Electric Power Systems Research 79 (2009) 562–568

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

A new methodology for identification of critical lines using damping sensitivity analysis

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ARTICLE INFO

Article history:
Received 5 April 2008
Received in revised form 14 July 2008
Accepted 17 August 2008
Available online 2 October 2008

Keywords:
Inter-area oscillation
Eigenvalue analysis
Damping sensitivity
Identification of critical lines
Small-signal stability

ABSTRACT

When an inter-area mode dominates a low-frequency oscillation in a stressed condition, control of the active power flow of interface lines, with compensating devices, can effectively reduce the electromechanical power oscillations. In general, interface lines in which inter-area oscillations are large are considered to be good locations for installation of compensating devices. A sensitivity analysis with respect to change in active power flow can provide an important factor in electric power system operation. This paper proposes a new methodology to calculate the damping sensitivity with respect to change in active power flow, which can be useful for accurate selection of critical lines from the viewpoint of small-signal stability. In the proposed methodology, a damping sensitivity index is used to select the critical lines to damp power system oscillations. This paper describes how to derive the damping sensitivity for the selected mode and illustrates an example applying the proposed algorithm to a simple two-area system and the New England 39-bus test system.

1. Introduction

With the advent of deregulation and privatization in the power market and the increasing trend of interconnection of power grids, many interconnected power systems worldwide experience low-frequency oscillation phenomena [1,2]. The need for analyzing the eigenvalue problems of these kinds of power systems is more gaining in order to obtain the reliable and secure operation of power systems. As the system becomes more stressed, weak transmission links and unexpected events may lead to a problem related to a low-frequency inter-area oscillation of small-signal stability. This problem even can cause a major system breakdown. When subjected to a disturbance, the eigenvalues will experience some change. The causes of low-frequency oscillation phenomena in a power system are mainly correlated with system structure, excitation systems, disturbances, and operating conditions. The active power flows on transmission lines, especially, are closely related to those kinds of conditions. In recent times, the use of flexible AC transmission systems (FACTS) devices has become a common practice in order to enhance the damping of inter-area power swings by controlling the active power through an interface line [3,4]. In this respect, the changes in the critical eigenvalues associated with the inter-area mode will affect the selection of the best installing location.

Many authors have researched this topic and have proposed various indices as documented in the literature [5–13]. These research efforts can be categorized into two methods. One is the residue technique, which is based on the modal control theory of linear time-variant systems. In [5], the location index for effective damping was proposed to find the suitable locations of compensating devices using the sensitivities of generator output power with respect to variable impedance. The other method is the damping torque analysis method, which is based on a physical understanding of the electromechanical oscillations of power systems. Application of the controllable series compensator in damping power system oscillations using the basis on the Phillips-Heffron model has been investigated in [7]. Recently, an estimation technique for on-line damping torque to provide information associated with poorly damped modes is proposed [12]. Consequently, those works have focused on the effects of general operating parameter changes on system performance. In large-scale interconnected power systems, the power flow oscillation on transmission lines affected by inter-area modes may depend on several machines and loads. It is known that the inter-area modes participated in hundreds of machines are more sensitive to the change in the power flow on critical lines [14,15]. Therefore, a study of the eigenvalue sensitivity analysis with respect to the change in power flow oscillation on transmission lines may provide more clear insight on the inter-area oscillations

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doi:10.1016/j.epsr.2008.08.006

than those by general system parameters. The objective of this paper is to determine the dominant interface line associated with the inter-area oscillation.

In this paper, we propose a new damping sensitivity analysis with respect to the change in active power flow of interface lines. We first introduce the identification of the critical eigenvalues associated with inter-area oscillation modes. Then the damping sensitivity index with respect to active power flow for the identified modes is then calculated. The proposed method is available to obtain information regarding the changes in the eigenvalues associated with the inter-area mode. Finally, a procedure for determining the critical lines from the viewpoint of small-signal stability is presented. The proposed method was tested on a simple two-area system and the IEEE 39-bus New England test system. In addition, the numerical results are validated through comparative simulations with Small Signal Analysis Tool (SSAT) [16]. The test and results shows the capabilities of the proposed method.

This paper is organized as follows. Damping sensitivity method is proposed to identify the critical lines in Section 2. Formulations regarding the implementation needed for the damping sensitivity analysis are provided in Section 3. The proposed ideas are illustrated with numerical tests in Section 4. Some comments about future work and conclusions are discussed in Section 5.

2. Sensitivity-based identification method

As mentioned before, eigenvalue analysis has been widely used to compute the mode identification of power system linear models. The new damping sensitivity with respect to the change in active power flow of interface lines will be described in the following sections by using the eigenvalue sensitivity techniques.

2.1. Eigenvalue sensitivity

In general, the equation describing the oscillatory behavior of a power system may be formulated in a state equation as follows:

$$\dot{x} = Ax \tag{1}$$

The state variables are given by the expression:

$$x(t) = \sum_{i=1}^{N} u_i v_i^{\mathrm{T}} x(0)\ \mathrm{e}^{\lambda_i t} \tag{2}$$

In Eq. (1), x is the vector of the difference variables that make states of the system. A is the state (Jacobian) matrix with distinct eigenvalues, λ_i ($i = 1, 2, \ldots, N$): in (2), u_i ($i = 1, 2, \ldots, N$) are the linearly independent eigenvectors of A which satisfy:

$$Au_i = \lambda_i u_i \tag{3}$$

and v_j ($j = 1, 2, \ldots, N$) are the corresponding eigenvectors of A^{T} which satisfy:

$$v_j^{\mathrm{T}} A = \lambda_j v_j^{\mathrm{T}} \tag{4}$$

The variables, u_i and v_j, satisfy the equation:

$$u_i^{\mathrm{T}} v_j = v_j^{\mathrm{T}} u_i \begin{bmatrix} = 0 & \text{for} & i \neq j \\ \neq 0 & \text{for} & i = j \end{bmatrix} \tag{5}$$

The corresponding fundamental problem in sensitivity theory is to determine the sensitivities of λ_i, u_i, and v_i ($i = 1, 2, \ldots, N$) to changes in the system parameters, i.e. to changes in the elements of the state matrix. Based on sensitivity analysis techniques, the desired eigenvalue sensitivity coefficients which relate changes in the λ_i to change in the system parameter σ are given by [17]

$$\frac{\partial \lambda_i}{\partial \sigma} = v_i^{\mathrm{T}} \frac{\partial A}{\partial \sigma} u_i \tag{6}$$

as the sensitivity of the ith eigenvalue with respect to the system parameter σ.

2.2. New damping sensitivity

When the active power flow of the transmission lines changes as the operating condition varies, the elements of the system matrix are perturbed, and then the eigenvalues and eigenvectors of the matrix will be affected. A small change in the tie line active power may cause a large change in the eigenvalues associated with the inter-area mode. The new sensitivity formulation with respect to the change in the active power flow of the transmission lines is given by

$$\frac{\partial \lambda_i}{\partial P_{\mathrm{ab}}} = v_i^{\mathrm{T}} \frac{\partial A}{\partial P_{\mathrm{ab}}} u_i \tag{7}$$

where u_i and v_i are respectively the right and left eigenvectors associated with the eigenvalue. In addition, P_{ab} is the active power flow in the transmission line between buses #a and #b. In order to evaluate the above sensitivity, the following quantities are calculated:

$$\frac{\partial A}{\partial P_{\mathrm{ab}}} = \sum_{i=1}^{n} \left(\frac{\partial A}{\partial E'_{\mathrm{q}i}} \frac{\partial E'_{\mathrm{q}i}}{\partial P_{\mathrm{ab}}} + \frac{\partial A}{\partial E'_{\mathrm{d}i}} \frac{\partial E'_{\mathrm{d}i}}{\partial P_{\mathrm{ab}}} + \frac{\partial A}{\partial \delta_i} \frac{\partial \delta_i}{\partial P_{\mathrm{ab}}} \right) \tag{8}$$

where $[\partial A/\partial E'_{\mathrm{q}i}]$, $[\partial A/\partial E'_{\mathrm{d}i}]$, and $[\partial A/\partial \delta_i]$ denote the Hessian matrices with respect to $E'_{\mathrm{q}i}$, $E'_{\mathrm{d}i}$, and δ_i. These Hessian terms can be easily determined, and the Hessian matrix by rotor speed is 0. The other terms, $[\partial E'_{\mathrm{q}i}/\partial P_{\mathrm{ab}}]$, $[\partial E'_{\mathrm{d}i}/\partial P_{\mathrm{ab}}]$, and $[\partial \delta_i/\partial P_{\mathrm{ab}}]$ cannot be directly calculated, because P_{ab} is not just a parameter. In order to obtain the eigenvalue sensitivity with respect to the change in the active power flow on the transmission lines, the Hessian matrices with respect to state variables of each generator and further links between the state variables and P_{ab} were determined by Eq. (8).

It is useful to know that the real part (σ) of the eigenvalue gives the damping and the imaginary part (ω) gives the frequency of oscillation. A positive real part represents oscillation of increasing amplitude whereas a negative real part represents a damped oscillation. For a complex pair of eigenvalue of $\lambda = \sigma + j\omega$, the frequency of oscillation (f) and the damping ratio (ζ) are given by [15]

$$f = \frac{\omega}{2\pi}, \quad \zeta = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}} \tag{9}$$

According to the proposed sensitivity, we assume $\partial \lambda_i / \partial P_{\mathrm{ab}} = \alpha_i \pm j\beta_i$ as the sensitivity of the eigenvalue with respect to change in the active power flow. Once the eigenvalues of the state matrix and the eigenvalue sensitivity with respect to P_{ab} are calculated, the damping sensitivity index is given by

$$\mathrm{Index} = \frac{\partial \zeta_{\mathrm{C}}}{\partial \sigma} \cdot \alpha_i + \frac{\partial \zeta_{\mathrm{C}}}{\partial \varpi} \cdot \beta_i \tag{10}$$

where ζ_{C} is the damping ratio of the eigenvalue associated with the inter-area mode. The proposed index is used as a measure to determine the best location for FACTS devices. By the installation of series-type compensation devices such as FACTS on the critical lines selected by the proposed index, active power flow can be controlled and hence the system stability by the inter-area modes can be effectively improved.