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A SMALL-SIGNAL STABILITY PROGRAM INCORPORATING ADVANCED GRAPHICAL USER INTERFACE

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SUMMARY

This paper describes the utilization of a small-signal stability analysis package, which has been developed by CEPEL over the last 20 years, and shows the advantages of using a modern Graphical User Interface (GUI) in the stabilization studies of large power systems. The various phases of development of the GUI as well as its main characteristics are discussed. Four case studies are described in order to review the main features of the GUI.

Keywords: small-signal stability analysis, graphical user interface

1. INTRODUCTION

Modal analysis and other advanced linear control design methods are now widely used [1,2,3,4,5] in the study of small-signal stability and control. CEPEL has had a long involvement in the development and use of these tools for damping control of inter-area oscillations in large-scale power systems [6].

Recent examples of these studies are the planning and operation studies of the Brazilian North/South interconnection and the study of the Argentinean Interconnected System (SADI). SINTEF / Statnett are currently carrying out small-signal stability studies in the NORDEL power system, which involves the interconnection of the Norway, Denmark, Finland and Sweden power systems [6]. The study of such high-order systems (Jacobian matrices of order 50,000) requires the utilization of efficiently-programmed and numerically robust partial eigensolution algorithms.

The design and tuning process of control systems, for example power system stabilizers, FACTS devices and AC/DC converters, requires the coordinated utilization of various small-signal stability functions available in PacDyn:

- Partial Eigensolution Algoritms
- Frequency Response (Nyquist and Bode Diagrams)
- Linear Time Response
- Modal Sensitivities and Shapes (Transfer Function Residues, Controllability and Observability Factors (Mode Shapes) and Participation Factors
- Root-Locus and Root-Contour Plots
- Reduced-Order Model and Coordinated Design

It is once again emphasized that these tools must be capable to deal with large power system models.

The coordinated use of these various functions and the analysis of results are made easier with the use of the modern Graphical User Interface, based on the Windows environment and supported by a relational database.

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2. DEVELOPMENT STAGES OF THE GRAPHICAL USER INTERFACE

The PacDyn GUI is a result of a continuous development work during the last 7 years. There were various development stages during this period, partly due to the fact that the Hardware, Operating Systems, Compilers and Graphical User Interface technologies are continuously evolving.

The development work has been carried out in a challenging environment:

- The need for a reliable version during all phases of the development process. Most recent versions are periodically distributed to customers (PacDyn Releases) and are also used in consulting work and other studies.
- PacDyn itself is continuously under development, with the implementation of new algorithms and program functions, a work that must be made in parallel with the GUI development.

The various development stages of the PacDyn GUI are described below.

The first PacDyn implementation used a single output file (Printout File in Figure 1) to store and plot (printer plotter) the various program functions results. This implementation was not a GUI, but it is mentioned here to illustrate the long-standing need for a GUI to more effectively visualize the large variety of program results.

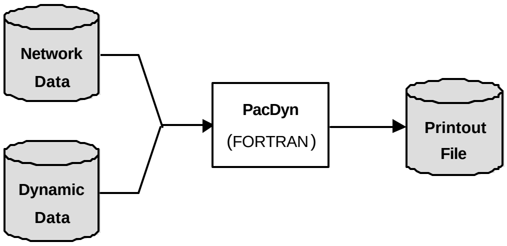


Figure 1 - *PacDyn without Graphical User Interface.*

The following step towards a true GUI was the implementation of various DOS-based Plotting Programs utilizing Graphical FORTRAN. The PacDyn FORTRAN code was modified to generate the program function results in separate output files, which were then utilized by the DOS-based Plotting Programs. The printout file was still generated but the default option only printed a summary of the functions executed and the parameters used during a PacDyn session.

The schematic diagram describing this approach is shown in Figure 2. Note that each PacDyn function requires a corresponding output file to store the results. Managing the data files and results files was a major task since there were no easy schemes to link the results files with the system data files. This is so because the system data files may be changed by the user at any instant, and the current files results may belong to previous system data files.

The major difficulty with this approach was the severe memory limitation (640 KB) imposed by the DOS-based Plotting Programs, due to the Graphical FORTRAN Compiler utilized. The solution to this problem only came with the arrival of the new version of the FORTRAN Compiler (Microsoft FORTRAN Power Station 4.0).

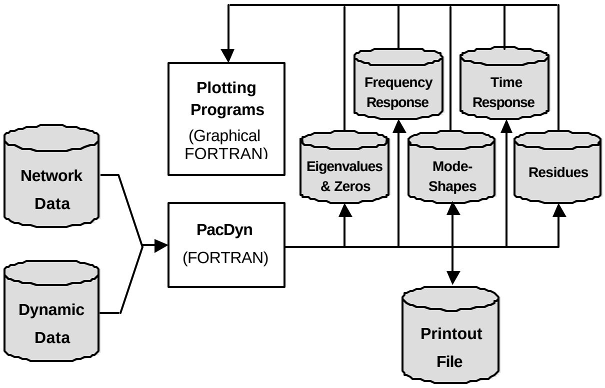


Figure 2 - *PacDyn with DOS-based Plotting Programs.*

The new FORTRAN compiler is a part of an integrated development platform, which includes the Microsoft Visual C++ 4.0. This is an important fact, which allows the simultaneous development of the FORTRAN code and of the new GUI in Visual C++.

The schematic diagram describing this approach is shown in Figure 3. Each PacDyn function still requires a result file, but managing these files became much more efficient with the development of the GUI.

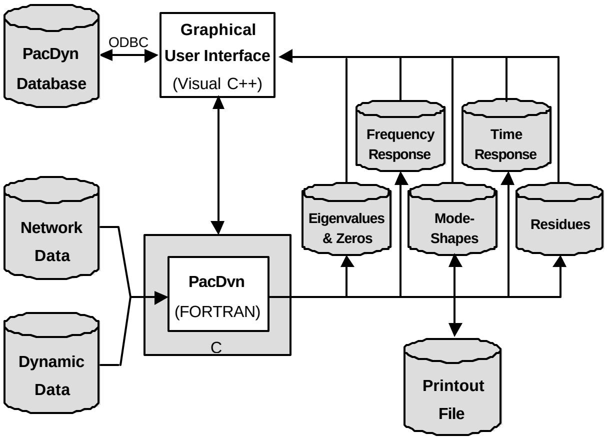


Figure 3 - *PacDyn for Windows with Graphical User Interface (Current Version).*

Development work continues in order to produce a better GUI structure, which is schematically represented in Figure 4. The development of a Results Manager Module, integrated with the GUI, will allow the user to store the results for a given case and from a given study in a more organized way. The various result files will be eliminated and all the results will be stored in a single relational database, connected to PacDyn through the GUI. The Results Manager Module will be responsible by the correct managing and validation of the results for a given case.

The network and dynamic datafiles, shown in Figure 2 and Figure 3, will eventually be replaced by the SAPRE database [7], shown in Figure 4, which will integrate the major power system analysis applications developed by CEPEL.

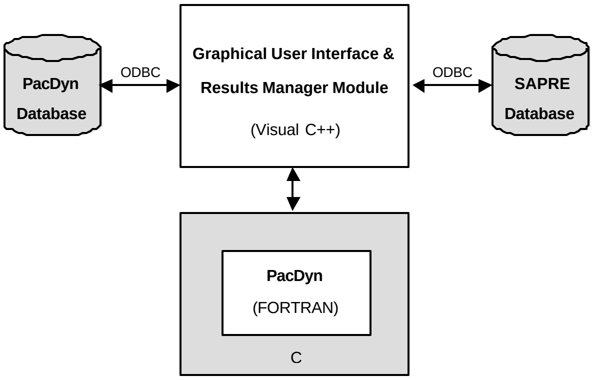
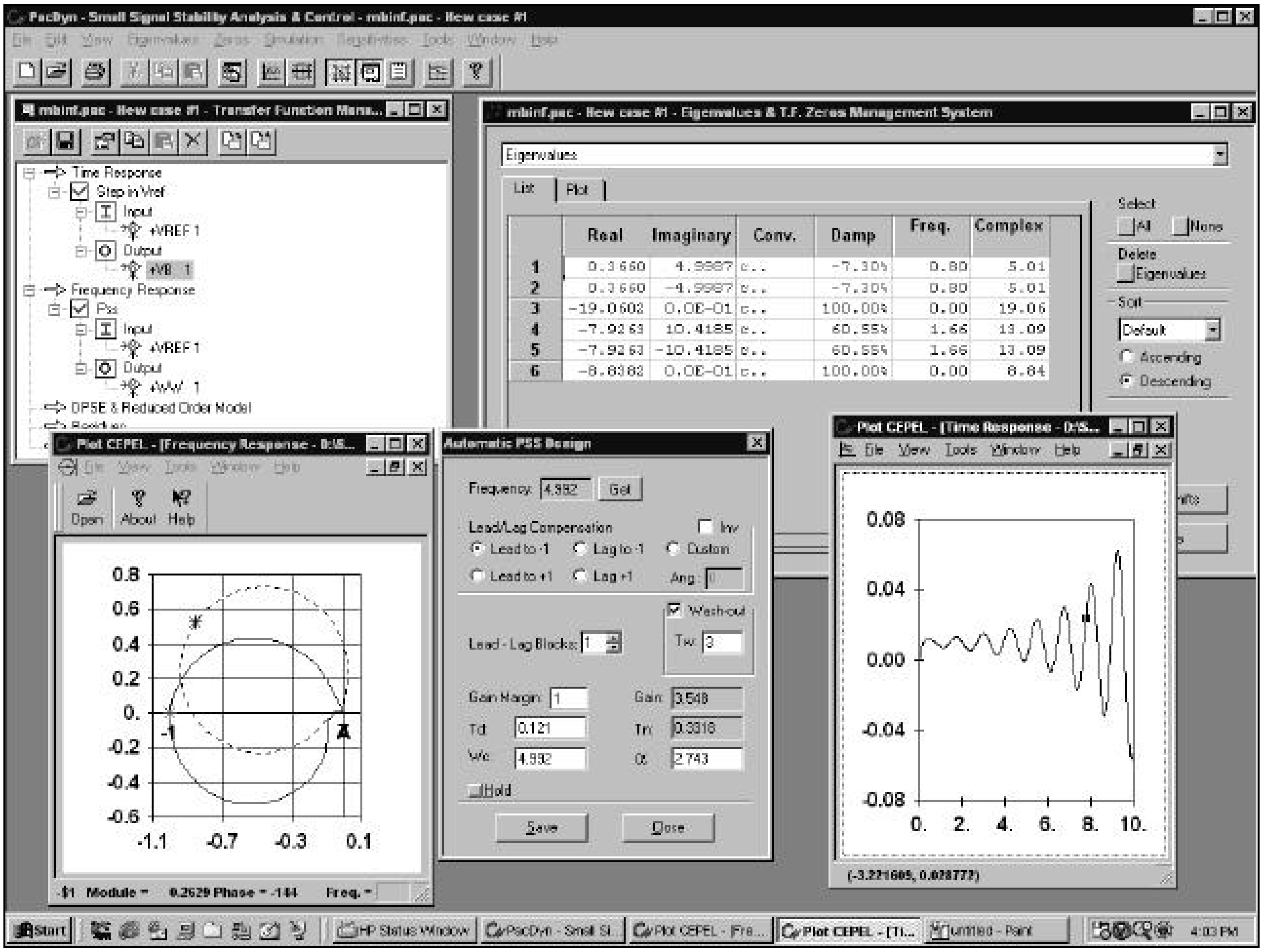


Figure 4 - *PacDyn for Windows with Graphical User Interface with Results Manager Module.*



	Real	Imaginary	Conv.	Damp	Freq.	Complex
1	0.3660	4.9987	c..	-7.30%	0.80	5.01
2	0.3660	-4.9987	c..	-7.30%	0.80	5.01
3	-19.0602	0.0E-01	c..	100.00%	0.00	19.06
4	-7.9263	10.4185	c..	60.55%	1.66	13.09
5	-7.9263	-10.4185	c..	60.55%	1.66	13.09
6	-8.8382	0.0E-01	c..	100.00%	0.00	8.84

Automatic PSS Design

Frequency: 4.992 Get

Lead/Lag Compensation ☐ Inv

● Lead to -1 ○ Lag to -1 ○ Custom

○ Lead to +1 ○ Lag +1 Ang: 0

☑ Washout Tw: 3

Lead - Lag Blocks: 1

Gain Margin: 1 Gain: 3.548

Td: 0.121 Tn: 0.3318

Wc: 4.992 α: 2.743

☐ Hold

Save Close

Figure 5 - *PacDyn main screen showing the various GUI modules.*

3. CURRENT FEATURES OF THE GRAPHICAL USER INTERFACE

The PacDyn GUI is currently divided in five major modules:

3.1 Case Manager Module

The Case Manager Module allows the user to choose the current study case, create new cases and delete or modify existing ones. The data needed to specify a valid case, related to a study being executed is: Case Identification, Name of the Network Data File and Names of the Dynamic Data Files.

These data are stored in the relational database pictured in Figure 3.

3.2 Eigenvalues and Zeros Management Module

The Eigenvalues and Zeros Management Module is responsible for the management of initial shifts, eigenvalues, eigenvectors and transfer function zeros of the case under analysis. These data are stored in the study relational database for future use.

The PacDyn functions related to eigenvalues and zeros receive information from the database-GUI ODBC connection and then from a GUI-PacDyn FORTRAN kernel through a C layer, as shown in Figure 3.

3.3 Transfer Function Management Module

This module is responsible for the management of the transfer functions related to several program functions. The transfer functions are stored in the study relational database for future use by the program functions.

3.4 Results Visualization Module

This module allows the visualization of results from the various program functions. The results are stored in the results files located in the various case directories, allowing a higher organization level than that achieved with the DOS GUI.

This module is the largest and will be further improved as described in Section 5.

3.5 Power System Stabilization Design Module

The Power System Stabilization Design Module is mostly based on frequency response methods (Nyquist Diagram). This module allows to automatically obtain several power system stabilizers designs and then compare their performance. Figure 6 presents the Nyquist diagram of the transfer function $\Delta\omega/\Delta V_{ref}$ of a synchronous generator, connected to an infinite bus through a reactance. The other three curves correspond to the same Transfer Function Nyquist diagram following compensation by three different power system stabilizers. The three compensated curves have the same gain (3.0) at the electromechanical frequency (about 5 rad/s), but different gain margins for the other crossover frequency at about 15 rad/s (exciter mode). Out of the three PSS designs being compared, the best choice is that one that presents the largest gain margin. The $\Delta\omega/\Delta V_{ref}$ plot was amplified by a factor of 20 in order to become compatible in size with the other curves. The design module includes a feature of partial pole location [8].

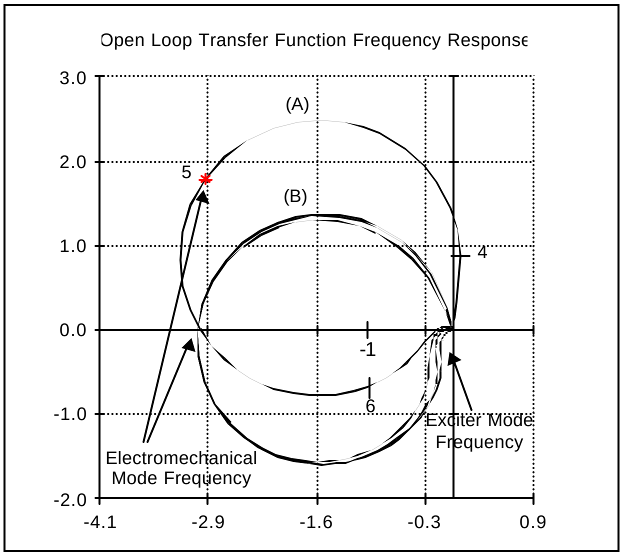


Figure 6 – *Nyquist plots of* $\Delta\omega/\Delta V_{ref}$ *(A) and* $\Delta V_{pss}/\Delta V_{ref}$ *(B), used for PSS design.*

4. RESULTS

This section shows the high-resolution graphics and advantages brought by the use of the PacDyn GUI in large power system studies.

4.1 Brazilian North-South Interconnection

The capacity of the North-Northeast interconnected system is about 13,000 MW while that of the South-Southeast-Centralwest system is 45,000 MW.

These two large systems were interconnected in early 1999 through the North-South 500 kV AC, 1,300 MW capacity, 1,000 km long, series-compensated transmission line. This interconnection caused the advent of the North-South mode, whose frequency ranges from 0.17 to 0.25 Hz according to the system conditions. Simulations showed this mode to have very poor or even negative damping for some system conditions in the absence of TCSCs or enhanced PSSs [9].

During the preliminary planning studies of the North-South interconnection, small-signal studies revealed that modified stabilizers on the generators in the Northeastern Region or a TCSC, located in the North-South link, would provide technically viable solutions for the damping of the North-South mode [11]. These results were later verified by transient stability simulations.

The multi-utility task force on the North-South Interconnection, convened by Eletrobras Planning Division, carried out extensive studies utilizing a large number of computer tools. One of these studies had the responsibility for the tuning of the power system stabilizers at critical locations together with the refinement in the damping controls of the two TCSCs, to be placed at the ends of the North-South link. PacDyn was utilized to help in these stabilization studies. Some examples of the PacDyn use are shown in the following subsections.

4.1.1 Mode-Shape for North-South Inter-Area Mode

The rotor speed mode-shape [10] for the North-South mode, for one of the most critical loading scenarios, is shown in Figure 7. This scenario, named R, has an active power flow of 1,000 MW from North to South, the northeastern generation level is high and the total system load is 46,000 MW. It is clearly seen that the generators at the North-Northeast oscillate with larger amplitude and coherently against those in the South-Southeast. The poorly damped mode has a frequency of approximately 0.2 Hz (1 rad/s).

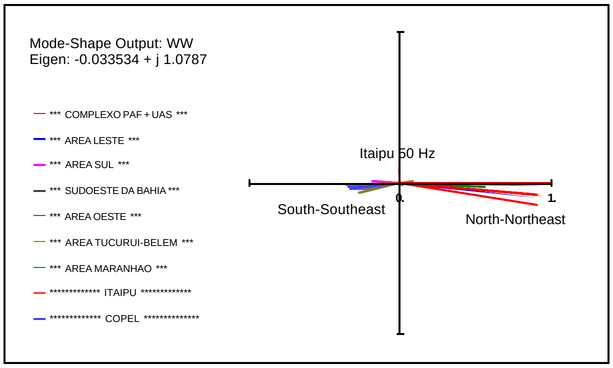


Figure 7 - *Mode-shape for North-South inter-area mode (l = -0.034 ± j 1.079).*

4.1.2 Example of Linear Step-Response Solution

A good part of the time response plots, needed in oscillation damping analysis and control, can be produced by step disturbances applied to the linearized power system model. The time responses, for systems containing fast-acting devices (HVDC links, FACTS devices), are obtained at least 50 times faster than those produced by transient stability programs.

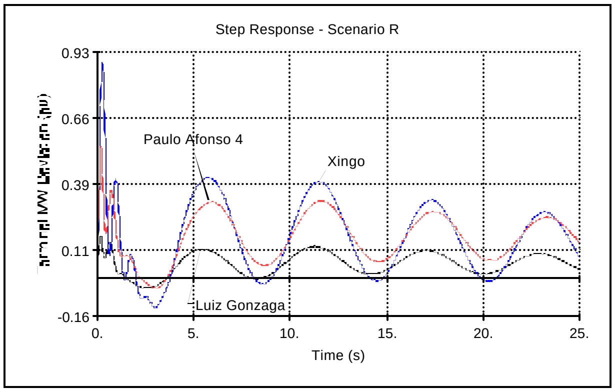


Figure 8 - *Step responses of major system generators for Scenario R (l = -0.034 ± j 1.079) (with existing PSSs and without TCSC stabilizer).*

Figure 8 displays the linear responses of the terminal powers of three major generating plants following a step disturbance, considering Scenario R. The chosen step disturbance promoted a large excitation of the North-South inter-area mode. These time responses show scenario R to be critical, due to the very poor damping observed on the North-South mode.

4.1.3 Model-Order Reduction Capabilities

The purpose of this section is to illustrate the effectiveness of the model-order reduction techniques available; these are based on the transfer function dominant modes of the full-size system.

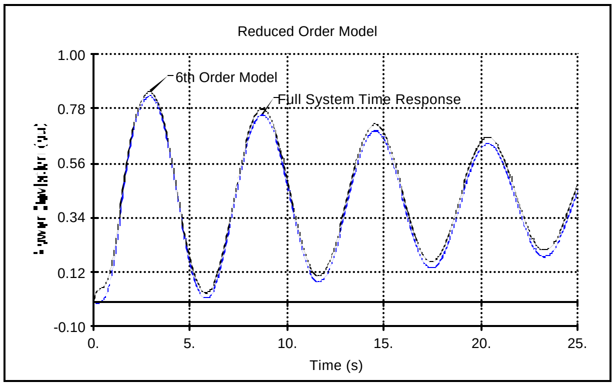


Figure 9 - *Active power flow in the North-South tie-line. Responses of the full model and the 6th order reduced model.*

Figure 9 compares the North-South tie-line power flow, obtained by step-by-step numerical integration on the full-size system (of order 1,700), with that obtained by Inverse Laplace Transform of a step disturbance applied to the 6th order transfer function equivalent model. The 6th order model was obtained according to the methodology described in [12]. The step response of the reduced model was produced by computing the 6th order approximation to *y(t)* every 20 milliseconds:

$$y(t) \cong \sum_{i=1}^{6} \frac{R_i}{l_i}(e^{l_i \cdot t} - 1)$$

where:

$l_{1,2}$ = -0.034 ± j 1.079 $R_{1,2}$ = 1.262 ± j 25.458

$l_{3,4}$ = -2.944 ± j 4.821 $R_{3,4}$ = 14.061± j 14.445

$l_{5,6}$ = -0.557 ± j 3.610 $R_{5,6}$ = 5.366 ± j 6.277

These results are for a Single-Input-Single-Output (SISO) transfer function. Reduced-models for Multi-Input-Multi-Output (MIMO) transfer functions are necessarily of a higher order, but can also be obtained at reasonable cost.

Highly reduced models for power system transfer functions have been reported to be very effective for the design of damping controllers [13,14,15,16].

4.1.4 Ranking the Most Effective PSSs and the Best Location for TCSCs Based on Transfer Function Residues

The residue ranking list (Figure 10) of transfer functions $\Delta\omega^i(\lambda)/\Delta V_{ref}^i(\lambda)$, $i = 1, ..., N_g$ (N_g being the total number of system generators, and $\lambda = -0.034 \pm j\,1.079$) helps locating the most effective generators for installing or retuning existing power system stabilizers for damping the inter-area mode [25,22]. Note that the ranking is based on the relative moduli of the various transfer function residues. The phase information is also relevant and helps determining the phase compensation characteristics of the PSS. Note that the largest magnitude residues are all related to power plants in the lower capacity Northeast Region, as previously discussed and in agreement with the concepts in [17].

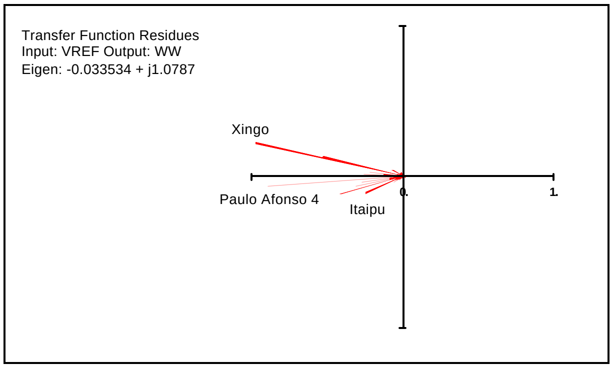


Figure 10 - *Diagram of transfer function residues, used to determine the most effective generators for installing or retuning existing stabilizers (l = -0.034 ± j 1.079).*

The residue ranking list (Figure 11) of transfer functions $\Delta P_{line}(\lambda)/\Delta B_{line}(\lambda)$, $line = 1, ..., N_l$ (N_l being the total number of lines in the system) helps to determine the most effective lines in which to place a Thyristor Controlled Series Compensator (TCSC) to damp the North-South inter-area mode [11,18]. As expected, the plot in Figure 11 establishes that the line sections of the North-South tie-line are the best candidates for TCSC placement. Note that the line B. Esperança/S.J. Piauí, a single circuit 500kV line linking the North to the Northeast Region, is also a good candidate for TCSC damping control of the North-South inter-area mode.

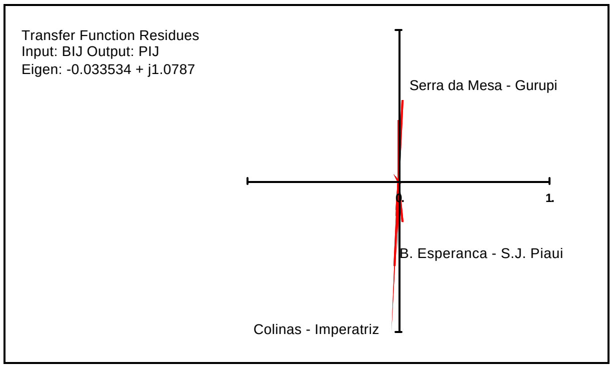


Figure 11 - *Phasor diagram representation of transfer function residues, used to determine the most effective system branches for installing TCSC devices (l = -0.034 ± j 1.079).*

Determining the effectiveness of different locations for damping controllers based on transfer function residues is very valuable, but ranking based on residue information needs to be further verified, since it is of an incremental nature and, additionally, there are some scaling problems not yet fully solved.

4.1.5 Example of Root-Locus Plots for Large System Models

Dominant pole eigenroutines [12] are employed to automatically obtain root-locus plots for high-order transfer functions, by repeatedly tracking the dominant pole spectrum for a sequence of small changes in a few controller parameters.

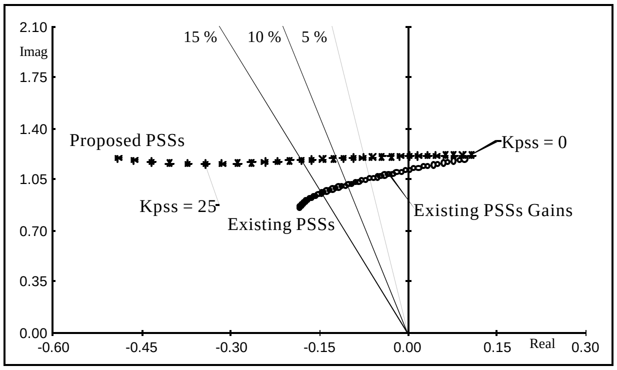


Figure 12 - *Locus of North-South mode following changes in the PSS gains at Xingó, Paulo Afonso IV and Itaparica power plants.*

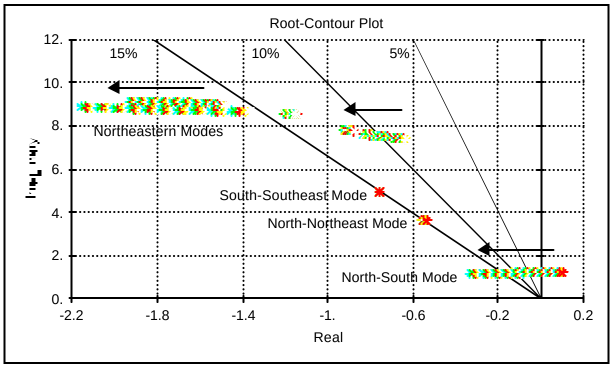


Figure 13 - *Root-contour plot as the gains of the PSSs at Xingó, Paulo Afonso IV and Itaparica are raised from zero to 25 pu/pu.*

Figure 12 compares two root-contour plots obtained when simultaneously varying the gains of both the existing and the proposed PSSs in Xingó, Paulo Afonso IV and Itaparica power plants. The North-South mode moves further into the left plane, as desired, as the PSS gains are raised. As the existing PSSs produce an excessive phase lead at 1.2 rad/s, they cause a reduction in the frequency of the North-South mode. An extra block (lag) in the proposed PSSs ensures correct phase compensation at the frequency of the North-South mode [9], as also shown in Figure 12.

Figure 13 shows the root-contour plot obtained when simultaneously varying the gains of the proposed PSSs in Xingó, Paulo Afonso IV and Itaparica power plants. The local northeastern as well as some inter-area modes (including the North-South) are depicted. There were no problems with exciter modes, even for PSS gains higher than needed.

4.2 Argentinean Interconnected System (SADI)

In 1994, the Argentinean Interconnected System (SADI) started to experience stability problems related to transmission constraints, being then decided that some operative improvements were urgently needed. The project's objective was to increase the loading of the Comahue-Buenos Aires 500kV transmission lines, from 2,700 MW to 3,300 MW, mainly through the elimination of the poorly damped oscillations which in 1995 brought serious generation dispatch restrictions and associated loss of revenue [19,20].

A total of 85 scenarios were studied. For the complete system analysis, 16 cases were studied. Sixty-two cases considered single contingencies and double contingencies were analyzed in 7 cases. CAMMESA specified that every synchronized generating unit in the system should be independently modeled, rather than use equivalent machines for each power plant. This yielded system models having 160 machines and 1,800 state variables. The whole study had to be carried out through sparse eigenanalysis, except for a few cases where full QR eigensolution was employed.

Figure 14 shows the location in the complex plane of the three major interarea modes in the Argentinean system, considering the 16 base cases analyzed. Figure 15 contains equivalent information for 62 cases involving N-1 outage conditions. The results described in these two figures were produced considering the presence of all the new stabilizers, and it is seen that they comply with the damping criteria for interarea modes for base cases (15%) and N-1 conditions (10%) specified in the Call for Bids of this project.

Figure 14 and Figure 15 were automatically produced by one of the several available Macro functions. Producing these results would be prohibitively expensive without the use of the sparsity based dominant pole spectrum eigenroutines [12]. This work is in line with a central design objective in wide-area control, which is to assure adequate damping of system oscillations over the greatest practical range of operating conditions [4].

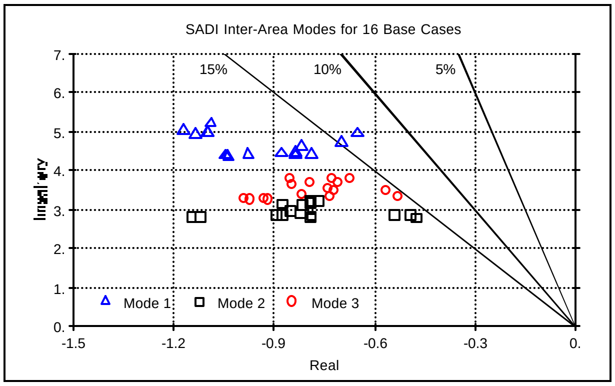


Figure 14 - *Inter-area modes for 16 base cases.*

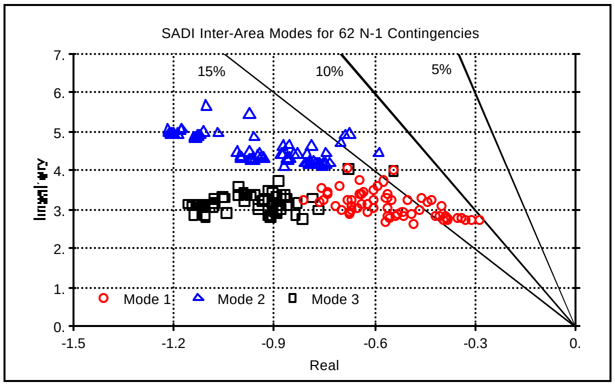


Figure 15 - *Inter-area modes for 62 N-1 contingencies.*

The small-signal stability studies not only supported the transient stability simulations and the PSS tuning, but also helped to find suitable locations for six dynamic system monitors. The work was done through the calculation of the observability factors, related to the two dominant eigenvalues associated with the Comahue area, and the other two modes associated with the other areas. These monitors were commissioned to verify that the damping levels of the major interarea modes complied with the specifications of the Call for Bids. These monitors were designed to be automatically triggered by undamped oscillations as well as other system events. The Argentinean system, since the commissioning of the new stabilizers (a total of 70 units), has not experienced poorly damped inter-area oscillations, but the dynamic monitors have been highly useful in recording other events of interest.

4.3 Nordic Interconnection (Nordel)

The Norwegian power system is part of the Nordic interconnection, *Nordel*. In the southern parts of Norway the system is dominated by several large hydro power plants in the west and south-west with long transmission lines to the main load centers in east/south-east. The study reported in [6] focuses on the "Hasle" corridor, which is a frequent bottleneck for power transfer between Southern Norway and Sweden. A main objective of the work was thus, to show that the power transfer on the "Hasle" corridor could be safely raised to 2,000MW.

There are two low damped system modes that are found to affect power oscillation damping on the "Hasle" corridor. These are the South-Norway/Sweden mode (0.48 Hz) and the "Finland" mode (0.32 Hz). Both are inter-area modes that to various degrees can be observed throughout the Nordel interconnection.

The study reported in [6] determined that three out of the seven SVC units in Norway, could be effectively used for damping these two inter-area modes. These three SVC units are located in southeast (the Oslo area). The analysis of transfer function $\Delta V_{ref}(s)/\Delta X_{ref}(s)$ residues for these units indicated that local bus frequency signals would be adequate for oscillating damping control.

Power Oscillation Dampers (PODs) for the three SVC units located in "Sylling", "Rød" and "Hasle" were then designed, using simple control structures (a first order washout filter, a gain and a second order lead-lag filter). The controllers were tuned to provide damping of both inter-area modes, but no proper coordination or optimization of the tuning was attempted. The controller design was performed using the base case load flow situation as the design model.

Figure 16 shows the corresponding root-locus plot when the same PODs are applied to the contingency case. The system is easily stabilized, and thus, apparently, it shows satisfactory robustness properties. Therefore, from the system oscillations point of view, the 2,000MW transfer through the "Hasle" corridor can be safely reached.

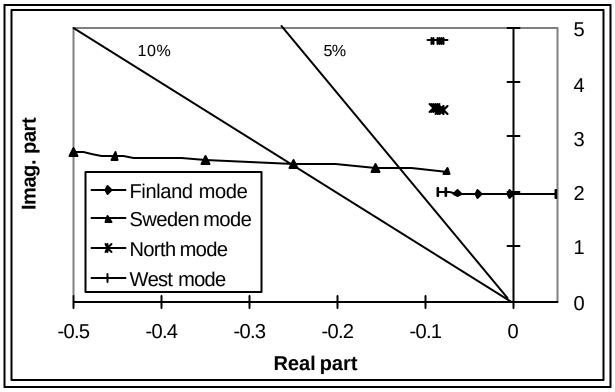


Figure 16 - *Root contour for SVC stabilizer design. Contingency case, 2050 MW export.*

The great challenge in this ongoing study is the dimension of the Nordel system, which is to date the biggest utilized in PacDyn. The system model has approximately 1,000 generators and 3,000 buses, generating 50,000-order jacobian matrices and 11,000 oscillation modes (eigenvalues). The preliminary results of the PacDyn studies carried out by SINTEF/Statnett were considered very promising [6]. These studies were only made possible by PacDyn ability to read the power flow dynamic data files of the PSS/E (Power System Technologies) software package.

4.4 UCPTE-CENTREL Interconnection

PacDyn is currently being utilized in the small-signal stability study of the UCPTE-CENTREL interconnection, in order to assess the critical system oscillation modes and the best alternatives for their damping control. This work is part of a joint collaboration project between Eletricité de France and CEPEL.

The UCPTE-CENTREL system is the interconnection of 14 electrical areas, each one representing a different country of the European continent. The system model utilized has 1900 buses, 3200 circuits, 810 transformers, 380 generators and associated controllers (excitation systems, power system stabilizers and speed-governors). The Jacobian matrix of the linearized system has order 11,000 and the number of state variables is 2,200.

As part of the EdF-CEPEL project, new facilities were added to PacDyn and CEPEL's power flow program (Anarede) to enable them to directly read the power flow and dynamic data files of EUROSTAG [23,24] format. As a result of this feature, the most recent data files utilized by EdF for the UCPTE-CENTREL dynamic studies can be used. The model and parameters for every system generator and controllers were validated between the two programs, by comparing the step responses following the application of small disturbances to the controller setpoints.

Following this individual generator and other equipment model validation, small disturbances were applied to the system model and the ensuing transients monitored in the major tie-lines. The results obtained by the two programs (EUROSTAG and PacDyn) matched well, which then validated PacDyn's ability to read EUROSTAG data files.

Preliminary results, obtained by EdF personnel in December 1999, were very promising and will be reported in a future publication.

5. FUTURE DEVELOPMENTS

Future developments to improve PacDyn for Windows capabilities include:

- More advanced GUI, with all results stored in a single database (see Figure 4).
- Better integration with power flow and transient stability tools. The user, for example, when performing transient stability studies, should be able to effectively run small-signal stability analysis with just a few mouse clicks.
- Implement advanced tools for the coordinated control design considering multiple operating conditions [21]. Some of these tools should involve constrained optimization methods. Help develop criteria for the coordinated design of multiple controllers, also specifying maximum levels of interaction.
- Non-linear search for stability boundaries in the control parameters or loading spaces. This allows the determination of the minimum distance in the control parameters, or system loading, space that will bring the system to the verge of small-signal instability. By increasing this minimum distance, through changes in the controller settings, one ensures a more robust system performance.
- More extensive use of Macro functions, with a higher degree of automation, through the development of customized program scripts. Verification of controller performance for a large number of probabilistic scenarios, considering equipment outages. Large improvements in the quality of results can be achieved just through greater automation.
- Develop adequate simulation models for a range of new controller types, which have potential application in power systems.
- Development of even more sophisticated tools, employing more advanced system theory (if practical) and computer graphics.

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