2B Model

1. Taken IEEE 11 bus 2 area 4 machine system
2. Formulate the admittance matrix

6.JPG

$$YV = I \qquad (6)$$

3. After that reduced the network equations

7.JPG

$$Y_{GG}^{red} = Y_{GG} - Y_{G,NG} * Y_{NG,NG}^{-1} * Y_{NG,G} \qquad (7)$$

4. Initialize the power, current, voltage in transient condition sub-transient condition etc.
5. Find out the transformation matrix inverse transformation matrix

$$T = \begin{bmatrix} e^{j\theta 1} & 0 & 0 & 0 \\ 0 & e^{j\theta 2} & 0 & 0 \\ 0 & 0 & e^{j\theta 3} & 0 \\ 0 & 0 & 0 & e^{j\theta 4} \end{bmatrix} inv\,T = \begin{bmatrix} e^{-j\theta 1} & 0 & 0 & 0 \\ 0 & e^{-j\theta 2} & 0 & 0 \\ 0 & 0 & e^{-j\theta 3} & 0 \\ 0 & 0 & 0 & e^{-j\theta 4} \end{bmatrix} \qquad (8)$$

8.JPG

6. Then the reduced equations into individual machine rotor coordinates.

9.JPG

$$M = inv(T) * Y_{GG}^{red*} T \qquad (9)$$

7. After applying the linearization of network equations in individual machine rotor coordinates.

$$I = I_0 + \Delta I \qquad (10)$$

$$E' = E'_0 + \Delta E' \qquad (11)$$

$$M = M_0 + \Delta M \qquad (12)$$

$$T = T_0 + \Delta T \qquad (13)$$

10.JPG

8. Small change in current is

$$\Delta I = [M_0 \Delta E' - j(\Delta\delta M_0 - M_0 \Delta\delta)E'_0] \qquad (14)$$

9. Linearization of differential equations: The mechanical side differential equations are given by

$$\frac{d\Delta\omega_i}{dt} = \frac{\Delta T_{mi} - \Delta T_{ei} - K_D \Delta\omega_i}{2H_i} \qquad (15)$$

10. Linearization of swing equation is

$$\frac{d\Delta\delta_i}{dt} = \omega_s \Delta\omega_i \qquad (16)$$

11. We illustrate how to include the damper windings in the formulation of state variables

$$\Delta\dot{E}'_q = -\frac{1}{T'_{q0}}[\Delta E'_q + (X_d - X'_d)\Delta I_d - \Delta E_{FD}] \qquad (17)$$

$$\Delta\dot{E}'_d = -\frac{1}{T'_{q0}}[\Delta E'_d + (X_q - X'_q)\Delta I_q] \qquad (18)$$

$$\Delta\dot{E}''_q = -\frac{1}{T''_{q0}}[\Delta E''_q + (X'_q - X''_q)\Delta I_d - \Delta E'_q] \qquad (19)$$

$$\Delta\dot{E}''_d = -\frac{1}{T''_{d0}}[\Delta E''_d + (X'_d - X''_d)\Delta I_d - \Delta E'_d] \qquad (20)$$

12. Finally our state variables are

$$\left[\Delta\omega \; \Delta\delta \; \Delta E'_q \; \Delta E'_d \; \Delta E'_d \; \Delta E''_d\right] \qquad (21)$$

13. Find out the eigen values from above state variables.

4.5 Eigen Analysis

With the linearized power system model in matrix form shown in equation the system can now be analyzed through the use of eigenvalues and eigenvectors. To examine the free response of the system the inputs are put to zero. where x is a state vector and A is the state matrix of size n

$$\Delta x = [A]\, x \qquad (22)$$

x n; The state equation given by is further analyzed by taking the Laplace transform. The new equation derived in the s domain is given by The values of s that satisfy (poles of system) are

$$\det\,(s[I] - [A]) = 0 \qquad (23)$$

known as eigenvalues of the matrix A. The eigenvalues may be real or complex. For an n x n matrix they are n eigenvalues. If A is real eigenvalues occur in complex conjugates of the form

$$\lambda = \sigma \pm j\omega. \qquad (24)$$

4.5.1 Eigenvalues and Stability

The power system is stable if all of the eigenvalues are on the left-hand side of the imaginary axis of the complex plane; otherwise it is unstable. If any of the eigenvalues comes over into the right hand side of the imaginary axis, the corresponding modes are said to be unstable, and so is the system. The desired aim then is to have all eigenvalues in the left hand plane. This stability is confirmed by looking at the time dependent characteristic of the oscillatory modes corresponding to each eigenvalue $\lambda given by e\lambda t$.

A real eigenvalue corresponds to a non oscillatory mode. A negative real eigenvalue indicates a mode that decays in time (the larger the magnitude of the eigenvalue the quicker the decay). A positive real eigen value indicates a mode that grows with time and is system will experience aperiodic instability. A conjugate pair complex eigenvalues indicate oscillatory modes of response.

$$\lambda = \sigma \pm j\omega. \qquad (24)$$

1. If a conjugate of pair of complex eigenvalues has negative real parts Ïf this corresponds to an oscillatory mode that decays with time and the system is said to be globally stable.

2. If a pair has positive real parts, the corresponding oscillatory mode grows exponentially with time and eventually dominates the system behavior. Such a system is said to be unstable.

3. If any one of the eigenvalues has a real part, the system will have an undamped oscillatory response.

   Eigenvalues associated with an unstable or poorly damped oscillatory mode are called dominant modes since their contribution dominates the time response of the system.

The real component of an eigen value gives the damping, and the imaginary part gives the frequency of oscillation.

Frequency of oscillation (Hz):

$$f = \frac{\omega}{2\pi} \tag{26}$$

The damping ratio:

$$\zeta = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}} \tag{27}$$

4.5.2 Eigen Vectors

Eigen analysis also includes the computation of eigenvectors. For any eigen value Î»i, the column vector Ï†i that satisfies is called the right eigenvector for Î»i. The right eigenvector show the

$$[A]\varphi i = \lambda\ \varphi i\ i = 1, 2, \ldots\ n$$

$$\varphi_i = \begin{bmatrix} \varphi_{1i} \\ \varphi_{2i} \\ \vdots \\ \vdots \\ \varphi_{2i} \end{bmatrix} \tag{28}$$

distribution of the modes of response (eigenvalues) through the power system state variables. Correspondingly, there is a row vector Ïˆi that satisfies (24) and is called the left eigenvector of [A] associated with the eigen value Î»i. The left eigenvectors, together with the initial conditions of

$$\psi i\ [A] = \lambda\ \psi i$$

$$\Psi_i = \begin{bmatrix} \Psi_{i1} \\ \Psi_{i2} \\ \vdots \\ \vdots \\ \Psi_{in} \end{bmatrix} \tag{29}$$

the system state vector x, determine the magnitudes of the modes.

4.5.3 Mode Shape

The right eigenvector gives the mode shape.

The mode shape is the relative activity of the state variables when a particular mode is excited. Thus the degrees of activity of the Kth state variable xk in the Ith mode is given by the element Ï†ki if the right eigenvector Ï†i.

The magnitude of the elements if Ï†i gives the extent of the activities of the n state variables in the Ith mode, and the angles of the elements give phase displacement of the state variables with regard to the mode. Thus we can use the mode shape to analyze the magnitude and phase displacement of the speed and rotor angle state variables in an oscillatory mode.

4.6 Participation Factors

The participation factor P is useful in identifying those states which have the most influence on any mode. The participation factor is non-dimensional. The element is called a participation factor.

$$\psi \mathbf{i}\ [\mathbf{A}] = \lambda\ \psi \mathbf{i}$$

$$\Psi_i = \begin{bmatrix} \Psi_{i1} \\ \Psi_{i2} \\ \vdots \\ \vdots \\ \Psi_{in} \end{bmatrix} \qquad (29)$$

It is a measure of the relative participation of the kth state variable in the ith mode, and vice versa. In effect participation factors are useful in identifying those state variables which have the most influence on any mode. The higher the value of participation factor of a state for a corresponding mode, the more active that state is in that mode when compared with the other states. Thus the values of participation factors can reveal which generators are involved in a particular mode. It can reveal which machine or machines could go out of step for any known mode or modes that might cause problem in the power system in the advent of load variation.

The participation factors are used to identify the areas in the power system where any mode or (oscillation) has most of its effect.

4.6.1 Eigen Value Sensitivity to Load Changes

The sensitivity of an eigen value lmbda i to an element alpha k j of the state matrix is equal to the product of the left eigenvector element psi ki and right eigenvector element phi ji. In this analysis the load power at a bus in the power system was varied and the system state matrix computed. The elements alpha kj , C of the state matrix that showed the greatest changes due to the load change were identified. Thus the sensitivity of the eigenvalues to these elements of the state matrix

$$P_i = \begin{bmatrix} P_{1i} \\ P_{2i} \\ \vdots \\ P_{ni} \end{bmatrix} \begin{bmatrix} \varphi_{1i}\Psi_{i1} \\ \varphi_{2i}\Psi_{i2} \\ \vdots \\ \varphi_{ni}\Psi_{in} \end{bmatrix} \tag{30}$$

A sys can be computed using equation. In computing the eigen value sensitivity the elements that show a large variation with a change in load give an indication of the sensitivity of the eigen value to load changes.

4.6.2 Simulation

The test system used in this investigation is the IEEE â“ 11 bus test system. PSAT environment was used to analyze this system. A new software was also written to perform the small signal analysis on the system. This program follows three main algorithms:

1. Loads system data
2. Performs load flow of system, calculates initial condition, linearize system equation and construct the matrices and finally the system state matrix A sys.
3. Calculate systemâ™s eigenvalues a check for unstable mode and gets the participation and mode shape for critical Eigenvalues.

The effect of loading was analyzed by increasing the load at a particular bus or buses. At each change in loading the initial conditions of the state variables were calculated after running a load flow . Next, linearization of the system equation was done and the state matrix A sys is formed.

Eigen-analysis of the system can then be performed by obtaining the eigenvalues of the state matrix. The eigenvalues are then check for stability.

4.6.3 Load Model Procedure

1. The type of load at various buses was selected i.e. changing parameters np and nq
2. The system matrix A sys was computed
3. The eigenvalues are computed and check for stability analysis.

Chapter 5

Flow chart of the Algorithm

The algorithm has step by step all the methods to analyze the system as shown in the flow chart. The A matrix is the system matrix of the whole system. By taking out the eigen values of the A matrix we can speculate the stability of the system. The flow of my algorithm is given below

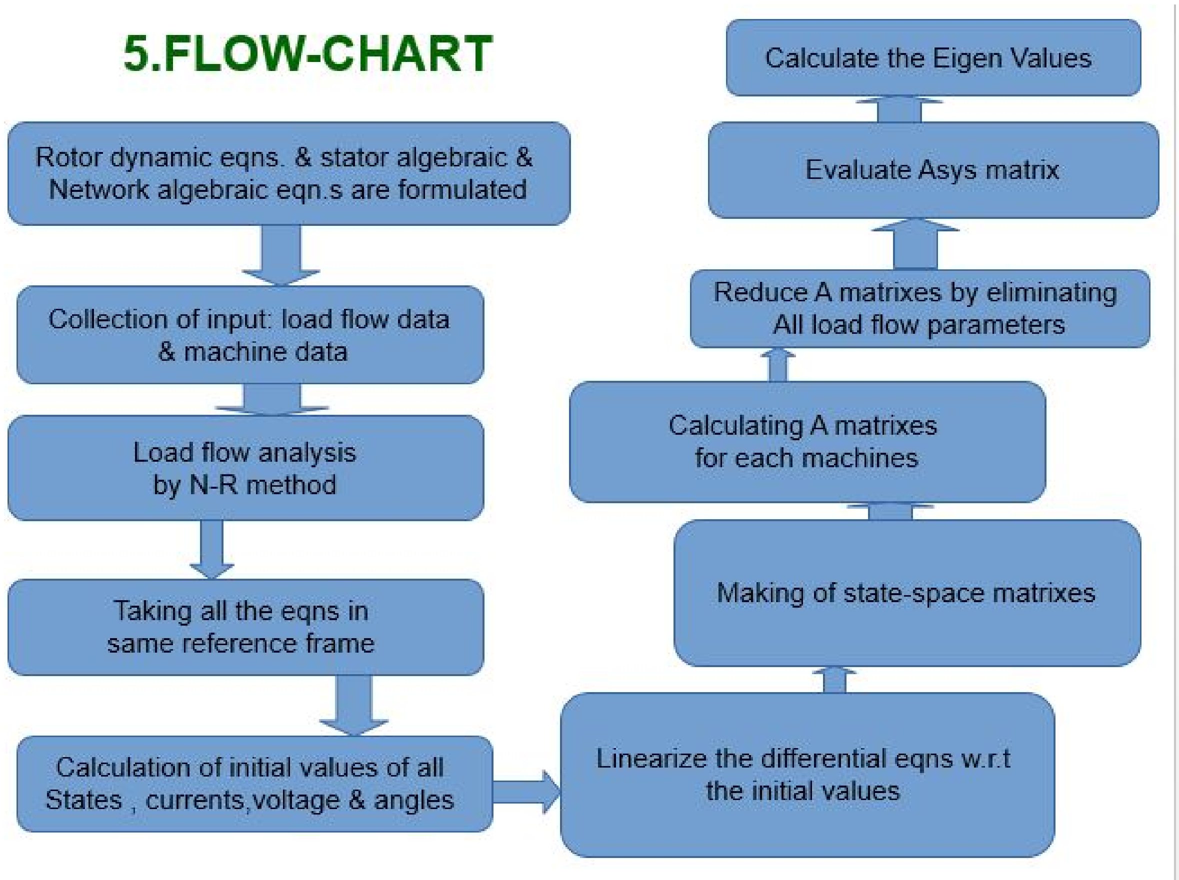

Figure 5.1: Flow chart of the proposed algorith

Chapter 6

Results

SMIB small signal stability probelm is taken from P.Kundur's example 12.5. The eigen values from Kundur's book is as followed The derived result from my SMIB programming is

Eigenvalues	
λ_1, λ_2	$-0.171 \pm j6.47$
λ_3	-0.200
λ_4	-2.045
λ_5	-25.01
λ_6	-37.85

Figure 6.1: Standard eigen values from Kundur's book

```
EIGEN =

 -39.3410 - 0.0225i
 -22.2113 - 0.0021i
  -0.7050 - 6.3423i
  -1.0230 - 6.3175i
  -0.1979 - 0.0001i
  -1.7969 - 0.0002i
```

Figure 6.2: Eigen values derived from my program

Error may be calculated in various ways. I have taken an averaging method by first, calculating the real sum and imaginary sum respect to the result , then tally the sum and calculate the error percentage.

In this way my program for SMIB has shown -2.5 percent error. So from here , it can be calculated that my program is appropriate.

Then the focus has been led onto multimachine problem. For this I have also took the standard IEEE 11 bus 4 machine system.PSAT is considered very popular and authentic software for this kind of steady state analysis for years.

So, firstly I ave simulated the 11 bus system in PSAT. There the system looks like Then I wrote my

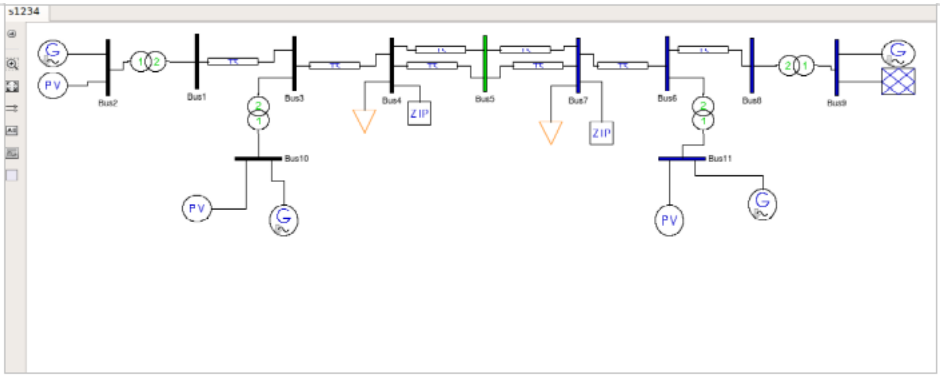

Figure 6.3: Eigen values derived from my program

own program to model the whole system in Matlab environment. From the modelling I have got same set of eigen values like PSAT. Now , the task comes to compare those two results one from

simulation, another from modelling with the reference one from Kundur's book. The eigen value

distribution from PSAT graphically as follows The eigen value distribution from PSAT graphically

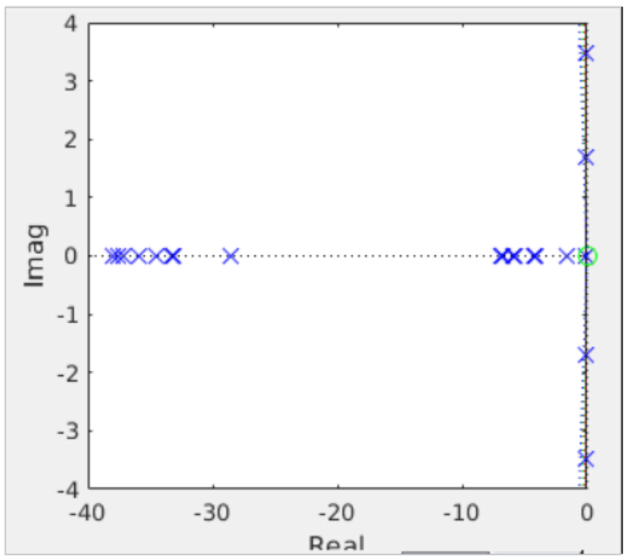

Figure 6.4: Eigen values derived from PSAT for IEEE 11 machine system

as follows From both the picture it is clear that the system is stable because all the eigen values

lies in the left half of imaginary axis. So after some time all the low frequency oscillations in the system will die out after steady state instability occurs. Now, for clear picture I have put all the 24

eigen values obtained by reference ,Matlab modelling and PSAT respectively. From the reference,

my matlab modelling gives 22 percent less stable system which should not be there ,even with unstability for two positive eigen values in case of programs output Whereas PSAT result has come

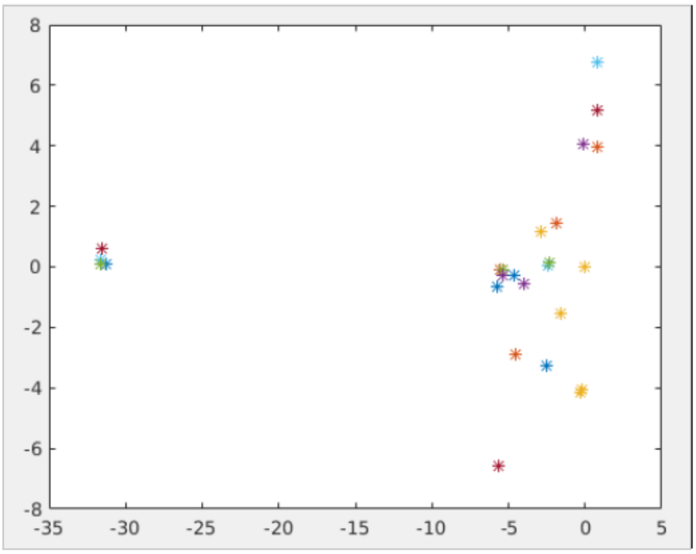

Figure 6.5: Eigen values derived from my matlab modelling for IEEE 11 machine system

Eigenvalues		
No.	Real	Imaginary
1,2	−0.76E−3	±0.22E−2
3	−0.96E−1	–
4,5	−0.111	±3.43
6	−0.117	–
7	−0.265	–
8	−0.276	–
9,10	−0.492	±6.82
11,12	−0.506	±7.02
13	−3.428	–
14	−4.139	–
15	−5.287	–
16	−5.303	–
17	−31.03	–
18	−32.45	–
19	−34.07	–
20	−35.53	–
21,22	−37.89	±0.142
23,24	−38.01	±0.38E−1

P.Kundur's Result

Command Window

```
Lambda =

 -31.2900 + 0.0908i
  -5.5602 - 0.1092i
  -0.1626 - 4.0674i
  -0.0865 + 4.0522i
  -5.3706 - 0.0738i
  -2.3796 + 0.0242i
 -31.5059 + 0.5986i
  -5.7241 - 0.6570i
   0.8283 + 3.9579i
  -0.2604 - 4.1502i
  -5.3962 - 0.2794i
  -2.3028 + 0.1199i
 -31.6480 + 0.2260i
   0.7623 + 5.1964i
  -2.5109 - 3.2576i
  -4.5812 - 2.9055i
  -2.8453 + 1.1683i
  -3.9465 - 0.5788i
 -31.6630 + 0.0764i
   0.8215 + 6.7820i
  -5.6653 - 6.5950i
  -4.5984 - 0.2909i
  -1.8867 + 1.4502i
  -1.6021 - 1.5256i

fx >>
```

Program's output

μ(A) #1 -28.5933 + j0
μ(A) #2 -37.9218 + j0
μ(A) #3 -35.9073 + j0
μ(A) #4 -33.2244 + j0
μ(A) #5 -37.5202 + j0
μ(A) #6 -37.0992 + j0
μ(A) #7 -33.1878 + j0
μ(A) #8 -34.5492 + j0
μ(A) #9 -1.5352 + j0
μ(A) #10 -0.0332 + j3.476
μ(A) #11 -0.0332 - j3.476
μ(A) #12 -6.7042 + j0
μ(A) #13 -6.9053 + j0
μ(A) #14 -5.8999 + j0
μ(A) #15 -4.1075 + j0
μ(A) #16 -0.00097 + j1.6893
μ(A) #17 -0.00097 - j1.6893
μ(A) #18 -6.7202 + j0
μ(A) #19 -4.2747 + j0
μ(A) #20 -5.7353 + j0
μ(A) #21 0 + j0
μ(A) #22 -1e-05 + j0
μ(A) #23 0 + j0
μ(A) #24 0 + j0

PSAT's output

Figure 6.6: Eigen value comparison f the two methods with reference

as 28 percent more stable system, which also should not be there.

Chapter 7

Conclusions

7.1 Discussion

In this investigation a dynamic model for the power system was developed to investigate the development of low frequency oscillations in a power system. The test system was used the IEEE 11 bus test system.

A power system model was enveloped in Matlab and testing was done to determine the power system stability. Software developed performed the following function: load flow of power system, calculation of the initial values of the power system model and the construction of the system state matrix. The software then applied the linear analysis tools to find Eigenvalues of A sys, Participation factors, and mode shape. The Eigenvalues of A sys, Participation factors, and Mode shape can be used to determine if system could develop oscillations and where they occur in the power system if excited.

The purpose of this research was to investigate the Contribution of load to low frequency oscillations in Power System . As a result the system was analysis by first examining the effect of loading on the development of system oscillations. Secondly the effect of load model on low frequency oscillation was determined. In the power system leads to the development of many oscillations at low frequency in the power system. Finally the effect of the load model was that it was easier to identify unstable modes of oscillation.

7.2 Future Scope

In this study renewable sources has not been considered. In case of wind energy penetration , Double fed induction generator (DFIG) modelling will be included . In case of photovoltaic penetration PV array modelling has to be introduced. Because of the photovoltaic penetration as the generation is not gettable always and it is very much dependant on weather condition , day or night . So there will be oscillations due to that. But DFIG has more heavier effect on stability as this generation also depend on wind energy availablity. As in case of synchronous generation PSS has improved the performance , there will be some control strategy to take care the osciallaitions afetr renewable integration. As the crisis of conventional energy sources are increasing the demand of better and obviously smart control strategy for stabiity of power system after renewable integration is required.

References

[1] Naser Abdel-Rahim and John E Quaicoe. Small-signal model and analysis of a multiple feedback control scheme for three-phase voltage-source ups inverters. In *PESC Record. 27th Annual IEEE Power Electronics Specialists Conference*, volume 1, pages 188–194. IEEE, 1996.

[2] Yashodhan P Agalgaonkar, Bikash C Pal, and Ravindra Singh. Impact of photo voltaic generation control on multi machine small signal stability. *IFAC Proceedings Volumes*, 45(21):1–6, 2012.

[3] C Concordia and H Poritsky. Synchronous machine with solid cylindrical rotor. *Transactions of the American Institute of Electrical Engineers*, 56(1):49–179, 1937.

[4] FP DeMello and LN Hannett. Determination of synchronous machine stability study constants. *Final Report Power Technologies, Inc., Schenectady, NY.*, 1980.

[5] Francisco P Demello and Charles Concordia. Concepts of synchronous machine stability as affected by excitation control. *IEEE Transactions on power apparatus and systems*, 88(4):316–329, 1969.

[6] Dharmendra Kumar Dheer, Nimish Soni, and Suryanarayana Doolla. Improvement of small signal stability margin and transient response in inverter-dominated microgrids. *Sustainable Energy, Grids and Networks*, 5:135–147, 2016.

[7] MK Donnelly, JE Dagle, DJ Trudnowski, and GJ Rogers. Impacts of the distributed utility on transmission system stability. *IEEE Transactions on Power Systems*, 11(2):741–746, 1996.

[8] A Elices, L Rouco, H Bourles, and T Margotin. Physical interpretation of state feedback controllers to damp power system oscillations. *IEEE Transactions on Power Systems*, 19(1):436–443, 2004.

[9] Robert W Erickson and Dragan Maksimovic. *Fundamentals of power electronics.* Springer Science & Business Media, 2007.

[10] Narain G Hingorani, Laszlo Gyugyi, and Mohamed El-Hawary. *Understanding FACTS: concepts and technology of flexible AC transmission systems*, volume 1. IEEE press New York, 2000.

[11] Jackson John Justo, Francis Mwasilu, Ju Lee, and Jin-Woo Jung. Ac-microgrids versus dc-microgrids with distributed energy resources: A review. *Renewable and sustainable energy reviews*, 24:387–405, 2013.

[12] H Bora Karayaka, Ali Keyhani, Gerald Thomas Heydt, Baj L Agrawal, and Douglas A Selin. Neural network based modeling of a large steam turbine-generator rotor body parameters from on-line disturbance data. *IEEE Transactions on Energy Conversion*, 16(4):305–311, 2001.

[13] F Katiraei, MR Iravani, and PW Lehn. Small-signal dynamic model of a micro-grid including conventional and electronically interfaced distributed resources. *IET generation, transmission & distribution*, 1(3):369–378, 2007.

[14] Maurice H Kent, Wayne R Schmus, Francis A Mccrackin, and Luther M Wheeler. Dynamic modeling of loads in stability studies. *IEEE Transactions on Power Apparatus and Systems*, (5):756–763, 1969.

[15] M Klein, GJ Rogers, S Moorty, and P Kundur. Analytical investigation of factors influencing power system stabilizers performance. *IEEE Transactions on Energy Conversion*, 7(3):382–390, 1992.

[16] Paul C Krause, Oleg Wasynczuk, and Scott D Sudhoff. *Analysis of electric machinery*, volume 564. McGraw-Hill New York, 1986.

[17] PC Krause, O Wasynczuk, SD Sudhoff, and Paul C Krause. Analysis of electric machinery and ieee power engineering society. In *Analysis of Electric Machinery and Drive Systems*, page 613. Wiley-Interscience, 2002.

[18] Awan Krismanto, N Mithulananthan, and Kwang Y Lee. Comprehensive modelling and small signal stability analysis of res-based microgrid. *IFAC-PapersOnLine*, 48(30):282–287, 2015.

[19] Natalia Kroutikova, Carlos A Hernandez-Aramburo, and Timothy C Green. State-space model of grid-connected inverters under current control mode. *IET Electric Power Applications*, 1(3):329–338, 2007.

[20] Prabha Kundur, Neal J Balu, and Mark G Lauby. *Power system stability and control*, volume 7. McGraw-hill New York, 1994.

[21] EV Larsen and DA Swann. Applying power system stabilizers part i: general concepts. *IEEE Transactions on Power Apparatus and systems*, (6):3017–3024, 1981.

[22] Ritwik Majumder. Some aspects of stability in microgrids. *IEEE Transactions on power systems*, 28(3):3243–3252, 2013.

[23] John P McDonald. Adequacy and philosophy of modeling dynamic system performance representation of the boiler-turbine. In *IEEE Winter Power Meeting*, pages 33–40, 1975.

[24] Francoise Mei and Bikash C Pal. Modelling and small-signal analysis of a grid connected doubly-fed induction generator. In *IEEE Power Engineering Society General Meeting, 2005*, pages 2101–2108. IEEE, 2005.

[25] Yateendra Mishra, S Mishra, Fangxing Li, Zhao Yang Dong, and Ramesh C Bansal. Small-signal stability analysis of a dfig-based wind power system under different modes of operation. *IEEE Transactions on Energy Conversion*, 24(4):972–982, 2009.

[26] Natthaphob Nimpitiwan and Somyot Kaitwanidvilai. Static output feedback robust loop shaping control for grid connected inverter using genetic algorithms. *Int. J. Innov. Comput. Inf. Control*, 8(9):6081–6093, 2012.

[27] Mojtaba Noroozian, Mehrdad Ghandhari, Göran Andersson, J Gronquist, and I Hiskens. A robust control strategy for shunt and series reactive compensators to damp electromechanical oscillations. *IEEE transactions on Power Delivery*, 16(4):812–817, 2001.

[28] Arizona State University. Department of Electrical Engineering and DP Gelopulos. *Midterm Simulation of Electric Power Systems.* The Institute, 1979.

[29] DW Olive. New techniques for the calculation of dynamic stability. *IEEE Transactions on Power Apparatus and Systems*, (7):767–777, 1966.

[30] KR Padiyar. *Power system dynamics: stability and control.* John Wiley New York, 1996.

[31] KR Padiyar and Kalyani Bhaskar. Analysis of small signal voltage stability in multimachine systems using detailed and reduced formulations. *International Journal of Electrical Power & Energy Systems*, 27(4):301–317, 2005.

[32] Nagaraju Pogaku, Milan Prodanovic, and Timothy C Green. Modeling, analysis and testing of autonomous operation of an inverter-based microgrid. *IEEE Transactions on power electronics*, 22(2):613–625, 2007.

[33] AW Rankin. Per-unit impedances of synchronous machines. *Electrical Engineering*, 64(8):569–573, 1945.

[34] Graham Rogers. Demystifying power system oscillations. *IEEE Computer Applications in Power*, 9(3):30–35, 1996.

[35] Graham Rogers. *Power system oscillations*. Springer Science & Business Media, 2012.

[36] JM Stephenson. Per-unit systems with special reference to electric machines. In *IEEE Monograph*. Cambridge University Press, 1970.

[37] Xisheng Tang, Wei Deng, and Zhiping Qi. Investigation of the dynamic stability of microgrid. *IEEE Transactions on power systems*, 29(2):698–706, 2013.

[38] Carlos E Ugalde-Loo and Janaka B Ekanayake. State-space modelling of variable-speed wind turbines: A systematic approach. In *2010 IEEE International Conference on Sustainable Energy Technologies (ICSET)*, pages 1–6. IEEE, 2010.

[39] Carlos E Ugalde-Loo, Janaka B Ekanayake, and Nicholas Jenkins. State-space modeling of wind turbine generators for power system studies. *IEEE Transactions on Industry Applications*, 49(1):223–232, 2012.

Appendix A

system parameters

The system consists of two similar areas connected by a weak tie. Each area consists of two coupled units, each having a 900MVA 20 KV. The generator parameters in per unit on the rated MVA and KV base are as follows.

R = 0.0001 pu/km	X_L = 0.001 pu/km	Bc = 0.00175 pu/km

Then the generating units loaded as given below.

G1	P = 700 MW	Q=185MW	$E_t = 1.03\angle 20.2^\circ$	G1
G2	P = 700 MW	Q = 235MW	$E_t = 1.01\angle 10.5^\circ$	G2
G3	P = 719 MW	Q = 176MW	$E_t = 1.03\angle -6.8^\circ$	G3
G4	P = 700 MW	Q = 202MW	$E_t = 1.01\angle -17.0^\circ$	G4

Each Step-up transformer has an impedance of 0 + j0.15 per unit on 900 MVA and 20/230 KV base, and has an off-nominal ratio of 1.0

The parameters lines in per unit on 900 MVA 230KV.

R = 0.0001 pu/km	X_L = 0.001 pu/km	Bc = 0.00175 pu/km

Then the generating units loaded as given below.

G1	P = 700 MW	Q=185MW	$E_t = 1.03\angle 20.2^\circ$	G1
G2	P = 700 MW	Q = 235MW	$E_t = 1.01\angle 10.5^\circ$	G2
G3	P = 719 MW	Q = 176MW	$E_t = 1.03\angle -6.8^\circ$	G3
G4	P = 700 MW	Q = 202MW	$E_t = 1.01\angle -17.0^\circ$	G4

Appendix B

Synchronous machine control diagram

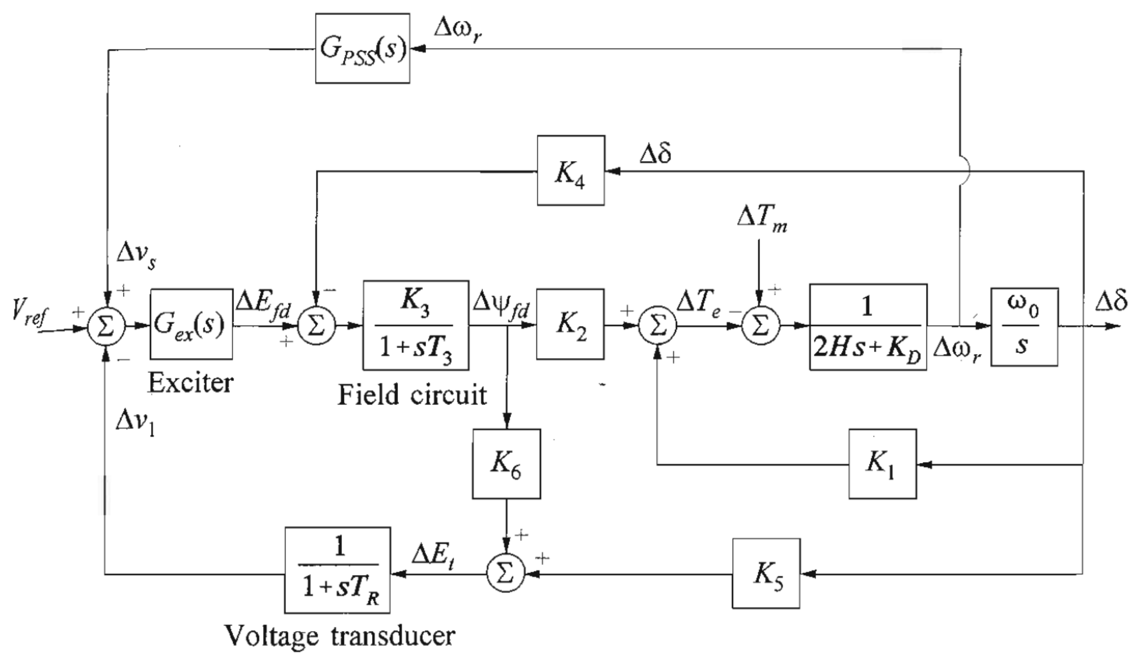

Figure B.1: Block diagram representation with AVR and PSS

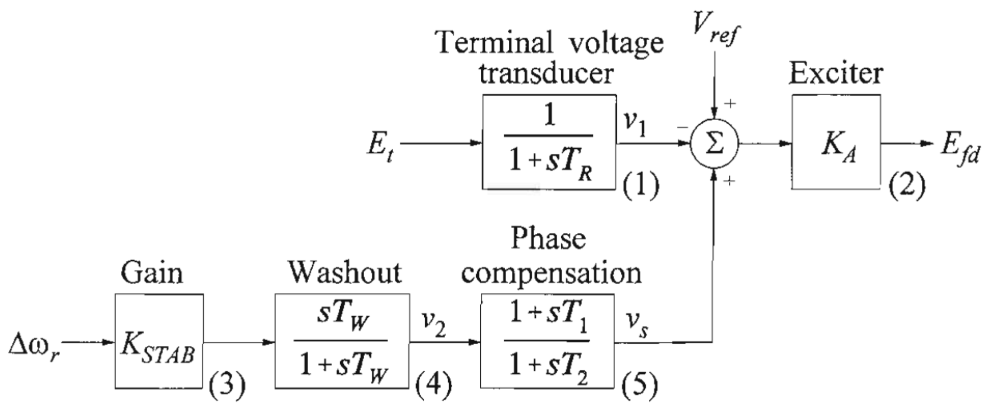

Figure B.2: Thyristor excitation system with AVR and PSS

Appendix C

Matlab program

The matlab coding in the command window is like

```
%%machines
%Gen no bus no   xd  xdd  xddd  Tdod  Tdodd  xq  xqd  xqdd  Tqod   Tqodd ra  xl   2H  Kd  Ksatd  ksatq  P  Q  Et delta Eb RE XE
% B means tranformer HT connected bus no, RE=resistance of transformer,XE= transformer reactance, 900 MVA & 20 kv base
e= [ 1 1 1.8 0.3 0.25 8.0 0.03 1.7 0.55 0.25 0.4 0.05 0.0025 0.2 12.35 0.00 0.874 0.874 0.77 0.26 1.01 0.183 6 0 0.15
     2 2 1.8 0.3 0.25 8.0 0.03 1.7 0.55 0.25 0.4 0.05 0.0025 0.2 12.35 0.00 0.874 0.874 0.77 0.26 1.01 0.183 6 0 0.15
     3 3 1.8 0.3 0.25 8.0 0.03 1.7 0.55 0.25 0.4 0.05 0.0025 0.2 13.00 0.00 0.922 0.922 0.79 0.26 1.03 -0.118 11 0 0.15
     4 4 1.8 0.3 0.25 8.0 0.03 1.7 0.55 0.25 0.4 0.05 0.0025 0.2 13.00 0.00 0.960 0.960 0.76 0.22 1.01 -0.296 10 0 0.15];

Ng=length(e(:,1));
NumN = max([max(Lines(:,1)),max(Lines(:,2))]);
Nl=NumN-Ng;
Numa=6*Ng;
Numb=2*Ng;
Numc=2*Nl;
A1=[];
B1=[];
B2=zeros(Numa,Numb);
W=[];
C1=[];
C2=[];
D1=[];
C3=[];
C4=[];
D2=zeros(Numb,Numb);
D3=zeros(Numb,Numc);
D5=zeros(Numc,Numb);
D6=zeros(Numc,Numc);


for j=1:Ng
    xadu=e(j,3)-e(j,14);
    xaqu=e(j,8)-e(j,14);
    Xmd=xadu*e(j,17);
    Xmq=xaqu*e(j,18);
```

```
xfd=((e(j,4)-e(j,14))*xadu)./(xadu-e(j,4)+e(j,14));
Rfd=(xfd+xadu)./(e(j,6)*377);
x1d=((e(j,5)-e(j,14))*xadu*xfd)./(xadu*xfd-(e(j,5)-e(j,14))*(xfd+xadu));
x1q=((e(j,9)-e(j,14))*xaqu)./(xaqu-e(j,9)+e(j,14));
x2q=((e(j,10)-e(j,14))*xaqu*x1q)./(x1q*xaqu-(e(j,10)-e(j,14))*(x1q+xaqu));
R1d=(x1d+(xfd*xadu)./(xfd+xadu))./(377*e(j,7));
R1q=(xaqu+x1q)./(e(j,11)*377);
R2q=(x2q+(xaqu*x1q)./(xaqu+x1q))./(377*e(j,12));
Et=e(j,21);
xd=e(j,3);
xdd=e(j,4);
xddd=e(j,5);
Tdod=e(j,6);
Tdodd=e(j,7);
xq=e(j,8);
xqd=e(j,9);
xqdd=e(j,10);
Tqod=e(j,11);
Tqodd=e(j,12);
ra= e(j,13);
xls=e(j,14);
It= (e(j,19)-e(j,20)*1i)/Et;
Eq0=Et+(ra+1i*xq).*It;
delta0=Res.An(j)+angle(Eq0);
a11=-(((xdd-xddd)*(xd-xdd))/(Tdod*(xdd-xls).^2))-1/Tdod;
b11=(((xd-xdd)*(xdd-xddd))/((xdd-xls)*Tdod))-(xd-xdd)/Tdod;
```

```
a12=-a11-1/Tdod;
w12=1/Tdod;
a21=w12;
a22=-a21;
b21=(xls-xdd)/Tdodd;
a33=-1/Tqod-(((xqd-xqdd)*(xq-xqd))/((xqd-xls).^2*Tqod));
b32=(xq-xqd)/Tqod-(((xq-xqd)*(xqd-xqdd))/((xqd-xls)*Tqod));
a43=a44=-(1/Tqodd);
a34=a33+(1/Tqod);
b42=(xls-xdd)/Tqodd;
a56=3.14*fnom*2;
%check initial
id0=real(It);
iq0=imag(It);
ifdo=(Eq0+rs*iq0+xd*id0)/xmd;
si1d0=xmd*(ifd0-id0);
si2q0=-(iq0*xmq);
H=e(j,15);
w61=1/H;
a=(xddd-xls)/(H*(xdd-xls));
b=(xdd-xddd)/(H*(xdd-xls));
c=(xqdd-xddd)/H;
d=(xqdd-xls)/(H*(xqd-xls));
f=(xqd-xqdd)/(H*(xqd-xls));
b62=-Eq0*a-b*si1d0-c*id0;
a61=-a*iq0-d*id0;
b61=f*si2q0-d*Eq0-c*iq0;
a62=-b*iq0;
```

```
a64=f*id0;
D=e(j,16);
a66=-(D/H);
A11=[a11 a12 0 0 0 0; a21 a22 0 0 0 0;0 0 a33 a34 0 0;0 0 a43 a44 0 0;0 0 0 0
B11=[b11 0;b21 0;0 b32;0 b42;0 0;b61 b62];
W1=[0 w12;0 0;0 0;0 0;0 0;w61 0];
A1=blkdiag(A1,A11);
B1=blkdiag(B1,B11);
W=blkdiag(W,W1);
c11=-a*H;
C12=-b*H;
c15=-Vn(j)*sin(delta0-An(j));
c23=-d*H;
c24=f*H;
c25=Vn(j)*cos(delta0-An(j));
C11=[c11 c12 0 0 c15 0;0 0 c23 c24 c25 0];
C21=[xddd ra;ra -xqdd];
C1=blkdiag(C1,C11);
C2=blkdiag(C2,C21);
d11=-c15;
d21=-c25;
d12=cos(delta0-An(j));
d22=sin(delta0-An(j));
D11=[d11 d12 0 0;d21 d22 0 0];
D1=blkdiag(D1,D11);
c315=Vn(j)*(id0*cos(delta0-An(j))-iq0*(sin(delta0-An(j))));
c325=Vn(j)*(-id0*sin(delta0-An(j))-iq0*(cos(delta0-An(j))));
C31=[0 0 0 0 c315 0;0 0 0 0 c325 0];
```

```
c422=c15;
c412=c25;
c421=c25;
C41=[c411 c412;c421 c422];
C4=blkdiag(C4,C41);


y.abs=abs(Ybus);
y.angle=angle(Ybus);
for k=1:NumN
     x1=x1+Vn(k)*y.abs(j,k)*sin(An(j)-An(k)-y.angle(j,k));
     x2=x2-Vn(k)*y.abs(j,k)*cos(An(j)-An(k)-y.angle(j,k));
end
D2(2*j-1,2*j-1)=iq0*Vn(j)*sin(delta0-An(j))-id0*cos(delta0-An(j))-Vn(j).^2*sin(y.angl
D2(2*j-1,2*j)=X2-Vn(j)*y.abs(j,j)*cos(y.angle(j,j))+id0*sin(delta0-An(j))+iq0*cos(del
if D2(2*j-1,:)=0
   for l=1:Ng
     D2(2*j-1,2*l-1)=Vn(j)*Vn(l)*y.abs(j,l)*sin(An(j)-An(l)-y.angle(j,l));
     D2(2*j-1,2*l)=-Vn(j)*y.abs(j,l)*cos(An(j)-An(l)-y.angle(j,l));
   end
end
 for k=1:NumN
     x3=x3+Vn(k)*y.abs(j,k)*cos(An(j)-An(k)-y.angle(j,k));
     x4=x4-Vn(k)*y.abs(j,k)*sin(An(j)-An(k)-y.angle(j,k));
end
D2(2*j,2*j-1)=id0*Vn(j)*sin(delta0-An(j))+iq0*cos(delta0-An(j))+Vn(j).^2*cos(y.angle(
D2(2*j,2*j)=X4+Vn(j)*y.abs(j,j)*cos(y.angle(j,j))+id0*cos(delta0-An(j))+iq0*sin(delta
```

```
    if D2(2*j,:)=0
       for l=1:Ng
         D2(2*j,2*l-1)=Vn(j)*Vn(l)*y.abs(j,l)*cos(An(j)-An(l)-y.angle(j,l));
         D2(2*j,2*l)=-Vn(j)*y.abs(j,l)*sin(An(j)-An(l)-y.angle(j,l));
       end
    end
    for m=1:Nl
        p=m+Ng;
        D3(2*j-1,2*m-1)=Vn(j)*Vn(p)*y.abs(j,p)*sin(An(j)-An(p)-y.angle(j,p));
        D3(2*j-1,2*m)=-Vn(j)*y.abs(j,p)*cos(An(j)-An(p)-y.angle(j,p));
        D3(2*j,2*m-1)=Vn(j)*Vn(p)*y.abs(j,p)*cos(An(j)-An(p)-y.angle(j,p));
        D3(2*j,2*m)=-Vn(j)*y.abs(j,p)*sin(An(j)-An(p)-y.angle(j,p));
        D5(2*m-1,2*j-1)=Vn(j)*Vn(p)*y.abs(p,j)*sin(An(p)-An(j)-y.angle(p,j));
        D5(2*m-1,2*j)=Vn(p)*y.abs(p,j)*cos(An(p)-An(j)-y.angle(p,j));
        D5(2*m,2*j-1)=-Vn(j)*Vn(p)*y.abs(p,j)*cos(An(p)-An(j)-y.angle(p,j));
        D5(2*m,2*j)=Vn(p)*y.abs(p,j)*sin(An(p)-An(j)-y.angle(p,j));
    end


end
```

```
for j=1:Nl
    p=Ng+j;
    for k=1:NumN
        x5=x5-Vn(k)*y.abs(p,k)*sin(An(p)-An(k)-y.angle(p,k));
        x6=x6+Vn(p)*y.abs(p,k)*cos(An(p)-An(k)-y.angle(p,k));
        x7=x7+Vn(k)*y.abs(p,k)*cos(An(p)-An(k)-y.angle(p,k));
        x8=x8+Vn(p)*y.abs(p,k)*sin(An(p)-An(k)-y.angle(p,k));
    end
    D6(2*j-1,2*j-1)=x5*Vn(p)-Vn(p).^2*y.abs(p,p)*sin(y.angle(p,p));
    D6(2*j-1,2*j)=x6+Vn(p)*y.abs(p,p)*cos(y.angle(p,p));
    D6(2*j,2*j-1)=x7*Vn(p)-Vn(p).^2*y.abs(p,p)*cos(y.angle(p,p));
    D6(2*j,2*j)=x8-Vn(p)*y.abs(p,p)*sin(y.angle(p,p));
    if D6(2*j-1,:)=0
      for l=1:Nl
          q=Ng+l;
          D6(2*j-1,2*l-1)=Vn(p)*Vn(q)*y.abs(p,q)*sin(An(p)-An(q)-y.angle(p,q));
          D6(2*j-1,2*l)=Vn(p)*y.abs(p,q)*cos(An(p)-An(q)-y.angle(p,q));
          D6(2*j,2*l-1)=-Vn(p)*Vn(q)*y.abs(p,q)*cos(An(p)-An(q)-y.angle(p,q));
          D6(2*j,2*l)=Vn(p)*y.abs(p,q)*sin(An(p)-An(q)-y.angle(p,q));
      end
    end
end
```

```
A1;
B1;
W;
C1;
C2;
C3;
C4;
D1;
D2;
D4;
D5;
D6;
D7=D2-D3*inv(D6)*D5;
B=[B1,B2];
E=[C2,D1;C4,D7];
E1=inv(E);
C5=[C1;C3];
Asys=A1-B*E1*C5;
Lambda=eig(Asys);
X=real(Lambda);
Y=imag(Lambda);
plot(X,Y)
```