Equivalent model of the Argentinian Electrical Power System for Stability Analysis of the Uruguayan Network

M. Artenstein, *Senior Member, IEEE*, and A. Giusto

Abstract--This work describes the building of an equivalent model of the Argentinian power system to be used in the study of dynamical phenomena of the Uruguayan system. By following the slow coherency methodology, the generators that oscillate coherently at the lowest natural frequencies of the interconnected system were identified with the help of the respective mode shapes. The corresponding linear model was built with second order classical generators models. In a second step, the coherent generators were clustered at the level of their internal nodes, building in this way the corresponding inertial equivalents. Finally, the system was reduced again with the help of classical linear techniques for the computation of static equivalents. The final result is an equivalent model of the Argentinian system that includes approximately 20% of the original machines and less than 5% of its nodes. The equivalent model was validated through the comparison of the transient response of the Uruguayan system to a set of significant faults.

***Index Terms*--Interconnected power systems, Power system modeling, Power system stability, Reduced order systems.**

I. Introduction

THIS paper describes the building of an equivalent model of the Argentinian electric system to be used in the study of dynamical phenomena in the Uruguayan system.
Both systems are strongly interconnected at their 500 kV subsystems. The complete model consists of approximately 1800 buses and 200 machines whose 15% approximately corresponds to the Uruguayan system. Thus, a strong stimulus exists for the development of reduced models of the Argentinian system in order to optimize the resources necessary to analize in detail the dynamical behavior of the Uruguayan network.

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This work was supported in part by the Programa de Desarrollo Tecnológico, PDT, under Grant PDT 47/05. The work of author A. Giusto was also partially supported by a Grant Quanam: www.quanam.com.

The methodology employed in this work is based in the slow coherency theory [1]. A subsystem including all the Uruguayan network was kept untouched, and the rest of the interconnected system was aggregated in a set of areas or "clusters". This aggregation was done in such a way that all the machines in each cluster oscillate coherently in all the slowest modes of interest.

The machines in each cluster were later substituted by an equivalent machine which is connected to the network through the terminal buses of the original machines, see [2]. This procedure allowed a significant reduction of the size of the Argentinian network.

Later, the network was again reduced by the classical method of Ward [3] in order to get the corresponding static equivalent.

The final result is an equivalent model of the Argentinian electric system which includes approximately the 20% of its generators and less than the 5% of its buses.

The accuracy of the model was assessed by comparison between the lowest natural frequencies of both models.
The validation also included the comparison of the transient response of both models to significant faults on the Uruguayan system.

This paper is organized in the following way. Section II briefly describes the slow coherency methodology and the inertial equivalents. In Section III the main characteristics of the computation procedure to get the dynamical equivalents are described. The application of this methodology to the interconnected Argentinian-Uruguayan system is included in Section IV along with the validation studies. The paper finishes with come concluding remarks.

II. Theoretical Basis

A. *Qualitative description*

The slow coherency theory is based on the empirical observation of the machines' dynamical behavior when a power system is submitted to a disturbance.
It has been found that the machines electrically distant from the fault point trend to form sets ("clusters") which oscillate coherently at relatively low frequencies during the postfault period [1]. The high oscillation frequencies are observed, instead, in nearby individual machines.

More generally, it can be said that the machines electrically closest to the fault will oscillate during the postfault period with a combination of natural frequencies defined both by the electrically distant machines (*inter-area modes*, of relatively low frequencies) and by the nearby machines (*local modes*, both of high and low frequencies).

The low frequency property of the interarea modes may be explained qualitatively by the low admittance connections–weak and/or sparse connections–which usually exist between distant machines, and also (in some cases) by the high inertia of the set of distant machines as "seen" from the fault point.

The building of dynamic equivalents based on the slow coherency theory will consist essentially in identifying both the inter-area modes associated with the distant machines and the clusters of machines associated to each one of these modes.

B. Formal development

The starting point is the power system classic model, composed by a set of nonlinear differential equations and a set of nonlinear algebraic equations:

$$\begin{aligned} M.d^2\,\delta/dt^2 &= f\,(\delta,V) \\ 0 &= g\,(\delta,V) \end{aligned} \qquad (1)$$

with δ: Machine angles

V: Complex voltages on load busbars

M: Diagonal matrix of machine inertias

Under the assumption of a classic second order machine model, the function f represents the swing equations and the function g represents the load flow equations on the load busbars. By linearizing these equations around an equilibrium point, we obtain a linear system with the general form:

$$\begin{aligned} M.d^2\Delta\delta/dt^2 &= K_1\Delta\delta + K_2\Delta V \;\; . \\ 0 &= K_3\Delta\delta + K_4\Delta V \end{aligned} \qquad (2)$$

Matrix K4 preserves essentially the structure of the network nodal admittance matrix. Thus, it can be written–by interchanging rows and/or columns if necessary–as a block-diagonal matrix, each block representing a system area electrically separated from the others. The entries of the off-diagonal blocks represent the connecting admittances between areas, so we may expect that these off-diagonal submatrices will be sparse and will have small non zero elements.

This particular structure of the matrix K4 allows us, after performing an adequate linear transformation of the system (2), to apply the singular perturbation theory [1],[4] to this dynamical system. According to this theory, the system solution can be interpreted as composed, approximately, by a linear combination of variables which oscillate "slowly" and variables which initially oscillate "fast".

If we perform effectively the linear transformation and apply the singular theory approximation to our system, we conclude that the slow variables y may be obtained by solving a reduced order linear dynamical system of the following general form :

$$\begin{aligned} M_a\, d^2y/dt^2 &= K'_{11}\, y + K_{13}\,\Delta V \\ 0 &= K_{31}\, y + K_4\,\Delta V \end{aligned} \qquad (3)$$

M_a: Diagonal matrix whose elements are the aggregate inertias $\sum m_i^k$ of each area "k".

$y=(y^{a1}, y^{a2}, \ldots\ldots\ldots y^{an})$, with $y^{ak} = \sum m_i^k\ \Delta\delta_i^k \,/\, \sum m_i^k$ (4) the centre of inertia of each area "k".

From this theoretical model we may obtain the following main practical results:

-The slow modes of the system may be obtained by solving a dynamical system of order equal to the number of coherent areas.

-The machines belonging to each coherent area may be represented by an equivalent machine with an inertia which is the sum of the individual inertias.

-The specific form of the matrices of system (4) allow us to conclude, also, that the equivalent machines have to be connected to the original machine terminal nodes by the transient reactances of the original machines, and that the external network connecting these terminal busbars is the same as the original one [1].

The final result is the aggregation of the coherent machines of each area as shown in Figure1. In this figure x'd is the transient reactance of each individual machine, E is the internal voltage behind the transient reactance of each individual machine and Vp is the internal voltage of the equivalent machine. The "phase shifter" transformers are included in order to match the individual voltage of each terminal node with the voltage of the common terminal node of the equivalent machine [2].

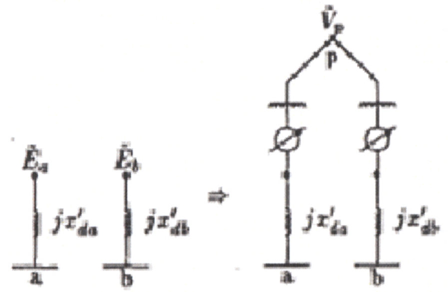

Fig. 1: Inertial aggregate of 2 machines.

III. Computation Details

The algorithm described in Section II was implemented in MATLAB with the help of the PSAT software [5]. Its main characteristics are described next:

A. Initial equilibrium point

The equivalent model is computed for an equilibrium point which is obtained by running the load flow module of the PSAT program.

B. Number of coherent areas

The system can be divided in an arbitrary number of coherent areas or clusters. This number is an important design tool since the performance of the equivalent model depends directly on it. The number of areas must be chosen to meet the following conditions:

Good accuracy of the equivalent model.

Number of areas not too big, in order to get a reasonable reduction of the size of the model.

The study area of interest -in our case, an area including all the Uruguayan network- must belong to an unique coherent area.

It is also assumed that the number of clusters must coincide with the number of lowest natural frequencies for which the generators belonging to each area oscillate coherently [1]. This criterion sets a practical upper bound for the number of coherent areas: it must not excede the number of natural frequencies which are less than (approximately) 1 Hz which is a typical upper bound for the inter-area oscillations [7] .

Finally, the number of coherent areas is obtained in an iterative way to meet the conditions above.

C. Identification of coherent machines

The identifications of the clusters of coherent machines is done through the analysis of the mode shapes, i.e. right eigenvectors, corresponding to each one of the lowest natural frequencies, see reference [1]. As it was metioned before, the number of coherent areas is obtained through an interative procedure. In our case, the computations were done in the MATLAB environment on the eigenstructure data obtained with PSAT.

D. Equivalent machines

Once identified the clusters of coherent machines, the reduction of the size of the model is done by the creation of equivalent machines which substitute the set of original machines. This procedure is repeated for all the areas, with the exception of the area including the Uruguayan network.

For convenience, the slack machine is kept individually in the model.

In order to ease the convergency of the load flows to be computed with the reduced model, the terminal buses of the original machines are kept as PV buses without active power generation and with their original voltage setting. This procedure imposes small ficticious injections of reactive power in these buses which do not significantly alter the accuracy of the equivalent model.

The setting of active power generation is, naturally, transferred to the equivalent machines.

IV. Application to the Argentinian-Uruguayan Interconnected System

A. Description of the system

The model describes the Argentinian-Uruguayan system in a secenario corresponding to the maximum demand of the winter of the year 2003, with mainly hydraulic generation.

The model consists of 1773 buses and 192 machines and also includes some buses corresponding to the interconnection with Paraguay. The Uruguayan subsystem comprises 294 buses and 23 generators.

The slack machine is the Argentinian "Central Embalse Nuclear".

The area of study is the Uruguayan system, slightly extended to include the Salto Grande binational hydroelectrical power station.

B. Coherent area aggregation

The most convenient number of clusters was found to be 11, which provides us a very good trade off between the objectives mentioned in Section III.B. The clusters are described in Table I. Notice that the cluster associated to the Uruguayan network includes the 23 Uruguayan generators and also 26 Argentinian generators. These 26 machines oscillate coherently with the Uruguayan network in the 11 lowest natural frequencies, listed in Table II.

TABLE I
Aggregation of the Argentinian and Uruguayan generators

Cluster	Machines	Geographic area
1	1	CENTRO
2	2	GBA
3	2	NEA
4	1	NOA
5	3	GBA
6	10	COMAHUE
7	20	NEA,PARAGUAY
8	21	CUYO
9	48	CENTRO,NOA
10	49	GBA,Bs.As,URUGUAY
11	35	COMAHUE

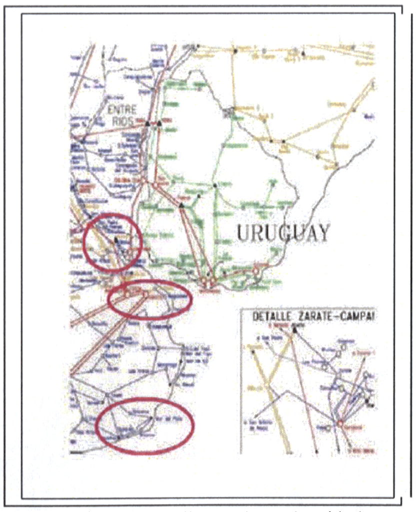

Fig. 2. Argentinian machines that oscillate coherently with the Uruguayan system

C. *Equivalent network*

The substitution of the individual machines in each cluster by the equivalent machine defines an equivalent network comprising 60 machines (49 in the area of study, 10 equivalent machines and the slack machine).

The 11 lowest natural frequencies of the equivalent network were computed and compared with the corresponding frequencies of the original model. Both sets of frequencies are listed in Table II. The quadratic deviation is 3.8% which confirms the accuracy of the methodology and the selection of the number of clusters.

TABLE II
COMPARISON OF THE LOWEST NATURAL FREQUENCIES FOR THE ORIGINAL AND EQUIVALENT MODEL.

Original (Hz)	Equivalent (Hz)
0	0
0,4823	0,5117
0,5972	0,6148
0,6702	0,6776
0,7157	0,7233
0,7499	0,7465
0,8357	0,7635
0,8844	0,8615
0,9151	0,8714
0,9253	0,9259
0,9830	0,9889

D. *Reduction of load buses*

The network was reduced again with the help of algebraic reduction methods which allow us to eliminate the load buses in the Argentinian network. The computations were performed with the corresponding module of the package PSS/E [6]. Some small machines (either real or equivalent) were eliminated to reduce further the model.

The final model consists of 53 machines and 344 buses. As the Uruguayan subsystem was kept untouched, the Argentinian system beyond Salto Grande was reduced from 169 generators and 1479 buses to only 30 generators and 50 buses. The process of bus reduction affects the natural frequencies of the equivalent system. A new evaluation of the 11 lowest frequencies shows a quadratic error of 7.2 % with respect to to the original system, which is considered satisfactory.

E. *Transient behavior facing important faults*

The validation of the reduced model through the comparison of its slowest modes is useful but it only provides a first order, linear, validation. To further validate the equivalent model, several time simulations were realized with the PSAT software. The transient response of the main Uruguayan machines following a critical fault –three phase short circuit at 500 kV branch Palmar- Montevideo A - was computed.

The simulations were done in 3 different scenarios for the Uruguayan system:

Scenario 1. Maximum 2003 ,winter, mainly hydraulic generation (the scenario used for the computation of the equivalent model);

Scenario 2. Maximum 2003 ,winter, with greater participation of thermal machines;

Scenario 3. Scenario 1 with uniform load reduction to 60%.

The system was simulated with complete machine models (order 5 for hydraulic, order 6 for thermal units) with constant excitation and mechanical power. The angular oscillations in some of the most important machines in the Uruguayan system are shown in Fig. 3 to 5. In these figures, the dashed graph represents the equivalent model, and the original model is depicted by the continuous line.

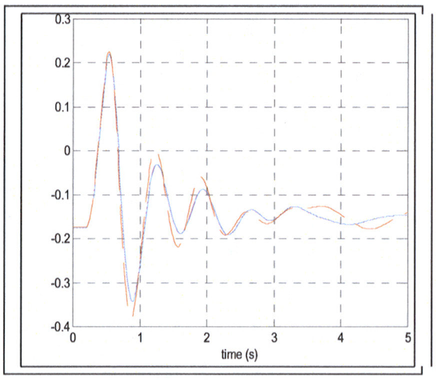

Fig. 3: Angular oscillations of generator Palmar, Scenario 1.

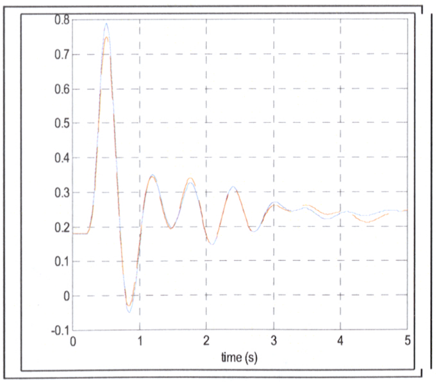

Fig. 4: Angular oscillations of generator Sexta, Scenario 2.

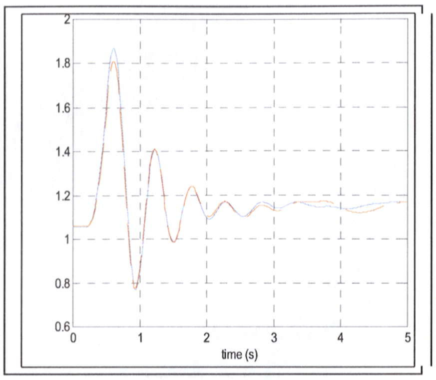

Fig. 5:Angular oscillations of generator Palmar, Scenario 3.

V. CONCLUSIONS

This article describes the obtention of a dynamical equivalent model of the Argentinian power system based on the slow coherency theory. The equivalent model is intended to be used in the study of the dynamic behavior of the Uruguayan power system.

The equivalent model includes, significantly, the presence of some Argentinian machines that oscillate coherently with the Uruguayan ones which evidences the need of a detailed model of these machines for dynamical studies of the Uruguayan network.

The equivalent model was validated trhough the comparison of the most significant modes and by time simulations following some critical faults on the Uruguayan 500 kV subsystem.

VI. ACKNOWLEDGMENT

The authors gratefully acknowledge the contributions of R. Franco, P. Monzón and C.M. Sena for their valuable comments and suggestions about the work reported in this document.

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VIII. BIOGRAPHIES

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