

Identification of low frequency oscillation modes in large transmission systems

Identificación de modos de oscilación de baja frecuencia en sistemas de transmisión

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ABSTRACT: There is a typical dynamical performance associated with every system. Oscillations are phenomena inherent to dynamical systems and the analysis of such phenomena is a fundamental issue for understanding the dynamical behavior of a particular system. Knowledge of the system natural modes, frequencies and its associated damping ratio, provide valuable information regarding the system performance after being subjected to a disturbance. Due to the operational requirements, topological changes in the transmission network of the electrical power systems are quite common. This causes modification in both frequency and damping values of the natural system modes. In the past, normal changes in the operating condition have kicked up undamped power oscillations in the Mexican system, thus assessing the damping of critical oscillation modes of the system is of utmost importance. This paper reports on the application of modal analysis and time domain simulations for computing and tracking the most dominant low frequency oscillations, also known as inter-area modes, in the Mexican power system under different operating conditions. As a result, the most influential system variables on the low frequency oscillations have been identified.

RESUMEN: Existe un comportamiento dinámico típico asociado a todo sistema. Las oscilaciones son fenómenos inherentes a los sistemas dinámicos, por lo que el análisis de estos resulta fundamental para entender el comportamiento dinámico de un sistema en particular. El conocimiento de la frecuencia de oscilación y su correspondiente razón de amortiguamiento, asociados con los modos naturales del sistema, resulta fundamental para inferir el comportamiento dinámico del sistema después de que ha experimentado un disturbio. En un sistema eléctrico de potencia los cambios topológicos en la red de transmisión son bastante comunes debido a los requerimientos operativos. Esto ocasiona cambios en los valores tanto de la frecuencia de oscilación como el amortiguamiento de los modos naturales del sistema. En el pasado, cambios normales en la condición de operación del sistema mexicano han dado como resultado la aparición de oscilaciones de potencia no amortiguadas, por esta razón el conocer el amortiguamiento asociado con los modos críticos del sistema resulta de vital importancia. Este artículo reporta la aplicación del análisis modal y simulaciones en el dominio del tiempo para el rastreo de las oscilaciones de baja frecuencia dominantes, también conocidas como modos inter-área, en el sistema eléctrico mexicano durante diferentes condiciones de operación. Los resultados obtenidos permiten identificar a las variables del sistema de potencia más importantes sobre las oscilaciones de baja frecuencia.

1. Introduction

The main objective of an electric power system is the energy conversion from any of the available forms (steam, hydro, wind, nuclear, etc.), to the electrical form

and transport it through the transmission network to the consumption centers. Modern power systems are constituted by a large number of generators together with its controllers, transmission network and the consumption centers composed by different types of load. Although power systems worldwide are different in size and structural components, all of them are nonlinear in nature and exhibit the same basic characteristics. One of these characteristics is the oscillatory behavior after the occurrence of a disturbance. From the operating point of view, the oscillations following a disturbance are

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acceptable as long as they decay and die out in a reasonable period of time.

Today's power systems operate closer to their security limits and have become more sensitive to failure occurrence due to a number of factors such as; the continuous growth in the electricity consumption, the environmental and the economic constraints for building up new transmission lines together with the growing number of independent power generators increasing the power systems generation (as a result of the deregulation and restructuring processes in the electric industry worldwide) [1-5]. Thus, the use of new technologies for the implementation of control actions as well as new control schemes have had to be considered with the aim of ensuring a secure and reliable operation of the power systems [1-5], turning the daily operation of today's power systems more complex than ever before [6]. In this context, inter-area modes or low frequency oscillations in power systems have emerged as an important problem for secure system operation. Since low frequency oscillations may become a serious constraint for increasing power transfer over certain geographical regions in a power system, particularly areas where the interconnection with each other is rather weak under heavy loading conditions, they are prone to experience low frequency oscillations which in some cases may grow in magnitude, leading the system to an unstable operating condition [7, 8].

A documented example of this type of problems experienced in real power systems is the August 10, 1996 blackout in Western North America [9]. Therefore, the first step for mitigating the negative effects associated with poorly damped low frequency oscillations, in power systems is to understand its behavior. With this aim, identifying the inherent characteristics of this type of oscillations (oscillatory frequency, damping coefficient and generator's participation factors in the oscillation modes) is an important issue. In general, there are two basic approaches for identifying the power system oscillation modes; dynamic component-based methods [7, 8] and measurement-based methods [10, 11]. In the dynamic component-based approach, the mathematical model of every element of the power system is linearized at a given operating condition to build up the dynamic system Jacobian matrix, whose eigenvalues indicate the stability condition of the system around the given operating condition. On the other hand, the measurement-based approach only analyzes a given signal of the system response including all nonlinearities inherent to the power system. It has been recognized that small-signal stability analysis using component-based methods and modal techniques is an excellent alternative for determining the nature of the inter-area oscillations in power systems [8, 12]. For medium-size power systems, with this approach, it is possible to compute all eigenvalues, eigenvectors and participation factors associated with the power system mathematical model.

A common practice during the analysis of these modes, when using the dynamic component-based approach, is the use of both small-signal stability analysis and transient stability analysis in a complementary way [12]. Subsequently, small-

signal stability analysis, based on modal techniques, uses a linearized model of the power system, thus the non-linear behavior of the system controllers (excitation systems, speed governing systems, etc.) is neglected. However, the non-linear behavior of the system controllers may be properly considered in the transient stability analysis [13]. Therefore, the use of eigenanalysis together with time domain simulations enable to obtain a better understanding of the different factors that influence the inter-area oscillations performance in a power system [8, 13].

The Mexican Interconnected System (MIS) is up to date set up by the interconnection of seven control areas, however, before 2005, one of those control areas used to operate isolated from the other control areas due to the uprising of unstable low frequency oscillations every time that such control area was synchronized to the MIS in those days. With the aim of implementing a definitively solution to the troublesome oscillations and maintaining the interconnection of NO control area to the MIS permanently a number of simulation studies were carried out [14]. From the analysis of the simulation results it was found out that a proper tuning of the existing Power System Stabilizers (PSSs) of some generator units of the NO control area would yield an important improvement on the damping of those troublesome oscillations, and the permanently interconnection of the NO control area with the MIS would be possible.

2. Computation of low frequency oscillations

Low frequency oscillations are inherent to large interconnected power systems; this type of oscillations are characterized by low frequency values usually in the range of 0.1 to 0.8 Hz [12] and involve groups of generators in one part of the system swinging against a group of generators located in another part of the system [8]. As mentioned before, small-signal stability analysis based on modal techniques is commonly used to assess oscillatory problems in power systems. In addition, this approach also allows the identification of some interactions among oscillation modes that would be difficult to achieve from time domain responses, either from transient stability simulations or from real-time measurements, which are of fundamental importance for implementing effective solutions to improve the overall damping of the power system [15, 16]. Modal analysis is still the most widely used technique for assessing oscillatory stability problems in power systems [17], it provides useful information for determining the generators with significant contribution to specific oscillations modes and for identifying groups of generators that oscillate in a coherent way.

Under normal operating conditions all the power system's modes are to be positively damped, i.e. all the system eigenvalues must have negative real component. In case of complex eigenvalues, i.e. $\lambda = \sigma \pm j\omega$, the real component (σ) represents the damping and the imaginary (ω) component

represents the oscillation frequency of the mode. The frequency of oscillation in Hz (f) may be computed using the following relationship; $f = (\omega/2\pi)$. A negative real component indicates that following a small disturbance the system will return to the pre-disturbance operating condition, and a measure of how fast the oscillation will die is given by the “damping ratio” (ζ) of the oscillation mode. This damping ratio is determined as follows; $\zeta = -\sigma/(\sigma^2 + \omega^2)^{1/2}$ [8]. For operating security reasons in the Mexican system, a damping ratio of at least 5% is considered as the minimum acceptable value and any oscillation mode with a damping ratio equal or less than 5% is considered as a critical one and appropriate actions must be taken in order to improve the damping of such a mode. Thus, identification of the poorly damped low frequency oscillations in the Mexican system was based on the above criterion. Since very low damped oscillations may compromise the stable operation of the whole power system [18]. In the past, the emergence of undamped power oscillations have been reported in the Mexican system under normal operating conditions [19].

2.1. Mathematical model of a power system

The power system mathematical model is represented by a set of non-linear differential Eq. (1) and a set of algebraic Eq. (2) as shown below,

$$\dot{x} = f(x, y, u) \quad (1)$$

$$0 = g(x, y, u) \quad (2)$$

Where x is a vector of state variables, y is a vector of algebraic variables and u is a vector of control variables. Generator and control dynamics are described by the differential equations, while the transmission network is described by the algebraic ones.

2.2. Modal analysis

Modal analysis is a methodology for identifying the inherent dynamic characteristics of a system such as natural frequencies, damping factors and mode shapes, using them to formulate a mathematical model, named the modal model, to describe the dynamical behavior of the system. Modal analysis includes both theoretical and experimental approaches. Theoretical approach relies on the description of physical properties of the system to obtain the modal model while experimental approach derives the modal model from Frequency Response Function data or measured response data. In this paper, the theoretical one is used for identifying the low frequency oscillations in a power system. Since modal analysis is a linear system analysis tool and the mathematical model of the power system is a nonlinear one, then Eqs. (1) and (2) must be linearized around a given operating condition (x_0, y_0, u_0). Therefore, the linearized mathematical model of the power system may be expressed by the matrix Eq. (3).

$$\begin{bmatrix} \Delta \dot{x} \\ 0 \end{bmatrix} = \begin{bmatrix} \left. \frac{\partial f}{\partial x} \right|_{x_0, y_0, u_0} & \left. \frac{\partial f}{\partial y} \right|_{x_0, y_0, u_0} \\ \left. \frac{\partial g}{\partial x} \right|_{x_0, y_0, u_0} & \left. \frac{\partial g}{\partial y} \right|_{x_0, y_0, u_0} \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} \quad (3)$$

Assuming that sub-matrix $\left. \frac{\partial g}{\partial y} \right|_{x_0, y_0, u_0}$ is nonsingular, Eq. (3) may be rewritten as Eq. (4)

$$\begin{aligned} \Delta \dot{x} &= \left[\left. \frac{\partial f}{\partial x} \right|_{x_0, y_0, u_0} - \left. \frac{\partial f}{\partial y} \right|_{x_0, y_0, u_0} \left. \frac{\partial g}{\partial y} \right|_{x_0, y_0, u_0}^{-1} \left. \frac{\partial g}{\partial x} \right|_{x_0, y_0, u_0} \right] \Delta x \\ &= [A] \Delta x \end{aligned} \quad (4)$$

Thus, the linearized set of differential algebraic equations may be reduced to a set of differential equations as shown in (4) and matrix A is usually known as the system state matrix.

At this point, the stability condition of the system around the given operating condition may be inferred from the eigenvalues of matrix A . The number of eigenvalues will depend on the number of state variables considered in the power system model and some of them will be complex ($\lambda = \sigma \pm j\omega$) and others real ($\lambda = \sigma$) numbers. Should at least one of the eigenvalues, has positive real part the system condition will be unstable. Associated with each eigenvalue (λ_i) there is a couple of vectors known as right- (ϕ_i) and left-eigenvector (φ_i) that satisfy Eqs. (5) and (6),

$$\Phi = [\phi_1 \ \phi_2 \dots \ \phi_n] \quad (5)$$

$$\varphi_i [A - \lambda_i I] = 0 \quad (6)$$

Since the right and left eigenvectors associated with different eigenvalues are orthogonal, it is easily inferred that their scalar product is null, it is, $\varphi_k \phi_i = 0$. However, if they are associated with the same eigenvalue, then the scalar product is not null, it is, $\varphi_k \phi_i = 1$, provided that the eigenvectors have been properly normalized. Therefore, the modal matrices of the system may be expressed by Eqs. (7), (8) and (9);

$$\Phi = [\phi_1 \ \phi_2 \dots \ \phi_n] \quad (7)$$

$$\Psi = [\varphi_1^t \ \varphi_2^t \dots \ \varphi_n^t]^t \quad (8)$$

$$\Lambda = \text{diag}\{\lambda_1 \ \lambda_2 \dots \ \lambda_n\} \quad (9)$$

Since matrices Φ and Ψ are orthogonal, then $\Phi \Psi = I$ and $\Psi = \Phi^{-1}$. If all system eigenvalues are considered at the same time, Eq. (5) may be expressed by Eqs. (10) and (11);

$$A\Phi = \Phi\Lambda \quad (10)$$

$$\Phi^{-1}A\Phi = \Lambda \quad (11)$$

Thus, considering a new state vector $[z]$ related to the original one $[\Delta x]$ by the following transformation; $\Delta x = \Phi z$, then the system defined by (4) may be represented by a set of uncoupled first order Eq. (12), as shown below,

$$\dot{z} = \Phi^{-1} A \Phi z = \Lambda z \quad (12)$$

The right eigenvector indicates the mode shape (the relative activity of the system state variables due to the excitation of a particular mode), while the left eigenvector indicates which combination of the system state variables displays only a particular mode. In other words, the right eigenvector measures the activity of the k -th variable in the i -th mode and the left eigenvector weighs the contributions of this activity to the i -th mode, as can be inferred from Eqs. (13) and (14),

$$\Delta x(t) = \Phi z(t) = [\phi_1 \phi_2 \dots \phi_n] z(t) \quad (13)$$

$$z(t) = \Psi \Delta x(t) = [\psi_1^t \psi_2^t \dots \psi_n^t]^t \Delta x(t) \quad (14)$$

The entries of both right and left eigenvectors are dependents on units and scaling associated with the system state variables. Thus, using the right and the left eigenvectors individually for determining the relationship between the system states and modes may be misleading. The use of participation factors provides an improved alternative to associate the states and the modes of the system. This is due to the fact that participation factors are dimensionless and combine the entries of both right and left eigenvectors. A participation factor is a measure of the relative participation of the k -th state in the i -th mode and vice versa, Eq. (15) indicates how participation factors are computed from the eigenvectors entries.

$$p_{ki} = \phi_{ki} \psi_{ik} \quad (15)$$

Where ϕ_{ki} is k -th element of the right eigenvector (column vector) associated with the i -th system mode, and ψ_{ik} is the k -th element of the left eigenvector (row vector) associated with the i -th system mode. Since the sensitivity of the eigenvalue λ_i to the element a_{kj} of the state matrix is equal to the product of the left eigenvector element ψ_{ik} and the right eigenvector element ϕ_{ji} , as shown in (16)

$$\frac{\partial \lambda_i}{\partial a_{kj}} = \psi_{ik} \phi_{ji} \quad (16)$$

It is worth to note that the participation factor p_{ki} , Eq. (17), indicates the sensitivity of the i -th mode to the diagonal element a_{kk} of the state matrix.

$$p_{ki} = \frac{\partial \lambda_i}{\partial a_{kk}} = \psi_{ik} \phi_{ki} \quad (17)$$

3. System description

This section describes briefly the relevant characteristics of the Mexican Power System (MPS). The overall installed capacity of the MPS is about 51 GW, the backbone of transmission network is built up by approximately 49000 km of transmission lines in the range of 400 kV, 230 kV and 161 kV. While the distribution system, is made up by more than 69000 km of lines at distribution voltage levels (115 kV or less). The system model considered in the simulations reported in this paper, is based on a medium loading condition, characterized by a system load of approximately 35,000 MW, and a system generation of about 36,000 MW, 5068 buses, 7333 branches and 399 generating units. A geographical representation of the Mexican interconnected power system is shown in Figure 1.

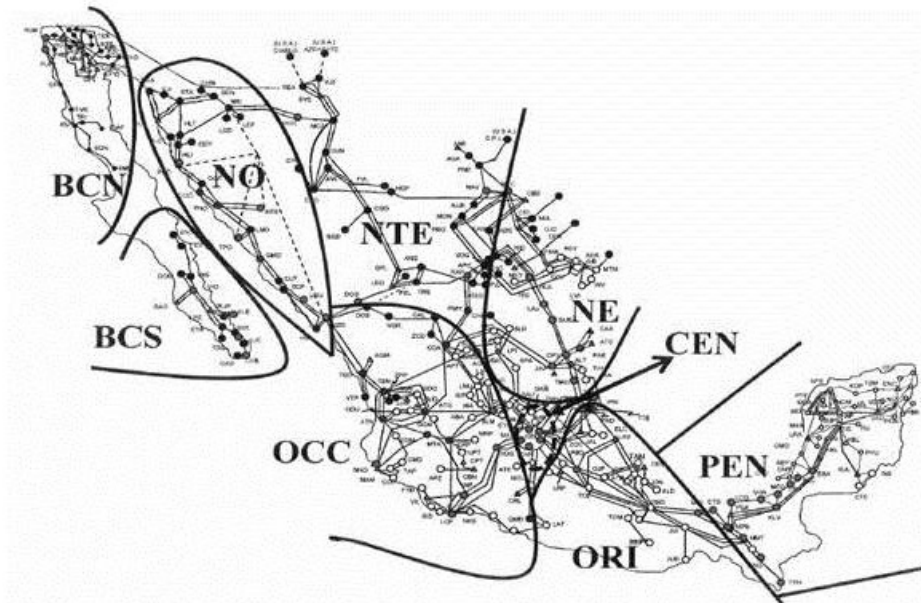


Figure 1 Mexican interconnected power system [20]

The system is composed by the following nine control areas; Baja California Norte (BCN), Baja California Sur (BCS), Noroeste (NO), Norte (NTE), Noreste (NE), Occidental (OCC), Central (CEN), Oriental (ORI) and Peninsular (PEN). The BCN and BCS control areas operate isolated from the rest of the control areas. From year 2005 to date, the Mexican interconnected system (MIS) is integrated by the NO, NTE, NE, CEN, OCC, ORI and PEN control areas. Each control area of the MIS coordinates the operation at a regional level and a National Control Centre establishes the overall operating policies, security limits and coordinates the operation of the MIS.

4. Case studies and simulation results

In this section, theoretical results from modal analysis and time domain analysis of different transmission system topologies of the MIS, for an operating scenario associated with the medium loading condition briefly described in the previous section, are reported. All the results reported in the paper were obtained using the commercial grade software DSATools [21].

4.1. Case study A

This case study is the base case and it is aimed to determine the inter-area modes oscillation frequency, damping ratio and the groups of units with important contribution on those modes.

4.2. Case study B

This case study assesses the trip of one of the three tie-lines between the NTE and NRE control areas on the inter-area oscillation modes of the MIS. The voltage level of this tie line is 400 kV which feeds 324 MW from NRE control area to NTE one.

4.3. Simulation results

All the results reported in this section correspond to the operating condition described in section III, and are associated with the particular conditions considered in cases A and B. Modal analysis of base case indicates the existence of four inter-area modes in the system, just two of them are considered of interest, since the damping value of mode 1 is below and the associated with mode 3 is just above of the critical value. The other two may be considered as well damped, as shown in Table 1. Thus, the attention will be focused on the performance of modes 1 and 3.

From the information provided in Table 1 and Figures 2 to 5, it can be inferred that mode 1 represents the oscillation of a group of generators located in the NRE against another group of generators located in ORI control area, being the generators in ORI control area the most dominant on that

Table 1 Characteristics of the four inter-area modes for case study A

Mode	Frequency (Hz)	Damping ratio (%)
1	0.8706	4.76
2	0.7210	14.24
3	0.5490	5.40
4	0.4308	10.44

oscillation mode. Figure 6 shows in the time domain the oscillations of those generators.

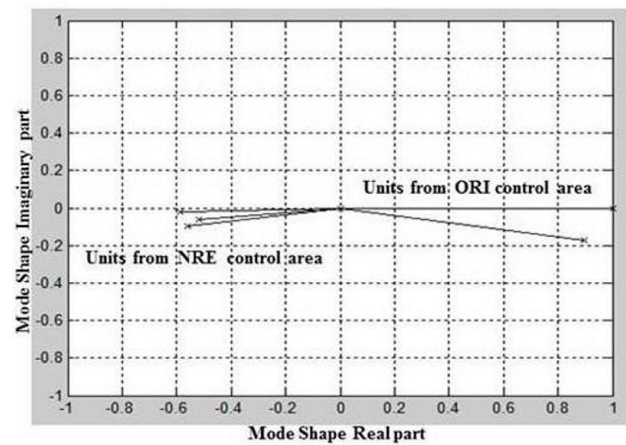


Figure 2 Mode shape associated with mode 1, case study A

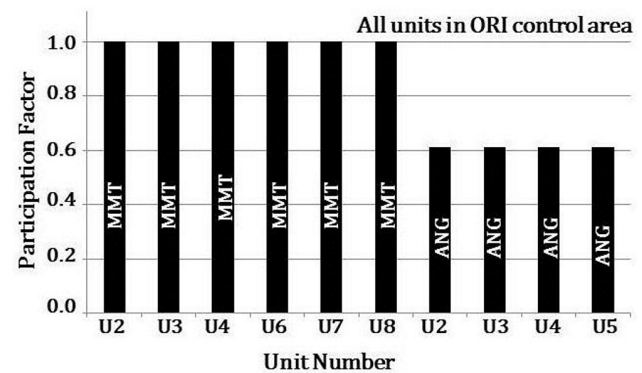


Figure 3 Participation factors associated with mode 1, case study A

On the other hand, mode 3 represents the oscillation of a group of generators located in PEN control area against groups of generators in CEN and NTE control areas. The group of generators located in PEN control area is the most dominant on this oscillation mode. Figure 7 shows the oscillations of those generators.

Figures 8 and 9 show the output power of generating units MMT-U8 and VAD-U8 (the most participating units on oscillation modes 1 and 3 respectively) located in control areas ORI and PEN respectively. Application of Prony's method to those signals revealed that the damping value of modes 1 and 3 computed from the time response is in very close agreement with the computed using modal analysis, as shown in Table 2.

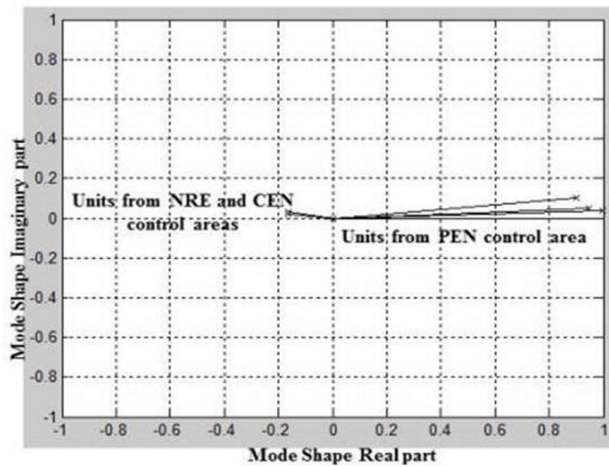


Figure 4 Mode shape associated with mode 3, case study A

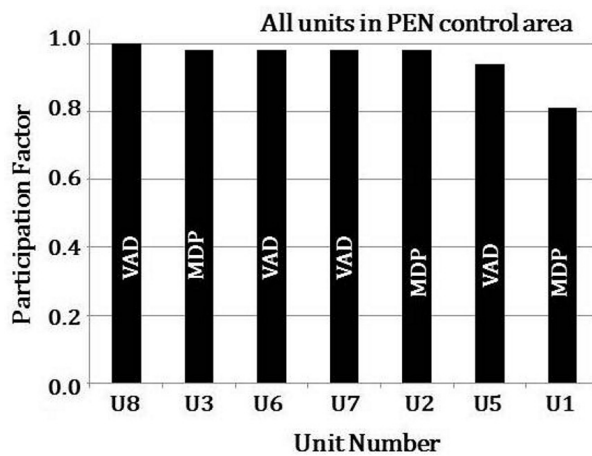


Figure 5 Participation factors associated with mode 3, case study A

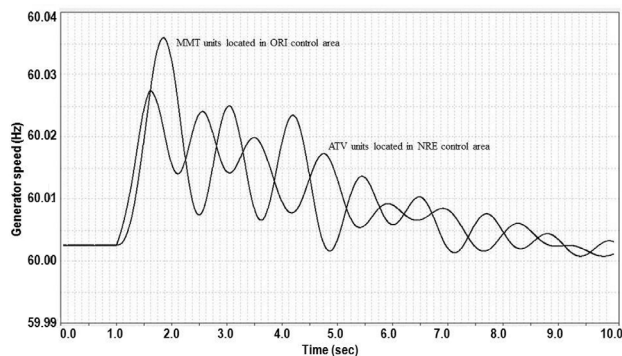


Figure 6 Oscillatory performance of generators located in ORI and NRE control areas

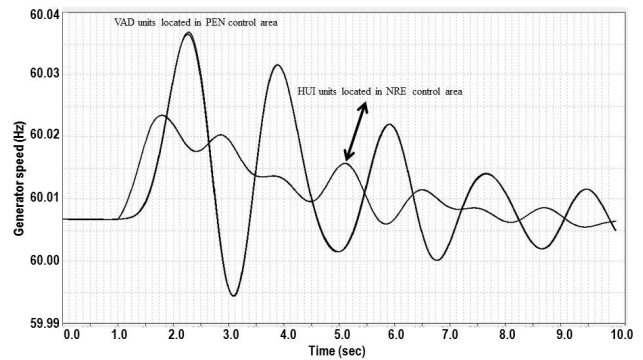


Figure 7 Oscillatory performance of generators located in PEN and NRE control areas

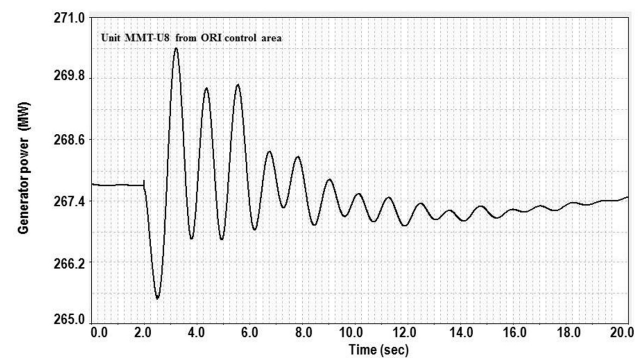


Figure 8 Electrical power (MW) unit MMT-U8

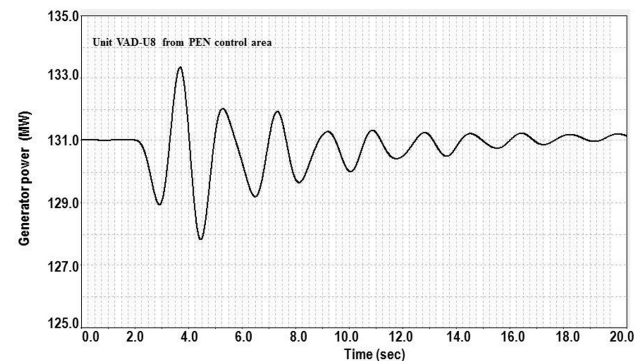


Figure 9 Electrical power (MW) unit VAD-U8

Results of case study B are summarized in Table 3. It is noted that the damping associated with the oscillations modes 1 and 3 turn them critical, since its value is less than 5%. While modes 2 and 4, remain well damped. The frequency of oscillation associated with each inter-area mode is less than the corresponding to the base case.

Table 2 Characteristics of inter-area modes 1 and 3 using Prony's method

Signal / Unit	Mode	Frequency (Hz)	Damping ratio (%)
Electrical Power (MW) / MMT U8	1	0.871	4.618
	3	0.547	5.472
Electrical Power (MW) / VAD U8	1	0.87	4.542
	3	0.549	5.323

Figures 10 and 11 indicate that in case study B mode 1 represents the oscillation of a group of generators in the NRE against another group of generators located in ORI control area and the generators of ORI control area are the most dominant on that oscillation mode.

Table 3 Characteristics of the four inter-area modes for case study B

Mode	Frequency (Hz)	Damping ratio (%)
1	0.8664	3.92
2	0.7091	15.82
3	0.5298	4.54
4	0.3824	15.54

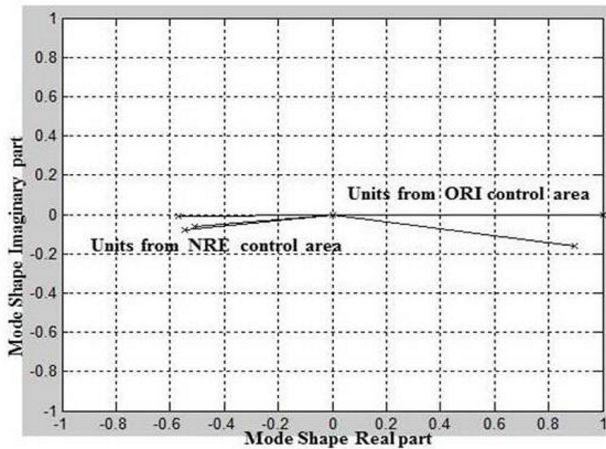


Figure 10 Mode shape associated with mode 1, case study B

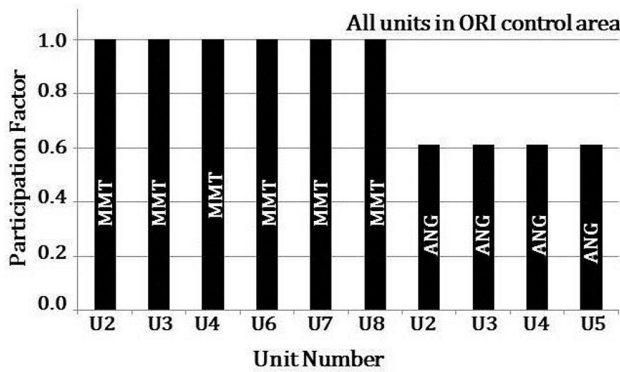


Figure 11 Participation factors associated with mode 1, case study B

Figures 12 and 13 indicate that in case study B mode 3 represents the oscillation of a group of generators located in the NRE against another group of generators located in PEN control area and the generators of PEN control area are the most dominant on that oscillation mode.

From Figures 3 and 11, it is easily inferred that the most dominant generators on oscillation mode 1 are the same in both cases. Furthermore, the magnitude of the participation of each generator on such a mode is the same. A similar

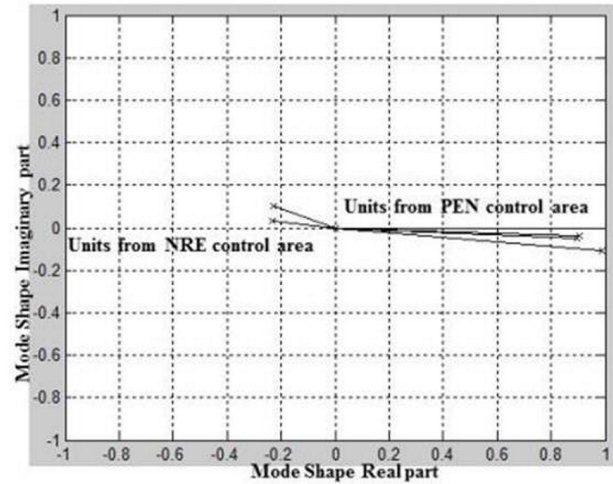


Figure 12 Mode shape associated with mode 3, case study B

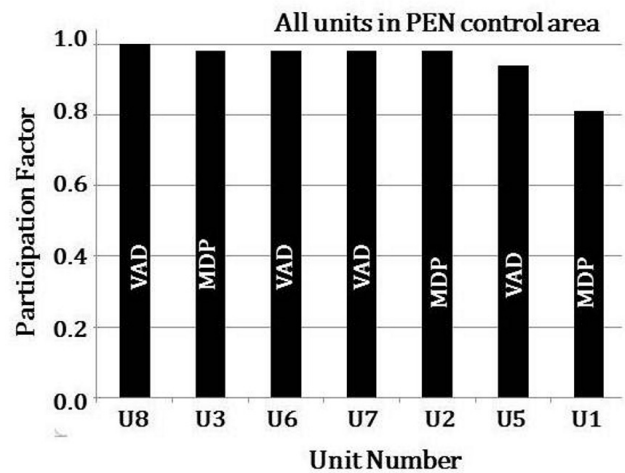


Figure 13 Participation factors associated with mode 3, case study B

inference holds for oscillation mode 3, from the information provided by Figures 5 and 13. The time domain performance of generating units located at ORI control area oscillating against a group of generators located in NRE control area and groups of generators in PEN control area oscillating against another unit located in NRE control area, is shown in Figures 14 and 15 respectively.

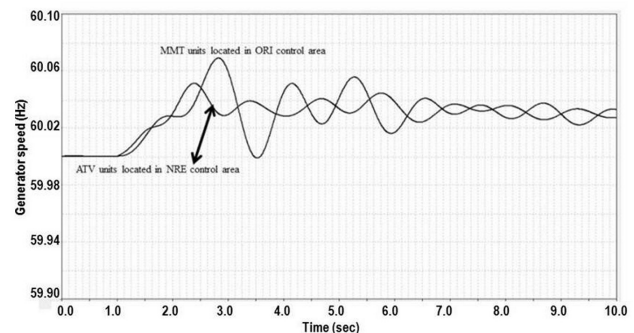


Figure 14 Oscillatory performance of generators located in ORI and NRE control areas

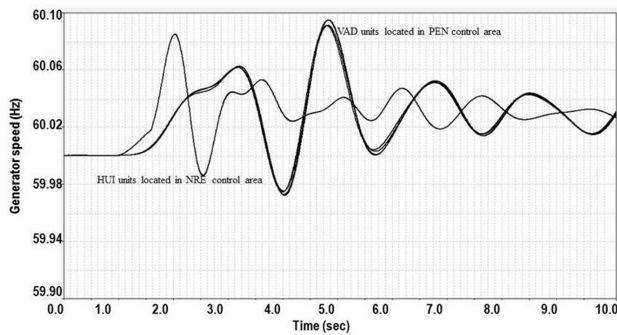


Figure 15 Oscillatory performance of generators located in PEN and NRE control areas

5. Conclusions

The paper has presented an application of modal and time domain analysis for the analysis, identification of critical inter-area modes in a real power system, over different operating conditions. Modal analysis was used to determine the main characteristics; frequency of oscillation, damping and the most influential variables of the power system on those modes. The knowledge of the most dominant generators on a specific oscillation mode is very useful information for taking actions to improve the damping of such a mode. Since the most cost effective measure for increasing the system damping is the application of power system stabilizers (PSS's), the most dominant generators on the poorly damped modes are very suitable locations for PSS's placement. Time domain analysis was used to simulate the power system behavior and to verify the conclusions reached from the results of modal analysis. Finally, it is concluded that the approach used in the paper may be very useful to determine the variables of a power system that should be monitored for tracking the performance of the critical modes over different operating conditions.

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