Paper accepted for presentation at 2009 IEEE Bucharest Power Tech Conference, June 28th - July 2nd, Bucharest, Romania

Power System Control Based on the Identification of Oscillation Modes

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***Abstract*—In this paper information provided by a synchronized phasor measurements system is used to identify the emergence of low damped oscillation, to select control parameters and to provide input signals to the controllers. Prony analysis is used for the oscillation modes identification. A gain-schedule control allows the selection of the parameters of a central controller according to the identified modes and mode shapes. The control parameters for selected operating points are determined by a nonconvex, nonsmooth optimization method.**

***Index Terms*—Small-signal stability, System identification, Gain-schedule control, Phasor measurements, Power system control.**

I. Introduction

Power system are subject to oscillations that emerge in several operating conditions in which the generators dampings are small or even negative. The use of power system stabilizers has been an efficient and widely employed solution to damp out those oscillations. However, restrictions on the transmission network expansion, due to environmental concern and economic constraints, the constant load increase coupled with the demands imposed by the deregulation of the electric industry in many countries have led to a more intensive use of the existing transmission facilities. This may lead to reduced stability margins. Better control schemes including new technologies can help to keep secure stability margins in this new scenario.

The development of phasor measurement systems [1] has made available a promising technology, already in use for monitoring, and with the capability of improving the current control schemes or allowing the implementation of new and more complex control structures. A considerable research effort has been done to develop methods for on-line identification of oscillation modes and their associated damping, using phasor measurements [2], [3], [4], [5], [6].

In this paper, the real-time identification of low-damped oscillation modes is used for power system control. The identification method is based on the Prony analysis. The mode shapes are also estimated from the synchronized phasor measurement system. Several power system critical operating conditions are detected from the dominant eigenvalues and mode shapes. A centralized controller, with several parameter sets designed in order to optimize the system performance for each of the critical operating conditions, is used in a gain-schedule control scheme. The performance of the proposed method is evaluated for a multimachine power system.

II. The control scheme

Power system control for damping electromechanical oscillations are currently based on decentralized controllers, the power system stabilizers, placed at the generators. The design of these controllers is carried out for typical operating points and system topology. The experience of several decades has shown that PSSs designed by classical control methods tend to be robust. However, several unusual conditions may lead to low damped oscillation or even to instability.

The strive for a high degree of reliability for modern power systems has led to the consideration of control methods that take into account changes in the system operating point as a result of load variation and changes in the system topology. Robust and adaptive control have been considered for the design of power system stabilizers [7], [8], [9], [10], [11], [12].

The spreading use of synchronized phasor measurements, has made available information that can be used as a complement to the current control structure used by the industry, especially when the system performance may degrade as a result of unusual operating conditions.

The control scheme proposed in this work is based on a gain-schedule adaptive control, using the identified oscillation modes and mode shapes as indication of the system operating point. A centralized control is employed and its parameters are switched according to the detected operating point.

The monitoring of the electromechanical oscillations allows the detection of the onset of low damped oscillations, and therefore of critical operating points, and an estimation of the system eigenvectors. The dominant eigenvalues associated to electromechanical modes and the corresponding mode shapes give an indication of the current operating point. The controllers are designed for selected operating point for which the system performance tend to deteriorate.

It is assumed that phasor measurement units are available at the terminal bus of each generator. The information acquired through these PMUs can be used either for identification or control.

In the next two sections the identification of the oscillation modes and the the control design are presented.

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Financial support of the Brazilian Government Research Agency (CNPQ)

III. Identification of critical operating conditions

Several methods have been developed for the identification of power system oscillation modes. Prony analysis [13], Hilbert transform [2], Kalman filtering [14], wavelets [15] are among those methods. In this work, the multisignal Prony method is used for the identification of the oscillation modes.

A. Multisignal Prony method

The identification of the oscillation modes is carried out using Prony analysis. The method has been applied to power systems in several works.

The Prony method allows the determination of the residues of a signal $x(t)$ as given by Eq. (1)

$$x(t) = \sum_{i=1}^{n} v_i(w_i^{'} x_0)e^{\lambda_i t} = \sum_{i=1}^{n} R_i x_0 e^{\lambda_i t} \quad (1)$$

where λ_i, v_i and w_i are the eigenvalues, right eigenvectors, and left eigenvectors, respectively.

The accuracy of the mode estimates in Prony method often results in conflicting frequency and damping estimates because the method assumes that the system is single output, so signals are analyzed individually. The multisignal Prony method [16], an extension of Prony analysis, allows multiple signals to be analyzed simultaneously resulting in one set of mode estimates.

The Prony method requires that the order of the model be specified. High order models can lead to a large computing time while low order models can lead to imprecision in the identification of the oscillation modes.

B. Estimation of mode shapes

Several works have presented methods for the estimation of mode shapes, from measurements acquired by the synchronized phasor measurement system. In [17] and [3], spectral measurements are used to estimate the mode shapes. In [2], the empirical mode decomposition is used to provide estimates of time dependent mode shapes. In [5], the eigenvector associated to a low damped oscillation mode is estimated by Fourier analysis.

In this work, the real power signals at the generator terminals were used to estimate the electrical power mode shapes associated to the low damped oscillation mode. The signals are acquired by the PMUS at the terminal bus of each generator. The application of the multisignal Prony method allows the determination of the residues of each signal corresponding to the low damped oscillation mode. These residues provide an estimation of the electrical power mode shapes.

C. Identification of the operating point

In [18] it is shown that the system configuration and operating conditions determine mode shape patterns in a test system. This is difficult to generalize, but the comparison of the calculated and identified dominant eigenvalues associated to electromechanical oscillations and the mode shapes can give an indication of critical operating conditions.

For a system of n_g generators, let

$$\mathbf{v} = \begin{bmatrix} \mathbf{v}_{g_1} \\ \mathbf{v}_{g_2} \\ \vdots \\ \mathbf{v}_{g_{n_g}} \end{bmatrix}$$

be the vector obtained from the eigenvector corresponding to the eigenvalue λ, associated to an oscillation mode, by considering the entries that correspond to generator electrical power.

Let $\hat{\mathbf{v}}$ be the entries corresponding to the mode shapes calculated by the method described in the preceding subsection.

The operating condition is determined on-line comparing the calculated and the identified critical eigenvalue and measuring the Mode Shape Index (MSI) defined as:

$$MSI = \frac{1}{n_g} \sum_{i=1}^{n_g} \left(\frac{\hat{\mathbf{v}}_{g_i}^T \mathbf{v}_{g_i} + \mathbf{v}_{g_i}^T \hat{\mathbf{v}}_{g_i}}{2\mathbf{v}_{g_i}^T \mathbf{v}_{g_i}} \right)$$

The critical condition is detected if the identified critical eigenvalue is close to the calculated one and if

$$|MSI - 1| < \epsilon$$

where ϵ is a small constant.

IV. Control structure

Power system stabilizers are designed for several operating conditions. Although they tend to be robust, several operating conditions may be very demanding, resulting in low system damping. A centralized control based on the use of synchronized phasor measurement could add additional damping to the conventional control scheme currently used in the industry [19]. The central control uses information of the synchronized phasor measurement system and generates control signals transmitted to the generators.

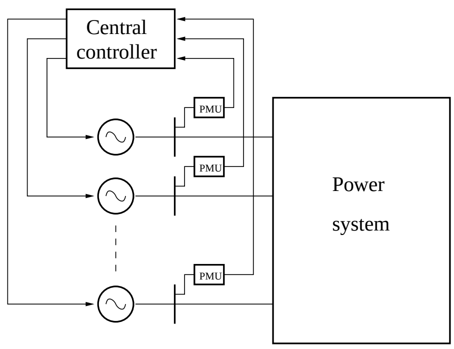

Fig. 1. Centralized control structure

Transmission delays from the PMUS to the central controller and from the central controller to the generators must be considered. The modelling of these delays are described in [19].

In this paper, sets of parameters for the central controller are determined to implement a gain-schedule control scheme. The parameters for each operating point are determined using the approach presented in [20] and summarized in the next section.

A. Control design

Consider a linear system given by

$$\dot{\mathbf{x}} = \mathbf{A}\,\mathbf{x} + \mathbf{B}_1\,\boldsymbol{\omega} + \mathbf{B}_2\,\mathbf{u} \quad (2)$$

$$\mathbf{z} = \mathbf{C}_1\,\mathbf{x} + \mathbf{D}_{11}\,\boldsymbol{\omega} + \mathbf{D}_{12}\,\mathbf{u} \quad (3)$$

$$\mathbf{y} = \mathbf{C}_2\,\mathbf{x} + \mathbf{D}_{21}\,\boldsymbol{\omega} + \mathbf{D}_{22}\,\mathbf{u} \quad (4)$$

where $\mathbf{x} \in \Re^n$, $\mathbf{u} \in \Re^m$, $\mathbf{u}$ is the control input, $\mathbf{y} \in \Re^p$ is the control output (sensor), $\boldsymbol{\omega}$ is the performance input signal and $\mathbf{z}$ is the performance output signal. For simplicity, it is assumed that the feedthrough matrix $\mathbf{D}_{22} = 0$.

The controller is given by

$$\dot{\mathbf{x}}_c = \mathbf{A}_c\,\mathbf{x}_c + \mathbf{B}_c\,\mathbf{u}_c \quad (5)$$

$$\mathbf{y}_c = \mathbf{C}_c\,\mathbf{x}_c + \mathbf{D}_c\,\mathbf{u}_c \quad (6)$$

where $\mathbf{x_c} \in \Re^{n_c}$ is the controller state vector, $\mathbf{u_c} \in \Re^p$ is the vector of stabilizing signals, $\mathbf{y_c} \in \Re^m$ is the vector of controller outputs.

The closed-loop system, with $\boldsymbol{\omega} = \mathbf{0}$, can be represented by:

$$\begin{bmatrix} \dot{\mathbf{x}} \\ \dot{\mathbf{x}}_c \end{bmatrix} = \begin{bmatrix} \mathbf{A} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \mathbf{x} \\ \mathbf{x}_c \end{bmatrix} + \begin{bmatrix} \mathbf{B}_2 & \mathbf{0} \\ \mathbf{0} & \mathbf{I} \end{bmatrix} \begin{bmatrix} \mathbf{D}_c & \mathbf{C}_c \\ \mathbf{B}_c & \mathbf{A}_c \end{bmatrix} \begin{bmatrix} \mathbf{C}_2 & \mathbf{0} \\ \mathbf{0} & \mathbf{I} \end{bmatrix} \begin{bmatrix} \mathbf{x} \\ \mathbf{x}_c \end{bmatrix} \quad (7)$$

Defining the matrices

$$\mathbf{A}_a = \begin{bmatrix} \mathbf{A} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \quad \mathbf{B}_a = \begin{bmatrix} \mathbf{B}_2 & \mathbf{0} \\ \mathbf{0} & \mathbf{I} \end{bmatrix}$$

$$\mathbf{C}_a = \begin{bmatrix} \mathbf{C}_2 & \mathbf{0} \\ \mathbf{0} & \mathbf{I} \end{bmatrix}$$

and the augmented state vector $\mathbf{x}_a = [\mathbf{x}^T\,\mathbf{x}_c^T]^T$, an augmented system can be defined by

$$\dot{\mathbf{x}}_a = \mathbf{A}_a\,\mathbf{x}_a + \mathbf{B}_a\,\mathbf{u}_a \quad (8)$$

$$\mathbf{y}_a = \mathbf{C}_a\,\mathbf{x}_a \quad (9)$$

and the controlled system given by (7) corresponds to the augmented system given by (8)-(9), with the output feedback

$$\mathbf{u}_a = -\mathbf{K}\,\mathbf{y}_a \quad (10)$$

where

$$\mathbf{K} = \begin{bmatrix} \mathbf{D}_c & \mathbf{C}_c \\ \mathbf{B}_c & \mathbf{A}_c \end{bmatrix} \quad (11)$$

The dimension of matrix $\mathbf{K}$ is $(n_u + n_c) \times (n_y + n_c)$. That is, $(n_u + n_c) \times (n_y + n_c)$ parameters must be determined. The case $n_c = 0$ corresponds to the static output feedback.

The power system control structures are modeled by a transfer-function matrix [19]:

$$\mathbf{PSS}(s) = \begin{bmatrix} pss_{11}(s) & \dots & pss_{1p}(s) \\ pss_{21}(s) & \dots & pss_{2p}(s) \\ \vdots & \vdots & \vdots \\ pss_{m1}(s) & \dots & pss_{mp}(s) \end{bmatrix} \quad (12)$$

where p and m are the number of inputs and outputs, respectively. For a decentralized control, this matrix is diagonal with $m = p$. This transfer function can be represented in the state-space form as (5)-(6). The design problem reduces to finding matrix K in (11).

The problem of output feedback synthesis may be set as a minimization problem of an adequate objective function. This function may include performance requirements such as system damping, settling time and robustness. The controller parameters for each operating point are designed using non-convex, non-smooth optimization.

In [21], a first-order optimization method based on gradient sampling was proposed. A detailed presentation of this method is found in [21], [22], [23].

In [24], the gradient sampling was combined with two optimization methods, a quasi-Newton and a local bundle algorithms leading to a hybrid algorithm. This algorithm has three steps:

1) a quasi-Newton (BGFS) algorithm provides a fast way to approximate a local minimizer
2) a local bundle phase attempts to verify local optimality for the best point found by the BFGS
3) the sampling gradient refines the approximation of the local minimizer in case the local bundle does not succeed

The hybrid algorithm is implemented in the Matlab package HIFOO, a freely available software [24], [25]. This software was used to design the central controller for several operating conditions.

B. The control algorithm

The control algorithm can be summarized as:

1) Identify the dominant oscillation modes and mode shapes
2) Calculate the index MSI
3) If the calculated and identified dominant eigenvalues, corresponding to electromechanical oscillation modes, are close, that is, if $\lambda_{Calculated} \cong \lambda_{Identified}$, and $|MSI - 1| < \epsilon$ then switch to the controller parameters set corresponding to the identified critical operating condition

V. Results

In this section the results of the application of the proposed approach to a test system are presented.

A. Test system

This is an equivalent of the South-Southeastern Brazil system. The single-phase diagram is presented in Figure 2. The complete data are found in [26].

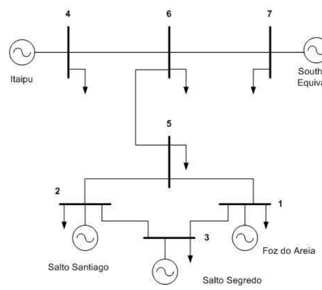

Fig. 2. Equivalent of Southern-Southeastern Brazil system

TABLE I
ELECTROMECHANICAL OSCILLATION MODES (WITHOUT PSS)

Eigenvalue	Frequency (Hz)	Damping (%)
$-2.01 \pm 9.17i$	1.46	21.44
$-1.80 \pm 9.18i$	1.46	19.26
$0.65 \pm 5.39i$	0.86	-11.91
$-0.22 \pm 5.88i$	0.93	3.84

B. Modal analysis

The modal analysis of this power system was performed and the electromechanical oscillation modes, without PSS are presented in Table I.

In [26], power system stabilizers were designed to stabilize this system. The electromechanical oscillation modes, with these PSSs, are shown in Table II.

TABLE II
ELECTROMECHANICAL OSCILLATION MODES (WITH PSS)

Eigenvalue	Frequency (Hz)	Damping (%)
$-0.33 \pm 5.21j$	0.83	6.38
$-1.207 \pm 3.24j$	0.51	34.92
$-1.77 \pm 13.90j$	2.21	12.63
$-1.84 \pm 13.87j$	2.21	13.18

In the identification process, the multisignal Prony method was used to estimate the eigenvalues and electrical power mode shapes for several contingencies.

It is assumed that all the five machine electrical power of the system is measured by the synchronized phasor system. The sampling frequency is 200 Hz and after a large excursion is detected, a ringdown, the identification process is initiated using a five-second data window. All the data is filtered and donwsampled to 20 Hz, in order to reduce computational burden in the identification process by the multisignal Prony method. The results (eigenvalues and residues) are ranked by the Modal Dominance Index (MDI) [27], which helps in the detection of critical modes (low damping) and indicates which poles are dominant even when they are not the slowest. Therefore, it is possible to compare the identified mode shapes associated with the critical modes with the ones previously calculated by the off-line linearization process and detect the critical condition to switch the centralized control. This process is assumed to take 500 ms.

For the identification process, data are obtained through nonlinear simulations after the occurrence of ringdowns. For all results, the size of the analysed data windows is 5 s.

For the base case, the identified critical eigenvalue and mode shapes are presented in Table III. The data for the identification were obtained after a 50 ms three-phase short-circuit at bus number 5, without line opening. The calculated and identified dominant eigenvalues and electric power mode shapes are in good agreement.

Although the conventional PSSs give a highly damped system, there are configurations for which the damping is considerably reduced. Two of the low damping configurations are considered in this work: **Case 1**, the loss one of the three identical transmission lines between bus 6 and the Southeastern system (bus 7) and **Case 2**, the loss of the transmission line between buses 2 and 5.

TABLE III
BASE CASE: MODE SHAPES AND EIGENVALUES

Mode Shape and Eigenvalues		Bus Number
Calculated	Identified	
$\lambda = -0.33 \pm 5.21j$	$\lambda = -0.36 \pm 5.22j$	
1 ∠0°	1 ∠0°	7
0.1736 ∠151.50°	0.1819∠149.58°	4
0.0932 ∠-167.86°	0.1063∠-165.46°	3
0.0874 ∠-166.30°	0.1004∠-164.25°	1
0.0644 ∠-162.54°	0.0731∠-160.26°	2
Mode Shape Index (MSI)		1.1010

The results of the identification of **Case 1** is presented in Table IV. The data for the identification is obtained by the application of a a 30 ms three-phase short-circuit at bus 6, followed by the opening of one of the three segments between buses $6-7$. This case results in almost zero damping. The discrepancy between the calculated and identified critical eigenvalue can be explained by the nonlinearities considered in the model during the nonlinear simulation.

TABLE IV
CASE 1: MODE SHAPES AND EIGENVALUES

Mode Shape and Eigenvalues		Bus Number
Calculated	Identified	
$\lambda = +0.021 \pm 4.62j$	$\lambda = -0.014 \pm 4.36j$	
1 ∠0°	1 ∠0°	7
0.2590 ∠124.39°	0.2840∠115.37°	4
0.0674 ∠179.62°	0.0618∠-167.00°	3
0.0663 ∠-178.05°	0.0619∠-164.47°	1
0.0500 ∠-174.18°	0.0467∠-160.65°	2
Mode Shape Index (MSI)		0.9588

The calculated and identified eigenvalues and electrical power mode shapes for **Case 2** are presented in Table V. The damping in this situation is $\zeta = 3.36\%$. The nonlinear simulation considers a 100 ms three-phase short-circuit at bus 2, followed by the opening of the transmission line connecting buses $2-5$.

TABLE V
CASE 2: MODE SHAPES AND EIGENVALUES

Mode Shape and Eigenvalues		Bus Number
Calculated	Identified	
$\lambda = -0.165 \pm 4.89j$	$\lambda = -0.166 \pm 4.87j$	
1 ∠0°	1 ∠0°	7
0.2184 ∠163.07°	0.2468∠165.09°	4
0.0690 ∠161.87°	0.0707∠164.31°	3
0.0651 ∠171.32°	0.0674∠170.94°	1
0.0505 ∠154.81°	0.0556∠158.44°	2
Mode Shape Index (MSI)		0.9436

A set of control parameters is designed for each of the two configurations, using the method described in the preceding section. The central controller is designed considering a 100 ms delay in the input signal and 100 ms delay in the output signal, totalizing 200 ms delay on transmission system data from the synchronized phasor measurement system to Phasor Data Concentrator (PDC) and from the PDC to the generators.

For **Case 1**, the designed control for the system changed the dominant pole locations from $\lambda = -0.014 \pm 4.36j$ to $\lambda = -0.67 \pm 4.79j$, with a damping $\zeta = 13.8\%$.

For **Case 2**, the controller changed the pole locations from $\lambda = -0.165 \pm 4.89j$ to $\lambda = -0.4048 \pm 4.9403j$, with a damping $\zeta = 8.17\%$.

In the next section, nonlinear simulation results are presented for the identification and the effect of the gain-schedule control.

C. Nonlinear simulations

In the simulation results, the control switching time occurs $5.5\ s$ after the detection of the ringdowns. This corresponds to the time window of $5\ s$ in which the data is acquired for the identification process and $500\ ms$ that is the time assumed for applying the Prony method and identifying the operating condition, totalizing $5.5\ s$.

A $100\ ms$ three-phase short-circuit at bus 2, followed by the opening of the transmission line connecting buses 2 and 5, leads to **Case 2**. The rotor angle of generators 2 and 4 are shown in Figure 3 and Figure 4, respectively. The control algorithm indicates that this corresponds to **Case 2** and the control parameter set suited to that case is switched after $5.5\ s$. The central control increases the system damping improving the system performance.

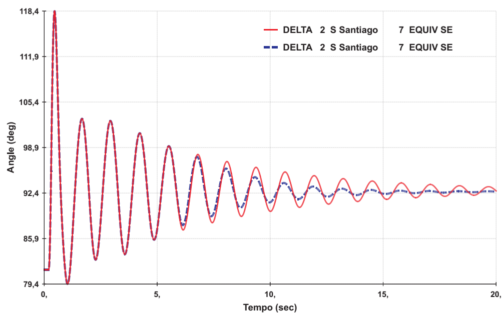

Fig. 3. Angle variations of generator 2: loss of line $2-5$.

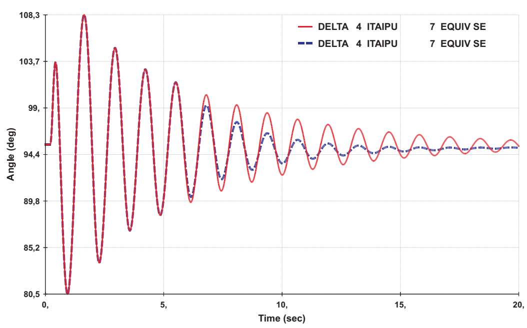

Fig. 4. Angle variations of generator 4: loss of line $2-5$.

A second fault, a $30\ ms$ three-phase short-circuit at bus 6, followed by the opening of one of the transmission lines connecting buses 6 and 7, leads to **Case 1**. The rotor angle of generators 1 and 4 are shown in Figure 5 and Figure 6, respectively. The operating condition is identified and the

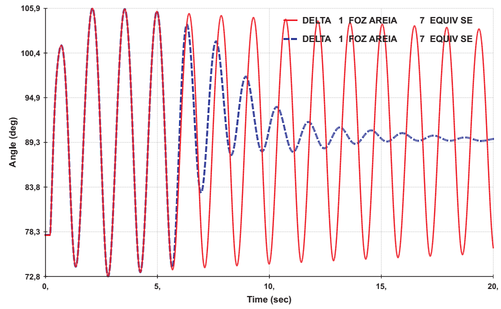

Fig. 5. Angle variations of generator 1: loss of line $6-7$.

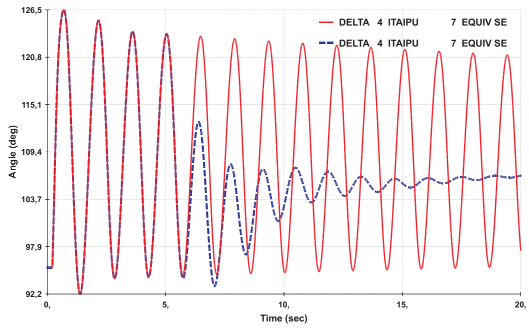

Fig. 6. Angle variations of generator 4: loss of line $6-7$.

control parameter set suited to this condition is switched. The system presents a higher damping with the centralized control.

The robustness of the centralized control scheme to the loss of a remote signal was tested. Assuming the loss of the Itaipu signal, the rotor angles of generators 2 and 4 are presented in Figure 7 and Figure 8, for the same fault. The system performance degrades but still an adequate damping is achieved.

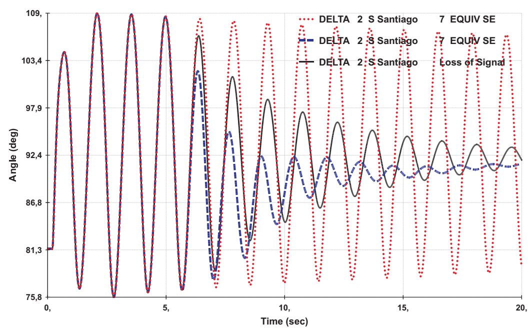

Fig. 7. Angle variations of generator 2: loss of line $6-7$ and loss of line $6-7$ followed by loss of Itaipu signal.

VI. Conclusions

A method for combining system identification and control, using synchronized phasor measurements was proposed in this paper.

The identification allows the detection of the emergence of low damped oscillation modes. Prony analysis was used, but other methods are currently available and can be tested for this

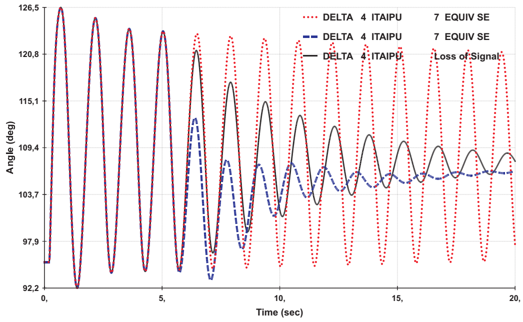

Fig. 8. Angle variations of generator 4: loss of line $6-7$ and loss of line $6-7$ followed by loss of Itaipu signal.

application. The identified dominant eigenvalues associated to the electromechanical modes and the identified mode shapes give an indication of the system configuration.

The tests performed as part of this work have shown that the oscillation modes and mode shapes can be identified in a time window that allows control action to be exerted. However, the application to larger systems must still be assessed.

The preliminary results of this research indicates the potential of synchronized phasor measurements as complement to the control scheme currently used in the industry.

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