# Extensive PSS Use in Large Systems: the Argentinean Case

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**Abstract**: In 1994 the Argentinean Interconnected System (SADI) presented the need to introduce some operative improvements in order to increase the generation capacity, by eliminating the transmission constraints caused by stability problems.

The Argentinean Energy Department instructed CAMMESA - the System Independent Operator - to accomplish the Project "SADI Stabilizing Resources".

The Project's objective was to increase the transmission capacity of the Comahue 500kV transmission lines, from 2,700 MW to 3,300 MW, eliminating the lack of damping which in 1995 brought very important transmission restrictions.

CAMMESA defined the results to be achieved, as well as the necessary studies and corrective actions. The most important action was to implement an extensive PSS use. CAMMESA also contracted other companies for consulting, performing studies and supplying of equipment.

This work presents the activities of PSS implementation, including field tests and an analysis of the Interconnected Power System. Not only the individual results are presented, but also the overall damping results. It also covers some changes in controllers and other developments related to the installation of new stabilizers.

**Keywords**: Oscillations, Damping, Stabilizers, Monitoring, Strategies.

## I. INTRODUCTION

The SADI is a radial system with important branches such as Comahue, Yacyretá and NOA. Figure 1 shows its general diagram.

A higher generation offer, in areas located very far from the load center, increased the transmission requirements, so that the interconnected grid came to be the most critical part of the system. This enforced the need for the "SADI Stabilizing Resources" [2]. The original Project was based upon studies made for the Comahue Generators, bottom left of the grid shown in Figure 1, where hydraulic generation is heavier.

An initial analysis pointed the necessary studies and corrective actions:

- processes and control systems identification and modeling;
- transient and small signal stability studies;
- extensive PSS use by retuning existing ones and introducing a few of them where they lacked;
- use of an Automatic Generator Dropping scheme;
- application of Oscillation Monitoring Systems - OMS.

Scenarios and conditions were defined, where mathematical models should respond, with good fidelity, like the real system. For this purpose, another company conducted specific tests in the generating units. Some generators, turbines and controllers that didn't have reliable models were identified in a short time.

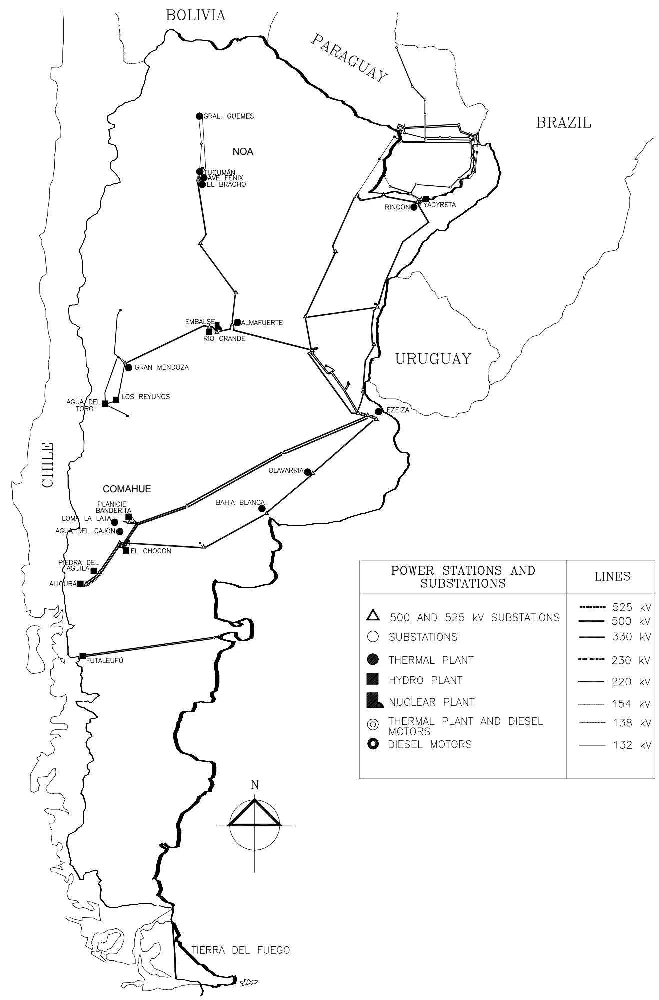


FIGURE 1 - The SADI.

PSS tuning studies were carried out, based on small signal analysis, followed by lots of transient stability runs, to serve as guidelines for the PSS setting and field tests.

PSS were installed in all of the largest power stations: a total of seventy three units, amounting to a installed capacity of 12,503 MW, a value higher than the country's 1996 peak load. Around fifty units were first specified to have their analog PSS (electric power based) retuned only. Because of the short commissioning time, lower costs and the many advantages of a new digital PSS (based on the integral of accelerating power), the installation of new PSS in all power stations proved to be the best solution.

Six OMS were supplied to the most important system substations, for the monitoring of electromechanical oscillations. When oscillations occur, the data is transmitted to two analysis centers, provided with curve visualization and analysis software [6].

Despite the obvious complexity of managing so many different agents, the whole project produced very good results, even surpassing the original objectives. Some inadequate operating procedures and control laws were detected in some of the power stations, and those were duly revised after the Project.

As one of the results, the Comahue area generation, previously limited to 37% of the total SADI load, could then be safely increased to a 43% level.

## II. PROJECT OBJECTIVES

One of the goals of the project was to increase the damping factor, of the low damped inter-area [7], [8] modes associated to the Comahue area, to a minimum of 15% for the base case scenarios, 10% for the case of losing one transmission system branch (the "N-1" scenarios) and 5% for the case of losing two branches of the transmission system ("N-2" scenarios). It was defined that the Supplementary Stabilization Scheme should significantly improve the damping of the inter-area modes associated with other areas. Those damping factors were limited to a minimum of 5%. The defined criteria was very rigorous. In USA, for instance, a 5% damping factor is adopted for normal operation and a lower value, 3%, is used for contingencies.

The stabilization resources should prevent the SADI from collapsing in the event of double outages (e.g. the two Comahue 500 kV lines opening during storms), reducing the amount of load shedding even under the worst operating conditions.

## III - THE ACCELERATING POWER PSS

### *1. Equipment*

The stabilizer used in this Project was the *REIVAX* digital model PWX500.

### *2 Physical Implementation*

It is mounted in a 19" rack (maximum dimensions: 483 x 177 x 230mm). With this small size, it is easily fitted in any of the commercial excitation systems.

### *3. Hardware*

The PWX500 is electronic, made with microprocessors and its control actions are numerically done.

It receives information from PTs and CTs only. Its adjustable output range (from -10 to +10VCC) feeds a suitable input resistor in the AVR summing point.

Two CPUs, one for Control and the second for Supervision/Transduction, are based on Intel's MCS 96 family of microcontrollers, developed to be used in real-time control applications.

The Control CPU does the frequency transduction, the control algorithm and all the on/off logic, parameters adaptation, etc.. The Supervision/Transduction CPU does the transduction of the generator's active power and terminal voltage. It also manages the man-machine interface.

All the controller parameters are stored in EEPROM and it is possible to make changes through a menu-driven man-machine interface, even with the system in operation.

### *4. Software*

The PWX500 runs over a real-time kernel and the synthesis of transfer functions is done through floating-point calculations. The algorithms were exhaustively tested and are based on very robust numerical integration and other techniques.

### *5. Operation Principle*

The experience in the use of the most popular types of power systems stabilizers (PSS), one derived of the speed or frequency deviation **f**, and the other derived of the electrical power **Pe**, indicates the complementary characteristics of these stabilizers.

The PSS of speed or its similar, that comes from the frequency of the terminal voltage, **f**, has good characteristics in low frequencies (below local mode frequency) and problems in high frequencies (destabilization of the exciter mode, noise, torsional oscillations) [9].

The **PSS-Pe** (power system stabilizer of electrical power) does not have any of these problems in the high frequencies, but it does have problems in the range below the local mode: voltage disturbances due to the variation of generation, load rejection, or due to the hydraulic disturbances in the turbine.

A solution would be to utilize a scheme as it is shown in the Figure 2, where **F(s)** is a low-pass filter which blocks the action of **f** in the high frequencies [13], [16].

The compensator includes the resets and lead-lags used to properly compensate the phase over a wide range of frequencies, usually from 0.1 to 3 Hz.

### *6. Block Diagram*

Figure 3 presents the PSS block diagram, with emphasis on the linear blocks.

The non-linear part of the PSS comprises the on/off logic and the non-linear reset.

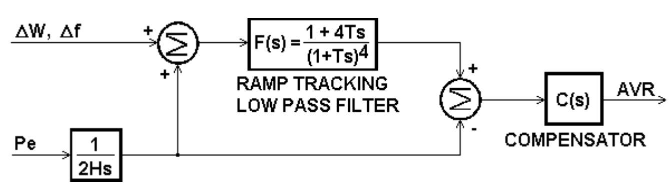


FIGURE 2 - PSS simplified synthesis.

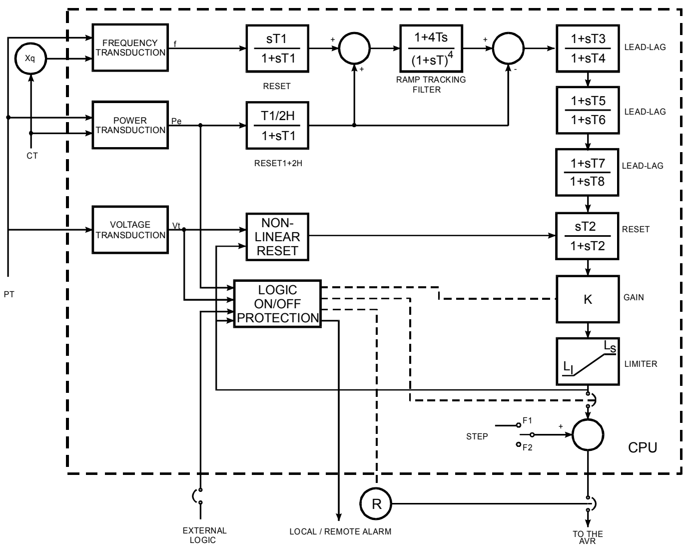


FIGURE 3 - PWX500 Block Diagram.

*7. Non-linear Reset*

In case of great disturbances, specially those involving frequency changes, a high gain PSS may reach its limits, thus losing its efficiency in damping the oscillations.

To prevent this problem, a non-linear characteristic was introduced in the last reset, in order to strongly reduce the PSS output when it reaches a certain level, associated with a terminal voltage change in the same direction [14]. A time delay avoids actuation during the inter-area or local mode oscillations. The PSS output quickly comes back to an user-defined range (e.g. ±2%) and then, the reset remains at its normal value.

This strategy avoids PSS saturation, keeps the terminal voltage at acceptable levels and maintains a good electromechanical oscillations damping during the short time when the reset is reduced.

*8. On/Off Logic*

Special care was given to the protection and on/off logic of the PWX500, in order not to put it into operation under non-favorable conditions.

All of these protections, dynamically coordinated with the output limiters, avoid excessive variations of terminal voltage, before any disturbances, either in the electrical system or inside the stabilizer.

To switch on the stabilizer it is necessary:

- machine synchronized;
- on/off switch in the frontal rack in the ON position;
- no faulty CPU or power supply.

The stabilizer gain can be changed as a function and over a pre-defined active power range, for generating or pumping operating conditions. For pumping operation, the polarity is also changed.

The prohibited operation range, gains, normal PSS output and limit values are easily entered through the man-machine interface, in order to get the stabilizer permanently ON or to switch it OFF safely with the stabilizer output in normal levels:

negative output ≤ output PWX500 ≤ positive output

*9. Protections*

There are some conditions where the PWX500 is switched-off:

- internal stabilizer failure;
- loss of frequency signal;
- opening of the group circuit-breaker or any other external command defined by the user;
- high or low generator voltage, with stabilizer contributing to aggravate the problem.

## IV. IDENTIFICATION AND MODELING

The accuracy of the system database, mainly the controller models, was initially questioned and therefore there was a need for identifying some controllers and processes.

The controllers, governors and excitation systems were identified by means of field tests, looking for static and dynamic characteristics using the classical methodology [4]. Load rejection tests [5] were done to obtain the generators parameters. All these activities were done in a short time.

## V. STABILITY STUDIES

*A. Transient Stability*

Studies were performed for two year's ahead scenarios. Comparisons between new and old scenarios were done through severe disturbances simulations.

Simulations were made to analyze the performances of brake resistors (used at El Chocón and Planicie Banderita), Automatic Generation Dropping and load shedding schemes.

The simulation results also became a reference for PSS tuning and commissioning. Unexpected on-site responses required an extra effort to update the models.

Transient and small signal stability studies were done almost simultaneously, both receiving feedback from the field stabilizers tests. This suitable procedure was taken because of the restrictions that affected some recommended settings in some particular power stations, like El Chocón. In this power station, a fast Joint Voltage Control, JVC, required field set tings quite different from those indicated by the studies. In other power stations, the estimated lead compensation was not implemented due to excessive noise or lack of damping of the exciter mode.

*B. Small Signal Stability*

The dynamic stability study [3] was done through modal analyses techniques [10], with a linearized system representation. The passive elements, controllable static compensators, rotating machines and their controllers were modeled. The evaluation of the dynamic stability was based in the damping factors of the eigenvalues associated to the various oscillation modes, taking into account different configurations and network operating conditions. A total of 85 scenarios, considering generation dispatches and transmission system configurations, 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.

Through the use of PACDYN [11] software, it was possible to analyze a lot of important aspects, such as:

- dominant modes of intra-plant, local, multi-machines and inter-area oscillations;
- observability of critical modes in relevant variables;
- transfer function residues, considering single or double contingencies applied in different points of the electrical network;
- PSS tuning for each generating unit, taking into account the machine running against an infinite bus or connected to the power system;
- sequential analysis of an electrical configurations set with different loads and generation dispatches, observing the variation of the dominant poles for a specific transfer function.

Two dominant modes existed in the Comahue area: one ranging from 0.43 to 0.52 Hz and the other from 0.52 to 0.60 Hz. Their damping, considering the presence of all the new stabilizers and constant impedance loads, remained above 20% for all base case scenarios. With a more realistic load model, constant-I (MW) and constant-Z (MVAr) adopted in the study, the PSS gains needed to be raised in order to kept the damping for these two modes above 15%. With these new PSS settings, the damping levels specified in the "Call for Bids", namely: 15% for base cases, 10% for "N-1" scenarios and 5% for "N-2" scenarios, could be achieved in the small signal stability studies.

Field tests and measurements showed some model inaccuracy. A review of the studies detected 7 "N" cases with damping factors lower than 15% and 11 "N-1" cases with damping factors lower than 10%. The "N-2" cases had damping factors higher than 5%. The problem was associated to the very poor dynamic performance of the Joint Voltage Control at El Chocón and Planicie Banderita. Later on, the voltage control laws of both power stations were significantly modified.

The studies also concluded that a slight degradation in the damping of the inter-area modes occurred when the governors were represented.

The small signal stability studies not only supported the transient stability simulations and the PSS tuning, but also helped to find a suitable location for the OMS. The work was done through the calculation of the observability factors, related to the two dominant eigenvalues associated to the Comahue area, and the other two modes associated to the other areas.

*C. Other Studies*

In some cases other type of studies, basically simulations, were necessary to support the field tests, particularly in special and unusual cases. These simulations were done by the field personnel and by the people that supported the tests at REIVAX headquarters. The Figure 4(a) shows a step response simulation at El Chocón with the machine running without PSS at 140 MW and 0 MVAr, in individual voltage control (IC) and in Joint Voltage Control (JVC). In this simulation only two machines are being represented, but in Figure 4(b) a field test is shown, when six machines were operating. It is possible to observe the significant difference in the machine behavior, mainly in the static gain, when submitted to the several control modes. It should also be noticed that with six machines the gain is much higher.

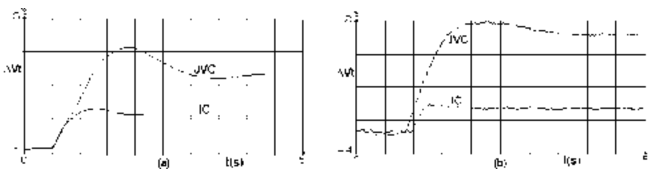


FIGURE 4 - El Chocón, 1% step response in one machine:
(a) - simulation with two machines in JVC;
(b) - field test with six machines in JVC.

## VI. IMPLEMENTATION

There were two power stations already equipped with the PWX500, in the Argentinean system, as shown in Table 1.

TABLE 1 - PSS REIVAX already operating in 1996.

| STATION | TYPE | UNITS x POWER |
|---|---|---|
| Loma de la Lata | Gas | 3 x 125 MW |
| Agua del Cajón | Gas | 1 x 125 MW |

New PSS implementations were split out in two phases, according to a strategy of first improving system damping in the most critical areas, and to a time schedule agreed upon among the many private agents involved in the project.

*A. Project Phase #1*

*A.1 Power Stations*

In Phase #1 the new PSSs were installed at the power stations listed in Table 2.

TABLE 2 - Power Stations

| STATION | TYPE | UNITS x POWER |
|---|---|---|
| Alicurá | Hydro | 4 x 250 MW |
| Agua del Toro | Hydro | 2 x 65 MW |
| El Chocón | Hydro | 6 x 215 MW |
| Los Reyunos | Hydro | 2 x 112 MW |

| | | |
|---|---|---|
| Planicie Banderita | Hydro | 2 x 230 MW |
| Rio Grande | Hydro | 4 x 189 MW |
| Piedra Buena | Coal | 2 x 310 MW |

The small signal stability studies pointed out a significant increase in the damping factors after this phase: they changed from a 2.5-5.9% range to 10.5-15.2% range depending on the dispatch condition. However, as it was seen later, there were modeling inaccuracies. The modeling corrections resulted in some inter-area modes damping lower than specified. This problem was solved by retuning the stabilizers in El Chocón and Planicie Banderita, at a later occasion.

*A.2 Field Tests*

Figures 5, 6 and 7 depict the step responses at the power stations of Alicurá, Planicie Banderita and Rio Grande.

A good performance could be observed in the damping of the intra-plant mode in all the machines tested.

Figure 8 shows the impact on the voltage in a fast load decrease at Alicurá, with the old and the new PSS. It's possible to observe the superior performance of the new PSS in rejecting variations of the mechanical power.

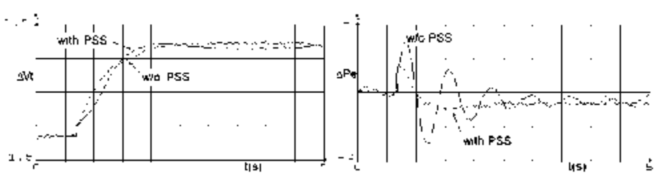


FIGURE 5 - Alicurá: 1% step response (250 MW).

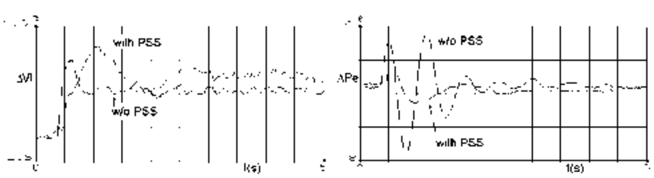


FIGURE 6 - Planicie Banderita: 1% step response (160 MW).

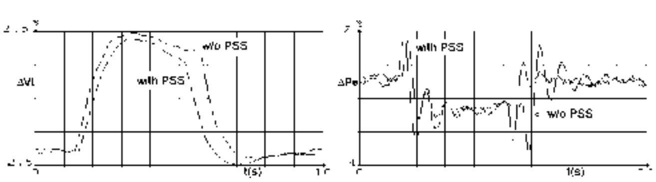


FIGURE 7 - Rio Grande: 2% step response (170 MW)

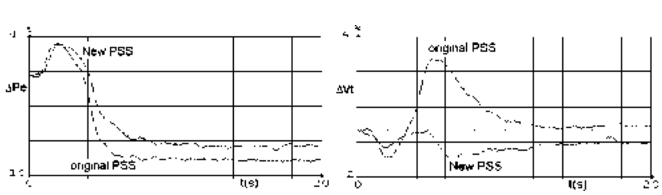


FIGURE 8 - Fast load decrease at Alicurá (starting from 89%).

*B. Project Phase #2*

*B.1 Power Stations*

Phase #2, carried out three months later, involved tests and PSS comissioning in the power stations listed in Table 3.

TABLE 3 - Power Stations

| STATION | TYPE | UNITS x POWER |
|---|---|---|
| Piedra del Aguila | Hydro | 4 x 350 MW |
| Salto Grande | Hydro | 14 x 135 MW |
| Yacyretá | Hydro | 20 x 155 MW |
| Agua del Cajón | Gas | 1 x 125 MW |
| Agua del Cajón | Gas | 5 x 48 MW |
| Güemes | Gas | 2 x 60 MW |
| Güemes | Gas | 1 x 125 MW |
| Embalse | Nuclear | 1 x 648 MW |

*B.3 Field Tests*

Figures 9 and 10 depict the step responses at the power stations of Piedra del Aguila and Embalse.

A good performance could be observed in the damping of the intra-plant mode in Piedra del Aguila. It was also possible to observe a good behavior in the local mode damping (one single machine) in Embalse.

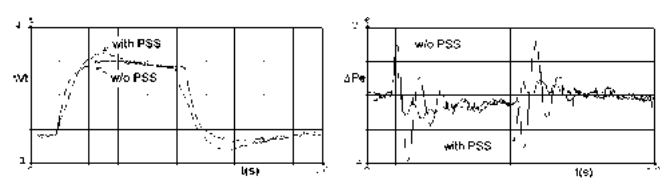


FIGURE 9 - Piedra del Aguila: 1% step response (350 MW).

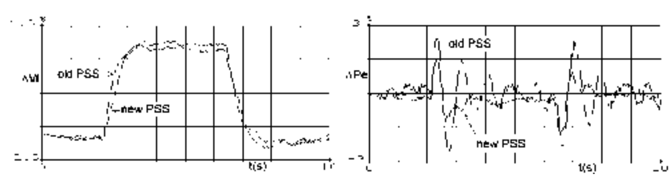


FIGURE 10 - Embalse: 1% step response (648 MW).

*C. Overall Results and Difficulties Faced in the Project*

Besides being such a large project, PSS implementation had to handle a few difficulties, such as:

- The slow response of brushless and rotating exciters required further care to tune the PSS for damping intra-plant modes;

- The fast JVC, mainly at El Chocón and Planicie Banderita, amplified the intra-plant modes. Furthermore, the JVC made the reactive power highly sensitive to mechanical power variations, even using the integral of accelerating power PSS, which is well known as having high rejection to that action;
- The different AVR adjustment criteria for machines within the same power station;
- The short time scheduled by the owners for commissioning critical power stations (in a six-machine gas based power station the PSS were all adjusted during one night).

Figure 11 shows a 0.5% step response test of one machine at El Chocón, under JVC, with all the six machines at full load. It must be observed the strong steady-state amplification, caused by the astatic characteristic of the JVC in the 500 kV bus side that greatly increases the static gain of the GEP(jw) function [15].

Figure 12 shows the different step responses obtained for three machines of Agua del Cajón at the same on-load operating condition.

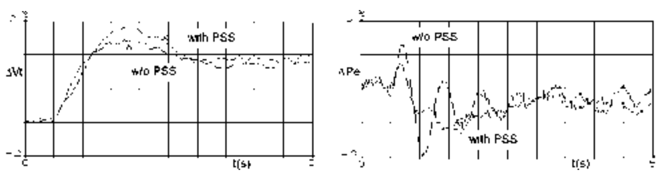


FIGURE 11 - El Chocón: 0.5% step response (200 MW).

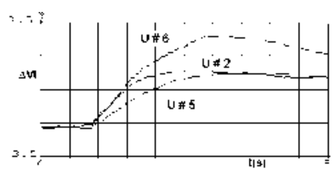


FIGURE 12 - Agua del Cajón: 1% step responses.

## VII. TESTS OF THE SADI

Some tests were conducted over the SADI to check performance and compare them to the transient stability simulations [1]. Recordings of these tests were produced by the OMS. Even though it was not possible to reproduce exactly the same system operating conditions, the results, in general, can be considered good. A reasonable approximation was obtained. The stability studies were found to be very conservative, because the system showed better damping than anticipated from the studies.

Figure 13 presents the active power flow transients in the El Chocón - Puelches 500 kV line for a three-phase disconnection (test #1) and single-phase fault (test # 4) in the Chocón Oeste - Choele Choel line (El Chocón side). Figure 14 presents the active power flow transients in the Rincón - Resistencia line in the same test. The simulations and tests are both presented.

Figure 15 presents the results in the Rincón - Salto Grande 500 kV line for a single-phase fault in the Resistencia - Romang line (Resistencia side).

Figure 16 presents the power flow transients in the Rincón - Yacyretá line in the same test. The simulations results and tests are compared in this plant.

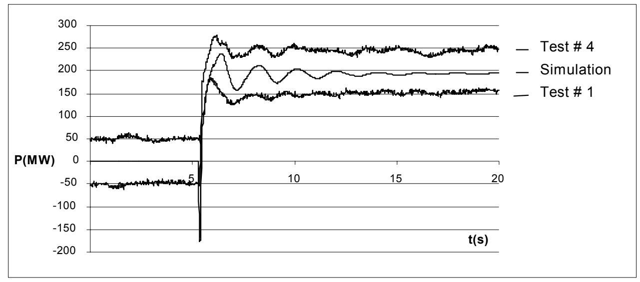


FIGURE 13 - Active power: El Chocón - Puelches line.

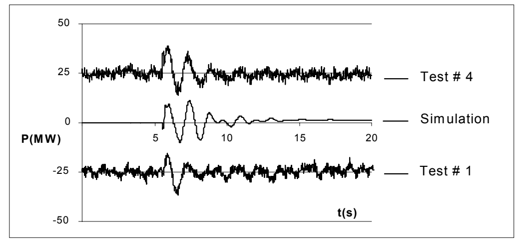


FIGURE 14- Active power: Rincón - Resistencia line.

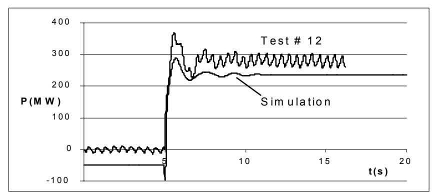


FIGURE 15 - Active power: Rincón - Salto Grande branch.

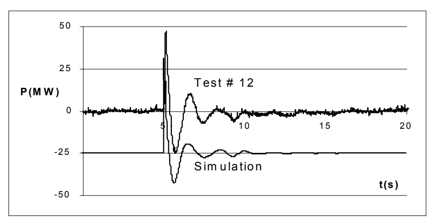


FIGURE 16 - Active power: Rincón - Yacyretá branch.

## VIII. FOLLOW-UP WORK

As a consequence of the fine results of this Project, four additional power stations, listed in Table 4, were equipped with new PSS. This added 1,126 MW to the generation implemented with the PWX500. Presently, the country has around 50% percent of the total installed power equipped with accelerating power PSS.

TABLE 4 - New PSS after the Project

| STATION | TYPE | UNITS x POWER |
|---|---|---|
| Futaleufú | Hydro | 4 x 100 MW |
| Tucumán | Gas | 2 x 140 MW |
| Ave Fenix | Gas | 4 x 61 MW |

| | | |
|---|---|---|
| Aluar | Gas | 4 x 40 MW |
| Aluar | Gas | 1 x 42 MW |

The voltage control laws were modified for the first and still important power stations of Comahue: El Chocón and Planicie Banderita, which up to that time were still responsible for the voltage control in the Comahue region. Because the above machines are now operating in individual control (with a slow Joint voltage Control acting as a secondary control), it is now possible to share that task with the other big power stations of Alicurá and Piedra del Aguila. This change made possible to retune the PSS, increasing significantly its gain, and thus obtaining higher damping factors, not only for the intra-plant, but mainly for the inter-area modes.

## IX. OTHER ASPECTS OF INTEREST

In a relatively short time, the SADI went through a deep dynamic transformation. This quick change of the system's dynamic profile could have shown itself as something dangerous, something never before done in such a large electrical system. However, with the aid of the studies, the two-step commissioning of the PSS was smoothly accomplished.

Because the control systems were connected to equipment under commercial operation, implementation scheduling and test execution required an important coordination effort in order to guarantee that the field works were executed without affecting the quality of the service due to failures or unforeseen circumstances.

The work in Argentina unveiled some interesting problems of interaction between PSS and governors. In systems such as this, where the slow mode of speed regulation (periods of 20 to 40s) presents very high amplitudes, caused by significant generation loss, severe problems may appear: general lack of damping resulting from the stabilizers simultaneous output saturation, and wrong actuation of the loss of excitation protection due to the lack of coordination with the Under Excitation Limiter and the PSS. The non-linear reset solution, implemented in the PWX500, proved to be efficient, remarkably in machines with excitation systems not equipped with an Under Excitation Limiter [15].

## X. COST-BENEFIT EVALUATION

The practical aspects of the project show that PSS use adds a high benefit with a low cost, mainly if supported by tuning and small signal studies. This is still more evident if compared to other alternatives as the use of FACTS devices or the transmission expansion. The total cost of the project was around US$10 million, (including all other systems like the Automatic Generation Disconnection, underfrequency relays and the supervisory systems). This cost is fifteen times lower than that needed for the structural expansion of the transmission system.

The apparatus now in operation allows for better quality and service and yearly savings of US$9.3 million, due to the increase of around 600 MW in the transmission capacity [12].

## XI. CONCLUSIONS

CAMMESA went into a lot of effort to obtain a better dynamic performance for the Argentinean system. It must be pointed out that only with well-defined rules and responsibilities, such as defined before the electrical system privatization, the joint efforts of all the partners produced good results towards the system optimization. The Call for Bids of the Project was very clearly written and detailed, a fact which was instrumental to the overall success of this work. This new reality provides for a better utilization of the system, by eliminating stability constraints to the generators and thus increasing the available energy.

The field tests, carried out to verify the damping levels of the major inter-area modes, showed the system's improved performance.

In this work the studies and field tests complemented each other, giving consistency to such a deep dynamic transformation in the power system.

The facilities of PSS testing and settings, combined with the newly implemented field procedures, allowed to work with a minimum of interference with the system operation.

Another important aspect is the availability of data transmission resources, which allows other specialists to work together with the field people, despite the distances involved.

Unnecessary and complicated control laws, such as the JVC of El Chocón and Planicie Banderita, were replaced by more suitable and robust control laws. These changes allowed a higher damping of the dynamic oscillations between machines in these plants.

In a project within a system this large, a very advantageous cost/benefit relationship is provided by extensive PSS use. Without the above referred support facilities, such as studies, tests, etc., the costs can increase up to the point of surpassing the equipment price.

This Project also showed that, instead of studying, modeling and retuning old analog electric power based stabilizers, it is more economical and technically more effective - both for the installation and in a long-term basis - to replace them with new digital accelerating power PSS.

## ACKNOWLEDGMENTS

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