Modal Analysis of the Uruguayan Electrical Power System

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Abstract—**The Uruguayan electric power system is facing deep challenges in the near future. The plans for 2015 include a significant expansion of generation based on renewable sources (wind, biomass) and a new HVDC international interconnection. These plans and the opening to multiple, distributed private generators pose significant challenges to the system operation and planning. This work describes the modal analysis of the Uruguayan Power System by considering a base 2004 scenario and two 2010 scenarios. These scenarios include conventional–thermal and hydro synchronous generation–and constitute a reference for a set of ongoing studies associated with the new expansion plans. The system comprises a relatively small electrical network with important hydroelectrical generation and highly interconnected with the neighboring countries. The main oscillation modes, which exhibit a poorly damped behavior, are analyzed in detail. The results were validated through simulations of the systems's response for different contingencies. The study includes the selection of appropriate machines to damp the oscillations and the tuning of Power System Stabilizers, PSS. The effects of this control action are then assessed via the modal analysis and validated via complete non linear simulation of transient response.**

Index terms: **Power systems stability, modal analysis, oscillation modes.**.

I. INTRODUCTION

Uruguay faces a set of very strong challenges in its energetic infrastructure. The traditional setting, dominated by hydro and oil-based thermal generation backed up by international AC interconnection, is strongly defied by the growth of the demand, the fuel prices, the lack of predictability of the regional gas supply and a worsening of the hydric scenario. The response to this panorama are the ongoing plans of energetic expansion and diversification that specify, for the year 2015, the following goals:

- the expansion of 500 MW of installed power based on renewable sources (200 MW from biomass and 300 MW from wind farms),
- the construction of a new HVDC 500kV, 500MW interconnection with Brazil,
- the opening to multiple, distributed, private generators.

The plans constitute a significant change for a system whose main characteristics can be summarized by the following parameters:

- peak demand (winter 2008): 1.4 GW,
- annual growth: 3-5 %,
- installed generation: 2.3 GW (1.4 hydro + 0.9 thermal),
- transmission system: 1000km @ 500kV, 3550km @150kV,
- AC interconnection with Argentina: 2GVA @500kV,
- HVDC interconnection with Brazil: 70MVA.

The new scenarios pose the need of continuous and deep studies of the dynamic behavior of the electrical power system in order to assess the different projects and to orientate the update of the grid code. These dynamic studies need to be compared with a baseline, i.e. the dynamic behavior of the current system.

In this work[1] we perform a small signal stability analysis of the Uruguayan power system for two 2010 scenarios and a base 2004 scenario. There exists some previous small signal stability analysis of the Uruguayan power system that were carried on for scenarios that are no longer present [1]. So, this study is intended to be used for comparison purposes for the dynamic studies of the future scenarios, and it is part of a series of studies that are being currently developed and reported, [5], [6].

The Uruguayan network has been facing, in the period 2005-2010, a sustained growth of the demand and the addition of significant generators and industrial consumers. It is strongly connected with the Argentinian system through a double link in 500kV, and with the Brazilian system via a 70 MVA back-to-back converter. The voltages of the transmission networks are 500 and 150kV, and the sub-transmission and distribution networks are in 60 and 30kV.

Generation comes mainly from the hydro-electrical units that are located in the north and center of the country, see Fig. 1. The biggest consumer center is located in the south of the country along with the thermal electrical units. The Uruguayan power system has been facing the incorporation of new industrial consumers with the possibility to operate as consumers or generators. These new industrial consumers have installed thermal units of 140MW, consuming 90 to 120MW, and injecting the surplus to the Uruguayan power system.

The model used in this study has approximately 50 generators and 360 buses. Since hydroelectric generation plays a very important role in the system, we conceive three different scenarios for the analysis. These scenarios combine mostly thermal or mostly hydroelectric regimes, together with the power flow foreseen for 2010. We also include the power flow of 2004 for comparison reasons.

The Uruguayan power system is strongly interconnected with the Argentinian. In this paper we focus on local modes, that is, those modes that involve Uruguayan generators and that can be effectively controlled by acting without international coordination. For this reason, the Argentinian power system is described by a simplified equivalent model. The Uruguayan generators were accurately modeled, including excitation and speed controllers. The power flow and dynamic data were given by UTE (the state-owned utility). The models were built on the DSAT package [2].

We have detected two important oscillation modes, with very poor damping. The first one is directly related to the hydroelectrical generation system located at the center of the country on the Negro River, which will be denoted in the sequel as the ”Río Negro” (RN) system. The natural frequency of this mode is approximately 1.1 Hz. The second mode is associated to a big industrial plant ’Botnia’ (BT), that was recently incorporated to the system. Their respective *mode*

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[1] This work was partially supported by Grant PDT 47/05. http://www.pdt.gub.uy/

shapes and participation factors [3], bring us important information about how each generator contributes to the mode oscillation and which units are more suitable for the mitigation of the problem (for example, by locating a PSS). The influence of the load models and some contingencies on the mode properties were also studied.

The article is organized as follows. In the next Section, we present the main characteristics of the Uruguayan network and the used models. We also describe the scenarios and contingencies that we analyze later. In Section III, the modal analysis is carried on, with particular emphasis on the behavior of two important local modes. Section IV includes studies conceived to validate the models and the linear analysis with the help of several simulations of the transient response for different contingencies. The allocation and tuning of a PSS, with the analysis of the resulting performance, are shown in Section V. Finally, some comments and conclusions close the work.

II. MODEL DESCRIPTION

The model comprises around 360 buses, with nearly 50 generator units. Most of them are hydroelectrical generators. The Argentinian network is represented by a reduced model with three equivalent generators, referred as 'Ezeiza', 'Almafuerte' and 'Rodríguez', and detailed descriptions of hydroelectrical generator units at 'Yacivretá' (Y) and 'Salto Grande' ('SG', shared by Uruguay and Argentina). The Uruguayan power system model includes the complete power grids of 500 and 150, part or the grid of 60 kV and the respective transformers. Synchronous machines of the hydroelectrical units are represented by 5th order models, while thermal unit modeled with order 6. Table I presents basic info and some details of the dynamical models for the machines. For the different scenarios, the load has a ZIP representation, with 30% of constant power and 70% of constant impedance for the active power (P) and 100% of constant impedance for the reactive power (Q). The models mentioned in the table refer to the standards IEEE [7] for excitation system o PSS/E [8] models. UDM stands for *User Defined Model* of DSAT and were developed for this work.

TABLE I
DYNAMICAL MODELS

Unit	Inst. pow. (MW)	source	Exc. system	speed control
ALMAFUERTE	710	equiv.	-	-
EZEIZA	1537	equiv.	-	-
RODRIGUEZ	200	equiv.	-	-
YACIRETA	18x100	hydro	-	-
SALTO GRANDE	14x135	hydro	UDM	IEEEG3
TERRA	4x35	hydro	UDM	-
BAYGORRIA	3x36	hydro	IEEET2	-
PALMAR	3x111	hydro	UDM	IEEEG3
BATLLE	50+80+125	therm.	UDM	IEEEG1
PTA del TIGRE	6x50	therm.	ESAC6A	IEESG0
BOTNIA	82+85	therm.	UDM	IEEEG1
CTR	2x113	therm.	IEEET2	-

It is worth to notice that the unique Uruguayan unit equipped with PSS, in service, is 'Salto Grande' station. Others units are equipped too, but the PSS were usually disabled at the time when this study was done.

A. Scenarios and contingencies

We focus on three base scenarios:

Sc#1: year 2010, with max. hydro generation,
Sc#2: year 2010, with max. thermal generation,
Sc#3: year 2004, with max. hydro generation.

The first scenario represents the most desirable situation of dispatch from the economical point of view. The second one considers the possible situation of lack of rains in the region, a very common phenomenon in the last decade. The third one is just a reference scenario. Starting from this basic configurations, auxiliary scenarios were introduced by changing the load models, specially for large consumers. The contingencies considered for the analysis include the tripping of several lines or interconnections.

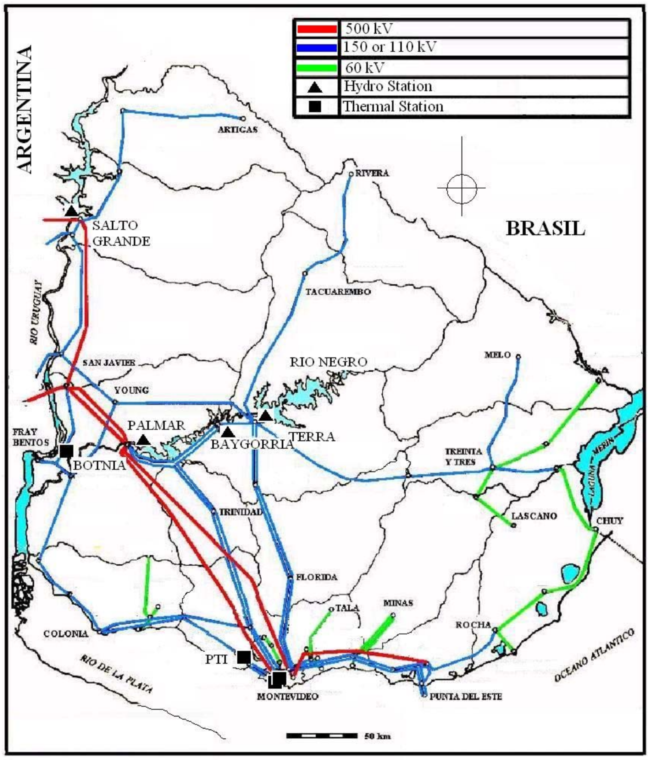

Fig. 1. Uruguayan transmission system.

- 150 kV line 'Young-Terra'.
- 150 kV line 'Fray Bentos-San Javier' ('FB-SJ').
- bus 'Trinidad', 150 kV.
- 500 kV line 'San Javier-Salto Grande' ('SJ-SGU').

The whole work explored several important contingencies for each scenario (more than 40 cases). We present here the more relevant results.

III. MODAL ANALYSIS

This Section presents the results of the modal analysis for the different scenarios introduced in Section II. We study the eigenvalues of each mode and their respective mode shapes and participation factors. We refer the reader to [3] for a detailed presentation of these concepts. All the calculations were performed in DSAT [2].

A limit of 5% was considered as the minimum acceptable damping coefficient for a given mode, that implies an attenuation of a least 73% between consecutive peaks of the damped oscillatory transient response. This criterion is set in regional grid codes and it is used as a reference in Uruguay.

Figure 2 and Table II show the eigenvalues of the electromechanical modes for the basic scenario #1. The real part is ticked in sec^{-1}, the imaginary part is ticked in rad/s at left and Hz at right. The figure also shows at top the damping factor (in %). Control modes are not included.

First of all, we must emphasize that all the modes have negative real part, so the system is small signal stable. Modes denoted by 'Z' correspond to the inertia center of the whole system and are not of interest. The slowest electromechanical mode is the one labeled 'Y', associated to the hydroelectrical facility 'Yaciretá'. It is an inter-area mode whose influence is perceived in all the system. The modes

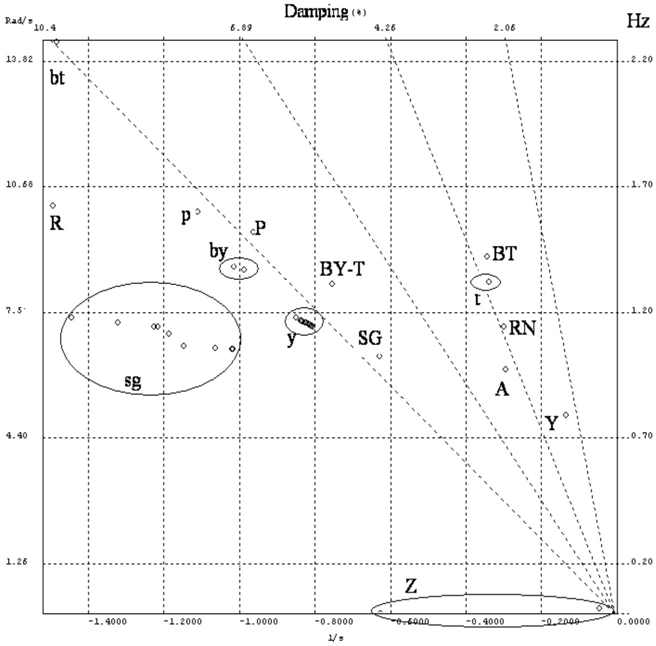

Fig. 2. *Electromechanical Modes, scenario # 1.*

TABLE II
ELECTROMECHANICAL MODES, SCENARIO # 1

Mode	Real sec^{-1}	Imag. rad/sec	Freq. Hz	Damping %
'Y'	-0.1331	4.9747	0.7918	2.68
'BT'	-0.3438	8.9453	1.4237	3.84
't'	-0.3392	8.2971	1.3205	4.08
'RN'	-0.2981	7.1757	1.1420	4.15
'A'	-0.2940	6.1098	0.9724	4.81
'BY-T'	-0.7537	8.2404	1.3115	9.11
'SG'	-0.6274	6.4543	1.0272	9.67
'P'	-0.9619	9.5451	1.5192	10.03
'bt'	-1.4845	14.3024	2.2763	10.32
'p'	-1.1098	10.0627	1.6015	10.96
'y'	-0.8179	7.2536	1.1544	11.21
'by'	-0.9871	8.6069	1.3698	11.39
'R'	-1.4945	10.2047	1.6241	14.49
'sg'	-1.1854	7.0096	1.1156	16.67

denoted[2] by 'y' in the figure are 17 and correspond to local modes of 'Yacyretá': some machines of this station oscillate in counter-phase with the others, while the rest of the system remains unaware of it. This kind of local modes are always faster and more damped than the collective mode of the whole station. For brevity, Table II only lists one of each set of local modes. As we have mentioned before, our objective focused on Uruguayan local modes. So, we only make some brief remarks regarding Argentinian modes: 'A' and 'R', related to the equivalent machines 'Almafuerte' and 'Rodríguez'.

The first relevant mode for our analysis is the one named 'RN'. It has a natural frequency of $\omega_n = 1.14$ Hz, and a damping of $\zeta = 4.1$ %. The most significant elements of the mode shape, depicted on Figure 3, show that this mode is principally related to the hydroelectrical plants 'Terra' and 'Baygorria' on the "Río Negro" system and in a minor extent to the 'Botnia' pulp mill. These machines oscillate approximately in phase[3]. In the present case, once this mode has been excited, there will be an oscillation of these machines of 1.14 Hz (with a period of approximately 880 ms) in counter-phase with the rest of the system. This oscillation is damped with a coefficient $\zeta = 4.1\%$, i.e., a 77 % of attenuation between consecutive peaks of the transient response. On the other hand, this mode is almost unobservable from the rest of the system. Table III lists the participation factors of the machines in this mode. The most involved ones are 'Terra' and 'Baygorria'. In order to mitigate this mode, we must act on these machines, see Section V.

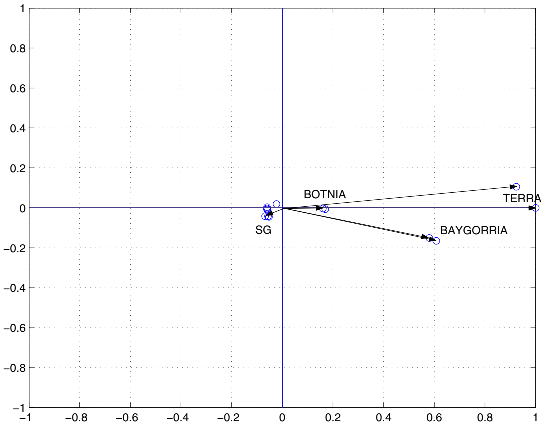

Fig. 3. *Mode shape of the 'RN' mode.*

TABLE III
PARTICIPATION FACTORS OF MODE 'RN'

Participation factor	Machine	Central
1	TER 131G13.8	'TERRA'
0,83	TER 134G13.8	'TERRA'
0,83	TER 132G13.8	'TERRA'
0,83	TER 133G13.8	'TERRA'
0,37	BAY 71G7.00	'BAYGORRIA'
0,37	BAY 72G7.00	'BAYGORRIA'
0,33	BAY 73G7.00	'BAYGORRIA'
0,04	BOT 101G10.5	'BOTNIA'

Thus, the 'RN' mode corresponds to the hydroelectrical facilities of the 'Río Negro' system, at the center of the country, oscillating against the rest of the system. We will analyze this mode for the different scenarios and contingencies. Table IV lists the eigenvalues of this mode for many cases, ordered by the damping factor. We conclude that the 'RN' mode does not have enough damping for the hydroelectric scenario of 2010, which can be really bad (around 3.4%). The worst contingency we have found for this scenario is the tripping of the line 'Young-Terra'.

Our analysis continues with the study of the mode denoted 'BY-T' in Figure 2. It essentially describes the oscillation of the machines of the hydroelectrical plant 'Baygorria' in counter-phase with the machines of the hydroelectrical plant 'Terra'. Once again, the rest of the system does not participate on this mode, which can be mitigated, along the modes 't', by acting on the machines of 'Terra'.

As we have mentioned earlier, the local modes of a plant are usually faster and more damped than the respective common modes. This can be verified on Figure 2, for the hydroelectrical plants 'Salto Grande'(SG), 'Palmar'(P) and 'Baygorria'(BY).

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[2] We will use lowercase for local modes, and uppercase for modes involving more than one station.

[3] A deeper look on the system shows that there is a direct relationship between the participation in this mode and the electrical distance to the 500 kV transmission system.

TABLE IV
MODE 'RN'

Real Part	Imag. Part.	Frequency (Hz)	Damping (%)	Scenario	Contingency
-0,24	6,95	1,11	3,44	1	Line 'Young-Terra'
-0,29	7,11	1,13	4,06	1	Line 'FB-SJ'
-0,29	7,19	1,14	4,07	1	Bar 'Trinidad'
-0,3	7,18	1,14	4,15	1	No fault
-0,31	7,18	1,14	4,28	1, with constant P	No fault
-0,4	7,38	1,17	5,37	3	Line 'Young-Terra'
-0,42	7,55	1,2	5,59	3	Bar 'Trinidad'
-0,43	7,56	1,2	5,65	3	No fault
-0,45	7,52	1,2	5,97	3, with constant P	No fault

Another important mode is related to the pulp mill 'Botnia' ('BT' at Figure 2), a private generator recently incorporated to the system. By looking carefully at the mode shapes and the participation factors, we quickly conclude that Botnia's machines oscillate in counter-phase with the rest of the system. The mode can only be seen and controlled from these machines. Table V shows the eigenvalues of this mode for many scenarios and contingencies, showing that there is not enough damping. The critical contingency is the tripping of the line 'SJ-FB', for the mostly hydroelectrical or mostly thermal scenarios of 2010.

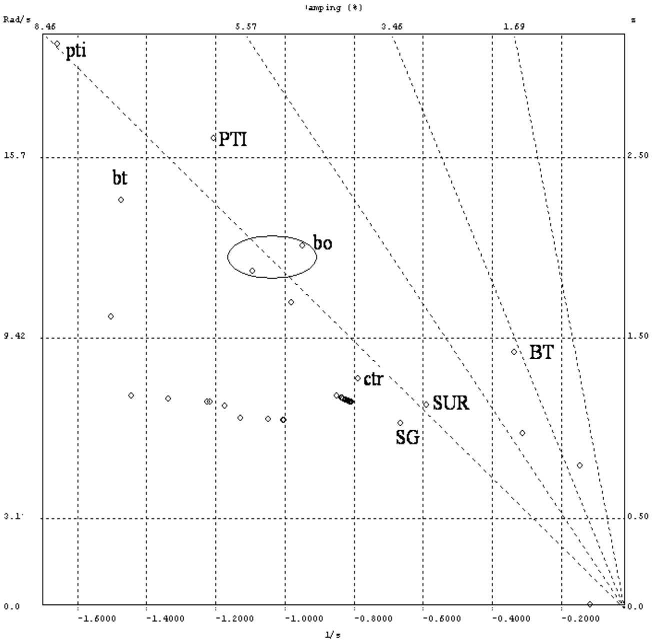

Fig. 4. *Electromechanical modes, scenario # 2.*

Consider now Figure 4. It shows the eigenvalues of the scenario #2, the mostly thermal regime for 2010. The 'RN' mode is not present because the regime is thermal and hydro machines are not dispatched. In addition to the 'BT' mode, some new modes associated to the thermal units near Montevideo city appear: 'Batlle y Ordóñez' ('BO'), 'CTR', and 'Punta del Tigre' ('PTI'). The mode 'SUR' ($\omega_n = 1.13$ Hz, $\zeta = 8.3$ %), exhibits a coherent oscillation of all the southern machines ('BO', 'CTR', 'PTI'), in counter-phase with the northern hydro central 'Salto Grande'. Although the mode is observable from these machines, the participation factors point out that the mode may be mitigated at 'CTR' or 'Salto Grande'. It also appear other modes associated to the thermal units: 'PTI', 'pti', 'bo' and 'ctr'. These *thermal* modes have reasonable damping greater than 7%.

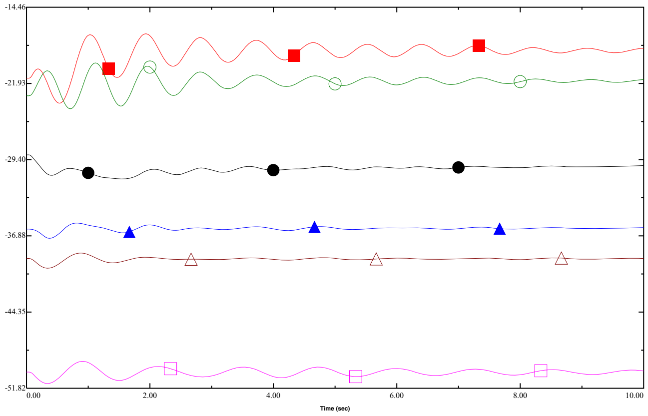

Fig. 5. *Fault on line 'Young-Terra', Scenario # 1. Angles (top to bottom) of machines TERRA, BAYGORRIA, BOTNIA, PALMAR, SALTO GRANDE, YACIRETÁ.*

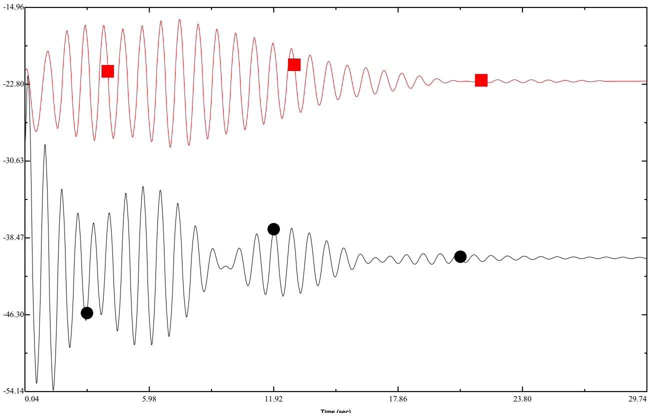

Fig. 6. *Fault on line 'SJ-FB', Scenario # 1. Angles (top to bottom) of machines TERRA and BOTNIA.*

IV. VALIDATION THROUGH SIMULATION OF THE TRANSIENT RESPONSE

Previous results were obtained using a linear approximation of the system. This Section is devoted to the validation of these results, performing simulations of the transient response of the complete non linear system. We will analyze the response of the system to several important faults. The obtained temporal responses will be correlated with the modal analysis of the previous Section. The main variables we will consider are the rotor angles. We have chosen the machine 'Ezeiza' as the angle reference. We emphasize that the nonlinearity of the system implies that there may be deviations between the obtained

TABLE V
'BT' MODE

Real Part	Imag. Part	Frequency (Hz)	Damping (%)	Scenario	Contingency
-0,19	8,21	1,31	2,35	1	Line 'FB-SJ'
-0,21	8,17	1,3	2,56	2	Line 'FB-SJ'
-0,32	8,85	1,41	3,61	2	Line 'Young-Terra'
-0,32	8,83	1,41	3,68	1	Line 'Young-Terra'
-0,33	8,93	1,42	3,71	2, with constant P	No fault
-0,34	8,94	1,42	3,76	1	No fault
-0,34	8,94	1,42	3,76	2	Bar Trinidad
-0,34	8,95	1,42	3,84	1 base	No fault
-0,34	8,94	1,42	3,84	1	Bar Trinidad
-0,36	8,86	1,41	4,05	1, with constant P	No fault

responses and the linear analysis, particularly when the perturbations are not small.

Firstly, consider Figure 5. It shows the system transient response to a three-phase fault on the line 'Young-Terra', near the Young end-point. The fault is cleared after 60 ms, by removing the line. After few seconds, when the response to a *large* disturbance decays, we may notice the presence of two well defined oscillations modes. The response of 'Yaciretá' contains a slow and persistent oscillation, the mode we have denoted by 'Y', with a period of approximately 1,25 s, which corresponds to a frequency of 0.8 Hz. 'Terra' and 'Baygorria' clearly oscillate coherently, with a period of 0.91 s (1.1 Hz). Here, we can recognize the 'RN' mode, see Table IV. A more detailed analysis of the responses, not included here, reveals a coherent oscillation between these machines with 'Palmar' and 'Botnia'. Trying to observe the mode 'BT' at Botnia's angle, we simulate a three-phase fault on the line 'FB-SJ', cleared after 60 ms. Figure 6 depicts the angles of 'Terra' and 'Botnia'. Both modes, 'RN' and 'BT', are present and they are persistent in time. After the initial transient, the angle of 'Terra' exhibits a damped sinusoidal behavior, with a period of 0.9 s (1.12 Hz), corresponding to the 'RN' mode.

The response of 'Botnia' is a little more complex. Since the fault also stimulates the 'RN' mode, we must look for a superposition of both modes. With this fact in mind, a new closer look at Figure 6 recalls us the frequency beating phenomenon, very common in Electronics and Signal Processing. It is the amplitude modulation due to the presence of two sinusoidal signals with very similar frequency[4]. We note the intermodulation of two sinusoidal signals with frequencies near to 0,075 Hz and 1.23 Hz, which corresponds to the superposition of sinusoidal signals of frequencies 1.16 Hz and 1.31 Hz. These observations are very close to the behavior predicted by the modal analysis, see Tables IV and V.

V. DAMPING OSCILLATIONS VIA PSS TUNING

In previous Sections, we have performed the modal analysis whose results predicted non acceptable oscillations in the system. We have confirmed these behaviors by analyzing simulations of the transient response on the complete non linear system. Now, we will study the mitigation of the problematic oscillations, by designing Power System Stabilizers, PSS. These devices inject control signals to the excitation systems of one or several machines by trying to produce an extra electric torque in counter-phase with the oscillations we want to damp. The reader can consult references [3], [9], [7] for a deep discussion and relevant standards. The PSS structure chosen for our application is the known by "Δ P- ω" and it is covered by the standard IEEE PSS2A [7]. The structure and final parameters are depicted in Fig. 8.

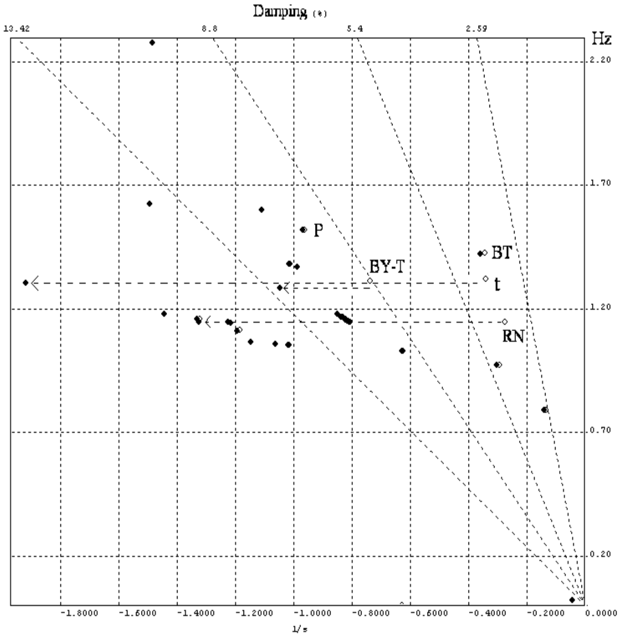

Fig. 7. *Effect of the addition of a PSS at 'Terra' on the electromechanical modes of scenario #1. Without PSS: ○; With PSS: ●.*

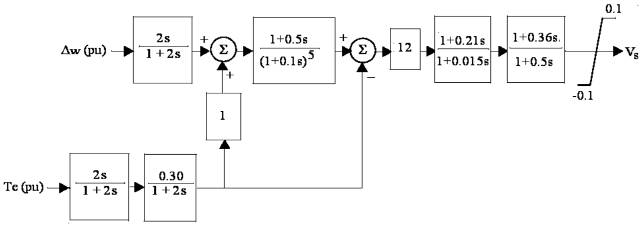

Fig. 8. PSS structure.

The objective is the damping of the RN mode which, from Table III, aims the Terra station as the most suitable location for PSSs. We

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[4] We will briefly explain this simple phenomenon. Consider the addition of two purely sinusoidal signals of frequencies f_1 and f_2 respectively

$$y(t) = y_1(t) + y_2(t) = Asen(2\pi f_1 t) + Asen(2\pi f_2 t)$$

The resulting signal $y(t)$ can be expressed, by using trigonometric identities, as

$$y(t) = 2Asen(2\pi \frac{f_2 + f_1}{2} t) cos(2\pi \frac{f_2 - f_1}{2} t)$$

So, the beating can be seen as a signal modulated in amplitude: a relatively slow signal of frequency $\frac{f_2 - f_1}{2}$ modulated in amplitude by the carrier of frequency $\frac{f_2 + f_1}{2}$, relatively high. The relationship between this frequencies makes the effect perceivable by direct observation.

tuned the PSS parameters by following classical procedures, see [3], [4]. Of course, an operative design should also include measurements and *in situ* tests.

Figure 7 shows the location of the eigenvalues of the electromechanical modes with and without the PSS at 'Terra'. The situation without the PSS is the same depicted in Figure 2. The presence of the PSS notoriously improves the damping factor of mode 'RN' and also the damping factors of the local modes of 'Terra' and 'Baygorria'. Our primary conclusion is that the designed PSS is suitable for an important improvement of system behavior, regarding the problematic oscillation modes.

Table VI lists the eigenvalues of the mode 'RN' for the four worst contingencies observed for the scenario #1. It can be noticed that the damping factor is over 17% in all the cases. Figures 9 and 10 show the damping effect of the PSS on the transient response of the system. The responses with and without the PSS are shown for two faults occurring in the 'Río Negro' system.

TABLE VI
'RN' MODE, WITH A PSS AT 'TERRA'

Real Part	Imag. Part	Freq. (Hz)	Damping (%)	Contingency
-1,19	6,88	1,09	17,01	Line 'Y-T'
-1,27	7,22	1,15	17,32	Line 'FB-SJ'
-1,32	7,21	1,15	18,07	No fault
-1,33	7,22	1,15	18,10	Bar 'Trinidad'

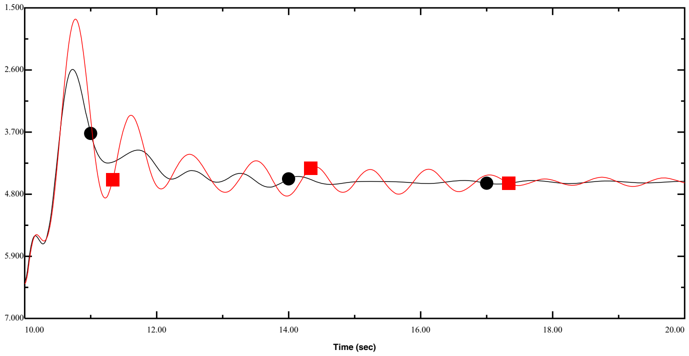

Fig. 9. *Fault on line 'Young-Terra'. Rotor angles of 'Terra' with and without PSS, degrees.*

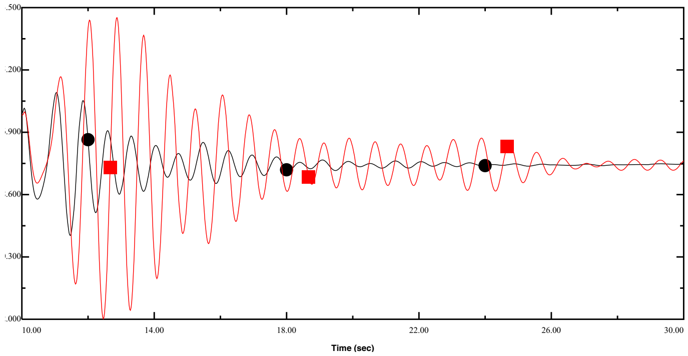

Fig. 10. *Fault on line 'SJ-FB'. Rotor angles of 'Terra' with and without PSS, degrees.*

VI. CONCLUSIONS

This article reports the modal analysis of the Uruguayan power system. It also briefly describes the Uruguayan power system, its main generation units and its dependence on the hydric regime. For three different basic scenarios (mostly hydroelectrical or mostly thermal generation, with several variants on the load composition), we have detected several under-damped modes, with unacceptable damping factors. By analyzing the mode shapes and the participation factors, we identified the machines that suffer the modes and that are able to mitigate them. We have focused only on local Uruguayan modes, disregarding inter-area modes. The worst two oscillation modes are described here. The mode 'RN', in which the main generators of the hydroelectrical system on the Negro River oscillate against the rest of the system, has a noticeable impact on a significant part of the generation park. The mode 'BT', which has the lowest damping, is constrained to a small part of the system and it is related to a specific big generator/consumer. These modes exhibit a under-damped response, with a very poor damping. The modal analysis based on the linear approximation of the system at the operating point was validated through simulations of several contingencies on the nonlinear system. The obtained transient responses were investigated in order to detect the problematic modes. The best sites for PSS allocation were determined with the help of the participation factors. New simulations show that for the compensated system, the involved mode behave correctly. We will continue these tasks, developing detailed model and studies for the planned new scenarios of the Uruguayan system.

VII. ACKNOWLEDGMENTS

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