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The localness of electromechanical oscillations in power systems

Sudipta Ghosh *, Nilanjan Senroy

Department of Electrical Engineering, Indian Institute of Technology Delhi, Hauz Khas, New Delhi 110 016, India

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ABSTRACT

An innovative index, indicative of the relative localness of electromechanical oscillations in electric power systems, is introduced in this paper. The L_{index} is calculated using the normalized participation factors obtained from a small signal analysis of the system. With the help of simple representative examples the efficacy of the index to understand power system dynamic behavior, like coherency identification is established.

1. Introduction

Power system response to small disturbances is oscillatory in nature. Monotonic instability due to small disturbances is rare, as a result of extensive and widespread use of modern continuous acting regulators. The focus of this paper is on oscillations that are electromechanical in nature, involving excursions of synchronous generator rotor angles and shaft speeds. Such oscillations are in the range of 0.1–2 Hz, and are a common cause for concern in large weakly meshed power systems. In multi-machine power systems, various generators participate in different modes of oscillations in varying degrees. The participating generators form patterns that well characterize the nature of the electromechanical modes of oscillations. Sustained, poorly damped and sometimes undamped oscillations introduce additional operating constraints, and severely hamper system reliability. The analysis of such electromechanical oscillations constitutes the first step towards designing controllers to improve their damping characteristics.

Electromechanical oscillations in power systems are adequately described and studied using small signal stability models employing linearization techniques. Broadly, two types of electromechanical oscillations are observed. Low frequency oscillations (less than 1 Hz) involving one part of the system against another, are termed as global or inter-area oscillations. The dynamic characteristics of the overall power system are best understood by analyzing these inter-area modes. On the other hand, a *local mode* of oscillation involves a single generator or a group of adjacent generators and its frequency is relatively higher – varying from 0.5 to 2 Hz. The damping action of the amortisseur windings located on the rotor of synchronous machines, manifests itself during the local mode oscillations [1]. In some cases, the readily available frequency of oscillation may hint at the nature of the mode, yet it is not a reliable tool to classify modes into local or inter-area types. In general, the frequency of an electromechanical mode may be negatively correlated with the number of machines participating in the mode, however as Fig. 1 shows, this correlation is not clearly defined.

Although an important step in the stability analysis of a power system, the classification of electromechanical oscillations into local/inter-area types is straightforward and performed in a somewhat routine manner. Nonetheless, in large systems it has been noticed that while distinguishing an inter-area mode from a local mode is straightforward, it is not always easy to determine the *most* global or local mode. Similarly, the relative 'localness' of a mode is not immediately clear from mere inspection of the participating generators. Alternatively, the well established link [2] between the energy of a mode and its description in the complex plane (using eigenvalues) suggests that the localness of the mode is closely related to the modal energy. Thus, an index that summarizes the modal energy information of various modes can be exploited to develop an efficient localness ranking strategy. Such a ranking strategy would be particularly useful in system-wide stability studies such as dynamic aggregation of generators and model order reduction of large power systems.

As part of a small signal stability analysis, the calculation of participation factors helps in associating generator states with the modes or eigenvalues of the system [3,4]. If a large number of dispersed generators are associated with a single mode, it is identified as an inter-area mode, while only a few generators are associated

* Corresponding author. Tel.: +91 9891 317925.
E-mail addresses: sudiptarit@gmail.com (S. Ghosh), nsenroy@ee.iitd.ac.in (N. Senroy).

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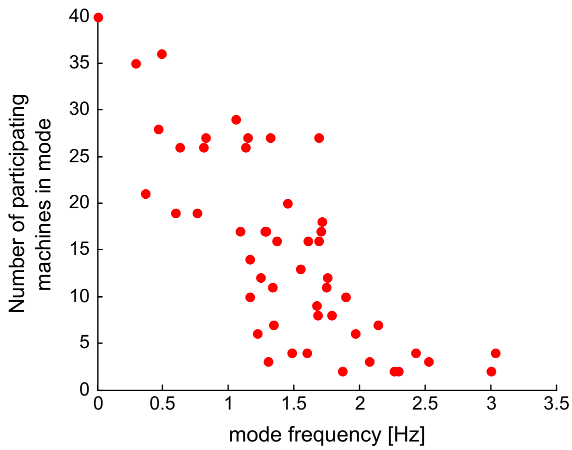

Fig. 1. The number of machines participating in an electromechanical mode versus its frequency, in modified IEEE 50-machine test system.

with a local mode. Further, it has also been recognized that in classically modelled power systems, with negligible line resistances and machine damping, the machine state participation factors indicate the energy of the corresponding machines in the mode [5,6]. All the participation factors for a mode sum to unity, indicating the relative contribution of individual machines to the total energy of that mode. In a normalized participation factor matrix each entry compares individual mode-machine associations, with the maximum association for that particular mode to a machine. Therefore, a vector consisting of all the normalized participation factors for a mode can be used as a pointer to the total modal energy [7–9].

This paper presents an innovative index, L_{index}, that is related to the individual modal energy and can be used to rank modes according to their localness. The index is heuristic in nature, designed intuitively from the patterns formed by the normalized participation factors of electromechanical modes. In addition to ranking, an important design objective of the index is its ability to cluster the modes according to their localness. Thus, not only the relative localness of the modes is revealed, effective separation between local and inter-area modes are also accomplished. Experiments on a mechanical mass-spring system analogy, along with power system examples demonstrate the utility of the L_{index} to understand evolving system dynamic behavior. Finally, as an illustrative application, the index is used to select modes that form an eigenspace, from which the dynamic coherency between generators is recognized. The groups are compared with the generator groups obtained if the slow coherency algorithm was used [10–13].

The rest of the paper is structured as follows. Section 2 summarizes the general state-space framework for small signal stability analysis of power systems. The L_{index} is designed and formulated in Section 3. The correlation of L_{index} with simple RLC network and one mechanical three mass spring system [3] is illustrated in Section 4. Section 5 discusses some important characteristic of L_{index} with help of Kundur's four machine test system [14], whereas Section 6 presents the application of this index for coherency grouping recognition in a 10 generator 39 bus test system [15]. Section 7 is the concluding section.

2. Modal analysis of power system

For small deviations around an operating equilibrium point, a multi-machine power system may be linearized in state space form as

$$\dot{\mathbf{x}}_{\Delta} = \mathbf{A}\mathbf{x}_{\Delta} \tag{1}$$

where $\mathbf{x}_{\Delta}$ is the vector consisting of the deviations in the system states, and **A** is the state matrix [1]. The dimensions of the **A**-matrix are determined by the number of states of the system. Although the total number of states increases for detailed modelling of the generators as compared to classical models, the number of generator electromechanical states remains the same. As the focus is on electromechanical oscillations, the **A**-matrix considered here corresponds to the two generator electromechanical states – rotor angle and speed. For a system of m electromechanical states, the eigen-analysis of the **A** matrix ($m \times m$) will produce m eigenvalues, λ_i, and corresponding right and left eigenvectors – $\mathbf{v}_i$ (m column vectors), and $\mathbf{u}_i$ (m row vectors) respectively. The *normalized* eigenvectors associated with ith eigenvalue λ_i satisfy (2).

$$\begin{aligned} \mathbf{A}\mathbf{v}_i &= \lambda_i \mathbf{v}_i \\ \mathbf{u}_i\mathbf{A} &= \lambda_i \mathbf{u}_i \end{aligned} \tag{2}$$

The element $\mathbf{v}_{ki}$ i.e. the kth element of right eigenvector $\mathbf{v}_i$ measures the activity of the kth state in the ith mode, whereas the kth element of the left eigenvector $\mathbf{u}_i$ indicates the importance of this activity in defining the mode. The coupling between a particular state and a mode is revealed by the participation factor [1], $p_{ki} = \mathbf{u}_{ki}\mathbf{v}_{ik}$ measuring the participation of the kth state in the ith mode; p_{ki} lies between 0 and 1. The participation factors for a mode are further normalized on the maximum participation for that mode. After normalization, p_{ki} has a maximum value of one indicating the maximum participation of a generator in a mode.

3. The localness index

For an N-generator system, the localness index of the ith electromechanical mode is calculated from the normalized participation factors as

$$L_{index,i} = \sum_{k=1}^{N} (1 - p_{ki})^n \tag{3}$$

The number of terms in the summation corresponds to the synchronous generators in the system. The exponent of each term, n, is chosen to give the property of clustering to the L_{index}. The primary purpose of L_{index} is to rank all modes according to their localness. The modes ranked at the bottom of such a list would be inter-area modes and the modes grouped at the top would be local modes. Additionally, the modes should form natural clusters, when ranked according to their L_{index}. In experiments with three test systems (Figs. 14–16 in the Appendix and Table 1), different values of the exponent n were considered for their usefulness as a clustering tool. For all the electromechanical modes of a system, the L_{index} was calculated using different values of the exponent n in (3). The individual mode L_{index} values were used to rank and cluster the modes to see which value of n yielded best mode clusters. The clustering validity was evaluated using the 'silhouette score', for every point (mode in this case) [17,18].

The silhouette score for a point in a cluster compares the similarity of the point to other members of its cluster, versus its remoteness from points in other clusters. Accordingly, points in

Table 1
Different test systems.

Test system	Description	Number of electromechanical modes
Test system A	Four machine system [14]	Four
Test system B	Six machine system [15]	Six
Test system C	Ten machine test system [16]	Ten