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PSAT

Power System Analysis
Toolbox

Introduction to PSAT:

A toolbox for Education and Research in Electric Power Engineering

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Outline I

1

Motivation

- Acknowledgment
- Main goals of this presentation
- Note

2

The Power System Analysis Toolbox (PSAT)

- PSAT Basics
- Available Models and Routines in the PSAT
 - Power System Model
 - Power Flow
 - Bifurcation Analysis
 - Optimal Power Flow
 - Small Signal Stability
 - Time Domain Simulations
- Case Studies
 - PSAT Routines
 - GAMS and UWPFLOW Interfaces

3

The PSAT as an Educational and Research Tool



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Outline II

- PSAT in learning, education and research
- Summary of the main subjects discussed in this talk
- Thanks!
- References

Acknowledgment

Many, many thanks!

- This talk is *mostly based* on the course *Power System Analysis in an Electricity Markets Environment* lectured by Dr. Federico Milano [1] of the University of Castilla-La Mancha, Spain; the *PSAT Documentation* [2], the *PSAT Version 1.3.4* [3] and in [4, 5].



Main Goals of this presentation

PSAT in your everyday life: an Educational and Research Tool

- To give a broad view of the PSAT and it's capabilities
- To demonstrate the use of some of the routines and models which are currently in the PSAT
- To show the capabilities of the PSAT through examples
- To present the use of the PSAT as a tool suitable of education and research
- To *encourage* **YOU** to use the PSAT as an everyday tool!

Note

- This presentation was elaborated using previous PSAT (Power System Analysis Toolbox) versions (older than 2.0).
- Even though most of the contents of this presentation still apply for version 2.0., there might be differences with the latest distribution.
- ... therefore, complaints will be sent to /dev/null

PSAT 1.3.4

Power Analysis Toolbox



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What is the PSAT? I

Power system analysis and control at your fingertips!

- PSAT is an open code Matlab based toolbox for electric power system analysis and control.
- PSAT can handle a wide variety of Power Systems: from small scale educational networks to medium size realistic power systems.
- PSAT is also GNU Octave compatible in it's command line version.
- Being PSAT and open code software it is suitable for research since it allows to modify the existing models/routines and/or to include new models/routines.
- The GUIs and Simulink library make it easy to use, thus, it's adequate for educational purposes such as teaching and self study; besides being free!

What is the PSAT? II

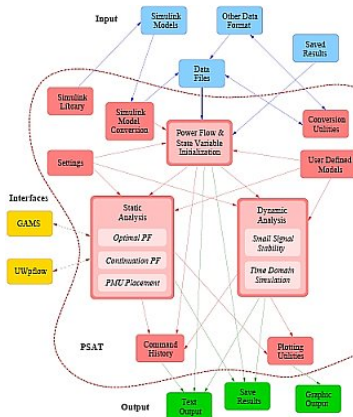
Power system analysis and control at your fingertips!

- PSAT makes a full use of Matlab vectorized computations and sparse matrix functions, this gives an optimal performance.



Structure of the PSAT

Scheme of the PSAT



Synoptic scheme

The figure presents the synoptic scheme of the PSAT. It can be observed that the Power Flow algorithm is used as the PSAT kernel, thus, this routine is needed to initialize the dynamic models for:

- 1 CPF (Continuation Power Flow)
- 2 OPF (Optimal Power Flow)
- 3 SSS (Small Signal Stability)
- 4 TDA (Time Domain Simulations)

PSAT Features

Available Routines in the PSAT

- PSAT has a wide number of available routines, such as:
 - Power Flow
 - Bifurcation Analysis (i.e. Continuation Power Flow)
 - Optimal Power Flow
 - SSS (Small Signal Stability Analysis)
 - Time Domain Simulations
 - Phasor measurement unit (PMU) Placement

PSAT Features

Available Models in the PSAT

- PSAT also has a broad number of static and dynamic models in order to perform thorough power system analysis:
 - Power Flow Data
 - Market Data
 - Switches
 - Measurements
 - Loads
 - Machines
 - Controls
 - Regulating Transformers
 - FACTS: SVCs, TCSCs, SSSCs, UPFCs
 - Wind Turbines
 - Other Models



PSAT Features

PSAT's Additional Tools

Tools:

In addition to the mathematical algorithms and models available, the PSAT also provides a variety of tools:

- 1 User friendly graphical user interfaces
- 2 A Simulink library useful to built one-line network diagrams
- 3 Data file conversion to and from other formats
- 4 User defined model editor and installer
- 5 Command line version

Due to the current limitation of GNU/Octave not all the tools are available for use in this platform.

Available Tools in Matlab and GNU/Octave

Function	Matlab	GNU/Octave
Continuation power flow	yes	yes
Optimal power flow	yes	yes
Small signal stability analysis	yes	yes
Time domain simulation	yes	yes
GUIs and Simulink library	yes	no
Data format conversion	yes	yes
User defined models	yes	no
Command line usage	yes	yes

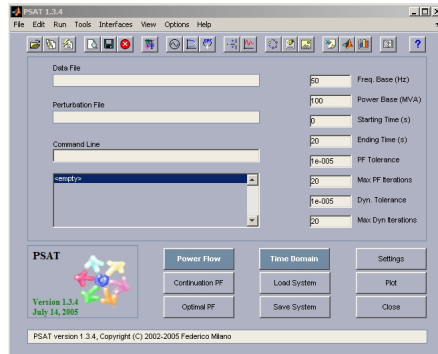


PSAT Features

Main GUI

Main GUI Features

- Once the PSAT is launched by typing » `psat` in the Matlab Command Window the Main GUI will be launched. By typing the above command all the required structures required by the toolbox are created.
- This GUI provides easy access to all the tools of the PSAT. This GUI provides also the possibility of assigning the main settings, such as: No. of iterations of the NR methods, system base values, etc.
- Moreover, PSAT does not rely in this GUIs and uses global variables to store the setting parameters of the routines and data for the models. Thus, allowing the PSAT to run in the command line version.

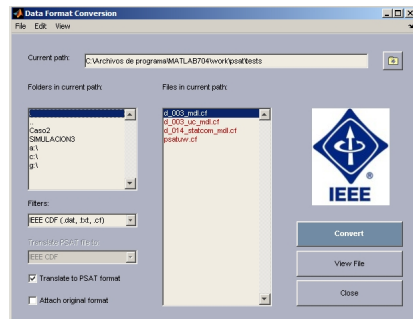


PSAT Features

Data Format Conversion (DFC) Features

DFC Features

- Both the DFC tool and the UDMs tool are aimed to promote contributions from the users, to enhance research capabilities and to ensure portability.
- The DFC functions are handled by means of a user friendly GUI (Matlab only)
- The DFC functions allow data file conversion from commonly used power system analysis commercial and research/educational formats to the PSAT and IEEE CDF formats.
- Currently, the PSAT can convert the data files of many programs, such as: IEEE CDF, CYME, MatPower, PST, EPRI WECC, SPP/E, PSAP, Eurostag, EPRI BPA, Tsinghua University, INPTC1 (Enel), VST, Simpow, Neplan, DigSilent, PowerWorld, PET and GE.



PSAT Features I

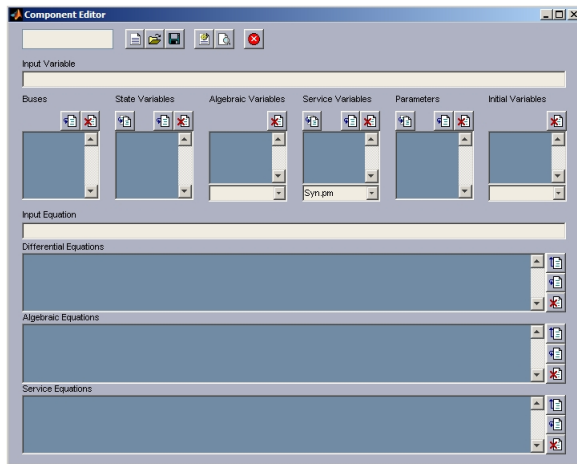
UDM (User Defined Models) GUI

User Defined Models (UDM) Features

- Both the DFC tool and the UDMs tool are aimed to promote contributions from the users, to enhance research capabilities and to ensure portability.
- The main aim of the UDM tool is to extend the capabilities of PSAT and assist end users with little programming capabilities to build and set up their own models.
- The UDM is only available in Matlab platforms since it makes use of the Symbolic Math Toolbox of Matlab.
- The first step is to introduce the variables and the system of Differential-Algebraic-Equations that describe the new model in the GUI of the UDM.
- PSAT then automatically compiles the equations, computes the symbolic expression of the Jacobian matrices and writes a Matlab function file for the new component.
- The user can save the model definition and/or install the model in PSAT.
- The UDM also has a Model Uninstaller, thus, when the model is not longer needed it can be safely uninstalled.
- This tool is at an early stage, but its conception ensures remarkable future capabilities.

PSAT Features II

UDM (User Defined Models) GUI

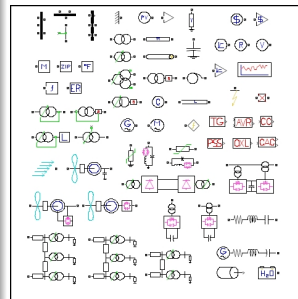


PSAT Features

Simulink Library

Simulink Library Features

- PSAT provides a Simulink graphical model library that enables the user to draw one-line network diagrams using pictorial blocks.
- The PMC (Physical Model Component) library of PSAT provides a complete set of Simulink blocks for network design, which are grouped as follows: connections, power flow data, OPF & CPF data, faults & breakers, measurements, loads, machines, controls, regulating transformers, FACTS, wind turbines, other models, and sub-transmission equivalent areas respectively.
- The PSAT is Matlab based and the Simulink environment is used only as a graphical tool.
- Thus, running time domain simulations from the Simulink model menus produces no effect, since no Simulink dynamic model is associated with PSAT blocks.
- Simulink network models built with the PCM library are read by PSAT to exploit the network topology and extract component data.
- An advantage of this approach is that the PSAT can run on GNU/Octave, which doesn't provide a Simulink environment.

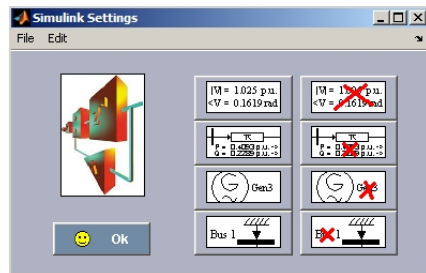


PSAT Features

Simulink Library

Displaying Results in Simulink Models

- After solving the power flow, there are many ways in which the results can be visualized.
- The PCM allows to display results such as the bus voltage magnitude and angle, and the power flow values within the Simulink model of the system.
- This is done through a user friendly GUI.
- This GUI also allows to export the Simulink models to EPS (Encapsulated Post Script) files.



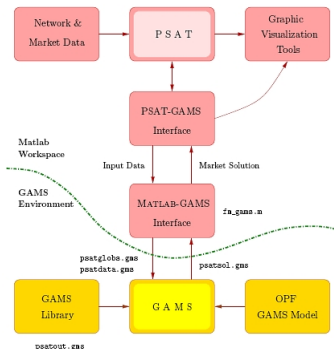
PSAT Features

Command Line Usage

- The command line version of PSAT is an adequate option when using the available routines (such as power flow) inside user defined routines.
- Thus, this allows the user to custom made routines that not rely on the PSAT GUI's, making it flexible and adequate for research.
- This feature allows using PSAT in the following conditions:
 - If is not possible or slow to visualize the graphic environment
 - When the user needs to write scripts that include the use of PSAT routines within custom made programs
 - When running PSAT on GNU/Octave, which currently does not provide a Simulink-like environment.

PSAT Features

Interface with GAMS



PGI (PSAT-GAMS Interface)

PSAT provides a graphical interface with GAMS (Generalized Algebra Modeling System) with the following purposes:

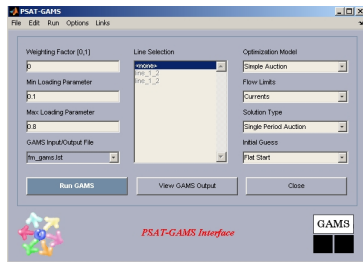
- To set up large scale power system test cases
- To solve OPF problems
- To visualize results by means of a user friendly GUI.

Also, the PGI has several improvements in comparison with the interface presented in [7]:

- The PGI is platform independent
- The PGI has a user friendly GUI
- The PGI does not require the user to have knowledge of Matlab or GAMS programming.

PSAT Features

Interface with GAMS



PSAT-GAMS Interface Gui

In order to make friendly the use of the interface between the PSAT and GAMS a GUI is used to perform the following tasks:

- Select the market clearing model
- Set the market model parameters
- Display the results from GAMS

PSAT Features

Interface with GAMS

Details of the use of the PGI:

- The first step is producing the data that describes the power system, this can be done by creating an on-line diagram with the Simulink library, writing a data file with the appropriate data format or loading a predefined model from the PSAT test cases.
- Next, the power flow routine must be run in order to store all the initial values and useful results.
- After running the power flow, the PSAT-GAMS interface can be opened to run the GAMS solver.

PSAT Features

Interface with GAMS

Internal functioning of the PGI:

- The system information is translated to a GAMS file named: `psatdata.gms`.
- The user settings as market clearing model, and global variables as the number of bus are written to the file `psatglobals.gms`.
- Once this data files have been written, GAMS is launched and the market clearing mechanism is solved.
- The routine `fm_gams.gms` used for solving the market procedures was designed to be general and without any limits except those derived from the GAMS solver and the computer memory.
- The output of the results from GAMS are stored in the file `psatso1.m` which is sent to Matlab in order to visualize the results and to perform further analysis with PSAT routines or custom user code.



PSAT Features

Interface with GAMS

Market Clearing Mechanisms Models

Currently, the PGI provides five optimization problems:

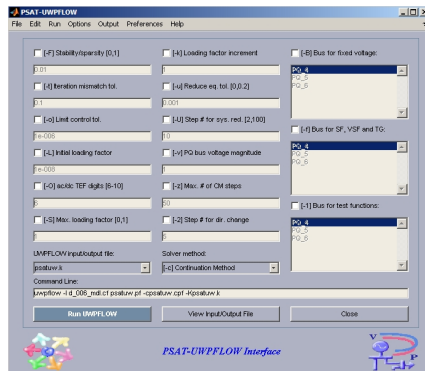
- Simple Auction
- Simplified market clearing mechanism
- Standard Optimal Power Flow (OPF)
- Voltage Stability Constrained Optimal Power Flow (VSC-OPF)
- Maximization of the maximum loading condition

PSAT Features

Interface with UWPFLOW

UWPFLOW Interface Features)

- UWPFLOW is a "commercial-grade" continuation power flow program, that can be used to research static voltage stability phenomena in detailed AC-HVDC-FACTS power system models. As PSAT, is open code and of free distribution, it can downloaded from: <http://thunderbox.uwaterloo.ca/>
- UWPFLOW consists of a set of C functions and libraries designed for voltage stability analysis of power systems, including voltage dependent loads, HVDC, FACTS and secondary voltage control.
- The UWPFLOW can be installed in Linux, Unix and Windows platforms; the installation in Windows is not straight forward, nevertheless, help is provided in the documentation and PSAT Forum.
- The UWPFLOW-PSAT Interface comes with an GUI. This GUI allows the user to set the desired settings and then run the UWPFLOW routines.
- This GUI also can be used to generate the command line used by UWPFLOW.



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PSAT Forum

Get Help and Report Bugs

Features of the PSAT Forum

- Currently, there is a PSAT Forum at: <http://groups.yahoo.com/groups/psatforum>
- This Forum is used also as a mail list and data repository.
- The member list of the Forum keeps growing, currently there are 540 members.
- You can use this Forum to report bugs, ask questions related to the PSAT; to download the latest PSAT distribution, data files, and to make your own contributions!

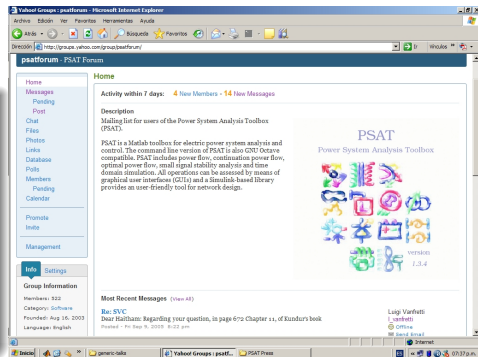


Figure: August 16, 2005 **Rensselaer**

PSAT Models & Routines

PSAT Routines

As pointed out earlier, the PSAT has the following available routines:

- Power Flow
- Bifurcation Analysis (Continuation Power Flow)
- Optimal Power Flow
- SSS (Small Signal Stability Analysis)
- Time Domain Simulations
- Phasor measurement unit (PMU) Placement

PSAT Models & Routines

Static and Dynamic Models Available in the PSAT

As pointed out earlier, the PSAT has the following static and dynamic models in order to do thorough power system analysis:

- Power Flow Data
- Market Data
- Switches
- Measurements
- Loads
- Machines
- Controls
- Regulating Transformers
- FACTS: SVCs, TCSCs, SSSCs, UPFCs
- Wind Turbines

PSAT Models & Routines

Static and Dynamic Models Available in the PSAT

- Other Models: synchronous machine dynamic shaft, sub-synchronous resonance model, solid oxide fuel cell, and sub-transmission area equivalents

Each of the models mentioned have an explications in the PSAT Documentation [2], since the aim of this talk to give a broad view of the PSAT, these models will not be discussed in detail.

PSAT Models & Routines I

Power System Model

The power system model is formed by a system of **D**ifferential **A**lgebraic **E**quations (DAE):

$$\begin{aligned}\dot{x} &= f(x, y, p) \\ 0 &= g(x, y, p)\end{aligned}\tag{1}$$

where x are state variables, y are the algebraic variables, p are the independent variables, f are differential equations, and g are algebraic equations. PSAT makes use of (1) in all the algorithms (routines) mentioned earlier.

The algebraic equations g are obtained from the sum of all the active and reactive power injections in each bus:

$$g(x, y, p) = \begin{bmatrix} g_p \\ g_q \end{bmatrix} = \begin{bmatrix} g_{pm} \\ g_{qm} \end{bmatrix} - \sum_{c \in C_m} \begin{bmatrix} g_{pc} \\ g_{qc} \end{bmatrix} \quad \forall m \in M \tag{2}$$

PSAT Models & Routines II

Power System Model

where g_{pm} and g_{qm} are the power flows in the transmission lines, M is the set of network buses, C_m and $[g_{pc}^T \ g_{qc}^T]^T$ are the set and the power injections of the power system components connected at bus m , respectively.



PSAT Models & Routines III

Power System Model

One of the most important characteristics of PSAT is that is component-oriented, this means that any component is defined independently of the rest of the program as a set of nonlinear differential-algebraic equations:

$$\begin{aligned}\dot{x}_c &= f_c(x_c, y_c, p_c) \\ P_c &= g_{pc}(x_c, y_c, p_c) \\ Q_c &= g_{qc}(x_c, y_c, p_c)\end{aligned}\tag{3}$$

where x_c are the component state variables; y_c the algebraic variables such as the voltage V and the angle θ at the buses where the element is connected; and p_c are independent variables.

- Afterwards, the differential equations f of (1) are built concatenating f_c of each of the components of the Power System.



PSAT Models & Routines IV

Power System Model

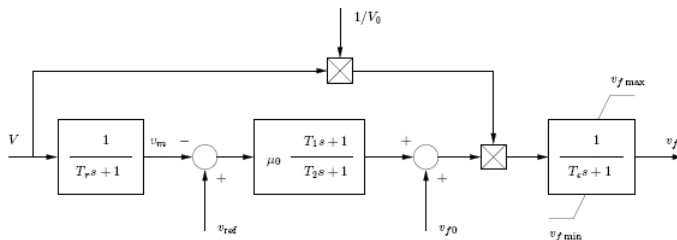
- The equations presented in (3) simultaneously with the Jacobian matrices are defined in a function which is used for static and dynamic analysis by means of a structure, which contains data, parameters and the interconnection & grid topology.



PSAT Models & Routines V

Power System Model

- As an example of the above mentioned, let us consider the mathematical model of an AVR. The PSAT has three types of models for different kinds of AVR, for this example, we can consider a very simple AVR that can be modeled and simulated by the AVR Type III model provided by PSAT.



PSAT Models & Routines VI

Power System Model

- The differential Algebraic Equations of the model are the following [2]:

$$\begin{aligned}
 \dot{V}_m &= \frac{(V - V_m)}{T_r} \\
 \dot{V}_r &= \frac{\mu_0 \left(1 - \frac{T_1}{T_2}\right) (V_{ref} - V_m) - V_r}{T_2} \\
 \dot{V}_f &= \frac{\left(V_r + \mu_0 \frac{T_1}{T_2} (V_{ref} - V_m) + V_{f0}\right) \frac{V}{V_0} - V_f}{T_2}
 \end{aligned} \tag{4}$$

- The next slide presents two tables. The first presents the parameters for the AVR Type III, the other presents all the fields of the structure Exc.con that defines the AVRs inside the PSAT.

PSAT Models & Routines VII

Power System Model

Exciter Type III Data Format (Exc.con)

Column	Variable	Description	Unit
1	-	Generator number	internal
2	3	Exciter type	internal
3	V_{fmax}	Maximum field voltage	p.u.
4	V_{fmin}	Minimum field voltage	p.u.
5	μ_0	Regulator gain	s
6	T_2	Regulator pole	s
7	T_1	Regulator zero	p.u.
8	V_{f0}	Field voltage offset	p.u.
9	V_0	Bus voltage offset	-
10	-	<i>not used</i>	-
11	T_r	Measurement time constant	s

Fields of the Exc.con structure

- 1 con : data chart of the Exc components.
- 2 n : total number of AVRs.
- 3 syn : generator numbers.
- 4 vrif : reference voltage V_{ref} .
- 5 vrif0 : reference voltage V_{ref0} *initial value*.
- 6 vr1 : indexes of state variable V_{r1} .
- 7 vr2 : indexes of state variable V_{r2} .
- 8 vr3 : indexes of state variable V_{r3} .
- 9 vm : indexes of state variable V_m .
- 10 vf : indexes of state variable V_f .



PSAT Models & Routines I

Power Flow

PSAT provides several options to solve power flow, namely:

- Newton-Raphson method
- Fast Decoupled Power Flow (XB and BX)
- Power Flow with a distributed slack bus model

The theory of these methods, in which PSAT bases the models and routines, are presented in [16, 25, 26].

The distributed slack bus model power flow is a feature which it's only available in PSAT among other Matlab based power system programs.

PSAT Models & Routines II

Power Flow

The power flow problem is formulated as (1) with zero first time derivatives $\dot{x}$:

$$\begin{aligned} 0 &= f(x, y, p) \\ 0 &= g(x, y, p) \end{aligned} \tag{5}$$

Differential equations are included in 5; some dynamic components as synchronous machines are initialized after the power flow analysis, this is due to the fact that the user does not know the input parameters of its dynamic model. Other models, such as load tap changers, can be included in the power flow as one typically knows the input parameters of the dynamic model.

PSAT Models & Routines III

Power Flow

- The distributed slack bus model is based in the concept of generalized power centers and consists in distributing losses among all generators, the theory behind this method is presented in [26].
- The loss distribution among the generators is obtained by rewriting the active powers P_G of the slack bus and PV generator as following:

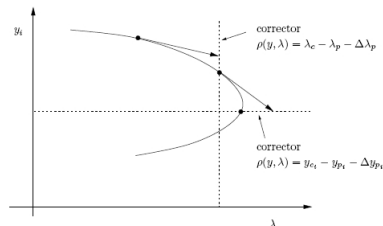
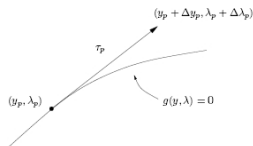
$$P_G = (1 + k_G \gamma) P_{G_0} \quad (6)$$

- where P_{G_0} are the desired generator active powers, k_G is scalar variable which distributes power losses among all generators and γ are the participation factors of the generators to the total losses.
- k_G is an unknown insofar as losses are unknown.
- If (6) can be written for all the generators, k_G is balanced by the phase reference equation.

PSAT Models & Routines I

Bifurcation Analysis - Continuation Power Flow (CPF)

- The PSAT includes a CPF function which is a novelty among the Matlab-based packages for power system analysis.
- The CPF algorithm consists in a predictor step which computes a normalized tangent vector and a corrector step that can be obtained either by means of a local parametrization or a perpendicular intersection.
- The theory behind the method is presented in [24]
- The images below present the method to obtain the predictor by means of a tangent and by means of local parametrization.



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PSAT Models & Routines II

Bifurcation Analysis - Continuation Power Flow (CPF)

- The CPF problem is defined based on 1:

$$\begin{aligned} 0 &= f(x, y, \lambda) \\ 0 &= g(x, y, \lambda) \end{aligned} \quad (7)$$

- Where λ is the *loading parameter*, which is used to vary the base case generation and load powers, P_{G_0} , P_{L_0} and Q_{L_0} respectively:

$$\begin{aligned} P_G &= (\lambda + \gamma k_G) P_{G_0} \\ [P_L, Q_L] &= \lambda [P_{L_0}, Q_{L_0}] \end{aligned} \quad (8)$$

- The PSAT also provides Direct Methods (DM) for computing Saddle-Node Bifurcation (SNB) points and Limit-Induced Bifurcation (LIB) points; this option will not be discussed here.



PSAT Models & Routines I

Optimal Power Flow (OPF)

- The Optimal Power Flow (OPF) is defined as a nonlinear constrained optimization problem. PSAT uses the Interior Point Method (IPM) with a Mehrotra's predictor-corrector method to solve the OPF problem.
- PSAT is the only Matlab-based program that provides an IPM algorithm to solve OPF based market clearing mechanisms.
- PSAT also provides several objective functions:
 - the maximization of the social benefit
 - the maximization of the distance to the maximum loading condition
 - A multi-objective approach

PSAT Models & Routines II

Optimal Power Flow (OPF)

- Here it will only be discussed the "standard" OPF which uses the maximization of the social as objective function.
- Nevertheless, it should be noted that it the VSC (Voltage Stability Constrained) OPF that maximizes the distance to the maximum loading condition and the multi-objective approach are also available to perform analysis in the psat



PSAT Models & Routines III

Optimal Power Flow (OPF)

Standard OPF Model

- The standard OPF commonly has the goal of maximizing the social benefit. The model is represented in PSAT as follows:

$$\begin{aligned}
 &\text{Minimize}_{(y,p)} && F(p) \\
 &\text{Subject to} && g(y,p) = 0 \\
 & && h_{\min} \leq h(y) \leq h_{\max} \\
 & && p_{\min} \leq p \leq p_{\max}
 \end{aligned} \tag{9}$$

- where g and y are defined as in 1, the control variables p are the power demand and supply bids P_D and P_S , while F and h are the inequality constraints, respectively.

PSAT Models & Routines IV

Optimal Power Flow (OPF)

- The goal is to maximize the social benefit, thus, the objective function F is defined as:

$$F = - \left(\sum_i C_{D_i} (P_{D_i}) - \sum_i C_{S_i} (P_{S_i}) \right) \quad (10)$$

- where C_S and C_D are quadratic functions of supply and demand bids, respectively.

PSAT Models & Routines V

Optimal Power Flow (OPF)

- The physical and security limits h included in PSAT are similar to what is used in [12], and take into account the following limits:
 - Transmission line thermal limits
 - Transmission line power flow limits
 - Transmission line power flow limits
 - Voltage security limits

PSAT Models & Routines I

Small Signal Stability (SSS)

- PSAT is also capable of performing SSS analysis, it has the option to perform both dynamic analysis and QV sensitivity analysis.
- PSAT is able to compute and plot the eigenvalues and the participation factors of the system, once the power flow has been performed.
- The eigenvalues are computed in the dynamic analysis from the state matrix of the dynamic system, for the QV sensitivity analysis they are computed from the Jacobian matrix
- A remarkable feature of this options is that the eigenvalues are computed using analytical Jacobian matrices, ensuring high precision results.
- Here, it will only be discussed the Dynamic Analysis, but it should be noted that the routine to perform QV sensitivity analysis is also available.

Dynamic Analysis



PSAT Models & Routines II

Small Signal Stability (SSS)

- The Jacobian matrix A_C of a dynamic system is defined by linearizing 5 around an operation point:

$$\begin{bmatrix} \Delta \dot{x} \\ 0 \end{bmatrix} = \begin{bmatrix} F_x & F_y \\ G_x & J_{LFV} \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} = [A_C] \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} \quad (11)$$

- where $F_x = \nabla_x f$, $F_y = \nabla_y f$, $G_x = \nabla_x g$ and $J_{LFV} = \nabla_y g$.
- Then the state matrix A_S is obtained by eliminating ∇_y , and implicitly assuming that J_{LFV} is non-singular:

$$A_S = F_x - F_y J_{LFV}^{-1} G_x \quad (12)$$

PSAT Models & Routines III

Small Signal Stability (SSS)

- The computation of all eigenvalues can be a lengthy process if the dynamic order of the system is high. Thus, PSAT is able to compute a reduced number of eigenvalues based on sparse matrix properties and eigenvalue relative values (i.e. largest or smallest magnitude, etc.)
- PSAT also computes the participation factors using right and left eigenvector matrices, as proposed in [16]

PSAT Models & Routines I

Time Domain Simulations

- PSAT also provides the option to perform time domain simulations.
- For this it uses two different integration methods (Trapezoidal rule and backward Euler) to solve 1 together using the SI (Simultaneous-implicit) method, this is also an option only available in PSAT among other Matlab-based packages for power system analysis.
- The SI method is more stable than the partitioned-explicit method which solves the differential equations and the algebraic equations separately as presented in [16].
- PSAT is able to introduce common disturbances by means of embedded functions. This embedded functions are useful to simulate common perturbations for transient analysis such as faults and breaker operations.

PSAT Models & Routines II

Time Domain Simulations

- Step perturbations can be obtained by changing parameter or variable values after completing the power flow.
- Any other disturbance can be defined through a custom made perturbation function, this functions can modify and include any global structure of the system.

Case Studies

An overview of the capabilities of PSAT through examples!

In this section an overview of the available routines of PSAT is presented through examples based in small scale power systems. The routines discussed here are the following:

- Power Flow
- Bifurcation Analysis
- OPF
- SSS
- Time Domain Simulations

Moreover, due to the fact that the available interfaces with GAMS and UWPFLOW expand the capabilities of PSAT to solve Optimal Power Flow and Continuation Power Flow problems, a simple example on the use of each of this interfaces is given.

Power Flow I

Power Flow Example

4 bus system

- Let us now solve a power flow example from [27].
- The images present the one-line diagram of the system and data from [27]
- The power system consists of four buses with PV and PQ generators.

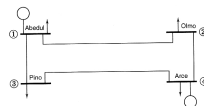


FIGURA 9.2
Diagrama unifilar para el ejemplo 9.2 en que se muestran los nombres y números de las barras.

TABLA 9.2
Datos de líneas para el ejemplo 9.2†

Líneas, de barra a barra	Serie Z		Serie $Y = Z^{-1}$		Y en paralelo	
	R por unidad	X por unidad	G por unidad	B por unidad	Mvar totales de carga†	Y / 2 por unidad
1-2	0.01008	0.05040	3.815629	-19.078144	10.25	0.05125
1-3	0.00744	0.03720	5.169561	-25.847809	7.75	0.03875
2-4	0.00744	0.03720	5.169561	-25.847809	7.75	0.03875
3-4	0.01272	0.06360	3.023705	-15.118528	12.75	0.06375

† Base 100MVA, 230 kV.

‡ A 230 kV.

TABLA 9.3
Datos de barras para el ejemplo 9.2

Barra	Generación			Carga			Observaciones
	P, MW	Q, Mvar	P, MW	Q, Mvar†	V, por unidad		
1	—	—	50	30.99	1.00	0°	Barra de compensación
2	0	0	170	105.35	1.00	0°	Barra de carga (inductiva)
3	0	0	200	123.94	1.00	0°	Barra de carga (inductiva)
4	318	—	80	49.58	1.02	0°	Voltaje controlado

† Los valores Q de la carga se calculan de los correspondientes valores de P suponiendo un factor de potencia de 0.85

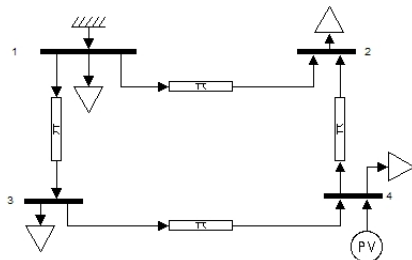


Power Flow II

Power Flow Example

Building the system in PSAT

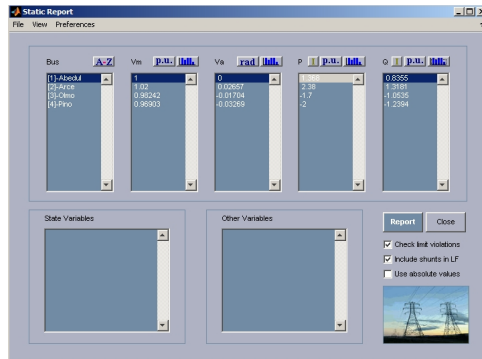
- The Simulink model library can be used to reproduce the same one-line diagram from [27].
- The images shows the resulting diagram created with the Simulink library.
- After loading the case and running the power flow routine, the results can be visualized in different ways.



Power Flow III

Power Flow Example

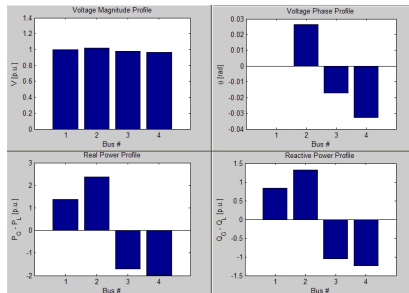
- The results can be viewed with the Static Report GUI, as depicted in the image below.



Power Flow IV

Power Flow Example

- The Static Report GUI also allows to view the results in a graphical manner by plotting the results of each field in individual graphics as depicted in the image below.



Power Flow V

Power Flow Example

- The PSAT can also produce a detailed report and export it to $\text{\LaTeX}$, Excel or plain ASCII files. The following tables, exported to a $\text{\LaTeX}$ file, show the power flow solution for the system.

Table: Network statistics

Buses:	4.00000
Lines:	4.00000
Generators:	2.00000
Loads:	4.00000

Table: Solution statistics

Number of iterations:	3.00000
Maximum p mismatch [mw]	0.00000
Maximum q mismatch [mvar]	0.00000

Table: Power flow results

Bus	V [kv]	Phase [rad]	P gen [mw]	Q gen [mvar]	P load [mw]	Q load [mvar]
Abedul	230.00000	0.00000	186.80318	114.53962	50.00000	30.99000
Arce	234.60000	0.02657	318.00000	181.38862	80.00000	49.58000
Olmo	225.95685	-0.01704	0.00000	0.00000	170.00000	109.35000
Pino	222.87705	-0.03269	0.00000	0.00000	200.00000	123.94000

Power Flow VI

Power Flow Example

Table: Line flows

From bus	To bus	Line	P flow [mw]	Q flow [mvar]	P loss [mw]	Q loss [mvar]
Abedul	Olmo	1.00000	38.70012	22.29678	0.22677	-8.93757
Pino	Arce	2.00000	-102.92301	-60.33156	1.83502	-3.44370
Abedul	Pino	3.00000	98.10306	61.25283	1.02607	-2.35561
Arce	Olmo	4.00000	133.24197	74.92076	1.71533	0.80512

Table: Line flows

From bus	To bus	Line	P flow [mw]	Q flow [mvar]	P loss [mw]	Q loss [mvar]
Olmo	Abedul	1.00000	-38.47336	-31.23436	0.22677	-8.93757
Arce	Pino	2.00000	104.75803	56.88786	1.83502	-3.44370
Pino	Abedul	3.00000	-97.07699	-63.60844	1.02607	-2.35561
Olmo	Arce	4.00000	-131.52664	-74.11564	1.71533	0.80512



Power Flow VII

Power Flow Example

Table: Total generation

Real power [mw]	504.80318
Reactive power [mvar]	295.92823

Table: Total load

Real power [mw]	500.00000
Reactive power [mvar]	309.86000

Table: Total shunt

Real power [mw]	0.00000
Reactive power (ind) [mvar]	0.00000
Reactive power (cap) [mvar]	0.00000



Power Flow VIII

Power Flow Example

Table: Total losses

Real power [mw]	4.80318
Reactive power [mvar]	-13.93177

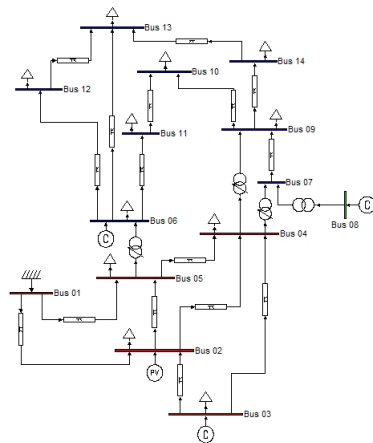


Bifurcation Analysis I

Continuation Power Flow Example

IEEE 14 Bus System

- The CPF can be computed using the CPF routine in PSAT.
- In this example we will compute the CPF for the IEEE 14 bus case.
- The Simulink model for this case is presented in the figure. Note that this data file is available with the current PSAT distribution.



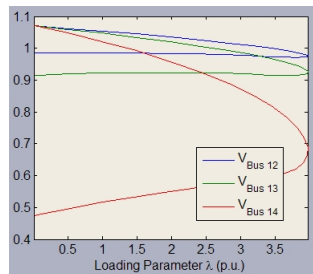
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Bifurcation Analysis II

Continuation Power Flow Example

IEEE 14 Bus System

- The graph on the right presents the nose curves of the voltage magnitude at bus 12, bus 13 and bus 14.
- Also, the PSAT is also capable of computing the $N - 1$ Contingency analysis which is based in the CPF.
- The following tables illustrate the results of the $N - 1$ contingency analysis for the 14-bus test system. The output is organized in four columns
- The first column depicts the transmission line or transformer while the second one shows for which line outage it has been found the minimum power in that line.
- The last two columns depict the actual power flow and the power flow limit, respectively, in the transmission line or transformer.



Bifurcation Analysis III

Continuation Power Flow Example

Table: Power flow limits (1)

line	line outage	p_{ij} [p.u.]	p_{ij} max [p.u.]
2-5	3-4	0.41710	0.54883
6-12	1-5	0.08037	0.09970
12-13	5-6	0.01857	0.02231
6-13	1-5	0.18272	0.22162
6-11	2-5	0.08180	0.10049
11-10	6-11	0.04565	0.05683
9-10	2-4	0.04487	0.05405
9-14	4-9	0.08719	0.10655
14-13	1-2	0.06371	0.07546
7-9	1-5	0.27203	0.37929



Bifurcation Analysis IV

Continuation Power Flow Example

Table: Power flow limits (2)

line	line outage	p_{ij} [p.u.]	p_{ij} max [p.u.]
1-2	5-6	1.57122	1.94547
3-2	5-6	0.73462	0.92663
3-4	7-9	0.23472	0.31835
1-5	7-9	0.75460	1.01484
5-4	3-4	0.60190	0.78458
2-4	5-6	0.55939	0.72114
5-6	1-5	0.45689	0.55747
4-9	1-5	0.15504	0.21438
4-7	1-5	0.27203	0.37929
8-7	1-5	0.00000	0.00000

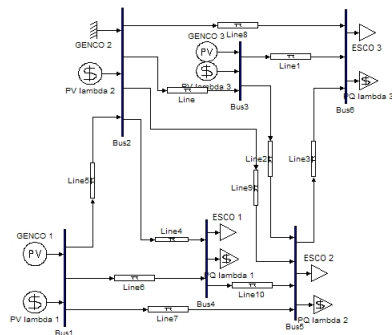


Optimal Power Flow I

OPF Example

6 Bus Test Case

- Let us now perform an OPF routine calculation.
- The example, in this case, is the 6 bus test case available in the current PSAT distribution that appear in the image.
- The standard OPF results with Active power limits appear in the following tables, note that not all the results from the routine are presented due to space restrictions.



Optimal Power Flow II

OPF Example

Table: Network statistics

Buses:	6.00000
Lines:	11.00000
Generators:	3.00000
Loads:	3.00000
Supplies:	3.00000
Demands:	3.00000

Table: Solution statistics

Objective function [\$ /h]:	-121.64928
Active limits:	8.00000
Number of iterations:	13.00000
Barrier parameter:	0.00000
Variable mismatch:	0.00000
Power flow equation mismatch:	0.00000
Objective function mismatch:	0.00000

Optimal Power Flow III

OPF Example

Table: Power supplies

Bus	Mu min	Ps min [mw]	Ps [mw]	Ps max [mw]	Mu max
Bus1	0.65773	0.00100	0.00100	20.00000	0.00000
Bus2	0.00000	0.00100	24.99999	25.00000	0.17662
Bus3	0.00000	0.00100	20.00000	20.00000	2.09680

Table: Power demands

Bus	Mu min	Pd min [mw]	Pd [mw]	Pd max [mw]	Mu max
Bus4	0.00000	0.00100	25.00000	25.00000	2.30396
Bus5	0.00000	0.00100	10.00000	10.00000	0.42491
Bus6	0.00000	0.00100	8.06936	20.00000	0.00000

Optimal Power Flow IV

OPF Example

Table: Reactive powers

Bus	Mu min	Qg min [mvar]	Qg [mvar]	Qg max [mvar]	Mu max
Bus2	0.00000	-150.00000	76.20599	150.00000	0.00000
Bus1	0.00000	-150.00000	44.62333	150.00000	0.00000
Bus3	0.00000	-150.00000	72.08442	150.00000	0.00000

Table: Voltages

Bus	Mu min	V min [p.u.]	V [p.u.]	V max [p.u.]	Mu max	Phase [rad]
Bus1	0.00000	0.90000	1.10000	1.10000	1.36003	0.01405
Bus2	0.00000	0.90000	1.10000	1.10000	0.69913	0.00000
Bus3	0.00000	0.90000	1.10000	1.10000	0.29865	-0.02463
Bus4	0.00000	0.90000	1.02114	1.10000	0.00000	-0.05066
Bus5	0.00000	0.90000	1.01295	1.10000	0.00000	-0.07318
Bus6	0.00000	0.90000	1.04035	1.10000	0.00000	-0.06760



Optimal Power Flow V

OPF Example

Table: Power flow

Bus	P [mw]	Q [mvar]	Rho p [\$/mwh]	Rho q [\$/mvarh]	Ncp [\$/mwh]	Pay [\$/h]
Bus1	90.00100	44.62332	9.02037	0.00000	-0.04872	-812.00000
Bus2	164.87536	76.20598	8.98048	0.00000	0.00000	-1481.00000
Bus3	80.00000	72.08440	9.14550	0.00000	0.07648	-732.00000
Bus4	-115.00000	-76.66499	9.56297	0.39306	0.20737	1100.00000
Bus5	-109.99999	-76.99999	9.65348	0.40762	0.29043	1062.00000
Bus6	-98.06933	-62.68975	9.42843	0.21472	0.23945	925.00000

Table: Totals

Total losses [mw]:	11.80700
Bid losses [mw]:	11.80700
Total demand [mw]:	43.06936
Ttl [mw]:	323.06936
Imo pay [\$ /h]:	62.12194

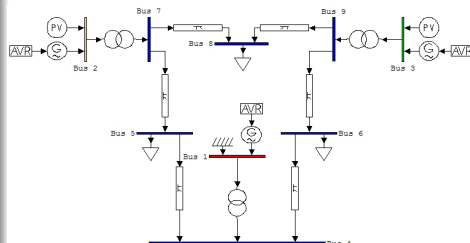


Small Signal Stability I

SSS Example

WSCC 9 Bus System

- Now we will address a small signal stability example.
- For this example we will simulate the WSCC 9 Bus System presented in [22]
- The Simulink network used to simulate the system is presented in the image. This model is available in the PSAT distribution.
- The following figures, and the small signal stability report depict the eigenvalue analysis for the WSCC 9-bus test system and have been generated with the Eigenvalue Analysis interface. The results of the detailed report are not presented here due to space limitations.



Small Signal Stability II

SSS Example

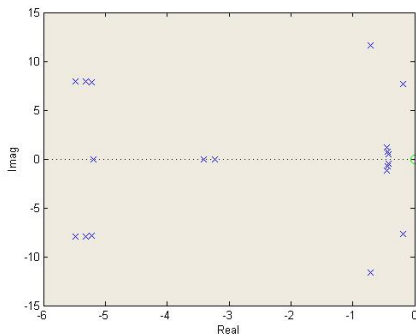


Figure: S-domain Eigenvalue Analysis

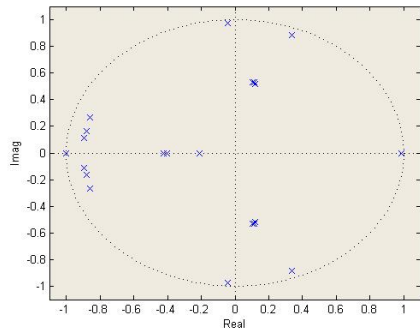


Figure: Z-domain Eigenvalue Analysis



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Small Signal Stability III

SSS Example

Table: State matrix eigenvalues (1)

Eigenvalue	Most associated states	Real part	Imag. part	Frequency
Eig as 1	Omega_syn_2, delta_syn_2	0.33825	0.88207	0.14039
Eig as 2	Omega_syn_2, delta_syn_2	0.33825	-0.88207	0.14039
Eig as 3	Delta_syn_1, omega_syn_1	-0.04559	0.97483	0.15515
Eig as 4	Omega_syn_1, delta_syn_1	-0.04559	-0.97483	0.15515
Eig as 5	Vr1_exc_2, vf_exc_2	0.11928	0.51904	0.08261
Eig as 6	Vr1_exc_2, vf_exc_2	0.11928	-0.51904	0.08261
Eig as 7	Vr1_exc_3, vf_exc_3	0.10297	0.53025	0.08439
Eig as 8	Vr1_exc_3, vf_exc_3	0.10297	-0.53025	0.08439
Eig as 9	Vr1_exc_1, vf_exc_1	0.11253	0.52758	0.08397
Eig as 10	Vr1_exc_1, vf_exc_1	0.11253	-0.52758	0.08397
Eig as 11	E1d_syn_1	-0.21238	0.00000	0.00000
Eig as 12	E1d_syn_2	-0.40303	0.00000	0.00000

Small Signal Stability IV

SSS Example

Table: State matrix eigenvalues (2)

Eigenvalue	Most associated states	Real part	Imag. part	Frequency
Eig as 13	E1q_syn_3, vr2_exc_3	-0.85684	0.26655	0.04242
Eig as 14	E1q_syn_3, vr2_exc_3	-0.85684	-0.26655	0.04242
Eig as 15	E1q_syn_3, e1q_syn_1	-0.88164	0.16504	0.02627
Eig as 16	E1q_syn_3, e1q_syn_1	-0.88164	-0.16504	0.02627
Eig as 17	E1q_syn_2, vr2_exc_1	-0.89257	0.11161	0.01776
Eig as 18	E1q_syn_2, vr2_exc_1	-0.89257	-0.11161	0.01776
Eig as 19	Delta_syn_3	-1.00000	0.00000	0.00000
Eig as 20	Omega_syn_3	-1.00000	0.00000	0.00000
Eig as 21	Vm_exc_3	0.98413	0.00000	0.00000
Eig as 22	Vm_exc_3	0.98413	0.00000	0.00000
Eig as 23	Vm_exc_1	0.98413	0.00000	0.00000
Eig as 24	E1d_syn_3	-0.42529	0.00000	0.00000



Small Signal Stability V

SSS Example

Table: Participation factors (euclidean norm) (1)

	Delta_syn_1	Omega_syn_1	E1q_syn_1	E1d_syn_1	Delta_syn_2
Eig as 1	0.08515	0.08515	0.00541	0.00557	0.38073
Eig as 2	0.08515	0.08515	0.00541	0.00557	0.38073
Eig as 3	0.30863	0.30863	0.01439	0.00623	0.04895
Eig as 4	0.30863	0.30863	0.01439	0.00623	0.04895
Eig as 5	0.00099	0.00099	0.01352	0.00162	0.00037
Eig as 6	0.00099	0.00099	0.01352	0.00162	0.00037
Eig as 7	0.00012	0.00012	0.00222	0.00117	0.00035
Eig as 8	0.00012	0.00012	0.00222	0.00117	0.00035
Eig as 9	0.00004	0.00004	0.00170	0.00058	0.00133
Eig as 10	0.00004	0.00004	0.00170	0.00058	0.00133
Eig as 11	0.00756	0.00756	0.00728	0.48124	0.01199
Eig as 12	0.00105	0.00105	0.00090	0.44933	0.00518



Small Signal Stability VI

SSS Example

Table: Participation factors (euclidean norm) (2)

	Delta_syn_1	Omega_syn_1	E1q_syn_1	E1d_syn_1	Delta_syn_2
Eig as 13	0.00079	0.00079	0.16025	0.01101	0.00046
Eig as 14	0.00079	0.00079	0.16025	0.01101	0.00046
Eig as 15	0.00082	0.00082	0.18937	0.00949	0.00021
Eig as 16	0.00082	0.00082	0.18937	0.00949	0.00021
Eig as 17	0.00066	0.00066	0.13694	0.00901	0.00145
Eig as 18	0.00066	0.00066	0.13694	0.00901	0.00145
Eig as 19	0.09334	0.09334	0.00000	0.00000	0.04432
Eig as 20	0.09334	0.09334	0.00000	0.00000	0.04432
Eig as 21	0.00000	0.00000	0.00000	0.00000	0.00000
Eig as 22	0.00000	0.00000	0.00000	0.00000	0.00000
Eig as 23	0.00000	0.00000	0.00000	0.00000	0.00000
Eig as 24	0.00000	0.00000	0.00000	0.00000	0.00000

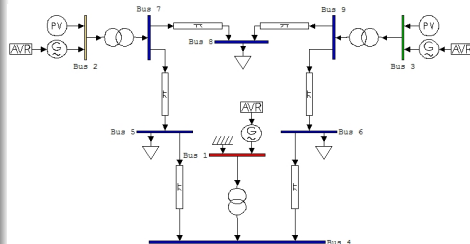


Time Domain Simulations

Disturbance Example

WSCC 9 Bus System

- In this example we will perform a time domain simulation with PSAT.
- For this example we will simulate the WSCC 9 Bus System presented in [22]
- The Simulink network used to simulate the system is presented in the image. This model is available in the PSAT distribution.
- The system will be subject to a disturbance, in this case, the speed of one of the generators is changed to 0.95 p.u.; this is done after the power flow has been calculated as following:
 $DAE.x(Syn.\omega(2)) = 0.95$
- After this, the time domain simulation can be performed. The results due to the perturbation are presented in the next figure.



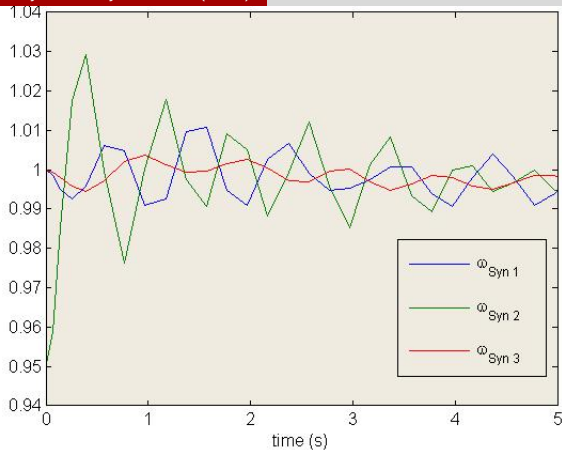


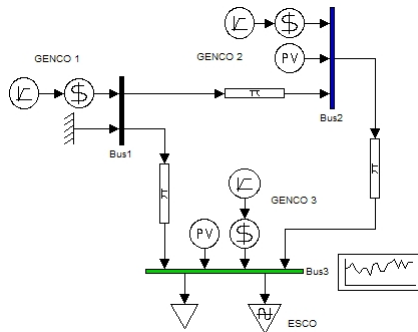
Figure: Results of the time domain simulation.

GAMS Interface I

Clearing Mechanisms - Electricity Markets Example

Simple Auction Example

- Let us now consider the use of the PSAT-GRAMS Interface (PGI)
- In this example we will compute the results of a single period simple auction.
- The Simulink network used to simulate the system is presented in the image. This model is available in the PSAT distribution.
- Once the network has been loaded and power flow has been performed, one is able to run the PGI and set the appropriate values for the market model.
- Afterwards, the market problem can be solved by GAMS within PSAT.
- The output file generated by the PGI, that shows the results of solving the single period simple auction, is presented in the next figures.



GAMS Interface II

Clearing Mechanisms - Electricity Markets Example

PSAT-GAMS Interface

Market Clearing Mechanism
Single-Period Auction
GAMS routine completed in 0.591 s

Newton-Raphson Method for Power Flow Computation
PF solver: Newton-Raphson method
Single slack bus model
Power Flow completed in 0.02 s

Power Supplies

Bus <i>	P _s [MW]	P _s max [MW]	P _s min [MW]
1	60	60	10
2	30	60	10
3	10	60	10

Power Demands

Bus <i>	P _d [MW]	P _d max [MW]	P _d min [MW]
3	100	100	100

Generator Reactive Powers

Bus <i>	Q _g [MVar]	Q _g max [MVar]	Q _g min [MVar]
1	2.9485	180	-180
2	2.6982	80	-20
3	125.6257	80	-20

Power Flow Solution

Bus <i>	V [p.u.]	theta [rad]	PG [MW]	PL [MW]	QG [MVar]
1	1	0.0000	80	0	2.9485
2	1	-0.0023	70	0	2.6982
3	1	-0.0767	80	200	125.6257

Prices and Pays

Bus <i>	LMP [\$/MWh]	Pay S [\$/h]	Pay D [\$/h]
1	10.7000	-856	0
2	10.7000	-749	0
3	10.7000	-525	2140

Flow limits are disabled.

Totals

Total Losses = 0 [MW]
Bid Losses = 0 [MW]
Total demand = 100 [MW]
Total Transaction Level = 200 [MW]
IMO Pay = 2.2727e-012 [\$/h]

Check file C:\Archivos de programa\MATLAB704\work\psat\fm_gams.lst for GAMS report.
GAMS model status: optimal
GAMS solver status: normal completion
PSAT-GAMS Optimization Routine completed in 1.9558 s

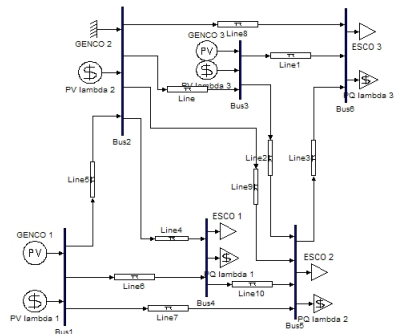


UWPFLOW I

Continuation Power Flow Example

6 Bus Test System

- In this final example we will perform CPF with the UWPFLOW-PSAT Interface.
- For this example we will simulate the some 6 Bus Test System used in the OPF example.
- The Simulink network used to simulate the system is presented in the image. This model is available in the PSAT distribution.
- After computing the power flow, the UWPFLOW-PSAT Interface can be initialized
- After this, CPF can be performed. The results of the CPF routine are presented in the next figure.



UWPFLOW II

Continuation Power Flow Example

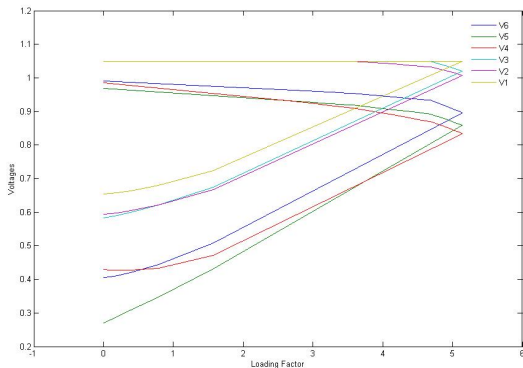


Figure: Results of CPF using the UWPFLOW-PSAT Interface



PSAT as a learning & teaching tool

- PSAT can be effectively be used in teaching. The GUIs and the Simulink graphical network environment are user friendly and self explaining, this will enable the students to focus in interpreting the results rather than in learning to use a package or program their own routines.
- Learning can be enhanced through the use of *What if?* examples. This is possible to do in PSAT because is easy to change the network topology, physical component model parameters and/or algorithms.
- PSAT can also be widely used for self study. You can reproduce the results given in your text books and in technical papers, thus, enhancing your learning experience.

PSAT as a research environment

- PSAT is an excellent ally to do research. Since PSAT is open source, it is possible to modify or/and add new component models or routines.
- Also, you can use the *command line* version of PSAT to build your custom made code and solve particular problems, without relying in the GUIs.
- PSAT has been used and it's been used by many people to do their thesis and scientific research.
- It's a good idea that you consider to use PSAT as a research tool to do your thesis or research; and maybe even share your custom made code and results with the rest of the user's of the PSAT worldwide!!!

Summary I

- An overview of PSAT was given in order to demonstrate it's main features, available routines, models and additional tools.
- A broad number of examples were presented in order to show the capabilities of the PSAT and it's interfaces.
- The PSAT was presented as a learning, teaching, self study and research tool; and you were *encouraged* to use PSAT as an everyday tool.



Thank you for your attention! I

Are you ready to start using the the PSAT?

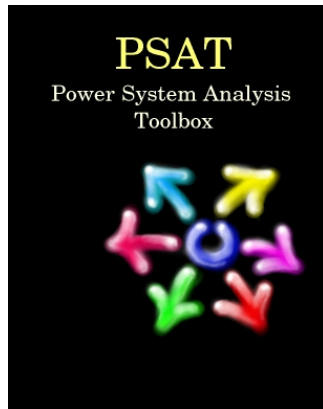
To download the PSAT...

- Please, feel free to download the latest version of the PSAT here:

<http://thunderbox.uwaterloo.ca/~fmilano>

- Also, we would like to hear from you in the PSAT Forum:

<http://groups.yahoo.com/groups/psatforum>



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References I

For further reading

The references have been divided in several categories:

- References on the PSAT
- References on Power System Operation, Control and Electricity Markets
- References on Power System Control and Stability
- References on Power System Analysis

Power System Analysis Toolbox I

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Power System Control and Stability II

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- 2] P.M. Anderson and A.A. Fouad, *Power system control and stability*. USA: IEEE Press, 2003.
- 3] G. K. Morison, B. Gao, and P. Kundur, "Voltage Stability Analysis using Static and Dynamic Approaches", *IEEE Transactions on Power Systems*, vol. 8, no. 3, pp. 1159-1171, Aug. 1993.
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