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Application of power system energy structures to track dominated oscillation paths and generator damping contribution during low-frequency oscillations

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ABSTRACT

The high penetration of renewable energy into power systems and expansion of interconnected power grid frequently and uncontrollably result in low-frequency oscillation. Low-frequency oscillation is potentially dangerous for power systems. However, acquiring dominated oscillation paths and generator damping properties are quite helpful for system operators when taking appropriate measures to suppress these oscillations. In this study, a method for the online tracking of dominated oscillation paths and generator damping contribution during low-frequency oscillations is proposed on the basis of the damping loss factor (DLF) and two improved forms of power system energy structure (PSES). DLF in elasticity mechanics is introduced to quantitatively establish the relationship between dissipation energy and damping ratio for each mode. On the basis of the PSES framework, the dissipation energy composition during low-frequency oscillation is analyzed. Then, based on the dominance of the aperiodic component in the dissipation energy, two improved forms of PSES are derived with different distributions of dissipation energy. Subsequently, based on the DLF and improved forms of PSES, two dissipation energy-based indexes are proposed to realize the online tracking of dominated oscillation paths and evaluate the generator damping contribution (including renewable energy generators) during low-frequency oscillations. Finally, the accuracy of the proposed method is verified by simulating the "16-machine, 5-area" system as a practical power system in China.

1. Introduction

Low-frequency oscillation is one of the major threats to security and stability of interconnected power systems. In recent power systems, low-frequency oscillations are either free oscillations, caused by bad tuning of control settings or abnormal operating conditions, or forced oscillations, attributed to the periodic disturbances. Mechanism analyses in frequency domain indicate that both of the two types of oscillations can be caused by changes of local dynamic components [1–3]. Hence, it is significant to locate the component and adopt appropriate measures to avert oscillation, especially when systems are already oscillating [4–7]. System operators need to collect sufficient oscillation information before they can make operational decisions. For the type of free oscillations, a comprehensive understanding of dominated oscillation paths and generator damping contribution can allow operators to fully characterize the effects of low-frequency oscillations on power systems.

Dominated oscillation paths are a group of transmission lines with the highest content of oscillation modes. Dominated oscillation paths vary according to different oscillation modes. Therefore, fast and precise online tracking of dominated oscillation paths is needed when employing appropriate preventive measures to suppress oscillation. A dominated inter-area oscillation path may be located on the tie line (i.e., theory of extended equal area), and thus, identifying the critical lines within numerous tie lines in the interconnected power system is important [8]. A main oscillation path index, which is based on the matrix pencil energy flow, can pinpoint the main inter-area oscillation interface and path by using wide-area measurement data [9,10]. Three algorithms were proposed to identify these dominant inter-area oscillation paths using different sets of voltage and current variables [11]. Implementing the identification process suggests that dominant inter-area oscillation paths can be used for wide-area damping control given that most signals are observable from the dominant path. However, the above approaches, which require the online identification of dominated oscillation paths, are constrained by problems related to the appropriate selection of data windows.

The damping of low-frequency oscillation is generally represented by the damping ratio in modal analysis based on the linearized state

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space model [1]. However, the damping ratio is a global index, and it cannot measure the damping contribution of power system components. The damping torque coefficient based on the linearized system model is also used to evaluate component damping. In [12] in which a single-machine system was considered, the Kalman filter technique were adopted for the optimal online evaluation of the damping torque coefficient. In [13–15], the damping torque of generators in multi-machine power systems was quite complex. Consequently, the mutual impact of generators on the damping torque hindered the accurate online evaluation of generator damping In [16,17], an energy-based method was proposed for determining the energy exchanges among groups of generators, and the findings showed that damping was strongly related to dissipation energy. In [17] in particular, the energy dissipation coefficient of the generator was used to evaluate individual damping. The findings on the energy-based method for interconnected multi-machine systems showed that the decentralized and energy-based index was required prior the online evaluation of generator damping.

From the perspective of system dynamics, oscillation energy conversion and transmission occur regardless of any form of oscillation, and damping causes a portion of the oscillator energy to be irreversibly converted into other energy forms through heat or acoustic noise. This process follows the law of energy conservation.

In this paper, we propose an energy-based method for the online tracking of dominated oscillation paths and generator damping contribution during low-frequency oscillations. The concept of damping loss factor (DLF) in elasticity mechanics is adopted to build the indexes that can evaluate dominated oscillation paths and generator damping contribution. This study continues the work in [18] wherein power system energy structures (PSES), through which the law of energy conservation has been emphasized, are built based on an analogous elastic network. The dissipation energy components are analyzed, and the aperiodic component in PSES is used to represent dissipation energy during light-damping oscillations. Branch- and port-form PSES are also derived to determine the distribution capability of dissipation energy. Subsequently, two dissipation energy-based indexes are proposed for the online tracking of dominated oscillation paths and the evaluation of generator damping contribution. Finally, simulation is conducted to verify the effectiveness of the proposed method.

The rest of the paper is organized as follows: DLF is introduced as a component of a simple elastic oscillation system in Section 2. The generator dissipation energy composition in PSES and two improved forms of PSES are explained in Section 3. The application of PSES for the online tracking of dominated oscillation paths and generator damping contribution is detailed in Section 4. The rationality and validity of the proposed method are established by presenting the simulation results in Section 5. Finally, the conclusions are presented in Section 6.

2. DLF in elasticity mechanics

The concept of DLF is regarded a significant index in elasticity mechanics, and it is used to evaluate component participation and damping contribution during oscillations. Here, we introduce the DLF to the assessment of electromechanical oscillation in power systems, which in turn allows us to fully understand DLF behavior. In this section, a single degree-of-freedom system (SDOF) is adopted to present DLF in detail.

For an SDOF system, the well-known second-order differential equation of motion is given as

$$m\ddot{x} + c\dot{x} + kx = 0 \tag{1}$$

where m is the mass; k is the stiffness; and c is the viscous damping coefficient. When light damping is excited by an oscillatory force, the response of the SDOF system can be expressed as

$$x \approx X\sin(\omega t + \phi) \tag{2}$$

where X is the response amplitude, which is almost constant in any given period; ω denotes the oscillation frequency; and φ is the phase angle. For each vibration cycle, the energy dissipated by the viscous damper is as follows [19]:

$$E_d = c\int_0^{\frac{2\pi}{\omega}} X^2\omega^2\cos^2(\omega t + \phi)dt = \pi c X^2\omega.. \tag{3}$$

The transient energy of the SDOF system is composed of kinetic and potential energies, which are represented as follows:

$$E_{kin} = \frac{1}{2}m\dot{x}^2 = \frac{1}{2}mX^2\omega^2\cos^2(\omega t + \phi) \tag{4}$$

$$E_{pot} = \frac{1}{2}kx^2 = \frac{1}{2}kX^2\sin^2(\omega t + \phi) \tag{5}$$

When the oscillation frequency ω is nearly equal to the natural frequency ω_n, the maximum transient energy is

$$W_m = \frac{1}{2\pi}\int_0^{\frac{2\pi}{\omega}} (E_{kic} + E_{pot})dt = \frac{1}{2}kX^2 \tag{6}$$

The DLF of an SDOF system is defined as:

$$\eta = \frac{1}{2\pi}\frac{E_d}{W_m} = \frac{c\omega_n}{k} \tag{7}$$

For the SDOF system in (1), the damping ratio of the modal analysis is $\zeta = c\omega_n/2k$. Substituting from (7), we can obtain the relationship between the DLF and the damping ratio:

$$\eta = 2\xi \tag{8}$$

The multiple degrees-of-freedom (MDOF) system can be described as the sum of the responses from several independent SDOF systems, and thus, the concept of DLF can be generalized in MDOF systems. The relationship between the damping ratios of DLF in MDOF can also be proven in terms of complex stiffness [19]. For a complex elastic system consisting of nc components, the DLF for mode r and the DLF of component j for mode r are defined as

$${}_r\eta = \frac{1}{2\pi}\frac{{}_rE_{j(TOT)}}{{}_rW_{mj(TOT)}} = \frac{\sum_{j=1}^{nc} {}_r\eta_j\, {}_rW_{mj}}{\sum_{j=1}^{nc} {}_rW_{mj}} = 2\,{}_r\xi \tag{9}$$

$${}_r\eta_j = \frac{1}{2\pi}\frac{{}_rE_j}{{}_rW_{mj}} \tag{10}$$

where ${}_rE_j$ and ${}_rW_{mj}$ are the dissipation energy and maximum transient energy of component j in a cycle of mode r, respectively.

DLF is an energy-based damping representation in elasticity mechanics, and it is proportionally related with the damping ratio in light-damping mode. Given that the damping ratio is a global index, the DLF is not suitable for measuring the damping contribution of components. However, the DLF can depict system damping from the perspective of dissipation energy, i.e., DLF can evaluate component participation and damping contribution in a dispersed manner.

3. Fundamentals of PSES

In Section 2, the DLF is defined based on dissipation energy, which is based on the framework of conserved transient energy. In applying DLF in the analysis of low-frequency oscillation of power systems, PSES is adopted to provide the framework for transient energy. In this section, we introduce PSES, which was proposed in [18]. Then, on the basis of the analytical results of dissipation energy composition, two improved forms of PSES are derived to lay the foundation for tracking dominated oscillation paths and generator damping contribution during low-frequency oscillations.

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