V SEPOPE
19 a 24 de maio de 1996
May, 19th to 24th - 1996
Recife (PE) - Brasil

V SIMPÓSIO DE ESPECIALISTAS EM PLANEJAMENTO DA
OPERAÇÃO E EXPANSÃO ELÉTRICA

V SYMPOSIUM OF SPECIALISTS IN ELECTRIC OPERATIONAL
AND EXPANSION PLANNING

SP 08

OSCILLATION DAMPING ANALYSIS AND CONTROL STUDIES OF THE FUTURE INTERCONNECTION BETWEEN THE NORTH-NORTHEAST AND SOUTH-SOUTHEAST SYSTEMS

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Introduction

Preliminary energetic studies indicated a gain of approximately 600 MW of guaranteed energy with the interconnection, through a 1000 MW capacity link, of the North-Northeast (N-NE) and the South-Southeast-Central West (S-SE-CW) systems. The multi-utility Task Force on the North-South Interconnection, convened by Eletrobrás, has been carrying out extensive studies utilizing a large number of computer tools. Many technical reports were produced by Eletrobrás/GTQT, dealing with a variety of topics, including these: Planning Studies, Special Studies, Alternative Routes, Cost Evaluations, DC Transmission Alternative, Environmental Issues.

One of the transmission alternatives studied for the North-South interconection is a series compensated, 1000 km long, single-circuit, 500kV AC line. A single-circuit AC line would probably be adequate during the initial years of operation, on the assumption of an **energetic-only** interconnection. A problem inherent to the synchronous interconnection of large systems is the advent of low-frequency inter-area modes of oscillation [1,2,3,4,5,6,7,8,18,19]. This paper describes the preliminary small-signal stability studies on the low-frequency, poorly-damped, inter-area mode associated with the AC North-South interconnection. The results on the DC transmission alternative will be described in another publication.

Brief Comments on the AC and DC Transmission Alternatives

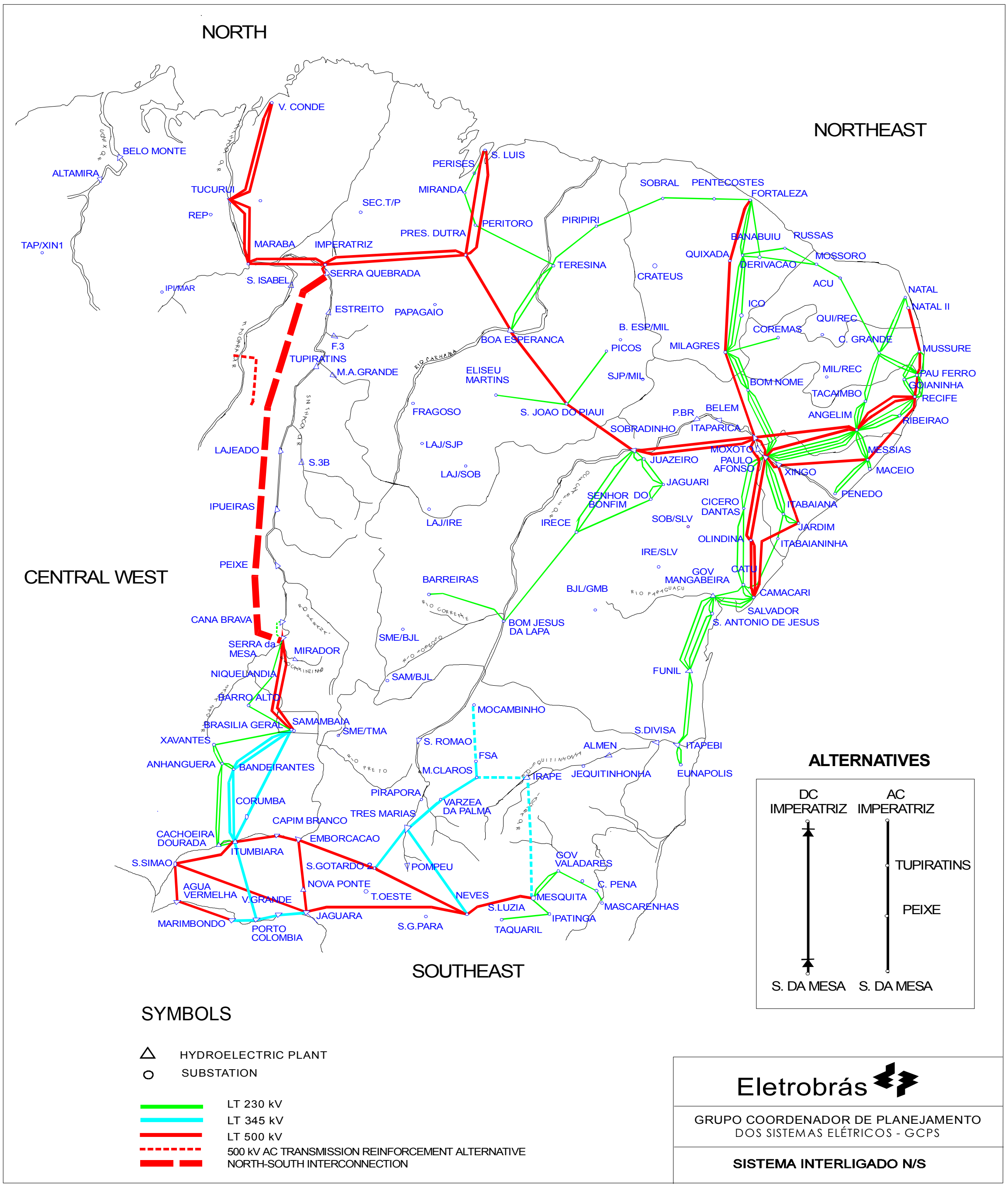
From a purely technical viewpoint, this low capacity interconnection between two large systems having different planning and operating criteria, is an ideal textbook application for High Voltage Direct Current (HVDC) transmission technology. From a strategic and political viewpoint, however, the AC transmission alternative is highly attractive for making cheap hydroelectric energy available to a rapidly growing, newly born, Federal State and to future developments located over a vast geographic area having enormous economic potential. Six hydroelectric plants are expected to be built along the same route in the next two decades and two other transmission links (500kV AC) are planned to cater for this additional generation. The network synthesis software utilized by Eletrobrás to produce the various transmission alternatives, considering several scenarios, has advanced graphical user interface and employs optimization based sensitivity indices to rank and select the best alternatives [9,10].

System Model Description

Figure 1 pictures the geographic locations of the current and future transmission lines associated with the planned interconnection which links the Serra da Mesa power plant (Central-West Region) to the Imperatriz substation (North Region). The six planned hydroelectric developments in the Tocantins River Basin can be seen in this figure: Cana Brava, Peixe, Ipueiras, Lajeado, Tupiratins, Serra Quebrada. Various scenarios of energy exchange have been studied by Eletrobrás/GTQD, but only two are dealt with in this paper. Table 1 summarizes the power exchanges between regions for the chosen scenarios A and R.

	North → Southeast	North → Northeast
Scenario A	-1000 MW	700 MW
Scenario R	+1000 MW	-700 MW

Table 1 - Major Power Exchanges between Regions for Scenarios A and R



Courtesy of Eletrobrás / GTQT

Figure 1 - Geographic Map of the Proposed North-South Interconnection

Preparing the dynamic data files on this large system for the small-signal stability program was a major task. Load modeling adopted was constant-current for the MW load and constant-impedance for the MVAr load. Detailed data for generator plus excitation systems and HVDC link have been used. Network and dynamic data are quite reliable as a result of a continuous effort by Eletrobrás and major Brazilian utilities in the maintenance of such a large data bank. Correct governor and turbine modeling are highly important to the study of such a low frequency oscillation. The governor/turbine effects are however not yet considered in this inter-area oscillation study. The system model comprises 1603 buses, 2676 lines, 91 generating plants and approximately 800 state variables.

Modal Analysis of the Inter-Area Oscillation

All results in this paper were obtained with PacDyn, a comprehensive small-signal stability package, developed by CEPEL [3]. Therefore, even the time response plots presented were produced by step disturbances applied to the linearized power system model. The linear time responses, for systems containing fast-acting devices (HVDC links, FACTS devices) are obtained 50 times faster than those of current transient stability programs. The preliminary tuning of oscillation damping controllers are therefore much more rapidly verified when using these linear step responses.

Attention is centered on the poorly-damped North-South inter-area mode, whose frequency varies from 0.16 Hz (scenario A) to 0.13 Hz (scenario R). Figure 2 and Figure 3 display the time responses, for scenarios A and R respectively, for the terminal powers of five major generating plants following a chosen step disturbance. This disturbance comprises a positive 1% step change to the mechanical powers of generators Xingó and P. Afonso 4 (located in the Northeast Region), combined with a negative 1% step change to the mechanical powers of S. Simão and Itaipu generators (located in the Southeast and South Regions). This disturbance was used to produce all the time responses pictured in this paper. The terminal power deviations in all plots are for the following generators: Tucuruí, P. Afonso 4, Xingó, Sobradinho and São Simão. Low-damped oscillations, of frequency about and above 1 Hz, are noticeable in some plants. This could be fixed with more careful PSS tuning (or modeling), but it was left untouched to help the reader gain a perspective view on the wide range of frequencies associated with electromechanical oscillations in this system. The eigenvalues associated with the North-South inter-area mode are shown within parenthesis in Figure 2 and Figure 3. Figure 4 shows the time plots for the active power flow deviations in the North-South tie-line for both scenarios, showing sustained oscillations for scenario R.

Figure 5 compares the North-South tie-line power flow obtained by step-by-step numerical integration on the full size system (800 state variables) with that obtained by Inverse Laplace Transform of a step disturbance applied to the 4th order transfer function equivalent model. The 4th order model was obtained according to the methodology described in [11]. The step response of the reduced model was produced by computing every 20 milliseconds the 4th-order approximation to $y(t)$:

$$y(t) \;\cong\; \frac{R_1}{\lambda_1}(e^{\lambda_1 \cdot t}-1) \;+\; \frac{R_1^*}{\lambda_1^*}(e^{\lambda_1^* \cdot t}-1) \;+$$

$$+\; \frac{R_2}{\lambda_2}(e^{\lambda_2 \cdot t}-1) \;+\; \frac{R_2^*}{\lambda_2^*}(e^{\lambda_2^* \cdot t}-1)$$

where the upperscript ‘*’ denotes complex-conjugate, and:

$\lambda_1 = -0.011 \pm j\, 0.802$ $\qquad R_1 = -0.006 \pm j\, 0.251$

$\lambda_2 = -0.275 \pm j\, 0.0044$ $\qquad R_2 = -0.039 \pm j\, 0.007$

Highly reduced models for power system transfer functions were reported to be very effective for robust controller design [7,12,13,21], but this topic is not dealt with in this paper.

The analysis of the mode shapes and residue ranking lists [1,4,14,15] reveals those system components mainly involved in the system oscillations and also the most suitable to exert damping action.

The rotor-speed mode shape for the inter-area mode pictured in Figure 6, shows the generators in the North-Northeast oscillating coherently against those in the South-Southeast. The residue ranking list (Figure 7) of transfer functions $\Delta\omega_i(\lambda)/\Delta V_{ref}^i(\lambda)$, $i = 1, \ldots, Ng$ (Ng being the total number of system generators, and λ = -0.011 ± j 0.802) help locate the most effective generators to be equipped with power system stabilizers to damp the inter-area mode. Note that ranking is based on the relative moduli of the various transfer function residues.

The residue ranking list (Figure 8) of transfer functions $\Delta P_{line}(\lambda)/\Delta B_{line}(\lambda)$, $line = 1, \ldots, Nl$ (Nl being the total number of lines in the system) help determine the most effective lines to place a Thyristor Controlled Series Compensator (TCSC) to damp the North-South inter-area mode [14,15]. As expected, the plot in Figure 8 points the various sections of the North-South tie-line as 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 (see Figure 1), is also a good candidate for TCSC damping control of the North-South inter-area mode.

Two alternatives for damping control of the North-South mode were studied, and are described in the following sections.

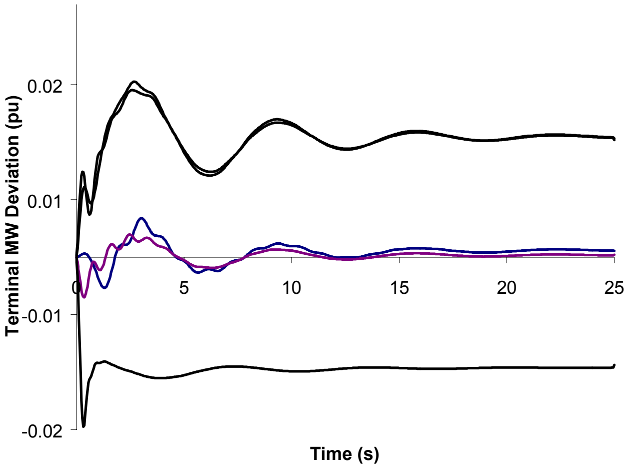


Figure 2 - Time Responses of Major System Generators for Scenario A (λ = -0.172 ± j 0.98)

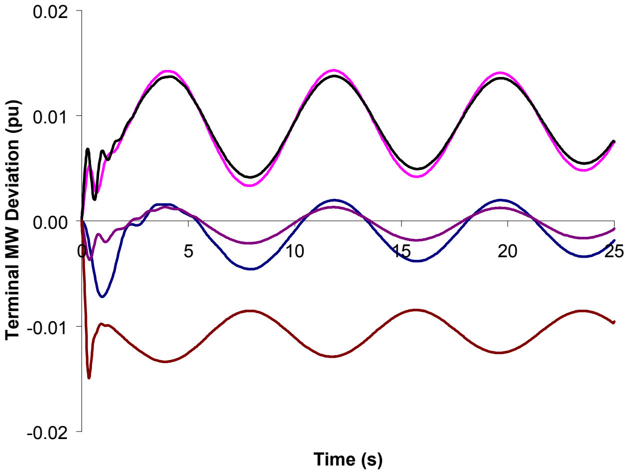


Figure 3 - Time Responses of Major System Generators for Scenario R (λ = -0.011 ± j 0.802)

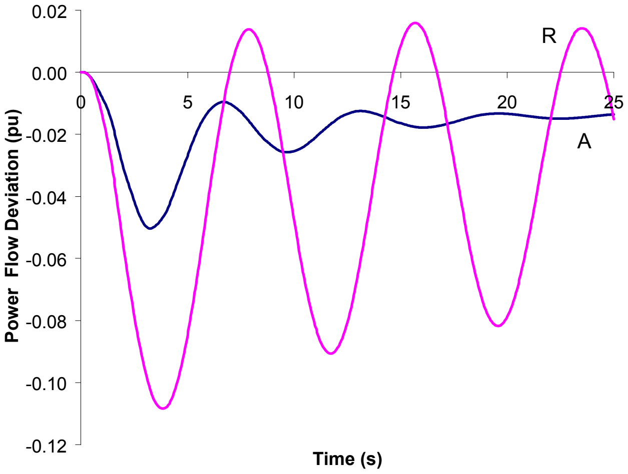
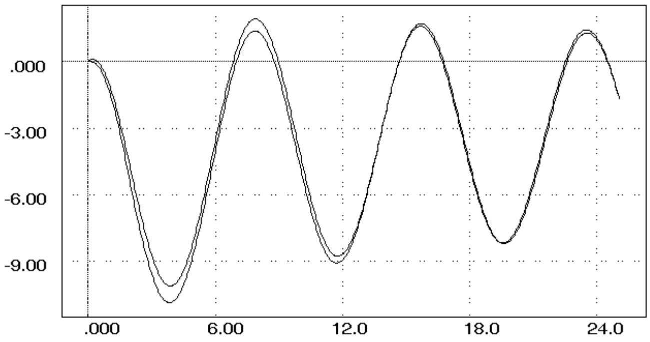


Figure 4 - Active Power Flow in the North-South Tie-Line (Scenarios A and R)



NOTE: Values in the y-axis should be multiplied by 10^{-2}.

Figure 5 - Active Power Flow in the North-South Tie-Line. Responses of the Full Model and the 4th order Reduced Model (λ_1 = -0.011 ± j 0.802; λ_2 = -0.275 ± j 0.0044)

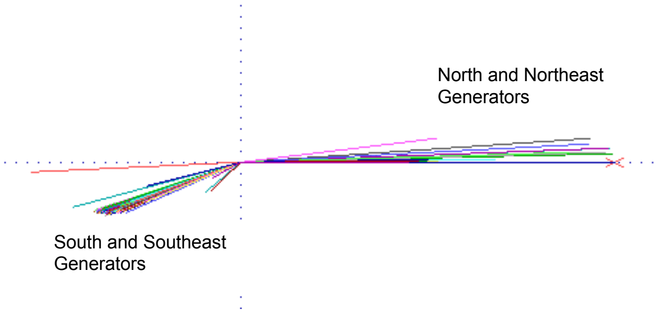


Figure 6 - Rotor Speed Mode Shape for Inter-Area Mode (λ = -0.011 ± j 0.802)

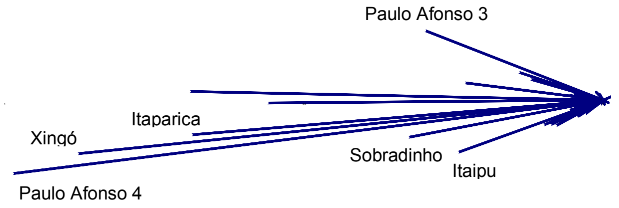


Figure 7 - Phasor Diagram Representation of Transfer Function Residues, used to Determine the Most Effective Generators for Installing Stabilizers (λ = -0.011 ± j 0.802)

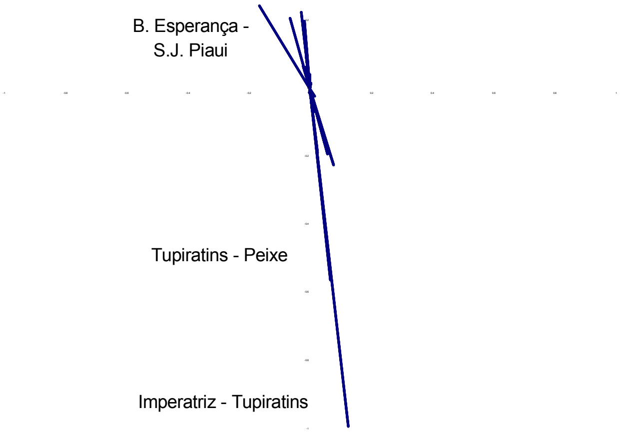


Figure 8 - Phasor Diagram Representation of Transfer Function Residues, used to Determine the Most Effective System Branches for Installing TCSC Devices. (λ = -0.011 ± j 0.802)

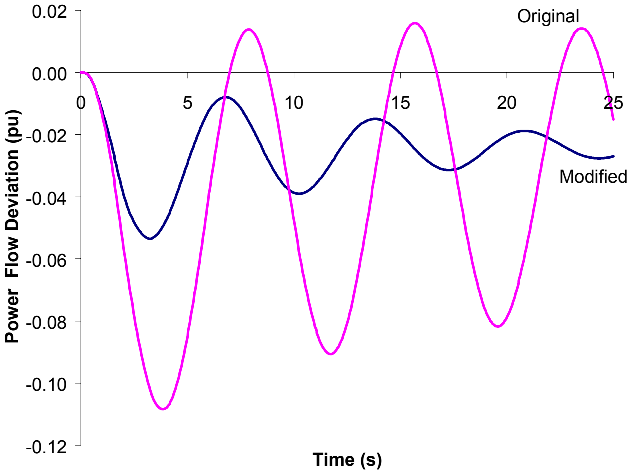


Figure 9 - Tie-Line MW Power Flows for Original and Modified Stabilizers in Xingó and P. Afonso 4 (Scenario R)

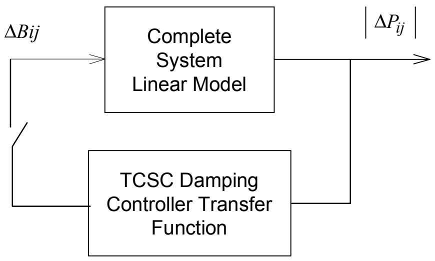
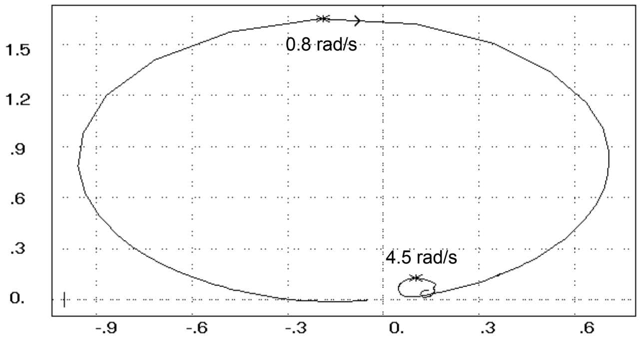
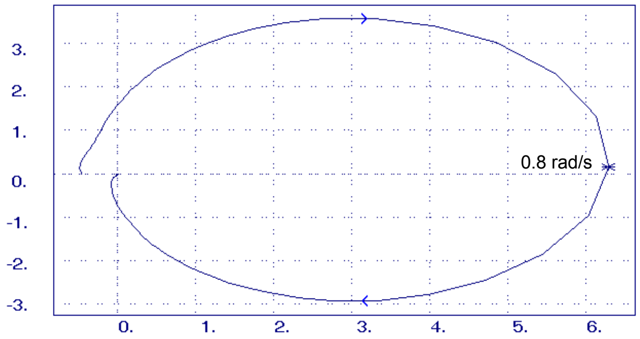


Figure 10 - Diagram Showing the TCSC Damping Controller Being Added to the Power System Model



Note: x-y axes define the complex plane

Figure 11 - Frequency Response of $\Delta\left|P_{ij}(s)\right|/\Delta B_{ij}(s)$ for Scenario R.



Note: x-y axes define the complex plane

Figure 12 - Frequency Response of Transfer Function $\left(\Delta\left|P_{ij}(s)\right|/\Delta B_{ij}(s)\right)\cdot\mathrm{TCSC}(s)$, for Scenario R

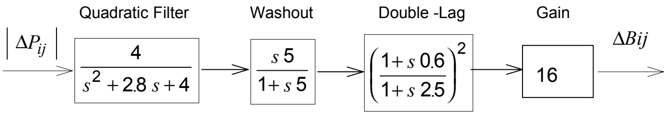


Figure 13 - Block Diagram for TCSC Damping Controller

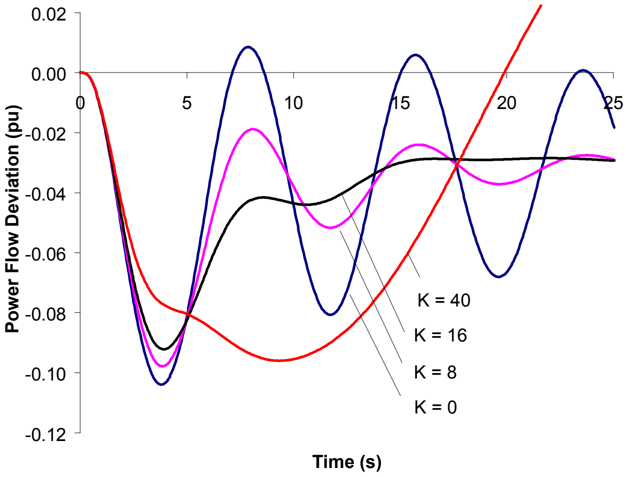


Figure 14 - Time Response of Tie-Line MW Flow as a Function of TCSC Damping Controller Gain (Scenario R)

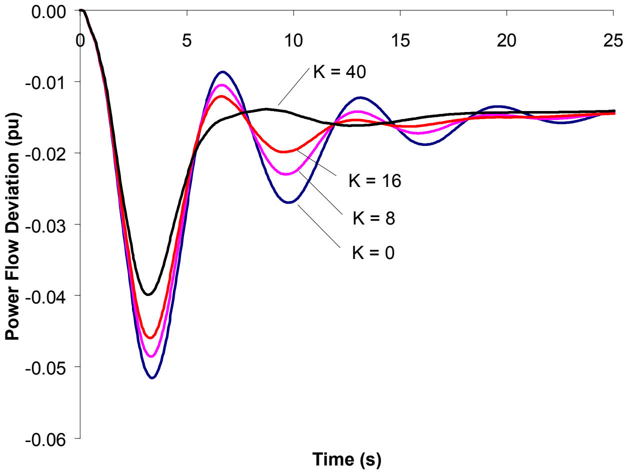


Figure 15 - Time Response of Tie-Line MW Flow as a Function of TCSC Damping Controller Gain (Scenario A)

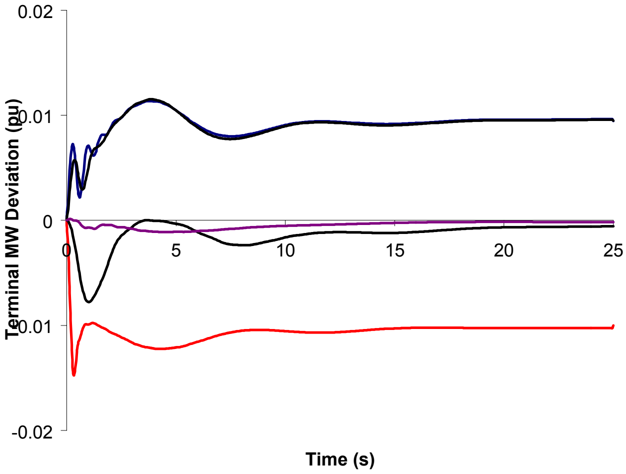


Figure 16 - Time Responses of Major System Generators for Scenario R with TCSC Damping Controller (λ = -0.251 ± j 0.823)

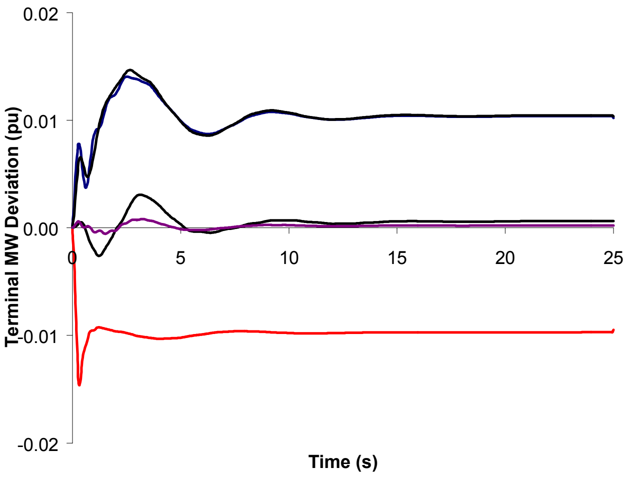
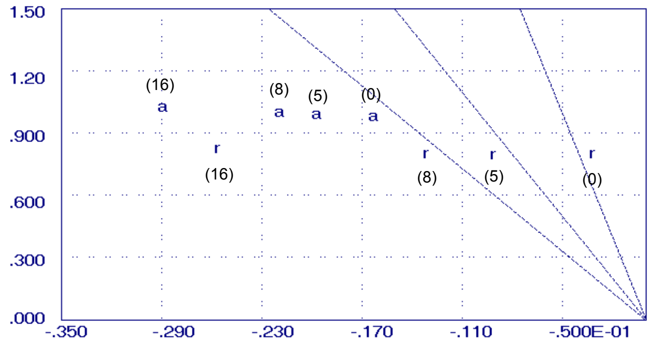


Figure 17 - Time Responses of Major System Generators for Scenario A with TCSC Damping Controller (λ = -0.286 ± j 1.022)



Note: TCSC gains are shown within parenthesis

Figure 18 - Inter-Area Eigenvalue Locus as a Function of TCSC Damping Controller Gain (Scenarios R and A)

Damping Control of the Inter-Area Mode of Oscillation by Modified Stabilizers

The ranking list in Figure 7 shows P. Afonso 4 and Xingó as the most adequate generating plants to install damping sources for this inter-area mode. These two generators already have power system stabilizers (PSS), which were then modified in order to damp the low frequency inter-area mode. Figure 9 compares responses of the tie-line MW flow with and without the modified PSS's. This damping control alternative presents, however, several disadvantages as compared to the TCSC alternative described in the following section. These disadvantages are listed below:

1. The modified PSS's, assumed to be of fixed structure and fixed parameters, would not always ensure adequate damping for the North-South mode for the various scenarios considered in the study;
2. Modified PSS's would be needed in all major power plants of the Northeast Region;
3. The frequency range of electromechanical oscillations, to be damped by the modified PSS's, is too wide to yield reliable operation;
4. Electromechanical oscillations within the Northeast Region and between the North-Northeast Regions could have their damping reduced by the action of these modified PSS's;
5. Practical limitations on maximum PSS gain at very low frequencies may reduce the damping action of these modified stabilizers.

Oscillation Damping by TCSC Modulation

The ranking list in Figure 8 showed the effectiveness of modulating the series impedance of the line sections in the North-South tie-line so as to damp the inter-area mode. There are two series capacitor banks in this tie-line. The idea of transforming part of a fixed series capacitor bank into a TCSC are shown here to be highly justified for dramatically increasing inter-area oscillation damping.

The TCSC based damping is considered to be a much more attractive alternative than the modification of stabilizers in the Northeastern generators. Additionally, the damping source for the inter-area mode would be directly located in the North-South tie-line. In the event of an interconnection break-up, the inter-area mode of oscillation together with the TCSC damping action cease to exist .

The TCSC damping controller must be robust to power flow reversal in the tie-line. Variables like line current magnitude, moduli of active or reactive power through the tie-line should therefore be used for they have been shown to be robust to power flow reversal [16,20]. TCSC modulation, derived from these variables has its oscillation damping effectiveness increased with the level of tie-line transfer [1,15,16], which is a valuable characteristic. The tuning of the TCSC damping controller will be initially made for the worst condition (scenario R) and later tested for robustness on scenario A, which presents tie-line power flow reversal.

Controller tuning will be carried out by frequency response design (Nyquist stability criteria) as described in [2]. The needed range of variable series capacitor compensation must be determined from transient stability studies, which are out of the scope of this paper.

Figure 10 shows a schematic diagram for the interconnected system and the TCSC damping controller, with the latter modeled as a feedback control loop. The TCSC damping action is exerted by varying the effective series capacitor reactance (ΔB_{ij}) in response to deviations in the modulus of tie-line MW power (ΔP_{ij}).

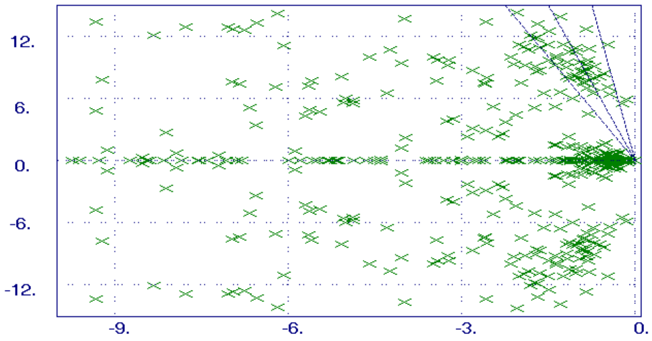
Figure 11 shows the Nyquist plot for the $\Delta\left|P_{ij}(s)\right|/\Delta B_{ij}(s)$ transfer function, where indices i and j stand for the terminal buses of one series capacitor bank in the North-South tie-line. In order to improve damping of the North-South mode, it is necessary to phase compensate the transfer function in Figure 11 so as to rotate clockwise the Nyquist plot by 90°, around a center frequency of 0.8 rad/s. Note that phase rotation is non-linear with applied frequency, distorting the original plot and identifying potential problems associated with the loop closure.

Both lead and lag compensation were tried in this case, but lag compensation proved more robust when taking both scenarios R and A into consideration. Figure 12 shows the plot of $\left(\left|\Delta P_{ij}(s)\right| / \Delta B_{ij}(s)\right) \cdot TCSC(s)$, where $TCSC(s)$ is the designed 5th - order transfer function for the damping controller.

Note, in Figure 12 , the effectiveness of the designed transfer function in quenching dynamic activity beyond 2 radians/second (0.3 Hz). The TCSC damping controller transfer function is shown in Figure 13, including a quadratic filter to reduce gain for frequencies higher than 0.3 Hz. The Nyquist plot in Figure 12 shows there is a value for the TCSC gain (k=32) beyond which the system becomes unstable. The value adopted for the TCSC controller gain (k=16) assumes that a gain margin of 2 is adequate .

Figure 14 pictures the North-South tie-line power flow transients for different values of gain in the TCSC damping controller (Scenario R). TCSC gain is limited by the appearance of an instability at a lower-frequency, a fact not uncommon when using phase lag compensation in damping controllers. This lower frequency mode is shown in Figure 14 to become unstable for higher values of TCSC gain (k > 32), as predicted by the Nyquist plot in Figure 12. Figure 15 shows the tie-line power flow transients for different values of TCSC gain (Scenario A).

Figure 16 and Figure 17 picture, for scenarios R and A with the TCSC controller, the terminal power deviations for the five major generators. The previous four figures clearly demonstrate the robustness of the TCSC damping controller to tie-line power reversal. Figure 18 shows the locus of the complex eigenvalue associated with the North-South inter-area mode for different values of TCSC gain (Scenarios R and A).



Units: x-axis in seconds^{-1}; y-axis in radians/s.

Figure 19 - Eigenvalue Spectrum of the 50,000 MW, North-South Interconnected, Brazilian Power System (Scenario R, with TCSC Modulation)

Nowadays, the full QR eigensolution for a 1000th order matrix can be fast and reliably obtained on any modern workstation. In order to dismiss remote fears regarding the existence of hidden modes, poorly damped or unstable, the full eigenvalue spectrum for the North-South interconnected Brazilian system is displayed in Figure 19. The three dotted lines, near the vertical axis, correspond to damping factors of 5, 10 and 15%. Note that three pairs of eigenvalues have damping factors smaller than 5%, a value usually taken as the acceptable minimum. Stabilizer placement or retuning would damp these three modes.

Conclusions

This paper reports the productivity gains achieved with the use of a comprehensive small-signal stability package in the damping analysis and control of the North-South inter-area mode. The package utilized was PacDyn, developed by CEPEL. PacDyn is quite powerful for small-signal stability analysis of large systems, individual controller design, model reduction and graphical display of results. It lacks, still, better tools for the coordinated design of the various system controllers dispersed throughout the system [17]. It does not yet consider robustness issues in controller design [6,8,21]. There is, therefore, a lot of extra development needed regarding controller synthesis.

The use of linear step response simulation, proved once again very valuable in the oscillation damping analysis and control of large systems. Obtaining the time response of the linear model takes 50 times less CPU time than that needed by current transient stability programs.

The authors believe that small-signal stability analysis tools will be increasingly used in major dynamic stability studies, to understand better the nature of the problems, compare control alternatives and determine preliminary settings for all system controllers, among other tasks. It must be emphasized that they are never a substitute to the non-linear transient stability program. The authors reckon the difficulties in pushing utility engineers to use new (and complex) software in production studies. These barriers are only overcome when the results produced by these new software prove to be a fundamental complement to those obtained with the other existing software.

During the IV SEPOPE, one panelist commented on the pressing need to turn small-signal stability packages more amenable to the non-specialist power systems engineer. The first two authors, when developing PacDyn over the last two years, have always kept this objective in mind. Despite the improvements made, it is still true that good usage of a software like PacDyn can only be made by a power system dynamics and control specialist. Anyhow, the same applies whether an advanced transient mid-term stability program is to be effectively utilized.

Acknowledgments

The authors would like to thank the support of Mr. Benedito A. Carraro, Planning & Engineering Director and Mr. J. Carlos Sili Salomão, Head of Transmission Planning Department, Eletrobrás. The following CEPEL engineers are also thanked for many helpful discussions, support and insightful comments: Mr. Xisto Vieira Filho (General Director), Mr. Marcio Szechtman (Research & Development Director), Mr. Eurico Salgado (Power System Planning and Operations Program, Manager), Mr. Antonio R.D. Carvalho and Mr. W.W. Ping (Senior Research Engineers).

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