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COMPARISON OF THREE POWER SYSTEM SOFTWARE PACKAGES FOR SMALL-SIGNAL STABILITY ANALYSIS

(PacDyn, PSAT and MatNetEig)

By

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Declaration

I know the meaning of plagiarism and declare that all the work in the document, save for that which is properly acknowledged, is my own.

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Abstract

Many power system simulation tools exist for small-signal stability analysis. This is due to the rapid development of computer systems, higher industrial growth and the need for reliable power system simulation tools for efficient planning and control of electric power systems. Three power system small-signal stability simulation tools have been selected for comparison and these are: PSAT 2.1.2, MatNetEig and PacDyn 8.1.1. These combine both open and closed source code industrial-grade power system analysis tools.

The objective of this thesis is to compare three simulation tools on power system small-signal stability analysis. Input formats, data output flexibility, dynamic components and synchronous machine saturation modelling in all three simulation tools were amongst other features investigated for comparative studies.

All tools have constant PQ load models, static non-linear ZIP load models, equivalent π–circuit AC transmission, synchronous generators with saturation, AVR excitation systems and power system stabilizers. All tools give the **A** matrix via the Matlab workspace. PacDyn and MatNetEig tools give both mode shapes and participation factors while PSAT gives the participation factors only. Additional Matlab scripts were written and Microsoft Excel was used for additional data formatting and visualisation.

PSAT 2.1.2 and MatNetEig tools are Matlab based open source simulation tools developed to run in Matlab environment in either graphical user interface or via the command line. Command line usage offers access to all internal data, unlimited simulation support for small-disturbances and plotting utilities. PSAT and MatNetEig Matlab codes can be easily modified for enhanced capabilities and to meet the user requirements.

PacDyn 8.1.1 is a closed code simulation tool with efficient algorithms and advanced graphical user interface. Time domain step and frequency disturbance simulations can be customised via the "Transfer function manager". PacDyn has additional editors for data, user-defined controllers and plotting utilities for enhanced modelling and analysis.

Small-signal stability is the ability of a power system to maintain synchronism under small-disturbances such as small changes in loads and generation. The disturbance is

considered small enough if equations governing the dynamics of the system can be linearized around an operating equilibrium point.

The single machine infinite bus (SMIB) and the "two-area, four-machine" (2A4M) power system models were selected for test purposes and different power system study cases were modelled and analysed using all three tools. The results were then compared using modal analysis (eigenvalues) technique, the **A** state matrix, mode shapes (eigenvectors), participation factors and time domain simulations.

The following network configurations were modelled for comparative tests and analysis in all two power system models using all three tools:

- Manual control
- System controlled by an AVR (with high transient gain and transient gain reduction)
- System controlled by AVR and PSS

The focus was on local and inter-area oscillatory modes and the following conclusions were drawn from the main findings:

- SMIB power system model

All tools gave similar results for different values of the damping coefficient. The effects are negligible on frequency but higher on the damping ratios. A positive damping coefficient increases the damping ratio while a negative value decreases the damping ratio. This was true for both modal and time domain simulations. The damping ratio is high on higher order generator models. PacDyn results closely matched MatNetEig results in all synchronous machine models with negligible differences. The differences in frequency and damping ratios between PacDyn and MatNetEig results were negligible while PSAT gave highest damping ratio changes when saturation was considered.

The effects of including as well as neglecting the armature resistance and leakage reactance are negligible in frequency and damping ratios in PacDyn and MatNetEig tools. These two simulation tools also gave similar time domain simulation plots.

The result from PSAT gave stable modes (that are wrong) for a system controlled by an AVR exciter. Both the saturation and the AVR model used in PSAT tool contributed to wrong results in both modal analysis and rotor angle response to applied step (small-disturbance) time domain simulations.

- 2A4M power system model

Three electromechanical oscillatory modes were identified in all tools with one inter-area mode and two local area modes. Eigenvectors and participation factors were used to identify these oscillatory modes. PSAT gave higher frequency and damping ratios compared to PacDyn and MatNetEig tools. The results in MatNetEig closely matched PacDyn results.

It was proved that setting a reference machine on the system eliminates redundant eigenvalues as expected. The effects of armature resistance, leakage reactance and saturation are small and negligible on numerical results for small-signal stability analysis. However, the effects of saturation are different due to the mathematical models used in these three simulation tools. A positive damping coefficient increases the damping ratio.

For a system with all four generators controlled by AVR (high transient gain and transient gain reduction models); PSAT tool gave higher frequency and damping ratios as compared to PacDyn and MatNetEig results. PSAT results were confirmed to be incorrect for this AVR excitation type. The results from PacDyn matched MatNetEig results with small differences due to rounding errors in MatNetEig. Incorrect results given by PSAT are due to the AVR models implemented in this simulation tool.

When the system was modelled with AVR and PSS on all synchronous machines; all tools gave stable electromechanical eigenvalues for PQ and ZIP load types on the local and inter-area oscillatory modes. The effects of saturation are much higher in PSAT. These can not be ignored for the purpose of small-signal stability analysis. Although slightly high, the effects of saturation in PacDyn and MatNetEig can be ignored.

Small-disturbance step response simulations in time domain analysis indicated the dynamic response as predicted using modal analysis in PacDyn and MatNetEig tools while PSAT gave unstable and contradictory responses. Unstable control modes were identified as the cause of instability in PSAT results. PacDyn and MatNetEig tools are more adequate and reliable as indicated by numerical and step response time domain simulation results. PacDyn is more advanced and recommended following the findings.

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Common Notations

This section highlights most important acronyms, abbreviations, symbols and measuring units used in this dissertation. These are commonly used in power system stability analysis context.

Abbreviations

Acronym	**Description of the acronym or abbreviation**
2A4M	"Two-area, four-machine" power system model.
abc	Phase current components in Park's transformation equations.
AC	Alternating current.
AVR	Automatic voltage regulator.
CDUEdit	User-defined controller data editor by CEPEL.
CEPEL	Centro de Pesquisas Energia Electrica, Brazilian company.
CPAT	CRIEPI's Power System Analysis Tool.
DAE	Differential algebraic equation(s).
DC	Direct current.
DFC	Data format conversion.
dq0	Direct, quadrature and zero sequence current components in Park's transformation equations.
EditCepel	Data editor for PacDyn supported data file formats from CEPEL.
FACTS	Flexible AC transmission systems.
GUI	Graphical user interface.
HTG	High transient gain.
HVDC	High voltage direct current.
IEEE	Institute of Electrical and Electronics Engineers.
Matlab	Compiler programming language software from MathWorks.
MatNetEig	Small-signal stability analysis simulation tool by G. Rogers.
OCC	Open-circuit characteristic curve (for magnetic saturation).
PacDyn	Small-signal stability analysis and control design simulation tool by CEPEL.
PlotCepel	CEPEL's Plotting, visualisation and data processing tool.
PMU	Phasor measurement unit.

PSAT	Power system analysis toolbox by F. Milano.
PSS	Power system stabilizer.
PSS/E	Power systems simulator for engineering.
PST	Power system toolbox (PST2 for PST version 2) by Cherry Tree Farm.
SAUPEC	Southern African Universities Power Engineering Conference.
SMIB	SMIB (One machine connected to an infinite bus).
SSSA	Small-signal stability analysis.
SVC	Static var compensator.
TEF	Transfer energy function.
TGR	Transient gain reduction.
UCT	University of Cape Town.
UDC(M)	User-defined controller (model).
VDL	Voltage dependent load.
VSMI	Voltage stability margin index.
ZIP (Load)	Static non-linear load with characteristic combinations of constant impedance (Z), constant current (I) and constant power (P).

Symbols used

Symbol	**Description of the symbol**
A	Power system state matrix.
d–	Direct axis component
f	Frequency.
H	Inertia constant.
I	Identity matrix.
j	90 degrees phase shift (used for complex representation).
K_d	Damping coefficient.
L	Inductance.
M	Moment of inertia.
P	Real power.
P_e	Electrical power output.
P_{ki}	Participation factor of state k on the mode i.
P_m, P_{mech}, P_{min}	Synchronous generator's mechanical input power.
Q	Reactive power.
q-	Quadrature axis component.
R	Resistance.

t	Time.
T_a	Net accelerating or decelerating torque.
T_e	Electrical torque.
T_m	Mechanical torque of a synchronous machine rotor shaft.
T_0	Time period.
X	Reactance.
Z	Impedance.
δ	Rotor angle.
Δ	Small perturbation (deviation).
Δf	Frequency deviation.
$\Delta\zeta$	Damping ratio deviation.
ε	Tolerance (error).
ζ	Damping ratio.
θ	Phase angle.
λ	Eigenvalue(s).
σ	Real part of the eigenvalue.
Φ_i	Right eigenvector corresponding to eigenvalue i.
Ψ_a	Flux linkage.
Ψ_i	Left eigenvector corresponding to eigenvalue i.
ω	Rotor speed (or imaginary component of the eigenvalue, depends on the context).

Measuring units

Unit	**Description of the measuring unit**
%	Percentage.
p.u (pu)	Per unit.
rad	Radians.
Hz	Hertz.
s	Seconds.
kV	Kilovolts.
MVA	Megavolt-amperes. Unit of apparent power (vector sum of real and reactive power).
°	Degrees.

Chapter 1:

1. Introduction

The power system continues to become larger due to the advancing technology and industrial development. This growth together with the deregulation of electric utilities makes the power system more complex and increase security of supply risk. Although the size of the power system continuously increases, there are reduction methods which are used to reduce various power system components while maintaining the nature and behaviour of the over-all power system. By identifying similar power system components with identical dynamic response, the size of the power system model can be eventually reduced to a single machine infinite bus (SMIB). The single-machine infinite-bus model is an adequate simulation tool for investigating the dynamics of a single generator (or power plant with multiple but identical machines) against the rest of the power system when one is only intersted in the local model of the plant [1]. The disadvantage is that the behaviour of individual component is lost during the process. To avoid this problem, simulation tools are development with the capability of modelling and simulating multi-machine power system models at relatively higher speed and less memory requirements essential for adequate planning, stability analysis and control designs [2].

As more and more power system simulation tools are becoming available on the market, it becomes difficult to specifically say which of the simulation tools is suitable to use for a specific study field. In 1979, CIGRE' study committee [3] recommended the development of powerful eigenvalue programs for small-signal stability analysis of power systems and hence the need for simulation packages. These tools are different, with different modelling techniques/algorithms and at times, numerical results differ; making it even more difficult to validate simulation results [4]. In addition, learning and mastering these tools is time consuming [4]. Power industries already using other tools become dependent on the already "working software" and become reluctant to change.

Power system software packages are classified as either Commercial or Educational/research-aimed software tool. Commercial tools are closed source code, well tested, generally efficient and well developed while educational tools are open source freely available with flexible and easy code expansion [5 – 7]. When choosing or changing a power system simulation package, it is crucial to consider the following aspects of the software tool:

- Reliability of the software.
- Modelling methodologies used by software.
- User-friendliness of the software.
- Adaptability of the software to meet user's requirements.
- Graphical user interface.
- Data input/output formats and data compatibility with other software packages.
- Reduced and detailed higher order component models.

There are many advantages of using power system simulation tools. Other factors to consider in small-signal stability applications include – but not limited to – modal solution analysis (eigenvalues and eigenvectors), the ability to conduct time domain simulations, linearization and efficient computational speed [8].

The needs for efficient power system modelling and analysis tools are to simplify and speed-up network computations [7, 9], to perform system reliability, stability, risk analyses for planning and control purposes, to estimate optimal productivity and reduced capital expenditure for high return on investment, to reduce obsolete parts and improved quality of supply to the consumers.

As part of the ongoing work to investigate and perform a comparative analysis of different power system software packages, the author's task is to compare three software packages for small-signal stability analysis. These software packages are: Power System Analysis Toolbox (PSAT 2.1.2 by Federico Milano), PacDyn (PacDyn 8.1.1 by CEPEL, Brazil) and MatNetEig by Graham Rogers of Cherry tree scientific software.

1.1. Background to the investigations

Small-signal stability is concerned with the ability of the power system to regain stability after small disturbances such as gradual changes in loads or generation. The small-signal stability of a system can be investigated through modal analysis (eigenvalues of the system A matrix), based on linear tools and techniques. If the real part of the eigenvalue is negative the system is stable, otherwise the system is unstable. This simple principle has been used for many years in large power system to coordinate various control devices such as automatic voltage regulators (AVR), power system stabilizers (PSS) and static var compensators (SVCs), etc. However, due to the differences in components modelling and solution methodology, for the same investigated power system, different simulation tools could give different results.

According to Kaberere [4], understanding why different simulation tools give different results is not a trivial issue. There are no industry-accepted standards for comparing the power system simulation tools available on the market. Some simulation tools used for small-signal stability analysis at the University of Cape Town have already been compared. These include:

- PSS/E [1].
- EUROSTAG [1, 10].
- DIgSILENT PowerFactory [11 – 12].
- Matlab Power System Toolbox (PST) [11 – 12, 14].
- PSCAD [11 – 13].
- SSAT [1]
- MatNetEig [1, 14].
- Matlab power system Blockset [15].
- CRIEPI's Power System Analysis Tool (CPAT) [16].

However, not all available software packages have been covered.

The objectives of this research are to extend the previous work and include new software packages such as PSAT and PacDyn for small-signal stability analysis. A software comparative study of this kind is a useful one, given that there are different software tools available on the market.

1.2. Overview of simulation tools to be compared

Three power system simulation tools were selected for comparison and these are PSAT, MatNetEig and PacDyn.

PSAT is an abbreviation for Power System Analysis Tool. It is an open source Matlab based power simulation package designed for analysis of both steady state and dynamic simulations. It has the following routines used for power system analysis: Power flow, continuation power flow, optimal power flow, small-signal stability analysis, Time domain simulations and phasor measurement unit (PMU) placement. Input data is specified in either Simulink PSAT library single lines or Matlab (PSAT format m-file). The tool has data conversion drivers to import data from various standard data formats [17] and a well developed graphical user interface [18].

PacDyn is a comprehensive small-signal stability analysis package developed by CEPEL (Centro de Pesquisas de Energia Electrica, Brazil). Data formats supported include formats such as PSS/E, ANARADE, Binary and PacDyn data file formats. It has built-in as well as user defined models [19]. It requires converged load flow in the form of electrical network data. PacDyn comes with data editors for different data formats as well as user-defined control editors for the modelling of unlimited dynamic models [9].

MatNetEig software tool is a Matlab based power system simulation tool and uses classes called net_c for network model structures. MatNetEig tool supports data file formats in PST V2, PSS/E or IEEE common data file format. Power system stability analysis can be done in either command line or by using graphical user interface (GUI) [20].

1.3. Justification of research

This research is a continuation of the work previously done in analysing and comparing power system software packages that are used for power system simulation analysis in different study fields. Worldwide, many power system simulation tools have been briefly investigated [5 – 6, 8].

1.4. Objectives and contributions

The objectives and contributions of this thesis project report are:

- To give background information on power system stability and analysis methods and the need for software tools in power system modelling and simulations.
- To provide a detailed description of the selected power system simulation tools and modelling requirements for small-signal stability analysis.

The contributions of this thesis are:

- To conduct simulations tests on two power system models using all three software packages and to study results for comparative studies.
- To show how variations in saturation affect simulation results.
- To show the effect of armature resistance and leakage reactance on modal solution.
- To give conclusions and recommendations on the findings of the investigations.

1.5. Research methodology

To successfully conduct comparative analysis of the three simulation tools on small-signal stability of power systems, a review of power system stability and component modelling were conducted followed by a brief study of all three simulation tools. Two power system models (SMIB and the 2A4M) were chosen for test purposes and different power system study cases were modelled and analysed using all three tools and the results were compared.

1.6. Limitations and scope

The scope of this thesis project is limited to the comparison of three power system simulation tools (i.e. PSAT, PacDyn and MatNetEig) for small-signal stability analysis. This implies that software tools available at the date of the commencement of the project were used.

PSAT version 2.1.2 was used in all PSAT cases even though there is a newer version of this simulation tool available (PSAT 2.1.3 released in April 2009 and PSAT 2.1.4 released in June 2009). PacDyn 8.1.1 is used instead of the newer PacDyn version 9.0 that was released in May 2009. There is one MatNetEig version available and this tool is analysed and compared with PacDyn 8.1.1 and PSAT 2.1.2 for small-signal stability of the two power system models on different excitation controls. The synchronous generators are modelled without turbine governors.

Although all three tools can model power systems for different types of analysis, only small-signal stability in the form of modal eigenvalue analysis, time domain simulations and sensitivity analysis are investigated and discussed.

1.7. Thesis outline

Chapter 2 gives detailed theory on power system stability and analysis methods used in power system small-signal stability.

Power system components and modelling techniques used for various power system components are presented in chapter 3 with emphasis on synchronous machine modelling, saturation, excitation systems, transformers, lines and loads.

Chapter 4 presents PSAT 2.1.2 simulation tool. Data input formats, usage and output in small-signal stability analysis are thoroughly investigated and discussed.

Chapter 5 gives an overview of MatNetEig simulation tool. All component models used in MatNetEig applicable to the selected SMIB and the 2A4M power system models are presented. Data input formats, usage and output in small-signal stability analysis are thoroughly discussed.

Chapter 6 highlights PacDyn 8.1.1 simulation tool. All component models used in PacDyn applicable to selected models are presented as well as data input formats, usage and output in small-signal stability analysis.

The descriptions of power system models as well as all test case studies conducted are presented in chapter 7.

Chapter 8 covers the simulation results and discussions for all three simulation tools using; modal analysis, time domain simulations, mode shapes (eigenvectors) and participation factors.

The conclusions and recommendations are given in chapter 9.

All power system data and additional simulation results are included in the Appendix.

Chapter 2:

2. Power System Stability

2.1. Background

The power system was first introduced in the early 1880s as a direct current (DC) station supplying few customers in a small geographic area [21]. The size of the area covered was about 1.5km in radius. This then rapidly developed with many interconnections of loads, transmission lines and generators as a DC system. The development of this electric power system resulted in the implementation of single phase and later three phase alternating current (AC) systems for efficient transmission of high voltages with long lines over larger geographic areas [21, 22].

Recent developments in power systems include the use of high voltage direct current (HVDC) transmission lines with hybrid inverter and converter stations at the end of the lines interconnecting AC systems. The use of HVDC transmission systems offers cost efficient means and more power transfer capabilities over AC systems on longer lines. There are many HVDC transmission systems worldwide to date. These include the ±533 kV DC transmission line in South Africa and the ±400 kV HVDC line in the United States [21].

Nevertheless AC systems have been favoured for centuries and resulted in many interconnections of synchronous machines, loads, AC transmissions line and HVDC transmission lines and their controls in various locations. This resulted in rapid growth in electric power system and the interconnection of different non-linear components, making the electric power system relatively large and complex to analyse without the use of digital computer simulations [21, 23, 24]. Computer packages are used to model and simulate power systems for planning, reliability, efficiency, stability analysis and control design. Reliability of the analyses results from the computer simulation tools heavily depends on accurate modelling and linearization of network equations [22].

Higher industrial development, load growth and deregulation of the electric power system results in constraints imposed on the power system [21 – 23]. Some of the constraints include operating the power system closer to the stability limits as well as overloading. Power system stability problem is of great concern in ensuring continuity of energy transfer from generation to loads at all time, recovery of system following disturbances and efficiently tuned stabilising control systems. This concept of stability will be discussed in detail with emphasis on small-signal stability analysis.

2.2. Terms and definitions in power system stability

Different terminologies used in power system stability are discussed following extensive literature survey on the power system stability concept.

- **Power system stability** is the ability of a power system to remain in a state of equilibrium under normal operating conditions and to regain acceptable state of equilibrium after being subjected to a disturbance [21, 25].

- **Transient stability** is the ability of the power system to maintain synchronism when subjected to severe or large disturbances. The disturbances can be sudden changes in system configuration as a result of faults, lightning, loss of lines and loss of generation [21 – 23, 25, 26]. Transient stability analysis is done on the first swing using the power – angle curve. If the electrical power output of the synchronous generator does not go out of step during the first swing, the system is transient stable. Otherwise the system loses synchronism and becomes unstable [21, 22, 25].

- **Dynamic stability** is the term used to describe transient stability in the presents of control systems. The control systems can be the automatic voltage regulators (AVR), automatic frequency controls and HVDC inverter and converter control systems. When the system is transient stable, the oscillatory behaviour following a disturbance is dependent on the time constants of the control systems on the synchronous machines and other dynamic system components [21, 22, 27]. The duration of stability analysis is more than the transient stability simulation duration. Analyses can be done over tens of seconds. According to Kundur [21], the term dynamic stability is not recommended to be used following recommendations from IEEE and CIGRE study committees due to different interpretations.

- **Rotor angle stability** is the ability of interconnected synchronous machines to remain in synchronism [21]. This form of stability is subdivided into small-signal and transient stability and is analysed using time domain and eigensolution techniques. Understanding synchronous machine dynamics is the fundamental to rotor angle stability analysis.

- **Small-signal stability** is the ability of a power system to maintain synchronism under small-disturbances such as small changes in loads and generation [21, 26]. The disturbance is considered small enough if the equations governing the dynamics of the system can be linearized around an operating equilibrium point [21].

- **Voltage stability** refers to the ability of the system to maintain steady acceptable voltages at all buses on the system. The system is said to be voltage stable if the increase in reactive power results in the increase in bus voltage magnitudes [21]. Instability may lead to voltage collapse. The analysis techniques include the V-Q sensitivity analysis, P-V curves and voltage stability margin index (VSMI) [24].

- **Oscillatory modes** is a term used for the complex eigenvalues, the imaginary part of the eigenvalue gives the oscillatory frequency of the system mode. The oscillatory modes are classified into four categories based on the frequency range and the location of dominant state variables. They are; local area mode, inter-area mode, control plant mode and torsional mode [2, 14, 21].

- **Inter-area mode** is associated with groups of machines in one part of the system swinging against synchronous machines in other parts of the system. The oscillatory frequency is in the range of 0.2 to 0.7 Hz [29]. This mode type is often found when there is a weak tie line interconnecting two areas or groups of synchronous machines.

- **Local plant (area) mode** refers to the swinging of units at a generating station with respect to the rest of the power system. The oscillatory frequency ranges from 0.7 Hz to about 2 Hz.

- **Control mode** is associated with synchronous generators and their control systems such as the AVR excitation systems [21]. The main cause of this is the inappropriate tuning and coordination of the controls system. The frequency is above 2 Hz.

- **Torsional mode** is rotational (*torsional*) oscillations associated with the mechanical shaft of a turbine-generator [21].

The control modes and torsional modes are shown in the power system stability classification diagram but not to be analysed further in this thesis.

2.3. Classifications of power system stability

Classification of system stability depends on the nature and severity of the disturbance, duration of analysis and the techniques used in analysing stability problem. Power system stability problems can easily be classified into two forms, i.e. rotor angle stability and voltage stability [21, 22, 25]. These are further subdivided as shown on the diagram in Fig. 2.1 [21]. Other authors classify the power system stability into three categories including frequency stability [2].

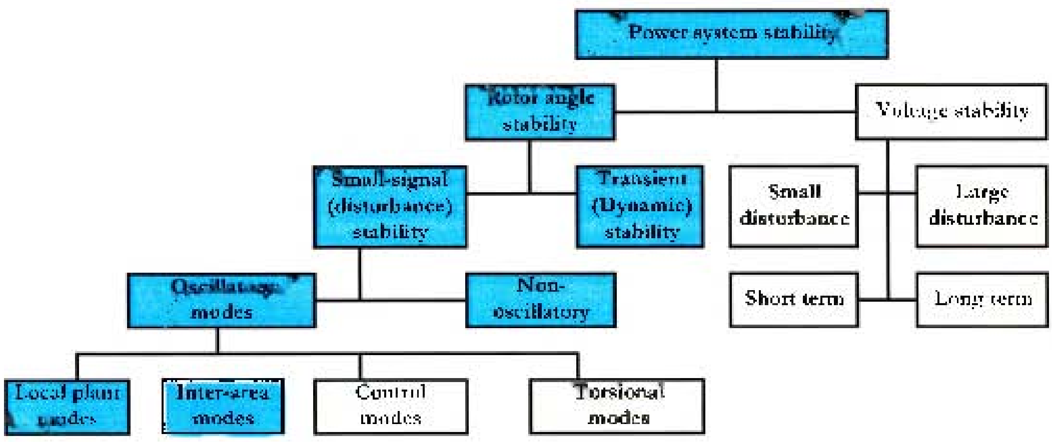


Figure 2.1: Classifications of power system stability [2, 21]

For the purpose of this research, the focus is on rotor angle stability in blue shaded blocks in Fig. 2.1.

2.4. Analysis methods used in small-signal stability studies

Various methods of analysing power system stability problems exist in literature as well as those implemented in different software packages for stability analysis. These include the swing equation, equal-area criterion and eigenanalysis techniques. The choice of analysis method depends on the type of stability problem. Eigenanalysis method is used for small-signal stability while the equal-area criterion is for transient stability analysis. *Both the swing equation and the equal-area criterion have been briefly discussed in the appendix.*

2.4.1. State space equations and modal analysis

The dynamic behaviour of a power system is modelled by a set of non-linear differential and algebraic equations (DAE) linearized around an equilibrium operating condition. The dynamic behaviour of the system is given by equation (2.1) below.

$$\begin{aligned} \dot{x} &= f(x,u,t) \\ y &= g(x,u,t) \end{aligned} \tag{2.1}$$

Where $\dot{x}$ – derivative of x with respect to time

x – State variables of dimension n x n

f – Vector of non-linear functions of size n x 1

u – Input variables of size m x 1

y – Output variables of size p x 1

g – Vector of non-linear functions of size p x 1

t – Time

n – Order of the power system model indicating the total number of eigenvalues

For systems that are time invariant (derivatives of the state variables are not explicit functions of time), the DAE equations in (2.1) can be simplified to (2.2) below.

$$\begin{aligned} \dot{x} &= f(x,u) \\ y &= g(x,u) \end{aligned} \tag{2.2}$$

When the power system is operating at steady-state equilibrium (x_0 and u_0 are constant at any time instant), the rates of change on any state variables are zero as follows:

$$\dot{x}_0 = f(x_0, u_0) = 0 \tag{2.3}$$

Power system small-signal stability involves small disturbances or perturbations on the state variables. If from an equilibrium position mentioned above the system is perturbed by small amounts Δx and Δu respectively, the new system state equations become (2.4).

$$\begin{aligned} \dot{x} &= f\,[(x_0 + \Delta x), (u_0 + \Delta u)] \\ y &= g[(x_0 + \Delta x), (u_0 + \Delta u)] \end{aligned} \tag{2.4}$$

where $x=x_0+\Delta x$ and $u=u_0+\Delta u$.

Taylor series expansion on (2.4) and neglecting second and other higher order terms of the partial derivatives results in linearized set of equations (2.5) is obtained [2, 3, 14, 21].

$$\begin{aligned} \Delta\dot{x} &= A\Delta x + B\Delta u \\ \Delta y &= C\Delta x + D\Delta u \end{aligned} \tag{2.5}$$

The linearized equations in (2.5) are commonly shown without the symbol "Δ" as follows:

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx + Du \end{aligned} \tag{2.6}$$

where:

A – is an n x n state matrix
B – is an n x r input matrix
C – is an m x n output matrix
D – is an m x r feed-forward matrix

The matrices **A**, **B**, **C** and **D** are vectors of partial derivatives of non-linear functions *f* and *g* with respect to time with appropriate dimensions as shown above. Power system stability performance is determined from the eigenvalues of a square dimensional state matrix **A** together with their corresponding eigenvectors (mode shapes) and participation factors [2, 11, 21]. These eigenvalues are then used in eigenvalue analysis technique –

often referred to as modal analysis – to determine the small-signal stability of a power system [2, 11, 21, 24].

Eigenvalue analysis methods allow one to identify the natural modes of a power system and to identify the damping, frequency and nature (mode shapes and participation factors) for these modes, for a given operating condition. This method is used in small-signal stability analysis without the need to experiment with the actual power system model or to perform time domain simulations.

2.4.1.1. Computation of eigenvalues

The eigenvalues of the state matrix **A** can be computed by solving the characteristic equation (2.7), the roots of which give the poles of state and output of the power system model.

$$\det(A - \lambda I) = 0 \tag{2.7}$$

Where λ are the eigenvalues and **I** is the identity matrix. The identity matrix is a square dimensional matrix with ones on the diagonal and zeros off-diagonal entries. Each eigenvalue of the system takes the form of equation (2.8)

$$\lambda = \sigma \pm j\omega \tag{2.8}$$

Where σ is the real part and ω is the imaginary part. These eigenvalues are either real or complex and they give the dynamic performance of the system as follows:

- Real eigenvalues indicate non-oscillatory modes.
- Complex eigenvalues occur in conjugate pairs for oscillatory modes.
- The real part gives the damping and the imaginary part gives the frequency of oscillation [21, 25].
- The system is stable if all real parts are negative.
- Positive real parts indicate an unstable system.
- The damping ratio (ζ) determines the rate of decay of the amplitude of the oscillations and is given by equation (2.9) below.

$$\zeta = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}} \tag{2.9}$$

The damping ratio is adequate if it is in the range 3 to 5 % where 3 % is too weakly damped while 5 % is weakly damped [21, 29]. The eigenvalues are commonly computed using the QR algorithm. Sparsity techniques are used for large systems [21, 24, 26].

2.4.1.2. Mode shapes and eigenvectors

For every eigenvalue (λ_i) there are corresponding right and left eigenvectors that satisfy the equations (2.10) below.

$$\begin{aligned} A\Phi_i &= \lambda_i \Phi_i \\ \Psi_i A &= \lambda_i \Psi_i \end{aligned} \tag{2.10}$$

for i=1, 2, ..., n

where Φ_i and Ψ_i are the right and left eigenvectors respectively corresponding to eigenvalue λ_i and n is the number of eigenvalues.

The right eigenvector (Φ) describes the activity of the state variables in a mode and is often referred to as a mode shape. The left eigenvector (Ψ) describes the contribution of the activity of a state variable to the mode. Left and right eigenvectors corresponding to different eigenvalues are orthogonal and their product is zero. The product of eigenvectors corresponding to the same eigenvalue is given by (2.11) [2, 21, 24, 29].

$$\Phi_i \Psi_i = C_i \tag{2.11}$$

where C_i is a non-zero constant. This constant is usually normalized so that C_i=1 as given by the function (2.12)

$$C_{ij} = \Phi_i \Psi_j = \begin{cases} 1, & \text{for } i = j \\ 0, & \text{for } i \neq j \end{cases} \tag{2.12}$$

2.4.1.3. Participation factors

Participation factors are the product of the left and right eigenvector components of the selected eigenvalue. They give the relative participation of state variable to a mode given by (2.13) as a measure of observability multiplied by controllability in a power system.

$$P_{ki} = \Phi_{ik}\Psi_{ki} \tag{2.13}$$

where P_{ki} is the participation factor of the selected state variable in a given eigenvalue mode, Ψ_{ki} and Φ_{ik} are the left and right eigenvector components respectively.

Participation factors are dimensionless quantities [24] often normalised to give a total sum of 1.0 (100 %) for all states participating in a given mode. The normalised participation factors are given by equation (2.14) below.

$$\sum P_{ki} = 1 \tag{2.14}$$

for k=1 to n

where n is the number of all states participating in a mode.

2.4.2. Other analysis methods

There are many power system stability analysis techniques such as Routh–Hurwitz (R-H) stability criterion and Transfer Energy Functions (TEF). R-H is necessary to analyse a single-input-single-output system without performing time domain simulations [30]. TEF are closely related to the swing equation and equal-area criterion where the TEF limit is the maximum energy gained from a disturbance in joules [21, 30].

2.5. Summary

Different terminologies used in power system stability were presented followed by the classification of different power system stability and analysis techniques used. Analysis method used depends on the type of power system stability problem to be solved.

Chapter 3:

3. Power System Components Modelling

3.1. Introduction

Power system stability results can only be accurate and reliable if all components are modelled to closely reflect the steady-state and dynamic behaviour of the actual power system. For this reason, it is important to understand different power system components as well as how they are modelled and interconnected. The power system is a complex and by far the largest human-made system on earth with many generators, transmission lines and loads. This makes it highly non-linear and difficult to predict the dynamic behaviour of such a big system due to non-linear components [1, 2, 11, 21].

The overall power system is subdivided into generation, transmission and distribution for bulk load supply. All these power system subsystems contribute to the stability of the power system [21, 23]. Higher load growth continuously forces these systems to operate closer to their stressed limits condition, requiring efficient computer simulation tools for efficient planning, stability analysis, design and control [26].

As complex and big as this system can be; it can be broken down into smaller subsystems whose dynamic characteristics can be easily modelled. Not only does the breaking down of the system into smaller subsystems make it easy to model, but it also makes it easy to study individual generator dynamics in the complex system when interested in local plant modes [1].

This chapter discusses different power system components modelling in power system stability analysis. A generic SMIB model in Fig. 3.1 adopted from [11] will be used to indicate different components applicable to this research. The system is further subdivided into individual components to easily discuss modelling techniques and fundamental characteristics thereof.

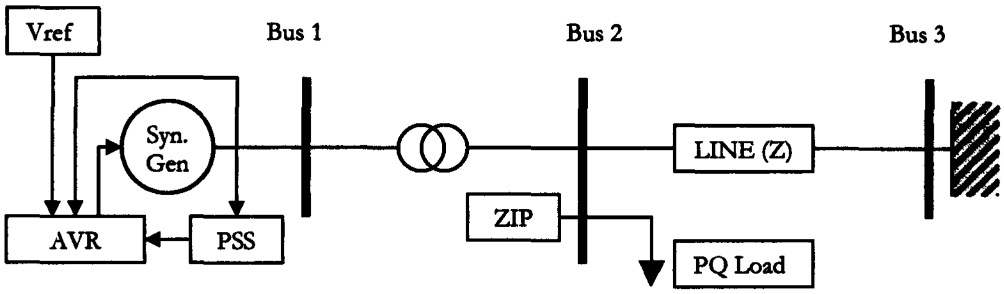


Figure 3.1: SMIB power system

The diagram in Fig. 3.1 has the following power system components applicable to the SMIB and the 2A4M system models chosen for test cases in this research:

- A synchronous generator, excitation system comprised of the automatic voltage regulator (AVR) and the power system stabilizer (PSS).
- Transmission line (Z) and a two-winding transformer.
- Infinite bus.
- Loads: Constant PQ loads and a static non-linear polynomial (ZIP) load models.
- Power system buses (nodes)

The power system is designed to continuously supply the load demand at all times. The electric generation must always match load demand and the losses across the entire transmission system during steady state operating condition [11]. When the power system is subjected to a disturbance, protection systems are required to provide protection functionalities to detect and eliminate minimal number of faulted components to enhance stability and recovery of the power system [31 – 33].

During and after the disturbance, the power system undergoes major oscillations. The excitation systems (AVR and PSS) initiate corrective measures to control the generator terminal voltage as well as damping of the power system oscillations [2, 14, 16, 21].

The transmission system is comprised of transmission lines and transformers that provide the transfer of power from different areas to the loads at different voltage levels for efficient power transfer capabilities [21, 22].

It is evident that the stability of the power system is dependent on different power system components. It is therefore important to accurately model all components. Power system components in Fig. 3.1 will be further discussed in detail to highlight fundamental characteristics important for small-signal stability analysis.

3.1.1. Synchronous generator.

Small-signal stability of a power system is about keeping all interconnected synchronous machines in synchronism [21]. Accurate modelling of the synchronous machine is therefore utmost important for reliable power system stability analysis results.

There are many synchronous machine models in theory and all have advantages and disadvantages in power system stability analysis. The simplest machine models are easy to model and analyse while they do not accurately reflect the dynamics of high order machine models. Detailed higher order machine models on the other hand accurately model generators for the analysis of small-signal stability but it is difficult to get the complete synchronous machine data from the manufacturers. When dealing with higher order machine models, additional complicated tests have to be done in order to acquire synchronous machine reactance, time constants and saturation data [1, 2, 14, 21, 34].

The synchronous machine models range from simplest classical (2^{nd} order) to detailed 8^{th} order machines. The 6^{th} order synchronous machine model is the preferred machine for small-signal stability analysis [2, 11, 14]. The order number indicates the number of states associated with the synchronous generator on the eigensolution.

Synchronous machines are modelled using either operational impedance model or the coupled-circuit model [2, 21]. The coupled-circuit model requires standard parameter data to be specified for direct axis (d-axis) and quadrature axis (q-axis) for the complete synchronous machine model. These models cater for the effects of magnetic saturation that will be discussed further in detail.

The d- and q-axis parameters are easily derived using Park's transformation by transforming phase quantities to dq0 quantities. The transformation is done using the matrix equations given by [16, 21] as follows:

Phase (abc) to dq0 equations

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{3.1}$$

dq0 to abc equations

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 1 \\ \cos(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{2\pi}{3}) & 1 \\ \cos(\theta + \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) & 1 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} \tag{3.2}$$

The equations above are actual values for both balanced and unbalanced systems where:

i_d, i_q and i_0 are the d-axis, q-axis and zero sequence currents respectively.

i_a, i_b and i_c are the phase currents.

θ is the phase angle.

Both equation (3.1) and (3.2) were adopted from [21]

This research covers models of 2nd to 6th order machines. The machine models discussed in this thesis are as follows:

(a) Classical 2nd order machine model

The classical machine is the simplest model used in stability analysis for the first electromechanical swing or when the duration of study is less than T''_{q0} time constant of the generator. The classical machine model is represented by a constant voltage (E') behind transient reactance (X'_d). This machine model simplifies network computations and has less data requirements [1, 21]. There are two states associated with the classical generator model i.e. speed ($\Delta\omega$) and rotor angle ($\Delta\delta$).

The classical machine model is represented by a non-linear differential swing equation for the synchronous generator rotor. The swing equation can be derived and explained using Newton's second law or the "mass-spring analogy" as follows [22, 25, 27]:

$$\begin{aligned} T_m - T_e &= T_a \\ P_a &= \frac{T_a}{\omega} \end{aligned} \tag{3.3}$$

where T_m, T_e, and T_a are mechanical torque, electrical torque and accelerating torque, respectively while ω is the rotor speed. By using the torque and power relationship and assuming the rated synchronous generator angular speed to be 1 per unit, we get (3.4)

$$\begin{aligned} &P_m - P_e = P_a \\ &\frac{2Hd^2\delta}{\omega_B dt^2} = P_m - P_e = P_a \\ &\frac{d\delta}{dt} = \omega_0 \Delta\omega_r \end{aligned} \tag{3.4}$$

Where ω_B is the base angular velocity in radians per second, δ(t) is the rotor angular position in radians, H is the inertia constant representing stored kinetic energy at synchronous speed in seconds (or MW-s/MVA), P_m is the mechanical power of the machine (p.u), P_e is the electrical power output and P_a is the net accelerating or decelerating power in p.u [11, 21, 28].

The equations (3.4) are non-linear and are solved by digital computer simulation tools using integration methods. The swing equation is given by [21] to include the effects of damping coefficient as follows:

$$\begin{aligned} &\frac{d\Delta\omega_r}{dt} = \frac{1}{2H}(\overline{T}_m - \overline{T}_e - K_D \Delta\overline{\omega} r) \\ &\frac{d\delta}{dt} = \omega_0 \Delta\omega_r \end{aligned} \tag{3.5}$$

where K_D is the damping coefficient and ω_r is the angular velocity of the synchronous machine rotor.

(b) Third order model

The third order model was developed as an extension of the classical model to include the effects of field windings. There are three states indicated by $\Delta\omega$, $\Delta\delta$ and Ψ_f, where Ψ_f is the flux linkages in the field windings [14].

(c) Fourth order model

This synchronous machine model is an extension of the 3[rd] order model [10]. It includes the effects of electrical damping by adding a damper winding on the quadrature (q-) axis. It has four states ($\Delta\omega$, $\Delta\delta$, Ψ_f and Ψ_{1q}), where Ψ_{1q} is flux linkages in the damper windings.

(d) Fifth order model

The 5[th] order machine model includes the damper winding in the direct (d-) axis and extends the 3[th] order with two additional states (Ψ_{1q} and Ψ_{1d}) to make the total states five. This machine is believed to be a good representation of a salient pole synchronous machine model in power system stability studies [14, 17, 21, 20, 35].

(e) Sixth order model

A round rotor machine is accurately modelled by a 6[th] order machine model. This model has an additional damper winding in the q-axis to cater for the eddy currents. It has six states represented by $\Delta\omega$, $\Delta\delta$, Ψ_f, Ψ_{1q}, Ψ_{1d} and Ψ_{2q}. This machine model is recommended for power system small-signal stability analysis [1, 2, 21]. Figure 3.2 indicates the coupled circuit (a) direct axis and (b) quadrature axis equivalent circuit for the 6[th] order model [2].

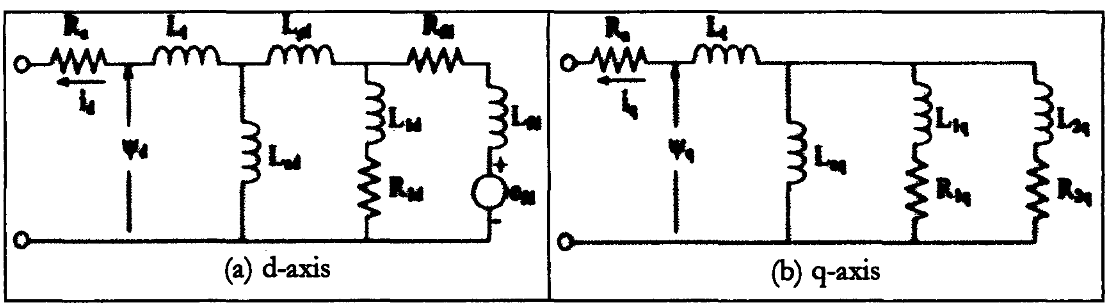


Figure 3.2: d- and q-axis circuits of a 6[th] order synchronous machine

The machine models in Fig. 3.2 (a) and (b) were indicated without the effects of saturation. The open-circuit characteristic curve (OCC) of the terminal voltage versus the field current is used along with the air-gap line to determine the saturation in d-axis for the synchronous machine. According to [2, 14, 17, 21, 20, 36], there are many models used to model machine saturation with no unique generally acceptable methods [4]. These mathematical saturation models are developed following reasonable assumptions.

The diagram in Fig. 3.3 indicates the saturation curves of a generic synchronous machine.

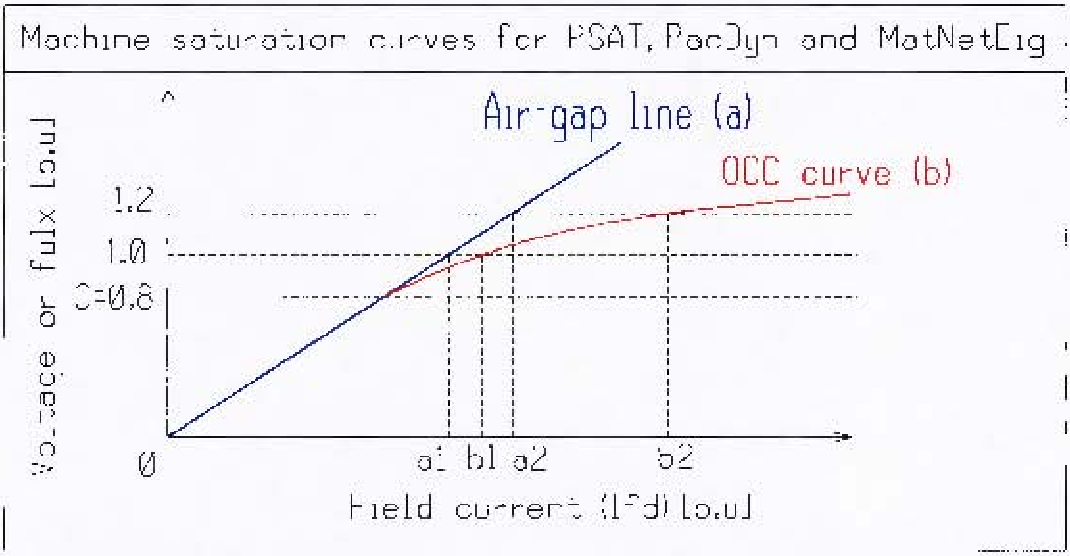


Figure 3.3: Synchronous machine saturation curve

Different authors and power system simulation tools use different saturation models but most common models use the exponential model given by equation (3.6) below:

$$S(\psi) = A_{sat} e^{B_{sat}[\Psi(t) - C]} \tag{3.6}$$

where A_{sat}, B_{sat} and C are the saturation parameters calculated from the OCC and air-gap curves shown in Fig. 3.3. C is normally used as 0.8 indicating the point on the voltage or flux where OCC and Air-gap line starts to split (beginning of the non-linear portion of the OCC line). Ψ(t) is the flux (or the voltage) at any time instant in per unit as follows:

$$\begin{aligned} S_{1.0} &= A_{sat} e^{B_{sat}(1.0-0.8)} \\ S_{1.2} &= A_{sat} e^{B_{sat}(1.2-0.8)} \end{aligned} \tag{3.7}$$

The values of $S_{1.0}$ and $S_{1.2}$ are calculated directly from the curves by taking field current values at points a_1, a_2, b_1 and b_2 as shown on Fig. 3.3 where a_1 and b_1 corresponds to voltage or flux values at 1.0 per unit on the air-gap and OCC lines respectively. Similarly, a_2 and b_2 are current values at 1.2 per unit voltages on the air-gap and OCC curves respectively. The values of $S_{1.0}$ and $S_{1.2}$ are then calculated as follows:

The saturation model defined in [20, 37] is given by equations (3.8).

$$S_{1.0} = \frac{b_1 - a_1}{a_1} = S_1$$
$$S_{1.2} = \frac{b_2 - a_2}{a_2} = S_2 \tag{3.8}$$

where [20] uses the the exponential saturation equation (3.6) with an additional factor Ψ_a-A_{sat} to fit the saturation curve.

Saturation model used in [17] is given by equations (3.9)

$$S_{1.0} = 1 - \frac{a_1}{b_1} = \frac{b_1 - a_1}{b_1}$$
$$S_{1.2} = 1 - \frac{a_2}{b_2} = \frac{b_2 - a_2}{b_2} \tag{3.9}$$

Model described by [2] is defined by equations (3.10)

$$S_{1.0} = \frac{a_1 - b_1}{b_1}$$
$$S_{1.2} = \frac{a_2 - b_2}{b_2} \tag{3.10}$$

Values found using equations (3.8) – (3.10) are then used to solve equation (3.7) simultaneously to get A_{sat} and B_{sat}. It is important to note that different simulation tools require saturation parameters to be specified differently. Some tools require the user to specify $S_{1.0}$ and $S_{1.2}$ while others require A_{sat}, B_{sat} and C. All these values are internally used to model the synchronous machine saturation characteristics using mathematical models used by the respective software tools [17, 20, 35, 37].

The usage requirements and data format specifications for the three simulation tools under comparative study are all discussed in components modelling for PSAT, MatNetEig and PacDyn in chapters 4, 5 and 6 respectively. These models are all different, *more detailed discussion and mathematical models of saturation used in these tools have been covered in appendix C*. The variations in mathematical saturation models used resulted in differences in numerical simulation results [2, 17, 20, 35], as shown in chapter 8.

3.1.2. AVR excitation system.

There are many types of automatic voltage regulation (AVR) excitation system models developed over the years. These include rotating DC, rotating AC and static thyristor AVR exciters in literature [2, 14, 17, 21, 20, 35]. The main function of all these AVR excitation systems is to provide direct current (dc) field voltage to control the generator terminal voltage [2, 14, 16, 21]. AVR models developed by IEEE are the most commonly used in power system studies and these include IEEE type-1 and IEEE type-2 exciter models. Although other exciter models exist and should be used, the IEEE models are mostly used due to simplicity and availability of data [21].

3.1.3. Power system stabilizer.

Power system stabilizers (PSS) are used to damp power system oscillations. They enhance the stability of a power system following a disturbance. The PSS uses auxiliary signals such as speed, frequency and voltage to improve the oscillatory behaviour of the power system [9, 11, 21]. The generic power system stabilizer block diagram below is used to explain functionalities of different components of a PSS.

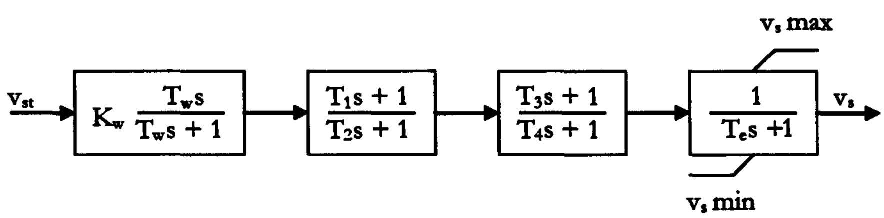


Figure 3.4: Generic power system stabilizer block diagram

Fig. 3.4 shows fundamental building blocks of a power system stabilizer as follows:

1. Gain and washout circuits: Used to filter the DC offset of the input signal and to provide right amount of damping required.

2. Lead-lag circuit*: Phase compensation to provide phase lead to the phase lag.

Note: * *The lead-lag circuit (2) can be one or two depending on the angle to be compensated for tuning the PSS to stabilise the synchronous generator.*

3.1.4. AC transmission lines.

AC transmission lines can be modelled using different models such as the short line model, medium line and long line model [22, 23, 26]. However, in this research work transmission lines have been modelled using a lumped-circuit equivalent π–circuit model for the analysis of voltages and currents at both ends of the lines [5, 22]. Transmission lines are generally represented by the "two port network" shown in Fig. 3.5. This shows the relationships between sending end voltages and currents with the receiving end voltages and currents [11, 22]

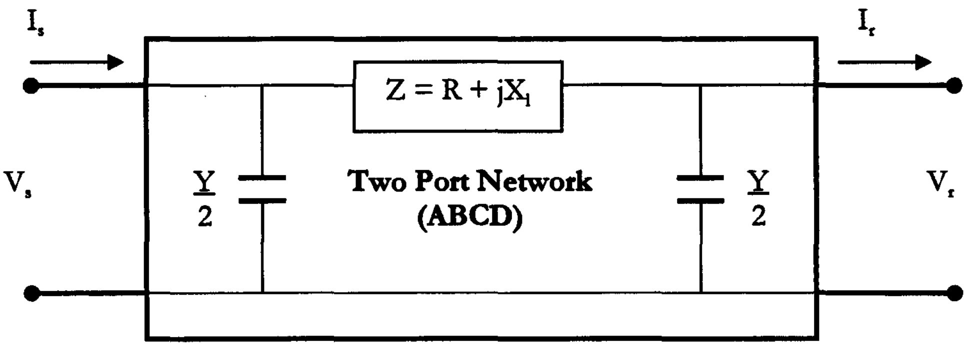


Figure 3.5: Equivalent π-circuit transmission line (two port network)

The diagram in Fig. 3.5 is the equivalent π-circuit of the transmission line with the following network components:

V_s and I_s are the sending end voltage and current.
V_r and I_r are the receiving end voltage and current.
$Z = R + jX_L$ is the series impedance of the line, per unit length.
Y is the shunt admittance of the line.

The impedance and admittance of the line are commonly represented by parameters A, B, C and D. The equivalent π-circuit (short line) model is used to model AC transmission line impedances of the transmission lines in all three simulation tools compared in this research [22, 23].

3.1.5. Two-winding transformer.

A transformer is used in transmission systems for the utilisation of different voltage levels and to enhance power transfer capability [11, 21, 22, 43]. A model used is an equivalent π–circuit transmission line with an "ideal transformer" represented by fixed or variable turns ratio (a:1) and both series reactance and shunt reactance given by "Ze" shown in Fig. 3.6 below [21, 38].

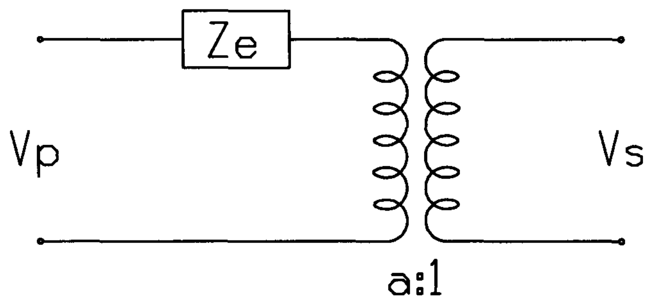


Figure 3.6: Ideal two-winding transformer

The diagram in Fig. 3.6 shows an ideal two-winding transformer with the following circuit components:

V_p and V_s are the primary and secondary voltages respectively.
a is the transformer voltage turns ratio.
Z_e is the transformer impedance normally modelled using an equivalent π-circuit.

3.1.6. Bus classifications.

A power system bus or node is a virtual point on the network where different power system components can be connected. There are different types of buses based on the components connected. Each bus has a total of four variables (i.e. real power, reactive power, magnitude of bus voltage and phase angle). Bus classification depends on the both the known and unknown variables prior to load flow solution [11, 18, 21 – 23].

(a) Swing bus
(b) PV or voltage controlled bus
(c) Load or PQ bus

The detailed discussion of bus classifications is covered in the Appendix.

3.1.7. Infinite bus.

In power system stability analysis terms, an infinite bus is a voltage source with constant voltage magnitude, phase angle and frequency. This represents the part of the power system relatively large enough not to be affected by the faults on the system. This bus also represents a big generator far from the point of fault (disturbance) [2, 21].

Different simulation tools use different methods in modelling an infinite bus. Some tools use a voltage source with constant voltage magnitude and phase angle while others use a classical machine resulting in additional redundant states [17, 20, 35]. The use of an infinite bus or a reference bus in stability analysis removes redundant states [19, 21].

3.1.8. Power system loads.

At any given instant, the power system generation must match the load demand and losses. With the high economic and industrial growth, the load demand increases and forces the power system to continuously operate close to the power system stability margin. It is important to understand the dynamics of the loads to accurately model all loads for power system stability analysis [1, 2, 11, 16, 21].

There are many types of electric power system loads but these are all classified in two main broad categories. These are static loads and dynamic loads. Static load models have algebraic functions of bus voltage magnitudes and frequency at any instant [2, 21].

It is important to note that is not always easy in the real life to know the exact representations of the load and in some system the load can have mixed characteristics of both dynamic and static loads [1, 16, 21].

Dynamic load models vary rapidly with changing voltage and frequency and they are given by algebraic functions of bus voltage magnitudes and frequency deviations dependent on the past instant [1, 2, 21]. Dynamic load models will not be discussed in detail as they are not used on any model in this thesis.

Static load models in power systems have different forms but only the exponential and polynomial load models are discussed in this thesis.

(a) Exponential load models

These load models have either constant power or constant current or constant impedance load characteristics. The exponential function defining the real and reactive power components are given by equations (3.11)

$$P = P_0\left(\frac{V}{V_0}\right)^a \qquad Q = Q_0\left(\frac{V}{V_0}\right)^b \tag{3.11}$$

where a and b are the exponents for the real and reactive power components of the load as follows: When the value of a (or b) is 0, 1 or 2: Then P (or Q) is constant power, constant current or constant impedance respectively.

The exponential load model above requires initial real and reactive power components (P_0 and Q_0) at the initial operating condition with bus voltages V_0 where subscript "0" denotes the initial condition.

(b) Polynomial load models (ZIP)

Static load can also be modelled using polynomial load models with algebraic functions of bus voltage magnitudes. These loads are also referred to as ZIP loads due to the components constant impedance (Z), constant current (I) and constant power (P) adding up to the overall load. Equation (3.12) below shows ZIP load models for real and reactive power components:

$$P = P_0[p_1(\overline{V}^2) + p_2(\overline{V}) + p_3] \qquad Q = Q_0[q_1(\overline{V}^2) + q_2(\overline{V}) + q_3] \tag{3.12}$$

where p_1, p_2 and p_3 are portions of constant impedance, constant current and constant power on the real component of the load (P); q_1, q_2 and q_3 are portions of constant impedance, constant current and constant power on the reactive component of the load (Q) and $\overline{V}$ is V/V_0 as described in the exponential load model.

The portion Z, I or P can be in percentage (%) or in per unit (fraction) depending on the simulation tool. Both q_1, q_2 and q_3 must add up to unity (for per unit) or 100 in %. Similarly the components p_1, p_2 and p_3 must add up to 100 %.

The exponential and polynomial load models discussed so far do not have frequency dependency. The frequency dependency of these loads are included by multiplying the first equation of (3.11) and (3.12) by an additional factor $(1+K_{fp}\Delta f)$ for real power component and by multiplying the second equation (3.11) and (3.12) by $(1+K_{fq}\Delta f)$ for reactive power component. This result in (3.13) and (3.14) below for exponential and ZIP load models respectively:

$$P = P_0\left(\frac{V}{V_0}\right)^a (1+K_{fp}\Delta f)$$
$$Q = Q_0\left(\frac{V}{V_0}\right)^b (1+K_{fq}\Delta f) \qquad (3.13)$$

$$P = P_0[p_1(\overline{V}^2)+p_2(\overline{V})+p_3](1+K_{fp}\Delta f)$$
$$Q = Q_0[q_1(\overline{V}^2)+q_2(\overline{V})+q_3](1+K_{fq}\Delta f) \qquad (3.14)$$

Where K_{fp} and K_{fq} are the active and reactive power frequency dependency constants respectively and Δf is the frequency deviation.

Equations (3.13) and (3.14) assume both the voltage and frequency dependency of the load as used by various power system simulation tools. Analysis of the three simulation tools used in this research indicated that all tools can model both exponential and polynomial load models. The effects of ZIP load models have been investigated and the findings were given in the discussion of the results in chapter 8.

3.2. Summary of components modelling.

This chapter highlighted power system component modelling techniques commended by different authors in the literature. These components include synchronous machines, excitation systems, transmission lines, two-winding transformers, infinite bus and load models. Different bus classifications were discussed and mathematical expressions for static load models were shown.

The three simulation tools investigated use different saturation models on synchronous machines. More specific details and usage formats for PSAT, PacDyn and MatNetEig will be discussed in chapters 4, 5 and 6 as used in small-signal stability analysis.

Chapter 4:

4. Features And Capabilities Of PSAT 2.1.2 Simulation Tool

4.1. Power System Analysis Toolbox (PSAT 2.1.2)

PSAT [17] is free open source Matlab based power system simulation package designed for the analysis of both steady state and dynamic simulations. It has the following routines used for power system analysis: Power flow, continuation power flow, optimal power flow, small-signal stability analysis, time domain simulations and phasor measurement unit (PMU) placement. It has documentation and quick reference manuals that offer users support and tutorials with network data files for examples. PSAT tool has an online discussion forum with over 7038 problem discussions messeges, challenges and suggested solutions with 1835 registered members up-to-date [34].

The load flow routine requires bus, line, slack generator, PV generators, constant power loads, FACTS devices and shunt admittances data in either Simulink PSAT library single lines or Matlab (PSAT m-file) data format. Dynamic simulations require additional dynamic components data defined by: Synchronous machine models, control system (AVR excitation, PSS, Turbine governors, etc), dynamic load models, faults, breakers and many other components not to be covered in this thesis. Data can also be imported from various standard data formats (i.e. CEPEL ANARADE, Chapman, Cyme, DIgSILENT PowerFactory, EPRI, Eurostag, Flowdemo, IEEE common format, Matpower, Neplan, Pcflo, PSS/E, PST2, PowerWorld, Simpow, VST and many other data formats) [17, 35].

The tool has data format conversion (DFC) modules used to convert supported data file formats to and from PSAT data format. The DFC promotes users to enhance research capabilities. The section on component modelling describes how each component is used and applicable mandatory data fields when using PSAT 2.1.2 data format.

Load flow is performed by making use of standard Newton-Raphson (NR), fast decoupled (BX and XB), Runge-Kutta, Lwamoto and simple robust method [17]. In this thesis, NR method is used for all load flow simulations. Load flow solution is an entry point for stability studies where dynamic components are initialised.

After a successful load flow simulation, dynamic network analyses are performed using analytical Jacobian matrices and Matlab's sparse algorithms to compute eigenvalues for small-signal stability (modal) analysis and time domain simulations. Integration methods used in time domain simulations are Trapezoidal rule and Forward Euler [17]. For more details on these methods, see [21, 26, 28]. PSAT allows users to model disturbances in the form of perturbation files or via the command line usage directly after load flow convergence. Faults and breakers are used extensively to model and simulate disturbances. This research covers modal analysis and time domain simulations for small-signal stability studies as well as the visualisation of eigenvalues and participation factors of the power system model.

PSAT 2.1.2 has a wide variety of output formats that can be set or used for analysis, viewing and presentation of simulation results. Results are mainly provided and accessible from the main graphical user interface (GUI) in both text and graphical formats. All results can be exported and saved in formats such as plain text, Excel, LATEX, html, Matlab scripts, Windows metafiles, colour EPS plot files and many other data formats. PSAT allows access to all internal variables via the Matlab work space.

Static and time domain simulation results are logged in a Command History log and this history log can be exported and saved in plain text ASCII file format. Small-signal stability analysis results (eigenvalues) can be viewed in graphical plots (Z-map and S-map), text and they can be exported to other file formats. When using Simulink network data formats, it is possible to view load flow results on the network single line diagram.

General program settings can be modified via the GUI settings options and can also be specified together with network related settings in the network model data file. All general program settings can also be set via the settings file (**Settings.m**) located under the PSAT root directory folder. Base and tolerance settings can be changed or set on the main program window (i.e. base MVA, frequency, start time, end time, maximum number of iterations, power flow tolerance and dynamic tolerance). Settings on the network data file has precedence and always overwrites the settings specified on the main GUI window when performing load flow and time domain simulations.

The following is PSAT graphical user interface showing the main window and all default settings, toolbars and program buttons.

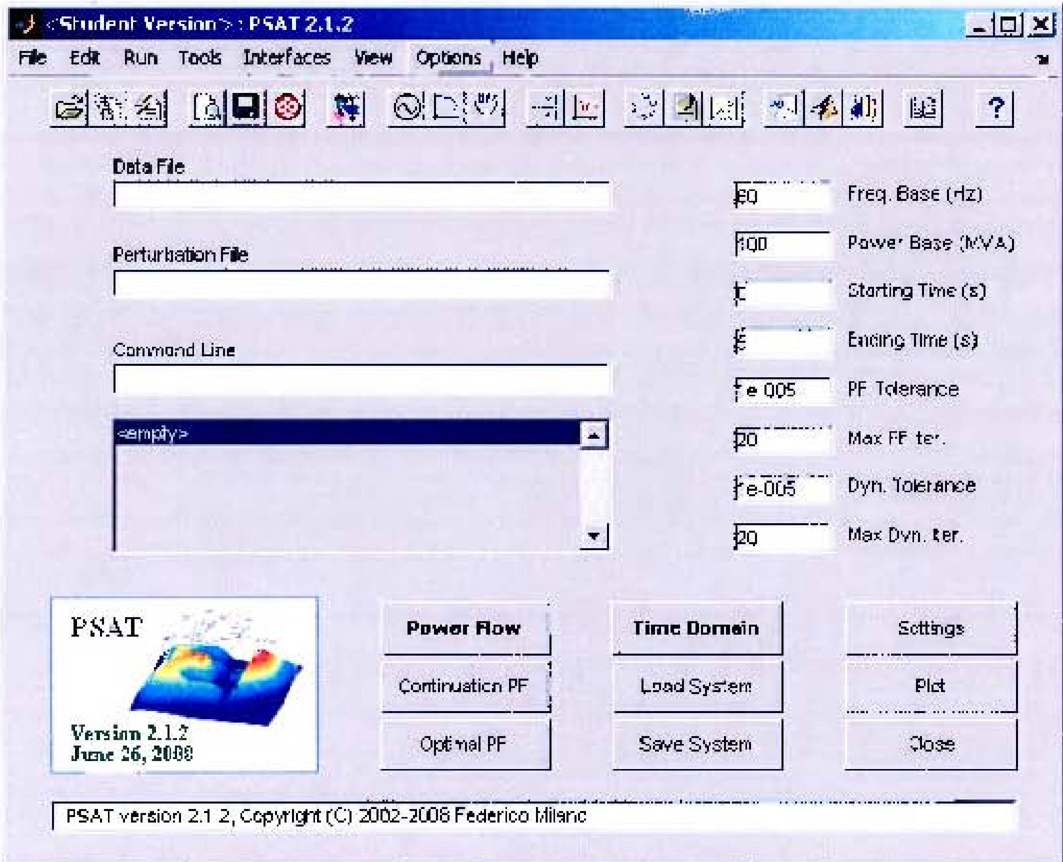


Figure 4.1 PSAT 2.1.2 main window (GUI)

The diagram in Fig. 4.1 above shows how PSAT interfaces with input data in various data formats, external interface (GAMS and UWPflow) and how output results are handled by the simulation tool. All power system analyses require load flow simulation to be performed prior to any other simulation. Advanced plotting utilities are available in Matlab graphical plots and this can be exported to many other formats.

4.2. Component modelling in PSAT 2.1.2

This section covers network component models used in PSAT data format. For simplicity, only those components used in the chosen power system models are discussed. Component names used in PSAT 2.1.2 (Matlab's m-file) data format are indicated in bold case. Perturbation files were used to model disturbances, but they will not be discussed here as there is no specific format. Good programming skills and reference to user manual is advised when using perturbation files. Table 4.1 below shows component models and data formats used in PSAT simulation tool [17].

Table 4.1: PSAT 2.1.2 components and data formats

Component Model	**PSAT 2.1.2**
Bus	PSAT 2.1.2 models a bus using **Bus.con** in matrix vector form. Mandatory fields are: [Bus_number nominal voltage in kV Voltage(p.u) angle(δ rad)]. The bus should have a corresponding vector **Bus.names** with bus names specified. i.e. Bus.names = {'Bus1';'Bus2';...};
Transmission line	Power system lines (AC) are modelled using **Line.con** in row vector matrix form per line. The required fields for the line using nominal π-circuit model are: [FromBus# ToBus# MVA kV Freq length* 0.0** R X B] Where Freq is the power system frequency, MVA is the system MVA base. This MVA base can also be set in the command line using **Settinngs.mva**=value; Note: *length is specified in km while R, X and B in per unit on the system base. ** Since R, X and B are in per unit, the line length does not have effect on the line model. Therefore, the value 0.0 is inserted.
Transformer	**Line.con** described above for lines is also used to model transformers, the following data fields are mandatory when **Line.con** is used for a transformer data: [FromBus# ToBus# MVA kV Freq **0.0 V_ratio** R* X* **0.0***] Note: * R and X are in per unit on the transformer ratings, 0.0 denotes values that are not applicable in a two-winding transformer.

Synchronous Machine	PSAT has 8 synchronous machine models ranging from second order classical to detailed 8th order model as follows: Classical model (II), 3rd order (III), 4th order (IV), 5th order (V.I), 5th order (V.II), 5th order (V.III), 6th order (VI) and 8th order (VIII). The order indicates the number of states associated with the synchronous generator. The 8th order model will not be used in this thesis and therefore not discussed.

The machine data is implemented in a row vector matrix data in **Syn.con** where each row represents a synchronous machine model using the following data format with 26 columns:

[Bus# MVA kV F(HZ) Model# Xl Ra Xd X'd X"d T'd0 T"d0 Xq X'q X"q T'q0 T"q0 M(2H) D Kw Kp rP rQ Taa S1.0 S1.2]

The data "Kw Kp rP rQ Taa S1.0 S1.2 " are optional and can only be included if modelling of machine saturation is required. Valid model numbers (Model#) are 2, 3, 4, 5.1, 5.2, 5.3, 6 and 8. All generator data are included depending on the machine type as defined in the user manual. Data not required should be set to 0.0.

There are three 5th order models indicated by 5.1, 5.2 and 5.3. They all have five states each. Machne model 5.1 assumes $x'_d = x''_d = x''_q$. Model 5.2 assumes only one additional circuit on the d-axis while model 5.3 considers the effects of speed variation on tyhe flux linkages [17]. Table 4.2 shows machine time constants and reactance applicable to different models of the synchronous machines.

Table 4.2: synchronous machine time constants and reactance.

Order	T'_{d0}	T'_{q0}	T''_{d0}	T''_{q0}	x_d	x'_d	x''_d	x_q	x'_q	x''_q
II						√				
III	√				√	√		√		
IV	√	√			√	√		√	√	
V.1	√	√		√	√	√		√	√	
V.2	√		√	√	√	√	√	√		√
V.3	√				√	√		√		
VI	√	√	√	√	√	√	√	√	√	√
VIII	√	√	√	√	√	√	√	√	√	√

	The user manual must be checked and used for other assumptions. The synchronous machine saturation is modelled by parameter data S1.0 and S1.2 in the **Syn.con** data given by S1.0=1-(a_1/b_1) and S1.2=1-(a_2/b_2). The saturation factors S1.0 and S1.2 are internally used to calculate A and B constants. The Saturation model used is the exponential model with I (eq') = $A.e^{B\,(eq' - C)}$ where C is internally fixed to 0.8 in the program code. The parameters a_1, a_2, b_1 and b_2 are taken from the air-gap/open circuit saturation curve as indicated in chapter 3.
Infinite Bus	The infinite bus is referred to as a "Slack generator" in PSAT. Each network model should have at least one slack generator but only one slack bus per network model can be selected as a reference node. Slack generators are modelled as "V θ" buses with constant voltage magnitude and phase angle as reference in small-signal stability. PSAT uses **SW.con** with each row vector representing a slack generator. The following structure shows mandatory data fields: [Bus# MVA kV V(p.u) V_angle(rad)] Optional data are the reactive power and voltage limits on the bus(es).
PV / PQ bus	Both PV bus and PQ generator bus models are available in PSAT in the variables named **PV.con** and **PQgen.con** for PV bus and PQ generator respectively. These data are specified to be used in load flow simulations before the initialisation of dynamic components, refere to data files in the appendix for usage. Case studies conducted in [18] revealed that the PV bus model has better convergence characteristics than the PQ generator bus model in terms of speed and accuracy.

	The following mandatory data formats are used on PV bus and PQ generator bus respectively: PV.con = [Bus# MVA kV V(p.u) Pg0(p.u)] PQgen.con = [Bus# MVA kV Pg0(p.u) Qg0(p.u)] Notes: PV bus has both reactive power and voltage limits as optional data while PQ generator has voltage limits on the optional data. For all small-signal stability cases in this thesis, a PV bus was used.
AVR Exciter	PSAT has three automatic voltage regulator (AVR) excitation types. AVR Type I is a standard Italian regulator (ENEL), AVR Type II is the standard IEEE model 1 and AVR Type III is the simplest AVR model used for "rough" stability analyses [34, 35]. AVRs are modelled to define primary voltage regulation of synchronous machines. The block diagrams of type I and II AVR are included in the appendix. All AVR exciters are modelled in a row vector format under the name **Exc.con** with the following distinctive structures where 0.0 indicate values that are not required for these AVR types respectively: AVR Type I [Gen# 1 V_{r_Max} V_{r_Min} u_0 T_1 T_2 T_3 T_4 T_e T_r A_e B_e status] AVR Type II [Gen# 2 V_{r_Max} V_{r_Min} K_a T_a K_f T_f 0.0 T_e T_r A_e B_e status] AVR Type III [Gen# 3 V_{f_Max} V_{f_Min} u_0 T_2 T_1 V_{f0} V_0 T_e T_r 0.0 0.0 status] where: A_e and B_e are the saturation coefficients, status (1 or 0) is used to set the AVR as either connected or not connected. Both A_e and B_e are not used in this thesis. The differences in these three AVR types can be seen on the required data as well as on the block diagrams.

<table>
<tr><td></td><td>

These three AVR types can all be used in one power system model with the exception that only one AVR is required per synchronous machine. AVR type III is the one that have been used in this thesis.

The diagram in Fig. 4.2 shows a type III AVR system. Refer to the appendix and the user manual for type I and II AVR block diagrams.

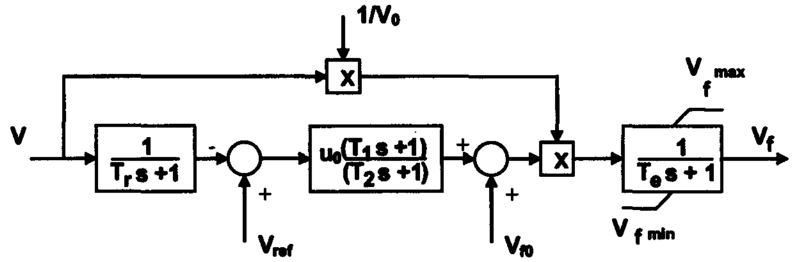


Figure 4.2 Type III AVR block diagram

Major restrictions are that some parameter data can not be set to zero (0.0) on these AVR models. It is not possible to minimally reduce the above model by setting other time constants to zero.

</td></tr>
<tr><td>

PSS

</td><td>

PSAT has five different types of power system stabilizers (PSS). Each PSS type supports three types of input signals (i.e. rotor speed ω, active power Pg and bus voltage magnitude Vg of the generator to which the PSS is connected through the AVR). The PSS output signal is the state variable V_{pss} that modifies AVR reference voltage (V_{ref}).

PSS data is modelled in row vector data format in a Vector named **PSS.con** with the following structure applicable to all PSS types:
[AVR# PSS_Model# PSS_sig V_{sMax} V_{sMin} K_w T_w T_1 T_2 T_3 T_4 ... K_a T_a K_p kV V_{a*Max} V_{a*Min} V_{s*Max} V_{s*Min} $e_{\_thr}$ $w_{\_thr}$ s_2 status]

PSS_Model# is the model number (1, 2, 3, 4 or 5) specifying the type of PSS model to use. PSS_sig indicates the input signal type as follows {1: Speed input, 2: Power input and 3: Voltage input}. Types 4 and 5 are similar to 1 and 2 respectively and checks for both the threshold voltage ($e_{\_thr}$) and speed threshold ($w_{\_thr}$) signals status.

</td></tr>
</table>

<table>
<tr><td></td><td>Power system stabilizers can not be used with 2nd order (II) generators. Algebraic modelling of the PSS does not allow some parameter data to be set to zero (0.0). For the purpose of this research, PSS type 1 with a speed input signal was used.

The block diagram in Fig. 4.3 below shows a PSS type II system; refer to the user manual for type 1, 3, 4 and 5 block diagrams.

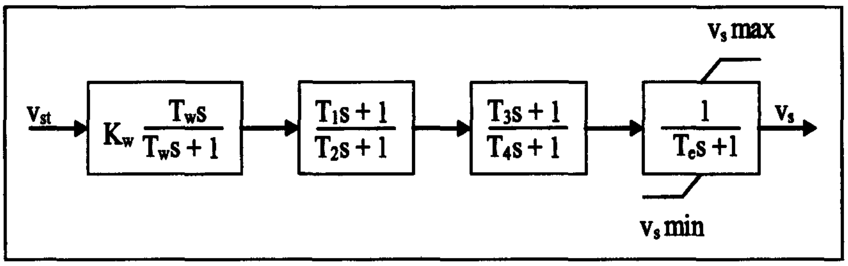


Figure 4.3 Type 2 PSS block diagram
The PSS block diagram in Figure 4.3 can be reduced by setting some of the parameter data to 0.0 if required (i.e. T_3 and/or T_e). The restriction is that T_4 can not be set to 0.0.</td></tr>
<tr><td>Load (1):
PQ Load</td><td>PQ loads are modelled using PQ.con in a row vector format and the mandatory data fields are structured as follows:
[Bus# MVA kV P_L(p.u) Q_L(p.u)]

Note: P_L and Q_L are in per unit on the system MVA and bus voltage kV ratings. Negative P_L and Q_L values can be used for excess power.

Optional data include voltage limits to be set to the bus where individual loads are connected and also allows for the conversion from PQ to impedance if the load flow solution is likely not to be reached within specified tolerance and/or number of iterations [17, 18].</td></tr>
<tr><td>Load (2):
Static non-linear Loads</td><td>PSAT has the following static-nonlinear load models: voltage dependent loads (VDL), ZIP loads, frequency dependent loads, exponential recovery loads, thermostatically controlled loads, Jimma</td></tr>
</table>

and mixed loads. All these load types are function of the bus voltage magnitudes. The use of VDL and ZIP loads (**Mn.con**) and their formats will be discussed. Only the results found when using ZIP loads (**Pl.con**) are presented.

Voltage dependent loads (VDL) are the exponential load models with the name **Mn.con** to model the load. Equations (4.1) represent the real and reactive power components of the load as monomial exponential power of the bus voltage magnitudes:

$$\begin{aligned} P &= P_0(|V|)^{\alpha p} \\ Q &= Q_0(|V|)^{\alpha q} \end{aligned} \tag{4.1}$$

where αp, αq = (0, 1, 2) for constant power, constant current and constant impedance respectively, V is the bus voltage magnitude (p.u).

The format for a VDL load (**Mn.con**) is as follows:

[Bus# MVA kV P_0 Q_0 αp αq z status]

where P_0: Active power rating % (p.u)
Q_0: Reactive power rating % (p.u)
αp: Active power exponent (0, 1, 2)
αq: Reactive power exponent (0, 1, 2)
z: {0/1, 1: Initialise after power flow}
status: {0/1, 1: Connected}

ZIP loads are modelled in PSAT using polynomial functions of bus voltages as **Pl.con**. These load models have components of the impedance (Z), current (I) and power (P), hence the name (ZIP). They have a quadratic expression of bus voltages follows:

$$P = g(\frac{V}{V_0})^2 + Ip(\frac{V}{V_0}) + Pn$$
$$Q = b(\frac{V}{V_0})^2 + Iq(\frac{V}{V_0}) + Qn \qquad (4.2)$$

Where V_0 is the initial voltage at the load bus as obtained by the power flow solution and V is the magnitude of the bus voltage in per unit.

ZIP loads can also be included directly in the power flow analysis with the following equations used when the initial voltage is not known.

$$P = g(V^2) + I_p(V) + P_n$$
$$Q = b(V^2) + I_q(V) + Q_n \qquad (4.3)$$

ZIP load models require a PQ load as modelled in Load (1) and the additional parameter data as defined in **Pl.con** below models the ZIP load as a percentages of the this PQ load.

[Bus# MVA kV F(HZ) g I_p P_n b I_q Q_n z status]

Where:

g: Conductance % (p.u) → constant impedance part
I_p: Active current % (p.u) → constant current part
$P_n(Q_n)$: Active(reactive) power % (p.u) → constant power
b: Susceptance % (p.u) → constant impedance part
I_q: Reactive current % (p.u) → constant current part
$z\{1/0\}$: Initialize after power flow
Status$\{1/0\}$: Connection status.

The exponential voltage dependent load (VDL) and polynomial (ZIP) load models can be modelled with frequency dependency in PSAT. The additional factors ($1+K_{pf}\Delta f$) for active power component and ($1+K_{qf}\Delta f$) for reactive power component are used. The frequency dependency of the load is accounted for by the change in frequency

	(Δf). Load frequency dependence was not modelled in this research.
Fault	PSAT is capable of simulating faults on the bus as specified on the **Fault.con** row vector matrix for balanced 3 phase faults. The fault data format is as follows: [Bus# MVA kV F(HZ) tf(s) tc(s) fR(p.u) fX(p.u)] where tf: Fault time (sec) tc : Fault clearance time (sec) fR: Fault resistance (p.u) on system base. fX: Fault reactance (p.u) on system base.
Breaker	Breakers in PSAT are modelled by using a variable name **Breaker.con** with the following data format: [Line# Bus# MVA kV F(HZ) status t_1 t_2] where: status {breaker initial state, 1: Closed, 0: Open} t_1: First intervention time (sec) t_2: Second intervention time (sec). Note: breaker operation interventions at t1 and t2 depend on initial state of the breaker (i.e. whether to open or close at these time instances). The breakers are all 3 pole breakers and operate on all phases simultaneously.
Disturbance	In addition to faults and breakers, PSAT uses **perturbation files** to model power system disturbances. The perturbation disturbances require knowledge of programming as well as an in-depth knowledge of internal input and output variable names. Disturbances modelled can include – but not limited to – changes in loads, generation, reference voltages, rotor speed, mechanical power input and others. Perturbation files with disturbance were used in the research but their usage is not described in details in this thesis.

4.3. PSAT components summary in small-signal stability analysis

Table 4.3 below shows a summary of component models as used in PSAT 2.1.2. This table can be used as a quick reference manual when modelling a power system for small-signal stability studies in PSAT 2.1.2 simulation tool.

Table 4.3 Summary of PSAT 2.1.2 Power system components model names

Component	Component description	PSAT model Name
Steady state components	Bus	**Bus.con**
	Bus names	**Bus.names**
	Line/transformer	**Line.con**
	Slack generator	**SW.con**
	PV bus	**PV.con**
	PQ generator	**PQgen.con**
	PQ load	**PQ.con**
	MVA Base	**Settings.mva**
Dynamic stability components	Synchronous generator	**Syn.con**
	Infinite bus / Slack generator	**SW.con**
	AVR excitation controller	**Exc.con**
	Power system stabilizer	**PSS.con**
	Voltage dependent load (exponential)	**Mn.con**
	ZIP load	**Pl.con**
	Fault	**Fault.con**
	Breaker	**Breaker.con**
	Disturbances (Generic)	**Perturbation files**

4.4. Summary

This chapter highlighted power system components and modelling techniques used in PSAT 2.1.2. PSAT has a wide variety of input data support and data conversion capabilities. It has advanced text and graphical plotting utilities for results viewing and analysis. Although the scope did not cover all component models, all static and dynamic components used in the selected power system models in this thesis were investigated and their usage requirements in small-signal stability analysis were explained.

All eight different types of synchronous machines ranging from classical 2nd order to detailed 8th order models were discussed. It was indicated that PSAT has three built-in AVR excitation types and five PSS types. All PSS types have three input signal types. PSAT 2.1.2 has a wide variety of static non-linear load models including voltage dependent loads and ZIP load models. PSAT supports dynamic load models such as thermostatically controlled loads; these load models are not covered in this thesis and therefore not discussed in detail. Fault data and breaker operation data structures and usage in time domain simulations were also indicated. In addition to faults and breaker operations, user defined disturbances can be modelled in perturbation files.

PSAT has well documented user manuals, quick reference manual and an up-to-date online discussion forum.

Chapter 5:

5. Features And Capabilities Of Matneteig Simulation Tool

5.1. MatNetEig

MatNetEig (version 1) is a comprehensive small-signal stability analysis tool. It has MatNetFlow as a power flow program for load flow simulations. This software tool is an open source Matlab based simulation tool and uses a class object called "**net_c**" for the complete network model structure. Matlab's vectorized and sparsity techniques are used for optimised memory and high processing speed. MatNetEig can only perform load flow and small-signal stability analysis. Small-signal stability analysis is done using modal analysis and small-disturbance simulations where small disturbance can be done using step response time domain and frequency response simulations. The simulation tool and corresponding documentations are available free from the owner [39].

MatNetFlow is specifically used for load flow simulations and can be called in Matlab command line or via the graphical user interface (GUI) by calling "**netview**" on Matlab's command prompt. Newton-Raphson is the only method used for load flow computations in MatNetEig. Data formats supported are Power system toolbox V2 (PST2), PSS/E (PTI26) and IEEE common format [20]. The PST2 data required for load flow are the bus and line specification matrices in m-file formats. MatNetEig cannot support single line diagrams.

The load flow engine "**netflow**" is called prior to the dynamic analysis to get a steady state solution prior to the initialisation of all dynamic components. Dynamic simulations are done via the customised GUI as well as on the Matlab command prompt using special MatNetEig commands. The small-signal stability analysis GUI is initialised and activated by typing the command "**SSView**" on Matlab command prompt

MatNetEig has graphical plots and Matlab output text results presentation formats. The netview GUI gives access to results, plots and functions. This GUI can be used when adding, deleting or modifying the power system components or models. Solved load flow cases can be exported and saved in Matlab (.mat) file, PSS/E PTI26 or IEEE common file formats. Small-signal stability analysis results provided via the GUI are eigenvalues, oscillatory frequencies and damping ratios. Additional results associated with each eigenvalue are the eigenvectors, participation factors, state numbers and state names. The eigensolution results mentioned above are calculated using the Implicitly Restarted Arnoldi method (IRAM). Frequency response results can be visualised in either linear or logarithmic (bode diagrams) plot types.

Figure 5.1 below shows the main SSSA GUI window through which load flow and small-signal stability analysis can be done in MatNetEig tool.

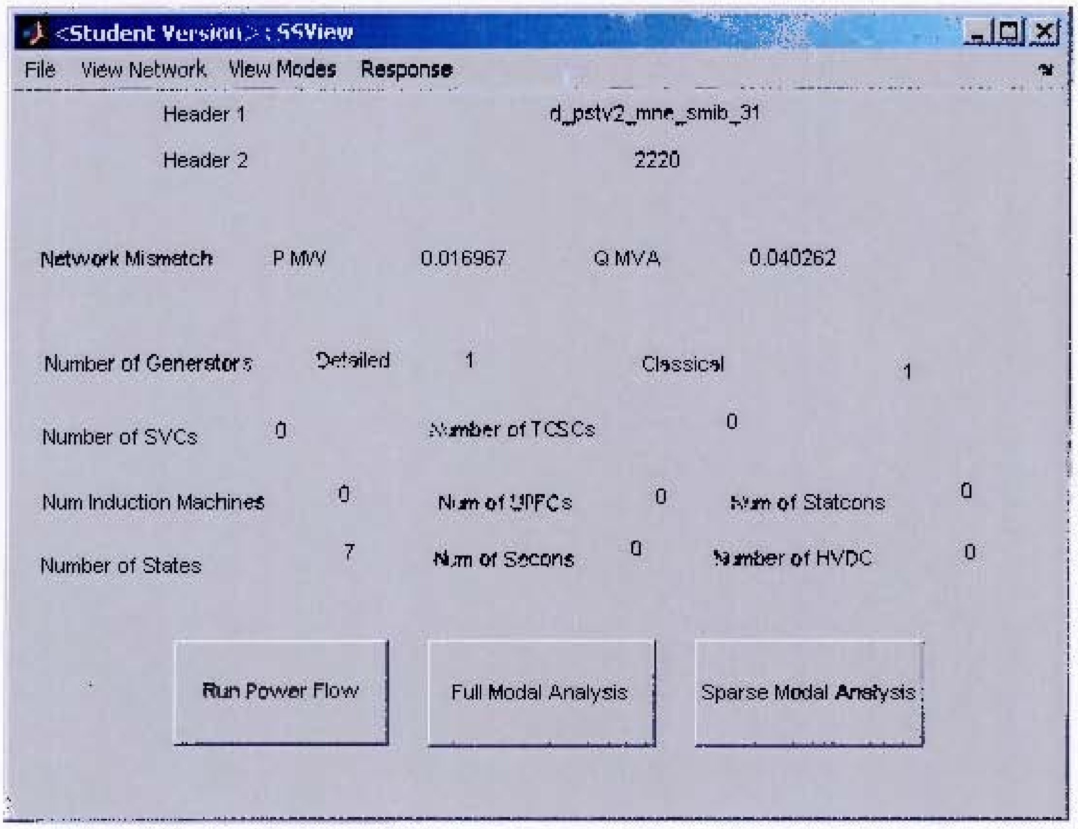


Figure 5.1 MatNetEig small-signal stability graphical user interface

Figure 5.1 indicates the main SSSA GUI window. Unlike PSAT 2.1.2, MatNetEig simulation tool's GUI is not well developed. It is small and relatively easy to use, the GUI menus and buttons provide access to most functionality and the simulation results supported by this tool.

MatNetEig's command-line usage provides unlimited access to all functionalities and results. Command-line usage requires good Matlab programming skills and learning this is time consuming. Plain text and Matlab's graphical plotting utilities are the main forms of output results when in command line usage.

The flowchart in Fig. 5.2 shows how net_c object is formed from input data file. A successful net_c object with a converged load flow solution is then used as an entry level for all small-signal stability analysis.

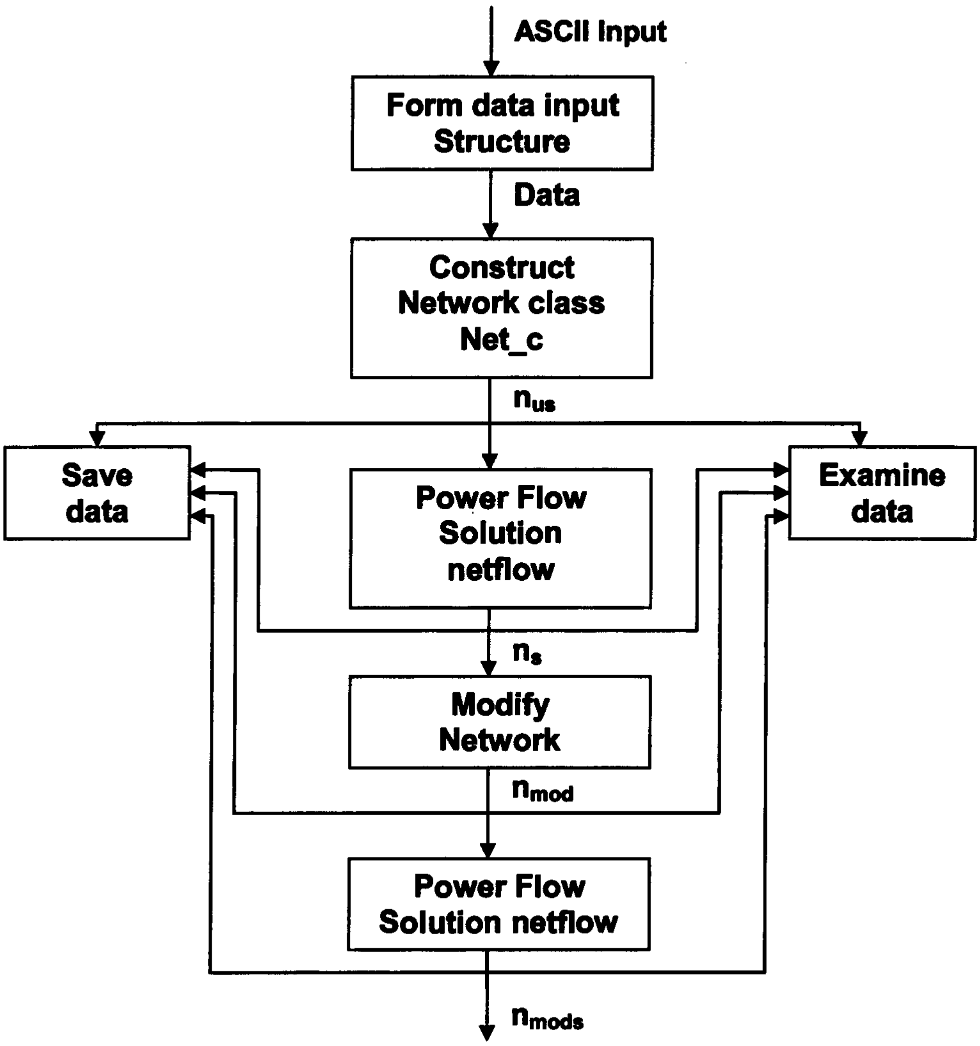


Figure 5.2 MatNetEig/MatNetFlow net_c object formation [20]

The ASCII input shown on the flow chart in figure 5.2 above can be in any of the three supported data formats (i.e. PST2, PSS/E and IEEE common format). The input data structure formed is similar for all input data types; this structure is then used to construct a net_c class object. In MatNetEig, a net_c class object can be used to reconstruct a network data file in any of the supported input data formats or can be saved as a Matlab (.mat) data file. The subscript "us" is for unsolved, "s" in n_{us} of Fig 5.2 is for solved, "mod" for modified data and "mods" for solved modified data.

Program settings can be changed directly by editing the source code or safely via the program GUI. Load flow related settings are accessible on the GUI via "Solve" → "Solution Options" menu where tolerance, iterations and other limits can be specified. The small-signal stability analysis GUI has no customisable settings. Time domain and frequency response analysis settings can be set via the GUI when doing step and frequency response simulations.

Small-signal stability analysis can be done using full or reduced sparse modal analysis. MatNetEig has additional drivers used to calculate frequency response between; single input – single output for full linearized models and their associated zeros, single input – single output for sparse linearized models and their associated zeros, multiple input – multiple output for sparse linearized models, few zeros and their left and right eigenvectors from sparse differential-algebraic equations [20].

MatNetEig has a **genview** GUI for generator functions that allows users to import synchronous machine data from dynamic data files. When using the genview GUI, users can; plot machine saturation curves, view performance charts (P vs. Q), view synchronous machine data and modify synchronous machine data.

5.2. Component modelling in MatNetEig

All power system components used in the chosen power system models are indicated and discussed in table 5.1. MatNetEig's (PST2) component names are shown in bold.

Table 5.1: MatNetEig/MatNetFlow Component model and data format

Component Model	MatNetEig
Bus	MatNetEig uses PST2 bus data in a row vector matrix named **bus**. The data format structure is shown below:

	[Bus# V_{mag}(p.u) V_{angle}(deg) P_g(p.u) Q_g(p.u) P_L(p.u) Q_L(p.u) G(p.u) B(p.u) type Q_{gmax} Q_{gmin} kV V_{max} V_{min}] where the bus type "type" is defined as follows: 1: Swing bus 2: PV generator bus 3: Load bus (PQ load or generator bus, depending on the load or generation data specified). Note: The per unit values are on the system base quantities.
Transmission line	MatNetEig models the transmission line using an equivalent π-circuit model. The PST2 data format used in MatNetEig for the line data is also in a row vector matrix called **line** with the following structure for mandatory data fields: [FromBus# ToBus# R(p.u) X(p.u) B(p.u) Tap_ratio Tap_phase] Note that this line data format is also used for tap changing transformers. The tap phase (Tap_phase, in degrees) is used when there is a phase shifting transformer. Setting Tap_ratio to 0.0 disables automatic tap changing.
Transformer	Transformers and lines share the same model name (**line**) and structure using a row vector matrix data. Additional data fields are the minimum step, maximum step and the step size in per unit for tap changing transformers as follows: [FromBus# ToBus# R(p.u) X(p.u) B(p.u) ... Tap_ratio Tap_phase **max_step min_step step_size**] If the transformer model is not an automatic tap changing transformer, the same line structure as indicated for a line is used.
Synchronous Machine	The synchronous machine data is modelled in a matrix named **mac_con** with the following data format: [Mac# Bus# MVA X_l R_a X_d X'_d X''_d T'_{do} T''_{do} X_q X'_q X''_q ... T'_{qo} T''_{qo} H D_0 D_1 type S_1 S_2 frP frQ]

The parameter "type" defines the machine type and the machine type determines the type of saturation model to use on the synchronous machine. The saturation is defined by both the type and the parameters S_1 and S_2. For other parameters, 0.0 can be used if those parameters are not applicable to a synchronous machine model.

MatNetEig supports only four synchronous machine models (i.e. classical model which is the 2nd order, transient 4th order, sub-transients 5th and 6th order).

The user manual does not include the 4th and 5th order models as part of the supported or available models. The program is designated such that neither X'd nor T'do can be set to zero, if any of these is set to zero, the system terminates with a system error. Table 5.2 shows required time constants and reactance.

Table 5.2: mac_con machine reactance and time constants table

Order	T'_{d0}	T'_{q0}	T''_{d0}	T''_{q0}	x_d	x'_d	x''_d	x_q	x'_q	x''_q
II						√				
IV	√	√			√	√		√	√	
V	√		√	√	√	√	√	√	√	√
VI	√	√	√	√	√	√	√	√	√	√

Table 5.2 above should be used together with a user manual for other system assumptions when modelling synchronous machines.

MatNetEig has three generator types and three saturation types as follows:

a) Generator types

The generator types are classical, salient and round rotor defined by "type" on **mac_con** data as discussed on synchronous machines:

type=1: **Classical generator**

types=2, 20, 21, 22 or 23: **Salient pole**

type=3, 30, 31, 32 or 33: **Round rotor**

b) Saturation types

When generator type is {21 or 31} : Saturation type is 1 given by (5.1)

$$\begin{cases} B_{sat} = 5.0\log\left(\frac{1.2S_2}{S_1}\right) \\ A_{sat} = S_1 e^{-0.2B_{sat}} \\ i = \psi_a + A_{sat} e^{B_{sat}(\psi_a - 0.8)} - A_{sat} \end{cases} \tag{5.1}$$

When generator type is {22 or 32} : Saturation type is 2 defined by the following equations:

$$\begin{cases} k_1 = 1.2S_2 - S_1 \\ k_2 = 2.4(S_2 - S_1) \\ k_3 = 1.2S_2 - 1.44S_1 \\ B_{sat} = \frac{k_2 - \sqrt{k_2^{\,2} - 4k_1k_3}}{2k_1} \\ A_{sat} = \frac{1.2S_2}{(1.2 - B_{sat})^2} \\ i = \psi_a + A_{sat}(\psi_a - B_{sat})^2 \end{cases} \tag{5.2}$$

$$\psi_a > B_{sat}$$

When generator type is {2, 20, 23, 3, 30 or 33} Saturation type is 3 and the following saturation equations are used:

$$\begin{cases} A_{sat} = S_1 \\ B_{sat} = \frac{\log(\frac{1.2S_2}{S_1})}{\log(1.2)} \\ i = \psi_a + A_{sat}(\psi_a)^{b_{sat}} \end{cases} \tag{5.3}$$

All saturation types in MatNetEig simulation tool are defined and specified by parameters S_1 and S_2 calculated from open-circuit saturation curve as follows: $S_1=(b_1-a_1)/a_1$ and $S_2 = (b_2-a_2)/a_2$. Refer to chapter 3 for a_1, a_2, b_1 and b_2 parameters.

	Saturation type 3 is the preferred type due to the continuity of the saturation curve and its slope at all points [20]. Type 1 saturation model closely match those used by PSAT 2.1.2 and PacDyn 8.1.1 simulation tools and was used for comparison purposes. A round rotor machine with saturation type 1 (i.e. type=31) was used when modelling saturation on these investigations a shown in equation (5.1). Any synchronous machine can be reduced into a classical machine by setting type=1 directly on the mac_con data structure or by using "**mac_con(nb,19)=1** on the data file, where nb is the bus number with the generator to be reduced to a classical machine. If all machines are to be set to classical generators, simply use **mac_con(:,19)=1**. The classical machine model has two system modes.
Infinite Bus	Any synchronous machine can be reduced to an infinite bus by using an additional command called **setib**. This command does not represent system data but is only a way of reducing the states of the system by eliminating the selected synchronous machine(s). The selected synchronous machines are modelled using a voltage behind transient reactance. An error occurs when changing a machine to infinite bus in a system where all the generators are electro-mechanical (classical) generators. To avoid this, at least one machine should be transient or sub-transient generator. If all machines are classical generators, an infinite bus is modelled by a classical machine used to represent an infinite bus as an external source. However, this adds two additional eigenvalues on the system.
MVA Base	The MVA base is specified during a simulation via a file dialog box. It is specified when MatNetEig prompts for the MVA and frequency.

PV / PQ bus	These are all part of the bus data as indicated in **bus**. The parameter "type" indicates the generator type as follows: When type is: 2: The bus is a PV generator bus 3: The bus is a PQ bus (PQ load bus or PQ generator bus). On a SMIB system, when a PQ bus type is used, MatNetEig fails to recognise the infinite bus as an external network capable of supplying or taking excess load, resulting in non-convergence error [18]. To avoid load flow convergence problems, a PV bus model was used in this thesis with a flat start voltage magnitudes and phase angles.
AVR Exciter	MatNetEig has 16 IEEE standard excitation systems for control of voltage at the generator's terminals. These exciters are all modelled using the same variable name **exc_con**. There are three DC type exciters, eight AC exciters and five static exciter models. All **exc_con** models have 31 data columns that must be specified. For this thesis, only data structures and block diagrams for the AC Type 7 exciter (AC4a) and Static Type 10 exciter (ST1a) are presented. These two models are the only models suitable to be customised to model and represent the simple AVR exciters from [21]. The following data format represent for the Type 7 AC4a exciter model. [Type Gen# R_c X_c T_r K_a T_a T_b T_c 0 0 0 0 V_{imx} V_{imn} ... 0 0 V_{rmx} V_{rmn} K_c 0 0 0 0 0 0 0 0 0 0 0] Figure 5.3 shows Type 7 AC4a exciter block diagram used in MatNetEig simulation tool.

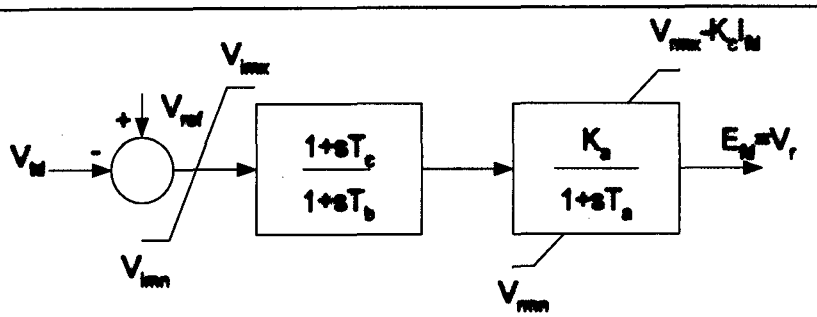


Figure 5.3 AC4a excitation system

By setting some parameters to 0.0 (i.e. T_c and T_b), it is possible to further reduce the above model to a simple AVR system used in this thesis accurately.

Type 10 Static exciter (ST1a) data and block diagram (Fig. 5.4) as used in **exc_con** model follows below:

[Type(u) Gen# R_c X_c T_r K_a T_a T_b T_c K_f T_f T_{b1} T_{c1} V_{imx} V_{imn} ... V_{amx} V_{amn} V_{rmx} V_{rmn} K_c 0 0 0 0 0 0 0 0 0 0 0]

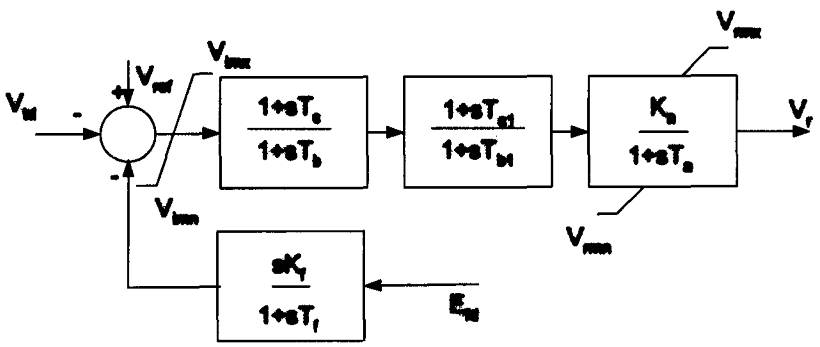
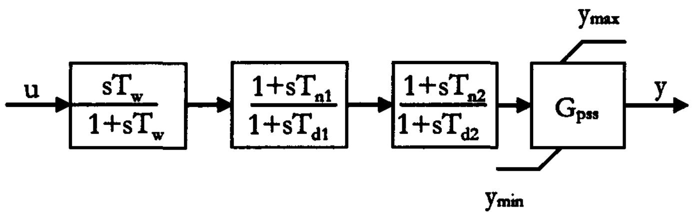


Figure 5.4: ST1a Excitation System (AVR)

The zero entry values in the data format indicate data not required on this excitation system model.

MatNetEig allows the user to set other parameters to 0.0 (i.e. T_c, T_b, T_{c1}, T_{b1} K_f and T_f) to further reduce the above model.

PSS	There is only one type of power system stabilizer (PSS) supported by MatNetEig. This PSS has 5 types of input signals (u) that can be individually selected by specifying the input type parameter. The PSS model in MatNetEig can be connected to any exciter except the DC3. The PSS is modelled by **pss_con** and the data format has the following structure: [Type Gen# G_{pss} T_w T_{n1} T_{d1} T_{n2} T_{d2} y_{max} y_{min} ... T_{wd} T_{nf} T_{df} nnf ndf G_p] MatNetEig uses the block diagram shown in Fig. 5.5 for the PSS.  **Figure 5.5: Power system stabilizer (PSS) block diagram** The input signal type (u) can be any of the following: 1: Speed input 2: Bus frequency input 3: Power input 4: Rate of change of power with respect to bus frequency with speed input 5: Rate of change of power with respect to bus frequency The data (T_{wd}, T_{nf}, T_{df}, nnf, ndf and Gp) are optional and were not used in this research. Note that this structure can not be further reduced due to the following restrictions: Lead and lag time constants (T_{n2} and T_{d2}) can not be set to zero. They can be set to any other value, hence introducing unwanted pole and zero at the negative reciprocal of these values (i.e. $\lambda_i = -1/T_{d2}$ and $z_i = -1/T_{n2}$). It is suggested that equal values be used (i.e. $T_{d2} = T_{n2} = 1.0$, placing the additional pole and zero at -1) [40].

Load (1): PQ Load	MatNetEig models the PQ load using the same data in **bus** as indicated at the beginning. PL and QL values are used within the bus data to model the load's real and reactive components of the load in per unit at the applicable base frequency, MVA and voltage level. The bus type should be set to 3 (indicating a PQ load bus).
Load (2): ZIP Load	ZIP loads are a combination of constant impedance (Z), constant current (I) and constant power (P). All ZIP loads can be modelled in MatNetEig by using **load_con.** To model ZIP loads, the following data format is used to for non-conforming load models: [Bus# Ap_fr Rp_fr Ac_fr Rc_fr] Where: Ap_fr: fraction of constant active power load Rp_fr: fraction of constant reactive power load Ac_fr: fraction of constant active current load Rc_fr: fraction of constant reactive current load All these fractions are set specified in per unit.
Fault and Breakers	Faults and breakers are not supported in MatNetEig. This simulation tool does not have support for transient simulations.
Disturbances	MatNetEig simulation tool does not have support for transient stability studies. It has frequency and step response simulations for small-signal stability analysis. These are all done via the customised GUI for small-signal stability analysis. A list of all internal variables is provided when running these simulations through which single-input-single-output or multi-input-multi-output variables can be selected for step and frequency domain simulations.

5.3. MatNetEig components summary in small-signal stability analysis

Table 5.3 shows a summary of all component models as used in MatNetEig simulation tool that are applicable to the selected SMIB system and the 2A4M system models. It can be used as a quick reference manual when modelling a power system for small-signal stability analysis in MatNetEig.

Table 5.3: Summary of MatNetEig Power system components model names

Component	Component description	MatNetEig model Name
Steady state components	Bus	**bus**
	Bus names	-
	Line/transformer	**line**
	Slack generator / Swing bus	Incorporated in **bus**
	PV bus and PQ generator	Incorporated in **bus**
	PQ load	Incorporated in **bus**
Dynamic stability components	Synchronous generator	**mac_con**
	Infinite bus	**setib, mac_con(:,19)**
	AVR excitation controller	**exc_con**
	Power system stabilizer	**pss_con**
	ZIP load	**load_con**
	Fault and Breakers	-
	Disturbances	**Frequency and step response**

The "–" indicates not applicable or not available in MatNetEig simulation tool.

5.4. Summary

MatNetEig uses Matlab object classes to construct a network structure model. The input data formats supported are PST2, PSS/E and IEEE common format. The simulation tool has a GUI for load flow and an additional GUI used for all small-signal stability analysis. Matlab command prompt can be used for all steady state and dynamic analysis. In this chapter, data supported and PST2 formats for all components models applicable to this thesis were discussed.

MatNetEig uses bus and line specification matrices for all steady state load flow simulations. Additional dynamic data has been indicated as follows: four synchronous machine models with three machine types (classical electromechanical, salient pole and round rotor types) and three types of saturation models specified by the machine type. There is a special command for setting any synchronous machine as an infinite bus.

There are 16 excitation types (DC, AC and Static AVR excitation systems) and one PSS model that support five types of input signals. The load is modelled on the bus data by specifying the load and bus type as a load bus. ZIP loads are modelled as non-conforming loads where the user can specify the load mix from constant impedance, constant current and constant power. This simulation tool does not support dynamic loads, FACTS devices or HVDC systems, transient faults or breaker models. Disturbances are simulated using frequency and step response simulations with multiple input-multiple output simulation capabilities.

The program comes with user documentation but the documentation lacks useful information such as all available generator models (4^{th} and 5^{th} order machines are not included in the manual). The procedure used when reducing a synchronous machine to infinite bus is not clearly indicated.

Chapter 6:

6. Features And Capabilities Of Pacdyn 8.1.1 Simulation Tool

6.1. PacDyn 8.1.1

PacDyn 8.1.1 is a closed source code software by CEPEL (Centro de Pesquisas de Energia Electrica). The version used in this thesis is licensed for educational purposes. PacDyn is an industrial-grade comprehensive package for the analysis of small-signal electromechanical stability and sub-synchronous resonance of large scale AC/DC power systems. It uses a graphical user interface (GUI) to access and launch all required functionalities. It is not possible to draw single line diagrams of the power system model in PacDyn simulation tool. However, user defined controllers can be drawn using block diagrams [9, 19].

PacDyn has algorithms to calculate eigenvalues, dominant eigenvalues, transfer function zeros, residues, step response, frequency response as well as generator synchronising and damping torques. Amongst other functionalities PacDyn is mainly used for investigations of small-signal stability and control interaction problems, synchronous resonance, analysis of multi-machine power systems, optimal placement of PSS to damp local and inter-area modes, identification of inadequate system controllers (AVRs, PSS, SVC, etc), linear time responses and local impact analysis [36, 41].

The program was written in FORTRAN and some routines in C++, resulting in speed and reliability of those applications. The default program settings limit the program to 16000 AC branches and the tool can compute up to 1000 eigenvalues for full eigensolution through the QR routine. The size of the network model can be altered on the Fortran Parameter statements. Modelling system can only be limited by the user's hardware installation and computer memory [9, 19, 41].

PacDyn 8.1.1 does not have load flow routines. It takes converged load flow solution data in the form of electrical network data. The load flow converged data is known as the electrical network data file. PacDyn 8.1.1 can read input data formats from PSS/E, EUROSTAG and binary files generated by AnaRede v9.3.3 (a CEPEL's load flow software tool).

Dynamic stability algorithms used include QR-Eispack full eigensolution algorithms, QZ algorithm, partial eigensolution algorithm, Rayleigh Quotient, Refactored Bi-Iteration algorithm, dominant transfer function pole algorithms, dominant pole spectrum, multiple input-multiple output transfer function dominant pole algorithm and transfer function zeros [19, 42]. PacDyn has user-defined and built-in controller models that can be used when modelling steady state and unlimited dynamic power system components.

The input data is then validated for convergence and dynamic components are initialised. User defined controllers are scanned for convergence using either Block scanning method or Newton's method. If the electrical network and dynamic components data files fail the convergence test, PacDyn terminates without performing small-signal stability analysis [41].

Results are visualised in a number of ways in PacDyn 8.1.1. It has an advanced state-of-the-art Windows graphical user interface (GUI) and allows the simultaneous visualization of various results using tables, plots and bar charts. The main result formats are on-screen graphical plots, on-screen plain text results, 132-column output data file and internal database tables used for graphical plotting and Matlab output data that can be easily read by the accompanying Matlab codes for the **A** matrix and modal analysis [19].

The program's accuracy when using standard settings has a default tolerance of 10^{-10} in all components of the vector given by equation (6.1) [41]

$$\varepsilon = Ax - \lambda \dot{x} \qquad (6.1)$$

where λ and x are eigenvalues and their corresponding right eigenvectors respectively.

PacDyn 8.1.1 has many power system model components, including AC buses, branches, synchronous machines, PQ loads, static non-linear ZIP loads, AVR excitation systems, power system stabilizers, induction motor loads, FACTS, SVC, TCSC, HVDC systems, dynamic loads and many other components not to be discussed in this thesis.

Figuire 6.1 shows PacDyn 8.1.1 main GUI window and the license registration details.

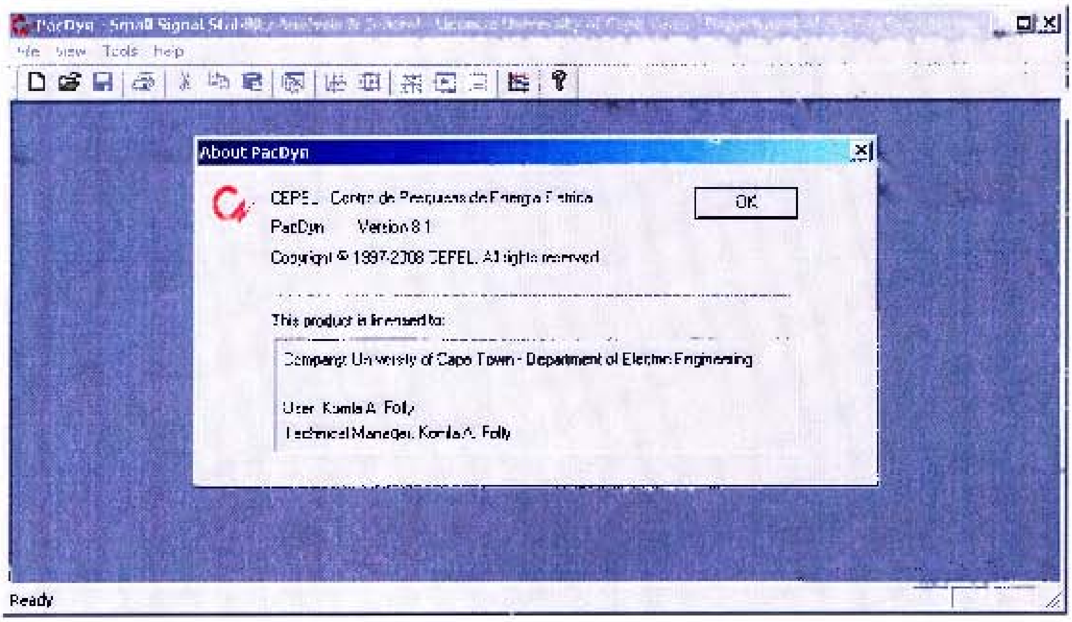


Figure 6.1: PacDyn 8.1.1 Licensed user details and main window

The program has few main menus through which all program functions can be accessed.

6.2. Component modelling in PacDyn 8.1.1

This section covers network component models used in PacDyn formatted electrical and dynamic data files. For simplicity, only those components used in this thesis are discussed. To avoid repetition, the following units and format conventions are used in all data formats: **(p.u)**: Per unit on the applicable system bases; **(---)**: No applicable unit, **A**: alphanumeric text format; **I**: integer; and **F**: decimal floating number. Table 6.1 shows applicable components and data formats.

Table 6.1: PacDyn 8.1.1 component models and data formats

Component Model	PacDyn 8.1.1
Bus	PacDyn 8.1.1 uses **BUS DATA** on the PacDyn Electrical network data format. The structure is in a row vector per bus data with 80-column card-record format as follows: Bus#(name)(volt)(angle)(pgen)(qgen)(pload)(qload)(gshunt)(bshunt)

The format indicated is available from the EditCEPEL program provided with PacDyn 8.1.1. *EditCEPEL is an editor that can be used for both electrical and dynamic data editing.* PacDyn data format indicated does not include character positions as required by PacDyn tool. Data used by this simulation tool has to be specified in exact position on the data fields. For example, qgen must be specified in column location number 38 to 46 in MVar using a decimal floating point number.

The card-record below shows the bus data parameters and required values in associated position using 80-column card-record format, this format will be used in all data formats.

BUS#	BUS NAME	VMAG	VANG	PGEN	QGEN	P LOAD	Q LOAD	G SHUNT	B SHUNT
(—)	(—)	(p.u)	(degrees)	(MW)	(MVar)	(MW)	(MVar)	(p.u)	(p.u)
I	A	F	F	F	F	F	F	F	F
1 2 3 4	5 6 7 8 9 10 1 2	3 4 5 6 7 8 9 20	1 2 3 4 5 6 7 8	9 30 1 2 3 4 5 6 7	8 9 40 1 2 3 4 5 6	7 8 9 50 1 2 3 4 5	6 7 8 9 60 1 2 3 4	5 6 7 8 9 70 1 2	3 4 5 6 7 8 9 80

Data not required can be set to 0.0 or left blank. The above is used as follows when using VMAG and PLOAD data entries as examples:

- VMAG: Magnitude of the bus voltage in per unit, using a decimal point floating point number. The value should be entered in the column location 13 to 20.
- PLOAD: A real part of the load is entered in MW with the decimal floating point number (F) in the location 47-55.

Note: The "A" format indicates a text string. Neither the double nor single quotes are required on string format. The end of the bus data is indicated by a "Terminator code" -999 in location 1-4 columns.

Transmission line

The AC branch data (**BRANCH DATA**) for an equivalent π–circuit model is used to model a line. All values are specified in per unit on the system base MVA, kV and frequency. The card below is used in an 80-column card-record format for the line data:

<table>
<tr><td></td><td>

FROM (–) I	TO# (–) I	R LINE (p.u) F	X LINE (p.u) F	B LINE (p.u) F	T RATIO (p.u) F	PHASE (p.u) F

Note: The user manual refers to BLINE as the "Total charging susceptance of a transmission line in MVar". Instead, BLINE should be specified in per unit and NOT in MVar.

A "Terminator code" -999 is used to indicate the end of the AC branch data. The value **-999** is specified in the columns 1 to 4 in place of the terminating bus number (FROM).</td></tr>
<tr><td>Transformer</td><td>PacDyn 8.1.1 uses the AC branch data as defined in Line above (BRANCH DATA)

FROM (–) I	TO# (–) I	R LINE (p.u) F	X LINE (p.u) F	B LINE (p.u) F	T RATIO (p.u) F	PHASE (p.u) F

Note that all voltages are in per unit; T RATIO and PHASE are left blank or set to 1.0 and 0.0 respectively. BLINE should be specified in per unit and NOT in MVar as mentioned in the user manual.

The end of the branch data (transformer) is indicated by a "Terminator code" -999 in columns 1-4.</td></tr>
<tr><td>Synchronous Machine</td><td>PacDyn 8.1.1 supports eight synchronous machine models from classical 2nd order to detailed 6th order with three 5th order and two 6th order synchronous machine models. The synchronous machines are all modelled using the data execution code DGEN with 86-column card-record format.

Synchronous machines may require one or two input data records in what is called primary and secondary record cards, depending on the model adopted for the machine.

Synchronous machine models #1, #2 and #3 require the primary</td></tr>
</table>

record only. Machine models #4, #5, #6, #7 and #8 use both the primary and second records. The machines' model number and order (state) relationship used in PacDyn are as shown on table 6.2.

Table 6.2: PacDyn synchronous machine models

Model#	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Order	2	3	4	5	6	5SSR	6SSR	5SSR

The highest machine order is 6th represented by machine model #5. Machine models #6, #7 and #8 are used for sub-synchronous resonance (SSR) studies. SSR models were not used in this thesis.

The cards below show fields of the data in the DGEN execution code: Primary record (Models #1, #2 and #3), Mandatory records only

IIGN	BUS# (—) I	NUMA	MREF	MODL	MVAB (MVA) F	H (kW.s/KVA) F	X'd (p.u) F	X'q (p.u) F	Xd (p.u) F	Xq (p.u) F	Ra (p.u) F	T'd0 (sec) F	T'q0 (sec) F	Xp (p.u) F	SFAC (—) I	D (p.u/p.u) F

where IIGN: Machine status (blank turns machine on, X turns off)

NUMA: Machine unit number to identify parallel machines

MREF: Control code (blank: normal, R: reference machine)

MODL: Synchronous machine model number (see table 6.2)

Optional data: (Location 82-86 columns, Freq (HZ) using **F** format.

Freq: (Default frequency is 60 Hz, when left blank)

When the power system is modelled without an angular reference machine or an infinite bus, state variable redundancy occurs in synchronous machines. Resulting in additional zero pole in the state matrix spectrum. Using a reference machine or an infinite bus reduces order number and eliminates the matrix redundant states [2, 40, 42].

Secondary record (Models #4 to #8), Mandatory records only:

NUMA	NUMT	X"d (p.u) F	X"q (p.u) F	T"do (sec) F	T"qo (sec) F	Xl (p.u) F	A (—) F	B (—) F	C (—) F

where NUMA: Machine number (identical to Primary record)

NUMT: Number of parallel units connected to this bus.

A, B and C: Saturation factors for machine models #4 to #8.

Optional data (Location 59-82 columns, Step-up transformer data) as follows: {Xt: HV reactance, Rtr: resistance, Xtr: reactance, Str: MVA}.

The reactance and time constants used depend on the machine model type and data requirements on that specific synchronous machine. Table 6.3 below shows the required data for each machine model:

Table 6.3: DGEN machine reactance and time constants table

Model#	Xd	Xq	X'd	X'q	X"d	X"q	Xl	Xp	T'd0	T'q0	T"d0	T"q0
1			√	√				√				
2	√	√	√	√				√	√			
3	√	√	√	√				√	√	√		
4	√	√	√	√	√	√		√	√		√	√
5	√	√	√	√	√	√	√		√	√	√	√
6	√	√	√		√	√	√		√		√	√
7	√	√	√	√	√	√	√		√	√	√	√
8	√	√	√		√	√	√		√		√	√

The user manual must be checked and used for other assumptions on these specific synchronous machine models.

Two different saturation models exist in PacDyn. The 1st model is used on machine models #2, #3 and #4 where the saturation factor (SFAC) is required on the primary record. The open-circuit magnetization curve relating terminal voltage to field current is used to fit the saturation curve given by the equation (6.2) below:

$$I_{fd} = V_{occ} + SFAC(V_{occ})^7$$
$$C_d = \frac{SFAC - 1.2}{1.2^7} \qquad (6.2)$$

Saturation models in PacDyn8.1 use equation (6.1) for models #2, #3 and #4 where C_d is internally used to derive d- and q-axis saturation models. The user enters the per unit field current (I_{fd}) at V_{occ}= 1.2 p.u (defining 1.0 p.u of I_{fd} as that current required to produce 1.0 p.u V_{occ} along the air-gap line) known as <u>SFAC</u> on the generator data [40].

	The second saturation model is used on synchronous machine models #5, #6, #7 and #8. Saturation factors A, B and C are used and specified on the secondary record. A, B and C are calculated from the manipulation of equations $S_1=(b_1-a_1)/a_1$ and $S_2=(b_2-a_2)/a_2$ to fit the curve $SAT=A.e^{B(\vert E'\vert -C)}$. SAT is then internally used when calculating d- and q-axis saturation models. C is normally used as 0.8 [37, 41 – 43], although PacDyn allows users to specify any value instead of 0.8 p.u. The end of the synchronous machine data (DGEN) is indicated by a "Terminator code" -999 in columns 2-5.
Infinite Bus	PacDyn models an infinite bus as an AC bus with constant voltage magnitude and phase angle. The same synchronous machine data execution code **DGEN** is used, with only the bus number (BUS#) specified on the primary record in columns 2 to 6 as shown on the data format below. There is no limit on the number of infinite buses that can be modelled. IIGN | BUS# (—) I Columns: 1 | 2 3 4 5 6 IIGN: Code X turns off the machine, while blank set the machine in-service. In other words, to model an infinite bus in PacDyn simulation tool, the user <u>ONLY</u> enters the bus number under the code **DGEN**. The use of infinite bus on the system removes redundant zero poles on the state matrix as described in synchronous machine model above. The end of the synchronous machine and infinite bus data (DGEN) is indicated by a "Terminator code" -999 in columns 2-5.
PV / PQ bus	This simulation tool has both PV and PQ generator models and their data is incorporated in the load flow electrical network data **BUS**

DATA as indicated in bus modelling.

BUS# (--) I	BUS NAME (--) A	VMAG (p.u) F	VANG (degrees) F	PGEN (MW) F	QGEN (MVar) F	P LOAD (MW) F	Q LOAD (MVar) F	G SHUNT (p.u) F	B SHUNT (p.u) F

VMAG and PGEN are used to define a PV bus while PGEN and QGEN define a PQ generator bus.

AVR Exciters

PacDyn 8.1.1 has five built-in AVR excitation models. It has support for user defined controllers (UDC) and user defined topologies (UDT) that can be used to model unlimited excitation controllers. The use of UDC and UDT will be described later and subsequently their usage will be explained. The built-in AVR excitation systems are modelled using a control code **DAVR**. Model 3 and 5 AVR excitation systems format and block diagrams are as follows:

Model 3 AVR system data format:

IIGN	BUS# (--) I	NUMA	Ka (--) F	Ta (sec) F	Kf (--) F	Tf (sec) F	Tn (sec) F	Td (sec) F	Ke (--) F	Te (sec) F	Se75 (--) Disabled	Sefm (--) Disabled	Vima (--) Disabled	NCOB (--) I	NMOD

Model 3 AVR system block diagram:

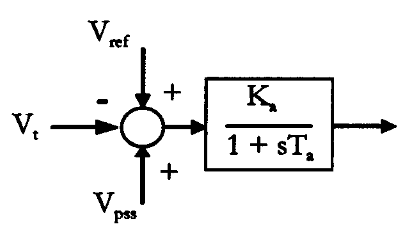
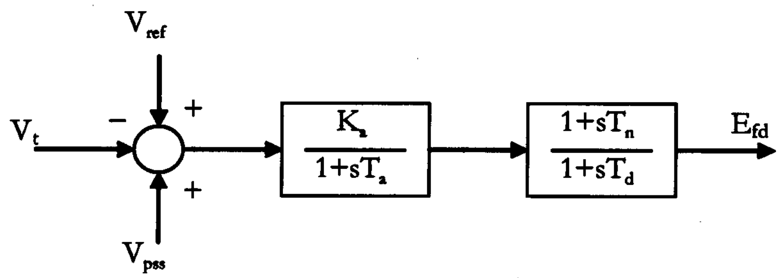


Figure 6.2: AVR Excitation system model 3

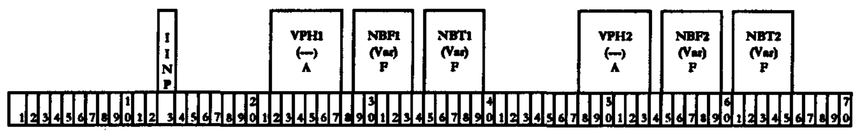
To use the data format above for a model 3 AVR system in Fig. 6.2, set $K_f=T_f=T_n=T_d=K_e=T_e=V_{sat}=V_{smx}=V_{smn}=0.0$ or leave blank. NCOB is the number of the bus whose voltage is to be controlled while NUMA is the machine number. K_a and T_a are the AVR data and NMOD is the AVR model number (3).

	Model 5 AVR system data format is as follows:
	<table><tr><td>IIGN</td><td>BUS# (—) I</td><td>NUMA</td><td>Ka (—) F</td><td>Ta (sec) F</td><td>Kf (—) F</td><td>Tf (sec) F</td><td>Tn (sec) F</td><td>Td (sec) F</td><td>Ke (—) F</td><td>Te (sec) F</td><td>Se75 (—) Disabled</td><td>Sefm (—) Disabled</td><td>Vfma (—) Disabled</td><td>NCOB (—) I</td><td>NMOD</td></tr></table>
	Model 5 AVR system block diagram.
	
	Figure 6.3: AVR Excitation system model 5
	To use the data format above for a model 5 AVR system shown in figure 6.3, set $K_f=T_f=K_e=T_e=V_{sat}=V_{smx}=V_{smn}=0.0$ or leave blank. K_a, T_a, T_n and T_d are the AVR data and NMOD is the model number (5).
	The built-in AVR models number 3 and 5 were used as well as the user defined controller (user defined topology) AVR models. PacDyn user defined AVR models are preferred over built-in AVR systems due to unlimited and flexible modelling capabilities [9, 19, 42].
	The end of the excitation control system data (DAVR) is indicated by a "Terminator code" -999 in columns 2-5.
PSS	There is one built-in power system stabilizer (PSS) modelled by the data execution code **DPSS**. It can have any number of input signals via the input summation block. The built-in PSS model can take a maximum of three input signals. DPSS code has three data records as follows: The output definition record, parameters record and input definition record. On this thesis, a PSS with speed input and V_{pss} output was used, the parameter data depends on the PSS model. The

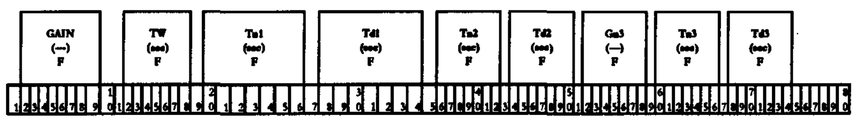
data format below and block diagram models a generic PSS model:

Output definition record:

Parameters record:



Parameters data:



Where: 1, 2 and 3 are the applicable 1st, 2nd and 3rd blocks respectively as can be seen in Fig. 6.4.

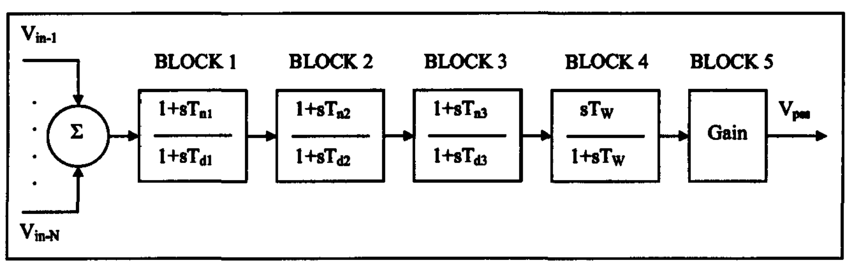


Figure 6.4: Generic power system stabilizer block diagram

Any of the "lead-lag" blocks in Fig. 6.4 can be eliminated by assigning equal numeric values to the numerator and denominator time constants of the block to be eliminated. For example, setting $T_{n3}=T_{d3}=1.0$ eliminates Block3 with one eigenvalue decoupled from the system and equal to -1.

In addition to built-in power system model; user defined controllers, user defined topology and associated user defined controller parameter data were used to model PSS for the selected power system

<table>
<tr><td></td><td>models.

The end of the power system stabilizer data (DPSS) is indicated by a "Terminator code" -999 in columns 2-5.</td></tr>
<tr><td>Load (1):
PQ Load</td><td>Constant PQ loads are modelled as part of the electrical network data file in BUS DATA.

The PLOAD and QLOAD parameter values should be specified in MW and MVar to model the PQ load data from a converged load flow solution in locations 47-55 and 56-64 respectively. The format below is used for bus modelling where load data is specified.

<table>
<tr><td>BUS# (—) I</td><td>BUS NAME (—) A</td><td>VMAG (p.u) F</td><td>VANG (degrees) F</td><td>PGEN (MW) F</td><td>QGEN (MVar) F</td><td>P LOAD (MW) F</td><td>Q LOAD (MVar) F</td><td>G SHUNT (p.u) F</td><td>B SHUNT (p.u) F</td></tr>
<tr><td>1234</td><td>56789012</td><td>34567890</td><td>12345678</td><td>901234567</td><td>890123456</td><td>789012345</td><td>678901234</td><td>56789012</td><td>34567890</td></tr>
</table>
Negative values can also be used for a generator bus.</td></tr>
<tr><td>Load (2):
ZIP Load</td><td>Static non-linear loads data execution code DNNL is used in an 80-column card-record format to represent polynomial (ZIP) loads.

ZIP load models can be set for individual buses or for all buses in an area or for all buses in the system, depending on code value in the field ITIP on the data field. Individual bus load modelling record has precedence over the area load modelling record, which has precedence over the whole system load modelling.

The equations (6.3) are used to model real and reactive power components of the load as static non-linear ZIP loads:

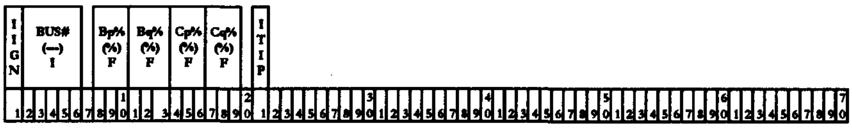
$$\begin{aligned} P &= P_0(Ap + Bp\,|V| + Cp\,|V|^2) \\ Q &= Q_0(Aq + Bq\,|V| + Cq\,|V|^2) \end{aligned} \qquad (6.3)$$

Where:</td></tr>
</table>

<table>
<tr>
<td></td>
<td>

$$\begin{aligned} Ap &= 100 - Bp - Cp\,(\%); \quad Bp + Cp \le 100\,\% \\ Aq &= 100 - Bq - Cq\,(\%); \quad Bq + Cq \le 100\,\% \end{aligned} \tag{6.4}$$

The ZIP load data execution code format is as follows in PacDyn:



Where Bp and Bq: Active and reactive power (%) of the total load proportional to the bus voltage magnitude (constant current).
Cp and Cq: Active and reactive power (in %) of the total load proportional to the square of the bus voltage magnitude (constant impedance).
ITIP: Load modelling code {B: Bus, A: Area, S: System)

The parameters A, B and C are the portions of the total load which is equivalent to constant power, constant current and constant impedance respectively. Subscripts p and q are for real and reactive power components of the load.

The end of the non-linear load data (ZIP loads) is indicated by a "Terminator code" -999 in columns 2-5.

</td>
</tr>
<tr>
<td>Fault</td>
<td>

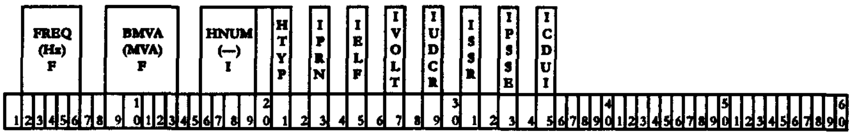
PacDyn 8.1.1 does not have faults and breaker models. It has **transfer functions** that can be customised via the activity centre database. The transfer function can be customised to model the behaviour of various power system components, input and output functions with relative weighting values are used. These transfer functions are then used in time domain and frequency domain analysis to closely simulate fault disturbances and breaker operations.

A list of variables (names) that can be used in input, output and power system components will be included in Appendix D for monitoring and control.

</td>
</tr>
</table>

<table>
<tr>
<td>System Base (MVA)</td>
<td>The system MVA base (MVA BASE) is defined in PacDyn formatted electrical network data file with the following format:

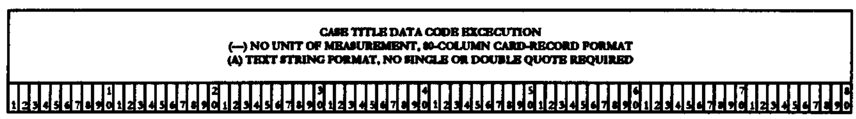
The MVA base is specified in location 09-14. There is no "Terminator code" since there is only one record to be specified.</td>
</tr>
<tr>
<td>System data configuration</td>
<td>PacDyn 8.1.1 requires the system data configuration to be specified on the dynamic data file. This is specified using the data execution code DSYS. DSYS uses an 80-column card record format to store all settings needed to specify configuration of how dynamic data and the simulation thereof is to be handled. The format is as follows:



The following defaults settings/values will be used:
HNUM: Number of history files = 0
HTYP: Electrical network type (A/H:Anarade, P:PacDyn) = P
IPRN: Network data printout on output file (Y/N) = Y
IELF: Abort if load flow data is inaccurate (Y/N) = Y
IVOLT: Check voltage stability analysis (Y/N) = N
IUCDR: Initial condition report (T/N) = T – Generate a report even if initial conditions are violated.
ISSR: Synchronous resonance stability analysis (1, 2, 3) = 1 conventional electromechanical stability analysis.
IPSSE: PSS/E machine compatible (Y/N) = N – PacDyn
ICDUI: User defined controller initialisation (Y: Block scanning, N: Newton) = Y – use block scanning and switch to Newton's method if block scanning fails.

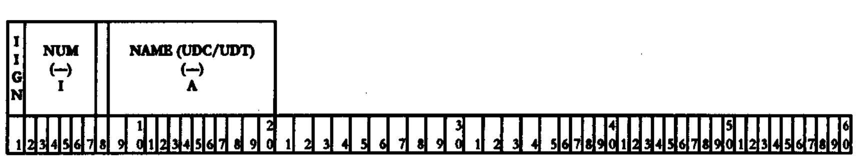
In summary, DSYS is an excecution code used in PacDyn data file</td>
</tr>
</table>

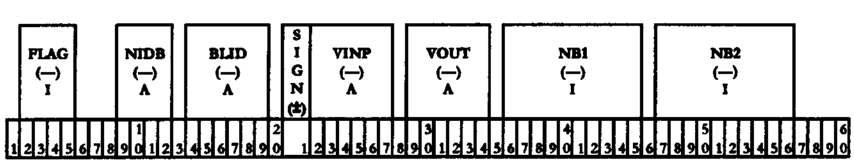
<table>
<tr><td></td><td>and it was used as follows in this thesis: Use PacDyn Electrical and dynamic components network data files, print network data on the output file, check initial condition and terminate if the load flow is not converged, do not perform voltage stability analysis, generate a report for debugging if initial conditions are violated, use electromechanical stability analysis (no SSR), PSS/E data is not used, user defined controller models to be scanned for convergence or switch to Newton's method for convergence.</td></tr>
<tr><td>Case Title</td><td>PacDyn uses a three line, 80-column text for case identification title with the header code TITU. The format is as follows:

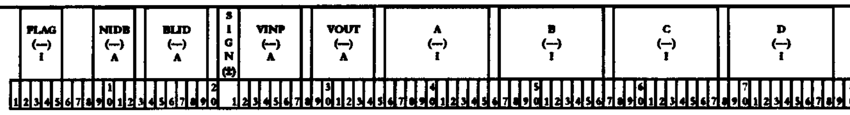


The three lines should all be specified, any of the three lines can be left blank but all lines should be available on the code. The title data specified is later printed as the dynamic case identification title on the output file. There is no "Terminator code" in the TITU code execution as the system requires only three lines with text data format.</td></tr>
<tr><td>User defined controllers</td><td>DUDC execution code and terminator code STOP are used when modelling a power system component model using a user defined controller (UDC). The actual component is modelled by using available variable codes and blocks IDs (BLID) or block diagrams.

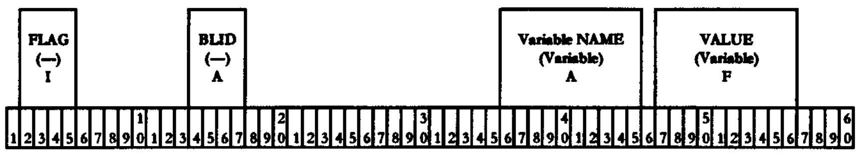
The UDC data structure applicable is in this sequence:

DUDC



</td></tr>
</table>



The next record-card format is used when the DPAR parameter is used for a variable name.



Each UDC requires a UDC number, UDC name, input variable specification, output variable specification and functional blocks. The following functional parameters/block IDs (BLID) are applicable to the AVR and PSS models used in this thesis and will be discussed:

IN: Defines the input parameter (V_{ref}, V_t, WW)
OUT: Defines the output parameter(E_{fd}, V_{pss})
SUM: Summation block with any number of input, one output
LDLG: Lead-lag block parameters given by (A+Bs)/(C+Ds)
GAIN: Gain block.

The UDC can be assigned fixed values or use variable names that can be assigned values within the UDC controller scheme.

UDC with variable parameter names can be used as a user defined topology (UDT) where the topology can be used as a library. This UDT can be imported and used by many models by assigning different UDT names and numbers with applicable parameter names and values. Refer to UDT for usage and data format in the next page.

The PacDyn simulation tool comes with an editor for UDC and UDT. The editor (CDUEdit) has support for single line block diagrams and dynamic code import/export for UDC and UDT. Figure 6.5 below shows a block diagram of a simple AVR modelled in CDUEdit ready to be exported to a dynamic data file.

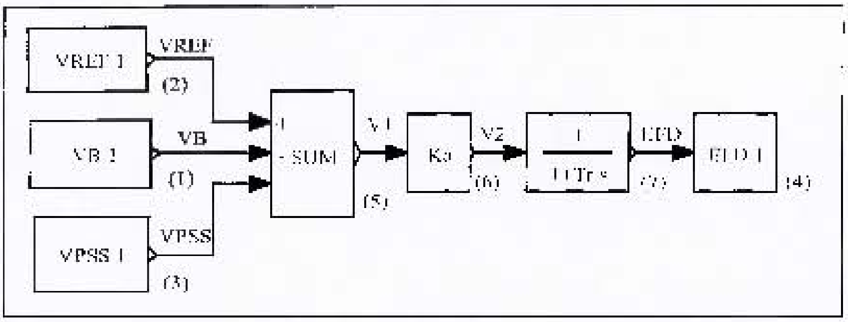


Figure 6.5: User defined controller – AVR Excitation system

The above was exported to a dynamic data file and the code shown in Fig. 6.6 was automatically generated.

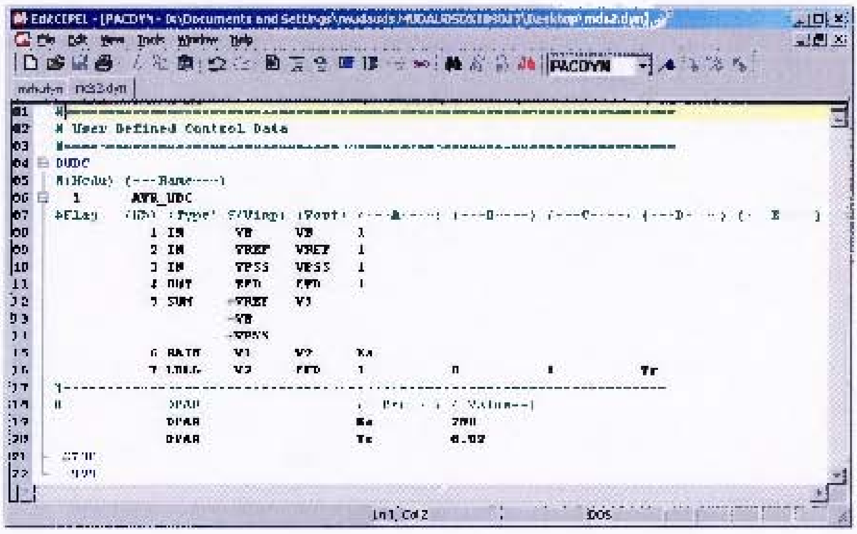
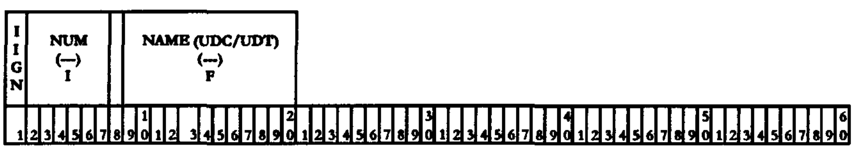
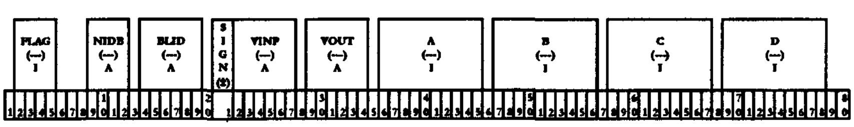
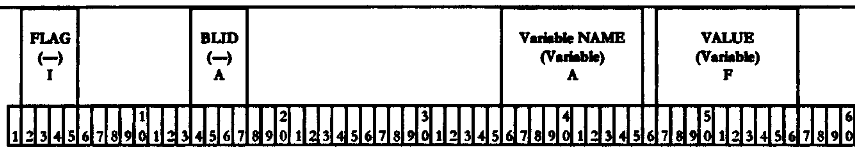


Figure 6.6: Dynamic data code for AVR user-defined controller

Each UDC/UDT can have unlimited models of dynamic power system components. The STOP code is used in location 2-5 to indicate the end of a model in an UDC/UDT scheme. The Terminator code -999 is used to end UDC/UDT scheme and is also used in location 2-5 of the 80-column card-record format.

UDC and UDT execution codes give flexibility to dynamic power system components modelling [9]. Additional excitation systems that are not available on the system library can be modelled as UDT and later imported to any dynamic data file. Test cases conducted in [9] for

	UDC models identical to built-in systems show that UDCs and UDTs are reliable in accurately modelling excitation systems [9, 41]. The terminator codes (STOP; -999) are used in location 2-5 to represent FLAG or the end of UDC/UDT data.
UDT and associated UDC parameter data	PacDyn 8.1.1 allows user the flexibility of building generic user defined controllers with variable parameters that can be used as extended libraries. These models can be imported and used with any dynamic data file as user defined topologies (**UDT**). The requirements for UDTs are the parameter specification for newly imported dynamic models. A UDT is identical to UDC as described with the exception that UDT have variable names defined after a **DPAR** statement for parameters to be changed on a particular model. The process of using a UDT is as follows: Use a data execution code **DUDT** for a new UDC. Import the UDT using its exact name and number to a new UDC model with a unique name and number. Specific data for the new UDC model has to be assigned via an associated user defined controller parameter data (**AUDC**). The code used to assign data to different parameters is **DPAR** followed by the parameter name and data value. The following formats show the data execution code for UDT and AUDC respectively: DUDT  Where NUM is the UDT number 

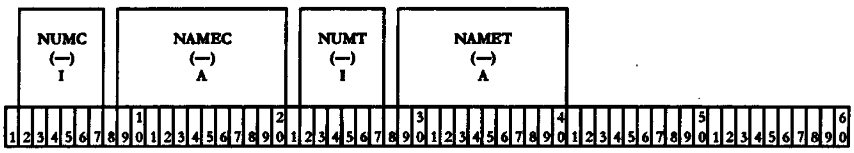


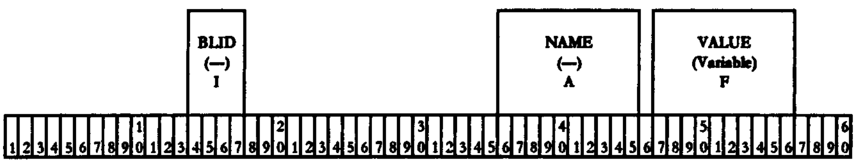
STOP

-999

Note: The usage of the UDC, UDT and AUDC can is included in the network data file in appendix.

AUDC





STOP

-999

UDC example; for a simple AVR exciter with Ka=200 and Tr=0.02. The UDT above will have two variables (Ka and Tr) as follows:

DPAR	Ka
DPAR	Tr

The associated user defined controller parameter data (AUDC) will also have two variables and two values as follows to model the AVR:

Ka	200.0
Tr	0.02

This makes it easy to have one generic controller to be used on models that have identical formats but different values. The end of the

	UDT/AUDC model data is indicated by a "Terminator code" -999 in columns 2-5.
End of dynamic data	PacDyn 8.1.1 requires an execution code to be used to indicate the end of the dynamic components data file. The code to use is **END** and it is used in the location 1-4.

6.3. PacDyn 8.1.1 components summary in small-signal stability analysis

Table 6.4 overleaf shows a summary of all component models as used in PacDyn 8.1.1 applicable to this research. This can be used as a quick reference manual when modelling a power system model for stability studies using PacDyn simulation tool. These components models are applicable when modelling – but not limited to – the SMIB as well as the 2A4M power system models for small-signal stability analysis.

Table 6.4: Summary of PacDyn 8.1.1 Power system components model names

Component	Component description	PacDyn 8.1.1 model Name
Steady state components	Bus	**BUS DATA**
	Bus names	**Incorporated in BUS DATA**
	Line/transformer	**BRANCH DATA**
	Slack generator	**N/A (No load flow data)**
	PV bus / PQ generator	**Incorporated in BUS DATA**
	PQ load	**Incorporated in BUS DATA**
	System base	**MVA BASE**
Dynamic stability components	Synchronous generator	**DGEN**
	Infinite bus	**Incorporated in DGEN**
	AVR excitation controller	**DAVR; DUDC; DUDT; AUDC**
	Power system stabilizer	**DPSS; DUDC; DUDT; AUDC**
	ZIP load	**DNNL; DUDC; DUDT; AUDC**
	Case title	**TITU**
	System data and settings	**DSYS**
	End of dynamic data file	**END**
	Fault	**Transfer function**
	Breaker	**Transfer function**

6.4. Summary

Different power system components and modelling techniques used in PacDyn 8.1.1 have been discussed. PacDyn 8.1.1 simulation tool requires three files for a complete power system model and analysis. It requires two network data files and an activity centre database. The network data files are the converged load flow electrical network and dynamic network data files. An activity centre database contains information about the network data files for a complete case analysis. PacDyn supports various data formats (PacDyn format, PSS/E, Eurostag and AnaRade) for electrical and dynamic network data files. Output results are available via a 132-column formatted text, Output window, lists, tables that can be exported to other formats and advanced graphical plotting formats. The program can export results to be easily read by supporting Matlab code.

PacDyn Electrical network data file and Dynamic network data files formats were discussed and the following components applicable to the selected models were indicated: System configuration settings format, eight Synchronous machine models ranging from classical 2nd order to detailed 6th order models. The machine models have two saturation models. The infinite bus is modelled as an AC bus with constant voltage magnitude and phase angle, it is modelled by setting the bus number to be used as an infinite bus. There are five built-in AVR excitation systems and one PSS that can be easily customised to model simple excitation control systems.

The simulation tool comes with different editing tools such as CDUEdit and EditCepel for advanced editing. The two editors allow for easy modelling of dynamic component models using user defined controllers, user defined topologies and associated user defined controller parameter specifications. The UDC, UDT and AUDC provide extended capabilities for component modelling using simple coding or block diagrams.

Constant PQ loads are modelled with the bus data in the electrical network data file. The program has support for static-nonlinear ZIP loads that can be modelled and used as a combination of constant impedance, constant current and constant power. The ZIP load models are easily set for individual buses, area or the whole system via a single data execution code parameter. PacDyn 8.1.1 does not have faults or breakers but these can be simulated using transfer functions in the Transfer Management database. The program has comprehensive user manual and tutorial documentations.

Chapter 7:

7. Description Of Power System Models And Case Studies

This chapter gives detailed description of the power system models used and case studies performed for stability analysis.

Two power system models were chosen for modelling and analyses for the purpose of this research. The models used were of varying complexity from 2^{nd} order classical generator to detailed 6^{th} order model. The two models are the "SMIB" and the "2A4M" systems. Each of these power systems is briefly described indicating power system components applicable to each specific model.

7.1. Power system models

7.1.1. Single machine infinite bus (SMIB) power system model

This model was adopted from [21]. It represents the simplest dynamic model to be used for small-signal stability analysis. The SMIB model has been used by many authors to study the dynamics of synchronous machines of varying degrees from classical to 6^{th} order models as well as the excitations systems (AVR, PSS and speed governors) on stability of power systems [2, 14]. Figure 7.1 below shows the single line diagram.

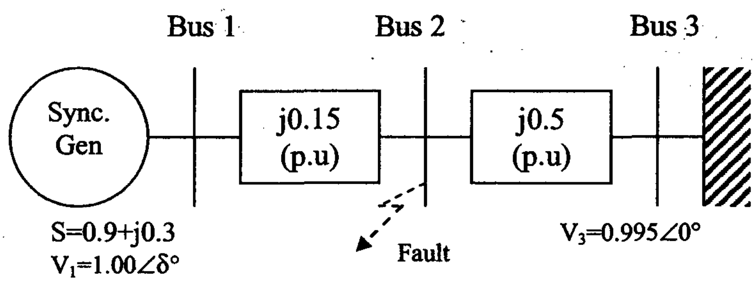


Figure 7.1: SMIB power system model [21]

The following assumptions and operational quantities were used for the SMIB in Fig. 7.1:

- The system base quantities are 2220MVA, 24 kV and 60 Hz.

- The impedance between Bus 1 and Bus 2 represents a 1:1 transformer and was replaced by an identical line impedance of j0.15 p.u on the system base.
- Bus 1 was modelled as a PV bus with P_0=0.9 p.u and V_0=1.00 p.u
- Bus 3 is an infinite bus with fixed voltage magnitude and angle as indicated.
- Time domain simulations were done by applying a small-disturbance on the system.
- All impedances and power are in per unit on a system base of 2220MVA at 24 kV.

Analyses were done for different synchronous machine models supported by each simulation tool on manual control (constant E_{FD}). The effect of leakage reactance, armature resistance and saturation on eigenvalues have been studied and analysed. The excitation controls (AVR and PSS) were modelled and their effects on modal solution analysed. Time domain simulations were also performed for a small-disturbance. *The complete network and excitation control systems data is included in the Appendix, section A.*

7.1.2. Two-area, four-machine (2A4M) power system model

Figure 7.2 shows a diagram of the "*2A4M*" model [21].

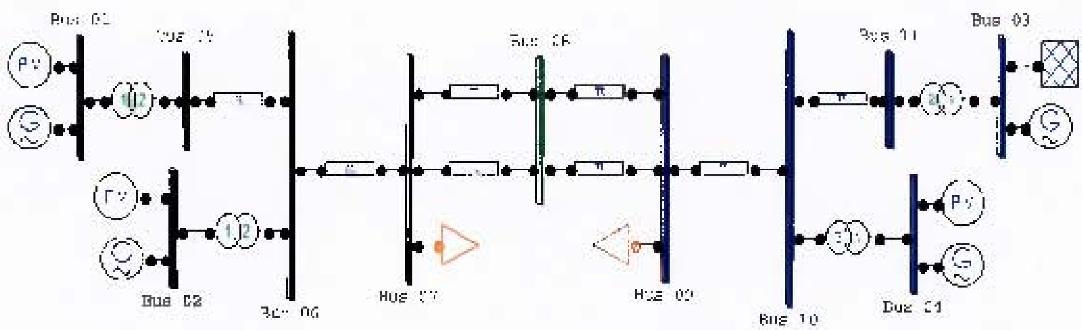


Figure 7.2: 2A4M power system model (2A4M)

Figure 7.2 above was drawn using Simulink single line library tools in PSAT, showing how PSAT can be used to model a power system network using single line diagrams. The "2A4M" system (2A4M), hereafter referred to as the "*two area system or abbreviated 2A4M*" is a small power system model operating at 60 Hz and 100MVA base with:

- 11 buses (power system nodes) and two identical areas connected by long transmission lines (weak ties) connecting Area 1 to Area 2.
- 4 x two-winding transformers (900MVA, 20/230 kV, X=j0.15 p.u on 900MVA base).

- 4 synchronous generators (900MVA, 20 kV, 60 Hz). Generators 1 and 2 in Area 1, generators 3 and 4 in Area 2.
- 2 constant PQ loads at 230 kV bus ratings, with excess reactive power injection into the power system. Static ZIP loads models were also modelled with active power as a constant current and reactive power components as constant impedance [14].

Although small, the two area system gives realistic power system dynamics of a large power system model for analysis [2]. Generators 1, 2 and 4 are modelled as PV buses. Generator 3 is the reference machine. There is no infinite bus on this system model.

Detailed generator models (6^{th} order) are used for all four synchronous machines with saturation included on manual control. The excitation control systems (AVR and PSS) were then modelled on all synchronous machines and their effects analysed. In all case studies, inter-area and local area oscillation modes are analysed.

Time domain analyses were done and the response of rotor speeds of all four synchronous generators were plotted. A comparison with modal analysis was made.

7.2. Case studies

A load flow solution was performed on the power system models in section 7.2.1 (SMIB) and 7.2.2 (2A4M) using PSAT and MatNetEig/MatNetFlow. The converged load flow results were used in PacDyn. This was done to ensure that the electrical network steady state solution has adequately converged for the initialisation of dynamic components and formation of state space equations before small-signal stability analysis can be done [11].

A total of 66 case studies were conducted using modal analysis with 33 cases done on the SMIB system and 33 cases done on the 2A4M system. Mode shapes and participation factors were computed and additional 24 calculations done for the deviations in frequency and damping ratios for the cases above to analyse the effects of various aspects on modal solutions. Time domain simulations were simulated on these cases. The case studies were conducted as follows:

7.2.1. SMIB power system study cases

The following case studies were conducted on the SMIB model using all three software packages and comparative analysis made on the eigenvalues.

7.2.1.1. Manual control

7.2.1.1.1. The effects of damping coefficient on modal solution

Three damping coefficient (K_D) values were used as follows: K_D=0, K_D= -10 and K_D=+10. Eigenvalues were analysed and the effects of K_D on modal solution noted.

7.2.1.1.2. Generator models and effect of saturation (2^{nd}, 4^{th} and 6^{th} order machines)

All generator models supported by the respective power system simulation tool were modelled, simulated and results analysed. For the purpose of this thesis, only the 4^{th} and 6^{th} order synchronous machine results are presented. Infinite bus modelling methodology on each software tool has been studied and the effect investigated.

The effect of including saturation as well as neglecting saturation was investigated on eigenvalues of the oscillatory modes. Saturation models used in all three software tools were investigated. A round rotor synchronous machine was used for the 6^{th} order model.

7.2.1.1.3. Effects of leakage reactance and armature resistance on modal solutions

The synchronous machine was modelled with leakage reactance X_l and armature resistance R_a neglected. Results were compared with those obtained with R_a and X_l considered in the synchronous machine model.

7.2.1.1.4. Time domain simulations

Time domain simulations were done to verify the interpretation of eigenvalues, frequency and damping on local area oscillatory modes on 4^{th} and 6^{th} order models.

7.2.1.2. System controlled by AVR excitation control, no power system stabilizer

7.2.1.2.1. Effect on 4^{th} order and 6^{th} order generator models

The effect of including the automatic voltage regulator (AVR) on eigenvalues of the SMIB system with a 4^{th} order and a 6^{th} order generators were analysed. Different types of AVR excitation systems supported by each simulation tool were all investigated.

7.2.1.2.2. Time domain simulations

Time domain simulations were done to verify the interpretation of modal solutions for systems with 4^{th} and 6^{th} order synchronous machines.

7.2.1.3. System with AVR excitation and power system stabilizer

7.2.1.3.1. Effect of AVR excitation on 4^{th} and 6^{th} order generator models

The effect of including the automatic voltage regulator (AVR) and the power system stabilizer (PSS) on eigenvalues of the SMIB system with 4^{th} order and 6^{th} order synchronous machine models have been analysed. Different types of AVR excitation systems supported by each simulation tool were investigated.

7.2.1.3.2. Time domain simulations

Time domain simulations were done to verify the interpretation of eigenvalues, frequency and damping on oscillatory modes for systems with 4^{th} and 6^{th} order synchronous machines. Step change in mechanical power input to the synchronous generator and the reference voltage input to the AVR were used as small-disturbances.

7.2.2. 2A4M power system study cases

Small-signal stability analysis of this power system model was performed on manual control with constant PQ load models. Eigenvalues were computed and oscillatory modes analysed.

The inter-area and local area oscillatory modes were identified using mode shapes and participation factors.

The effect of including and neglecting the armature resistance, leakage reactance, saturation and different excitation controls were analysed. Finally, time domain simulations were done on each case and comparisons made on the results of the investigations as follows:

7.2.2.1. Manual control

The system under investigation was modelled on manual control with constant E_{fd} and the following case studies were conducted:

7.2.2.1.1. Generator 3 modelled as a reference machine

This was done to analyse how the use of reference machines affect the total number of states and small-signal stability analysis. Different modelling conventions were used depending on the simulation tool's modelling technique (i.e. Reference machine, infinite bus, slack or swing bus).

Another case was conducted with the power system modelled without a reference or infinite bus. Redundant states and additional eigenvalues were analysed. Results obtained when Bus 3 was set as a reference machine with all generators modelled on manual control were noted for comparison.

Mode shapes and participation factors were computed and plotted using compass plots and histograms for the identification of inter-area and local area modes.

7.2.2.1.2. Effects of armature resistance and leakage reactance on oscillatory modes

The effect of including armature resistance and leakage reactance on all synchronous machines were investigated and results compared with (7.2.2.1.1) above.

7.2.2.2. System with thyristor exciter with high transient gain, no PSS

At this stage, thyristor (AVR) excitation systems with high transient gain were modelled on all synchronous machines and tested. The following simulations were performed:

7.2.2.2.1. Modal analysis on inter-area and local area modes

The effect of modelling generators with high transient gain thyristor excitation controls for primary voltage regulation was investigated. The effects of armature resistance, leakage reactance and saturation were then analysed and a comparison made for all three simulation tools. In PacDyn tool, both the user-defined AVR controllers and built-in AVR models were used to accurately model the simple thyristor AVR excitations system.

The effects of saturation were analysed on all three tools. Mode shapes and participation factors were computed and plotted using compass plots and histograms for the identification of inter-area and local area modes.

7.2.2.3 Thyristor exciter with transient gain reduction (TGR), no PSS

Thyristor (AVR) excitation systems with transient gain reduction (TGR) were then modelled and tested. Modal analysis and time domain simulations were conducted. Their effects on stability of the power system model were determined in modal analysis on inter-area and local area modes.

Time domain simulation results were compared with modal solution results. The effects of saturation were analysed and compared. Eigenvectors and participation factors were used for the identification of inter-area and local area modes.

7.2.2.4. Thyristor exciter with high transient gain and PSS

Thyristor AVR excitation systems described in Case 2 above were modelled together with power system stabilizers and the following simulations performed:

7.2.2.4.1. Modal analysis and time domain simulations on inter-area and local area modes

The effects of thyristor exciters and PSS were determined in modal analysis and time domain simulations. The effects of saturation were analysed. Eigenvectors and participation factors were used to identify oscillatory modes.

7.2.2.4.2. Time domain simulations

Time domain simulations were done using each software simulation tool and the results were compared for all three simulation tools.

7.3 Summary

Two different power system models used for small-signal stability analysis in this thesis were presented. These were modelled and simulated using all three software tools. Identical network data was used for a comparative study. A brief overview of the case studies to be conducted were also presented. Simulation results of all simulation tools are covered in chapter 8.

Chapter 8:

8. Simulation Results And Discussions

8.1 Results on the SMIB model

The SMIB power system was modelled using different synchronous machine models from classical 2nd order to detailed 6th order models. Case studies conducted included generator on manual control where the effects of damping coefficient, saturation, armature resistance and leackage reactance were investigated and compared for all three simulation tools. Other case studies simulated were done when the synchronouns machine was controlled by AVR excitation only as well as AVR and PSS on the generator.

8.1.1 Manual control

a) The effects of damping coefficient without saturation

The synchronous machine on the SMIB power system was modelled using a classical electromechanical generator (2nd order) and all three simulation tools (PacDyn 8.1.1, PSAT 2.1.2 and MatNetEig) gave similar results. The table below shows results from each software tool for different values of damping coefficient (K_d) without saturation considered.

Table 8.1: Effect of damping coefficient on modal solution (classical model)

K_d	PacDyn 8.1.1	PSAT 2.1.2	MatNetEig
0	$\lambda_{1,2}$=0±j6.3862 f=1.0164 Hz ζ=0.00 %	$\lambda_{1,2}$=0±j6.3862 f=1.0164 Hz ζ=0.00 %	$\lambda_{1,2}$=0±j6.3862 f=1.0164 Hz ζ=0.00 %
-10	$\lambda_{1,2}$=0.7143±j6.3461 f=1.01 Hz ζ= -11.185 %	$\lambda_{1,2}$=0.7143±j6.3461 f=1.01 Hz ζ= -11.185 %	$\lambda_{1,2}$=0.7143±j6.3461 f=1.01 Hz ζ= -11.18 %
+10	$\lambda_{1,2}$= -0.7143±j6.3461 f=1.01 Hz ζ=11.185 %	$\lambda_{1,2}$= -0.7143±j6.3461 f=1.01 Hz ζ=11.185 %	$\lambda_{1,2}$= -0.7143±j6.3461 f=1.01 Hz ζ=11.18 %

Table 8.1 shows the eigenvalues, the oscillatory frequencies and damping ratios for different damping coefficients. When using SSView graphical user interface in MatNetEig tool, results are rounded off, resulting in small differences in damping ratios as compared to PacDyn and PSAT results. By making use of the command line version of this tool, all simulation tools gave the same results. The rounded off damping ratio results were ±11.18 % as opposed to ±11.185 % when the damping coefficients were ±10. PacDyn gives damping ratios in percentages while MatNetEig tool gives damping ratios in per unit, additional calculations were done to change these to percentages. PSAT does not provide damping ratios, a Matlab script was written to calculate damping ratios in percentage from the eigenvalues for PSAT in this regard.

A damping coefficient (K_d) of 0.0 resulted in a frequency of 1.0164 Hz and a damping ratio of 0.0 %. When K_d was set to -10, the system became unstable as expected with positive real parts of the eigenvalues oscillating with a frequency of 1.01 Hz and a damping ratio of -11.185 %. A positive damping coefficient (K_d = +10) resulted in a stable system oscillating at 1.01 Hz with a damping ratio of +11.185 %.

A small-disturbance was applied at the mechanical power input of the synchronous machine (Pmec was increased by 0.01 p.u) at time t=0 and lasted for 5 s. Time domain simulation results for the rotor speed response were plotted for five seconds as shown in Fig. 8.1 for the case where the damping coefficient was zero using PacDyn tool.

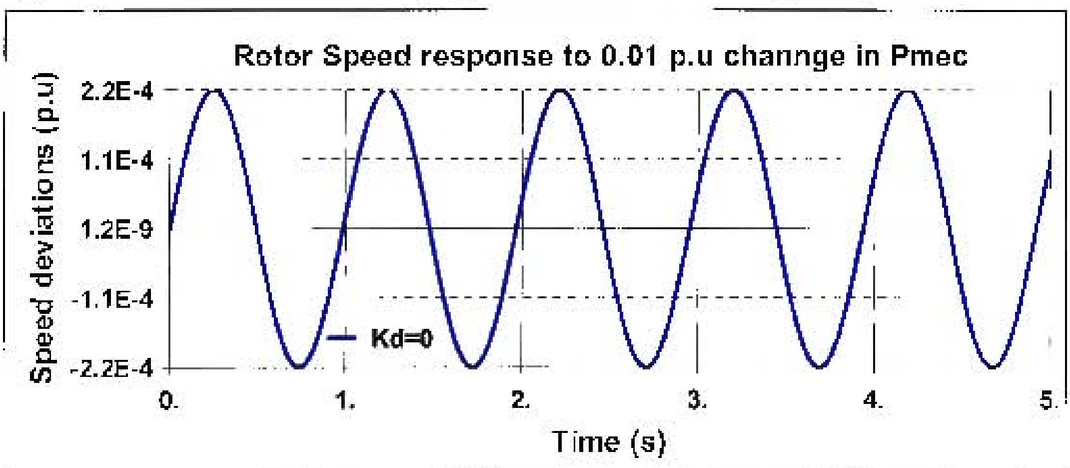


Figure 8.1: PacDyn rotor speed response for no damping coefficient [Kd=0]

Fig. 8.1 shows that there is a no damping on the classical generator in PacDyn simulation tool. The maximum rotor speed deviation is 2.24×10^{-4} per unit.

Sample time measurements were taken to calculate the average period (T_0) and the oscillatory frequency of the rotor speed in Fig. 8.1. The measured frequency was 1.016399 Hz while the frequency from the modal solution was 1.0164 Hz. The difference between this and the measured frequency is $1x10^{-6}$ Hz, small enough to be ignored.

Figure 8.2 shows a step response on the same classical machine model for negative damping coefficient in PacDyn simulation tool.

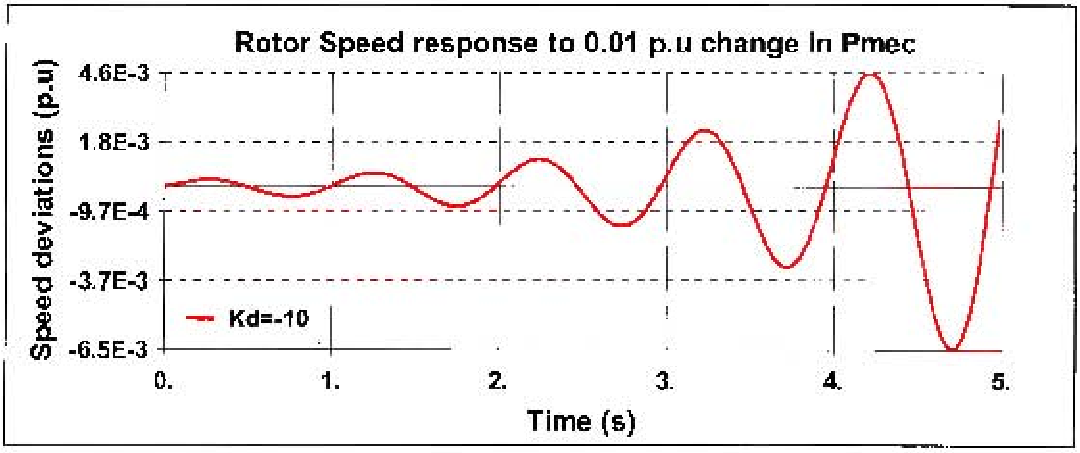


Figure 8.2: PacDyn rotor speed deviation response for negative damping coefficient

A negative damping coefficient (Kd= -10) results in an unstable system with increasing speed amplitude shown in Fig. 8.2 above, agreeing with interpretation of modal solution.

Figure 8.3 shows a step response on the same classical machine model for a positive damping coefficient in PacDyn simulation tool.

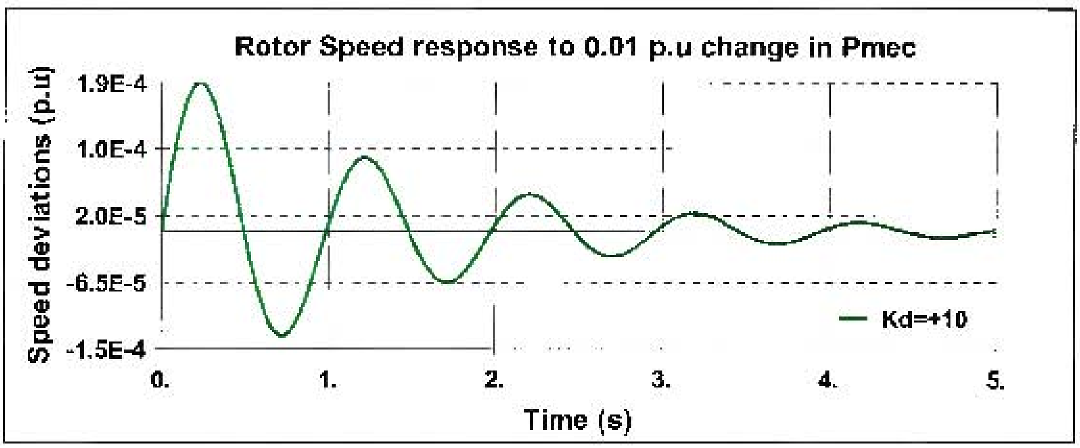


Figure 8.3: PacDyn rotor speed deviation response for positive damping coefficient

When a positive damping coefficient was used, the system response was stable and damped out in five seconds. The graph in Fig. 8.3 confirms what was predicted using modal analysis technique in PacDyn results.

MatNetEig simulation tool was used for time domain simulations and the rotor speed deviations were plotted for different values of the damping coefficient. The disturbance was applied on the synchronous machine's mechanical power input (pmin) where a step change of 0.01 per unit (p.u) was used. The small-disturbance step change was applied at time t=0 and lasted for five seconds. Figure 8.4 below shows the simulation results.

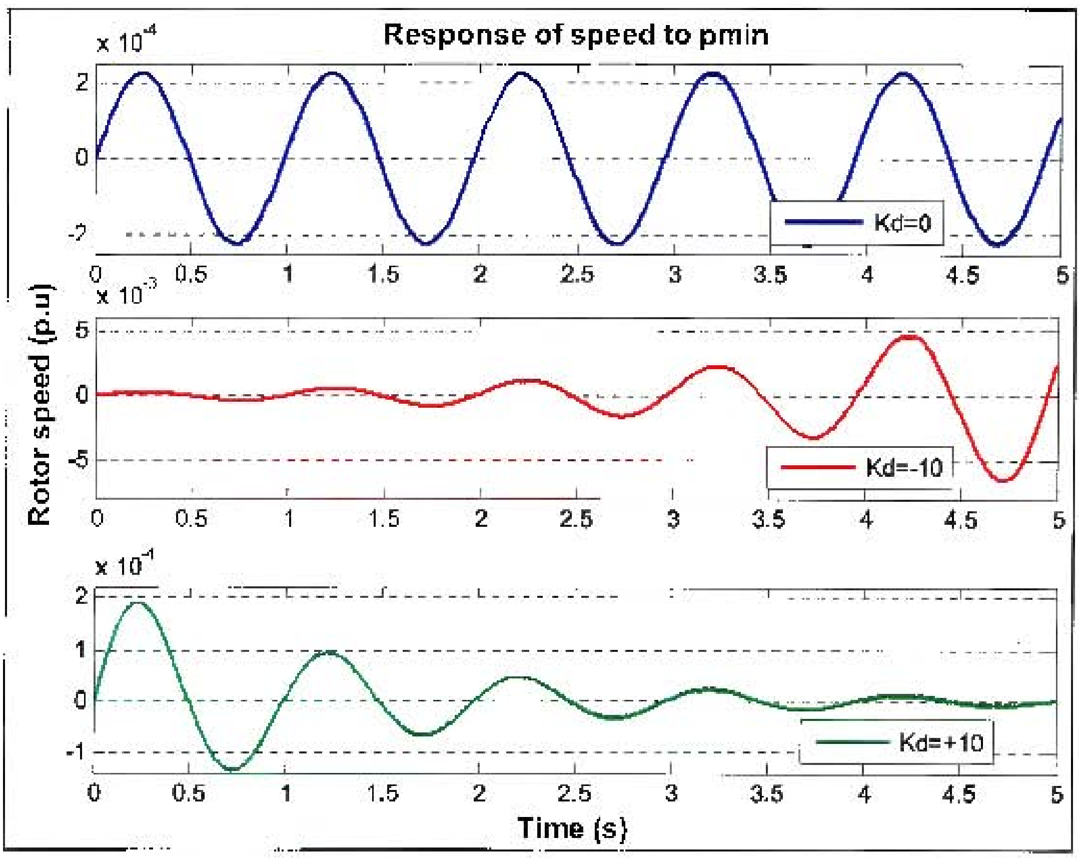


Figure 8.4: MatNetEig rotor speeds response for different damping coefficients

Rotor speed deviation on the top of Fig. 8.4 is for a system with a zero damping coefficient. The system was oscillating with constant amplitude and had a maximum speed deviation of 2.24×10^{-4} p.u showing that there was no damping on the synchronous generator. When the damping coefficient was set to -10, the oscillatory mode was unstable with increasing rotor speed as shown in the middle of Fig. 8.4. The last graph shows the case when the damping coefficient was +10 and the system proved to be stable as indicated by the decaying speed amplitude. The oscillations were damped in five seconds.

The rotor speed response graphs in Fig. 8.4 are similar to those obtained in PacDyn simulation tool results and accurately predict the stability of the power system model as described using modal solutions indicated in table 8.1.

A small disturbance of 0.01 p.u step increase in the mechanical input power of the 2nd order synchronous machine model was simulated using PSAT. PSAT tool gives rotor speeds in per unit as opposed to deviations in PacDyn and MatNetEig. A Matlab script was written to convert result to deviations. The results in Fig. 8.5 below show the rotor speed deviations.

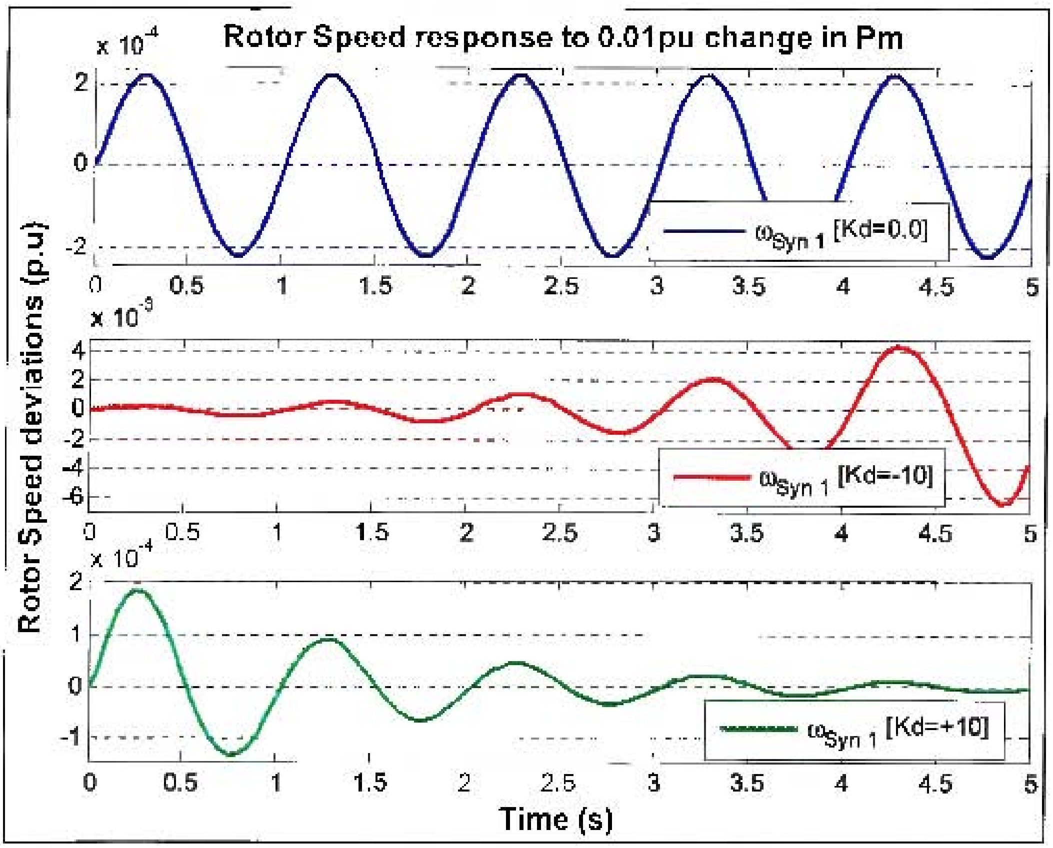


Figure 8.5: PSAT rotor speed response for a small disturbance, Kd effects

The time domain simulation plots in Fig. 8.5 above show an undamped oscillatory mode when the damping coefficient was K_d=0 for the top graph with a maximum speed deviation of 2.24x10^{-4} p.u. The system was unstable for K_d= -10 on the middle graph indicated by a growing speed amplitude on Fig. 8.5 while the system was stable for K_d=+10 on the bottom graph. When the damping coefficient was and K_d=+10, the oscillations were damped in 5 seconds.

PSAT rotor speed plots in Fig. 8.5 predict the system response as interpreted on the modal solution. The oscillatory frequencies from the plots accurately match the frequencies given in the modal solution table.

All three tools gave similar results using both modal analysis technique and rotor speed dynamics for all values of damping coefficient used.

b) Effect of saturation on the generator models

The 4th and 6th order detailed synchronous machines were modelled with leakage reactance (X_l) and armature resistance (R_a) and no damping coefficient (K_d=0) in all synchronous machine models. The effects of including and neglecting saturation have been investigated as shown in table 8.2. The round rotor 4th and 6th order synchronous machines with the exponential saturation (type 1) as described in chapter 5 were used in MatNetEig tool.

Table 8.2: Modal solutions of systems with and without saturation

Case	Order	PacDyn 8.1	PSAT 2.1.2	MatNetEig
Saturation neglected	4th order	$\lambda_{2,3}$= -0.1428±j6.3822 f=1.058 Hz ζ=2.2363 %	$\lambda_{2,3}$= -0.164±j7.1989 f=1.1457 Hz ζ=2.277 %	$\lambda_{2,3}$= - 0.1428±j6.3823 f=1.0158 Hz ζ=2.24 %
	6th order	$\lambda_{2,3}$= -0.203±j6.4206 f=1.0219 Hz ζ=3.1603 %	$\lambda_{2,3}$= -0.2647±j7.2239 f=1.1497 Hz ζ=3.661 %	$\lambda_{2,3}$= -0.203±j6.4207 f=1.0219 Hz ζ=3.16 %
Saturation included	4th order	$\lambda_{2,3}$= -0.1624±j6.4331 f=1.0239 Hz ζ=2.5231 %	$\lambda_{2,3}$= -0.24148±j7.1989 f=1.1457 Hz ζ=3.3525 %	$\lambda_{2,3}$= - 0.1141±j6.4486 f=1.0263 Hz ζ=1.77 %
	6th order	$\lambda_{2,3}$= -0.2109±j6.4012 f=1.0188 Hz ζ=3.2935 %	$\lambda_{2,3}$= -0.34065±j7.2383 f=1.1520 Hz ζ=4.7010 %	$\lambda_{2,3}$= -0.1656±j6.477 f=1.0308 Hz ζ=2.56 %

The results in table 8.2 show that for PacDyn, PSAT and MatNetEig simulation tools; the 6th order machine has higher damping ratios as compared to the 4th order synchronous machine model. The system is stable for all generator models with saturation included and when the saturation is neglected.

The damping ratios are slightly higher on generators with saturation in PacDyn and PSAT while lower for systems with saturation on MatNetEig software tool. PacDyn and MatNetEig gave similar results for systems modelled without saturation. The differences are attributed to different saturation models used by the respective simulation tools.

When using PSAT simulation tool, the frequency and damping ratios remain the same on the 4th order and increased on the 6th order synchronous machine model when the system was modelled with saturation included. The frequency decreased in PacDyn tool while it increased in MatNetEig tools respectively when saturation parameters were included.

The change in frequency (Δf) and damping ratio (Δζ) due to saturation on the 4th order and 6th order synchronous machines were calculated using the following equations (8.1):

$$\begin{aligned} \Delta f &= f_{sn} - f_{si} \\ \Delta \zeta &= \zeta_{sn} - \zeta_{si} \end{aligned} \qquad (8.1)$$

Subscripts "sn" and "si" are for saturation "neglected" and "included" respectively. Results in table 8.3 shows the effects of saturation noted on the frequency and damping ratio by means of deviations in equations (8.1). Δf or Δζ is negative for an increase.

Table 8.3: Damping ratio and frequency deviations due to saturation

Order	Change	Saturation effect on modal solution		
		PacDyn 8.1.1	**PSAT 2.1.2**	**MatNetEig**
4th order	Δf	0.0341 Hz	0.0000 Hz	-0.0105 Hz
	Δζ	-0.287 %	-1.076 %	0.470 %
6th order	Δf	0.0031 Hz	-0.0023 Hz	-0.0089 Hz
	Δζ	-0.133 %	-1.040 %	0.600 %

The frequency deviations due to saturation shown in table 8.3 can be summarised as follows for PacDyn, PSAT and MatNetEig simulation tools: The highest frequency deviation is in PacDyn (a decrease in frequency of 0.0341 Hz) followed by an increase in frequency of 0.0105 Hz in MatNetEig. PSAT gave an increase of 0.0023 Hz on the 6th order and no change on the 4th order model.

The damping ratios changed with a maximum increase of 1.076 % on the 4th order synchronous machine model in PSAT, a maximum damping ratio increase of 0.287 % was noticed on the 4th order machine in PacDyn tool and reductions in damping ratios in MatNetEig with a maximum deviation of 0.6 % on the 6th order machine model.

Saturation in PacDyn for both the 4th and 6th order machine models showed an increase in damping ratio and a decrease in oscillatory frequency. In MatNetEig tool, the inclusion of saturation resulted in an increase in frequency and a reduction in the damping ratio respectively. PSAT tool gave a negligible frequency deviation and higher damping ratio increase on all machine models. The differences are attributed to different mathematical saturation models implemented in these tools as indicated in the Appendix.

c) Time domain simulations showing saturation effects

Time domain simulations were performed and results plotted on one set of axes to compare differences in damping and frequency of oscillations on classical, 4th order and 6th order generator models <u>without saturation</u>. The simulations were done for a step change in mechanical power input to the synchronous machine using PacDyn 8.1.1 simulation tool and results shown in Fig. 8.6.

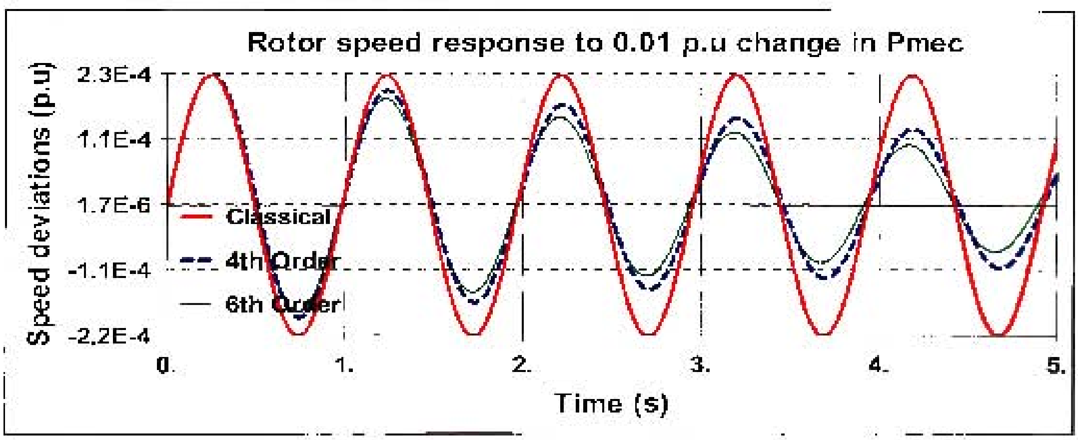


Figure 8.6: PacDyn rotor speed deviation plots for different machine models

The plots on Fig. 8.6 show that the 6^{th} order model has a higher damping ratio compared to 4^{th} order model, which in turn has higher damping ratio compared to the classical machine model. The frequency and damping (decay rate) ratio patterns agree with the interpretation of results found using modal analysis in table 8.2 for the synchronous machine model without saturation.

Similar step response time domain simulations on classical machine, 4^{th} order and 6^{th} order synchronous machine models without saturation included were also observed in PSAT and MatNetEig simulation tools.

Note that the reduction in time period on the graph indicates an increase in frequency while the reduction in amplitude means an increase in damping ratio and vice-versa.

Figure 8.7 shows the effects of saturation on 6^{th} order synchronous machine in PacDyn.

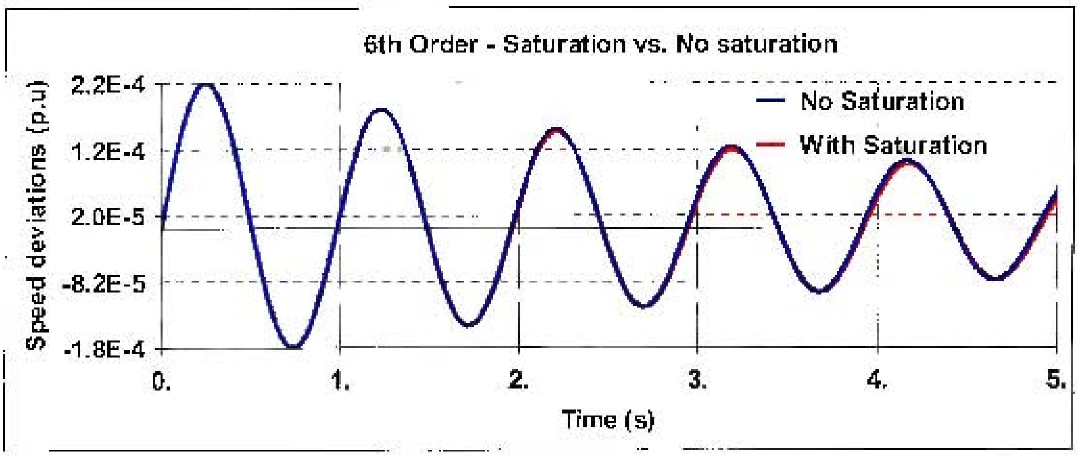


Figure 8.7: PacDyn saturation effects on 6th order synchronous machine models

From the diagram in Fig. 8.7 above, the effects can be neglected over the whole time frame. The difference due to saturation is marginal on the frequency and damping over five seconds simulation interval.

The effects of saturation on the 4^{th} order synchronous machine are negligible during the entire five seconds with a slight increase in damping and frequency noticeable after two seconds on synchronous machine with saturation. The system remains stable when saturation is either included or neglected in these synchronous machine models.

Figure 8.8 shows saturation effects on the 6[th] order synchronous machine in MatNetEig.

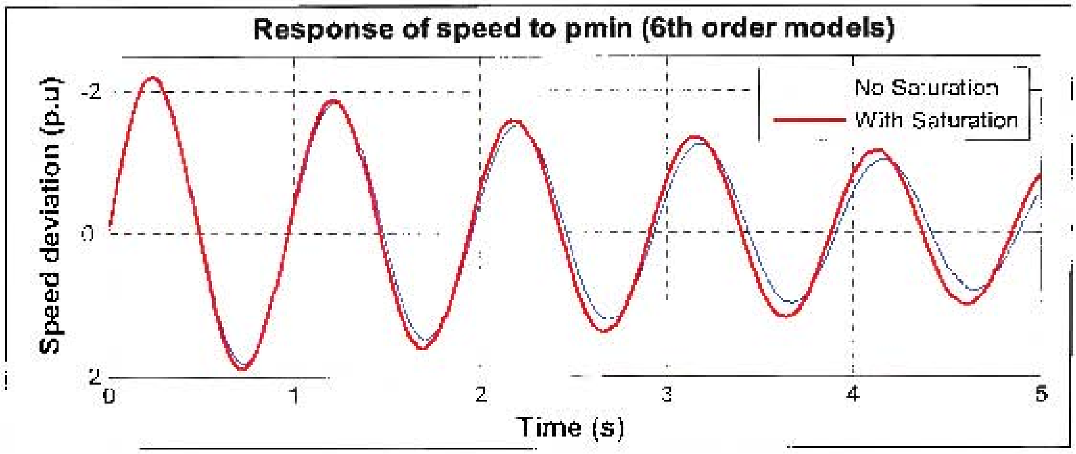


Figure 8.8: MatNetEig speed deviations due to saturation on 6th order model

Figure 8.8 shows that the damping ratio is less and the frequency is high on the system with saturation. This corresponds to the interpretation made on modal analysis. The 4[th] order machine model gave a similar speed response. The effects are small on frequency and damping ratio for the first two seconds. Saturation effects given by MatNetEig are opposite PacDyn results where the damping ratio increased while frequency decreased.

Figure 8.9 shows saturation effects on the rotor speed following a small disturbance described of 0.01 p.u change in mechanical power input as simulated using PSAT tool.

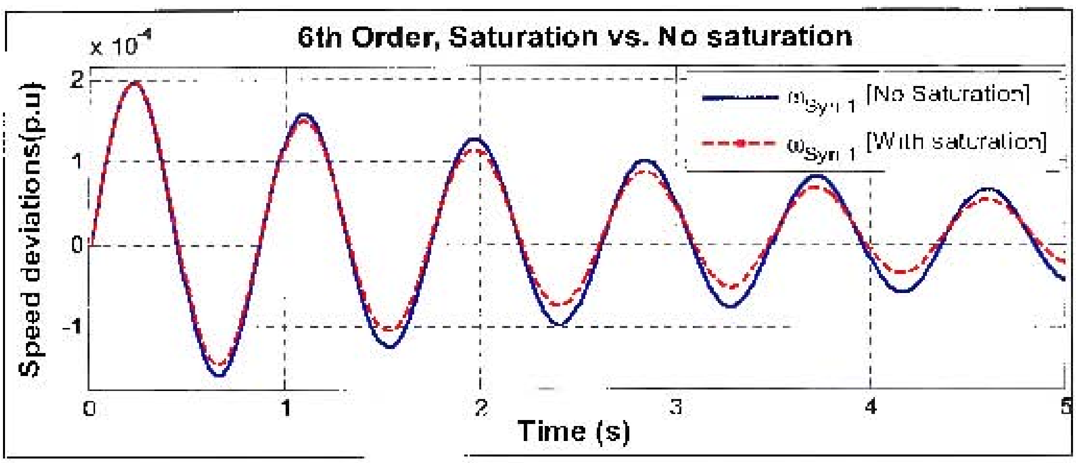


Figure 8.9: PSAT rotor speed plots, effects of saturation on 6th order model

The rotor speeds plotted in Fig. 8.9 show a stable response. The damping is higher when the synchronous machine is modelled with saturation. The effects of saturation on the frequency are negligible but to some extent, high on the damping.

d) Effects of armature resistance and leakage reactance

The effect of neglecting armature resistance (R_a) and leakage reactance (X_l) on the synchronous machine has also been investigated. In general, the resistance can be neglected but not the leakage reactance. However, the leakage reactance has been neglected here in order to investigate the effects of including or excluding these parameters on small-signal stability analysis. For all three power system simulation tools to be analysed, synchronous machine models <u>without</u> saturation were used.

Table 8.4 below shows modal solutions for all three tools when R_a and X_l parameters were neglected, compared with results in table 8.2 when saturation was not included.

Table 8.4: Effects of armature resistance and leakage reactance (no saturation)

Case	Order	PacDyn 8.1	PSAT 2.1.2	MatNetEig
(Ra) and (Xl) not included	4th order	$\lambda_{1,2}$= -0.1429±j6.3591 f=1.0121 Hz ζ=2.246 %	$\lambda_{1,2}$= -0.1429±j6.3591 f=1.0121 Hz ζ=2.246 %	$\lambda_{1,2}$= -0.1429±j6.3591 f=1.0121 Hz ζ=2.246 %
	6th order	$\lambda_{1,2}$= -0.2077±j6.3833 f=1.0159 Hz ζ=3.253 %	$\lambda_{1,2}$= -0.21±j6.3576 f=1.0118 Hz ζ=3.301 %	$\lambda_{1,2}$= -0.2077±j6.3833 f=1.0159 Hz ζ=3.253 %

The change in frequency and damping ratio due to R_a and X_l on classical, 4th order and 6th order synchronous machines were calculated. PacDyn and MatNetEig gave similar results. All tools gave similar result for the 4th order synchronous machine model without R_a and X_l. PSAT results differ with both PacDyn and MatNetEig result on 6th order.

Equations (8.2) below were used to compute the change in frequency (Δf) as well as the change in damping ratio (Δζ):

$$\Delta f = f_i - f_n$$
$$\Delta\zeta = \zeta_i - \zeta_n \qquad (8.2)$$

where the subscripts "i" and "n" indicate "included" or "neglected" respectively. The results in table 8.5 shows the effects as calculated using the above equations.

Table 8.5: Effects of armature resistance and leakage reactance on modal solution

Order	Change	Effects of R_a and X_l on modal solution		
		PacDyn 8.1.1	**PSAT 2.1.2**	**MatNetEig**
4th order	Δf	0.0459 Hz	0.1336 Hz	0.0459 Hz
	$\Delta\zeta$	-0.010 %	0.032 %	-0.010 %
6th order	Δf	0.006 Hz	0.1379 Hz	0.006 Hz
	$\Delta\zeta$	-0.092 %	0.361 %	-0.092 %

Analyses of modal solutions in table 8.4 and deviations on frequency and damping ratios in table 8.5 reveal slight increase in damping ratio (i.e. 0.010 % and 0.092 % on 4th and 6th order machine models respectively), as well as negligible frequency drop on these machine models on both PacDyn and MatNetEig tools when R_a and X_l are neglected.

PSAT results show that neglecting armature resistance and leakage reactance decreases both the frequency and damping ratio of the 4th and 6th order synchronous machines. A maximum damping ratio deviation of 0.361 % and a maximum frequency reduction of 0.1379 Hz were noticed on the 6th order synchronous machine model. These deviations are small and can be ignored in small-signal stability analysis.

Figure 8.10 shows the rotor speed deviation plots when R_a and X_l are both neglected and included in PacDyn simulation tool. A step increase in Pmec of 0.01 p.u was applied. For simplicity, only the 6th order model in all three tools is compared.

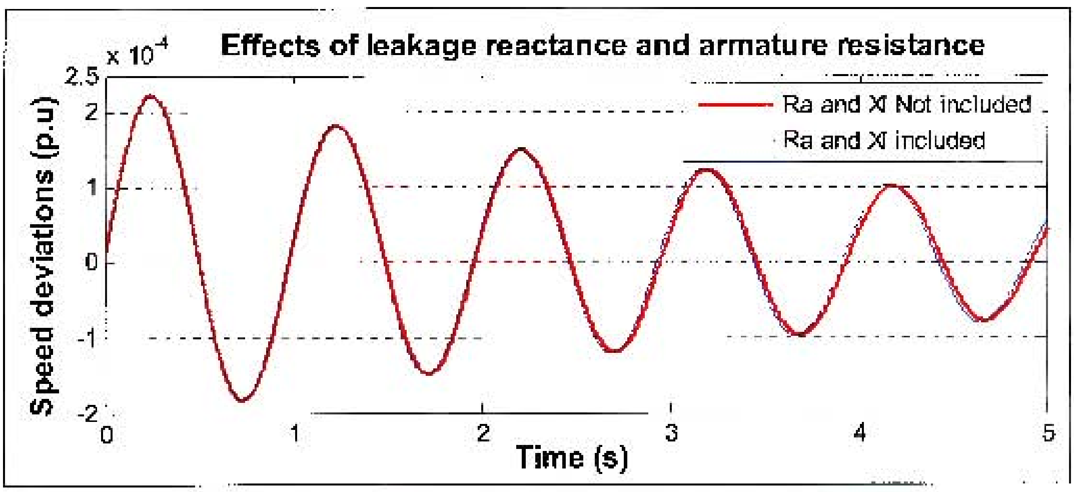


Figure 8.10: PacDyn speed plots: Effects of Ra and Xl on the 6th order machine

Although small and negligible during the first two seconds, the frequency increase can be seen on Fig. 8.10 above when R_a and X_l were included on the last three seconds of the simulation. The effect on damping ratio can be safely ignored in PacDyn simulation tool. MatNetEig step response simulations gave rotor speed deviations response identical to PacDyn plots in Fig. 8.10 above, confirming modal analysis results.

The 6^{th} order synchronous machine with and without R_a and X_l was simulated for a small-disturbance change in mechanical power input. The rotor speed responses were plotted against each other over five seconds in Fig. 8.11 for PSAT simulation results.

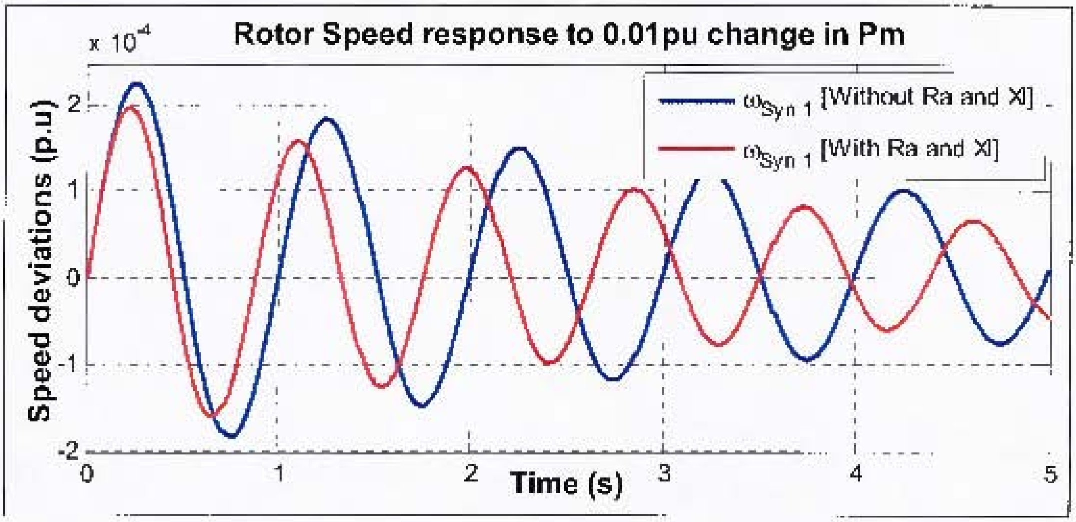


Figure 8.11: PSAT rotor speed plots: Effects of R_a and X_l on the 6th order machine

The rotor speed responses in Fig. 8.11 indicate that the system is stable. The frequency and damping ratio increased when both R_a and X_l are included. At three and half seconds, the two models have rotor speeds at 180 degrees apart. These variations are too big and can not be ignored. The speed response simulation results contradict the modal solution where the effects of neglecting R_a and X_l were negligible on PSAT results.

8.1.2 Generator controlled by AVR excitation with no power system stabilizer

The modal solutions were computed to analyse the effect of AVR excitation control on 4^{th} order and 6^{th} order synchronous machine models with saturation considered. Only the local oscillatory modes are shown and discussed. *The full eigenvalues are in Appendix H.2.*

The simple AVR exciter given by Kundur [21] is modelled using the three simulation tools as follows (*The descriptions and block diagrams are covered in chapters 4, 5 and 6 for PSAT, MatNetEig and PacDyn respectively*):

- PSAT: AVR Type III - simplest AVR model used for "rough" stability analyses.
- MatNetEig: AC Type 7 exciter (AC4a) and Static Type 10 exciter (ST1a).
- PacDyn: Simple AVR excitator represented by built-in model 3 and UDC.

To avoid repetition, modal results for the system under manual control (mc) are not included in this section; Please, refer to section 8.1.1(b) table 8.2 with saturation included. Table 8.6 shows modal solutions for the 4th and 6th order models for all simulation tools.

Table 8.6: Modal solutions of SMIB system with AVR excitation only

Order	PacDyn 8.1.1	PSAT 2.1.2	MatNetEig
4th	λ=0.5123±j7.4098 f=1.1793 Hz ζ= -6.8979 %	λ= -0.3422±j6.9507 f=1.1062 Hz ζ=4.918 %	λ=0.4488±j7.3462 f=1.1692 Hz ζ= -6.1 %
6th	λ=0.4927±j7.3433 f=1.1687 Hz ζ= -6.694 %	λ= -0.5033±j7.0521 f=1.1224 Hz ζ=7.119 %	λ=0.4542±j7.4026 f=1.1782 Hz ζ= -6.12 %

The modal eigenvalues presented in table 8.6 provide the following:

- PacDyn and MatNetEig simulation tools predict that the system is unstable (real parts of the eigenvalues are positive) on the 4th and 6th order synchronous machine models.
- PSAT predicts a stable system for all synchronous machine models. Results from

MatNetEig and PacDyn simulation tools gave five eigenvalues while PSAT gave a total of seven eigenvalues for the power system modelled with a 4th order synchronous machine model and an AVR exciter. For a 6th order machine model, PSAT gave nine eigenvalues while PacDyn and MatNetEig gave seven eigenvalues each. Additional eigenvalues in PSAT are all due to AVR model used. Refer to chapter 4 section 4.2 on modelling of AVR excitation systems for disadvantages of AVR excitation models in PSAT. The simple AVR excitation system used "adds" one additional state on the system and thus PacDyn and MatNetEig results are more realistic than results given by PSAT. PacDyn and MatNetEig are closer to those given by [2, 11, 14, 21, 43].

The effects of the AVR exciter were calculated using the deviation in damping ratios and frequencies on the 4th order and 6th order synchronous machines using equations (8.3).

$$\begin{aligned} \Delta f &= f_{mc} - f_{AVR} \\ \Delta \zeta &= \zeta_{\mathrm{mc}} - \zeta_{AVR} \end{aligned} \tag{8.3}$$

The subscripts "mc" and "AVR" are for "manual control" and "AVR excitation control" respectively. Table 8.7 shows the effects as calculated using equations (8.3).

Table 8.7: SMIB with AVR only: Effects on frequency and damping ratios

Order	**Change**	**Frequency and damping ratios deviations due to AVR**		
		PacDyn 8.1.1	**PSAT 2.1.2**	**MatNetEig**
4th order	Δf	-0.1554 Hz	0.0395 Hz	-0.1534 Hz
	Δζ	9.420 %	-1.566 %	8.340 %
6th order	Δf	-0.1499 Hz	0.0296 Hz	-0.1563 Hz
	Δζ	9.988 %	-2.418 %	9.280 %

It is evident from table 8.7 that the AVR exciter had marginal increase in frequency on PacDyn and MatNetEig tools for all two synchronous machine models. The frequency decreased in PSAT results for all models with AVR exciters. There were higher reduction in damping ratios of 9.42 % and 9.988 % for both 4th and 6th order machine models in PacDyn respectively, while the reduction in damping ratios were 8.34 % and 9.28 % on 4th and 6th order machines respectively in MatNetEig. Damping ratios in PSAT increased on the 4th and 6th order machine models by 1.566 % and 2.418 % respectively. Negligible variations in results were noticed between PacDyn and MatNetEig results.

Time domain simulation rotor speed deviation plots for a step change of 0.01 p.u mechanical input power change were simulated. PacDyn and MatNetEig tools' time domain simulations gave unstable oscillatory speed deviations with negligible differences in amplitudes. Differences are due to the saturation models used by these simulation tools as predicted using modal analysis. PSAT step response indicated a decaying speed with very little damping. PacDyn and MatNetEig simulation tools' results are closely related and comparable for the purpose of small-signal stability analysis.

8.1.3 System controlled by an AVR and a power system stabilizer

Modal solution and the effects of AVR exciter and power system stabilizer (PSS) on 4th and 6th order synchronous machine models were analysed. All synchronous machines were modelled with R_a, X_l and saturation considered. A PSS model and data given by [21] was used with peed input signal. Eigenvalues found were compared for all three simulation tools as shown in table 8.8.

Table 8.8: Modal solutions of SMIB system with AVR and PSS

Case	Order	PacDyn 8.1.1	PSAT 2.1.2	MatNetEig
Manual control	4th order	λ= -0.1624±j6.4331 f=1.0239 Hz ζ=2.5231 %	λ= -0.24148±j7.1989 f=1.1457 Hz ζ=3.3525 %	λ= -0.1141±j6.4486 f=1.0263 Hz ζ=1.77 %
	6th order	λ= -0.2109±j6.4012 f=1.0188 Hz ζ=3.2935 %	λ= -0.34065±j7.2383 f=1.1520 Hz ζ=4.7010 %	λ= -0.1656±j6.477 f=1.0308 Hz ζ=2.56 %
AVR and PSS	4th order	λ= -1.0806±j6.6851 f=1.064 Hz ζ=15.958 %	λ=0.1787±j7.5872 f=1.2075 Hz ζ= -2.355 %	λ= -0.9183±j6.7085 f=1.0677 Hz ζ=13.56 %
	6th order	λ= -1.058±j6.7366 f=1.0722 Hz ζ=16.199 %	λ=0.1645±j7.499 f=1.1935 Hz ζ= -2.193 %	λ= -1.0061±j6.7253 f=1.0704 Hz ζ=14.8 %

Table 8.8 shows that the system with either 4th or 6th order synchronous machine model is stable and well damped in PacDyn and MatNetEig tools. The damping ratio of the 6th order synchronous machine is higher than that of the 4th order synchronous machine. PSAT results show that the system is unstable as indicated by positive real parts of the eigenvalues on all synchronous machine models with AVR and PSS.

PacDyn is more optimistic compared to MatNetEig that has slightly lower damping ratios. PSAT results are incorrect in this case study.

The change in damping ratios and oscillatory frequencies on the 4th order and 6th order synchronous machines were calculated using (8.4).

$$\Delta f = f_{mc} - f_{AVR+PSS}$$
$$\Delta \zeta = \zeta_{mc} - \zeta_{AVR+PSS} \tag{8.4}$$

where the subscripts "mc" indicates system on "manual control" and "AVR+PSS" indicates system with AVR and PSS excitation control. An increase in damping ratio is indicated by a negative deviation ($\Delta\zeta$) while a negative frequency deviation is for an increase due to AVR and PSS on the synchronous machine model. The effects of AVR and PSS are shown in table 8.9 as calculated using equations (8.4).

Table 8.9: SMIB with AVR and PSS effects on frequency and damping ratios

Order	Change	System with AVR and PSS		
		PacDyn 8.1.1	**PSAT 2.1.2**	**MatNetEig**
4th order	Δf	-0.0401 Hz	-0.0618 Hz	-0.0414 Hz
	$\Delta\zeta$	-13.435 %	5.708 %	-11.79 %
6th order	Δf	-0.0534 Hz	-0.0415 Hz	-0.0396 Hz
	$\Delta\zeta$	-12.906 %	6.894 %	-12.24 %

Changes in damping ratios and frequencies in table 8.9 can be summarised as follows:

PacDyn and MatNetEig simulation tools' results: Both the frequency and damping ratio increased on all synchronous machine models. The maximum change in frequency for PacDyn was found to be on the 6th order machine (0.0534 Hz) while the maximum frequency deviation in MatNetEig was on the 4th order machine (0.0414 Hz). The deviation in damping ratio in PacDyn is higher on the 4th order compared to 6th order machine model while in MatNetEig it is higher on the 6th order compared to 4th order synchronous machine model.

PSAT results showed an increase in frequency for systems modelled with AVR and PSS compared to systems modelled under manual control. The frequency deviation was maximum on the 4th order machine model (i.e. Δf=0.0618 Hz). The damping ratios decreased in all machines. The damping ratio deviation on 6th order model in PSAT was +6.894 % compared to -12.906 % and -12.24 % in PacDyn and MatNetEig respectively. The type of PSS used in PSAT does not accurately model the one given by Kundur [21].

Time domain simulation plots for system with AVR and PSS

Time domain simulations were performed to validate and verify modal solutions. PacDyn's rotor speed plots for small disturbance in the generator's mechanical input power (Pmec) as well as the reference input voltage of the AVR (Vref) in Fig. 8.12.

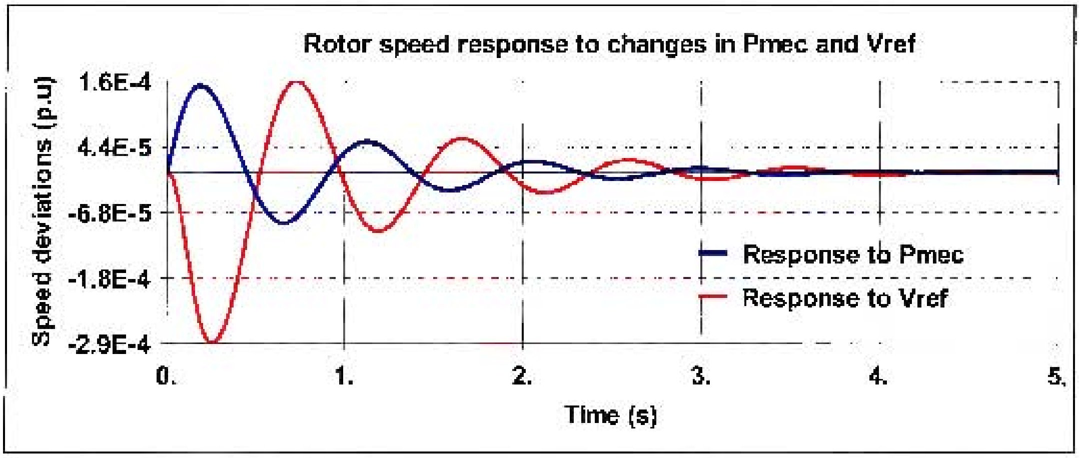


Figure 8.12: PacDyn rotor speed plot for a 6th order machine with AVR and PSS

The system is stable and the oscillations in PacDyn's 6^{th} order synchronous machine model were damped in four seconds for all disturbance types. The maximum speed deviation was $1.56x10^{-4}$ when a step change was applied on the reference voltage.

Figure 8.13 shows the speed responses to the reference voltage of the AVR (Vref) as well as mechanical power input (Pmin) in MatNetEig simulation tool.

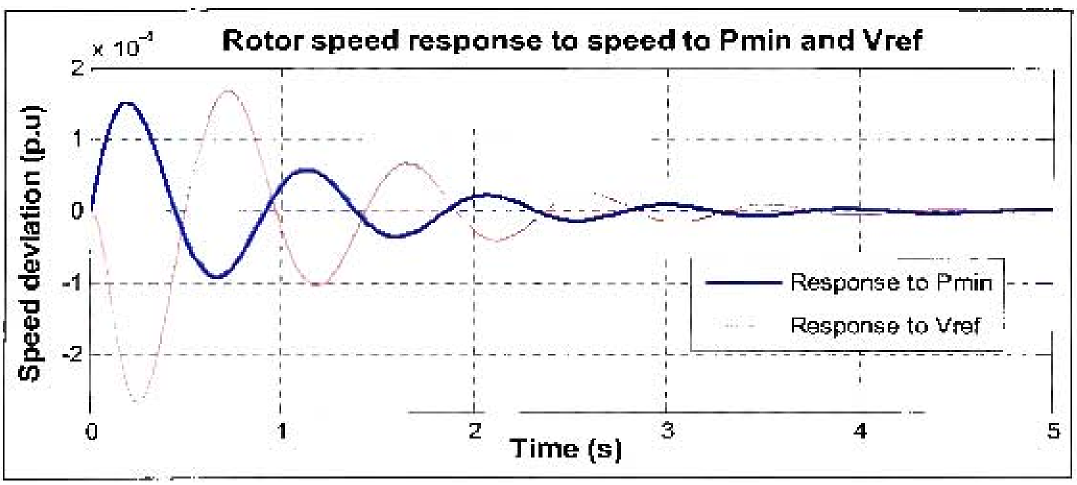


Figure 8.13: MatNetEig rotor speed for 6th order machine with AVR and PSS

Rotor speed deviations plots for a step disturbance in Pmin as well as Vref closely match those in PacDyn. The system is stable and damped in four seconds in MatNetEig. The responses are as predicted by the interpretation of modal solution for a system with AVR and a PSS where the system is stable with negative real part on the eigenvalues. The response in Fig. 8.13 matched PacDyn simulation results. The maximum speed deviation was 1.68×10^{-4} when a step change was applied on the reference voltage.

Figure 8.14 indicates time domain simulations results in PSAT for a small disturbance on the mechanical input power.

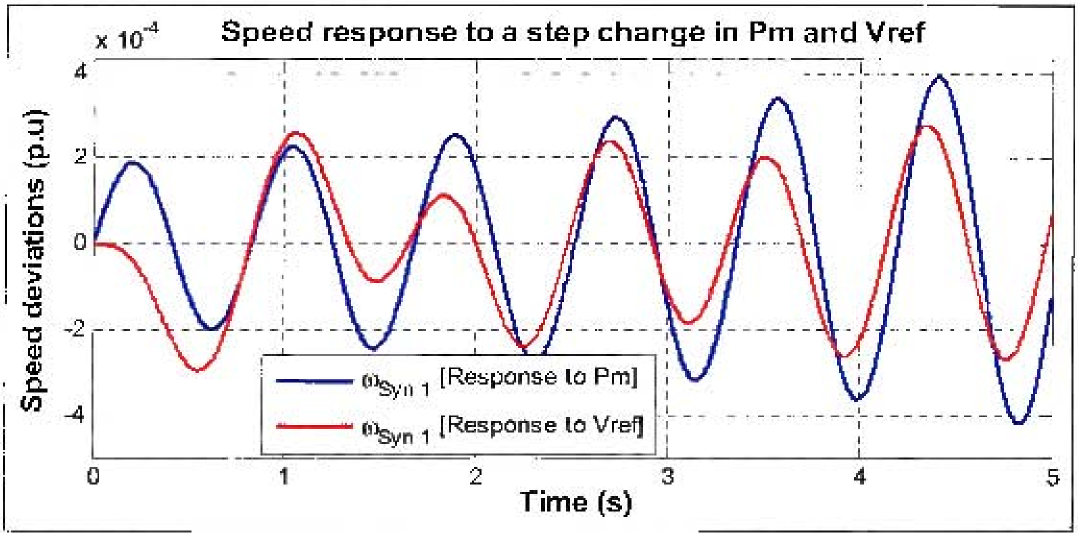


Figure 8.14: PSAT speed responses for 6th order with AVR and PSS

The rotor speed responses to step changes in Pm and Vref indicated Fig. 8.14 above show unstable system for all types of disturbances. Reference to [2, 11, 14, 21, 42] shows that PacDyn and MatNetEig are more optimistic while PSAT results are incorrect for this power system model.

8.1.4 Accessibility of the system's A state matrix in the simulation tools

The use of command line tools in PSAT and MatNetEig simulation tools provide access to the **A** matrix of the power system model. PacDyn simulation tool has an option to export the state space model that can be read by the accompanying Matlab script codes to construct the **A** matrix. *The* ***A*** *state matrix from all three simulation tools for the classical machine model, 6th order model on manual control, 6th order on AVR excitation and 6th order model on AVR and PSS excitation systems are included in the Appendix H, section H.3.*

8.2 Results on the 2A4M system model

The synchronous machine models were modelled using 6^{th} order models for all four machines. The effects of varying damping coefficients, including as well as neglecting R_a, X_l and saturation have been investigated. Additional simulated cases included the effects of static non-linear ZIP (and voltage dependent VDL in PSAT) loads as opposed to constant PQ load models using all three simulation tools. Inter-area and local area oscillatory modes were identified and comparisons made on these modes using modal analysis and time domain simulations.

8.2.1 Manual control

The first test case was modelled with generator number 3 set as a reference machine in PacDyn tool. The eigenvalues computed gave 23 modes with two local area modes and one inter-area oscillatory mode. Both PSAT and MatNetEig gave 24 eigenvalues. This was due to the absence of absolute rotor angular reference in PSAT and MatNetEig tools. When the system was modelled without a reference bus in PacDyn, the tool gave 24 eigenvalues with one pair of oscillatory mode close to the origin.

PSAT tool does not allow small-signal stability analysis of a system without at least one slack bus while MatNetEig requires one bus to be defined as a swing generator in order to successfully get a converged load flow solution and initialize dynamic components. This resulted in no redundant states in both PSAT and MatNetEig tools.

The infinite bus in PacDyn was modelled as described in chapter 6 section 6.2. In MatNetEig tool, the infinite bus (Bus 3) was set using the command "**setib**" as described in chapter 5 section 5.2. To set an infinite bus in PSAT, a swing bus is defined using **SW.con** with the synchronous machine on that specific bus. The eigenvalues found were 18 for all simulation tools when the generator on bus 3 was set as an infinite bus.

The infinite bus and reference bus in these power system simulation tools eliminated redundant states on the system modes. This is consistent with [2, 11, 14, 21, 43].

Table 8.10 shows the modal solutions for the inter-area and local area modes in all three software tools for the system on manual control with constant PQ loads. The system was still modelled with generator 3 set as a reference bus in PacDyn or swing bus in both

PSAT and MatNetEig simulation tools. The synchronous machines were all modelled neglecting saturation and the effects of armature resistance and leakage reactances were analysed in all tools.

Table 8.10: Manual control: Inter-area and local area modes

Case	Mode	PacDyn 8.1.1	PSAT 2.1.2	MatNetEig
R_a and X_l neglected	Inter-area	λ= -0.09919±j3.4218 f=0.5446 Hz ζ=2.898 %	λ= -0.26259±j3.3127 f=0.5272 Hz ζ=7.902 %	λ= -0.09921±j3.422 f=0.5446 Hz ζ=2.898 %
	Local area 1	λ= -0.572±j6.6935 f=1.0653 Hz ζ=8.514 %	λ= -0.57005±j6.5517 f=1.0427 Hz ζ=8.668 %	λ= -0.5719±j6.694 f=1.065 Hz ζ=8.514 %
	Local area 2	λ= -0.576±j6.9176 f=1.101 Hz ζ=8.299 %	λ= -0.57992±j6.698 f=1.066 Hz ζ=8.626 %	λ= -0.576±j6.914 f=1.101 Hz ζ=8.298 %
R_a and X_l considered	Inter-area	λ= -0.09211±j3.4265 f=0.5453 Hz ζ=2.687 %	λ= -0.20162±j3.7576 f=0.5980 Hz ζ=5.358 %	λ= -0.09213±j3.427 f=0.5453 Hz ζ=2.688 %
	Local area 1	λ= -0.5726±j6.8115 f=1.0841 Hz ζ=8.376 %	λ= -0.89861±j7.8217 f=1.2449 Hz ζ=11.414 %	λ= -0.5726±j6.811 f=1.0841 Hz ζ=8.376 %
	Local area 2	λ= -0.5742±j7.0355 f=1.1197 Hz ζ=8.1343 %	λ= -0.9227±j8.0393 f=1.2795 Hz ζ=11.403 %	λ= -0.5742±j7.036 f=1.1197 Hz ζ=8.134 %

Table 8.10 above shows that the system is stable in all tools. There are low damping ratios in PacDyn and MatNetEig in the inter-area mode. PSAT has higher frequency and much higher damping ratios compared to MatNetEig and PacDyn in all modes. The results in MatNetEig are similar to results given by PacDyn when R_a and X_l are neglected, the differences are due to rounding errors discussed in in section 8.1.1 (b).

PacDyn and MatNetEig gave results that are closely similar with the following due to R_a and X_l: The frequencies increased in all modes with a maximum deviation of 0.0188 Hz in local area 1, wich is small and negligible. The damping ratios decreased in all modes, the maximum deviation is 0.1647 % in local area 2 mode due to the inclusion of R_a and X_l in the generator models.

The frequency differences between PSAT and PacDyn are 0.0527 Hz in inter-area mode, 0.1608 Hz in local area 1 and 0.1598 Hz in local area 2. The maximum damping ratio difference is 2.671 % in inter-area mode when both R_a and X_l were neglected and it is 3.038 % in local area 1 and 3.269 % in local area 2 when these parameters are considered respectively. These differences are big and can not be neglected.

Both PacDyn and MatNetEig tools' results are consistent with recent research and analyses results in this model and therefore deemed correct.

8.2.1.1. Effects of Damping coefficients on frequency and damping ratios

Similar to the test case simulated on the SMIB power system model, the 2A4M model was analyed for the effects of varying the damping coefficients. Three damping coefficient values (K_d=0, K_d=-10 and K_d=+10) were used for the synchronous machines modelled without saturation while both R_a and X_l were included. Table 8.11 below shows results found when K_d was set to zero on all four generators.

Table 8.11: Manual control modes for zero damping coefficients on MatNetEig

Kd=0	Eigenvalue	Freq. (Hz)	Damp (%)	Mode (Bus number)
Inter-area	-0.09213±j3.427	0.5453	2.688	Speed BUS 01
Local area-1	-0.5726±j6.811	1.0840	8.376	Speed BUS 01
Local area-2	-0.5742±j7.036	1.1197	8.134	Speed BUS 01

The system was modelled and simulated for the cases when the damping coefficient values were set to K_d=-10 and K_d=+10 respectively and K_d=+10 respectively and the results (included in the Appendix) were analysed. Table 8.12 shows the effects of varying K_d on the modal frequency and damping ratios as simulated in MatNetEig

Table 8.12: Effects of damping coefficients on frequency and damping ratios

Case		Δf (Hz)	Δζ (%)		Case	Δf (Hz)	Δζ (%)
Kd=-10	Inter-area	0.0063	11.640%		Kd=+10	0.0012	-11.432%
	Local area-1	0.0031	5.897%			1E-04	-5.844%
	Local area-2	0.004	5.993%			0.0003	-5.936%

A negative damping coefficient (Kd=-10) decreased both the frequency and damping ratio while a positive damping coefficient (Kd=+10) resulted in an increase in both the frequency and damping ratios on the local and inter-area oscillatory modes. The effects are small and negligible on the frequency but big on the damping ratios on all three simulation tools. The system remained stable for all values of damping coefficient used on PadDyn while unstable on the inter-area mode on PSAT and MatNetEig tools for a damping coefficient of -10. PSAT and PacDyn tools' result are in Appendix.

8.2.1.2. Identification of oscillatory modes in PacDyn software

The sensitivities of the generators' rotor speeds were computed in PacDyn in the electromechanical oscillatory modes using mode shapes and participation factors. These mode shapes and participation factors were calculated on the selected modes associated with speed output of the synchronous machines to show how generators are oscillating against each other. This helped to identify inter-area and local area oscillatory modes.

Mode shapes indicate relative magnitude and phase of oscillations of a given system variable while participation factors give a measure of how a given state variable participate in an oscillatory mode.

Different forms of sensitivity results from PacDyn are available (i.e. polar plots, histograms and lists). Figure 8.15 (a) and (b) show mode shapes for the system with synchronous generators on manual control using polar plots and histograms. *The list of mode shapes showing amplitudes, phase angles and bus names together with the bus numbers for participating generators are included in Appendix H.2.*

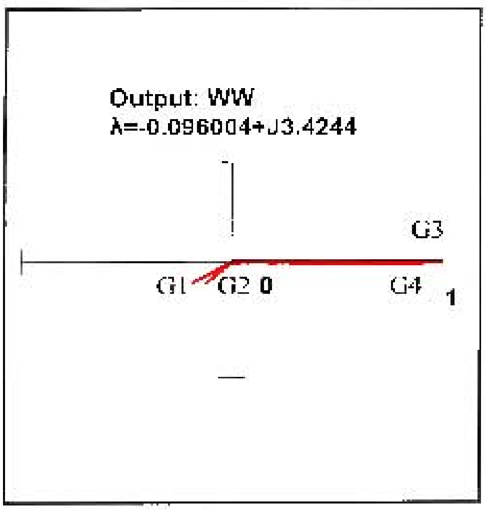


Figure 8.15(a) Mode shapes: Manual control

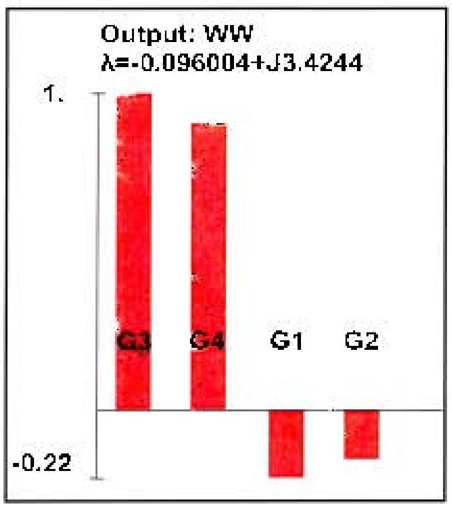


Figure 8.15(b) Mode shapes: Histograms

The results in Fig 8.15 (a) and (b) show the following reports for analysis of the eigenvalue $\lambda = -0.096 + j3.4244$:

(a) Mode shapes in polar plot for all four generators participating in the speed mode.

(b) The same mode shapes in (a) were presented using Histograms with relative amplitudes and directions taken into consideration.

The mode shapes in Fig. 8.15 indicate that generators 1 and 2 are swinging together against 3 and 4. It is an inter-area mode with two areas swinging against each other.

The results in Fig.8.16 indicate mode shapes for the eigenvalue λ= -0.5759+j6.7766:

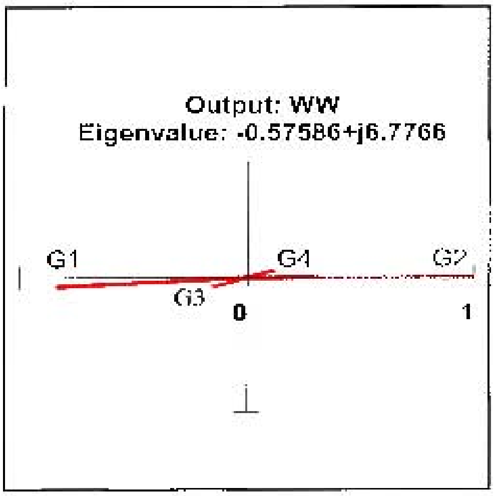


Figure 8.16(a) Manual control: Mode shapes (Polar)

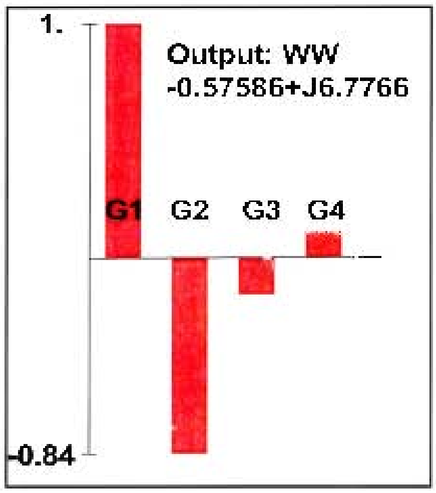


Figure 8.16(b) Manual control: Mode shapes (Histograms)

The results in Fig.8.16 indicate the following for both (a) and (b) respectively on the given eigenvalue; where (a) is polar plot and (b) is a histogram of the mode shapes: Generator 1 is oscillating against generator 2 while negligible generators 3 and 4 are and oscillating against each other. This is a local area 1 oscillatory mode.

The results in Fig. 8.17 (a) and (b) indicate the mode shapes using vector plot and histograms for the eigenvalue λ= -0.5795+j7.0008:

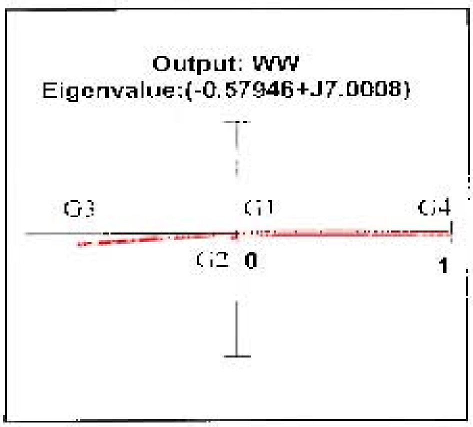


Figure 8.17(a) Manual control: Polar

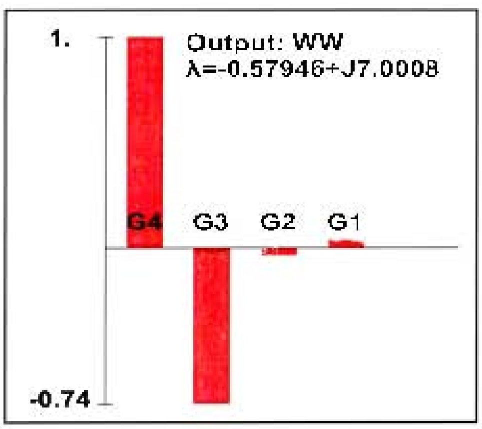


Figure 8.17(b) Manual control: Histograms

The modeshapes in polar plot (a) and histograms (b) of Fig. 8.17 indicate that the synchronous machine 3 is oscillating against machine 4 while generators 1 and 2 are negligible on this mode. This mode is a local area 2 mode.

Apart form the mode shapes, PacDyn provides participation factors in the form of lists and histograms. The speed mode participation factors for the system on manual control in PacDyn were computed as shown using the histograms in Fig. 8.18 (a), (b) and (c).

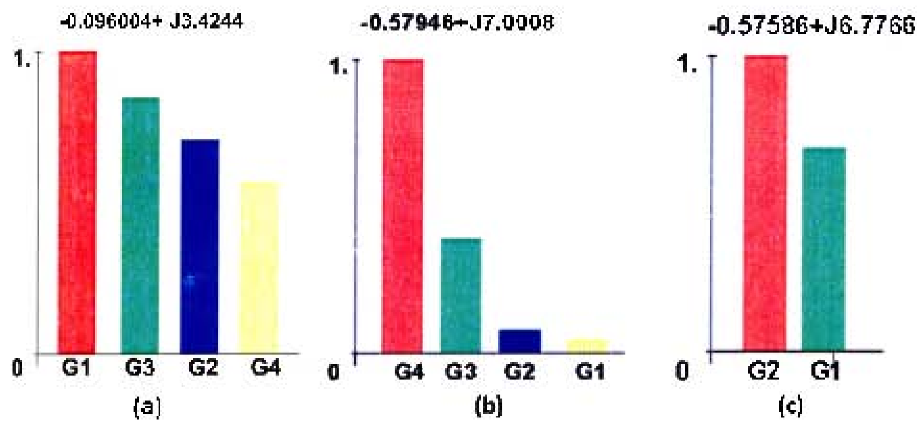


Figure 8.18: Manual control: Participation factors

The histograms shown in Fig. 8.18(a), (b) and (c) indicate the following for the eigenvalues specified on the titles:

(a) Generators 3 and 4 have higher participation factors as compared to generators 1 and 2. Analysis of the amplitudes and phase angles revealed that generators 1 and 2 are oscillating against generators 3 and 4. This is an inter-area mode.
(b) Generator 3 oscillates against generator 4. This is a local area 2 oscillatory mode where generators in area 1 have negligible participation factors.
(c) Generator 1 is oscillating against generator 2. The mode is a local area 1 oscillatory mode.

8.2.1.3. Identification of inter-area and local area oscillatory modes in PSAT

PSAT simulation tool gives participation factors using the magnitudes (Euclidean norm) on each eigenvalue computed. These are indicated on the eigenvalue report file after small-signal stability simulation. Participation factors associated with each mode were noted and the histograms used to indicate relative participation of each generator on the speed mode. Figure 8.19 shows results for the system on manual control.

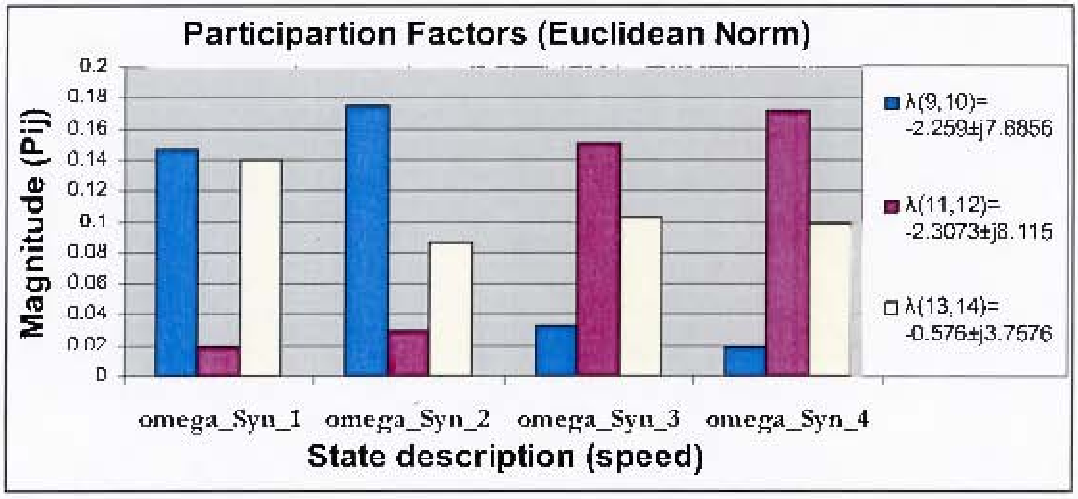


Figure 8.19: PSAT Participation factors for system on manual control

The bar plots have the following interpretations for a system on manual control:

- The eigenvalues $\lambda_{(9,10)}$ have dominant participation factors on rotor speeds on generators 1 and 2 indicating that an electromechanical local area mode in area 1.
- Eigenvalues $\lambda_{(11,12)}$ have dominant participation factors in area 2 where generator 3 is oscillating against generator 4. This speed oscillatory mode is a local area 2 mode.
- Modes $\lambda_{(13,14)}$ show that all synchronous machines are participating on the speed oscillatory mode. Generators 1 and 2 are swinging together against generators 3 and 4 in area 2. This mode is an inter-area oscillatory mode.

It was noticed that participation factors on rotor speeds were equal to the rotor angle participation factors for all generators.

8.2.1.4. Identification of inter-area and local area oscillatory modes in MatNetEig

MatNetEig tool provides the list of eigenvectors and participation factors in complex forms. Eigenvectors associated with oscillatory rotor speeds of all generators were taken from the results of the small-signal stability simulations and plotted in vectors formats using compass plots. Figure 8.20 (a), (b) and (c) show the process used to identify inter-area and local area modes for the system on manual control using eigenvectors in compass plot formats.

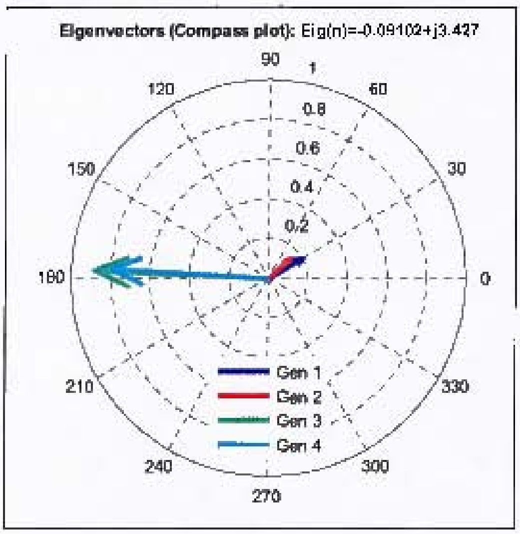


Figure 8.20(a) Manual Control

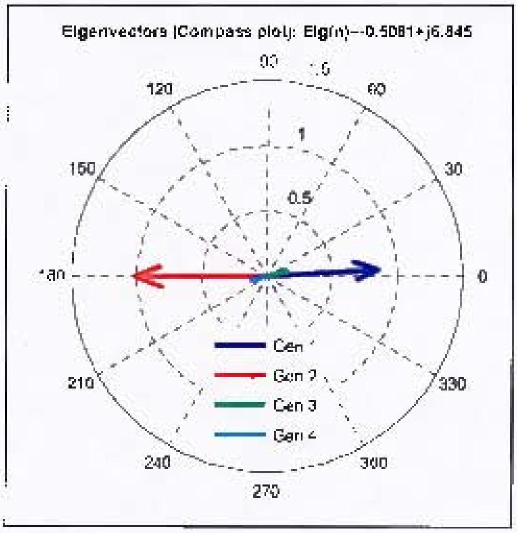


Figure 8.20(b) Manual Control

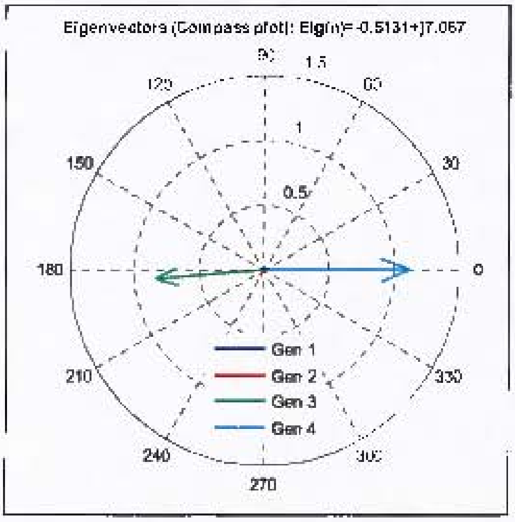


Figure 8.20(c) Manual Control

The diagrams in (a), (b) and (c) show the eigenvectors in compass plots for MatNetEig simulation tool.

The eigenvectors were calculated on the oscillatory modes given by the eigenvalue indicated on the title of each compass plot.

These three modes can be interpreted as follows for system on manual control:

(a) Indicates that generators 3 and 4 in area 2 are swinging together against generators 1 and 2 in area 1. This mode is an inter-area mode with area 1 oscillating against a stronger area 2.

(b) Shows that generator 1 and 2 are oscillating against each other. This mode is a local area 1 electromechanical oscillatory mode.

(c) Indicates a local area 2 mode with generator 4 oscillating against 3. The generators in area 1 have negligible eigenvectors on this mode.

The eigenvalues computed by each of the three tools were investigated and analysed. Electromechanical oscillatory modes associated with rotor speed modes were identified using participation factors and eigenvectors as either inter-area or local area modes.

The system has one inter-area mode and two local area modes. One local area mode was identified in area 1 where generator number 1 is oscillating against generator number 2; this was shown as local area 1. The second local area mode was identified in area 2 where generator 3 is oscillating against generator 4; this mode is shown on as local area 2.

8.2.1.5. Effects of saturation on modal solution of systems on manual control

Table 8.13 shows the modal solutions for the inter-area and local area modes in all three simulation tools for the system under manual control with saturation considered. The results are compared with those in table 8.10 when saturation was neglected. Both R_a and X_l were included these case studies.

Table 8.13: Manual control: Effects of saturation on inter-area and local area modes

Case	Mode	PacDyn 8.1.1	PSAT 2.1.2	MatNetEig
Saturation considered (With R_a and X_l included)	Inter-area	λ= -0.09564±j3.4238 f=0.5449 Hz ζ=2.792 %	λ= -0.21811±j3.7593 f=0.5983 Hz ζ=5.792 %	λ= -0.0906±j3.428 f=0.5456 Hz ζ=2.653 %
	Local area 1	λ= -0.549±j6.809 f=1.0837 Hz ζ=8.036 %	λ= -0.95557±j7.8289 f=1.2460 Hz ζ=12.116 %	λ= -0.5086±j6.847 f=1.09 Hz ζ=7.408 %
	Local area 2	λ= -0.5527±j7.0328 f=1.1193 Hz ζ=7.8352 %	λ= -0.98057±j8.0471 f=1.2807 Hz ζ=12.096 %	λ= -0.5135±j7.069 f=1.125 Hz ζ=7.245 %

It is evident from table 8.13 that the system is still stable in all three tools. MatNetEig and PacDyn still have relatively lower damping ratios while the damping ratios in PSAT results are adequate in all modes. When comparing the results with those in table 8.10 with R_a and X_l included; PacDyn gave slight decrease in frequency in all modes, an increase in damping ratios in the inter-area mode. PSAT gave an increase in frequency in local area 1 mode while MatNetEig tool showed an increase in frequency in all modes as well as a decrease in damping ratios.

The effects of including saturation on synchronous machines can easily be analysed using deviations in frequency and damping ratios using the following equations (8.5):

$$\begin{aligned} \Delta f &= f_{sn} - f_{si} \\ \Delta\zeta &= \zeta_{sn} - \zeta_{si} \end{aligned} \qquad (8.5)$$

The subscripts "sn" and "si" are for saturation "neglected" and "included" respectively. Results from table 8.10 and 8.13 were used to calculate variations in frequency and damping ratios using equations (8.5).

The deviations are shown in table 8.14.

Table 8.14: Manual control: Effects of saturation on oscillatory modes

Mode	Change	Effects of saturation on modal solution		
		PacDyn 8.1.1	**PSAT 2.1.2**	**MatNetEig**
Inter-area	Δf	0.0004 Hz	-0.0096 Hz	-0.0003 Hz
	Δζ	-0.105 %	0.152 %	0.035 %
Local area 1	Δf	0.0004 Hz	-0.0668 Hz	-0.006 Hz
	Δζ	0.340 %	0.566 %	0.968 %
Local area 2	Δf	0.0004 Hz	-0.1596 Hz	-0.005 Hz
	Δζ	0.299 %	0.627 %	0.889 %

The results in table 8.14 above can be summarised as follows for all three tools:

PacDyn: Damping ratios increased in the inter-area mode and decreased in all local area modes with a maximum deviation of 0.34 % in local area 1 mode. The frequency decreased with a deviation of 0.0004 Hz in all modes.

PSAT: The frequency increased in the local area 1 mode with a deviation of 0.0546 Hz in and decreased in the inter-area and local area 2 oscillatory modes. The damping ratios decreased in all modes with a maximum change of 0.627 % in local area 2.

MatNetEig: The frequency increased in all modes with a maximum deviation of 0.006 % in the local area 1 mode, the damping ratios decreased in all modes with a maximum of 0.968 % deviation on the local area 1 mode.

It is clear that the effects of saturation on small-signal stability analysis are different in all these three tools. PacDyn and PSAT gave small deviations compared to MatNetEig. Hoever, all these are small and can be ignored. The differences are due to variations in mathematical models of saturation used in these tools as discussed chapter 3 and the Appendix C.

8.2.2 Thyristor exciter AVR with high transient gain, no PSS

The 2A4M power system was then modelled with thyristor exciter with high transient gain (AVR with HTG) on all four synchronous machines. There were no turbine governors and no power system stabilizers in the generators. The effects of saturation and AVR with HTG on all generators were analysed with R_a and X_l included. Table 8.15 shows the results of the inter-area and local area modes for all three simulation tools.

Table 8.15: AVR with high transient gain: Effects of saturation

Case	Mode	PacDyn 8.1.1	PSAT 2.1.2	MatNetEig
AVR with HTG Saturation neglected	Inter-area	λ=0.01501±j3.8491 f=0.6126 Hz ζ= -0.390 %	λ=0.14643±j3.7246 f=0.5928 Hz ζ= -3.9284 %	λ=0.01506±j3.8491 f=0.6126 Hz ζ= -0.3911 %
	Local area 1	λ= -0.6594±j7.1858 f=1.1437 Hz ζ=9.138 %	λ= -0.22065±j5.454 f=0.8680 Hz ζ= -4.0423 %	λ= -0.6594±j7.186 f=1.144 Hz ζ=9.138 %
	Local area 2	λ= -0.6572±j7.4092 f=1.1792 Hz ζ=8.835 %	λ= -2.3031±j8.4406 f=1.3434 Hz ζ=26.324 %	λ= -0.6572±j7.409 f=1.179 Hz ζ=8.835 %
AVR with HTG Saturation considered	Inter-area	λ=0.04222±j3.8492 f=0.6126 Hz ζ= -1.097 %	λ=0.28801±j3.4495 f=0.549 Hz ζ= -8.32 %	λ=0.01492±j3.833 f=0.6100 Hz ζ= -0.389 %
	Local area 1	λ= -0.6011±j7.1557 f=1.1389 Hz ζ=8.371 %	λ= -2.258±j8.2267 f=1.3093 Hz ζ=26.468 %	λ= -0.5824±j7.1585 f=1.139 Hz ζ=8.108 %
	Local area 2	λ= -0.6039±j7.3765 f=1.174 Hz ζ=8.159 %	λ= -2.3031±j8.4406 f=1.3434 Hz ζ=26.324 %	λ= -0.5855±j7.383 f=1.175 Hz ζ=7.906 %

Table 8.15 shows that the system is unstable for both cases in all simulation tools as can be seen in the inter-area mode. PacDyn and MatNetEig tools gave similar results when neglecting saturation. There are marginal differences in both the frequency and damping

ratios in PacDyn and MatNetEig tools in all local area modes due to the inclusion of saturation. In PSAT tool; the frequency is lower in the inter-area mode, while the damping ratios are much higher than in both MatNetEig and PacDyn tools in all oscillatory modes.

In PacDyn, the frequencies decreased with a maximum deviation of 0.0052 Hz while the damping ratios decreased with a maximum deviation of 0.7672 % when saturation parameters were considered. The effects of including and neglecting R_a and X_l resulted in increased frequencies and reduction in damping ratios in all modes when both R_a and X_l were included. Results are included in appendix.

The thyristor exciter with high transient gain shifted the real part of the eigenvalues into the positive half of the complex plane, thereby introducing unstable oscillatory modes. In all three power system simulation tools, there are very small changes in frequency and damping due to saturation.

8.2.2.1. Identification of oscillatory modes in PacDyn, PSAT and MatNetEig tools

The same procedure used when the system was on manual control and for all generators modelled with thyristor AVR exciters with high transient gain was followed to identified inter-area and all two local area modes. The modes as indicated in table 8.15 as the discussions thereof were confirmed to be either inter-area or local area as indicated. *Participation factors and mode shapes were computed for the system controlled by AVR excitation systems with transient gain reduction are included in Appendix H for all three tools.*

8.2.3 Thyristor exciter with transient gain reduction (AVR TGR), no PSS

The two area system was modelled with generators controlled by thyristor exciter with transient gain reduction (AVR TGR) excitation system on all four synchronous machines. The system had no turbine governors or power system stabilizers. Similar to the previous test cases, the system was modelled with R_a and X_l included and the effects of saturation on all generators were analysed.

The results in table 8.16 are the inter-area and local area modes for all three power system simulation tools.

Table 8.16: AVR with transient gain reduction: Effects of saturation

Case	Mode	PacDyn 8.1.1	PSAT 2.1.2	MatNetEig
AVR TGR, No PSS Saturation considered	Inter area	λ=0.1219±j3.4656 f=0.5516 Hz ζ= -3.517 %	λ= - 0.65222±j3.7834 f=0.6021 Hz ζ=16.988 %	λ=0.1329±j3.474 f=0.5529 Hz ζ= -3.823 %
	Local area 1	λ= -0.5107±j6.8459 f=1.0896 Hz ζ=7.439 %	λ= -2.2585±j7.9133 f=1.2594 Hz ζ=27.445 %	λ= -0.474±j6.881 f=1.095 Hz ζ=6.872 %
	Local area 2	λ= -0.5177±j7.0706 f=1.1253 Hz ζ=7.303 %	λ= -2.3064±j8.1418 f=1.2958 Hz ζ=27.255 %	λ= -0.4819±j7.105 f=1.131 Hz ζ=6.767 %

From table 8.16, PSAT modal solution predicts a stable system while PacDyn and MatNetEig show that the system is unstable in the inter-area mode. PSAT has higher damping ratios compared to MatNetEig and PacDyn. In PacDyn and MatNetEig, the damping ratios have slightly increased on all modes due to saturation. The difference between PacDyn and MatNetEig on the damping ratio for the inter-area is 0.306 % while the difference between PSAT and PacDyn is 13.471 % in inter-area and 19.952 % in local area 2.

The effects of saturation on the inter-area and local area modes are investigated using the deviations in frequency and damping ratio with the aid of equations (8.6).

$$\begin{aligned} \Delta f &= f_{AVR\_TGR(sn)} - f_{AVR\_TGR(si)} \\ \Delta \zeta &= \zeta_{AVR\_TGR(sn)} - \zeta_{AVR\_TGR(si)} \end{aligned} \qquad (8.6)$$

Where Δf and Δζ are frequency and damping ratio deviations in Hz and % respectively due to saturation. *The results computed using equations (8.6) are included in the Appendix.*

The results computed using equations (8.6) above shows that there are small deviations in both frequency and damping ratios in all modes computed by MatNetEig and PacDyn simulation tools. PSAT gave higher deviations in both frequency and damping ratios compared to MatNetEig and PacDyn results.

Knowledge of this power system model and reference to [2, 14, 21] reveals that this system is unstable and thus the results given by PSAT are incorrect. The excitation system modelled in this power system used in PSAT is not adequately representing the actual AVR exciter and this is the main reason for incorrect results.

8.2.4 Thyristor exciter AVR with high transient gain and PSS

The last test case was when the power system was modelled with all synchronous generators controlled by a thyristor AVR exciter with high transient gain (AVR with HTG) and a power system stabilizer. There were no speed governors on the power system model.

Table 8.17 overleaf shows the results.

Table 8.17: AVR with HTG and PSS: Effects of saturation

Case	Mode	PacDyn 8.1.1	PSAT 2.1.2	MatNetEig
AVR with HTG and PSS (Saturation neglected)	Inter-area	λ= -0.7167±j3.8154 f=0.6072 Hz ζ=17.462 %	λ= -0.19954±j3.7728 f=0.600 Hz ζ=5.282 %	λ= -0.7167±j3.816 f=0.6073 Hz ζ=18.46 %
	Local area 1	λ= -2.1602±j8.2667 f=1.3157 Hz ζ=25.282 %	λ= -0.4709±j6.1014 f=0.971 Hz ζ=7.695 %	λ= -2.16±j8.267 f=1.316 Hz ζ=25.28 %
	Local area 2	λ= -2.2428±j8.6236 f=1.3725 Hz ζ=25.170 %	λ= -0.47712±j6.238 f=0.993 Hz ζ=7.626 %	λ= -2.243±j8.624 f=1.373 Hz ζ=25.17 %
AVR with HTG and PSS (Saturation considered)	Inter-area	λ= -0.6937±j3.8623 f=0.6147 Hz ζ=17.677 %	λ= -0.36627±j3.6064 f=0.5740 Hz ζ=10.104 %	λ= -0.6734±j3.78 f=0.6016 Hz ζ=17.54 %
	Local area 1	λ= -2.01±j8.2694 f=1.3161 Hz ζ=23.618 %	λ= -1.8085±j8.1369 f=1.295 Hz ζ=21.697 %	λ= -2.06±j8.01 f=1.275 Hz ζ=24.9 %
	Local area 2	λ= -2.0985±j8.6114 f=1.3705 Hz ζ=23.677 %	λ= -1.8541±j8.3519 f=1.3292 Hz ζ=21.672 %	λ= -2.166±j8.368 f=1.332 Hz ζ=25.06 %

Table 8.17 shows that the system is stable in all tools with high damping ratios. The frequency and damping ratios increased when compared to results of the manual control presented in section 8.2.1. There are no major differences in MatNetEig and PacDyn

simulation results in all modes for cases when saturation was neglected; the negligible differences are due to rounding errors in MatNetEig. There are slight variations in results between PacDyn and MatNetEig tools for the case when saturation was considered. PSAT has lower damping ratios compared to MatNetEig and PacDyn in all cases.

The effects of saturation in PSAT resulted in major increases in damping ratios in all modes (i.e. 4.822 % in the inter-area and 14.002 % increases in the local area 2 mode). The effects reported by PSAT are too big and cannot be ignored.

The effects of saturation in the inter-area and local area modes are also investigated using change in frequency and damping ratio using equations (8.7).

$$\begin{aligned}\Delta f &= f_{AVR\_HTG+PSS(sn)} - f_{AVR\_HTG+PSS(st)} \\ \Delta\zeta &= \zeta_{AVR\_HTG+PSS(sn)} - \zeta_{AVR\_HTG+PSS(st)}\end{aligned} \tag{8.7}$$

Where Δf and Δζ are deviations due to saturation on synchronous machines controlled by thyristor exciter with high transient gain (AVR with HTG) and a power system stabilizer (PSS) on all synchronous machines.

Table 8.18 below shows the change in frequency and damping ratios for all three simulation tools' results.

Table 8.18: AVR with high transient gain and PSS: Effects of saturation

Mode	Change	Effect of saturation on modal solution		
		PacDyn 8.1.1	PSAT 2.1.2	MatNetEig
Inter-area	Δf	-0.0075 Hz	-0.0055 Hz	0.0057 Hz
	Δζ	0.785 %	-4.822 %	0.920 %
Local area 1	Δf	0.0042 Hz	-0.324 Hz	0.041 Hz
	Δζ	1.493 %	-14.002 %	0.380 %
Local area 2	Δf	-0.0004 Hz	-0.3362 Hz	0.041 Hz
	Δζ	1.664 %	-14.046 %	0.110 %

Table 8.18 can be summarised as follows:

In PSAT, the inter-area mode has a negligible frequency increase of 0.0055 Hz and the frequency increased in local area modes by 0.324 Hz and 0.3362 Hz in local area 1 and 2 respectively. The damping ratios increased in all modes. The deviations are 14.002 % and 14.046 % in local area 1 and 2 modes respectively. These changes due to saturation are big and can not be ignored.

PacDyn and MatNetEig showed small deviations in frequency and damping ratios due to saturation as compared to PSAT. The effects are different on the frequency while the damping ratios decreased when considering saturation in the synchronous machines. The effects are higher on damping ratios and negligible on the frequencies in all oscillatory modes in all simulation tools.

8.2.4.1. Time domain simulations for system with AVR and PSS in PacDyn

Time domain simulations were performed and the rotor speed deviations plotted for a small disturbance in rotor speed change of 0.01 p.u input on the power system stabilizer. The disturbance was applied for 0.07 seconds on generator 2. The system was modelled with a thyristor AVR with high transient gain and power system stabilizers on all synchronous machines using PacDyn tool.

The diagram in Fig. 8.21 shows the speed response for all four generators for the disturbance applied.

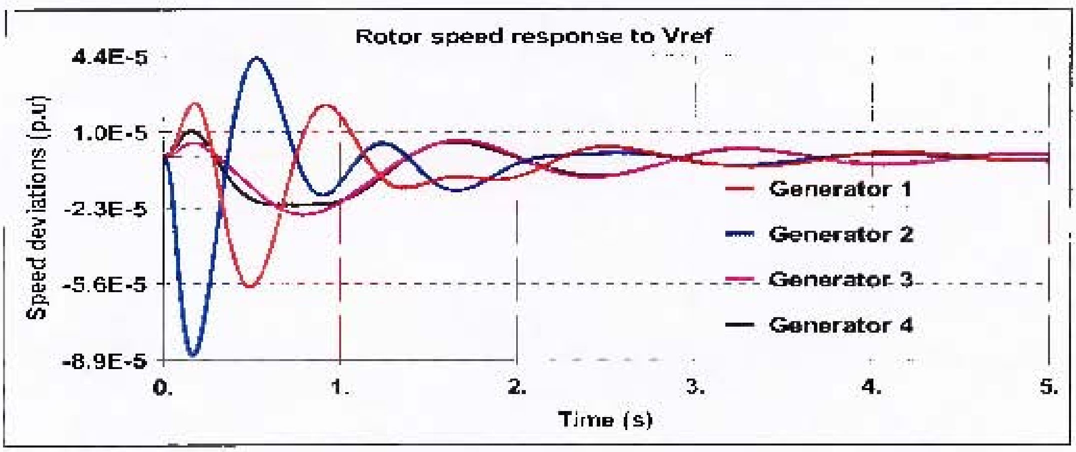


Figure 8.21: PacDyn: Speed deviations for a change in V_{ref} on generator 2

The speed response plots above indicate that the system is stable. For the duration 0 to 2.5s, generators 1 and 2 are oscillating against each other while generators 3 and 4 are swinging together. After 2.5s, generators 1 and 2 started swinging together against generators 3 and 4. At different time frames, both local area and inter-area modes can be seen on the rotor speed response plot.

8.2.4.2. Time domain simulations for system with AVR and PSS in PSAT

Time domain simulations were performed on all rotor speed for a small disturbance in rotor speed change of 0.01 p.u input on the power system stabilizer of generator 2. The step change was applied for the duration of the simulation. The diagram in Fig. 8.22 shows the speed response for all four generators for 5 seconds.

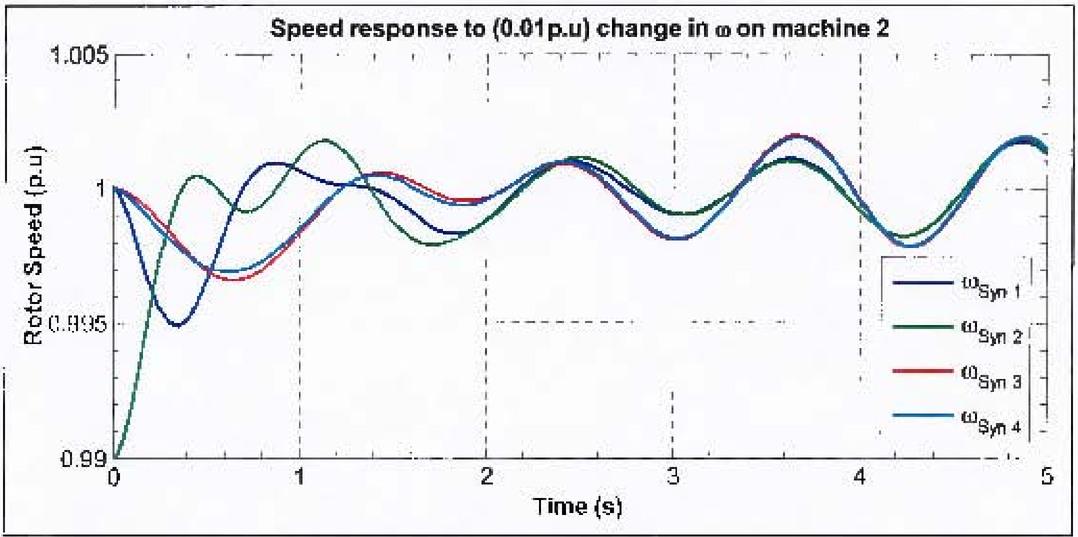


Figure 8.22: PSAT: Speed deviations for a change in ω in generator 2 (2A4M)

The speed response plots above indicate that generators 1 and 2 are oscillating against each other while generators 3 and 4 are swinging together. At 1.9s, generators 1 and 2 started swinging together and eventually caught up with generators 3 and 4 at 3.1s. All generators were then oscillating together with gradual increase in speed amplitude until the system became unstable. Increasing the simulation time to 20 seconds indicated that the system lost stability.

There were additional control modes eigenvalues with positive real parts indicating system instability; this is due to the AVR model used in PSAT.

8.2.4.3. Identification of inter-area and local area modes in MatNetEig

The power system was modelled with thyristor AVR with high transient gain and power system stabilizers on all synchronous machines. Inter-area and local area modes were identified as shown on the compass plots indicated in Fig. 8.23 overleaf.

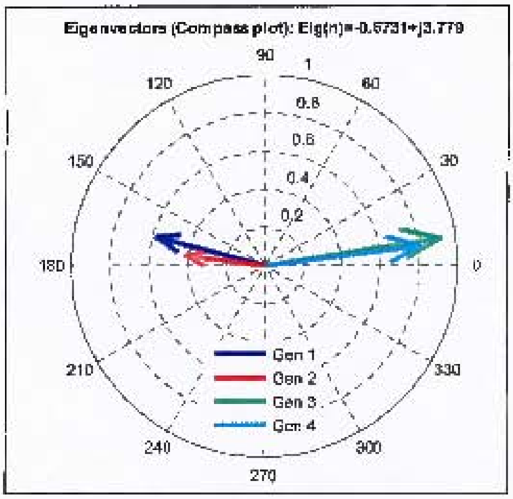


Figure 8.23(a) AVR with HTG and PSS

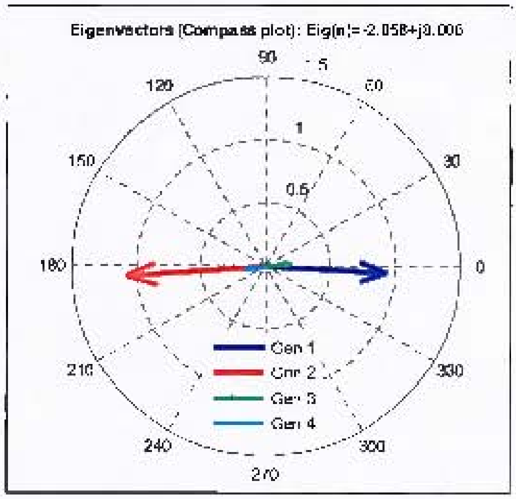


Figure 8.23(b) AVR with HTG and PSS

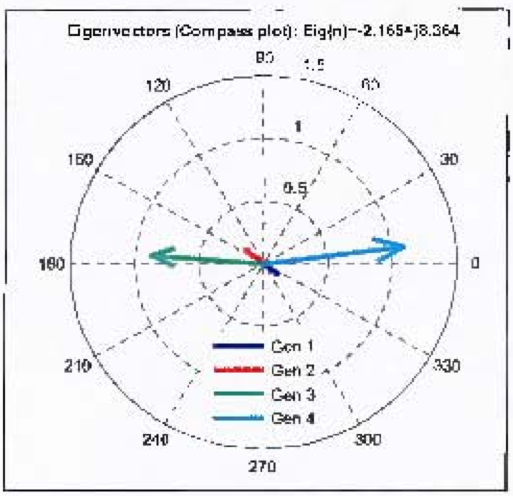


Figure 8.23(c) AVR with HTG and PSS

Figure 8.24(a), (b) and (c) show the eigenvectors in compass plots for MatNetEig simulation tool. Eigenvectors were calculated on the speed oscillatory mode for the system with thyristor AVR excitation with high transient gain and a power system stabilizer on each synchronous machine.

These three modes can be interpreted as follows:

(a) Indicates that all four synchronous machines participate in this mode. It is an inter-area mode with area 1 oscillating against area 2.

(b) Generators 1 and 2 are oscillating against each other. Eigenvectors for generators 3 and 4 in area 2 are negligible. This is a local area 1 oscillatory mode.

(c) This indicates a local area 2 mode with generator 3 oscillating against generator number 4.

8.2.4.4. Time domain simulations for system with AVR and PSS in MatNetEig

A small disturbance was applied on the reference voltage of the AVR using step response for time domain simulations in MatNetEig tool. A step change of 0.01 p.u was applied on generator 2 and rotor speed responses for all generators were plotted over 5s interval. The step change was applied at t=0 for five seconds and Fig. 8.24 shows results of the simulations.

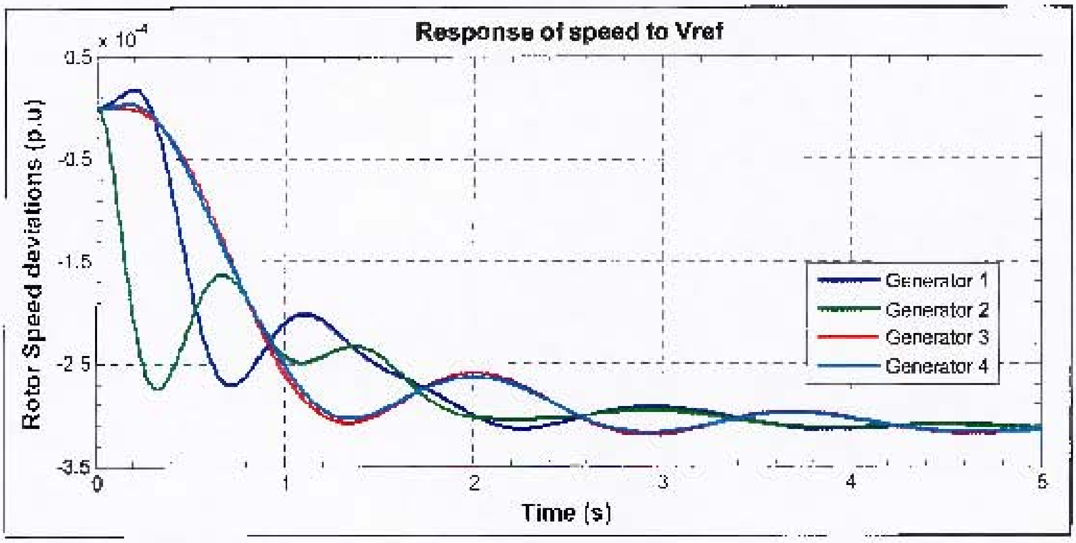


Figure 8.24: MatNetEig: Speed response to change in V_{ref} on bus 2 AVR+PSS

The diagram above shows that the system is stable at a new operating condition (i.e. $3.1x10^{-4}$ p.u below the initial operating point). For the period 0 to 2.5 seconds, generators 1 and 2 swing against each other while generator 3 and 4 are oscillating together. After 2½ seconds, generators 1 and 2 start oscillating together against generators 3 and 4 indicating an inter-area mode. The time domain simulation plot speed responses confirm modal analysis results as discussed in the previous sections.

Chapter 9:

9. Conclusions And Recommendations

9.1. Conclusions

The features and capabilities of PSAT 2.1.2, PacDyn 8.1.1 and MatNetEig power system simulation tools were investigated and compared. Comparisons were made on flexibility in input data, output results formats, components modelling and capabilities of each tool for small-signal stability analysis. All three tools have constant PQ load models, static non-linear ZIP load models, equivalent π–circuit AC transmission line model, synchronous generator models with saturation, AVR excitation systems and power system stabilizers.

PacDyn tool provides mode shapes in polar, histograms and lists while PSAT and MatNetEig give these results in list formats only. PSAT and MatNetEig tools give participation factors using Euclidean norm (all add up to unity) while PacDyn gives normalized participation factors (maximum state participation is 1 p.u at 0 degrees). PacDyn and MatNetEig tools give both mode shapes and participation factors while PSAT gives the participation factors only. All three tools provide access to the **A** state space matrix via Matlab workspace. PacDyn and MatNetEig give the time domain plots in deviations as opposed to the actual per unit quantities given by PSAT tool. Additional Matlab scripts were written and Microsoft office Excel plots were used to enhance simulations and results visualisation to have common comparative results.

PSAT 2.1.2 and MatNetEig tools are Matlab based open source simulation tools. They have been developed to run in Matlab environment in either graphical user interface or via the command line. The command line usage in these two tools offers additional functionalities such as access to all internal data, unlimited simulation support for small-disturbances and plotting utilities. Both MatNetEig and PSAT program codes can be easily modified to meet the user requirements and enhanced capabilities. The built-in disturbances in MatNetEig give limited flexibility as compared to PacDyn and PSAT.

PacDyn 8.1.1 is designed as a closed code simulation tool from CEPEL written in FORTRAN and Visual C++ with efficient algorithms and advanced graphical user interface. It has the "Transfer function Manager" through which the time domain step and frequency disturbance simulations can be customised with additional plotting and control variables. This tool is highly developed with advanced functionalities for power system modelling, simulations and analysis. CEPEL provides additional editors for data, user-defined controllers and plotting utilities to further enhance modelling and analysis.

Two power system benchmark models were modelled and analysed using all three simulations. The two models used are the SMIB and the 2A4M power system models. The results were compared using eigenvalues, mode shapes, participation factors, time domain simulations and the **A** state space matrices.

The following conclusions were drawn following the finding of the comparative investigations and analysis reseults:

9.1.1. SMIB power system model.

- **System on manual control**

  When the power system was modelled with a classical generator, all tools gave identical results for different values of the damping coefficient when using modal analysis and time domain simulations. A positive damping coefficient increases the damping ratio while a negative value decreases the damping ratio. The oscillatory frequencies measured from the rotor speed deviation plots closely matched the oscillatory frequency given in the eigenvalue reports for all three tools. The process used to measure the frequency from the time domain plots is adequate but time consuming.

  The 6th order generator model had higher damping ratios compared to 4th order and classical machines in all tools. This is consistent with theory on additional damper windings on higher order models. PacDyn results closely matched MatNetEig results in all synchronous machine models with negligible differences.

The effects of saturation on all machine models are different but small and negligible in all three simulation tools. Time domain simulation results showed negligible effects of saturation in 4^{th} and 6^{th} order generator models in MatNetEig and PacDyn tools confirming modal analysis results. PSAT gave highest damping ratio deviations.

The effects of including as well as neglecting the armature resistance and leakage reactance resulted in negligible changes in frequency and damping ratios for all cases in PacDyn and MatNetEig tools. PSAT gave higher changes in frequency and damping ratios when using time domain simulations while there were negligible changes in modal solution due to the armature resistance and leakage.

- **System controlled by an AVR excitation control without a PSS**

  The eigenvalues of the 4^{th} and 6^{th} order synchronous machines gave unstable system modal solutions from PacDyn and MatNetEig tools while PSAT gave stable modes due to AVR model used.

  The AVR exciter increased frequency and reduced damping ratios compared to a system on manual control in PacDyn and MatNetEig tools for all generator models. Differences are mainly due to the mathematical saturation models implemented as well as the AVR used in PSAT tool.

- **System controlled by an AVR and a power system stabilizer excitation system**

  PacDyn and MatNetEig gave stable modal solutions while PSAT eigenvalues indicated an unstable system.

  Time domain simulation results in PacDyn and MatNetEig matched the modal analysis. The rotor speed response to step changes in reference voltage of the AVR (V_{ref}) and mechanical power input (Pm) were damped in four seconds in both MatNetEig and PacDyn tools. PSAT gave incorrect results in both the modal eigenvalues and time domain simulation.

9.1.2. 2A4M power system model

The eigenvectors and participation factors were used to successfully identify the electromechanical modes as inter-area, local area 1 and local area 2 modes in all test cases used on the 2A4M power system model. Setting a reference machine resulted in reduced number of eigenvalue due to the elimination of redundant eigenvalues. The effects of varying damping coefficient are minimal on the oscillatory frequencies but significant on the damping ratios. A positive damping coefficient increases the damping ratio while a negative value decreases the damping ratio.

- **System on manual control: Neglecting R_a and X_l on synchronous machines**

  Three electromechanical oscillatory modes were identified in all tools as inter-area, local area 1 and local area 2 modes. For the system on manual control, the eigenvalues of these three modes gave a stable system in all tools. PSAT gave lower frequency and damping ratios compared to PacDyn and MatNetEig tools in all cases conducted. The results in MatNetEig closely matched PacDyn results.

  The eigenvector plots as well as participation factors in PacDyn and MatNetEig gave similar sensitivities of all generators for all three speed oscillatory modes.

- **System on manual control with R_a and X_l included**

  The system modal solution predicted a stable system with negligible effects of ZIP loads as compared to PQ load models. The effects are similar in MatNetEig and PacDyn tools on the frequency and damping ratios. PSAT tool results are negligible although contrary to the results given by the other two tools. MatNetEig results slightly differ from PacDyn due to negligible rounding errors in MatNetEig tool.

- **Effects of saturation on a synchronous machine**

  The system remained stable in all tools with negligible effects of saturation in all tools for the system on manual control.

- **System controlled by a thyristor AVR exciter with high transient gain**

  The system had unstable eigenvalues in the inter-area mode in all tools when using this type of AVR excitation system. The AVR exciters introduced unstable modes.

  The effects of saturation were very small and negligible in all cases for the purpose of small-signal stability analysis in PacDyn and MatNetEig. PSAT gave incorrect results when all generators were modelled with saturation.

- **System controlled by a thyristor AVR exciter with transient gain reduction**

  PacDyn and MatNetEig gave unstable eigenvalues in the inter-area mode for all load types while PSAT gave stable eigenvalues. The results from PSAT tool showed higher frequency and damping ratios as compared to PacDyn, MatNetEig and reference to recent research on this benchmark model. PSAT results were confirmed to be incorrect for this AVR excitation system type. The effects of saturation were negligible in all tools.

- **System controlled by thyristor AVR exciters with high transient gain and PSS**

  All simulation tools gave stable system on the electromechanical oscillatory modes. The effects of saturation are small and negligible in the frequency in MatNetEig and PacDyn tools, while PSAT higher in all modes in PSAT.

  Small-disturbance step response simulations in time domain analysis indicated the dynamic response as predicted using modal analysis in PacDyn and MatNetEig tools. Generators 1 and 2 started oscillating against each other and later against generators 3 and 4 indicating both the local area and inter-area modes in all three simulation tools. The rotor speed in PSAT gave an unstable response noticed after 20 seconds. Unstable control modes were identified as the cause on instability in PSAT simulation results due to AVR models used.

9.2. Recommendations

- Mode shapes to be implemented in PSAT tool for small-signal stability analysis.

- The participation factors and eigenvectors plots to be implemented in both MatNetEig and PSAT simulation tools.

- The user should be able to specify the output results precision for the eigenvalues, oscillatory frequency and damping ratios in MatNetEig tool. This should be implemented on the small-signal stability analysis GUI in MatNetEig.

- Small-signal stability results in PSAT 2.1.2 differed in almost all cases conducted on detailed higher order synchronous machine models, saturation case studies and AVR excitor models. The tool gave good load flow results and should be used for load flow steady-state analysis.

- Reference or infinite bus modelling to be fully developed in MatNetEig and implemented with the network data file as opposed to using command line usage and code modification. This eliminates redundant eigenvalues from the modal solution.

- Armature resistance and leakage reactance data of the synchronous machines have negligible effects on small-signal stability analysis and should only be used when accurate data is available. This can save on computer memory requirements and increase processing speed.

- The effects of saturation are small for systems on manual control but increases when modelling systems with AVR and PSS excitation systems. Appropriate saturation parameters should be calculated when simulation tools have different mathematical saturation models.

- Time domain simulations performed in PSAT gave results contradicting modal analysis and therefore not reliable. Further research to be done to investigate causes of differences between modal and time domain simulations.

- The AVR excitation system and power system stabilizer used in PSAT resulted in more eigenvalues compared to MatNetEig, PacDyn and other references. The models implemented in PSAT are inaccurate in modelling the simple AVR and PSS models. PSAT is not advisable for small-signal stability analysis of power systems with AVR and PSS excitation systems.

- Results from PacDyn and MatNetEig tools were closely similar in all case studies performed with negligible differences in frequencies and damping ratios due to saturation and leackage reactance. These tools are suitable for power systems small-signal stability analysis. However, they have different saturation models that should be closely investigated.

- PacDyn is recommended for power systems small-signal stability analysis due to advanced features, modelling capabilities and the results.

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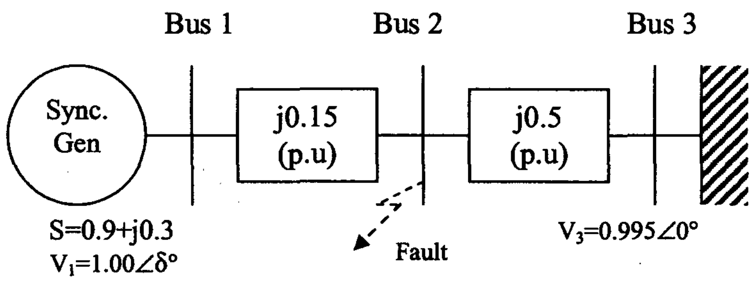
Appendix

A. Power System Data

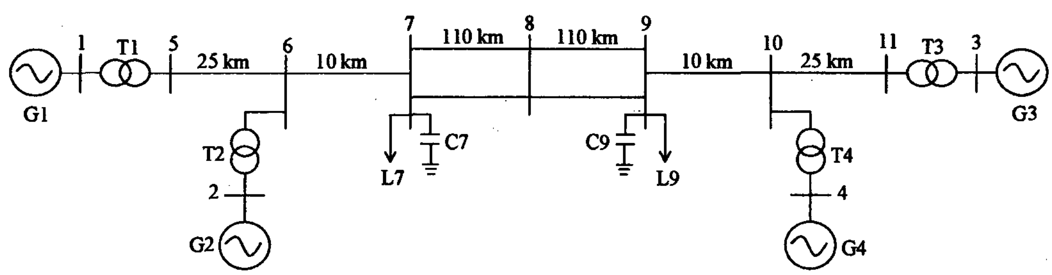
A.1. SMIB data



Bus 1, 2 and 3: kV = 24
Base MVA = 2220
Transformer impedance between Bus 1 and Bus 2: X=j0.15 p.u
Line (Bus 2 to Bus 3) R=0.0 p.u, X=j0.5 p.u and B=0.0 p.u

Synchronous Machine Data	X'd	X'q	Xd	Xq	T'd0	T'q0	X"d	X"q	T"d0	T"q0
	0.3	0.65	1.81	1.76	8	1	0.23	0.25	0.03	0.07
	H	Kd	Ra	Xl	A_{sat}	B_{sat}	$C=\Psi_{T1}$	Freq	MVA	kV
	3.5	0	0.003	0.16	0.031	6.93	0.8	60	2220	24
AVR Exciter Data	Ka	Tr		**PSS Data**			Gw	Tw	T1	T2
	200	0.02					9.5	1.4	0.154	0.033

A.2. 2A4M data



Bus 1, 2, 3 and 4: kV = 20; Bus 5, 6, 7, 8, 9, 10 and 11: kV = 230, Base MVA = 100
Transformers T1, T2, T3 and T4: 900MVA, 20/230 kV, X=j0.15 p.u, 60 Hz
Lines R=0.0001 p.u/km, X=j0.001 p.u/km and B=0.00175 p.u/km

Machine Data	X'd	X'q	Xd	Xq	T'd0	T'q0	X"d	X"q	T"d0	T"q0	
	0.30	0.55	1.80	1.70	8.0	0.40	0.25	0.25	0.03	0.05	
	H	Kd	Ra	Xl	A_{sat}	B_{sat}	$C=\Psi_{T1}$	Freq	MVA	kV	
	***	0	0.0025	0.20	0.015	9.6	0.9	60	900	20	
AVR Data	Ka	Tr	T1	T2	**PSS Data**	Gw	Tw	T1	T2	T3	T4
	200	0.01	1.00	10.0		20.0	10.0	0.05	0.02	3	5.4

Note: *** Generators 1 and 2: H=6.5, Generators 3 and 4: H=6.175

B. Data files

B.1. SMIB system with AVR and PSS

B.1.1. PacDyn

(a) Electrical network data file

```
# SMIB System, Circuit# 2 of Line 2-3 out of service
MVA BASE
#     (base)
     2220.0

BUS DATA
#bus( name )( volt )( ang )( pgen )( qgen )( pload )( qload )(gshunt)(bshunt)
  1  BUS1  1.00000 36.0109 1998.000 666.4774  0.0000  0.0000 0.0000  0.000
  2  BUS2  0.96446 27.9646  0.0000  0.00000   0.0000  0.0000 0.0000  0.000
  3  BUS3  0.99500  0.0000 -1998.00 632.4089  0.0000  0.0000 0.0000  0.000
-999

BRANCH DATA
#b#1 b#2( res )( rea )(charg )(tap )(phase)
  1  2 0.00000  0.15000 0.000000.0000
  2  3 0.00000  0.50000 0.000000.0000
-999
```

(b) Dynamic data file

```
TITU
SMIB System, Machine model#5, Kd=0.0 AVR WITHOUT A PSS
PacDyn Format Electical Network Data File
PacDyn Dynamic Data File, DS Mudau

DSYS
# N = Network File: A = ANAREDE Fomatted  File
#              H = ANAREDE History   File
#              P = PACDYN  Formatted File (DEFAULT)
# P = Network printout | T = Initial conditions test | V = Voltstab analysis
#(freq) (base) (no) N P T V I
 60.000 2220.0 0001 P Y Y N A

DGEN
#(Nb1)noRM(Base)(HH)(X'd)(X'q)(Xd)(Xq)(Ra)(T'd0)(T'q0)(Xp)(-Sat-)(-DD-)(Frq)
#(Nb1)noUU(-X"d)(-X"q)(T"d0)(T"qo)(-Xl-)(-A--)(-B--)(-C--)(-Xt-)(-Rtr)(-Xtr)(-Str)
   1  52220.0 3.500 0.300 0.650 1.810 1.760 0.003 8.00  1.00  0.00 1.7948 0.000 60.0
   1  1 0.230 0.250 0.030 0.070 0.160 0.031 6.930 0.80
 00003
 -999

DUDC
#(Ncdu) (---Name---)
```

```
000001 AVR-GEN.1
#Flag  (Nb) (Type) S(Vinp) (Vout) (---A----) (---B----) (---C----) (---D----) (---E----)
     1  OUT   EFD  EFD  1
     2  IN    VB   ET   1
     3  IN    VREF  VREF  1
     4  IN    VPSS  VPSS  1
#     (Nb) (Type) S(Vinp) (Vout) (---A----) (---B----) (---C----) (---D----) (---E----)
     5  LDLG   ET   X1   1.0      0.00    1.0000    0.0200
     6  SUM   +VREF  X2
             -X1
             VPSS
 STOP  7  GAIN  X2   EFD   200.0
 000002 PSS-GEN.1
# AVR and PSS data from page 775
#Flag  (Nb) (Type) S(Vinp) (Vout) (---A----) (---B----) (---C----) (—D----) (---E—-)
     1  OUT   VPSS  VPSS  1
     2  IN    WW    WW    1
#Flag  (Nb) (Type) S(Vinp) (Vout) (---A----) (—B----) (—C----) (---D----) (---E----)
     4  GAIN   WW    X12   9.500
     3  LDLG   X12   X13   0.000     1.400     1.000     1.400
 STOP  5  LDLG   X13   VPSS  1.000     0.154     1.000     0.033
 -999
END
```

B.1.2. PSAT

```
 % Data File by DS Mudau 'd_smib_kundur_p864.m'
 % PSAT 2.1.2 Data file
 % 24 September 2008
 % Load flow, Eigen value analysis and transient simulations
 %            -----------------------------------------------------

Bus.con = [...
    1   24  1.0 0.0;
    2   24  1.0 0.0;
    3   24  1.0 0.0;
    ];
Bus.names = {'Bus1'; 'Bus2';'Bus3'};
Line.con = [...
    1   2   2220    24  60  0   0   0   0.15    0;
    2   3   2220    24  60  0   0   0   0.50    0;
    ];
SW.con = [...
    3   2220    24  0.995  0.0;
    ];
PV.con = [...
    1   2220    24  0.90    1.0;
    ];

 % Syn.con format, 6th Order
 % B#    MVA kV  Hz  M#   xl     ra     xd    x'd    x"d    T'do   T"do
 %                                xq     x'q    x"q   T'qo   T"qo   M=2H   D
Syn.con= [...
 1   2220  24   60   6    0.16   0.003   1.81 0.3    0.23   8.0   0.03 ...
```

```
                         1.76  0.650  0.25 1.0   0.07  7.0  0.0 ...
                         1   1   1   1   1  0.1103  0.3314;
   ];
 % AVR Type III, simplest AVR model used for stability analyses
 % G# Exc Vfmax Vfmin  u0 T2  T1  vf0  V0  Te     Tr    -   con
Exc.con = [ ...
  1  3  7  -6.4  200  1  1.00  0.0  0.0  1.0  0.02  0   0   1];

Pss.con = [ ...
  1  2  1  999  -999  9.5  1.4  0.154  0.033  1  1  1  1  1  1 ...
                                       1  -1  1  -1  0  0  1  1];
```

B.1.3. MatNetEig

```
 % Data File by DS Mudau
 % PST V2 data file format (PST V2.0.0  and MatNetEig)
 % ------------------------------------------         ------------

 % Bus data format
 % No |V| Angle Pg Qg Pload Qload G B Bus Qgmax Qgmin V r  Vmax Vmin
 % col10 bus_type bus_type - 1, swing bus
 %                       - 2, generator bus (PV bus)
 %                         3, load bus (PQ bus,  PQ generator bus)
bus = [...
1   1.00   0  0.90 0 0 0 0 0 2 999 -999  24.0  1.05  0.95;
2   1.00   0  0.00 0 0 0 0 0 3 999 -999  24.0  1.05  0.95;
3   0.995  0  0.00 0 0 0 0 0 1 999 -999  24.0  1.05  0.95;
];

 % Line data format
 %  From To  R     X      H       Tap  phs  max min  size
line = [...
    1  2  0.000  0.150  0.000  0.000  0.000  0.000  0.000  0.000;
    2  3  0.000  0.500  0.000  0.000  0.000  0.000  0.000  0.000;
 %2  3  0.000  0.930  0.000  0.000  0.000  0.000  0.000  0.000;
    ];

 % Machine data format
 %#  b# MVA  xl ra xd  x'd x"d T'do T"do xq  xq' xq" T'qo T"qo H ...
 %                                     d0  d1 type S1 S1.2 frP frQ
mac_con = [
    1 1 2220 0.16 0.003 1.81 0.30 0.23 8.0 0.03 1.76 0.65 0.25 ...
                         1.0 0.07 3.5 0 0 31 0.1240  0.4957 1 1;
    2 3 2.2e6 0 0 0 1e-6 0 0 0 0 0.00 0 0 0 1e6 0.000 0 1 0 0 1 1;
];

 % gsib idx = 2; % infinite bus on machine number

disp('ST1a Static excitation system as a simple exciter model - 10')
exc_con = [
    10  1  0  0  0.02  200  0  0  0  0  0  0  0  999  -999  999 ...
                 -999  999  -999  0  0  0  0  0  0  0  0  0  0  0  0;
    ];

disp('Power System Stabilizer, speed input')
 % Type Gen# Gpss Tw Tn1 Td1 Tn2 Td2 ymax ymin Twd Tnf Tdf nnf ndf Gp
pss_con = [
```

```
1  1  9.5  1.4  0.154  0.033  1  1 999 -999  0  0  0  0  0  0;
];
```

B.2. 2A4M system controlled by AVR with HTG and PSS

B.2.1. PacDyn

(a) Electrical network data file

```
# Two area system data, from Kundur. DS Mudau
MVA BASE
#    (base)
     100.00

BUS DATA
#bus( name )( volt )( ang )( pgen )( qgen )( pload )( qload )(gshunt)(bshunt)
  1 BUS01 1.03   20.0477 700.00   179.0027 0     0
  2 BUS02 1.01   10.2984 700.00   220.1040 0     0
  3 BUS03 1.03   -6.8    718.4967 168.7902 0     0
  4 BUS04 1.01   -16.959 700.00   185.0345 0     0
  5 BUS05 1.0074 13.5908 0      0      0      0
  6 BUS06 0.9805 3.5314  0      0      0      0
  7 BUS07 0.9652 -4.8323 0      0      967.0  -100.0
  8 BUS08 0.9536 -18.579 0      0      0      0
  9 BUS09 0.9763 -32.045 0      0      1767.0 -250.0
 10 BUS10 0.9862 -23.686 0      0      0      0
 11 BUS11 1.0094 -13.415 0      0      0      0
-999

BRANCH DATA
#b#1 b#2( res )( rea )(charg )(tap )(phase)
  1  5 0.0000 0.0166667 0.00000
  2  6 0.0000 0.0166667 0.00000
  3 11 0.0000 0.0166667 0.00000
  4 10 0.0000 0.0166667 0.00000
  5  6 0.0025 0.0250000 0.04375
  6  7 0.0010 0.0100000 0.01750
  7  8 0.0110 0.1100000 0.19250
  7  8 0.0110 0.1100000 0.19250
  8  9 0.0110 0.1100000 0.19250
  8  9 0.0110 0.1100000 0.19250
  9 10 0.0010 0.0100000 0.01750
 10 11 0.0025 0.0250000 0.04375
-999
```

(b) Dynamic data file

```
TITU
2A4M system, UDT AVRs (Thyristor with High Transient Grain) and PSSs
PacDyn Format Electical Network Data File
PacDyn Dynamic Data File, DS Mudau
```

```
DSYS
# N = Network File: A = ANAREDE Fomatted  File
#              H = ANAREDE History  File
#              P = PACDYN  Formatted File (DEFAULT)
# P = Network printout | T = Initial conditions test | V = Voltstab analysis
#(Freq) (Base) (No) N P T V I M E C
 60.000 100.00 0001 P Y Y N A 1 N Y
DGEN
#(Nb1)noRM(Base)(HH)(X'd)(X'q)(Xd)(Xq)(Ra)(T'd0)(T'q0)(Xp)(-Sat-)(-DD-)(Frq)
#(Nb1)NoUU(-X"d)(-X"q)(T"d0)(T"qo)(-Xl-)(-A--)(-B--)(-C--)(-Xt-)(-Rtr)(-Xtr)(-Str)
   1  5 900  6.50 0.300  0.55  1.80 1.700 0.0025 8.00  0.40  0.00 0.000  0.000
   1  1 0.25 0.25  0.03  0.05  0.20 0.015 9.6  0.9
   2  5 900  6.50 0.300  0.55  1.80 1.700 0.0025 8.00  0.40  0.00 0.000  0.000
   2  1 0.25 0.25  0.03  0.05  0.20 0.015 9.6  0.9
   3 R5 900  6.175 0.300  0.55  1.80 1.700 0.0025 8.00  0.40  0.00 0.000  0.000
   3  1 0.25 0.25  0.03  0.05  0.20 0.015 9.6  0.9
   4  5 900  6.175 0.300  0.55  1.80 1.700 0.0025 8.00  0.40  0.00 0.000  0.000
   4  1 0.25 0.25  0.03  0.05  0.20 0.015 9.6  0.9
-999

DUDT
#(Ncdu) (---Name---)
  1000 AVR
#Flag  (Nb) (Type) S(Vinp) (Vout) (---A----) (---B----) (---C----) (---D----) (---E----)
       1 IN     VB    ET    #Nb
       2 IN     VREF  X2    #Nb
       3 IN     VPSS  X3    #Nb
       4 OUT    X5    EFD   #Nb
       5 LDLG   ET    X1    1       0       1       0.01
       6 SUM    -X1   X4
             +X2
             +X3
       7 GAIN   X4    X5    200
        DPAR              #Nb
STOP
-999

AUDC
# AVRs for all generators
#(No ) (---NOME---) (No ) (---NOME---)
 1001  AVR-Gen.1     1000 AVR
#                    (--NAME--) (-VALUE--)
                    #Nb      1
STOP
 1002  AVR-Gen.2     1000 AVR
#                    (--NAME--) (-VALUE--)
                    #Nb      2
STOP
 1003  AVR-Gen.3     1000 AVR
#                    (--NAME--) (-VALUE--)
                    #Nb      3
```

```
 STOP
  1004 AVR-Gen.4     1000 AVR
 #                   (--NAME--) (-VALUE--)
                    #Nb     4
 STOP
 -999
 DUDC
 #(Ncdu) (---Name---)
  000011 PSS-Gen.1
 #Flag  (Nb) (Type) S(Vinp) (Vout) (---A----) (---B----) (---C----) (---D----) (---E----)
      1  OUT    VPSS  VPSS  1
      2  IN     WW    WW    1
 #Flag  (Nb) (Type) S(Vinp) (Vout) (---A----) (---B----) (---C----) (---D----) (---E----)
      3  GAIN   WW    X12   20.00
      4  LDLG   X12   X13   0.000    10.00    1.000    10.00
      5  LDLG   X13   X14   1.000    0.050    1.000    0.020
 STOP 6  LDLG   X14   VPSS  1.000    3.000    1.000    5.400
  000012 PSS-Gen.2
 #Flag  (Nb) (Type) S(Vinp) (Vout) (---A----) (---B----) (---C----) (---D----) (---E----)
      1  OUT    VPSS  VPSS  2
      2  IN     WW    WW    2
 #Flag  (Nb) (Type) S(Vinp) (Vout) (---A----) (---B----) (---C----) (---D----) (---E----)
      3  GAIN   WW    X22   20.00
      4  LDLG   X22   X23   0.000    10.00    1.000    10.00
      5  LDLG   X23   X24   1.000    0.050    1.000    0.020
 STOP 6  LDLG   X24   VPSS  1.000    3.000    1.000    5.400
  000013 PSS-Gen.3
 #Flag  (Nb) (Type) S(Vinp) (Vout) (---A----) (---B----) (---C----) (---D----) (---E----)
      1  OUT    VPSS  VPSS  3
      2  IN     WW    WW    3
 #Flag  (Nb) (Type) S(Vinp) (Vout) (---A----) (---B----) (---C----) (---D----) (---E----)
      3  GAIN   WW    X32   20.00
      4  LDLG   X32   X33   0.000    10.00    1.000    10.00
      5  LDLG   X33   X34   1.000    0.050    1.000    0.020
 STOP 6  LDLG   X34   VPSS  1.000    3.000    1.000    5.400
  000014 PSS-Gen.4
 #Flag  (Nb) (Type) S(Vinp) (Vout) (---A----) (---B----) (---C----) (---D----) (---E----)
      1  OUT    VPSS  VPSS  4
      2  IN     WW    WW    4
 #Flag  (Nb) (Type) S(Vinp) (Vout) (---A----) (---B----) (---C----) (---D----) (---E----)
      3  GAIN   WW    X42   20.00
      4  LDLG   X42   X43   0.000    10.00    1.000    10.00
      5  LDLG   X43   X44   1.000    0.050    1.000    0.020
 STOP 6  LDLG   X44   VPSS  1.000    3.000    1.000    5.400
 -999
 END
```

B.2.2. PSAT

```
% 2 Area 4machine power system data in PSAT 2.1.2 format
% DS Mudau
% Data from P Kundur, pp 813-814
```

```
% All Transformer impedances converted to 100MVA base
% ------------------------------------------------------

% Bus data in PSAT format
%  # kV      V pu       V_angle(rad)
Bus.con = [ ...
  1        20      1.03          0;
  2        20      1.01          0;
  3        20      1.03          0;
  4        20      1.01          0;
  5        230     1.00          0;
  6        230     1.00          0;
  7        230     1.00          0;
  8        230     1.00          0;
  9        230     1.00          0;
  10       230     1.00          0;
  11       230     1.00          0;
];

% All Transformer impedances converted to 100MVA base
% Line data in PSAT format
% 1. Line (LINE) Structure
% From To    MVA kV F(HZ) l(km) -     R(p.u)  X(p.u)  B(p.u) % LINE
% 2. Transformer (TRFR) Structure
% From To    MVA kV F(HZ) -   Vratio  R(p.u)  X(p.u)   - %TRFR
Line.con = [ ...
  1     5    900 20   60   0    20/230  0.0000  0.15     0.0000;
  2     6    900 20   60   0    20/230  0.0000  0.15     0.0000;
  3     11   900 20   60   0    20/230  0.0000  0.15     0.0000;
  4     10   900 20   60   0    20/230  0.0000  0.15     0.0000;
  5     6    100 230 60   0    0.0000  0.0025  0.0250   0.04375;
  6     7    100 230 60   0    0.0000  0.0010  0.0100   0.0175;
  7     8    100 230 60   0    0.0000  0.0110  0.1100   0.1925;
  7     8    100 230 60   0    0.0000  0.0110  0.1100   0.1925;
  8     9    100 230 60   0    0.0000  0.0110  0.1100   0.1925;
  8     9    100 230 60   0    0.0000  0.0110  0.1100   0.1925;
  9     10   100 230 60   0    0.0000  0.0010  0.0100   0.0175;
  10    11   100 230 60   0    0.0000  0.0025  0.0250   0.04375;
 ];

% PQ (Load) data
%Bus# MVA kV    P pu    Q pu
PQ.con = [ ...
  7  100  230   9.67   -1.00;
  9  100  230  17.67   -2.50;
 ];

% PV Generator bus data
%Bus# MVA kV   P0 pu  V0 pu
PV.con = [ ...
  1  100  20   7  1.03;
  2  100  20   7  1.01;
  4  100  20   7  1.01;
 ];

% Slack bus data (Reference voltage and angle)
%Bus# MVA kV  V pu   V_angle(rad)
SW.con = [ ...
  3  100  20  1.03  -0.1187;
];
```

```
% Synchronous machine Generator data, with saturation
%Bus# MVA kV F(HZ) Model Xl Ra    Xd   X'd  X"d T'd0 T"d0 ...
%                        Xq X'q X"q T'q0 T"q0 M(2H) D ...
% Optional data          Kw Kp Kp KQ Taa S1.0 S1.2

Syn.con = [ ...
  1  900  20  60  6  0.2  0.0025  1.8  0.3  0.25  8  0.03  ...
                     1.7  0.55  0.25  0.4  0.05  13  0.00 ...
                     1  1  1  1  1  0.0377  0.2109;
  2  900  20  60  6  0.2  0.0025  1.8  0.3  0.25  8  0.03  ...
                     1.7  0.55  0.25  0.4  0.05  13  0.00 ...
                     1  1  1  1  1  0.0377  0.2109;
  3  900  20  60  6  0.2  0.0025  1.8  0.3  0.25  8  0.03  ...
                     1.7  0.55  0.25  0.4  0.05  12.35  0.0 ...
                     1  1  1  1  1  0.0377  0.2109;
  4  900  20  60  6  0.2  0.0025  1.8  0.3  0.25  8  0.03  ...
                     1.7  0.55  0.25  0.4  0.05  12.35  0.0 ...
                     1  1  1  1  1  0.0377  0.2109;
 ];

 % AVR Type III, simplest AVR model used for stability analyses
 % G# Exc Vfmax Vfmin  u0 T2   T1  vf0  V0  Te      Tr      -  - con
Exc.con = [ ...
  1  3  7  -6.4  200  1  1.00  0.0 1.0  1.0  0.01  0  0  1;
  2  3  7  -6.4  200  1  1.00  0.0 1.0  1.0  0.01  0  0  1;
  3  3  7  -6.4  200  1  1.00  0.0 1.0  1.0  0.01  0  0  1;
  4  3  7  -6.4  200  1  1.00  0.0 1.0  1.0  0.01  0  0  1;
  ];

 % AVR# PSS Input Vsmax Vsmin Kw Tw T1 T2 T3 T4 Ka Ta Kp kV ...
 %                   Vamax Vamin Vs*max Vs*min ethr wthr s2 con
Pss.con = [ ...
  1  2  1  0.2  -0.2  20.0  10.0  0.05  0.02  3.0  5.4  25  0.5 ...
                20  5  0.045  0.045  0.045  -0.045  1  0.95  0  1;
  2  2  1  0.2  -0.2  20.0  10.0  0.05  0.02  3.0  5.4  25  0.5 ...
                20  5  0.045  0.045  0.045  -0.045  1  0.95  0  1;
  3  2  1  0.2  -0.2  20.0  10.0  0.05  0.02  3.0  5.4  25  0.5 ...
                20  5  0.045  0.045  0.045  -0.045  1  0.95  0  1;
  4  2  1  0.2  -0.2  20.0  10.0  0.05  0.02  3.0  5.4  25  0.5 ...
                20  5  0.045  0.045  0.045  -0.045  1  0.95  0  1;
 ];

Bus.names = {...
  'Bus 01';'Bus 02';'Bus 03';'Bus 04';'Bus 05';'Bus 06';'Bus 07'; ...
  'Bus 08'; 'Bus 09'; 'Bus 10'; 'Bus 11';
  };
```

B.2.3. MatNetEig

```
% 2 Area 4machine power system data
% DS Mudau
% All Transformer impedances converted to 100MVA base
% ----------------------------------------------------------

% Bus data format
%  1    2     3      4      5      6       7       8        9  ...
%  bus volt angle  p_gen  q_gen  p_load q_load  G_shunt ...
% 10    11    12    13     14     15
%  B_shunt type q_max q_min v_rate v_max v_min
```

```
bus = [ ...
1   1.03   20.20   7.00   1.85   0.00   0.00   0   0   2 ...
                                        99  -99 20  1.2 0.8;
2   1.01   10.50   7.00   2.35   0.00   0.00   0   0   2 ...
                                        99  -99 20  1.2 0.8;
3   1.03   -6.80   7.19   1.76   0.00   0.00   0   0   1 ...
                                        99  -99 20  1.2 0.8;
4   1.01   -17.00  7.00   2.02   0.00   0.00   0   0   2 ...
                                        99  -99 20  1.2 0.8;
5   1.00   0.00    0.00   0.00   0.00   0.00   0   0   3 ...
                                        0   0   230 1.2 0.8;
6   1.00   0.00    0.00   0.00   0.00   0.00   0   0   3 ...
                                        0   0   230 1.2 0.8;
7   1.00   0.00    0.00   0.00   9.67   -1.00  0   0   3 ...
                                        0   0   230 1.2 0.8;
8   1.00   0.00    0.00   0.00   0.00   0.00   0   0   3 ...
                                        0   0   230 1.2 0.8;
9   1.00   0.00    0.00   0.00   17.67  -2.50  0   0   3 ...
                                        0   0   230 1.2 0.8;
10  1.00   0.00    0.00   0.00   0.00   0.00   0   0   3 ...
                                        0   0   230 1.2 0.8;
11  1.00   0.00    0.00   0.00   0.00   0.00   0   0   3 ...
                                        0   0   230 1.2 0.8;
];

 % line data format
 % line: from bus, to bus, resistance(pu), reactance(pu),
 % line charging(pu), tap ratio, tap phase, tapmax, tapmin, tapsize
line = [ ...
    1   5   0.0000  0.15/9  0.0000  0   0   0   0   0;
    2   6   0.0000  0.15/9  0.0000  0   0   0   0   0;
    3   11  0.0000  0.15/9  0.0000  0   0   0   0   0;
    4   10  0.0000  0.15/9  0.0000  0   0   0   0   0;
    5   6   0.0025  0.0250  0.0438  0   0   0   0   0;
    6   7   0.0010  0.0100  0.0175  0   0   0   0   0;
    7   8   0.0110  0.1100  0.1925  0   0   0   0   0;
    7   8   0.0110  0.1100  0.1925  0   0   0   0   0;
    8   9   0.0110  0.1100  0.1925  0   0   0   0   0;
    8   9   0.0110  0.1100  0.1925  0   0   0   0   0;
    9   10  0.0010  0.0100  0.0175  0   0   0   0   0;
    10  11  0.0025  0.0250  0.0438  0   0   0   0   0;
  ];

 %#  b# MVA  xl ra xd  x'd x"d T'do T"do xq  xq' xq" T'qo T"qo H ...
 %                                     d0  d1 type S1 S1.2 frP frQ
mac_con = [ ...
    1 1 900 0.2 0.0025 1.8 0.3 0.25 8.0 0.03 1.7 0.55 0.25 0.4 ...
                       0.05    6.500 0 0 31  0.0392  0.2672 1 1;
    2 2 900 0.2 0.0025 1.8 0.3 0.25 8.0 0.03 1.7 0.55 0.25 0.4 ...
                       0.05    6.500 0 0 31  0.0392  0.2672 1 1;
    3 3 900 0.2 0.0025 1.8 0.3 0.25 8.0 0.03 1.7 0.55 0.25 0.4 ...
                       0.05    6.175 0 0 31  0.0392  0.2672 1 1;
    4 4 900 0.2 0.0025 1.8 0.3 0.25 8.0 0.03 1.7 0.55 0.25 0.4 ...
                       0.05    6.175 0 0 31  0.0392  0.2672 1 1;
    ];

disp('ST1a Static excitation system: simple exciter model - 10')
exc_con = [
    10  1  0  0  0.01  200  0  0  0  0  0  0  0  999  -999  999 ...
           -999  999  -999  0  0  0  0  0  0  0  0  0  0  0;
    10  2  0  0  0.01  200  0  0  0  0  0  0  0  999  -999  999 ...
```

```
        -999  999  -999  0  0  0  0  0  0  0  0  0  0  0  0;
    10  3  0  0  0.01  200  0  0  0  0  0  0  0  999  -999  999 ...
        -999  999  -999  0  0  0  0  0  0  0  0  0  0  0  0;
    10  4  0  0  0.01  200  0  0  0  0  0  0  0  999  -999  999 ...
        -999  999  -999  0  0  0  0  0  0  0  0  0  0  0  0;
    ];

disp('Power system stabiliser, PSS')
pss_con = [
    1  1  20  10  0.05  0.02  3.0  5.4  999 -999  0  0 0 0 0 0;
    1  2  20  10  0.05  0.02  3.0  5.4  999 -999  0  0 0 0 0 0;
    1  3  20  10  0.05  0.02  3.0  5.4  999 -999  0  0 0 0 0 0;
    1  4  20  10  0.05  0.02  3.0  5.4  999 -999  0  0 0 0 0 0;
    ];
```

C. Saturation models

Magnetic saturation in synchronous machines presents a complex generator models in power system stability and analysis. To account for flux linkages in stator and rotor dynamics, mathematical models have been developed for synchronous machine models. Various power system simulation tools use different modelling concepts and different mathematical models for saturation. The differences in mathematical models used in simulation tools results in variations in simulation results.

A total saturation model is widely used to model machine saturation. This model accounts for the linear and no-linear characteristics of the magnetic saturation along the air-gap line. Figure C.1 below shows the open-circuit and the air-gap lines mostly used for total saturation modelling in power systems [2, 4, 21, 44].

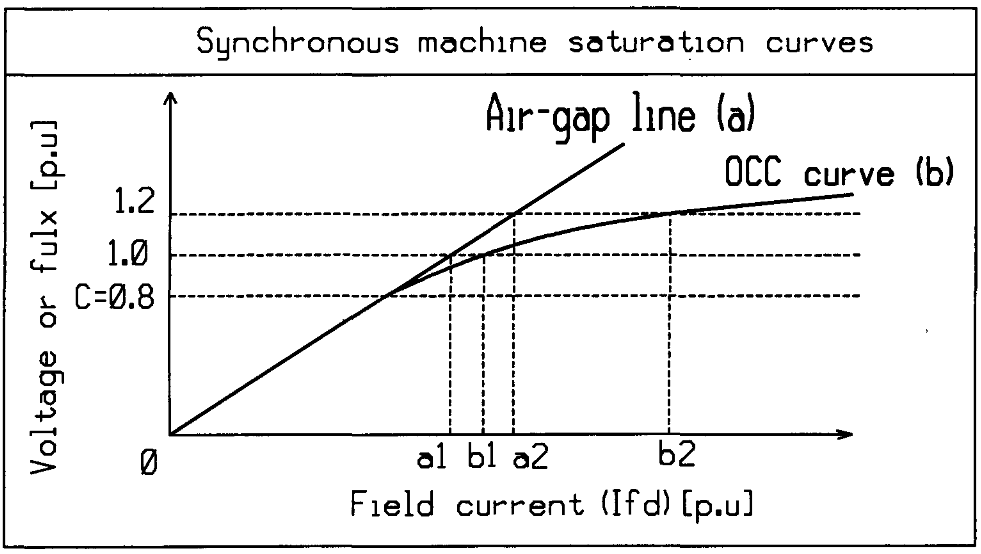


Figure C.1: Synchronous machine saturation model

The open circuit saturation curve (OCC) line in Fig.C.1 above is used to define the direct-axis (d-axis) saturation of the synchronous machine. The saturation model in other simulation tools is defined using the direct-axis only while others assume similar direct- and quadrature (q-) axis saturation models. The synchronous machine saturation models on the d- and q-axis are either similar, different or neglected depending on the respective simulation tools.

The OCC curve in Fig.C.1 is linear up to a flux (Ψ) or voltage (e') level C=Ψ_{T1}=0.8 per unit. The non-linear curve is defined by equation (C.1) [2, 4, 14, 21, 44].

$$\begin{aligned} I_{fd}(\psi) &= A_{sat} e^{B_{sat}(\psi - C)} \\ C &= \psi_{T_1} \end{aligned} \qquad \text{(C.1)}$$

The equation C.1 is used to calculate the values $S_{1.0}$ and $S_{1.2}$ that are differently used by simulation tools. The parameters $S_{1.0}$ and $S_{1.2}$ can be calculated from the air-gap line and OCC curve using a_1, a_2, b_1 and b_2 indicated in Fig.C.1 where a1 is the field current at required to produce 1.0 p.u flux on the air-gap line, a2 is the field current required to produce 1.2 p.u flux, b1 and b2 are field current required for a 1.0 p.u flux and 1.2 p.u on the OCC curve respectively. The next sections show mathematical models used by PSAT, PacDyn and MatNetEig simulation tools for synchronous machine modelling.

C.1. PacDyn model

PacDyn synchronous machine models are subdivided into two groups [41]. Group 1 covers machines that require what is termed "primary record" only and group 2 covers machines that need both primary and secondary records. Group 1 machines are classical, 3rd order and 4th order synchronous generators, while group 2 machines are 5th order, 6th order and synchronous machines used for sub-synchronous resonant models. The machines in group 1 use the mathematic models given by equations (C.2) and (C.3).

$$\begin{aligned} I_{fd} &= V_{occ} + SFAC(V_{occ})^7 \\ C_d &= \frac{SFAC - 1.2}{1.2^7} \end{aligned} \qquad \text{(C.2)}$$

where C_d is internally used to derive the d- and q-axis saturation models. The user enters the per-unit field current I_{fd} at V_{occ}= 1.2 p.u (defining 1.0 p.u of I_{fd} as that current required to produce 1.0 p.u V_{occ} along the air-gap line). This I_{fd} value is called SFAC on the synchronous machine data [40, 41]. The equation (C.2) is used to fit an OCC curve.

Group 2 synchronous machine models use the equation (C.3) to fit the OCC curve.

$$SAT = A_{sat} e^{B_{sat}(|E|-C)} \tag{C.3}$$

SAT is internally used when calculating SAT_{d} and SAT_{q} for the d- and q-axis saturation models with C is normally used as 0.8 [37, 41 – 44]. Equation (C.3) is similar to (C.1) and thus machine models in group 2 of PacDyn use the same OCC curve indicated in (C.1).

C.1.1. Saturation parameters in PacDyn

The saturation data in PacDyn is specified using SFAC for group 1 and A_{sat}, B_{sat} and C for group 2 synchronous machines. Given the OCC curve, the user can calculate both $S_{1.0}$ and $S_{1.2}$ using equations (C.4) below.

$$\begin{aligned} S_{1.0} &= \frac{b_1 - a_1}{a_1} = \frac{b_1}{a_1} - 1 \\ S_{1.2} &= \frac{b_2 - a_2}{a_2} = \frac{b_2}{a_2} - 1 \end{aligned} \tag{C.4}$$

Where a_1, a_2, b_1 and b_2 are the field current values shown in Fig.C.1. Manipulating equations (C.4) results in equations (C.5) for b_1 and b_2 respectively.

$$\begin{aligned} b_1 &= 1 + a_1(S_{1.0}) \\ b_2 &= 1 + a_2(S_{1.2}) \end{aligned} \tag{C.5}$$

The equations (C.5) are used to compare PacDyn with both PSAT and MatNetEig tools' saturation models.

C.2. PSAT model

The equation used to fit OCC curve in PSAT is similar to both (C.1) and (C.3) used by PacDyn group 2 machine models. However, both (C.3) and PSAT model use the per unit voltage instead of flux shown in equation (C.1). PSAT fits the OCC saturation curve using the equation (C.6) as follows:

$$I_{fd}(e'_q) = A_{sat} e^{B_{sat}(e'_q - C)} \tag{C.6}$$

The equation (C.6) shows that PSAT models the generator saturation using the sub-transient voltage (e'_q) from the quadrature axis synchronous machine parameters.

C.2.1. Saturation parameters in PSAT

Saturation data is specified using $S_{1.0}$ and $S_{1.2}$ in PSAT simulation tool and the following equations (C.7) are used:

$$\begin{aligned} S_{1.0} &= 1 - \frac{a_1}{b_1} \\ S_{1.2} &= 1 - \frac{a_2}{b_2} \end{aligned} \tag{C.7}$$

These equations are used to calculate b_1 and b_2 as follows:

$$\begin{aligned} b_1 &= \frac{1}{a_1 - S_{1.0}} \\ b_2 &= \frac{1}{a_2 - S_{1.2}} \end{aligned} \tag{C.8}$$

Analysis of (C.8) above shows that b_1 is inversely proportional to $S_{1.0}$. This applies to b_2 as a function of $S_{1.2}$. Comparing (C.8) and (C.5) used in PacDyn shows that in PacDyn, b_1 and b_2 are proportional to $S_{1.0}$ and $S_{1.2}$ respectively. Although the OCC curves used by these two simulation tools are similar, the overall mathematical modelling of generator saturation in PacDyn and PSAT are different.

C.3. MatNetEig model

MatNetEig simulation tool has three saturation models [14, 20]. The round rotor synchronous generator model given by "type 21 or 31" as defined in MatNetEig uses mathematical model given by equations (C.9)

$$
\begin{aligned}
I_{fd}(\psi) &= \psi_a + A_{sat}e^{B_{sat}(\psi_a - 0.8)} - A_{sat} \\
B_{sat} &= 5.0\log\left(\frac{1.2S_{1.2}}{S_{1.0}}\right) \\
A_{sat} &= S_{1.0}e^{-0.2B_{sat}}
\end{aligned} \tag{C.9}
$$

The equations above indicate that the mathematical model is identical to (C.2) and (C.6) with an additional term given by Ψ_a-A_{sat}. The value of C is fixed at 0.8 per unit. MatNetEig uses the flux as opposed to voltage used in PacDyn and PSAT. The OCC saturation in MatNetEig differs from the models used in both PacDyn and PSAT tools.

C.3.1. Saturation parameters in MatNetEig

Synchronous machine saturation data is specified using $S_{1.0}$ and $S_{1.2}$ in MatNetEig simulation tool and the following apply:

$$
\begin{aligned}
S_{1.0} &= \frac{b_1 - a_1}{a_1} \\
S_{1.2} &= \frac{b_2 - a_2}{a_2}
\end{aligned} \tag{C.10}
$$

Since a_1=1 and a_2=1.2, we get b_1 and b_2 as follows:

$$
\begin{aligned}
b_1 &= a_1 + a_1S_{1.0} = 1 + a_1S_{1.0} \\
b_2 &= a_2 + a_2S_{1.2} = 1.2 + a_2S_{1.2}
\end{aligned} \tag{C.11}
$$

Taking the additional factor into consideration, the above can be written as:

$$
\begin{aligned}
b_1 &= 2 + a_1(S_{1.0}) - A_{sat} = (1 - A_{sat}) + [1 + a_1(S_{1.0})] \\
b_2 &= 1.2[2.4 + a_2(S_{1.2}) - A_{sat}] = (1.88 - 1.2A_{sat}) + [1 + (a_2)^2(S_{1.2})]
\end{aligned} \tag{C.12}
$$

The equations (C.10), (C.11) and (C.12) suggest that the saturation models in MatNetEig is different from the model used in PacDyn by the factors 1-A_{sat} and 1.88-1.2A_{sat} for b_1 and b_2 respectively, with b_2 proportional to $(a_2)^2$ compared to a_2 in PacDyn and PSAT.

The mathematical models used in PSAT, PacDyn and MatNetEig simulation tools are all different as indicated in this section. The simulation results from these three tools are therefore expected to be different following these variations in magnetic saturation in generator models.

The effects of variations in saturation models in PSAT, MatNetEig and PacDyn simulation tools are indicated in the results and discussion section of this thesis.

D. Description of internal variables

Appendix D highlights the system internal variables accessible for monitoring and control of power system in PacDyn, MatNetEig and PSAT simulation tools. These variable names are case sensitive and can all be monitored or controlled after load flow convergence. Usage of these variables can be seen on the data and perturbation files in PSAT, on the UDC data and transfer function manager in PacDyn and in the time domain simulation GUI in MatNetEig.

D.1. PacDyn variables

Table D.1 below shows the names and description of variables that can be used for control and monitoring purposes in PacDyn simulation tool.

Table D.1: PacDyn tool's internal variables

Name	Variable description (Unit)	NB1	NB2
DELT	Synchronous machine rotor angle (rad)	Bus number.	Machine number.
ED2	Direct axis sub-transient voltage (p.u)	Bus number.	Machine number.
EFD	Synchronous machine field voltage (p.u)	Bus number.	Machine number.
EQ1	Quadrature axis transient voltage (p.u)	Bus number.	Machine number.
EQ2	Quadrature axis sub-transient voltage (p.u)	Bus number.	Machine number.
FREQ	Bus frequency (p.u)	Bus number.	-
IFD	Synchronous machine field current (p.u)	Bus number.	Machine number.
PMEC	Mechanical power applied to generator (p.u)	Bus number.	Machine number.
PT	Generator terminal active power (p.u)	Bus number.	Machine number.
VB	Bus voltage magnitude (p.u)	Bus number.	-
VBI	V magnitude at bus "i" of branch "i-j" (p.u)	Bus number "i"	Bus number "j"
VBJ	V magnitude at bus "j" of branch "i-j" (p.u)	Bus number "i"	Bus number "j"
VPSS	Synchronous machine stabilizing signal (p.u)	Bus number	Machine number.
VREF	AVR reference voltage (p.u)	Bus number.	Machine number.
VUDC	User Defined Controller variable	UDC number.	Block number.
WW	Synchronous machine speed in (p.u)	Bus number.	Machine number.

D.2. MatNetEig variables

The list in table D.2 gives the input and output variables commonly used for monitoring and control of power systems in MatNetEig simulation tool for stability analysis.

Table D.2: MatNetEig tool's internal variables

Name	Variable description	Unit
vref	Reference voltage input of the AVR	p.u
pmin	Generator mechanical input power	p.u
vmag	Bus voltage magnitude	p.u
vang	Bus voltage phase angle	p.u
busf	Bus frequency	p.u
speed	Rotor speed	p.u
pelec	Generator electrical power output	p.u
efd	Output voltage of the AVR	p.u
ifd	Field current	p.u
pm	Generator mechanical power set point	p.u
pt	Generator terminal real power output	p.u
qt	Generator terminal reactive power output	p.u

D.3. PSAT variables

Appendix D.3 covers the variable names used in PSAT simulation tool. Only the variables that were used in step response and time domain simulation perturbation files are indicated. It is important to note that all data structures defining the steady-state and dynamic component models can be monitored and controlled via the GUI command or via the Matlab command prompt. Table D.3 shows commonly used variables in PSAT.

Table D.3: PSAT tool's internal variables

Name	Variable description	Unit
DAE	Differential algebraic equation	-
vref0	AVR voltage setpoint	p.u
vref	Reference voltage of the AVR	p.u
vbus	Bus voltage	p.u
Varout	Vector of variable list	-
Syn	Synchronous machine	-
pm0	Generator machenical power setpoint	p.u
pm	Mechanical power input of the generator	p.u
omega	Rotor speed	p.u
Exc	AVR excitation	-
delta	Rotor angle	p.u

All the system internal variable names in tables D.1, D.2 and D.3 are case sensitive.

E. Matlab script listings

This section covers the author's Matlab codes developed to use with PSAT, MatNetEig or PacDyn simulation tools.

E.1. Matlab code listing for saturation parameters

```
function y = abc2s_sat(a ,b , c);
 %--------------------------------------------------------------------------
 % Converts givet ABC or A, B & Flux to S1.0 & S1.2
 % Computes a1, a2, b1 & b2
 % Calculates saturation factors for PacDyn, PSAT & MatNetEig
 % By: DS Mudau, 20 January 2009
 %
 % Usage: y = abc2s_sat(A, B, C); %  where S = A*exp[B*(Vt-C)]
 % Results: [SFAC, A, B, C, S1_0, S1_2, S1, S2]
 %--------------------------------------------------------------------------

 % Check and verify all inputs
if (nargin==2); disp('A, B specified, defalt [C=0.8] used'); c=0.8;
elseif (nargin < 2);
    disp('Warning: A, B & C required. y=abc2s_sat(A,B,C)');
    disp('Program terminated, use correct syntax'); return
else; if (c < 0); c= -c; disp('C >=0, abs(C) used.'); end
    if (a == 0); a=1e-9;
        disp('For numerical stability, A = 1e-9 used.');
    end
end

% Calcuclate S1.0, S1.2 & boundry conditions
s1_0 = a*exp(b*(1-c)); s1_2 = a*exp(b*(1.2-c));
S1 = a*exp(b*(1-c))-a; S2 = (a*exp(b*(1.2-c))-a)/1.2; %MNE Type 1
 %S1m3 = a; S2m3 = a*(1.2^b)/1.2;          %MNE Type 3
b10 = 1 + s1_0; a10 = 1; a12 = 1.2; b12 = 1.2 + (1.2*s1_2);

% Saturation factors for all simulation tools
s10=(b10-a10)/a10; s12=(b12-a12)/a12; SFAC=b12; % PacDyn
(S1.0,S1.2,SFAC)
A=s10/(exp(b*(1-c))); B=log(s12/A)/(1.2-c); C=c; % PacDyn (A, B & C)
S1_0=1-(a10/b10); S1_2=1-(a12/b12);  % PSAT (S1.0 & S1.2)
S1m1=b10-a10; S2m1=(b12-a12)/a12; % MatNetEig  Modified (S1 & S2)
y=[SFAC, A, B, C, S1_0, S1_2, S1, S2]; % All outputs

% Print a summary report
fprintf(...
    '\n=================== SUMMARY REPORT ========================\n')
fprintf(...
 '|- PacDyn Data -|- PSAT Data -|- MatNetEig -|- Modified MNE -|\n')
fprintf(...
 ' SFAC A    B     C    S1.0    S1.2    S1      S2        S1       S2\n')
fprintf(...
  ' %6.3f %6.4f %6.4f %6.4f %6.4f %6.4f %6.4f %6.4f %6.4f
%6.4f\n',...
        SFAC, A, B, C, S1_0, S1_2, S1, S2, S1m1, S2m1)
fprintf(...
  '------------------------- END ==============================\n\n')
end
```

E.2. Matlab code listing for saturation curve plotting

```
function sat=sat_plot(k, p);
%-----------------------------------------------------------------------
 % Plot of machine saturation curves as defined in PacDyn 8.1
documentation
 % Saturation curve defined by: Ifd = Voc + (k*Voc^7)
 %                     Cd=(SFAC-1.2)/1.2^7; PacDyn 8.1
 % For PacDyn [SFAC, A, B, C]; PSAT [S1.0, S1.2] & MatNetEig [S1, S2]
 % Saturation using Total Saturation model
 %
 % Usage: f=sat_plot(k, p);
 %   Where k is the saturation constant [k >= 0]
 %          p = 0/1 or false/true to (disable)/(enable) marks
 % Returns [k, SFAC, A, B, C, S1.0, S1.2, S1, S2] with 1e-4 tolerance
 % DS Mudau, 14 Jan 2009
 %----------------------------------------------------------------------

format; clc; pp = 0; % set default number format and clear the screen

 %Check & verify the k factor specified & set defaults if needed.
if (nargin<1);
  disp('No k entered, k=0.1 will be used. Usage: y=sat_plot(k, p)');
  k = 0.1; p = 0; % pp = 0;
else % Enable or disable plot intersection marks [p=1 or p=0].
  if (nargin > 1 & p > 0); pp = p; p = 1; else; p = 0; end
  if (k<0);
      disp('Warning: k can not be less than zero, default k=1 used');
      k=1;
  elseif (k==0);
      disp('For numerical stability, k=1e-9 will be used');
      k=1e-9;
  end
end
 % Prepare the plot title and labels.
figure(1); hold on
title(...
      'Generator saturation curves for [PacDyn, PSAT & MatNetEig]')
xlabel('Current [Ifd (pu)]'); ylabel('Voltage [e1q (pu)]')

 % Calculations for function curves
v=0:0.01:1.4; i0=v+(0.0*v.^7); ik=v+(k*v.^7);

 % Linear & exponential saturation factors boundry conditions
 % Test with 2A4M data from Kundur (0.015,9.6,0.9)
a10=1; a12=1.2; b10=1+k; b12=1.2+(k*1.2^7);

 % Saturation factors for all simulation tools
s10=(b10-a10)/a10; s12=(b12-a12)/a12; % S1.0 & S1.2 for PacDyn
SFAC=b12; A=s10^2/s12; B=5*log(s12/s10);C=0.8; % PacDyn (SFAC,A,B&C)
S1_0=1-(a10/b10); S1_2=1-(a12/b12); % PSAT (S1.0 & S1.2)
S1=b10-a10; S2=(b12-a12)/1.2;   % MatNetEig (S1 & S2)

sat=[k, SFAC, A, B, C, S1_0, S1_2, S1, S2]; %All outputs

 % Plot Air gap line & Saturation curve
plot(i0,v,'m'); plot(ik,v,'b');
 % Plot Vertical lines and Horizontal lines
```

```
plot(a10,v,'k'); plot(a12,v,'r'); plot(b10,v,'k');
plot(b12,v,'r'); plot(max(i0,ik),1.0,'k');
plot(max(i0,ik),1.2,'r'); plot(max(i0,ik),0.8,'b');

 % Plot intersection marks at 1.0 & 1.2 p.u voltages respectively
if (k>0.02 & p == 1);
 % Comment out if marks are not needed
    plot(a10,1,'bo'); plot(b10,1,'bo');
    plot(a12,1.2,'ro'); plot(b12,1.2,'ro');
end

disp('------------------------------------------------------------------')
disp('Saturation results: PacDyn 8.1, PSAT 2.1.2 & MatNetEig')
fprintf('Script/Code by: DS Mudau\n14 January 2009\n')
disp('==================================================================')

 % Print PacDyn results
fprintf('\nSaturation constant specified [k = %6.4f]\n\n', k)
disp('------ FOR PacDyn 8.1 [ DGEN ] for #1, #2, #3 and #4 --------')
fprintf('\nSaturation Factor [SFAC] to be used\nSFAC = %6.4f\n\n',
SFAC)
disp('------ FOR PacDyn 8.1 [ DGEN ] for #5, #6, #7 and #8 -------')
fprintf('* [S10 = %6.4f, S12 = %6.4f]\n', s10, s12)
fprintf('\nSaturation Factors [A, B &  C] to be used\n\n')
fprintf('A = %6.4f\nB = %6.4f\nC = %6.4f\n\n', A, B, 0.8)

 % Print PSAT results
disp('--------- FOR PSAT 2.1.2 [Syn.con] for ALL models ----------')
disp('a1.0 & a1.2 --> Air gap line at 1 pu & 1.2 pu respectively')
disp('b1.0 & b1.2 --> Saturaion curve at 1 pu & 1.2 pu respectively')
fprintf(...
   '* [a1.0= %6.4f,b1.0= %6.4f]\n* [a1.2 = %6.4f, b1.2 =
%6.4f]\n',...
      a10, b10, a12, b12)
fprintf(...
   'Saturation Factors [S1.0 & S1.2] to be used on PSAT 2.1.2\n\n')
fprintf('S1.0 = %6.4f\nS1.2 = %6.4f\n\n',S1_0, S1_2)

 % Print MatNetEig results
disp('------- FOR MatNetEig [mac_con] for ALL model types ---------')
fprintf('* [S1 = %6.4f, 1.2S2 = %6.4f]\n\n', S1, 1.2*S2)
fprintf('Saturation Factors [S1 & S2] to be used on MatNetEig\n\n')
fprintf('S1 = %6.4f\nS2 = %6.4f\n', S1, S2)
disp('______________________________________________________________')

 % Print a summary report
fprintf(...
 '\n==================== SUMMARY REPORT =======================\n')
fprintf(...
 '|Input|---- PacDyn Data -----|-- PSAT Data --|-- MatNetEig --|\n')
fprintf(' k    SFAC    A     B      C      S1.0     S1.2     S1       S2\n')
fprintf(...
  ' %6.3f %6.4f %6.4f %6.4f %6.4f %6.4f %6.4f %6.4f %6.4f\n',...
        k, SFAC, A, B, C, S1_0, S1_2, S1, S2)
fprintf(...
 '======================== END ==============================\n\n')
if (nargin < 1 | pp > 1);
    disp('Warning: (k>=0) should be specied & p = 0/1/true/false')
end
end
```

E.3. Matlab code listing for PSAT step change on Pm

```
% DS Mudau
% 05 August 2009
% PSAT Time domain simulation script
% Increase Pm by 0.01 p.u
% -------------------------      -------------------------------------
-
clear t; clear Varout.t; clear speed;
initpsat; Settings.mva=100; %2220;
Settings.dyntol=1e-005; Settings.fixt = 1; Settings.tstep = 1e-2;

what

nc=input('Number of cases ? > ');

for c = 1:nc
    what
    fn = input('File name : ','s');
    runpsat(fn,'data')
    runpsat('pf')
    Syn.pm0(1)=Syn.pm0(1)+0.01;
    runpsat('sssa')
    mds_a
    tdc=input('Do time domain simulations [0/1] ? ');
    if tdc > 0
        cc = 1;
        runpsat('td'); t=Varout.t; speed(:,c)=Varout.vars(:,2);
    else
        cc = 0;
    end
end

cl=['b','r','g','m','y'];
if cc > 0
    for ic = 1:c
       subplot(c,1,ic)
       plot(t,speed(:,ic)-1,'LineWidth',2,'Color',cl(ic))
       if ic==1
         title('Rotor Speed response to 0.01 pu change in Pm',...
            'FontName','Helvetica','FontSize',12,'FontWeight','bold')
       end
       if c > 2
          if (ic > 1) & (ic < c)
              ylabel('Rotor Speed (p.u)','FontName','Helvetica',...
                     'FontSize',12,'FontWeight','bold')
          end
       else
           ylabel('Rotor Speed (p.u)','FontName','Helvetica', ...
               'FontSize',12,'FontWeight','bold')
       end
       if ic == c
          xlabel('Time (s)','FontName','Helvetica','FontSize',12,...
                'FontWeight','bold')
       end
       legend('\omega_{Syn 1} [Kd=0.0?]')
       ylim([min(speed(:,ic)-1)*1.1 max(speed(:,ic)-1)*1.1])
       GRID ON; set(gca,'YTick',[0],'XGrid','on','YGrid','on')
    end
end
```

E.4. Matlab code listing for PSAT step change on V_{ref}

```
initpsat
runpsat('d_2area_avr_htg pss pq.m','data')
runpsat('pf')

Settings.fixt = 1;
Settings.tstep = 0.01;
Exc.vrif0(2) = Exc.vrif0(2)+0.01;

runpsat('td')
t=Varout.t;
angle=Varout.vars(:,1);
speed=Varout.vars(:,2);

figure
plot(t,speed)
title('Speed')
xlabel('Time (s)')
ylabel('Rotor Speed (p.u)')

figure
plot(t,angle)
xlabel('Time (s)')
ylabel('Rotor angle (p.u)')
```

E.5. Matlab code listing for PSAT A matrix computation

```
global DAE
 % Com puting state matrix A and eigenvalues for PSAT
A = DAE.Fx - DAE.Fy*inv(DAE.Gy)*DAE.Gx; % Sparse Matrix
A = full(A) % Full state matrix
e = eig(A) % Eigenvalues
```

E.6. Matlab code listing for PSAT perturbation files

```
function y=p_pm_increse()
 % Increase mechanical input power (Pm) by 0.01 pu.
      Syn.pm0=Syn.pm0+0.01;
       %Syn.pm0=Syn.pm0*1.01;
end

function y=p_speed_increse()
 % Increase the speed by 0.01 pu
      DAE.x(Syn.omega(1))=DAE.x(Syn.omega(1))+0.01;
       %DAE.x(Syn.omega(1))=1.01;
end
```

E.7. Matlab code listing for MatNetEig modified SSSA program

```
 % Set a specified machine as an infinite bus
 % Call: mne_inf();
 % DS Mudau
 % Rev 0, March 2009
 % -------------------------------------------------------------------
clear all
SVCD=[];
TCSCD=[];
UPFCD=[];
```

```
HVDCCD=[];
ibg_idx=[];

[S,GenSys,SVCD,TCSCD,UPFCD,HVDCC,geib_idx,gsib_idx,...
    lmod_con,rlmod_con,load_con] = rdpstv2;
[n,lf_solve]=netflow(net_c(S),'no_print',1);
[sgc,strgc,e_flag] = formgss(GenSys,n);
[suc,sys_state,StateName,DeviceName,strsuc,e_flag]=formuss(n, ...
      GenSys,lmod_con,rlmod_con,load_con,SVCD,TCSCD,UPFCD,HVDCCD);

ibg_idx = 0;

inf_bus = inputdlg(...
      {'Machine Number(s) to be set as infinite bus(es) :'},...
      'Inifinite Bus',1,{''},'on');

ibg_idx = [str2num(inf_bus{1})]';

if (ibg_idx > 0)
 % Set a specified machine as an infinite bus
    disp(' ')
    fprintf('Infinite bus number specified: %i\n',ibg_idx)
    [suc,sys_stater,StateNamer,DeviceNamer,strsuc,error_flag]= ...
         setib(suc,sys_state,StateName,DeviceName,strsuc,ibg_idx);
end

[sps,strsps] = fullssm(suc,strsuc,n);
[l,ld,damp,freq,u,v,p] = fullma(sps);

disp(' ')
disp('Eigenvalue             freq [ Hz]        damping ratio')
format short
disp([l freq damp])
```

E.8. Matlab code listing for Compass plots

```
function a=my_plots(x1,x2,x3,x4)
 %Participation fators in MatNetEig
 %DS Mudau
 %01 June 2009
 %-------------------------------
    x1=0.00111-0.000409i; x2=0.00109-0.00201i; x3=0.211-0.00431i;
    x4=0.311+0.0165i; y=[x1 x2 x3 x4];

    figure; compass(max(y),'m*'); hold on
    compass(x1,'b-');
    compass(x2,'r-');
    compass(x3,'g-');
    compass(x4,'c-');
    title('Participation factors(Compass plot): Eig(n)= σ±jω')
    legend('Max','Gen 1','Gen 2','Gen 3','Gen 4')
end
```

F. Power system bus classifications

A power system bus or node is a virtual point on the network where different power system components can be connected. This is an optimal location to measure system voltages with respect to the reference node.

There are different types of buses based on the components connected and both the known and unknown variables prior to loadflow solution. Each bus has a total of four variables (i.e. real power, reactive power, magnitude of bus voltage and phase angle). To describe and easily classify different types of buses used in power systems, a generic bus (Bus k) adopted from [11] shown in Fig. F.1 is used [11, 21, 22].

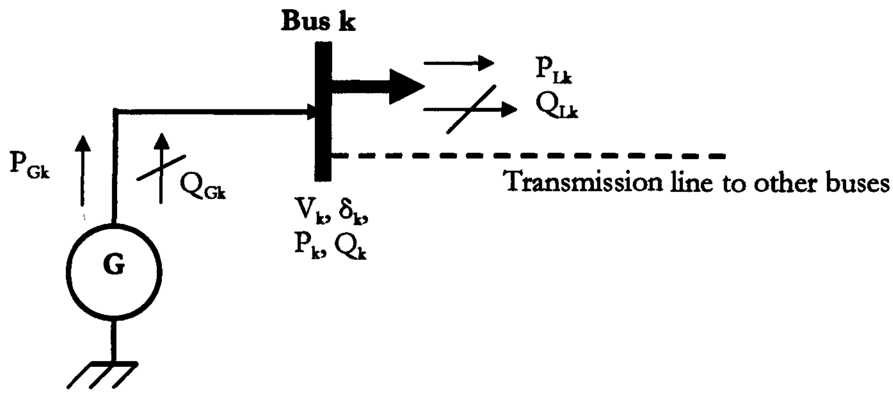


Figure F.1: A general bus of interest – Bus k

Bus k in Fig. F.1 shows real and reactive load (P_{Lk} and Q_{Lk}), real and reactive power injected (P_{Gk} and Q_{Gk}) as well as the bus voltage magnitude and phase angle (V_k and δ_k). Real and reactive components of the load on the bus are given by equation (F.1) below:

$$\begin{aligned} P_k &= P_{Gk} - P_{Lk} \\ Q_k &= Q_{Gk} - Q_{Lk} \end{aligned} \tag{F.1}$$

The complex power at bus k is the vector sum of real and reactive power components.

$$S_k = P_k + jQ_k = \sqrt{P_k^2 + Q_k^2}\angle\theta \tag{F.2}$$

For the N bus system, the total complex power at each bus "k" is given by the following summation:

$$S_i = \sum_{i=1}^{N} \sqrt{P_{ki}^2 + Q_{ki}^2} \tag{F.3}$$

A loadflow solution is achieved when the bus voltages, phase angles, loads (real and reactive), generation (real and reactive), system losses and currents converge to steady-state values. At each bus, two four variables at Bus k should be specified while the other two are solved by the loadflow program, leading to classification of buses as follows:

F.1.1. Swing bus

The swing bus (or the slack bus) is the system reference associated with an infinite capacity generator connected. The voltage magnitude (V_k) and phase angle (δ_k) are known while the real and reactive powers are not known prior to the loadflow convergence. The voltage magnitude at this bus is usually set to rated bus voltage (1.0 p.u) and the phase angle set to zero while P_k and Q_k are unknown.

F.1.2. PV or voltage controlled bus

At this bus, the total real power P_{Gk} injected to the bus is known and voltage magnitude V_k is fixed. The reactive power and the phase angle are not known. At this location, voltage regulating devices such as static var compensators (SVC), shunt reactors and shunt capacitors can be installed for the control of voltage magnitude. It is customary to set reactive power limits on this bus type [18, 21].

F.1.3. Load (PQ) bus

A load bus has known real and reactive powers while the voltage magnitude and phase angle are not known. This bus is ideal for connecting large power users where the total load required is known well in advance. The voltage limits are specified on loadflow data.

It is evident from all bus classifications that there are always two known and two unknown variables. This implies that at least two algebraic equations are required to solve the load flow problem.

Note that when the voltage magnitudes and phase angles are not known, it is common practice to set initial estimates at 1.0 p.u and 0.0 degrees for voltages and angles respectively. This is known as a flat start and it help to speed up the loadflow convergence [18, 21, 23].

G. The swing equation and equal-area criterion

G.1. The swing equation

This method is used to analyse the rotor angular difference of any rotating machine with respect to a synchronous reference machine. The swing equation is a nonlinear differential equation for the synchronous generator rotor. The equation can be derived and easily explained using the Newton's second law or the "mass-spring analogy" as follows [22, 25, 27]:

$$\begin{aligned} &\mathrm{Tm} - \mathrm{Te} = \mathrm{Ta} \\ &\mathrm{T_m} = \frac{\mathrm{P_m}}{\omega_r} \end{aligned} \tag{G.1}$$

where T_m, T_e, and T_a are mechanical torque, electrical torque and accelerating torque respectively, Pm is the mechanical power and ω_r is the rotor speed. By using the torque and power relationship at rated synchronous generator angular speed (ω_r=1 pu), we get

$$\begin{aligned} &P_m - P_e = P_a \\ &\frac{2Hd^2\delta}{\omega_B dt^2} = P_m - P_e = P_a \\ &\frac{d\delta}{dt} = \omega_0 \Delta\omega_r \end{aligned} \tag{G.2}$$

Where ω_B is the base angular velocity in radians per second, $\delta(t)$ is the rotor angular position in radians, H is the inertia constant representing stored kinetic energy at synchronous speed, P_m is the mechanical power of the machine, P_e is the electrical power output and P_a is the net accelerating or decelerating power [11, 21, 28].

The equations (G.2) are non-linear and are solved by digital computer simulation tools using analytical and numerical integration methods. The swing equation given by [21] including the effects of damping coefficient is as follows:

$$
\begin{aligned}
\frac{d\Delta\omega_r}{dt} &= \frac{1}{2H}(\overline{T}_m - \overline{T}_e - K_D\Delta\overline{\omega}r) \\
\frac{d\delta}{dt} &= \omega_0\Delta\omega_r
\end{aligned}
\tag{G.3}
$$

Where K_D is the damping coefficient, ω_r is the angular velocity of the synchronous machine rotor and Δ is a small perturbation.

G.2. Equal-area criterion

A two machine system or the SMIB system is used to derive the power transfer as a function of rotor angle (G.4). This method is based on the swing equation assuming the voltage behind sub-transient reactance and that the voltage at the infinite bus remains constant during analysis period [21, 23, 25, 27].

$$
P_e = \frac{E_1 E_2}{X_{12}}\sin(\delta) \tag{G.4}
$$

Where P_e is the electrical power transferred from machine 1 to machine 2, E_1 is the bus voltage magnitude at machine 1, E_2 is the bus voltage magnitude at machine 2, X_{12} is the total impedance between the two machines and δ is the phase angle difference of the two synchronous machine rotors.

Figure G.1 shows the power–angle curve of the two machine system or a SMIB system.

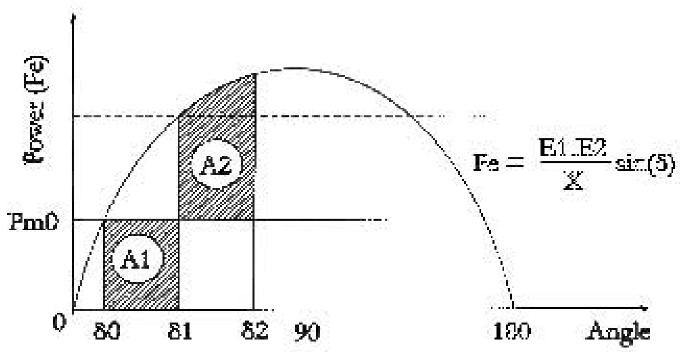


Figure G.1: Power-angle curve.

Analysis of stability is done by calculating the accelerating area "A_1" and the decelerating area "A_2". The two areas must be equal for stability to be attained after clearing the fault.

The maximum power is transferred when the angle (δ) is 90 degrees and this is known as the steady-state stability limit. Power systems are normally operated below this steady-state stability limit angle for improved stability margins [21, 22, 26]. During a normal steady-state condition, the synchronous generator mechanical power P_{m0} is equal to the output electrical power P_e. After a disturbance, the electrical power output drops and the generator control mechanism speed up the rotor to generate more electrical power. This forces the rotor angle to accelerate, when the new electrical power is equal to the mechanical power output, the rotor continues to rotate due to the mechanical torque of the machine. Deceleration takes place until the rotor stops and goes back; this makes it oscillate around the new synchronous rotor position [11].

If the two areas are equal and angle δ_2 is less than 180°, then stability of the system is maintained or a new steady state operating condition is attained; otherwise the system becomes unstable and loses synchronism. There is a critical clearing angle (time) during a fault condition under which the system regains stability [21, 23, 27]. The rotor angle δ_1 should be less than the critical clearing angle δ_{cr} for stability to be maintained. The accelerating and decelerating areas are calculated by integrating the power–angle transfer function as given by the equation (G.5) below:

$$Area = \int P_e(\delta)d\delta \tag{G.5}$$

The resulting areas (A_1 and A_2) for the above curve are then given by:

$$\begin{aligned} A_1 &= \int_{\delta_0}^{\delta_1} P_e d\delta = P_{m0}(\delta_1 - \delta_0) \\ A_2 &= \int_{\delta_1}^{\delta_2} P_e d\delta = -\frac{E_1 E_2}{X_{12}}\cos(\delta)\,|_{\delta_1}^{\delta_2} \end{aligned} \tag{G.6}$$

When analysing power system stability using the swing equation and equal-area criterion, three operating conditions are checked. These are; pre-fault, faulted and post-fault conditions. These operating conditions give different power transferred due to changes in line admittance [23].

The diagram in Fig. G.2 shows different power transfer curves for three operating conditions. Areas A_1 and A_2 are equal for a stabile system.

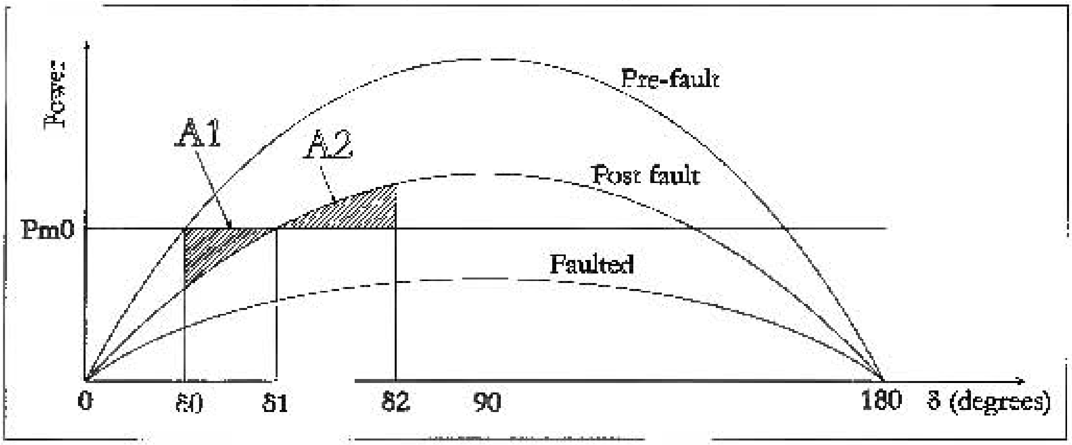


Figure G.2: Power-angle curve for different operating conditions

Analysis of Fig. G.2 shows that the power transfer capability changes at different operating conditions. The severity and duration of the fault affects the critical angle.

H. Simulation results

H.1. Load flow results

The load flow results for the two power system models computed by PSAT and MatNetEig are included as follows:

H.1.1. SMIB

H.1.1.1. PSAT results

POWER FLOW REPORT

P S A T 2.1.2

Author: Federico Milano, (c) 2002-2008
e-mail: Federico.Milano@uclm.es
website: http://www.uclm.es/area/gsee/Web/Federico

File: F:\My Documents\MSc current\Final Simulations\psat\M1. SMIB Model\1. Manual Control\c. Saturation effect\d_psat_smib_6th_order
Date: 28-Aug-2009 10:53:14

NETWORK STATISTICS

Buses:	3
Lines:	2

Generators: 2
Loads: 0

SOLUTION STATISTICS

Number of Iterations: 4
Maximum P mismatch [p.u.] 0
Maximum Q mismatch [p.u.] 0
Power rate [MVA] 2220

POWER FLOW RESULTS

Bus	V [p.u.]	phase [rad]	P gen [p.u.]	Q gen [p.u.]	P load [p.u.]	Q load [p.u.]
Bus1	1	0.62851	0.9	0.30022	0	0
Bus2	0.96446	0.48807	0	0	0	0
Bus3	0.995	0	-0.9	0.28487	0	0

STATE VARIABLES

delta_Syn_1	1.3989
omega_Syn_1	1
e1q_Syn_1	0.84054
e1d_Syn_1	0.47182
e2q_Syn_1	0.77792
e2d_Syn_1	0.65961

OTHER ALGEBRAIC VARIABLES

vf_Syn_1	0.995
pm_Syn_1	2.1006
p_Syn_1	0.9027
q_Syn_1	0.9

LINE FLOWS

From Bus	To Bus	Line	P Flow [p.u.]	Q Flow [p.u.]	P Loss [p.u.]	Q Loss [p.u.]
Bus1	Bus2	1	0.9	0.30022	0	0.13502
Bus2	Bus3	2	0.9	0.1652	0	0.45006

LINE FLOWS

From Bus	To Bus	Line	P Flow [p.u.]	Q Flow [p.u.]	P Loss [p.u.]	Q Loss [p.u.]
Bus2	Bus1	1	-0.9	-0.1652	0	0.13502
Bus3	Bus2	2	-0.9	0.28487	0	0.45006

GLOBAL SUMMARY REPORT

TOTAL GENERATION

REAL POWER [p.u.] 0
REACTIVE POWER [p.u.] 0.58508

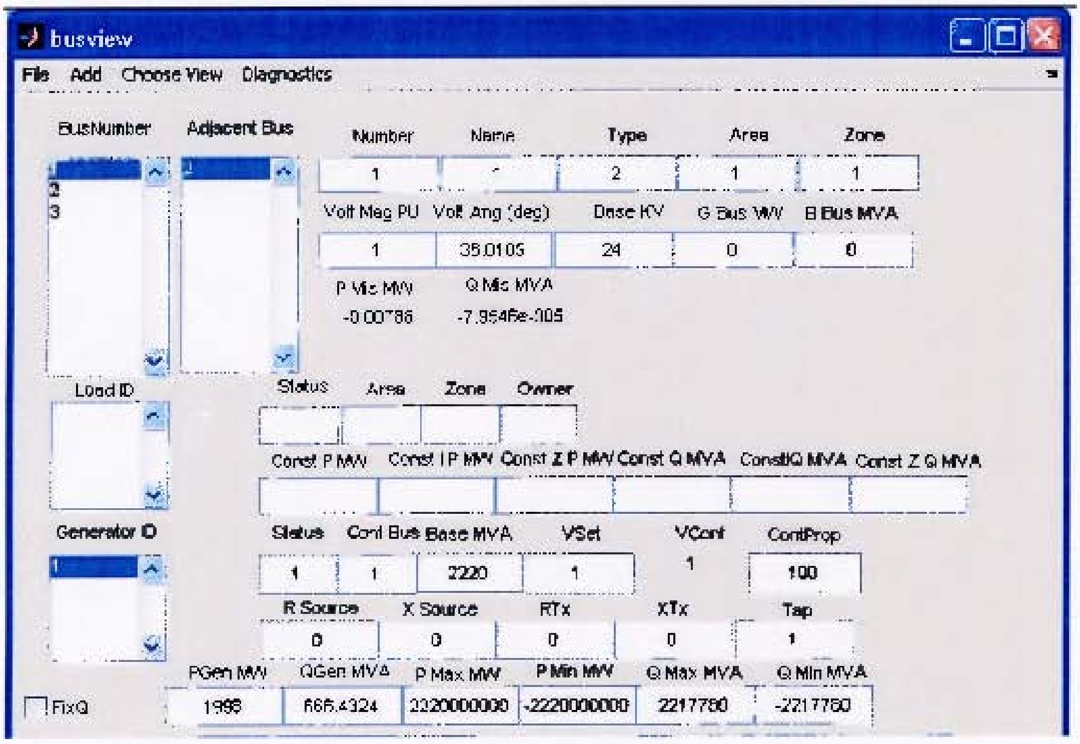
TOTAL LOAD

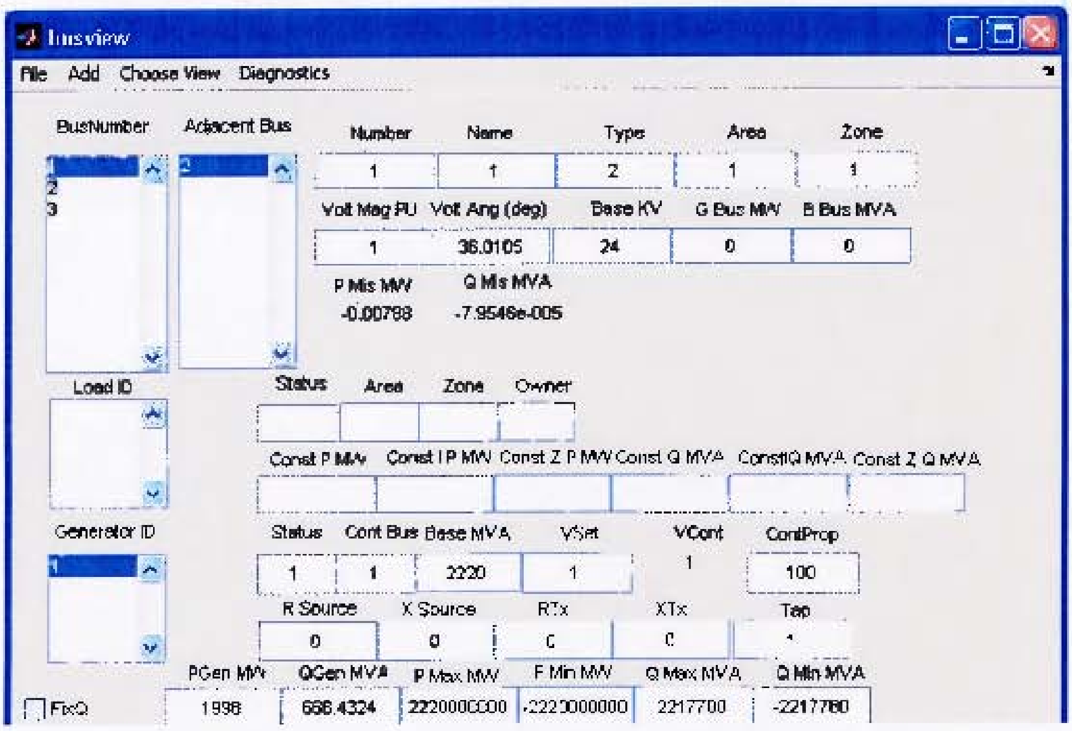
REAL POWER [p.u.] 0
REACTIVE POWER [p.u.] 0

TOTAL LOSSES

REAL POWER [p.u.] 0
REACTIVE POWER [p.u.] 0.58508

H.1.1.2. MatNetEIg Results




busview
File
Add
Choose View
Diagnostics
BusNumber
Adjacent Bus
Number
Name
Type
Area
Zone
1
1
2
1
1
Volt Mag PU
Volt Ang (deg)
Base KV
G Bus MW
B Bus MVA
1
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24
0
0
P Mis MW
Q Mis MVA
-0.00798
-7.9546e-005
Load ID
Status
Area
Zone
Owner
Const P MW
Const I P MW
Const Z P MW
Const Q MVA
ConstIQ MVA
Const Z Q MVA
Generator ID
Status
Cont Bus
Base MVA
VSet
VCont
ContProp
1
1
2220
1
1
100
R Source
X Source
RTx
XTx
Tap
0
0
0
0
1
PGen MW
QGen MVA
P Max MW
P Min MW
Q Max MVA
Q Min MVA
FixQ
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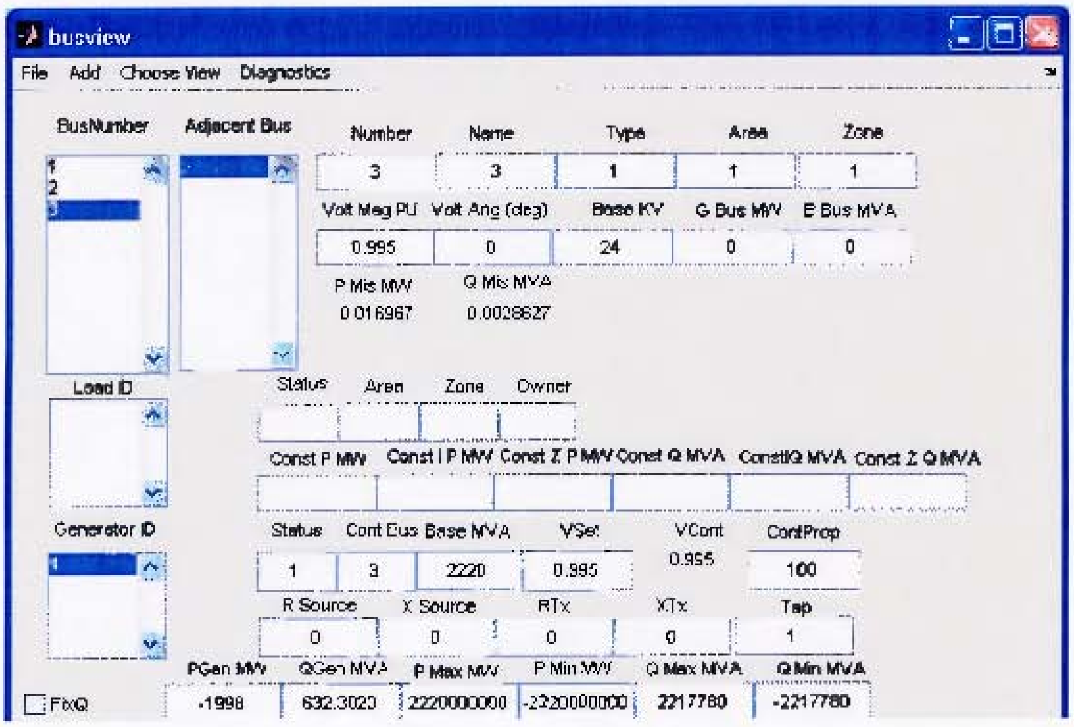
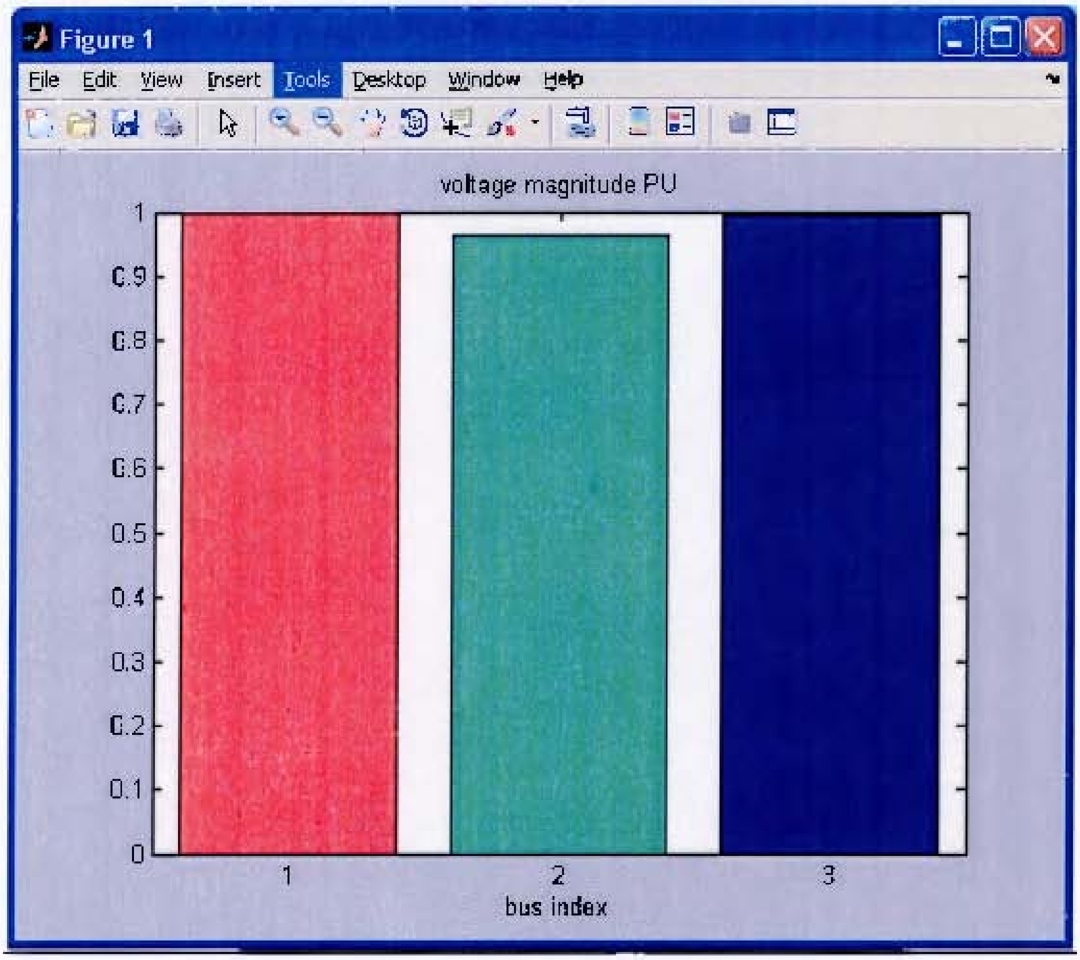
-2220000000
2217700
-2217780


busview
File
Add
Choose View
Diagnostics
BusNumber
Adjacent Bus
Number
Name
Type
Area
Zone
3
3
1
1
1
Volt Mag PU
Volt Ang (deg)
Base KV
G Bus MW
B Bus MVA
0.995
0
24
0
0
P Mis MW
Q Mis MVA
0.016967
0.0028627
Load ID
Status
Area
Zone
Owner
Const P MW
Const I P MW
Const Z P MW
Const Q MVA
ConstIQ MVA
Const Z Q MVA
Generator ID
Status
Cont Bus
Base MVA
VSet
VCont
ContProp
1
3
2220
0.995
0.995
100
R Source
X Source
RTx
XTx
Tap
0
0
0
0
1
PGen MW
QGen MVA
P Max MW
P Min MW
Q Max MVA
Q Min MVA
FixQ
-1998
632.3020
2220000000
-2220000000
2217780
-2217780



H.1.2. 2A4M

H.1.2.1. PSAT results

POWER FLOW REPORT

P S A T 2.1.2

Author: Federico Milano, (c) 2002-2008
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website: http://www.uclm.es/area/gsee/Web/Federico

File: f:\My Documents\MSc current\Final Simulations\psat\M2. Two Area 4 Machine Model\1. Manual Control\d_2area_manual_with_sat_with_xl
Date: 28-Aug-2009 10:57:55

NETWORK STATISTICS

Buses:	11
Lines:	8
Transformers:	4

Generators: 4
Loads: 2

SOLUTION STATISTICS

Number of Iterations: 5
Maximum P mismatch [p.u.] 0
Maximum Q mismatch [p.u.] 0
Power rate [MVA] 100

POWER FLOW RESULTS

Bus	V [p.u.]	phase [rad]	P gen [p.u.]	Q gen [p.u.]	P load [p.u.]	Q load [p.u.]
Bus 01	1.03	0.34983	7	1.7897	0	0
Bus 02	1.01	0.17969	7	2.2005	0	0
Bus 03	1.03	-0.1187	7.1849	1.6875	0	0
Bus 04	1.01	-0.29598	7	1.8498	0	0
Bus 05	1.0074	0.23716	0	0	0	0
Bus 06	0.98052	0.06161	0	0	0	0
Bus 07	0.9653	-0.08435	0	0	9.67	-1
Bus 08	0.95369	-0.32425	0	0	0	0
Bus 09	0.97637	-0.55924	0	0	17.67	-2.5
Bus 10	0.98626	-0.41337	0	0	0	0
Bus 11	1.0094	-0.23413	0	0	0	0

STATE VARIABLES

delta_Syn_1	1.0582
omega_Syn_1	1
e1q_Syn_1	0.85008
e1d_Syn_1	0.48574
e2q_Syn_1	0.81519
e2d_Syn_1	0.64935
delta_Syn_2	0.87813
omega_Syn_2	1
e1q_Syn_2	0.84584
e1d_Syn_2	0.47085
e2q_Syn_2	0.80862
e2d_Syn_2	0.62945
delta_Syn_3	0.60886
omega_Syn_3	1
e1q_Syn_3	0.83854
e1d_Syn_3	0.49651
e2q_Syn_3	0.80292
e2d_Syn_3	0.66374
delta_Syn_4	0.42375
omega_Syn_4	1
e1q_Syn_4	0.82978
e1d_Syn_4	0.48262

e2q_Syn_4	0.79365
e2d_Syn_4	0.64518

OTHER ALGEBRAIC VARIABLES

vf_Syn_1	1.0094
pm_Syn_1	1.8112
p_Syn_1	7.0137
q_Syn_1	7
vf_Syn_2	1.7897
pm_Syn_2	1.8706
p_Syn_2	7.0147
q_Syn_2	7
vf_Syn_3	2.2005
pm_Syn_3	1.8192
p_Syn_3	7.1991
q_Syn_3	7.1849
vf_Syn_4	1.6875
pm_Syn_4	1.8233
p_Syn_4	7.0143
q_Syn_4	7

LINE FLOWS

From Bus	To Bus	Line	P Flow [p.u.]	Q Flow [p.u.]	P Loss [p.u.]	Q Loss [p.u.]
Bus 01	Bus 05	1	7	1.7897	0	0.8201
Bus 02	Bus 06	2	7	2.2005	0	0.87969
Bus 03	Bus 11	3	7.1849	1.6875	0	0.85572
Bus 04	Bus 10	4	7	1.8498	0	0.85648
Bus 05	Bus 06	5	7	0.96958	0.12312	1.188
Bus 06	Bus 07	6	13.8769	1.1024	0.20158	1.9992
Bus 07	Bus 08	7	2.0027	0.05157	0.04758	0.29858
Bus 07	Bus 08	8	2.0027	0.05157	0.04758	0.29858
Bus 08	Bus 09	9	1.9551	-0.24701	0.04653	0.28605
Bus 08	Bus 09	10	1.9551	-0.24701	0.04653	0.28605
Bus 09	Bus 10	11	-13.8529	1.4339	0.20349	2.018
Bus 10	Bus 11	12	-7.0564	0.40914	0.12845	1.2409

LINE FLOWS

From Bus	To Bus	Line	P Flow [p.u.]	Q Flow [p.u.]	P Loss [p.u.]	Q Loss [p.u.]
Bus 05	Bus 01	1	-7	-0.96958	0	0.8201
Bus 06	Bus 02	2	-7	-1.3208	0	0.87969
Bus 11	Bus 03	3	-7.1849	-0.8318	0	0.85572
Bus 10	Bus 04	4	-7	-0.99327	0	0.85648
Bus 06	Bus 05	5	-6.8769	0.21842	0.12312	1.188
Bus 07	Bus 06	6	-13.6753	0.89686	0.20158	1.9992

Bus 08	Bus 07	7	-1.9551	0.24701	0.04758	0.29858
Bus 08	Bus 07	8	-1.9551	0.24701	0.04758	0.29858
Bus 09	Bus 08	9	-1.9085	0.53306	0.04653	0.28605
Bus 09	Bus 08	10	-1.9085	0.53306	0.04653	0.28605
Bus 10	Bus 09	11	14.0564	0.58414	0.20349	2.018
Bus 11	Bus 10	12	7.1849	0.8318	0.12845	1.2409

GLOBAL SUMMARY REPORT

TOTAL GENERATION

REAL POWER [p.u.] 28.1849
REACTIVE POWER [p.u.] 7.5274

TOTAL LOAD

REAL POWER [p.u.] 27.34
REACTIVE POWER [p.u.] -3.5

TOTAL LOSSES

REAL POWER [p.u.] 0.84487
REACTIVE POWER [p.u.] 11.0274

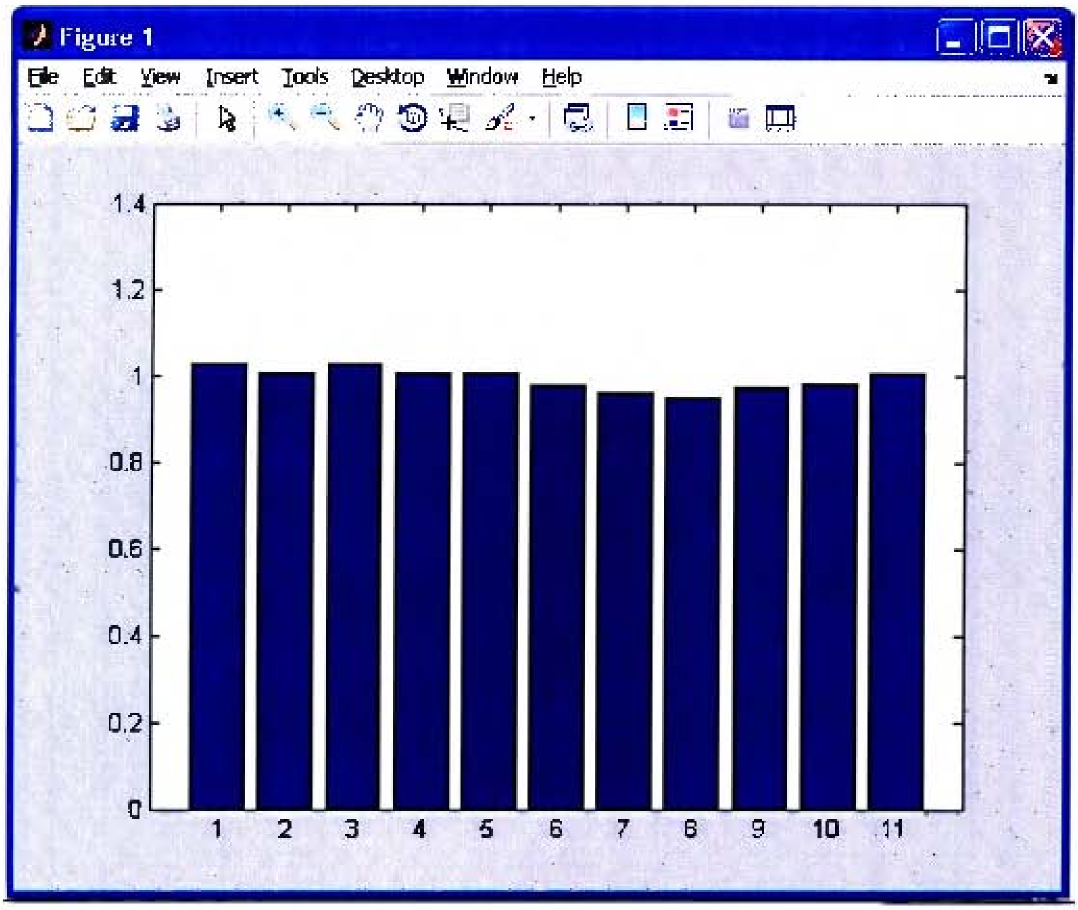
H.1.2.1. MatNetEig results

number of controlling generators 4
iteration number 0
maximum power error at bus 4 is 24.7177 pu
reactive power error at bus 1 is 3.8051 pu
number of controlling generators 4
number of generator controlled buses 4
number of controlling shunts 0
iteration number 1
maximum power error at bus 4 is 3.8001 pu
reactive power error at bus 10 is 8.3274 pu
number of controlling generators 4
number of generator controlled buses 4
number of controlling shunts 0
iteration number 2
maximum power error at bus 4 is 0.25705 pu
reactive power error at bus 10 is 0.76773 pu
number of controlling generators 4
number of generator controlled buses 4
number of controlling shunts 0
iteration number 3
maximum power error at bus 9 is 0.0075332 pu
reactive power error at bus 10 is 0.010553 pu
number of controlling generators 4
number of generator controlled buses 4

number of controlling shunts 0
iteration number 4
maximum power error at bus 9 is 7.2317e-006 pu
reactive power error at bus 10 is 3.6416e-006 pu
number of Newton-Raphson iterations 4
reset discrete shunts
load flow d_pstv2_2area_with_xl_with_sat
converged in 4 iterations
area reset
transformer Freeze, shunt Mode reset
Elapsed time is 0.065631 seconds.

ans =

```
   1.0300   20.0450
   1.0100   10.2965
   1.0300   -6.8000
   1.0100  -16.9575
   1.0074   13.5894
   0.9805    3.5310
   0.9653   -4.8318
   0.9537  -18.5769
   0.9764   32.0412
   0.9863  -23.6834
   1.0094   13.4138
```



H.2. Eigenvalue results

H.2.1. SMIB

H.2.1.1. PSAT results
1. Manual control

EIGENVALUE REPORT

P S A T 2.1.2

Author: Federico Milano, (c) 2002-2008
e-mail: Federico.Milano@uclm.es
website: http://www.uclm.es/area/gsee/Web/Federico

File: f:\My Documents\MSc current\Final Simulations\psat\M1. SMIB Model\1. Manual Control\c. Saturation effect\d_psat_smib_6th_order
Date: 28-Aug-2009 11:00:54

STATE MATRIX EIGENVALUES

Eigevalue	Most Associated States	Real part	Imag. Part	Pseudo-Frequenc	Frequency
Eig As #1	e2q_Syn_1	-36.2155	0	0	0
Eig As #2	e2d_Syn_1	-21.5382	0	0	0
Eig As #3	omega_Syn_1, delta_Syn_1	-0.34065	7.2383	1.152	1.1533
Eig As #4	omega_Syn_1, delta_Syn_1	-0.34065	-7.2383	1.152	1.1533
Eig As #5	e1d_Syn_1	-1.9926	0	0	0
Eig As #6	e1q_Syn_1	-0.02094	0	0	0

PARTICIPATION FACTORS (Euclidean norm)

	delta_Syn_1	omega_Syn_1	e1q_Syn_1	e1d_Syn_1	e2q_Syn_1
Eig As #1	0.00419	0.00417	0.01027	0	0.98135
Eig As #2	0.00125	0.00125	2e-005	0.04679	8e-005
Eig As #3	0.47617	0.47637	0.02986	0.00167	0.0135
Eig As #4	0.47617	0.47637	0.02986	0.00167	0.0135
Eig As #5	0.00054	0.00053	0.00171	0.95076	2e-005
Eig As #6	0.00025	0.00019	0.99521	0.00207	0.00209

PARTICIPATION FACTORS (Euclidean norm)

	e2d_Syn_1
Eig As #1	1e-005
Eig As #2	0.9506

Eig As #3	0.00243
Eig As #4	0.00243
Eig As #5	0.04644
Eig As #6	0.0002

STATISTICS

DYNAMIC ORDER	6
# OF EIGS WITH Re(mu) < 0	6
# OF EIGS WITH Re(mu) > 0	0
# OF REAL EIGS	4
# OF COMPLEX PAIRS	1
# OF ZERO EIGS	0

2. AVR and PSS

EIGENVALUE REPORT

P S A T 2.1.2

Author: Federico Milano, (c) 2002-2008
e-mail: Federico.Milano@uclm.es
website: http://www.uclm.es/area/gsee/Web/Federico

File: f:\My Documents\MSc current\Final Simulations\psat\M1. SMIB Model\3. AVR and PSS\d_psat_smib_6th_order
Date: 28-Aug-2009 11:04:10

STATE MATRIX EIGENVALUES

Eigevalue	Most Associated States	Real part	Imag. Part	Pseudo-FrequencFrequency	
Eig As # 1	vm_Exc_1	-49.111	0	0	0
Eig As # 2	e2q_Syn_1	-37.174	0	0	0
Eig As # 3	v2_Pss_1	-31.2155	0	0	0
Eig As # 4	e2d_Syn_1	-21.522	0	0	0
Eig As # 5	omega_Syn_1, delta_Syn_1	0.16453	7.499	1.1935	1.1938
Eig As # 6	omega_Syn_1, delta_Syn_1	0.16453	-7.499	1.1935	1.1938
Eig As # 7	vf_Exc_1, e1q_Syn_1	-0.58167	3.8107	0.60649	0.61352
Eig As # 8	vf_Exc_1, e1q_Syn_1	-0.58167	-3.8107	0.60649	0.61352
Eig As # 9	v1_Pss_1	-0.74085	0	0	0
Eig As #10	e1d_Syn_1	-1.8682	0	0	0
Eig As #11	vr3_Exc_1	-1	0	0	0
Eig As #12	v3_Pss_1	-1	0	0	0

PARTICIPATION FACTORS (Euclidean norm)

	delta_Syn_1	omega_Syn_1	e1q_Syn_1	e1d_Syn_1	e2q_Syn_1
Eig As # 1	5e-005	0.00022	0.01586	0	0.06252

Eig As # 2	0.00231	0.01582	0.01224	1e-005	0.7943
Eig As # 3	0.00077	0.02371	0.02031	1e-005	0.11886
Eig As # 4	0.00199	0.00187	0.00058	0.04656	0.0009
Eig As # 5	0.37221	0.42049	0.06023	0.00115	0.0071
Eig As # 6	0.37221	0.42049	0.06023	0.00115	0.0071
Eig As # 7	0.12701	0.01422	0.34301	0.01704	0.04284
Eig As # 8	0.12701	0.01422	0.34301	0.01704	0.04284
Eig As # 9	0.03517	0.00037	0.00043	0.0028	1e-005
Eig As #10	0.00278	0.0042	0.00504	0.92757	0.0003
Eig As #11	0	0	0	0	0
Eig As #12	0	0	0	0	0

PARTICIPATION FACTORS (Euclidean norm)

	e2d_Syn_1	vm_Exc_1	vr3_Exc_1	vf_Exc_1	v1_Pss_1
Eig As # 1	1e-005	0.90455	0	0.01653	0
Eig As # 2	0.00021	0.09744	0	0.02066	0.00026
Eig As # 3	0.00022	0.00975	0	0.01923	0.00057
Eig As # 4	0.94653	0.00051	0	0.00057	0
Eig As # 5	0.00179	0.0025	0	0.08144	0.00758
Eig As # 6	0.00179	0.0025	0	0.08144	0.00758
Eig As # 7	0.00879	0.03285	0	0.34392	0.02115
Eig As # 8	0.00879	0.03285	0	0.34392	0.02115
Eig As # 9	6e-005	0.00054	0	0.00119	0.95574
Eig As #10	0.04244	7e-005	0	0.01091	0.00432
Eig As #11	0	0	1	0	0
Eig As #12	0	0	0	0	0

PARTICIPATION FACTORS (Euclidean norm)

	v2_Pss_1	v3_Pss_1
Eig As # 1	0.00026	0
Eig As # 2	0.05675	0
Eig As # 3	0.80656	0
Eig As # 4	0.00048	0
Eig As # 5	0.0455	0
Eig As # 6	0.0455	0
Eig As # 7	0.04916	0
Eig As # 8	0.04916	0
Eig As # 9	0.00369	0
Eig As #10	0.00236	0
Eig As #11	0	0
Eig As #12	0	1

STATISTICS

DYNAMIC ORDER	12
# OF EIGS WITH Re(mu) < 0	10
# OF EIGS WITH Re(mu) > 0	2
# OF REAL EIGS	8

OF COMPLEX PAIRS 2
OF ZERO EIGS 0

H.2.1.2. PacDyn results

Manual control

PacDyn - Small Signal Stability Analysis of Electrical Power Systems

==

CEPEL - Centro de Pesquisas de Energia Eletrica

Version 8.1 - August 2008

Initializing dynamic data

Reading dynamic data .... P:\data files\pacdyn\M1. SMIB Model\1. Manual Control\c. Saturation effect\smib_6th_order.dyn

Case Title

SMIB System (Machine model#5 [6]), Kundur's Saturation parameters
PacDyn Format Electical Network Data File
PacDyn Dynamic Data File, DS Mudau

System Data

System Frequency : 60.0 Hertz
System MVA Base : 2220.0 MVA

Initializing network data
Reading network data .... P:\data files\pacdyn\M1. SMIB Model\1. Manual Control\c. Saturation effect\smib_cct2_out.sav

BUS DATA

```
X----X-----------X--X--X--------X---------X--------X----------X---------X---------X---------X-
      BUS          VOLTAGE      GENERATION        LOAD
SHUNT
 NUM.  NAME   TP AR MAGNIT.  ANGLE     MW       Mvar      MW       Mvar
MW     Mvar
X----X-----------X--X--X--------X---------X--------X----------X---------X---------X---------X-

   1  BUS1       1.0000 36.0109  1998.00  666.48   0.00    0.00    0.00    0.00
   2  BUS2       0.9645 27.9646     0.00    0.00   0.00    0.00    0.00    0.00
   3  BUS3       0.9950  0.0000 -1998.00  632.41   0.00    0.00    0.00    0.00
```

LINE DATA

```
X---------X---X---------X----------X----------X---------X---------X
   BUS   CIRC  RESIST.   REACT.   SUSCEP.    TAP    ANGLE
 FROM  TO  NUM.    pu        pu       Mvar       pu     Degree
X---X----X---X----------X---------X---------X----------X---------X

   1   2   1    0.0000    0.1500    0.0000
   2   3   2    0.0000    0.5000    0.0000
```

Converged Load Flow

Maximum specified tolerances:

```
Voltage module:    0.00072 ( pu    ).
 Voltage angle :   0.05000 (degrees).
 Active   power:    1.00000 ( %      ).
 Reactive power:    1.00000 ( %      ).
```

Maximum differences found :

```
Voltage module:  0.28242E-05 ( pu     ) on bus    2.
Voltage angle :  0.50997E-04 (degrees) on bus    2.
Active   power:  0.18576E-02 (MW      ) on bus    1.
Reactive power:  0.14044E-02 (Mvar   ) on bus    1.
```

Synchronous Machine Dynamic Data

```
----------------------------------------------------------------------------------------------
+------- Identification -------+--- Mechanical ----+--------------- Reactances (pu) ----------
----+------+--- Time Constants (s) ----+---- Saturation ----+------+
 S Bus   Gen.                    MVA         Damp  Transient    Synchronous   Sub-Transient
Ra   Transient    Sub-Transient                       Freq.
 T No.   No.    Bus Name   M UP  Base  Inert. (1/s) D-axis Q-axis D-axis Q-axis D-axis
Q-axis Potier  (pu)  D-axis Q-axis D-axis Q-axis   A      B      C     (HZ)
+-+-----+----+------------+-+--+------+------+-----+------+------+------+------+------+-----
     1    0    BUS1      5  1 2220.0  3.500  0.00 0.3000 0.6500 1.8100 1.7600 0.2300 0.2500
0.0000 0.003  8.000  1.000  0.030  0.070  0.031  6.930  0.800  60.00
     3    0    BUS3      0    2220.0  0.000  0.00 0.0000 0.0000 0.0000 0.0000
0.0000        0.000  0.000                               60.00
     3    0    BUS3      Machine modelled as infinite bus.
```

INITIAL CONDITIONS

```
   (------ bus ------) s/m   rotor  mechanic (  terminal power   ) ( terminal voltage)
terminal   field
```

name	no.	no.	angle degree	power MW	active MW	reactive Mvar	modulus pu	angle degree	current pu	voltage pu
BUS1	1	0	78.974	2003.99	1998.00	666.48	1.0000	36.011	0.949	2.4333

System Summary		On	Off	Tot.	Max.
AC buses				3	120
AC branches				2	25000
Non-linear loads				0	16000
Dynamic loads				0	16000
PV/Slack buses				0	3000
Infinite buses				1	16000
Induction motors		0		0	500
HVDC converters		0		0	40
Synchronous machines		1	0	1	3000
Excitation systems	(built-in)	0	0	0	3000
Excitation systems	(UDC)	0	0	0	4000
Rotor speed control systems	(built-in)	0	0	0	3000
Rotor speed control systems	(UDC)	0	0	0	4000
Power system stabilizers	(built-in)	0	0	0	1000
Power system stabilizers	(UDC)	0	0	0	4000
FACTS devices	(built-in)	0	0	0	20
User defined controllers		0	0	0	4000

System Summary	
Reference generator bus number	0
Reference generator number	0
Abort on power flow error ?	YES

Matrix Summary: Jacobian & State Matrices

Description	Num.	Max.
Jacobian matrix dimension	23	150000
Number of non-zero elements	66	900000
Number of state variables	6	
Number of algebraic variables	15	
Number of null variables	2	
State matrix dimension (for full system eigensolution)	6	4000

Synchronous Machine Control Data

```
--------------------------------------------------------------------------
 Bus          Gen.  Synchr. AVR    GOV     PSS
 No.  Bus Name  No.  M Conden. (M)/UD  (M)/UD  (M)/UD  Inp1 Inp2 Inp3 ...
+-----+------------+----+-+-------+-------+-------+-------------------------+
   1  BUS1       0 5 no
```

Spining Reserve Data

```
--------------------------------------------------------------------------
 Bus  Gen.          No.   MVA Base   Gener. Load.
 No.  No.  Bus Name  Unt.  Unit  Total  MVA %      Status
+-----+----+------------+----+-------+-------+-------+-----+-----------------+
   1   0   BUS1       1  2220.0  2220.0  2106.2  94.9 Ok
```

EIGENVALUES

```
                  -----------
 No.    Real      Imaginary     Damp (%) Freq (HZ) Maximum Participation Factor
---- -------------  ------------- --- ---------- --------- ----------------------------

  1 -36.34772                            EQ"   BUS1   #  1
  2 -21.44648                            ED"   BUS1   #  1
  3 -.2109401   +j 6.401203   <<<   3.29    1.02 DELT    BUS1   #  1
  4
  5 -2.159397                            ED'   BUS1   #  1
  6 -.1658894                            EQ'   BUS1   #  1
```

AVR and PSS

PacDyn - Small Signal Stability Analysis of Electrical Power Systems

==

CEPEL - Centro de Pesquisas de Energia Eletrica

Version 8.1 - August 2008

Initializing dynamic data

Reading dynamic data .... P:\data files\pacdyn\M1. SMIB Model\3. AVR and PSS\smib_6th_order_avr_and_pss.dyn

Case Title

SMIB System, Machine model#5, Kd=0.0 AVR WITHOUT A PSS
PacDyn Format Electical Network Data File

PacDyn Dynamic Data File, DS Mudau

System Data

System Frequency : 60.0 Hertz
System MVA Base : 2220.0 MVA

Initializing network data
Reading network data .... P:\data files\pacdyn\M1. SMIB Model\3. AVR and PSS\smib_cct2_out.sav

BUS DATA

BUS				VOLTAGE		GENERATION		LOAD		SHUNT	
NUM.	NAME	TP	AR	MAGNIT.	ANGLE	MW	Mvar	MW	Mvar	MW	Mvar
1	BUS1			1.0000	36.0109	1998.00	666.48	0.00	0.00	0.00	0.00
2	BUS2			0.9645	27.9646	0.00	0.00	0.00	0.00	0.00	0.00
3	BUS3			0.9950	0.0000	-1998.00	632.41	0.00	0.00	0.00	0.00

LINE DATA

BUS		CIRC	RESIST.	REACT.	SUSCEP.	TAP	ANGLE
FROM	TO	NUM.	pu	pu	Mvar	pu	Degree
1	2	1	0.0000	0.1500	0.0000		
2	3	2	0.0000	0.5000	0.0000		

Converged Load Flow

Maximum specified tolerances:

Voltage module: 0.00072 (pu).
Voltage angle : 0.05000 (degrees).
Active power: 1.00000 (%).
Reactive power: 1.00000 (%).

Maximum differences found :

Voltage module: 0.28242E-05 (pu) on bus 2.
Voltage angle : 0.50997E-04 (degrees) on bus 2.
Active power: 0.18576E-02 (MW) on bus 1.

Reactive power: 0.14044E-02 (Mvar) on bus 1.

```
-----------------------------------------------------------------------------

Synchronous Machine Dynamic Data
------------------------------------------------------------------------------------------------
+------- Identification -------+--- Mechanical ----+--------------- Reactances (pu) ----------
----+------+--- Time Constants (s) ----+---- Saturation ----+------+
 S Bus   Gen.              MVA       Damp  Transient   Synchronous  Sub-Transient
Ra  Transient   Sub-Transient              Freq.
 T No.  No.   Bus Name  M UP  Base  Inert. (1/s) D-axis Q-axis D-axis Q-axis D-axis
Q-axis Potier  (pu)  D-axis Q-axis D-axis Q-axis  A    B    C   (HZ)
+-+-----+----+-----------+-+--+------+------+-----+------+------+------+------+------+-----
   1   0   BUS1    5  1 2220.0  3.500  0.00 0.3000 0.6500 1.8100 1.7600 0.2300 0.2500
0.0000  0.003  8.000  1.000  0.030  0.070  0.031  6.930  0.800  60.00
   3   0   BUS3    0   2220.0  0.000  0.00 0.0000 0.0000 0.0000 0.0000
0.0000      0.000  0.000                        60.00
   3   0   BUS3    Machine modelled as infinite bus.
```

USER DEFINED CONTROLLER DATA

```
---------------------------

 UDC (--Block---)  (- Variable -) (------------------ Parameters ------------------------)
 No.  No. Type  Input  Output   A       B       C       D       E

   1 -------------------------- AVR-GEN.1
      1 OUT    EFD    EFD   1
      2 IN     VB     ET    1
      3 IN     VREF   VREF  1
      4 IN     VPSS   VPSS  1
      5 LDLG   ET     X1    1.0       0.00     1.0000     0.0200
      6 SUM    +VREF  X2    1.0
               -X1          1.0
               VPSS         1.0
STOP    7 GAIN   X2     EFD   200.0

   2 ------------------------- PSS-GEN.1
      1 OUT    VPSS   VPSS  1
      2 IN     WW     WW    1
      4 GAIN   WW     X12   9.500
      3 LDLG   X12    X13   0.000     1.400     1.000     1.400
STOP    5 LDLG   X13    VPSS  1.000     0.154     1.000     0.033
%Dynamic data file line #   43.
%Warning: More outputs than references. Some outputs will be calculated.
```

INITIAL CONDITIONS

```
-----------------

 (------ bus ------) s/m   rotor  mechanic (  terminal power   ) ( terminal voltage)
terminal  field
```

name	no.	no.	angle	power	active	reactive	modulus	angle	current	voltage
			degree	MW	MW	Mvar	pu	degree	pu	pu
BUS1	1	0	78.974	2003.99	1998.00	666.48	1.0000	36.011	0.949	2.4333

INITIALIZATION THROUGH NEWTON

USER DEFINED CONTROLLER VARIABLES

UDC	Var.	Init. Value	Variation	Mismatch
1	ET	1.0000	0.0000	0.0000
	VREF	1.0122	0.59952E-16	0.0000
	VPSS	0.0000	0.0000	0.0000
	X1	1.0000	0.0000	0.0000
	X2	0.12166E-01	0.59952E-16	0.0000
	EFD	2.4333	0.0000	-0.11990E-13

UDC	Var.	Init. Value	Variation	Mismatch
2	WW	1.0000	0.0000	0.0000
	X12	9.5000	0.0000	0.0000
	X13	0.53291E-15	0.53291E-15	0.17764E-14
	VPSS	0.53291E-15	0.53291E-15	0.0000

Number of iterations to calculate initial values of UDC variables: 2.

System Summary	On	Off	Tot.	Max.
AC buses			3	120
AC branches			2	25000
Non-linear loads			0	16000
Dynamic loads			0	16000
PV/Slack buses			0	3000
Infinite buses			1	16000
Induction motors	0		0	500
HVDC converters	0		0	40
Synchronous machines	1	0	1	3000
Excitation systems (built-in)	0	0	0	3000
Excitation systems (UDC)	1	0	1	4000
Rotor speed control systems (built-in)	0	0	0	3000
Rotor speed control systems (UDC)	0	0	0	4000
Power system stabilizers (built-in)	0	0	0	1000
Power system stabilizers (UDC)	1	0	1	4000
FACTS devices (built-in)	0	0	0	20
User defined controllers	2	0	2	4000

System Summary

Reference generator bus number	0
Reference generator number	0
Abort on power flow error ?	YES

Matrix Summary: Jacobian & State Matrices

Description	Num.	Max.
Jacobian matrix dimension	36	150000
Number of non-zero elements	99	900000
Number of state variables	9	
Number of algebraic variables	25	
Number of null variables	2	
State matrix dimension (for full system eigensolution)	9	4000

Synchronous Machine Control Data

Bus No.	Bus Name	Gen. No.	Synchr. M Conden.	AVR (M)/UD	GOV (M)/UD	PSS (M)/UD	Inp1 Inp2 Inp3 ...
1	BUS1	0 5	no	1		2	WW

Spining Reserve Data

Bus No.	Gen. No.	Bus Name	No. Unt.	MVA Base Unit	Total	Gener. MVA	Load. %	Status
1	0	BUS1	1	2220.0	2220.0	2106.2	94.9	Ok

EIGENVALUES

No.	Real	Imaginary		Damp (%)	Freq (HZ)	Maximum Participation Factor
1	-54.43249					X 0005 AVR-GEN.1 # 1
2	-34.03553					X 0005 PSS-GEN.1 # 2
3	-13.42491	+j 17.19172	<<	61.55	2.74	EQ' BUS1 # 1
4						
5	-21.60378					ED" BUS1 # 1
6	-1.105838	+j 6.736551	<<<	16.20	1.07	DELT BUS1 # 1
7						
8	-1.675415					ED' BUS1 # 1
9	-.7499622					X 0003 PSS-GEN.1 # 2

H.2.1.3. MatNetEig results
Manual control

```
>> mne_inf
load flow d_mne_smib_sub_6_gen_31_with_sat
 converged in 3 iterations

Eigenvalue          freq [ Hz]     damping ratio
      0              0          1.0000
      0              0          1.0000
  -0.1824            0          1.0000
  -1.9029            0          1.0000
  -0.1656 - 6.4770i  1.0308     0.0256
  -0.1656 + 6.4770i  1.0308     0.0256
 -23.2738            0          1.0000
 -37.6757            0          1.0000
```

AVR and PSS

```
>> mne_inf
AC4a Exciter set up as a simple static exciter model - 7  OR
ST1a Static excitation system as a simple exciter model - 10
Power System Stabilizer, speed input
load flow d_mne_smib_sub_6_gen_31
 converged in 3 iterations

Eigenvalue          freq [ Hz]     damping ratio
      0              0          1.0000
      0              0          1.0000
  -0.7348            0          1.0000
  -1.0000            0          1.0000
  -1.9512            0          1.0000
  -1.0061 - 6.7253i  1.0704     0.1480
  -1.0061 + 6.7253i  1.0704     0.1480
 -13.0514 -16.6384i  2.6481     0.6172
 -13.0514 +16.6384i  2.6481     0.6172
 -24.4369            0          1.0000
 -34.7023            0          1.0000
 -54.4431            0          1.0000
```

H.2.2. 2A4M

H.2.2.1. PSAT results

1. Manual control
EIGENVALUE REPORT

P S A T 2.1.2

Author: Federico Milano, (c) 2002-2008
e-mail: Federico.Milano@uclm.es
website: http://www.uclm.es/area/gsee/Web/Federico

File: f:\My Documents\MSc current\Final Simulations\psat\M2. Two Area 4 Machine Model\1. Manual Control\d_2area_manual_with_sat_with_xl
Date: 28-Aug-2009 11:05:42

STATE MATRIX EIGENVALUES

Eigevalue	Most Associated States	Real part	Imag. Part	Pseudo-FrequencFrequency	
Eig As # 1	e2d_Syn_4	-38.7826	0	0	0
Eig As # 2	e2d_Syn_2	-38.0858	0	0	0
Eig As # 3	e2q_Syn_1, e2q_Syn_3	-36.1901	0.14938	0.02377	5.7599
Eig As # 4	e2q_Syn_1, e2q_Syn_3	-36.1901	-0.14938	0.02377	5.7599
Eig As # 5	e2q_Syn_2	-32.7307	0	0	0
Eig As # 6	e2q_Syn_4	-31.4018	0	0	0
Eig As # 7	e2d_Syn_3	-24.4096	0	0	0
Eig As # 8	e2d_Syn_1	-22.0929	0	0	0
Eig As # 9	omega_Syn_2, delta_Syn_2	-2.2591	7.8857	1.2551	1.3055
Eig As #10	omega_Syn_2, delta_Syn_2	-2.2591	-7.8857	1.2551	1.3055
Eig As #11	omega_Syn_4, delta_Syn_4	-2.3074	8.1151	1.2916	1.3428
Eig As #12	omega_Syn_4, delta_Syn_4	-2.3074	-8.1151	1.2916	1.3428
Eig As #13	omega_Syn_1, delta_Syn_1	-0.57598	3.7578	0.59807	0.60506
Eig As #14	omega_Syn_1, delta_Syn_1	-0.57598	-3.7578	0.59807	0.60506
Eig As #15	e1d_Syn_2	-6.5614	0	0	0
Eig As #16	e1d_Syn_4	-6.6185	0	0	0
Eig As #17	e1d_Syn_3	-4.7052	0	0	0
Eig As #18	e1d_Syn_2	-3.7273	0	0	0
Eig As #19	e1q_Syn_2	0.31625	0	0	0
Eig As #20	e1q_Syn_2	-0.2021	0	0	0
Eig As #21	e1q_Syn_3	-0.19611	0	0	0
Eig As #22	e1q_Syn_3	-0.01119	0	0	0
Eig As #23	delta_Syn_1	0	0	0	0
Eig As #24	omega_Syn_1	-0.00265	0	0	0

PARTICIPATION FACTORS (Euclidean norm)

	delta_Syn_1	omega_Syn_1	e1q_Syn_1	e1d_Syn_1	e2q_Syn_1
Eig As # 1	0	0	0.00035	0.01281	0.0256
Eig As # 2	0.00074	0.00074	0.00269	0.03149	0.10204
Eig As # 3	0.00292	0.00292	0.01832	0.00633	0.25713
Eig As # 4	0.00292	0.00292	0.01832	0.00633	0.25713
Eig As # 5	1e-005	1e-005	0.00075	0.00047	0.2937

Eig As # 6	0	0	0.00043	0.00048	0.09792
Eig As # 7	3e-005	3e-005	7e-005	0.01981	0.00024
Eig As # 8	0.00039	0.00039	0.00016	0.02353	0.00027
Eig As # 9	0.14594	0.14599	0.06576	0.01048	0.01654
Eig As #10	0.14594	0.14599	0.06576	0.01048	0.01654
Eig As #11	0.01908	0.01909	0.00772	0.0023	0.00196
Eig As #12	0.01908	0.01909	0.00772	0.0023	0.00196
Eig As #13	0.13978	0.13987	0.04652	0.00036	0.00557
Eig As #14	0.13978	0.13987	0.04652	0.00036	0.00557
Eig As #15	0.01118	0.01117	0.00695	0.31797	0.00214
Eig As #16	0.00145	0.00145	0.00098	0.04555	0.00032
Eig As #17	0.0006	0.0006	3e-005	0.20309	1e-005
Eig As #18	0.00695	0.00694	0.00118	0.25752	0.00021
Eig As #19	0.01606	0.01445	0.19074	0.00299	0.00278
Eig As #20	0.00643	0.00667	0.31187	0.00427	0.00067
Eig As #21	0.00834	0.00869	0.16171	0.00201	0.00032
Eig As #22	0.00055	0.00157	0.25991	2e-005	0.00095
Eig As #23	0.27833	0	0	0	0
Eig As #24	0.01689	0.25044	0.0039	0	2e-005

PARTICIPATION FACTORS (Euclidean norm)

	e2d_Syn_1	delta_Syn_2	omega_Syn_2	e1q_Syn_2	e1d_Syn_2
Eig As # 1	0.09622	0.00017	0.00017	0.00047	0.02056
Eig As # 2	0.23507	0.00108	0.00108	0.00138	0.03221
Eig As # 3	0.04661	0.0032	0.0032	0.01001	0.00262
Eig As # 4	0.04661	0.0032	0.0032	0.01001	0.00262
Eig As # 5	0.00346	0.00038	0.00038	0.01511	0.00211
Eig As # 6	0.00349	1e-005	1e-005	2e-005	0.0016
Eig As # 7	0.19208	0.00017	0.00017	0.00119	0.00987
Eig As # 8	0.36126	0	0	0.00047	0.01727
Eig As # 9	0.00631	0.17453	0.17458	0.05779	0.03278
Eig As #10	0.00631	0.17453	0.17458	0.05779	0.03278
Eig As #11	0.00144	0.02994	0.02995	0.01267	0.00347
Eig As #12	0.00144	0.02994	0.02995	0.01267	0.00347
Eig As #13	0.0001	0.08612	0.08619	0.0413	0.00213
Eig As #14	0.0001	0.08612	0.08619	0.0413	0.00213
Eig As #15	0.04351	0.00873	0.00872	0.00676	0.36948
Eig As #16	0.00624	0.00248	0.00248	0.00188	0.08768
Eig As #17	0.02058	0.00337	0.00337	0.00123	0.13917
Eig As #18	0.01621	7e-005	7e-005	0.00214	0.26736
Eig As #19	0.00057	0.01849	0.01659	0.24805	0.00373
Eig As #20	0.00065	6e-005	6e-005	0.36727	0.00442
Eig As #21	0.00031	0.00554	0.00574	0.10652	0.00127
Eig As #22	0	0.00042	0.00125	0.19453	1e-005
Eig As #23	0	0.25175	0	0	0
Eig As #24	0	0.00268	0.24314	0.00388	0

PARTICIPATION FACTORS (Euclidean norm)

	e2q_Syn_2	e2d_Syn_2	delta_Syn_3	omega_Syn_3	e1q_Syn_3
Eig As # 1	0.02406	0.15446	1e-005	1e-005	0.00079
Eig As # 2	0.0394	0.2405	0.00038	0.00038	0.00113
Eig As # 3	0.11894	0.0193	0.0027	0.0027	0.01658
Eig As # 4	0.11894	0.0193	0.0027	0.0027	0.01658
Eig As # 5	0.38693	0.01542	2e-005	2e-005	0.00633
Eig As # 6	0.15511	0.01171	0.00011	0.00012	0.00729
Eig As # 7	0.00113	0.09573	1e-005	1e-005	0
Eig As # 8	0.00429	0.26508	0	0	0.0001
Eig As # 9	0.01439	0.01974	0.03227	0.03228	0.01444
Eig As #10	0.01439	0.01974	0.03227	0.03228	0.01444
Eig As #11	0.00331	0.00217	0.15072	0.15078	0.06836
Eig As #12	0.00331	0.00217	0.15072	0.15078	0.06836
Eig As #13	0.00501	0.00062	0.10308	0.1031	0.01072
Eig As #14	0.00501	0.00062	0.10308	0.1031	0.01072
Eig As #15	0.00234	0.05056	0.0014	0.0014	0.00132
Eig As #16	0.00061	0.01201	0.00821	0.0082	0.00577
Eig As #17	0.00015	0.0141	0.00034	0.00034	1e-005
Eig As #18	5e-005	0.01683	0.00053	0.00054	0.00339
Eig As #19	0.00365	0.00071	0.01746	0.01906	0.17412
Eig As #20	0.00077	0.00067	0.00107	0.00111	0.10614
Eig As #21	0.0002	0.00019	0.01291	0.01345	0.34134
Eig As #22	0.00073	0	0.00042	0.00124	0.3092
Eig As #23	0	0	0.24592	0	0
Eig As #24	2e-005	0	0.00148	0.23291	0.00039

PARTICIPATION FACTORS (Euclidean norm)

	e1d_Syn_3	e2q_Syn_3	e2d_Syn_3	delta_Syn_4	omega_Syn_4
Eig As # 1	0.02826	0.0589	0.21227	0.00034	0.00034
Eig As # 2	0.01409	0.03943	0.1052	0.00035	0.00035
Eig As # 3	0.00703	0.24063	0.0518	0.00316	0.00316
Eig As # 4	0.00703	0.24063	0.0518	0.00316	0.00316
Eig As # 5	0.00048	0.13761	0.00349	0.00014	0.00014
Eig As # 6	0.00014	0.24587	0.00104	2e-005	2e-005
Eig As # 7	0.04156	4e-005	0.40304	0.00023	0.00023
Eig As # 8	0.0115	0.00159	0.17657	0.00063	0.00063
Eig As # 9	0.00172	0.00367	0.00103	0.01834	0.01834
Eig As #10	0.00172	0.00367	0.00103	0.01834	0.01834
Eig As #11	0.00848	0.0178	0.0053	0.17169	0.17173
Eig As #12	0.00848	0.0178	0.0053	0.17169	0.17173
Eig As #13	0.00742	0.00123	0.00215	0.09867	0.09869
Eig As #14	0.00742	0.00123	0.00215	0.09867	0.09869
Eig As #15	0.06885	0.00046	0.00942	0.00247	0.00247
Eig As #16	0.28203	0.00188	0.03864	0.01016	0.01015
Eig As #17	0.32163	0	0.0326	0.00392	0.00393
Eig As #18	0.16973	0.00019	0.01068	0.01128	0.0113
Eig As #19	0.0029	0.00258	0.00055	0.01957	0.0214
Eig As #20	0.00146	0.00021	0.00022	0.00419	0.00435

Eig As #21	0.00418	0.00061	0.00064	0.00718	0.00746
Eig As #22	1e-005	0.0012	0	0.00034	0.00106
Eig As #23	0	0	0	0.22401	0
Eig As #24	0	0	0	0.01569	0.22826

PARTICIPATION FACTORS (Euclidean norm)

	e1q_Syn_4	e1d_Syn_4	e2q_Syn_4	e2d_Syn_4
Eig As # 1	0.00013	0.04204	0.00629	0.31575
Eig As # 2	0.0001	0.01616	0.01339	0.12062
Eig As # 3	0.01201	0.00278	0.14545	0.0205
Eig As # 4	0.01201	0.00278	0.14545	0.0205
Eig As # 5	0.00514	0.00074	0.12175	0.00542
Eig As # 6	0.00146	0.00378	0.44167	0.02771
Eig As # 7	0.00134	0.0217	0.00086	0.21046
Eig As # 8	0.00538	0.00747	0.00836	0.11465
Eig As # 9	0.0049	0.00436	0.00119	0.00262
Eig As #10	0.0049	0.00436	0.00119	0.00262
Eig As #11	0.05343	0.03381	0.01367	0.02114
Eig As #12	0.05343	0.03381	0.01367	0.02114
Eig As #13	0.00731	0.01027	0.00083	0.00297
Eig As #14	0.00731	0.01027	0.00083	0.00297
Eig As #15	0.00094	0.06283	0.0003	0.0086
Eig As #16	0.00721	0.4064	0.00253	0.05567
Eig As #17	0.0012	0.22662	0.00016	0.02297
Eig As #18	0.01217	0.19169	0.00091	0.01207
Eig As #19	0.21589	0.0037	0.00324	0.00071
Eig As #20	0.17475	0.00207	0.00032	0.00031
Eig As #21	0.30677	0.00358	0.00051	0.00055
Eig As #22	0.22569	0	0.00091	0
Eig As #23	0	0	0	0
Eig As #24	0.00029	0	0	0

STATISTICS

DYNAMIC ORDER	24
# OF EIGS WITH Re(mu) < 0	22
# OF EIGS WITH Re(mu) > 0	1
# OF REAL EIGS	16
# OF COMPLEX PAIRS	4
# OF ZERO EIGS	1

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2. AVR and PSS

EIGENVALUE REPORT

P S A T 2.1.2

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File: f:\My Documents\MSc current\Final Simulations\psat\M2. Two Area 4 Machine Model\4. Thyristor Exciter with high transient gain & PSS\d_2area_avr_pss_with_xl_with_sat
Date: 28-Aug-2009 11:06:32

STATE MATRIX EIGENVALUES

Eigevalue	Most Associated States	Real part	Imag. Part	Pseudo-Frequenc	Frequency
Eig As # 1	vm_Exc_1	-99.9137	0	0	0
Eig As # 2	vm_Exc_3	-99.915	0	0	0
Eig As # 3	vm_Exc_4	-99.9054	0	0	0
Eig As # 4	vm_Exc_2	-99.9025	0	0	0
Eig As # 5	v2_Pss_3	-49.9071	0	0	0
Eig As # 6	v2_Pss_1	-49.9121	0	0	0
Eig As # 7	v2_Pss_2	-49.9802	0	0	0
Eig As # 8	v2_Pss_4	-50.0013	0	0	0
Eig As # 9	e2q_Syn_1, e2q_Syn_3	-37.4036	0.61164	0.09735	5.9537
Eig As #10	e2q_Syn_1, e2q_Syn_3	-37.4036	-0.61164	0.09735	5.9537
Eig As #11	e2d_Syn_4, e2d_Syn_3	-38.0957	0.04634	0.00738	6.0631
Eig As #12	e2d_Syn_4, e2d_Syn_3	-38.0957	-0.04634	0.00738	6.0631
Eig As #13	e2q_Syn_2	-33.5057	0	0	0
Eig As #14	e2q_Syn_4	-32.1439	0	0	0
Eig As #15	e2d_Syn_3	-24.5559	0	0	0
Eig As #16	e2d_Syn_1	-22.3417	0	0	0
Eig As #17	delta_Syn_4, omega_Syn_4	-1.8541	8.3519	1.3292	1.3616
Eig As #18	delta_Syn_4, omega_Syn_4	-1.8541	-8.3519	1.3292	1.3616
Eig As #19	delta_Syn_2, omega_Syn_2	-1.8085	8.1369	1.295	1.3266
Eig As #20	delta_Syn_2, omega_Syn_2	-1.8085	-8.1369	1.295	1.3266
Eig As #21	e1q_Syn_4, e1q_Syn_3	0.55643	4.6535	0.74062	0.7459
Eig As #22	e1q_Syn_4, e1q_Syn_3	0.55643	-4.6535	0.74062	0.7459
Eig As #23	e1q_Syn_1, vf_Exc_1	-0.34701	4.8675	0.77468	0.77665
Eig As #24	e1q_Syn_1, vf_Exc_1	-0.34701	-4.8675	0.77468	0.77665
Eig As #25	e1d_Syn_4	-6.2	0	0	0
Eig As #26	e1d_Syn_2	-6.1594	0	0	0
Eig As #27	e1d_Syn_3	-4.8181	0	0	0
Eig As #28	e1d_Syn_1	-4.2824	0	0	0
Eig As #29	delta_Syn_3, omega_Syn_3	-0.36627	3.6064	0.57397	0.57692
Eig As #30	delta_Syn_3, omega_Syn_3	-0.36627	-3.6064	0.57397	0.57692
Eig As #31	vf_Exc_1, e1q_Syn_1	-0.96	2.9163	0.46414	0.48864
Eig As #32	vf_Exc_1, e1q_Syn_1	-0.96	-2.9163	0.46414	0.48864
Eig As #33	vf_Exc_4, e1q_Syn_4	-0.9714	2.8521	0.45392	0.47953
Eig As #34	vf_Exc_4, e1q_Syn_4	-0.9714	-2.8521	0.45392	0.47953

Eig As #35	v3_Pss_2	-0.23124	0	0	0
Eig As #36	v3_Pss_3	-0.18227	0	0	0
Eig As #37	v3_Pss_1	-0.17935	0	0	0
Eig As #38	v3_Pss_3	-0.17919	0	0	0
Eig As #39	v1_Pss_3	-0.10136	0	0	0
Eig As #40	v1_Pss_1	-0.10273	0	0	0
Eig As #41	v1_Pss_3	-0.1028	0	0	0
Eig As #42	v1_Pss_2	0.00611	0	0	0
Eig As #43	v1_Pss_2	-0.00035	0	0	0
Eig As #44	delta_Syn_2	0	0	0	0
Eig As #45	vr3_Exc_1	-1	0	0	0
Eig As #46	vr3_Exc_2	-1	0	0	0
Eig As #47	vr3_Exc_3	-1	0	0	0
Eig As #48	vr3_Exc_4	-1	0	0	0

PARTICIPATION FACTORS (Euclidean norm)

	delta_Syn_1	omega_Syn_1	e1q_Syn_1	e1d_Syn_1	e2q_Syn_1
Eig As # 1	0	0	0.00046	0	0.00076
Eig As # 2	0	0	0	0	1e-005
Eig As # 3	0	0	0.00023	0	0.00034
Eig As # 4	0	0	0.00021	0	0.00029
Eig As # 5	0	2e-005	2e-005	0	9e-005
Eig As # 6	5e-005	0.00086	0.00077	0	0.00361
Eig As # 7	0	0.00014	0.00014	0	0.00039
Eig As # 8	0	0	0	0	1e-005
Eig As # 9	0.00373	0.00321	0.00904	0.01552	0.23176
Eig As #10	0.00373	0.00321	0.00904	0.01552	0.23176
Eig As #11	0.00065	0.00056	0.00114	0.00494	0.04926
Eig As #12	0.00065	0.00056	0.00114	0.00494	0.04926
Eig As #13	3e-005	7e-005	0.00964	0.00128	0.25269
Eig As #14	0	0	0.0025	4e-005	0.08257
Eig As #15	7e-005	7e-005	0.00047	0.01797	0.00115
Eig As #16	0.00025	0.00026	0.00022	0.02607	0.00054
Eig As #17	0.01733	0.01699	0.00569	0.00149	0.00141
Eig As #18	0.01733	0.01699	0.00569	0.00149	0.00141
Eig As #19	0.14566	0.14104	0.06645	0.00771	0.01676
Eig As #20	0.14566	0.14104	0.06645	0.00771	0.01676
Eig As #21	0.01608	0.02882	0.07279	0.00842	0.0102
Eig As #22	0.01608	0.02882	0.07279	0.00842	0.0102
Eig As #23	0.02677	0.02664	0.12704	0.00809	0.01821
Eig As #24	0.02677	0.02664	0.12704	0.00809	0.01821
Eig As #25	0.00066	0.00081	0.00088	0.01763	0.00022
Eig As #26	0.01766	0.02137	0.01792	0.29861	0.004
Eig As #27	0.00281	0.00304	0.00121	0.13173	0.0002
Eig As #28	0.00089	0.00088	0.00035	0.34975	5e-005
Eig As #29	0.07516	0.07371	0.05269	0.00358	0.0053
Eig As #30	0.07516	0.07371	0.05269	0.00358	0.0053
Eig As #31	0.03169	0.03511	0.1591	0.04293	0.01483
Eig As #32	0.03169	0.03511	0.1591	0.04293	0.01483

Eig As #33	0.00363	0.00308	0.01617	0.0044	0.00148
Eig As #34	0.00363	0.00308	0.01617	0.0044	0.00148
Eig As #35	0.00614	0.02458	0.00012	0	0
Eig As #36	0.00411	5e-005	3e-005	1e-005	0
Eig As #37	0.01729	7e-005	0.00027	0.00026	0
Eig As #38	7e-005	1e-005	0	0	0
Eig As #39	0.00346	1e-005	1e-005	0	0
Eig As #40	0.01439	2e-005	0.00014	0.00012	0
Eig As #41	0.00016	0	0	0	0
Eig As #42	0.02818	0.10487	2e-005	0	0
Eig As #43	0.02669	0.09922	0	0	0
Eig As #44	0.17284	3e-005	0	0	0
Eig As #45	0	0	0	0	0
Eig As #46	0	0	0	0	0
Eig As #47	0	0	0	0	0
Eig As #48	0	0	0	0	0

PARTICIPATION FACTORS (Euclidean norm)

	e2d_Syn_1	delta_Syn_2	omega_Syn_2	e1q_Syn_2	e1d_Syn_2
Eig As # 1	1e-005	0	0	0.00037	0
Eig As # 2	0	0	0	1e-005	0
Eig As # 3	1e-005	0	0	0.00021	0
Eig As # 4	2e-005	0	0	0.00031	0
Eig As # 5	0	0	6e-005	5e-005	1e-005
Eig As # 6	3e-005	5e-005	0.0007	0.00064	5e-005
Eig As # 7	2e-005	0	0.00014	0.00014	0
Eig As # 8	0	0	0	0	0
Eig As # 9	0.11522	0.00377	0.00375	0.00103	0.0131
Eig As #10	0.11522	0.00377	0.00375	0.00103	0.0131
Eig As #11	0.03692	0.00185	0.00152	0.00497	0.00938
Eig As #12	0.03692	0.00185	0.00152	0.00497	0.00938
Eig As #13	0.00937	0.00059	1e-005	0.00885	0.00203
Eig As #14	0.00031	3e-005	1e-005	0.00292	0.00117
Eig As #15	0.17155	0.0002	0.00021	0.00271	0.00897
Eig As #16	0.36965	0	0	0.0035	0.01895
Eig As #17	0.00097	0.02761	0.02674	0.01141	0.00235
Eig As #18	0.00097	0.02761	0.02674	0.01141	0.00235
Eig As #19	0.00489	0.17177	0.16818	0.04359	0.0244
Eig As #20	0.00489	0.17177	0.16818	0.04359	0.0244
Eig As #21	0.00344	0.00882	0.01744	0.07727	0.0089
Eig As #22	0.00344	0.00882	0.01744	0.07727	0.0089
Eig As #23	0.00308	0.02149	0.01095	0.09751	0.00644
Eig As #24	0.00308	0.02149	0.01095	0.09751	0.00644
Eig As #25	0.00237	0.00253	0.0032	0.00315	0.04628
Eig As #26	0.04003	0.01417	0.01821	0.02184	0.37638
Eig As #27	0.01383	0.00586	0.00464	0.00529	0.08454
Eig As #28	0.03014	4e-005	0.00015	0.01521	0.27677
Eig As #29	0.00103	0.07534	0.07295	0.01964	0.00606
Eig As #30	0.00103	0.07534	0.07295	0.01964	0.00606

Eig As #31	0.00933	0.03676	0.01713	0.14132	0.03302
Eig As #32	0.00933	0.03676	0.01713	0.14132	0.03302
Eig As #33	0.00094	0.00584	0.00466	0.02725	0.00654
Eig As #34	0.00094	0.00584	0.00466	0.02725	0.00654
Eig As #35	0	0.01062	0.02601	0.00017	0
Eig As #36	0	0.00334	5e-005	3e-005	1e-005
Eig As #37	4e-005	0.01378	3e-005	0.00024	0.00025
Eig As #38	0	0.00023	1e-005	0	0
Eig As #39	0	0.00283	1e-005	1e-005	1e-005
Eig As #40	2e-005	0.01146	1e-005	0.00013	0.00012
Eig As #41	0	0.00026	0	0	0
Eig As #42	0	0.04739	0.10883	3e-005	0
Eig As #43	0	0.04486	0.10297	0	0
Eig As #44	0	0.35222	3e-005	0	0
Eig As #45	0	0	0	0	0
Eig As #46	0	0	0	0	0
Eig As #47	0	0	0	0	0
Eig As #48	0	0	0	0	0

PARTICIPATION FACTORS (Euclidean norm)

	e2q_Syn_2	e2d_Syn_2	delta_Syn_3	omega_Syn_3	e1q_Syn_3
Eig As # 1	0.0006	2e-005	0	0	1e-005
Eig As # 2	2e-005	0	0	0	0.00049
Eig As # 3	0.00034	1e-005	0	0	0.00022
Eig As # 4	0.00046	1e-005	0	0	0.00016
Eig As # 5	0.00029	5e-005	5e-005	0.00094	0.00085
Eig As # 6	0.00281	0.0004	0	5e-005	5e-005
Eig As # 7	0.00047	3e-005	0	6e-005	6e-005
Eig As # 8	1e-005	0	0	1e-005	1e-005
Eig As # 9	0.01962	0.09726	0.00281	0.00243	0.00637
Eig As #10	0.01962	0.09726	0.00281	0.00243	0.00637
Eig As #11	0.1564	0.07005	0.00276	0.00244	0.00379
Eig As #12	0.1564	0.07005	0.00276	0.00244	0.00379
Eig As #13	0.40536	0.01481	0.0001	0.00031	0.00362
Eig As #14	0.14222	0.00853	0.00024	0.00044	0.01482
Eig As #15	0.00318	0.08565	5e-005	5e-005	2e-005
Eig As #16	0.0035	0.26868	0	0	0.0013
Eig As #17	0.00291	0.00154	0.14941	0.14473	0.06896
Eig As #18	0.00291	0.00154	0.14941	0.14473	0.06896
Eig As #19	0.00976	0.01548	0.02944	0.02836	0.0136
Eig As #20	0.00976	0.01548	0.02944	0.02836	0.0136
Eig As #21	0.01095	0.00363	0.01511	0.02522	0.10949
Eig As #22	0.01095	0.00363	0.01511	0.02522	0.10949
Eig As #23	0.01386	0.00245	0.03352	0.04172	0.05195
Eig As #24	0.01386	0.00245	0.03352	0.04172	0.05195
Eig As #25	0.00069	0.00622	0.01335	0.01676	0.01655
Eig As #26	0.00504	0.05045	0.0007	0.00125	0.00269
Eig As #27	0.00083	0.00888	0.00289	0.00319	0.00307
Eig As #28	0.0022	0.02385	0	4e-005	0.0044

Eig As #29	0.00267	0.00175	0.07932	0.07638	0.06209
Eig As #30	0.00267	0.00175	0.07932	0.07638	0.06209
Eig As #31	0.01317	0.00718	0.00946	0.00127	0.02728
Eig As #32	0.01317	0.00718	0.00946	0.00127	0.02728
Eig As #33	0.00248	0.00139	0.03066	0.02504	0.14058
Eig As #34	0.00248	0.00139	0.03066	0.02504	0.14058
Eig As #35	0	0	0.00888	0.02734	0.00012
Eig As #36	0	0	0.00435	4e-005	3e-005
Eig As #37	0	4e-005	4e-005	1e-005	0
Eig As #38	0	0	0.01753	7e-005	0.00028
Eig As #39	0	0	0.00369	1e-005	2e-005
Eig As #40	0	2e-005	3e-005	0	0
Eig As #41	0	0	0.01455	2e-005	0.00014
Eig As #42	0	0	0.03885	0.1127	2e-005
Eig As #43	0	0	0.03677	0.10662	0
Eig As #44	0	0	0.16646	3e-005	0
Eig As #45	0	0	0	0	0
Eig As #46	0	0	0	0	0
Eig As #47	0	0	0	0	0
Eig As #48	0	0	0	0	0

PARTICIPATION FACTORS (Euclidean norm)

	e1d_Syn_3	e2q_Syn_3	e2d_Syn_3	delta_Syn_4	omega_Syn_4
Eig As # 1	0	2e-005	0	0	0
Eig As # 2	0	0.00081	1e-005	0	0
Eig As # 3	0	0.00032	2e-005	0	0
Eig As # 4	0	0.00023	1e-005	0	0
Eig As # 5	0	0.00394	4e-005	6e-005	0.00069
Eig As # 6	0	0.00021	0	0	2e-005
Eig As # 7	0	0.00017	1e-005	0	6e-005
Eig As # 8	0	2e-005	0	0	1e-005
Eig As # 9	0.0122	0.17116	0.09057	0.00261	0.00244
Eig As #10	0.0122	0.17116	0.09057	0.00261	0.00244
Eig As #11	0.0225	0.16652	0.16797	0.00501	0.00486
Eig As #12	0.0225	0.16652	0.16797	0.00501	0.00486
Eig As #13	0.00136	0.12665	0.0099	0.00017	0
Eig As #14	0.00021	0.21968	0.00153	7e-005	4e-005
Eig As #15	0.04299	5e-005	0.41035	0.00023	0.00025
Eig As #16	0.01126	0.00169	0.15969	0.00041	0.00043
Eig As #17	0.00646	0.0181	0.00424	0.17066	0.16754
Eig As #18	0.00646	0.0181	0.00424	0.17066	0.16754
Eig As #19	0.00139	0.00345	0.00088	0.01642	0.01631
Eig As #20	0.00139	0.00345	0.00088	0.01642	0.01631
Eig As #21	0.00613	0.01653	0.0025	0.01066	0.01554
Eig As #22	0.00613	0.01653	0.0025	0.01066	0.01554
Eig As #23	0.00765	0.00882	0.00291	0.01463	0.01928
Eig As #24	0.00765	0.00882	0.00291	0.01463	0.01928
Eig As #25	0.26031	0.00375	0.035	0.01589	0.02044
Eig As #26	0.03006	0.00061	0.00403	0.00281	0.00281

Eig As #27	0.39424	0.00052	0.0414	0.00527	0.00435
Eig As #28	0.11159	0.00064	0.00962	0.00169	0.00078
Eig As #29	0.01341	0.00739	0.00387	0.06451	0.06107
Eig As #30	0.01341	0.00739	0.00387	0.06451	0.06107
Eig As #31	0.00585	0.00256	0.00127	0.00499	0.00634
Eig As #32	0.00585	0.00256	0.00127	0.00499	0.00634
Eig As #33	0.03549	0.01287	0.00755	0.03623	0.02503
Eig As #34	0.03549	0.01287	0.00755	0.03623	0.02503
Eig As #35	0	0	0	0.00451	0.02893
Eig As #36	1e-005	0	0	0.0039	4e-005
Eig As #37	0	0	0	0.00024	1e-005
Eig As #38	0.00025	0	4e-005	0.01435	3e-005
Eig As #39	1e-005	0	0	0.0033	1e-005
Eig As #40	0	0	0	0.00011	0
Eig As #41	0.00011	0	2e-005	0.01169	1e-005
Eig As #42	0	0	0	0.01964	0.11706
Eig As #43	0	0	0	0.0186	0.11075
Eig As #44	0	0	0	0.3082	4e-005
Eig As #45	0	0	0	0	0
Eig As #46	0	0	0	0	0
Eig As #47	0	0	0	0	0
Eig As #48	0	0	0	0	0

PARTICIPATION FACTORS (Euclidean norm)

	e1q_Syn_4	e1d_Syn_4	e2q_Syn_4	e2d_Syn_4	vm_Exc_1
Eig As # 1	0	0	0	0	0.54407
Eig As # 2	0.00033	0	0.00054	3e-005	0.00381
Eig As # 3	0.00028	0	0.00043	1e-005	0.23875
Eig As # 4	0.00029	0	0.00043	0	0.21013
Eig As # 5	0.00064	5e-005	0.00279	0.00045	0
Eig As # 6	2e-005	0	8e-005	0	3e-005
Eig As # 7	6e-005	0	0.00018	1e-005	0
Eig As # 8	1e-005	0	3e-005	0	0
Eig As # 9	0.00303	0.01058	0.07508	0.07857	0.00306
Eig As #10	0.00303	0.01058	0.07508	0.07857	0.00306
Eig As #11	0.00219	0.02454	0.05465	0.18325	0.00072
Eig As #12	0.00219	0.02454	0.05465	0.18325	0.00072
Eig As #13	0.00241	0.00053	0.11085	0.00387	0.00383
Eig As #14	0.00955	0.00326	0.4518	0.02382	0.00095
Eig As #15	0.00342	0.0226	0.00646	0.21567	0.00011
Eig As #16	0.00753	0.00732	0.00293	0.1038	0.0001
Eig As #17	0.03791	0.02597	0.00861	0.01704	0.0001
Eig As #18	0.03791	0.02597	0.00861	0.01704	0.0001
Eig As #19	0.00251	0.003	0.00049	0.0019	0.00101
Eig As #20	0.00251	0.003	0.00049	0.0019	0.00101
Eig As #21	0.11579	0.00726	0.01714	0.00296	0.00352
Eig As #22	0.11579	0.00726	0.01714	0.00296	0.00352
Eig As #23	0.05061	0.00618	0.00815	0.00235	0.00573
Eig As #24	0.05061	0.00618	0.00815	0.00235	0.00573

Eig As #25	0.02424	0.41226	0.00566	0.05543	3e-005
Eig As #26	1e-005	0.03184	0	0.00427	0.0004
Eig As #27	0.00817	0.22942	0.00136	0.02409	3e-005
Eig As #28	0.01462	0.10082	0.0021	0.00869	2e-005
Eig As #29	0.04213	0.01038	0.00494	0.003	0.00203
Eig As #30	0.04213	0.01038	0.00494	0.003	0.00203
Eig As #31	0.01534	0.00478	0.00143	0.00104	0.00479
Eig As #32	0.01534	0.00478	0.00143	0.00104	0.00479
Eig As #33	0.16327	0.04011	0.01491	0.00854	0.00047
Eig As #34	0.16327	0.04011	0.01491	0.00854	0.00047
Eig As #35	0.00016	0	0	0	4e-005
Eig As #36	3e-005	1e-005	0	0	1e-005
Eig As #37	0	0	0	0	3e-005
Eig As #38	0.00026	0.00026	0	4e-005	0
Eig As #39	2e-005	1e-005	0	0	0
Eig As #40	0	0	0	0	1e-005
Eig As #41	0.00013	0.00012	0	2e-005	0
Eig As #42	2e-005	0	0	0	0
Eig As #43	0	0	0	0	0
Eig As #44	0	0	0	0	0
Eig As #45	0	0	0	0	0
Eig As #46	0	0	0	0	0
Eig As #47	0	0	0	0	0
Eig As #48	0	0	0	0	0

PARTICIPATION FACTORS (Euclidean norm)

	vr3_Exc_1	vf_Exc_1	vm_Exc_2	vr3_Exc_2	vf_Exc_2
Eig As # 1	0	0.00047	0.43588	0	0.00038
Eig As # 2	0	0	0.01107	0	1e-005
Eig As # 3	0	0.00023	0.22798	0	0.00022
Eig As # 4	0	0.00021	0.32181	0	0.00032
Eig As # 5	0	2e-005	0	0	7e-005
Eig As # 6	0	0.00095	2e-005	0	0.00079
Eig As # 7	0	0.00014	1e-005	0	0.00015
Eig As # 8	0	0	0	0	0
Eig As # 9	0	0.00577	0.00023	0	0.00045
Eig As #10	0	0.00577	0.00023	0	0.00045
Eig As #11	0	0.00129	0.00216	0	0.00392
Eig As #12	0	0.00129	0.00216	0	0.00392
Eig As #13	0	0.00773	0.0039	0	0.00852
Eig As #14	0	0.00206	0.00151	0	0.00331
Eig As #15	0	0.00034	0.00047	0	0.00147
Eig As #16	0	0.00035	0.00091	0	0.00329
Eig As #17	0	0.00271	0.00021	0	0.0033
Eig As #18	0	0.00271	0.00021	0	0.0033
Eig As #19	0	0.01523	0.00156	0	0.03059
Eig As #20	0	0.01523	0.00156	0	0.03059
Eig As #21	0	0.0836	0.00375	0	0.08613
Eig As #22	0	0.0836	0.00375	0	0.08613

Eig As #23	0	0.11414	0.00428	0	0.08212
Eig As #24	0	0.11414	0.00428	0	0.08212
Eig As #25	0	0.0007	6e-005	0	0.0019
Eig As #26	0	0.01159	0.00061	0	0.01583
Eig As #27	0	0.00113	0.00012	0	0.00449
Eig As #28	0	0.00047	0.00066	0	0.01926
Eig As #29	0	0.02662	0.00106	0	0.02182
Eig As #30	0	0.02662	0.00106	0	0.02182
Eig As #31	0	0.16343	0.00435	0	0.13996
Eig As #32	0	0.16343	0.00435	0	0.13996
Eig As #33	0	0.0168	0.00083	0	0.02696
Eig As #34	0	0.0168	0.00083	0	0.02696
Eig As #35	0	7e-005	9e-005	0	0.00015
Eig As #36	0	1e-005	1e-005	0	0
Eig As #37	0	0	2e-005	0	1e-005
Eig As #38	0	0	0	0	0
Eig As #39	0	0	0	0	0
Eig As #40	0	1e-005	1e-005	0	2e-005
Eig As #41	0	0	0	0	0
Eig As #42	0	1e-005	1e-005	0	2e-005
Eig As #43	0	0	0	0	0
Eig As #44	0	0	0	0	0
Eig As #45	1	0	0	0	0
Eig As #46	0	0	0	1	0
Eig As #47	0	0	0	0	0
Eig As #48	0	0	0	0	0

PARTICIPATION FACTORS (Euclidean norm)

	vm_Exc_3	vr3_Exc_3	vf_Exc_3	vm_Exc_4	vr3_Exc_4
Eig As # 1	0.0161	0	1e-005	0.00082	0
Eig As # 2	0.58458	0	0.0005	0.39744	0
Eig As # 3	0.22895	0	0.00022	0.30097	0
Eig As # 4	0.16715	0	0.00016	0.29749	0
Eig As # 5	3e-005	0	0.00105	2e-005	0
Eig As # 6	0	0	6e-005	0	0
Eig As # 7	0	0	6e-005	0	0
Eig As # 8	0	0	1e-005	0	0
Eig As # 9	0.0023	0	0.00435	0.00096	0
Eig As #10	0.0023	0	0.00435	0.00096	0
Eig As #11	0.0025	0	0.00447	0.00072	0
Eig As #12	0.0025	0	0.00447	0.00072	0
Eig As #13	0.00113	0	0.00252	0.00105	0
Eig As #14	0.0032	0	0.00672	0.00469	0
Eig As #15	0	0	2e-005	0.00073	0
Eig As #16	0.00036	0	0.00132	0.00118	0
Eig As #17	0.00103	0	0.0136	0.00155	0
Eig As #18	0.00103	0	0.0136	0.00155	0
Eig As #19	0.00023	0	0.00289	0.00016	0
Eig As #20	0.00023	0	0.00289	0.00016	0

Eig As #21	0.00524	0	0.09421	0.00536	0
Eig As #22	0.00524	0	0.09421	0.00536	0
Eig As #23	0.00317	0	0.08763	0.00284	0
Eig As #24	0.00317	0	0.08763	0.00284	0
Eig As #25	0.00039	0	0.01106	0.00069	0
Eig As #26	7e-005	0	0.00185	0	0
Eig As #27	0.00012	0	0.00342	0.00031	0
Eig As #28	0.0002	0	0.00572	0.00057	0
Eig As #29	0.00261	0	0.05939	0.00174	0
Eig As #30	0.00261	0	0.05939	0.00174	0
Eig As #31	0.00086	0	0.02665	0.00046	0
Eig As #32	0.00086	0	0.02665	0.00046	0
Eig As #33	0.00422	0	0.14216	0.0049	0
Eig As #34	0.00422	0	0.14216	0.0049	0
Eig As #35	4e-005	0	7e-005	8e-005	0
Eig As #36	1e-005	0	1e-005	1e-005	0
Eig As #37	0	0	0	0	0
Eig As #38	3e-005	0	0	3e-005	0
Eig As #39	0	0	0	0	0
Eig As #40	0	0	0	0	0
Eig As #41	2e-005	0	1e-005	1e-005	0
Eig As #42	0	0	1e-005	1e-005	0
Eig As #43	0	0	0	0	0
Eig As #44	0	0	0	0	0
Eig As #45	0	0	0	0	0
Eig As #46	0	0	0	0	0
Eig As #47	0	1	0	0	0
Eig As #48	0	0	0	0	1

PARTICIPATION FACTORS (Euclidean norm)

	vf_Exc_4	v1_Pss_1	v2_Pss_1	v3_Pss_1	v1_Pss_2
Eig As # 1	0	0	0	0	0
Eig As # 2	0.00034	0	0	0	0
Eig As # 3	0.00029	0	0	0	0
Eig As # 4	0.00029	0	0	0	0
Eig As # 5	0.00079	0	0.01141	0	0
Eig As # 6	2e-005	0	0.51461	0	0
Eig As # 7	6e-005	0	0.34494	0	0
Eig As # 8	1e-005	0	0.12161	0	0
Eig As # 9	0.00184	0	0.00278	0	0
Eig As #10	0.00184	0	0.00278	0	0
Eig As #11	0.00134	0	0.00047	0	0
Eig As #12	0.00134	0	0.00047	0	0
Eig As #13	0.00231	0	0.0002	0	0
Eig As #14	0.01027	0	1e-005	0	0
Eig As #15	0.0023	0	1e-005	0	0
Eig As #16	0.00425	0	1e-005	0	0
Eig As #17	0.02986	2e-005	0.0005	3e-005	4e-005
Eig As #18	0.02986	2e-005	0.0005	3e-005	4e-005

Eig As #19	0.00316	0.00023	0.00481	0.00034	0.0002
Eig As #20	0.00316	0.00023	0.00481	0.00034	0.0002
Eig As #21	0.09819	0.00027	0.00169	0.0004	0.00023
Eig As #22	0.09819	0.00027	0.00169	0.0004	0.00023
Eig As #23	0.07183	0.00052	0.00369	0.00078	0.00046
Eig As #24	0.07183	0.00052	0.00369	0.00078	0.00046
Eig As #25	0.0178	0	5e-005	0	1e-005
Eig As #26	1e-005	6e-005	0.00113	0.0001	7e-005
Eig As #27	0.00884	0	5e-005	1e-005	3e-005
Eig As #28	0.01757	0	0	0	0
Eig As #29	0.03917	0.00152	0.00602	0.00227	0.00116
Eig As #30	0.03917	0.00152	0.00602	0.00227	0.00116
Eig As #31	0.01605	0.00157	0.00463	0.00241	0.00165
Eig As #32	0.01605	0.00157	0.00463	0.00241	0.00165
Eig As #33	0.16483	0.00018	0.0005	0.00027	0.00031
Eig As #34	0.16483	0.00018	0.0005	0.00027	0.00031
Eig As #35	0.00013	0.01405	0.00013	0.13437	0.02792
Eig As #36	1e-005	0.00505	2e-005	0.25488	0.00413
Eig As #37	0	0.02188	9e-005	0.51304	0.01733
Eig As #38	1e-005	0.0001	0	0.00216	0.00028
Eig As #39	0	0.25514	1e-005	0.00268	0.20907
Eig As #40	0	0.52796	4e-005	0.01153	0.4195
Eig As #41	2e-005	0.00564	0	0.00013	0.00936
Eig As #42	1e-005	0.07195	1e-005	0.00106	0.14657
Eig As #43	0	0.07834	0	7e-005	0.15965
Eig As #44	0	3e-005	0	0	5e-005
Eig As #45	0	0	0	0	0
Eig As #46	0	0	0	0	0
Eig As #47	0	0	0	0	0
Eig As #48	0	0	0	0	0

PARTICIPATION FACTORS (Euclidean norm)

	v2_Pss_2	v3_Pss_2	v1_Pss_3	v2_Pss_3	v3_Pss_3
Eig As # 1	0	0	0	0	0
Eig As # 2	0	0	0	0	0
Eig As # 3	0	0	0	0	0
Eig As # 4	0	0	0	0	0
Eig As # 5	0.03382	0	0	0.53517	0
Eig As # 6	0.42946	0	0	0.03114	0
Eig As # 7	0.3562	0	0	0.14928	0
Eig As # 8	0.17377	0	0	0.27648	0
Eig As # 9	0.00029	0	0	0.00212	0
Eig As #10	0.00029	0	0	0.00212	0
Eig As #11	0.00179	0	0	0.00169	0
Eig As #12	0.00179	0	0	0.00169	0
Eig As #13	0.00258	0	0	0.00095	0
Eig As #14	0.00017	0	0	0.00088	0
Eig As #15	0.0001	0	0	0	0
Eig As #16	1e-005	0	0	0	0

Eig As #17	0.00082	6e-005	0.00022	0.00502	0.00033
Eig As #18	0.00082	6e-005	0.00022	0.00502	0.00033
Eig As #19	0.00432	0.0003	5e-005	0.00101	7e-005
Eig As #20	0.00432	0.0003	5e-005	0.00101	7e-005
Eig As #21	0.0014	0.00033	0.00028	0.00176	0.00042
Eig As #22	0.0014	0.00033	0.00028	0.00176	0.00042
Eig As #23	0.00328	0.00069	0.00056	0.00397	0.00084
Eig As #24	0.00328	0.00069	0.00056	0.00397	0.00084
Eig As #25	0.00021	2e-005	6e-005	0.00105	9e-005
Eig As #26	0.00123	0.00011	1e-005	0.00017	1e-005
Eig As #27	0.00026	4e-005	1e-005	6e-005	1e-005
Eig As #28	3e-005	1e-005	0	1e-005	0
Eig As #29	0.00459	0.00173	0.00098	0.00389	0.00146
Eig As #30	0.00459	0.00173	0.00098	0.00389	0.00146
Eig As #31	0.00489	0.00254	0.00032	0.00094	0.00049
Eig As #32	0.00489	0.00254	0.00032	0.00094	0.00049
Eig As #33	0.0009	0.00048	0.00156	0.00444	0.0024
Eig As #34	0.0009	0.00048	0.00156	0.00444	0.0024
Eig As #35	0.00026	0.26694	0.01406	0.00013	0.13447
Eig As #36	2e-005	0.20827	0.00525	2e-005	0.26486
Eig As #37	7e-005	0.4064	6e-005	0	0.00144
Eig As #38	0	0.00636	0.02222	0.0001	0.50563
Eig As #39	1e-005	0.0022	0.27023	1e-005	0.00284
Eig As #40	4e-005	0.00916	0.00119	0	3e-005
Eig As #41	0	0.00021	0.51955	5e-005	0.01168
Eig As #42	3e-005	0.00217	0.06929	1e-005	0.00103
Eig As #43	0	0.00013	0.07544	0	6e-005
Eig As #44	0	0	2e-005	0	0
Eig As #45	0	0	0	0	0
Eig As #46	0	0	0	0	0
Eig As #47	0	0	0	0	0
Eig As #48	0	0	0	0	0

PARTICIPATION FACTORS (Euclidean norm)

	v1_Pss_4	v2_Pss_4	v3_Pss_4
Eig As # 1	0	0	0
Eig As # 2	0	0	0
Eig As # 3	0	0	0
Eig As # 4	0	0	0
Eig As # 5	0	0.40651	0
Eig As # 6	0	0.01248	0
Eig As # 7	0	0.14707	0
Eig As # 8	0	0.42799	0
Eig As # 9	0	0.00098	0
Eig As #10	0	0.00098	0
Eig As #11	0	0.00077	0
Eig As #12	0	0.00077	0
Eig As #13	0	0.00074	0
Eig As #14	0	0.00048	0

Eig As #15	0	0.0001	0
Eig As #16	0	0.00023	0
Eig As #17	0.00018	0.00408	0.00027
Eig As #18	0.00018	0.00408	0.00027
Eig As #19	2e-005	0.00036	3e-005
Eig As #20	2e-005	0.00036	3e-005
Eig As #21	0.00025	0.00154	0.00036
Eig As #22	0.00025	0.00154	0.00036
Eig As #23	0.00033	0.00233	0.00049
Eig As #24	0.00033	0.00233	0.00049
Eig As #25	7e-005	0.0014	0.00012
Eig As #26	0	0	0
Eig As #27	2e-005	0.0002	3e-005
Eig As #28	2e-005	0.00016	4e-005
Eig As #29	0.00056	0.0022	0.00083
Eig As #30	0.00056	0.0022	0.00083
Eig As #31	0.00015	0.00045	0.00023
Eig As #32	0.00015	0.00045	0.00023
Eig As #33	0.00179	0.00511	0.00276
Eig As #34	0.00179	0.00511	0.00276
Eig As #35	0.02548	0.00024	0.24368
Eig As #36	0.00469	2e-005	0.23667
Eig As #37	0.00029	0	0.00676
Eig As #38	0.01809	8e-005	0.41149
Eig As #39	0.24184	1e-005	0.00254
Eig As #40	0.00384	0	8e-005
Eig As #41	0.41668	4e-005	0.00937
Eig As #42	0.12826	2e-005	0.0019
Eig As #43	0.1397	0	0.00012
Eig As #44	4e-005	0	0
Eig As #45	0	0	0
Eig As #46	0	0	0
Eig As #47	0	0	0
Eig As #48	0	0	0

STATISTICS

DYNAMIC ORDER	48
# OF EIGS WITH Re(mu) < 0	44
# OF EIGS WITH Re(mu) > 0	3
# OF REAL EIGS	30
# OF COMPLEX PAIRS	9
# OF ZERO EIGS	1

AVR and PSS with ZIP Loads (Eigenvalues only)

EIGENVALUE REPORT

P S A T 2.1.2

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File: D:\Common Data\My Documents\MSc\Reports\Simulations\T1. PSAT Cases\M2. Two Area 4Machine Model - ZIP Loads\4. Thyristor Exciter with high transient gain & PSS\d_2area_avr_htg_pss_pq
Date: 02-Jul-2009 09:06:12

STATE MATRIX EIGENVALUES

Eigevalue	Most Associated States	Real part	Imag. Part	Pseudo-Frequenc	Frequency
Eig As # 1	vm_Exc_1	-99.9137	0	0	0
Eig As # 2	vm_Exc_3	-99.915	0	0	0
Eig As # 3	vm_Exc_4	-99.9054	0	0	0
Eig As # 4	vm_Exc_2	-99.9025	0	0	0
Eig As # 5	v2_Pss_3	-49.9071	0	0	0
Eig As # 6	v2_Pss_1	-49.912	0	0	0
Eig As # 7	v2_Pss_2	-49.9801	0	0	0
Eig As # 8	v2_Pss_4	-50.001	0	0	0
Eig As # 9	e2q_Syn_1, e2q_Syn_3	-37.4053	0.62022	0.09871	5.9541
Eig As #10	e2q_Syn_1, e2q_Syn_3	-37.4053	-0.62022	0.09871	5.9541
Eig As #11	e2d_Syn_4, e2d_Syn_3	-38.0901	0.08943	0.01423	6.0622
Eig As #12	e2d_Syn_4, e2d_Syn_3	-38.0901	-0.08943	0.01423	6.0622
Eig As #13	e2q_Syn_2	-33.5066	0	0	0
Eig As #14	e2q_Syn_4	-32.1486	0	0	0
Eig As #15	e2d_Syn_3	-24.5488	0	0	0
Eig As #16	e2d_Syn_1	-22.3321	0	0	0
Eig As #17	delta_Syn_4, omega_Syn_4	-1.8541	8.3527	1.3294	1.3617
Eig As #18	delta_Syn_4, omega_Syn_4	-1.8541	-8.3527	1.3294	1.3617
Eig As #19	delta_Syn_2, omega_Syn_2	-1.8085	8.1374	1.2951	1.3267
Eig As #20	delta_Syn_2, omega_Syn_2	-1.8085	-8.1374	1.2951	1.3267
Eig As #21	e1q_Syn_4, e1q_Syn_3	0.55571	4.6584	0.7414	0.74666
Eig As #22	e1q_Syn_4, e1q_Syn_3	0.55571	-4.6584	0.7414	0.74666
Eig As #23	e1q_Syn_1, vf_Exc_1	-0.34582	4.8685	0.77485	0.7768
Eig As #24	e1q_Syn_1, vf_Exc_1	-0.34582	-4.8685	0.77485	0.7768
Eig As #25	e1d_Syn_4	-6.1999	0	0	0
Eig As #26	e1d_Syn_2	-6.1593	0	0	0
Eig As #27	e1d_Syn_3	-4.8173	0	0	0
Eig As #28	e1d_Syn_1	-4.2804	0	0	0
Eig As #29	delta_Syn_3, omega_Syn_3	-0.36709	3.6045	0.57367	0.57664
Eig As #30	delta_Syn_3, omega_Syn_3	-0.36709	-3.6045	0.57367	0.57664
Eig As #31	vf_Exc_1, e1q_Syn_1	-0.96008	2.9163	0.46414	0.48865
Eig As #32	vf_Exc_1, e1q_Syn_1	-0.96008	-2.9163	0.46414	0.48865
Eig As #33	vf_Exc_4, e1q_Syn_4	-0.97143	2.8521	0.45393	0.47953
Eig As #34	vf_Exc_4, e1q_Syn_4	-0.97143	-2.8521	0.45393	0.47953
Eig As #35	v3_Pss_2	-0.22686	0	0	0

Eig As #36	v3_Pss_3	-0.18232	0	0	0
Eig As #37	v3_Pss_1	-0.17934	0	0	0
Eig As #38	v3_Pss_3	-0.17921	0	0	0
Eig As #39	v1_Pss_3	-0.10134	0	0	0
Eig As #40	v1_Pss_1	-0.10273	0	0	0
Eig As #41	v1_Pss_3	-0.1028	0	0	0
Eig As #42	v1_Pss_2	-0.00843	0	0	0
Eig As #43	v1_Pss_2	0.00022	0	0	0
Eig As #44	delta_Syn_2	0	0	0	0
Eig As #45	vr3_Exc_1	-1	0	0	0
Eig As #46	vr3_Exc_2	-1	0	0	0
Eig As #47	vr3_Exc_3	-1	0	0	0
Eig As #48	vr3_Exc_4	-1	0	0	0

Eigenvalues of 2A4M on manual control for different damping coefficients (PSAT)

Effects of Damping coefficients on frequency and damping ratios - PSAT							
		Δf (Hz)	Δζ (%)			Δf (Hz)	Δζ (%)
Kd=-10	Inter-area	0.0046	10.7243		Kd=+10	0.0021	-10.6044
	Local area-1	0.0015	5.1798			0.0015	-5.1374
	Local area-2	0.0014	5.2419			0.0019	-5.2041

EIGENVALUE REPORT

P S A T 2.1.2

Author: Federico Milano, (c) 2002-2008
e-mail: Federico.Milano@uclm.es
website: http://www.uclm.es/area/gsee/Web/Federico

File: T:\psat\M2. Two Area 4 Machine Model\1. Manual Control\d_2area_kd0
Date: 23-Nov-2009 10:27:40

STATE MATRIX EIGENVALUES

Eigevalue Most Associated States Real part Imag. Part Pseudo-
FrequencFrequency
Eig As # 9 delta_Syn_2, omega_Syn_2 -0.89861 7.8217 1.2449 1.2531
Eig As #10 delta_Syn_2, omega_Syn_2 -0.89861 -7.8217 1.2449
1.2531
Eig As #11 omega_Syn_4, delta_Syn_4 -0.9227 8.0393 1.2795 1.2879
Eig As #12 omega_Syn_4, delta_Syn_4 -0.9227 -8.0393 1.2795 1.2879
Eig As #13 omega_Syn_1, delta_Syn_1 -0.20162 3.7576 0.59803
0.59889
Eig As #14 omega_Syn_1, delta_Syn_1 -0.20162 -3.7576 0.59803
0.59889

EIGENVALUE REPORT

P S A T 2.1.2

Author: Federico Milano, (c) 2002-2008
e-mail: Federico.Milano@uclm.es
website: http://www.uclm.es/area/gsee/Web/Federico

File: T:\psat\M2. Two Area 4 Machine Model\1. Manual Control\d_2area_kdm10
Date: 23-Nov-2009 10:28:00

STATE MATRIX EIGENVALUES

Eigevalue	Most Associated States	Real part	Imag. Part	Pseudo-FrequencFrequency	
Eig As # 9	delta_Syn_2, omega_Syn_2	-0.48796	7.8124	1.2434	1.2458
Eig As #10	delta_Syn_2, omega_Syn_2	-0.48796	-7.8124	1.2434	1.2458
Eig As #11	delta_Syn_4, omega_Syn_4	-0.49566	8.0303	1.2781	1.2805
Eig As #12	delta_Syn_4, omega_Syn_4	-0.49566	-8.0303	1.2781	1.2805
Eig As #13	delta_Syn_1, omega_Syn_1	0.20039	3.7288	0.59345	0.59431
Eig As #14	delta_Syn_1, omega_Syn_1	0.20039	-3.7288	0.59345	0.59431

EIGENVALUE REPORT

P S A T 2.1.2

Author: Federico Milano, (c) 2002-2008
e-mail: Federico.Milano@uclm.es
website: http://www.uclm.es/area/gsee/Web/Federico

File: T:\psat\M2. Two Area 4 Machine Model\1. Manual Control\d_2area_kdp10
Date: 23-Nov-2009 10:28:13

STATE MATRIX EIGENVALUES

Eigevalue	Most Associated States	Real part	Imag. Part	Pseudo-FrequencFrequency	
Eig As # 9	omega_Syn_2, delta_Syn_2	-1.3111	7.8123	1.2434	1.2608
Eig As #10	omega_Syn_2, delta_Syn_2	-1.3111	-7.8123	1.2434	1.2608
Eig As #11	omega_Syn_4, delta_Syn_4	-1.3519	8.0277	1.2776	1.2956
Eig As #12	omega_Syn_4, delta_Syn_4	-1.3519	-8.0277	1.2776	1.2956
Eig As #13	omega_Syn_1, delta_Syn_1	-0.60549	3.7446	0.59597	0.60371

Eig As #14 omega_Syn_1, delta_Syn_1 -0.60549 -3.7446 0.59597
0.60371

H.2.2.2. PacDyn results

1. Manual control

PacDyn - Small Signal Stability Analysis of Electrical Power Systems

==

CEPEL - Centro de Pesquisas de Energia Eletrica

Version 8.1 - August 2008
Initializing dynamic data

Reading dynamic data .... P:\2area 26089\2area_dyn_with_xl_ra_with_sat.dyn

Case Title

Two area system, Manual Control, Bus#3 as a reference machine
PacDyn Format Electical Network Data File
PacDyn Dynamic Data File, DS Mudau

System Data

System Frequency : 60.0 Hertz
System MVA Base : 100.0 MVA

Initializing network data
Reading network data .... P:\2area 26089\2area_elec.sav

BUS DATA

X----X------------X--X--X--------X---------X--------X----------X---------X---------X---------X-
--------X

BUS				VOLTAGE		GENERATION		LOAD		SHUNT	
NUM.	NAME	TP	AR	MAGNIT.	ANGLE	MW	Mvar	MW	Mvar	MW	Mvar
1	BUS01			1.0300	20.0477	700.00	179.00	0.00	0.00	0.00	0.00
2	BUS02			1.0100	10.2984	700.00	220.10	0.00	0.00	0.00	0.00
3	BUS03			1.0300	-6.8000	718.50	168.79	0.00	0.00	0.00	0.00
4	BUS04			1.0100	-16.9590	700.00	185.03	0.00	0.00	0.00	0.00

5	BUS05	1.0074	13.5908	0.00	0.00	0.00	0.00	0.00	0.00
6	BUS06	0.9805	3.5314	0.00	0.00	0.00	0.00	0.00	0.00
7	BUS07	0.9652	-4.8323	0.00	0.00	967.00	-100.00	0.00	0.00
8	BUS08	0.9536	-18.5790	0.00	0.00	0.00	0.00	0.00	0.00
9	BUS09	0.9763	-32.0450	0.00	0.00	1767.00	-250.00	0.00	0.00
10	BUS10	0.9862	-23.6860	0.00	0.00	0.00	0.00	0.00	0.00
11	BUS11	1.0094	-13.4150	0.00	0.00	0.00	0.00	0.00	0.00

LINE DATA

X---------X---X----------X----------X----------X----------X----------X

BUS FROM	TO	CIRC NUM.	RESIST. pu	REACT. pu	SUSCEP. Mvar	TAP pu	ANGLE Degree
1	5	1	0.0000	0.0167	0.0000		
2	6	2	0.0000	0.0167	0.0000		
3	11	3	0.0000	0.0167	0.0000		
4	10	4	0.0000	0.0167	0.0000		
5	6	5	0.0025	0.0250	4.3750		
6	7	6	0.0010	0.0100	1.7500		
7	8	7	0.0110	0.1100	19.2500		
7	8	8	0.0110	0.1100	19.2500		
8	9	9	0.0110	0.1100	19.2500		
8	9	10	0.0110	0.1100	19.2500		
9	10	11	0.0010	0.0100	1.7500		
10	11	12	0.0025	0.0250	4.3750		

Converged Load Flow

Maximum specified tolerances:

Voltage module: 0.00072 (pu).
Voltage angle : 0.05000 (degrees).
Active power: 1.00000 (%).
Reactive power: 1.00000 (%).

Maximum differences found :

Voltage module: 0.80255E-04 (pu) on bus 7.
Voltage angle : 0.44803E-03 (degrees) on bus 5.
Active power: 0.79873E-01 (MW) on bus 1.
Reactive power: 0.17854E-01 (Mvar) on bus 1.

Synchronous Machine Dynamic Data

```
+------- Identification -------+--- Mechanical ---+--------------- Reactances (pu) -----------
----+------+--- Time Constants (s) ---+--- Saturation ----+------+
 S Bus   Gen.                MVA        Damp  Transient   Synchronous  Sub-Transient
Ra  Transient    Sub-Transient                  Freq.
 T No.  No.   Bus Name  M UP  Base  Inert. (1/s) D-axis Q-axis D-axis Q-axis D-axis
Q-axis Potier  (pu)  D-axis Q-axis D-axis Q-axis  A     B     C    (HZ)
+-+-----+----+-----------+-+--+------+------+----+------+------+------+------+------+-----
     1   0  BUS01     5  1  900.0  6.500  0.00 0.3000 0.5500 1.8000 1.7000 0.2500 0.2500
0.0000  0.003  8.000  0.400  0.030  0.050  0.015  9.600  0.900  60.00
     2   0  BUS02     5  1  900.0  6.500  0.00 0.3000 0.5500 1.8000 1.7000 0.2500 0.2500
0.0000  0.003  8.000  0.400  0.030  0.050  0.015  9.600  0.900  60.00
     3   0  BUS03     5  1  900.0  6.175  0.00 0.3000 0.5500 1.8000 1.7000 0.2500 0.2500
0.0000  0.003  8.000  0.400  0.030  0.050  0.015  9.600  0.900  60.00
     4   0  BUS04     5  1  900.0  6.175  0.00 0.3000 0.5500 1.8000 1.7000 0.2500 0.2500
0.0000  0.003  8.000  0.400  0.030  0.050  0.015  9.600  0.900  60.00
                              INITIAL CONDITIONS
                              ------------------

   (------ bus ------) s/m   rotor  mechanic (  terminal power   ) ( terminal voltage)
terminal   field
        name        no. no.  angle   power    active   reactive  modulus   angle   current
voltage
                         degree    MW        MW        Mvar       pu        degree    pu      pu

      BUS01       1  0    63.381   701.37    700.00    179.00   1.0300     20.048    7.015
1.9358
      BUS02       2  0    52.887   701.47    700.00    220.10   1.0100     10.298    7.265
2.0035
      BUS03       3  0    37.676   719.92    718.50    168.79   1.0300     -6.800    7.166
1.9473
      BUS04       4  0    26.981   701.43    700.00    185.03   1.0100    -16.959    7.169
1.9540

---------------------------------------------------------------------
 System Summary                                On    Off   Tot.  Max.
+-------------------------------------------+------+------+------+------+
 AC buses                                          11   120
 AC branches                                        12  25000
 Non-linear loads                                    0  16000
 Dynamic loads                                       0  16000
 PV/Slack buses                                      0   3000
 Infinite buses                                    0  16000
 Induction motors                          0          0   500
 HVDC converters                            0          0    40
+-------------------------------------------+------+------+------+------+
 Synchronous machines                        4     0     4  3000
 Excitation systems        (built-in)       0     0     0  3000
 Excitation systems        (UDC)             0     0     0  4000
 Rotor speed control systems (built-in)       0     0     0  3000
 Rotor speed control systems (UDC)             0     0     0  4000
 Power system stabilizers   (built-in)       0     0     0  1000
```

Power system stabilizers	(UDC)	0	0	0	4000
FACTS devices	(built-in)	0	0	0	20
User defined controllers		0	0	0	4000

System Summary

Reference generator bus number	3
Reference generator number	0
Abort on power flow error ?	YES

Matrix Summary: Jacobian & State Matrices

Description	Num.	Max.
Jacobian matrix dimension	90	150000
Number of non-zero elements	318	900000
Number of state variables	23	
Number of algebraic variables	58	
Number of null variables	9	
State matrix dimension (for full system eigensolution)	23	4000

Synchronous Machine Control Data

Bus No.	Bus Name	Gen. No.	M	Synchr. Conden.	AVR (M)/UD	GOV (M)/UD	PSS (M)/UD	Inp1 Inp2 Inp3 ...
1	BUS01	0	5	no				
2	BUS02	0	5	no				
3	BUS03	0	5	no				
4	BUS04	0	5	no				

Spining Reserve Data

Bus No.	Gen. No.	Bus Name	No. Unt.	MVA Base Unit	Total	Gener. MVA	Load. %	Status
1	0	BUS01	1	900.0	900.0	722.5	80.3	Ok
2	0	BUS02	1	900.0	900.0	733.8	81.5	Ok
3	0	BUS03	1	900.0	900.0	738.1	82.0	Ok
4	0	BUS04	1	900.0	900.0	724.0	80.4	Ok

EIGENVALUES

No.	Real	Imaginary	Damp (%)	Freq (HZ)	Maximum Participation Factor

```
 1 -37.17218                          EQ"   BUS02   #  2
 2 -37.10766                          EQ"   BUS03   #  3
 3 -35.86773                          ED"   BUS02   #  2
 4 -35.65510                          ED"   BUS03   #  3
 5 -34.96023                          EQ"   BUS03   #  3
 6 -34.12909                          EQ"   BUS01   #  1
 7 -29.93128                          ED"   BUS03   #  3
 8 -28.95899                          ED"   BUS01   #  1
 9 -.5527338    +j 7.032781   <<    7.84    1.12 DELT   BUS04   #  4
10
11 -.5489639    +j 6.809021        8.04    1.08 DELT   BUS02   #  2
12
13 -5.268755                          ED'   BUS04   #  4
14 -5.238942                          ED'   BUS02   #  2
15 -3.835550                          ED'   BUS03   #  3
16 -.9563500E-01 +j 3.423770  <<<   2.79    0.54 DELT   BUS01   #  1
17
18 -3.102541                          ED'   BUS02   #  2
19 -.3140507                          EQ'   BUS02   #  2
20 -.2168714                          EQ'   BUS01   #  1
21 -.2078740                          EQ'   BUS03   #  3
22 -.5774135E-01                       WW    BUS03   #  3
23 -.1836858E-12                       WW    BUS01   #  1
```

2. AVR and PSS

PacDyn - Small Signal Stability Analysis of Electrical Power Systems

===

CEPEL - Centro de Pesquisas de Energia Eletrica

Version 8.1 - August 2008

Initializing dynamic data

Reading dynamic data .... P:\AVR HTG and PSS\2area_dyn_with_xl_ra_with_sat.dyn

Case Title

Two area system, Manual Control, Bus#3 as a reference machine
PacDyn Format Electical Network Data File
PacDyn Dynamic Data File, DS Mudau

System Data

System Frequency : 60.0 Hertz

System MVA Base : 100.0 MVA

Initializing network data
Reading network data .... P:\AVR HTG and PSS\2area_elec.sav

BUS DATA

BUS				VOLTAGE		GENERATION		LOAD		SHUNT	
NUM.	NAME	TP	AR	MAGNIT.	ANGLE	MW	Mvar	MW	Mvar	MW	Mvar
1	BUS01			1.0300	20.0477	700.00	179.00	0.00	0.00	0.00	0.00
2	BUS02			1.0100	10.2984	700.00	220.10	0.00	0.00	0.00	0.00
3	BUS03			1.0300	-6.8000	718.50	168.79	0.00	0.00	0.00	0.00
4	BUS04			1.0100	-16.9590	700.00	185.03	0.00	0.00	0.00	0.00
5	BUS05			1.0074	13.5908	0.00	0.00	0.00	0.00	0.00	0.00
6	BUS06			0.9805	3.5314	0.00	0.00	0.00	0.00	0.00	0.00
7	BUS07			0.9652	-4.8323	0.00	0.00	967.00	-100.00	0.00	0.00
8	BUS08			0.9536	-18.5790	0.00	0.00	0.00	0.00	0.00	0.00
9	BUS09			0.9763	-32.0450	0.00	0.00	1767.00	-250.00	0.00	0.00

BUS DATA

BUS				VOLTAGE		GENERATION		LOAD		SHUNT	
NUM.	NAME	TP	AR	MAGNIT.	ANGLE	MW	Mvar	MW	Mvar	MW	Mvar
10	BUS10			0.9862	-23.6860	0.00	0.00	0.00	0.00	0.00	0.00
11	BUS11			1.0094	-13.4150	0.00	0.00	0.00	0.00	0.00	0.00

LINE DATA

BUS		CIRC	RESIST.	REACT.	SUSCEP.	TAP	ANGLE
FROM	TO	NUM.	pu	pu	Mvar	pu	Degree
1	5	1	0.0000	0.0167	0.0000		
2	6	2	0.0000	0.0167	0.0000		
3	11	3	0.0000	0.0167	0.0000		
4	10	4	0.0000	0.0167	0.0000		
5	6	5	0.0025	0.0250	4.3750		
6	7	6	0.0010	0.0100	1.7500		

7	8	7	0.0110	0.1100	19.2500
7	8	8	0.0110	0.1100	19.2500
8	9	9	0.0110	0.1100	19.2500
8	9	10	0.0110	0.1100	19.2500
9	10	11	0.0010	0.0100	1.7500
10	11	12	0.0025	0.0250	4.3750

```
--------------------------------------------------------------------------
Converged Load Flow
--------------------------------------------------------------------------

Maximum specified tolerances:
----------------------------
Voltage module:    0.00072 ( pu     ).
Voltage angle :   0.05000 (degrees).
Active   power:    1.00000 ( %      ).
Reactive power:    1.00000 ( %      ).

Maximum differences found   :
----------------------------
Voltage module: 0.80255E-04 ( pu     ) on bus    7.
Voltage angle : 0.44803E-03 (degrees) on bus    5.
Active   power: 0.79873E-01 (MW     ) on bus    1.
Reactive power: 0.17854E-01 (Mvar   ) on bus    1.

--------------------------------------------------------------------------
Synchronous Machine Dynamic Data
----------------------------------------------------------------------------------------------------
+------- Identification -------+--- Mechanical ----+--------------- Reactances (pu) ----------
----+------+--- Time Constants (s) ----+---- Saturation ----+------+
 S Bus  Gen.                 MVA        Damp  Transient    Synchronous   Sub-Transient
Ra  Transient    Sub-Transient                 Freq.
 T No.  No.   Bus Name  M UP  Base  Inert. (1/s) D-axis Q-axis D-axis Q-axis D-axis
Q-axis Potier  (pu)  D-axis Q-axis D-axis Q-axis  A     B     C    (HZ)
+-+-----+----+-----------+-+--+------+------+-----+------+------+------+------+------+-----
    1   0  BUS01      5  1  900.0  6.500  0.00 0.3000 0.5500 1.8000 1.7000 0.2500 0.2500
0.0000 0.003 8.000 0.400 0.030 0.050 0.015 9.600 0.900 60.00
    2   0  BUS02      5  1  900.0  6.500  0.00 0.3000 0.5500 1.8000 1.7000 0.2500 0.2500
0.0000 0.003 8.000 0.400 0.030 0.050 0.015 9.600 0.900 60.00
    3   0  BUS03      5  1  900.0  6.175  0.00 0.3000 0.5500 1.8000 1.7000 0.2500 0.2500
0.0000 0.003 8.000 0.400 0.030 0.050 0.015 9.600 0.900 60.00
    4   0  BUS04      5  1  900.0  6.175  0.00 0.3000 0.5500 1.8000 1.7000 0.2500 0.2500
0.0000 0.003 8.000 0.400 0.030 0.050 0.015 9.600 0.900 60.00
```

USER DEFINED CONTROLLER MODEL DATA

```
                 --------------------------------

 UDC  (-Block-)  (- Variable --) (------------------ Parameters ------------------------)
 No.   No. Type  Input   Output    A         B         C         D         E
------ ---- ------ ------  ------ ---------- ---------- ---------- ---------- ----------
```

```
 1000 ------------------------- AVR
      1 IN     VB     ET    #NB
      2 IN     VREF   X22   #NB
      3 IN     VPSS   X23   #NB
      4 OUT    X25    EFD   #NB
      5 LDLG   ET     X21   1      0      1      0.01
      6 SUM    -X21   X24   1.0
             +X22         1.0
             +X23         1.0
      7 GAIN   X24    X25   200
       DPAR             #NB
STOP
```

USER DEFINED CONTROLLER DATA

```
UDC (--Block---)  (- Variable -) (----------------- Parameters ----------------------)
No.  No. Type  Input  Output   A        B        C        D        E
------ ---- ------ ------ ------ ---------- ---------- ---------- ---------- ----------

   1 ------------------------ AVR-GEN.1      1000    AVR
                  #NB      1

   2 ------------------------ AVR-GEN.2      1000    AVR
                  #NB      2

   3 ------------------------ AVR-GEN.3      1000    AVR
                  #NB      3

   4 ------------------------ AVR-GEN.4      1000    AVR
                  #NB      4
```

USER DEFINED CONTROLLER DATA

```
UDC (--Block---)  (- Variable -) (----------------- Parameters ----------------------)
No.  No. Type  Input  Output   A        B        C        D        E
------ ---- ------ ------ ------ ---------- ---------- ---------- ---------- ----------

  11 ------------------------ PSS-GEN.1
      1 OUT    VPSS   VPSS   1
      2 IN     WW     WW     1
      3 GAIN   WW     X12    20.00
      4 LDLG   X12    X13    0.000    10.00    1.000    10.00
      5 LDLG   X13    X14    1.000    0.050    1.000    0.020
STOP   6 LDLG   X14    VPSS   1.000    3.000    1.000    5.400
%Dynamic data file line #   72.
%Warning: More outputs than references. Some outputs will be calculated.

  12 ------------------------ PSS-GEN.2
      1 OUT    VPSS   VPSS   2
```

```
        2 IN    WW    WW   2
        3 GAIN   WW    X22   20.00
        4 LDLG   X22   X23  0.000    10.00    1.000    10.00
        5 LDLG   X23   X24  1.000    0.050    1.000    0.020
  STOP    6 LDLG  X24   VPSS  1.000    3.000    1.000    5.400
 %Dynamic data file line #   81.
 %Warning: More outputs than references. Some outputs will be calculated.

    13 -------------------------- PSS-GEN.3
        1 OUT    VPSS   VPSS  3
        2 IN    WW    WW   3
        3 GAIN   WW    X32   20.00
        4 LDLG   X32   X33  0.000    10.00    1.000    10.00
        5 LDLG   X33   X34  1.000    0.050    1.000    0.020
  STOP    6 LDLG  X34   VPSS  1.000    3.000    1.000    5.400
 %Dynamic data file line #   90.
 %Warning: More outputs than references. Some outputs will be calculated.

    14 -------------------------- PSS-GEN.4
        1 OUT    VPSS   VPSS  4
        2 IN    WW    WW   4
        3 GAIN   WW    X42   20.00
        4 LDLG   X42   X43  0.000    10.00    1.000    10.00
        5 LDLG   X43   X44  1.000    0.050    1.000    0.020
  STOP    6 LDLG  X44   VPSS  1.000    3.000    1.000    5.400
 %Dynamic data file line #   99.
 %Warning: More outputs than references. Some outputs will be calculated.


                          INITIAL CONDITIONS
                          ------------------

   (------ bus ------) s/m  rotor  mechanic (  terminal power  ) ( terminal voltage)
terminal  field
       name     no. no.  angle  power   active  reactive  modulus  angle  current
voltage
                    degree  MW      MW     Mvar    pu      degree   pu     pu

     BUS01      1  0   63.381  701.37  700.00   179.00  1.0300   20.048   7.015
1.9358
     BUS02      2  0   52.887  701.47  700.00   220.10  1.0100   10.298   7.265
2.0035
     BUS03      3  0   37.676  719.92  718.50   168.79  1.0300   -6.800   7.166
1.9473
     BUS04      4  0   26.981  701.43  700.00   185.03  1.0100  -16.959   7.169
1.9540

       INITIALIZATION THROUGH NEWTON

          USER DEFINED CONTROLLER VARIABLES
```

1000 AVR

UDC	Var.	Init. Value	Variation	Mismatch
1	ET	1.0300	0.0000	0.0000
	X22	1.0397	0.94369E-16	0.0000
	X23	0.0000	0.0000	0.0000
	X21	1.0300	0.0000	0.0000
	X24	0.96791E-02	0.94369E-16	0.0000
	X25	1.9358	0.0000	-0.18874E-13

1000 AVR

UDC	Var.	Init. Value	Variation	Mismatch
2	ET	1.0100	0.0000	0.0000
	X22	1.0200	0.27534E-15	0.0000
	X23	0.0000	0.0000	0.0000
	X21	1.0100	0.0000	0.0000
	X24	0.10018E-01	0.53291E-16	-0.22204E-15
	X25	2.0035	0.0000	-0.10658E-13

1000 AVR

UDC	Var.	Init. Value	Variation	Mismatch
3	ET	1.0300	0.0000	0.0000
	X22	1.0397	0.25646E-15	0.0000
	X23	0.0000	0.0000	0.0000
	X21	1.0300	0.0000	0.0000
	X24	0.97366E-02	0.34417E-16	-0.22204E-15
	X25	1.9473	0.0000	-0.68834E-14

1000 AVR

UDC	Var.	Init. Value	Variation	Mismatch
4	ET	1.0100	0.0000	0.0000
	X22	1.0198	0.56621E-16	0.0000
	X23	0.0000	0.0000	0.0000
	X21	1.0100	0.0000	0.0000
	X24	0.97699E-02	0.56621E-16	0.0000
	X25	1.9540	0.0000	-0.11324E-13

UDC	Var.	Init. Value	Variation	Mismatch
11	WW	1.0000	0.0000	0.0000
	X12	20.000	0.0000	0.0000
	X13	0.0000	-0.35527E-14	-0.35527E-14
	X14	0.0000	-0.34417E-14	0.0000
	VPSS	0.0000	-0.35527E-14	-0.86351E-16

UDC	Var.	Init. Value	Variation	Mismatch
12	WW	1.0000	0.0000	0.0000

```
    X22    20.000    0.0000     0.0000
    X23    0.0000   -0.35527E-14 -0.35527E-14
    X24    0.0000   -0.34417E-14  0.0000
    VPSS    0.0000   -0.35527E-14 -0.86351E-16

 UDC  Var.  Init. Value  Variation    Mismatch
------ ------ ----------- ------------ -----------
  13 WW     1.0000     0.0000     0.0000
    X32    20.000    0.0000     0.0000
    X33    0.0000   -0.35527E-14 -0.35527E-14
    X34    0.0000   -0.34417E-14  0.0000
    VPSS    0.0000   -0.35527E-14 -0.86351E-16

 UDC  Var.  Init. Value  Variation    Mismatch
------ ------ ----------- ------------ -----------
  14 WW     1.0000     0.0000     0.0000
    X42    20.000    0.0000     0.0000
    X43    0.0000   -0.35527E-14 -0.35527E-14
    X44    0.0000   -0.34417E-14  0.0000
    VPSS    0.0000   -0.35527E-14 -0.86351E-16

Number of iterations to calculate initial values of UDC variables:    2.

------------------------------------------------------------------------
 System Summary                                On    Off   Tot.  Max.
+--------------------------------------------+------+------+------+------+
 AC buses                                          11   120
 AC branches                                         12  25000
 Non-linear loads                                     0  16000
 Dynamic loads                                        0  16000
 PV/Slack buses                                       0   3000
 Infinite buses                                     0  16000
 Induction motors                              0          0    500
 HVDC converters                                0          0    40
+--------------------------------------------+------+------+------+------+
 Synchronous machines                              4     0     4  3000
 Excitation systems          (built-in)          0     0     0  3000
 Excitation systems          (UDC)                4     0     4  4000
 Rotor speed control systems (built-in)            0     0     0  3000
 Rotor speed control systems (UDC)                   0     0     0  4000
 Power system stabilizers    (built-in)          0     0     0  1000
 Power system stabilizers    (UDC)                4     0     4  4000
 FACTS devices               (built-in)          0     0     0    20
 User defined controllers                       8     0     8  4000
------------------------------------------------------------------------


------------------------------------------------------------------------
 System Summary
+---------------------------------------------------------------+------+
 Reference generator bus number                                    3
 Reference generator number                                      0
```

Abort on power flow error ? YES

Matrix Summary: Jacobian & State Matrices

Description	Num.	Max.
Jacobian matrix dimension	150	150000
Number of non-zero elements	470	900000
Number of state variables	39	
Number of algebraic variables	102	
Number of null variables	9	
State matrix dimension (for full system eigensolution)	39	4000

Synchronous Machine Control Data

Bus No.	Bus Name	Gen. No.	Synchr. M Conden.	AVR (M)/UD	GOV (M)/UD	PSS (M)/UD	Inp1 Inp2 Inp3 ...
1	BUS01	0	5 no	1		11	WW
2	BUS02	0	5 no	2		12	WW
3	BUS03	0	5 no	3		13	WW
4	BUS04	0	5 no	4		14	WW

Spining Reserve Data

Bus No.	Gen. No.	Bus Name	No. Unt.	MVA Base Unit	Total	Gener. MVA	Load. %	Status
1	0	BUS01	1	900.0	900.0	722.5	80.3	Ok
2	0	BUS02	1	900.0	900.0	733.8	81.5	Ok
3	0	BUS03	1	900.0	900.0	738.1	82.0	Ok
4	0	BUS04	1	900.0	900.0	724.0	80.4	Ok

EIGENVALUES

No.	Real	Imaginary	Damp (%)	Freq (HZ)	Maximum Participation Factor
1	-97.56031				X 0005 AVR-GEN.4 # 4
2	-97.49699				X 0005 AVR-GEN.2 # 2
3	-95.94106				X 0005 AVR-GEN.3 # 3
4	-95.34011				X 0005 AVR-GEN.2 # 2
5	-50.57113				X 0005 PSS-GEN.4 # 14
6	-50.52309				X 0005 PSS-GEN.2 # 12
7	-50.30550				X 0005 PSS-GEN.3 # 13
8	-50.25535				X 0005 PSS-GEN.1 # 11
9	-36.15705				ED" BUS04 # 4
10	-36.05449				ED" BUS02 # 2
11	-31.68160				ED" BUS03 # 3

```
12 -30.86805                                  ED"   BUS01   #  1
13 -17.48323    +j 18.73111       68.23    2.98 EQ'   BUS04    #   4
14
15 -25.31529                                  EQ"   BUS03   #  3
16 -24.69490                                  EQ"   BUS01   #  1
17 -18.19558    +j 15.35513       76.42    2.44 EQ'   BUS01    #   1
18
19 -13.69759                                  EQ'   BUS02   #  2
20 -12.99581                                  EQ'   BUS04   #  4
21 -2.098535    +j 8.611350       23.68    1.37 DELT   BUS04    #   4
22
23 -2.009961    +j 8.269362   <<    23.62    1.32 WW    BUS02   #   2
24
25 -.6936547    +j 3.862263   <<<    17.68    0.61 DELT    BUS01    #   1
26
27 -3.687203                                  ED'   BUS04   #  4
28 -3.534369                                  ED'   BUS02   #  2
29 -2.755530                                  ED'   BUS01   #  1
30 -2.705929                                  ED'   BUS03   #  3
31 -1.240491                                  WW    BUS02   #  2
32 -.3714346                                  X 0006 PSS-GEN.2  #   12
33 -.1786782    +j 0.3224392E-03     100.00    0.00 X 0006 PSS-GEN.3  #   13
34
35 -.1779373                                  X 0006 PSS-GEN.4  #   14
36 -.1033928                                  X 0004 PSS-GEN.4  #   14
37 -.1030594    +j 0.1858201E-03     100.00    0.00 X 0004 PSS-GEN.3  #   13
38
39 0.3816402E-12          ***           X 0004 PSS-GEN.2  #   12
```

Eigenvalues of 2A4M on manual control for different damping coefficients (PacDyn)

Effects of Damping coefficients on frequency and damping ratios - PacDyn							
		Δf (Hz)	Δζ (%)			Δf (Hz)	Δζ (%)
Kd=-10	Inter-area	0.0003	1.283		Kd=+10	-3E-04	-1.2805
	Local area-1	0.0002	0.6527			-1E-04	-0.652
	Local area-2	0.0002	0.6633			-2E-04	-0.6626

```
Kd=0  Real    Imaginary      Freq. (Hz)     Damp(%)      Participation Factor
Inter-area    -0.09211       3.4265 0.5453 2.6873 DELT    BUS01    #   1
Local area-1  -0.5726 6.8115 1.0841 8.3764 DELT    BUS02    #   2
Local area-2  -0.5742 7.0355 1.1197 8.1343 DELT    BUS04    #   4
```

```
Kd=-10        Real     Imaginary       Freq. (Hz)      Damp(%)       Participation
Factor
Inter-area    -0.04809         3.4244 0.545   1.4043 DELT    BUS01    #   1
Local area-1  -0.5276 6.8102 1.0839 7.7237 DELT    BUS02    #   2
Local area-2  -0.527  7.0342 1.1195 7.471   DELT    BUS04    #   4
```

Kd=+10	Real	Imaginary	Freq. (Hz)	Damp(%)	Participation Factor
Inter-area	-0.1361	3.428	0.5456	3.9678	DELT BUS01 # 1
Local area-1	-0.6176	6.8125	1.0842	9.0284	DELT BUS02 # 2
Local area-2	-0.6214	7.0366	1.1199	8.7969	DELT BUS04 # 4

AVR and PSS with ZIP loads (Eigenvalues only)

	Real	Imaginary	Module	Freq. (Hz)	Damp(%)	Part. Factor
1	-0.5361	3.8744	3.9113	0.6166	13.706	DELT BUS01 # 1
2	-0.5361	-3.8744	3.9113	-0.6166	13.706	
3	-2.0854	8.4650	8.7181	1.3473	23.920	DELT BUS04 # 4
4	-2.0854	-8.4650	8.7181	-1.3473	23.920	
5	-2.0140	8.1567	8.4017	1.2982	23.971	WW BUS02 # 2
6	-2.0140	-8.1567	8.4017	-1.2982	23.971	
7	-17.544	22.482	28.517	3.5781	61.522	EQ' BUS04 # 4
8	-17.544	-22.482	28.517	-3.5781	61.522	
9	-18.479	16.623	24.855	2.6456	74.347	EQ' BUS01 # 1
10	-18.479	-16.623	24.855	-2.6456	74.347	
11	-97.483	0.	97.483	0.	100.00	X 0005 AVR-GEN.3 # 3
12	-97.423	0.	97.423	0.	100.00	X 0005 AVR-GEN.1 # 1
13	-95.649	0.	95.649	0.	100.00	X 0005 AVR-GEN.1 # 1
14	-94.502	0.	94.502	0.	100.00	X 0005 AVR-GEN.4 # 4
15	-50.540	0.	50.540	0.	100.00	X 0005 PSS-GEN.4 # 14
16	-50.503	0.	50.503	0.	100.00	X 0005 PSS-GEN.2 # 12
17	-50.216	0.	50.216	0.	100.00	X 0005 PSS-GEN.3 # 13
18	-50.202	0.	50.202	0.	100.00	X 0005 PSS-GEN.1 # 11
19	-36.139	0.	36.139	0.	100.00	ED" BUS04 # 4
20	-36.032	0.	36.032	0.	100.00	ED" BUS02 # 2
21	-31.550	0.	31.550	0.	100.00	ED" BUS03 # 3
22	-30.701	0.	30.701	0.	100.00	ED" BUS01 # 1
23	-24.781	0.	24.781	0.	100.00	EQ" BUS03 # 3
24	-24.048	0.	24.048	0.	100.00	EQ" BUS01 # 1
25	-14.417	0.	14.417	0.	100.00	EQ' BUS01 # 1
26	-13.647	0.	13.647	0.	100.00	EQ' BUS04 # 4
27	-3.6340	0.	3.6340	0.	100.00	ED' BUS04 # 4
28	-3.4983	0.	3.4983	0.	100.00	ED' BUS02 # 2
29	-2.7821	0.	2.7821	0.	100.00	ED' BUS01 # 1
30	-2.7337	0.	2.7337	0.	100.00	ED' BUS03 # 3
31	-0.5818	0.	0.5818	0.	100.00	X 0006 PSS-GEN.4 # 14
32	-0.4703	0.	0.4703	0.	100.00	X 0006 PSS-GEN.4 # 14
33	-0.1802	0.	0.1802	0.	100.00	X 0006 PSS-GEN.3 # 13
34	-0.1786	0.	0.1786	0.	100.00	X 0006 PSS-GEN.1 # 11
35	-0.1781	0.	0.1781	0.	100.00	X 0006 PSS-GEN.3 # 13
36	-0.1033	0.	0.1033	0.	100.00	X 0004 PSS-GEN.3 # 13
37	-0.1031	0.	0.1031	0.	100.00	X 0004 PSS-GEN.1 # 11
38	-0.1023	0.	0.1023	0.	100.00	X 0004 PSS-GEN.3 # 13
39	-2.31967e-015	0.	2.31967e-015	0.	100.00	X 0004 PSS-GEN.2 # 12

H.2.2.3. MatNetEig results

Manual control

>> mne_inf
load flow d_pstv2_2area_100mva_31
converged in 4 iterations

Eigenvalue	freq [Hz]	damping ratio
0.0023	0	-1.0000
-0.0023	0	1.0000
-0.0559	0	1.0000
-0.2699	0	1.0000
-0.2807	0	1.0000
-0.3020	0	1.0000
-2.9568	0	1.0000
-0.0910 - 3.4279i	0.5456	0.0265
-0.0910 + 3.4279i	0.5456	0.0265
-3.6482	0	1.0000
-4.9409	0	1.0000
-4.9779	0	1.0000
-0.5086 - 6.8466i	1.0897	0.0741
-0.5086 + 6.8466i	1.0897	0.0741
-0.5135 - 7.0693i	1.1251	0.0725
-0.5135 + 7.0693i	1.1251	0.0725
-30.1888	0	1.0000
-31.1724	0	1.0000
-34.8168	0	1.0000
-35.6715	0	1.0000
-36.6895	0	1.0000
-36.8536	0	1.0000
-37.8393	0	1.0000
-37.9281	0	1.0000

AVR and PSS

>> mne_inf
ST1a Static excitation system as a simple exciter model - 10
Power system stabiliser, PSS
load flow d_pstv2_2area_100mva_31
converged in 4 iterations

Eigenvalue	freq [Hz]	damping ratio
-0.0000 - 0.0005i	0.0001	0.0027
-0.0000 + 0.0005i	0.0001	0.0027
-0.1023 - 0.0001i	0.0000	1.0000
-0.1023 + 0.0001i	0.0000	1.0000
-0.1025	0	1.0000
-0.1800	0	1.0000
-0.1803 - 0.0003i	0.0000	1.0000

-0.1803 + 0.0003i	0.0000	1.0000
-0.3714	0	1.0000
-1.2299	0	1.0000
-3.7469	0	1.0000
-3.8336	0	1.0000
-0.6734 - 3.7799i	0.6016	0.1754
-0.6734 + 3.7799i	0.6016	0.1754
-4.2778	0	1.0000
-4.4394	0	1.0000
-2.0598 - 8.0104i	1.2749	0.2490
-2.0598 + 8.0104i	1.2749	0.2490
-2.1659 - 8.3682i	1.3318	0.2506
-2.1659 + 8.3682i	1.3318	0.2506
-11.0617	0	1.0000
-11.5880	0	1.0000
-17.8348 -14.9458i	2.3787	0.7665
-17.8348 +14.9458i	2.3787	0.7665
-17.2693 -18.3798i	2.9252	0.6847
-17.2693 +18.3798i	2.9252	0.6847
-25.6021	0	1.0000
-26.0629	0	1.0000
-32.4262	0	1.0000
-33.2875	0	1.0000
-37.5576	0	1.0000
-37.6409	0	1.0000
-50.2586	0	1.0000
-50.3100	0	1.0000
-50.5443	0	1.0000
-50.5919	0	1.0000
-95.3255	0	1.0000
-95.9214	0	1.0000
-97.4829	0	1.0000
-97.5446	0	1.0000

Eigenvalues of 2A4M on manual control for different damping coefficients (MatNetEig)

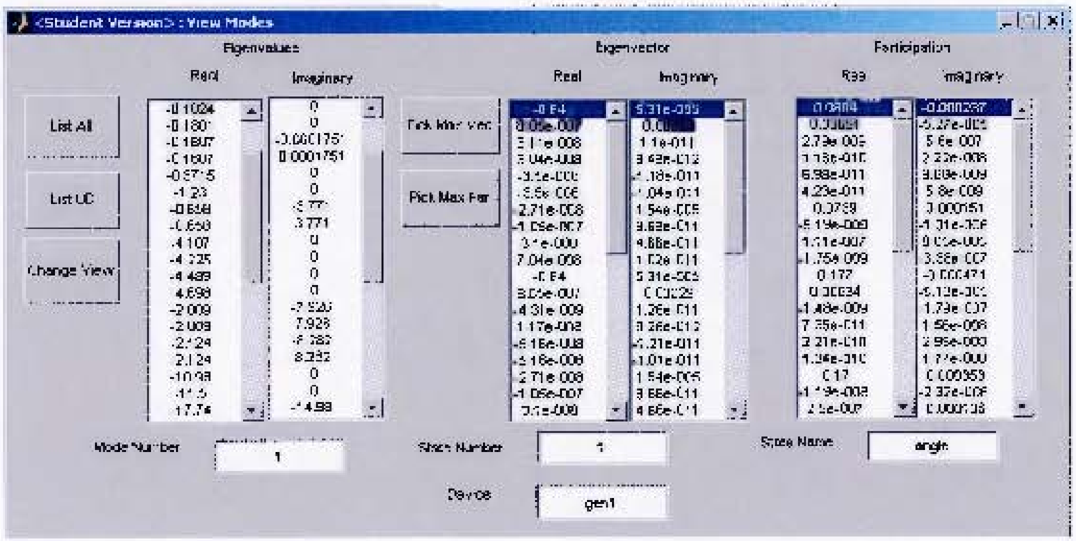
Effects of Damping coefficients on frequency and damping ratios - MatNetEig							
		Δf (Hz)	Δζ (%)			Δf (Hz)	Δζ (%)
Kd=-10	Inter-area	0.0063	11.640%		Kd=+10	0.0012	-11.432%
	Local area-1	0.003	5.897%			0	-5.844%
	Local area-2	0.004	5.993%			0	-5.936%

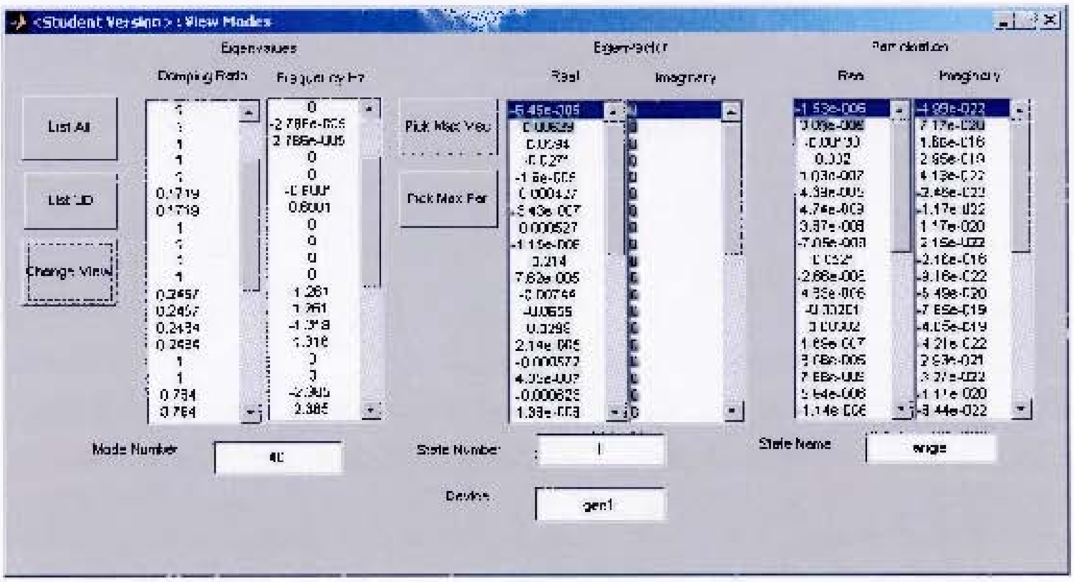
Kd=0	Eigenvalue	freq [Hz]	damping ratio
Inter-area	-0.09213 + 3.427i	0.5453	2.688%
Local area-1	-0.5726 + 6.811i	1.084	8.376%
Local area-2	-0.5742 + 7.036i	1.12	8.134%

Kd= -10	Eigenvalue	freq [Hz]	damping ratio
Inter-area	0.3044 + 3.387i	0.539	-8.952%
Local area-1	-0.1684 + 6.791i	1.081	2.479%
Local area-2	-0.1502 + 7.013i	1.116	2.141%

Kd= +10	Eigenvalue	freq [Hz]	damping ratio
Inter-area	-0.4877 + 3.419i	0.5441	14.120%
Local area-1	-0.9786 + 6.812i	1.084	14.220%
Local area-2	-1.0 + 7.035i	1.120	14.070%

AVR and PSS with ZIP loads (Eigenvalues only)





H.3. A matrix

Due to the volume of the data, only the A matrix results for the 2A4M model with AVR and PSS are presented.

H.3.1. PSAT

```
>> mds_psat_td

                < P S A T >
      Copyright (C) 2002-2008 Federico Milano
               Version 2.1.2
               June 26, 2008

PSAT comes with ABSOLUTELY NO WARRANTY; type 'gnuwarranty'
for details. This is free software, and you are welcome to
redistribute it under certain conditions; type 'gnulicense'
for details.

Host:       Matlab 7.6.0.324 (R2008a)
Session:     28-Aug-2009 11:54:25
Usage:      Command Line
Path:       F:\My Documents\MSc current\Final Simulations\psat\M2. Two Area 4
Machine Model\4. Thyristor Exciter with high transient gain & PSS

M-files in the current directory F:\My Documents\MSc current\Final
Simulations\psat\M2. Two Area 4 Machine Model\4. Thyristor Exciter with high
transient gain & PSS

d_2area_avr_pss_with_xl_no_sat     fm_call
d_2area_avr_pss_with_xl_with_sat
Number of cases ? > 1

M-files in the current directory F:\My Documents\MSc current\Final
Simulations\psat\M2. Two Area 4 Machine Model\4. Thyristor Exciter with high
transient gain & PSS

d_2area_avr_pss_with_xl_no_sat     fm_call
d_2area_avr_pss_with_xl_with_sat

File name : d_2area_avr_pss_with_xl_with_sat
Load data from file...

Newton-Raphson Method for Power Flow Computation
Data file "F:\My Documents\MSc current\Final Simulations\psat\M2. Two Area 4
Machine Model\4. Thyristor Exciter with high transient gain &
PSS\d_2area_avr_pss_with_xl_with_sat"
Writing file "fm_call" ...
PF solver: Newton-Raphson method
Single slack bus model
```

Iteration = 1   Maximum Convergency Error = 0.51524
Iteration = 2   Maximum Convergency Error = 0.09606
Iteration = 3   Maximum Convergency Error = 0.0082594
Iteration = 4   Maximum Convergency Error = 6.8443e-005
Iteration = 5   Maximum Convergency Error = 6.4914e-009
Initialization of Synchronous Machines completed.
Initialization of Automatic Voltage Regulators completed.
Initialization of Power System Stabilizers completed.
Power Flow completed in 0.11 s

A =

1.0e+003 *

Columns 1 through 10

0	0.3142	0	0	0	0	0	0	0	0
-0.0001	0	0	0	-0.0001	0.0001	0.0001	0	0	0
-0.0004	0.0001	-0.0001	0	-0.0004	0.0000	0.0003	0	0	0
0.0023	0	0	-0.0025	0.0004	-0.0046	-0.0024	0	0	0
-0.0026	0	0.0333	0	-0.0362	-0.0000	0.0021	0	0	0
0.0062	0	0	0.0200	0.0010	-0.0325	-0.0064	0	0	0
0	0	0	0	0	0	0	0.3142	0	0
0.0001	0	0	0	0.0001	-0.0001	-0.0001	0	0	0
0.0002	0	0	0	0.0004	0.0000	-0.0003	0.0001	-0.0001	0
-0.0033	0	0	0	-0.0006	0.0035	0.0034	0	0	-0.0025
0.0013	0	0	0	0.0030	0.0008	-0.0024	0	0.0333	0
-0.0088	0	0	0	-0.0016	0.0095	0.0090	0	0	0.0200
0	0	0	0	0	0	0	0	0	0
0.0000	0	0	0	0.0000	0.0000	0.0000	0	0	0
0.0000	0	0	0	0.0000	0.0000	0.0000	0	0	0
-0.0001	0	0	0	-0.0000	0.0001	-0.0002	0	0	0
0.0000	0	0	0	0.0002	0.0002	0.0002	0	0	0
-0.0003	0	0	0	-0.0001	0.0003	-0.0006	0	0	0
0	0	0	0	0	0	0	0	0	0
0.0000	0	0	0	0.0000	0.0000	0.0000	0	0	0
0.0000	0	0	0	0.0001	0.0000	0.0000	0	0	0
-0.0003	0	0	0	-0.0002	0.0002	-0.0006	0	0	0
0.0000	0	0	0	0.0005	0.0003	0.0003	0	0	0
-0.0007	0	0	0	-0.0005	0.0005	-0.0015	0	0	0
-0.0031	0	0	0	0.0702	0.0597	0.0019	0	0	0
0	0	0	0	0	0	0	0	0	0
-0.0001	5.5556	0	0	0.0012	0.0011	0.0000	0	0	0
-0.0008	0	0	0	0.0059	0.0056	-0.0016	0	0	0
0	0	0	0	0	0	0	0	0	0
-0.0000	0	0	0	0.0001	0.0001	-0.0000	5.5556	0	0
-0.0001	0	0	0	0.0004	0.0005	0.0001	0	0	0
0	0	0	0	0	0	0	0	0	0
-0.0000	0	0	0	0.0000	0.0000	0.0000	0	0	0
-0.0003	0	0	0	0.0008	0.0010	-0.0000	0	0	0
0	0	0	0	0	0	0	0	0	0

-0.0000	0	0	0	0.0000	0.0000	-0.0000	0	0	0
0	-0.0020	0	0	0	0	0	0	0	0
0	-1.5000	0	0	0	0	0	0	0	0
0	0.0041	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	-0.0020	0	0
0	0	0	0	0	0	0	-1.5000	0	0
0	0	0	0	0	0	0	0.0041	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0

Columns 11 through 20

0	0	0	0	0	0	0	0	0	0
0.0001	-0.0001	0.0000	0	0	0	0.0000	-0.0000	0.0000	0
0.0004	-0.0001	0.0000	0	0	0	0.0000	0.0000	0.0000	0
0.0008	0.0035	-0.0000	0	0	0	0.0002	0.0002	0.0001	0
0.0031	-0.0002	0.0001	0	0	0	0.0002	0.0000	0.0004	0
0.0022	0.0096	-0.0000	0	0	0	0.0004	0.0004	0.0002	0
0	0	0	0	0	0	0	0	0	0
-0.0001	0.0001	0.0000	0	0	0	0.0000	-0.0000	0.0000	0
-0.0003	0.0001	0.0000	0	0	0	0.0001	0.0000	0.0001	0
0.0006	-0.0060	-0.0001	0	0	0	0.0002	0.0003	-0.0000	0
-0.0358	0.0001	0.0003	0	0	0	0.0005	0.0001	0.0008	0
0.0016	-0.0361	-0.0002	0	0	0	0.0006	0.0008	-0.0000	0
0	0	0	0.3142	0	0	0	0	0	0
0.0000	-0.0000	-0.0001	0	0	0	-0.0001	0.0001	0.0001	0
0.0001	0.0000	-0.0004	0.0001	-0.0001	0	-0.0003	0.0000	0.0003	0
-0.0000	0.0003	0.0023	0	0	-0.0025	0.0005	-0.0047	-0.0020	0
0.0005	0.0002	-0.0026	0	0.0333	0	-0.0359	0.0001	0.0024	0
-0.0000	0.0007	0.0063	0	0	0.0200	0.0013	-0.0327	-0.0054	0
0	0	0	0	0	0	0	0	0	0.3142
0.0000	0.0000	0.0001	0	0	0	0.0001	-0.0001	-0.0001	0
0.0001	0.0001	0.0002	0	0	0	0.0004	0.0001	-0.0003	0.0001
-0.0003	0.0005	-0.0030	0	0	0	-0.0005	0.0033	0.0038	0
0.0011	0.0005	0.0015	0	0	0	0.0035	0.0010	-0.0018	0
-0.0007	0.0013	-0.0081	0	0	0	-0.0013	0.0089	0.0103	0
0.0076	0.0035	0.0003	0	0	0	0.0007	0.0002	0.0009	0
0	0	0	0	0	0	0	0	0	0
0.0001	0.0001	0.0000	0	0	0	0.0000	0.0000	0.0000	0
0.0718	0.0578	0.0005	0	0	0	0.0014	0.0005	0.0018	0
0	0	0	0	0	0	0	0	0	0
0.0013	0.0011	0.0000	0	0	0	0.0000	0.0000	0.0000	0
0.0011	0.0008	-0.0029	0	0	0	0.0697	0.0612	0.0029	0
0	0	0	0	0	0	0	0	0	0
0.0000	0.0000	-0.0001	5.5556	0	0	0.0012	0.0011	0.0001	0
0.0021	0.0016	-0.0001	0	0	0	0.0070	0.0059	0.0004	0
0	0	0	0	0	0	0	0	0	0

0.0000	0.0000	-0.0000	0	0	0	0.0001	0.0001	0.0000	5.5556
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	-0.0020	0	0	0	0	0	0
0	0	0	-1.5000	0	0	0	0	0	0
0	0	0	0.0041	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	-0.0020
0	0	0	0	0	0	0	0	0	-1.5000
0	0	0	0	0	0	0	0	0	0.0041

Columns 21 through 30

0	0	0	0	0	0	0	0	0	0
0	0	0.0000	-0.0000	0	0	0	0	0	0
0	0	0.0001	-0.0000	0	0	0.0001	0	0	0
0	0	0.0004	0.0002	0	0	0	0	0	0
0	0	0.0005	-0.0001	0	0	0	0	0	0
0	0	0.0011	0.0006	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0.0000	-0.0000	0	0	0	0	0	0
0	0	0.0001	-0.0000	0	0	0	0	0	0.0001
0	0	0.0006	0.0005	0	0	0	0	0	0
0	0	0.0012	-0.0001	0	0	0	0	0	0
0	0	0.0017	0.0014	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0.0001	-0.0001	0	0	0	0	0	0
0	0	0.0004	-0.0001	0	0	0	0	0	0
0	0	0.0010	0.0033	0	0	0	0	0	0
0	0	0.0036	-0.0002	0	0	0	0	0	0
0	0	0.0028	0.0090	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	-0.0001	0.0001	0	0	0	0	0	0
-0.0001	0	-0.0002	0.0001	0	0	0	0	0	0
0	-0.0025	0.0008	-0.0064	0	0	0	0	0	0
0.0333	0	-0.0347	0.0002	0	0	0	0	0	0
0	0.0200	0.0021	-0.0374	0	0	0	0	0	0
0	0	0.0016	0.0001	-0.1000	0	0	0	0	0
0	0	0	0	0	-0.0010	0	0	0	0
0	0	0.0000	0.0000	-0.2000	0.0010	-0.0010	0	0	0
0	0	0.0032	0.0004	0	0	0	-0.1000	0	0
0	0	0	0	0	0	0	0	-0.0010	0
0	0	0.0001	0.0000	0	0	0	-0.2000	0.0010	-0.0010
0	0	0.0089	0.0035	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0.0002	0.0001	0	0	0	0	0	0
0	0	0.0732	0.0590	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0

0	0	0.0013	0.0011	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0

Columns 31 through 40

0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0.0001	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0.0001	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0.2778	0.1111	0.2000	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0.2778
-0.1000	0	0	0	0	0	0	0	0	0
0	-0.0010	0	0	0	0	0	0	0	0
-0.2000	0.0010	-0.0010	0	0	0	0	0	0	0
0	0	0	-0.1000	0	0	0	0	0	0
0	0	0	0	-0.0010	0	0	0	0	0

0	0	0	-0.2000	0.0010	-0.0010	0	0	0	0
0	0	0	0	0	0	-0.0001	0	0	0
0	0	0	0	0	0	-0.0750	-0.0500	0	0
0	0	0	0	0	0	0.0002	0.0001	-0.0002	0
0	0	0	0	0	0	0	0	0	-0.0001
0	0	0	0	0	0	0	0	0	-0.0750
0	0	0	0	0	0	0	0	0	0.0002
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0

Columns 41 through 48

0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0.1111	0.2000	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0.2778	0.1111	0.2000	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0

0	0	0	0	0	0.2778	0.1111	0.2000
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
-0.0500	0	0	0	0	0	0	0
0.0001	-0.0002	0	0	0	0	0	0
0	0	-0.0001	0	0	0	0	0
0	0	-0.0750	-0.0500	0	0	0	0
0	0	0.0002	0.0001	-0.0002	0	0	0
0	0	0	0	0	-0.0001	0	0
0	0	0	0	0	-0.0750	-0.0500	0
0	0	0	0	0	0.0002	0.0001	-0.0002

e =

-99.9124
-99.9137
-99.9051
-99.9024
-49.8959
-49.8897
-49.9795
-50.0013
-39.2340 + 0.6757i
-39.2340 - 0.6757i
-38.7845 + 0.7068i
-38.7845 - 0.7068i
-34.3071
-32.1017
-24.5008
-22.2862
-0.2134 + 7.6194i
-0.2134 - 7.6194i
-0.1877 + 7.4514i
-0.1877 - 7.4514i
0.0930 + 5.0449i
0.0930 - 5.0449i
0.7349 + 4.5306i
0.7349 - 4.5306i
-6.4757
-6.4302
-4.8252
-4.2804
-0.6538 + 3.1890i
-0.6538 - 3.1890i
-1.2134 + 2.7050i
-1.2134 - 2.7050i
-1.2100 + 2.6566i
-1.2100 - 2.6566i
-0.2312

```
-0.1817
-0.1781
-0.1779
-0.1016
-0.1033
-0.1034
 0.0059
-0.0004
-0.0000
-1.0000
-1.0000
-1.0000
-1.0000
```

Do time domain simulations [0/1] ? 0

H.3.2. PacDyn

>> a=pacstat('F:\My Documents\MSc current\Final Simulations\PacDyn - 2A4M\2A4M\AVR HTG and PSS\Case#04\matlab.out')

State Matrix Dimension = 39

Reading State Matrix...

a =

1.0e+003 *

Columns 1 through 10

-0.0343	-0.0003	0.0323	0	0.3472	-0.0016	0.0013	-0.0005	0	0
0.0008	-0.0255	0	0.0185	0	0.0028	0.0019	0.0045	0	0
0.0017	-0.0001	-0.0020	0	0.6944	-0.0001	0.0001	-0.0000	0	0
-0.0008	0.0070	0	-0.0107	0	0.0002	0.0001	0.0003	0	0
-0.0001	0.0000	0	0	0	-0.0001	0.0000	-0.0001	0	0
0	0	0	0	0.3770	0	0	0	0	0
0.0014	-0.0000	0	0	0	0.0008	-0.0346	-0.0006	0.0323	0
0.0001	0.0049	0	0	0	-0.0045	0.0018	-0.0267	0	0.0185
0.0001	-0.0000	0	0	0	0.0000	0.0017	-0.0001	-0.0020	0
0.0000	0.0003	0	0	0	-0.0003	-0.0007	0.0070	0	-0.0107
0.0000	-0.0001	0	0	0	0.0001	-0.0001	0.0000	0	0
0	0	0	0	0	0	0	0	0	0
0.0001	-0.0000	0	0	0	0.0001	0.0002	-0.0001	0	0
0.0001	0.0005	0	0	0	-0.0004	0.0004	0.0007	0	0
0.0000	-0.0000	0	0	0	0.0000	0.0000	-0.0000	0	0
0.0000	0.0000	0	0	0	-0.0000	0.0000	0.0000	0	0
0.0000	-0.0000	0	0	0	0.0000	0.0000	-0.0000	0	0
0.0002	-0.0000	0	0	0	0.0002	0.0003	-0.0001	0	0

0.0001	0.0008	0	0	0	-0.0007	0.0004	0.0012	0	0
0.0000	-0.0000	0	0	0	0.0000	0.0000	-0.0000	0	0
0.0000	0.0001	0	0	0	-0.0000	0.0000	0.0001	0	0
0.0000	-0.0000	0	0	0	0.0000	0.0000	-0.0000	0	0
0	0	0	0	0	0	0	0	0	0
0.0566	0.0458	0	0	0	-0.0098	0.0190	0.0065	0	0
0.0156	0.0127	0	0	0	-0.0027	0.0561	0.0391	0	0
0.0018	0.0009	0	0	0	0.0002	0.0031	0.0008	0	0
0.0026	0.0019	0	0	0	-0.0002	0.0046	0.0020	0	0
0	0	0	0	-0.0020	0	0	0	0	0
0	0	0	0	-1.5000	0	0	0	0	0
0	0	0	0	0.0041	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0

Columns 11 through 20

0	0.0012	0.0001	-0.0001	0	0	0	0.0000	-0.0002	0
0	-0.0032	0.0005	0.0002	0	0	0	0.0008	0.0001	0
0	0.0001	0.0000	-0.0000	0	0	0	0.0000	-0.0000	0
0	-0.0002	0.0000	0.0000	0	0	0	0.0001	0.0000	0
0	0.0001	-0.0000	-0.0000	0	0	0	-0.0000	-0.0000	0
0	0	0	0	0	0	-0.3770	0	0	0
0.3472	-0.0014	0.0001	-0.0002	0	0	0	0.0001	-0.0003	0
0	0.0041	0.0007	0.0004	0	0	0	0.0012	0.0004	0
0.6944	-0.0001	0.0000	-0.0000	0	0	0	0.0000	-0.0000	0
0	0.0003	0.0000	0.0000	0	0	0	0.0001	0.0000	0
0	-0.0001	-0.0000	-0.0000	0	0	0	-0.0000	-0.0000	0
0.3770	0	0	0	0	0	-0.3770	0	0	0
0	0.0002	-0.0344	-0.0004	0.0323	0	0.3472	0.0011	-0.0007	0
0	-0.0004	0.0012	-0.0258	0	0.0185	0	0.0023	0.0040	0
0	0.0000	0.0017	-0.0001	-0.0020	0	0.6944	0.0001	-0.0000	0
0	-0.0000	-0.0008	0.0070	0	-0.0107	0	0.0002	0.0003	0
0	0.0000	-0.0001	0.0000	0	0	0	0.0000	-0.0001	0
0	0.0003	0.0013	-0.0002	0	0	0	-0.0348	-0.0008	0.0323
0	-0.0008	0.0008	0.0045	0	0	0	0.0027	-0.0274	0
0	0.0000	0.0001	-0.0000	0	0	0	0.0017	-0.0001	-0.0020
0	-0.0001	0.0001	0.0003	0	0	0	-0.0006	0.0070	0
0	0.0000	0.0000	-0.0001	0	0	0	-0.0001	0.0000	0
0	0	0	0	0	0	-0.3770	0	0	0
0	0.0046	0.0019	-0.0009	0	0	0	0.0025	-0.0020	0
0	-0.0048	0.0031	-0.0010	0	0	0	0.0043	-0.0025	0
0	0.0010	0.0558	0.0451	0	0	0	0.0186	0.0040	0
0	0.0008	0.0160	0.0103	0	0	0	0.0553	0.0359	0

0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
-0.0020	0	0	0	0	0	0	0	0	0
-1.5000	0	0	0	0	0	0	0	0	0
0.0041	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	-0.0020	0	0	0
0	0	0	0	0	0	-1.5000	0	0	0
0	0	0	0	0	0	0.0041	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0

Columns 21 through 30

0	0	0.0002	-0.0125	0	0	0	0.0174	0.0069	0.0125
0	0	0.0003	0	0	0	0	0	0	0
0	0	0.0000	-0.0250	0	0	0	0.0347	0.0139	0.0250
0	0	0.0000	0	0	0	0	0	0	0
0	0	0.0000	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0.0004	0	-0.0125	0	0	0	0	0
0	0	0.0003	0	0	0	0	0	0	0
0	0	0.0000	0	-0.0250	0	0	0	0	0
0	0	0.0000	0	0	0	0	0	0	0
0	0	0.0000	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0.0013	0	0	-0.0125	0	0	0	0
0	0	-0.0023	0	0	0	0	0	0	0
0	0	0.0001	0	0	-0.0250	0	0	0	0
0	0	-0.0002	0	0	0	0	0	0	0
0	0	0.0001	0	0	0	0	0	0	0
0	0.3472	-0.0014	0	0	0	-0.0125	0	0	0
0.0185	0	0.0053	0	0	0	0	0	0	0
0	0.6944	-0.0001	0	0	0	-0.0250	0	0	0
-0.0107	0	0.0004	0	0	0	0	0	0	0
0	0	-0.0001	0	0	0	0	0	0	0
0	0.3770	0	0	0	0	0	0	0	0
0	0	0.0033	-0.1000	0	0	0	0	0	0
0	0	0.0048	0	-0.1000	0	0	0	0	0
0	0	0.0072	0	0	-0.1000	0	0	0	0
0	0	-0.0007	0	0	0	-0.1000	0	0	0
0	0	0	0	0	0	0	-0.0001	0	0
0	0	0	0	0	0	0	-0.0750	-0.0500	0
0	0	0	0	0	0	0	0.0002	0.0001	-0.0002
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0

0	-0.0020	0	0	0	0	0	0	0	0
0	-1.5000	0	0	0	0	0	0	0	0
0	0.0041	0	0	0	0	0	0	0	0

Columns 31 through 39

0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0.0174	0.0069	0.0125	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0.0347	0.0139	0.0250	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0.0174	0.0069	0.0125	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0.0347	0.0139	0.0250	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0.0174	0.0069	0.0125
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0.0347	0.0139	0.0250
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
-0.0001	0	0	0	0	0	0	0	0
-0.0750	-0.0500	0	0	0	0	0	0	0
0.0002	0.0001	-0.0002	0	0	0	0	0	0
0	0	0	-0.0001	0	0	0	0	0
0	0	0	-0.0750	-0.0500	0	0	0	0
0	0	0	0.0002	0.0001	-0.0002	0	0	0
0	0	0	0	0	0	-0.0001	0	0
0	0	0	0	0	0	-0.0750	-0.0500	0
0	0	0	0	0	0	0.0002	0.0001	-0.0002

H.3.3. MatNetEig

sps.a

```
ans =

  Columns 1 through 7

       0    1.0000         0         0         0         0         0
-27.8963         0  -16.0760  -17.1477   -0.8254   -6.4597         0
 -0.0900    1.9649   -1.1312    0.9267   -0.0008   -0.0062  -37.0370
 -3.0002         0   28.9592  -35.7769   -0.0266   -0.2082         0
 -0.2354         0   -0.0969   -0.1033   -9.6169    8.5884         0
 -3.0763         0   -1.2658   -1.3501   14.3394  -27.7789         0
       0    0.0053         0         0         0         0   -0.1000
       0   -3.9789         0         0         0         0   75.0000
       0    0.0109         0         0         0         0   -0.2058
 -9.8108         0   26.2464   27.9962   -5.0405  -39.4471         0
       0         0         0         0         0         0         0
 27.9488         0    5.6365    6.0122    2.3860   18.6729         0
  0.0474         0    0.0363    0.0387    0.0001    0.0005         0
  1.5800         0    1.2104    1.2911    0.0021    0.0163         0
  0.3875         0   -0.0105   -0.0112    0.0463    0.3622         0
  5.0630         0   -0.1376   -0.1468    0.6048    4.7329         0
       0         0         0         0         0         0         0
       0         0         0         0         0         0         0
       0         0         0         0         0         0         0
 -2.7324         0    7.2491    7.7323   -1.3948  -10.9155         0
       0         0         0         0         0         0         0
  2.9238         0    0.3603    0.3843    0.2838    2.2207         0
  0.0064         0    0.0036    0.0038    0.0002    0.0017         0
  0.2149         0    0.1190    0.1269    0.0071    0.0554         0
  0.0319         0   -0.0059   -0.0062    0.0046    0.0357         0
  0.4171         0   -0.0766   -0.0817    0.0595    0.4659         0
       0         0         0         0         0         0         0
       0         0         0         0         0         0         0
       0         0         0         0         0         0         0
  0.1948         0    0.8475    0.9040   -0.1037   -0.8117         0
       0         0         0         0         0         0         0
  4.6328         0    0.8163    0.8708    0.4131    3.2327         0
  0.0086         0    0.0058    0.0062    0.0001    0.0011         0
  0.2873         0    0.1923    0.2051    0.0045    0.0354         0
  0.0578         0   -0.0046   -0.0049    0.0074    0.0575         0
  0.7555         0   -0.0597   -0.0637    0.0961    0.7519         0
       0         0         0         0         0         0         0
       0         0         0         0         0         0         0
       0         0         0         0         0         0         0
 -0.1999         0    1.2187    1.2999   -0.2045   -1.6007         0

  Columns 8 through 14

       0         0         0         0         0         0         0
       0         0         0   26.0287         0    1.8658    1.9902
 14.8148   26.6667  -26.6667    0.0686         0    0.0336    0.0359
```

0	0	0	2.2856	0	1.1213	1.1961
0	0	0	0.2724	0	-0.0787	-0.0840
0	0	0	3.5592	0	-1.0287	-1.0972
0	0	0	0	0	0	0
-50.0000	0	0	0	0	0	0
0.0823	-0.1852	0	0	0	0	0
0	0	-100.0000	4.6162	0	8.7881	9.3740
0	0	0	0	1.0000	0	0
0	0	0	-32.2656	0	-19.1339	-20.4095
0	0	0	-0.0821	1.9649	-1.1383	0.9191
0	0	0	-2.7356	0	28.7229	-36.0289
0	0	0	-0.3567	0	-0.1300	-0.1387
0	0	0	-4.6606	0	-1.6990	-1.8122
0	0	0	0	0.0053	0	0
0	0	0	0	-3.9789	0	0
0	0	0	0	0.0109	0	0
0	0	0	-4.8189	0	26.0198	27.7544
0	0	0	0	0	0	0
0	0	0	4.2172	0	0.1537	0.1640
0	0	0	0.0117	0	0.0051	0.0055
0	0	0	0.3898	0	0.1715	0.1829
0	0	0	0.0376	0	-0.0153	-0.0163
0	0	0	0.4913	0	-0.1997	-0.2130
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0.9912	0	1.4363	1.5321
0	0	0	0	0	0	0
0	0	0	6.8938	0	0.6686	0.7132
0	0	0	0.0165	0	0.0086	0.0092
0	0	0	0.5498	0	0.2868	0.3059
0	0	0	0.0733	0	-0.0172	-0.0184
0	0	0	0.9579	0	-0.2249	-0.2398
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0.7841	0	2.1426	2.2854

Columns 15 through 21

0	0	0	0	0	0	0
2.7361	21.4133	0	0	0	0	1.0857
0.0031	0.0240	0	0	0	0	0.0087
0.1021	0.7988	0	0	0	0	0.2908
0.0428	0.3351	0	0	0	0	-0.0087
0.5594	4.3781	0	0	0	0	-0.1135
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
-0.7353	-5.7546	0	0	0	0	1.9186
0	0	0	0	0	0	0

-0.9641	-7.5454	0	0	0	0	2.2176
0.0013	0.0098	-37.0370	14.8148	26.6667	-26.6667	0.0138
0.0418	0.3270	0	0	0	0	0.4614
-9.6263	8.5149	0	0	0	0	-0.0027
14.2167	-28.7389	0	0	0	0	-0.0348
0	0	-0.1000	0	0	0	0
0	0	75.0000	-50.0000	0	0	0
0	0	-0.2058	0.0823	-0.1852	0	0
-4.3117	-33.7434	0	0	0	-100.0000	2.7222
0	0	0	0	0	0	0
0.4648	3.6373	0	0	0	0	-30.9930
0.0006	0.0048	0	0	0	0	-0.0895
0.0203	0.1585	0	0	0	0	-2.9847
0.0065	0.0512	0	0	0	0	-0.2636
0.0855	0.6695	0	0	0	0	-3.4445
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
-0.0928	-0.7266	0	0	0	0	-8.3537
0	0	0	0	0	0	0
0.6995	5.4744	0	0	0	0	27.1449
0.0007	0.0052	0	0	0	0	0.0547
0.0221	0.1729	0	0	0	0	1.8219
0.0109	0.0857	0	0	0	0	0.3244
0.1431	1.1196	0	0	0	0	4.2386
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
-0.2187	-1.7115	0	0	0	0	0.0527

Columns 22 through 28

0	0	0	0	0	0	0
0	-0.7031	-0.7500	0.2347	1.8364	0	0
0	0.0015	0.0015	0.0008	0.0062	0	0
0	0.0484	0.0516	0.0265	0.2072	0	0
0	-0.0187	-0.0199	0.0019	0.0145	0	0
0	-0.2438	-0.2600	0.0242	0.1895	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0.8479	0.9044	0.0935	0.7319	0	0
0	0	0	0	0	0	0
0	-0.8823	-0.9412	0.3942	3.0852	0	0
0	0.0030	0.0032	0.0012	0.0090	0	0
0	0.1006	0.1073	0.0384	0.3002	0	0
0	-0.0272	-0.0290	0.0039	0.0303	0	0
0	-0.3554	-0.3791	0.0505	0.3954	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0

0	1.4025	1.4960	0.1021	0.7987	0	0
1.0000	0	0	0	0	0	0
0	-18.3886	-19.6145	-0.7900	-6.1824	0	0
1.9649	-1.1326	0.9252	-0.0001	-0.0011	-37.0370	14.8148
0	28.9133	-35.8258	-0.0045	-0.0354	0	0
0	-0.1111	-0.1185	-9.6197	8.5666	0	0
0	-1.4519	-1.5487	14.3031	-28.0630	0	0
0.0053	0	0	0	0	-0.1000	0
-3.9789	0	0	0	0	75.0000	-50.0000
0.0109	0	0	0	0	-0.2058	0.0823
0	25.9302	27.6588	-4.9580	-38.8018	0	0
0	0	0	0	0	0	0
0	4.3857	4.6781	2.4924	19.5056	0	0
0	0.0339	0.0362	0.0012	0.0091	0	0
0	1.1316	1.2070	0.0387	0.3026	0	0
0	-0.0348	-0.0371	0.0432	0.3379	0	0
0	-0.4547	-0.4851	0.5642	4.4158	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	7.4195	7.9141	-1.1337	-8.8725	0	0

Columns 29 through 35

0	0	0	0	0	0	0
0	0	0.7820	0	-1.4035	-1.4971	0.3046
0	0	0.0127	0	0.0011	0.0012	0.0013
0	0	0.4239	0	0.0364	0.0388	0.0446
0	0	-0.0283	0	-0.0311	-0.0331	0.0014
0	0	-0.3693	0	-0.4059	-0.4330	0.0177
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	3.2761	0	1.1610	1.2384	0.2115
0	0	0	0	0	0	0
0	0	2.0992	0	-1.9021	-2.0289	0.5357
0	0	0.0208	0	0.0030	0.0032	0.0020
0	0	0.6942	0	0.0993	0.1059	0.0670
0	0	-0.0281	0	-0.0469	-0.0501	0.0038
0	0	-0.3675	0	-0.6133	-0.6541	0.0493
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	4.8291	0	1.9947	2.1277	0.2689
0	0	0	0	0	0	0
0	0	23.8519	0	0.3880	0.4139	2.7596
26.6667	-26.6667	0.0714	0	0.0297	0.0317	0.0039
0	0	2.3800	0	0.9914	1.0575	0.1313
0	0	0.1941	0	-0.0977	-0.1042	0.0377
0	0	2.5361	0	-1.2766	-1.3617	0.4927
0	0	0	0	0	0	0

0	0	0	0	0	0	0
-0.1852	0	0	0	0	0	0
0	-100.0000	7.1677	0	8.5976	9.1708	-0.4532
0	0	0	1.0000	0	0	0
0	0	-38.6715	0	-23.2594	-24.8100	-1.0521
0	0	-0.0798	1.9649	-1.1421	0.9151	0.0029
0	0	-2.6590	0	28.5982	-36.1620	0.0968
0	0	-0.4555	0	-0.1609	-0.1716	-9.6328
0	0	-5.9520	0	-2.1022	-2.2424	14.1317
0	0	0	0.0053	0	0	0
0	0	0	-3.9789	0	0	0
0	0	0	0.0109	0	0	0
0	0	-0.6368	0	25.6784	27.3903	-3.9582

Columns 36 through 40

0	0	0	0	0
2.3840	0	0	0	0
0.0105	0	0	0	0
0.3489	0	0	0	0
0.0106	0	0	0	0
0.1389	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
1.6554	0	0	0	0
0	0	0	0	0
4.1921	0	0	0	0
0.0157	0	0	0	0
0.5245	0	0	0	0
0.0295	0	0	0	0
0.3859	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
2.1048	0	0	0	0
0	0	0	0	0
21.5966	0	0	0	0
0.0308	0	0	0	0
1.0275	0	0	0	0
0.2951	0	0	0	0
3.8558	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
-3.5468	0	0	0	0
0	0	0	0	0
-8.2336	0	0	0	0
0.0227	-37.0370	14.8148	26.6667	-26.6667
0.7574	0	0	0	0
8.4639	0	0	0	0

-29.4044	0	0	0	0
0	-0.1000	0	0	0
0	75.0000	-50.0000	0	0
0	-0.2058	0.0823	-0.1852	0
-30.9775	0	0	0	-100.0000

I. PSAT AVR excitation system block diagrams [17]

PSAT simulation tool has three AVR excitation systems [17]. The block diagrams in for type I, type II and type III are shown below for reference, these were taken from the PSAT 2.0.0 user manual.

I.1. PSAT AVR type I

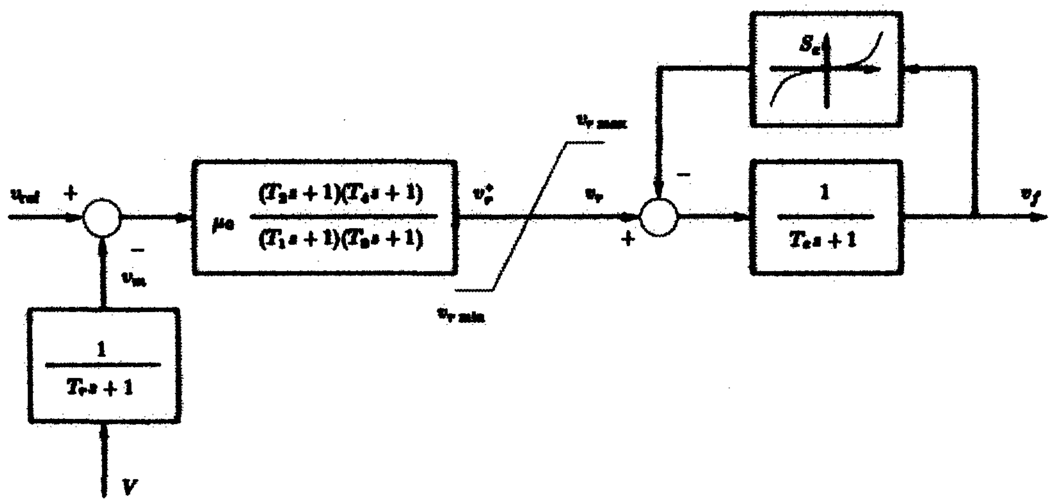


Figure I.1: AVR type I [17]

I.2. PSAT AVR type II

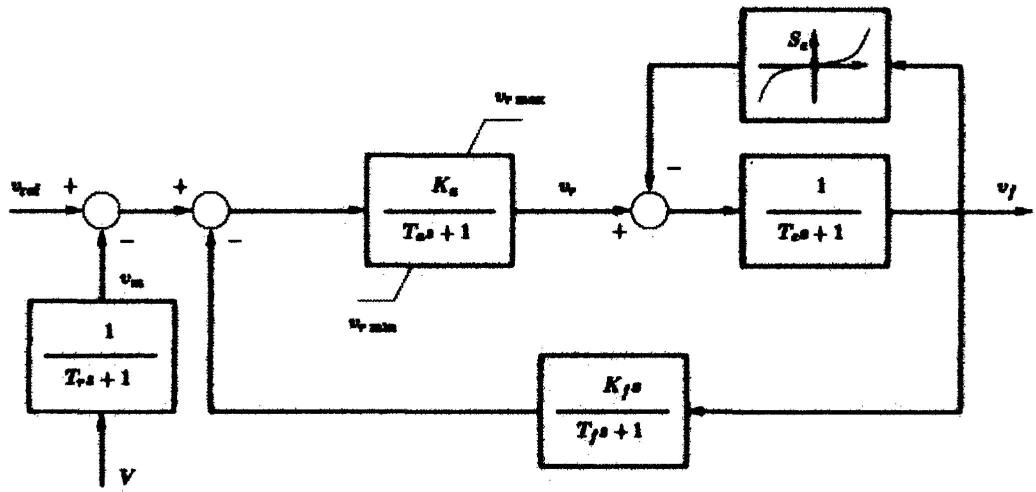


Figure I.2: AVR type II [17]

I.1. PSAT AVR type III

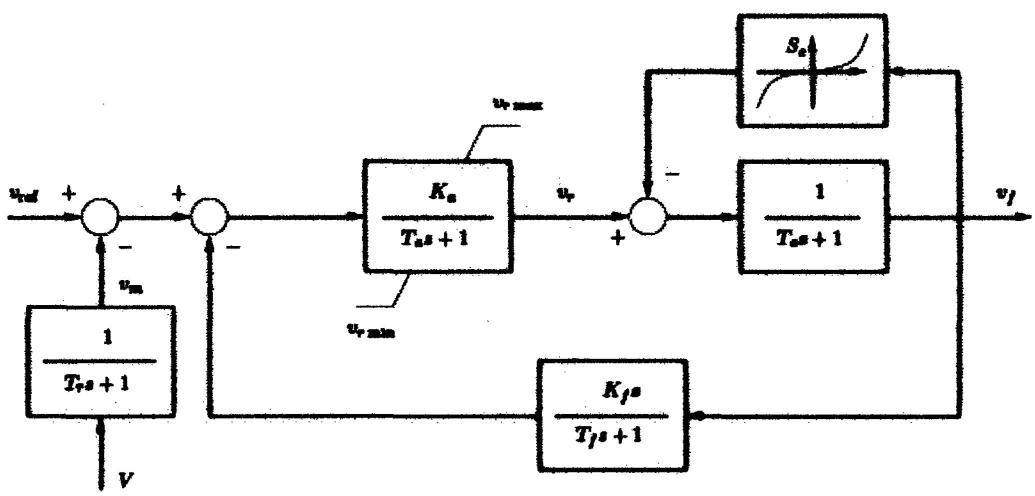


Figure I.3: AVR type III [17]

J. Author's publications

I wrote three conference papers that were submitted to the conference review committees for presentation and publications. One paper was presented submitted to SAUPEC 2009 conference review committee and accepted as a discussion paper. The second paper was submitted to IEEE Africon 2009 conference; it was accepted, presented and published on the IEEE Explore. The last paper summarising the dissertation is submitted to the SAUPEC 2010 conference. The details of all three papers are as follows:

J.1. SAUPEC 2009, Stelenbosch, South Africa

DS. Mudau, KA. Folly, "Effect of initial angle estimate on the convergence of Newton-Raphson method used for load flow studies", Discussion paper presented during the conference, SAUPEC, University of Stellenbosch, Stellenbosch, South Africa, 2009

J.2. IEEE AFRICON 09, Nairobi, Kenya

DS. Mudau, KA. Folly, K. Awodele, "User defined controllers in power system stability analysis using PacDyn 8.1.1 simulation tool", Paper submitted to IEEE AFRICON (peer reviewed, presented at the conference and published), Nairobi, Kenya, 23–25 September 2009.

J.3. SAUPEC 2010, University of the Witwatersrand, Johannesburg, South Africa

DS. Mudau, KA. Folly, K. Awodele, "Effects of variations in mathematical modelling of synchronous machine saturation on small-signal stability analysis", Paper submitted to SAUPEC 2010 for 28–29 January 2010 SAUPEC conference, Wits University, RSA.