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Transient energy dissipation of resistances and its effect on power system damping

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ABSTRACT

The transient energy flow method is a newly proposed method for locating the sources of low frequency oscillations and shows good performances in tests and actual applications. It is found in previous work that resistances in networks or loads may produce transient energy and exhibit as oscillation sources. In this paper, the transient energy dissipation of resistances and its effect on power system damping is studied. The transient energy flow into a resistance is generally non-conservative but whether it is dissipative is indefinite. A resistance may dissipate or produce transient energy. However, the relationship between system damping represented with the real-part of the eigenvalue and the total energy dissipation is definite, and an equation describing the relationship is obtained in simple power systems. Transient energy dissipation is an indicator of the damping of a component. When a resistance dissipates transient energy, it is beneficial to system damping, otherwise it is detrimental. The results are verified with simulations and explanations for constant impedance loads at different locations having different effects on damping are given.

1. Introduction

Low frequency oscillation is one of the major problems threatening the security of power systems. There are two types of oscillations in recent power systems. One is free or natural oscillation often caused by bad tuning of control systems or large amount of power transfer over a weak network. The other is forced oscillation caused by periodic disturbances resulting from equipment failures or malfunctioning control systems. Regardless of the type of oscillation, the most efficient way to mitigate sustained oscillations is to locate the component causing the oscillations, i.e., the oscillation source, and undertake countermeasures [1,2].

An energy-based method is proposed in [3] to locate the oscillation source, and it is further developed in [4,5] to evaluate generator damping. Herein and in subsequent sections, "energy" refers to transient energy [6,7], not electrical energy. The energy dissipation of a component reflects its damping property, and can be obtained from the energy flow computed with measurements from phasor measurement units (PMU). A generator producing energy can be identified as the oscillation source. The method is tested in [8] with comprehensive test cases and selected as the candidate for practical use due to its satisfactory performance, and then it is further developed in [9] to improve the robustness and reliability of the application with actual PMU data.

In [9], it is found that lossy networks and constant impedance loads may produce energy and exhibit as oscillation sources. Although tests with real events demonstrate that the method can still be efficiently used for actual systems, this troublesome phenomenon still needs further investigation for the validity of the energy-based method. As energy dissipation corresponds to damping, the above phenomenon reflects that the damping of resistance in networks or loads is complicated, which is also found in previous literature. The effect of network resistance on system damping is studied in [10] with eigenvalue sensitivities to line impedances. The sign of the real part of the sensitivity to line resistance, which reflects the effect of line resistance on damping, is indefinite. The investigation on static load models in [11] reveals that as compared to constant power load, constant impedance load is detrimental to damping at the sending end but beneficial at the receiving end. However, the explanation is deficient by now.

In the paper the transient energy dissipation of resistance is studied. The result illustrates the effect of resistances in networks or loads on power system damping. The relationship between eigenvalue and total transient energy dissipation, where the transient energy dissipation of the resistance is an essential part, is testified. The paper is organized as follows. Section 2 reviews the

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concept of transient energy flow. Section 3 studies the transient energy flow into an impedance. Sections 4 and 5 study the transient energy dissipation of resistance and its effect on system damping in the single-machine infinite-bus (SMIB) system and the two-machine system respectively. Section 6 presents the results of the four-machine system with detailed models. Section 7 is the conclusion. It should be noted again that the notion “energy” in the paper means transient energy, not electrical energy, otherwise a resistance producing “energy” will be confusing.

2. Transient energy flow

The concept of energy flow is proposed in [3–5] for low frequency oscillation source location and damping evaluation. The energy flow through branch L_{ij} from bus i to bus j is calculated with:

$$\begin{aligned} W_{TEFL} &= \int \mathrm{Im}(\boldsymbol{I}_{ij}^{*}\mathrm{d}\boldsymbol{U}_i) = \int (I_{ij,x}\mathrm{d}U_{i,y} - I_{ij,y}\mathrm{d}U_{i,x}) \\ &= \int \left(P_{ij}\mathrm{d}\theta_i + \frac{Q_{ij}}{U_i}\mathrm{d}U_i\right) = \int (P_{ij}\mathrm{d}\theta_i + Q_{ij}\mathrm{d}(\ln U_i)) \end{aligned} \tag{1}$$

where $U_i\angle\theta_i = U_{i,x} + \mathrm{j}U_{i,y}$ is the voltage of bus i, $I_{ij,x} + \mathrm{j}I_{ij,y}$ is the current in L_{ij} out of bus i, and P_{ij} and Q_{ij} are the active and reactive power in L_{ij} respectively.

The energy flow into a component is composed of two parts. One is the transient energy variation of the component, and the other is the energy dissipated by the component [3–5]. The energy dissipation reflects the damping of the component.

The following classical generator model is taken as an example:

$$\begin{aligned} &\dot{\delta} = \omega_0\omega \\ &T_J\dot{\omega} = P_m - P_e - D\omega \end{aligned} \tag{2}$$

The energy flow into the internal bus of the generator is [3]:

$$W_{inG} = \left(\frac{1}{2}T_J\omega_0\omega^2 - P_m\delta\right)\Big|_{x_0}^{x} + D\omega_0\int \omega^2\mathrm{d}t \tag{3}$$

The energy flow has two parts, i.e., $(\frac{1}{2}T_J\omega_0\omega^2 - P_m\delta)\big|_{x_0}^{x}$ as the transient energy variation of the generator [6,7], which is a path independent integral term and can be named conservative term, and $D\omega_0\int\omega^2\mathrm{d}t$ as the energy dissipated by the damping, which is path dependent and can be named non-conservative term. A non-conservative term is dissipative if its derivative with respect to time is always non-negative. Obviously, $D\omega_0\int\omega^2\mathrm{d}t$ is a dissipative term. The energy dissipation is consistent with the damping of the generator. For more detailed generator models including the third-order model [3], the fourth-order model [4] and the sixth-order model [5], the above decomposition is still valid.

The energy flow into a component is composed of its transient energy variation and energy dissipation (or production). The energy dissipation or production reflects its contribution to the damping of the oscillation, which is used to locate the oscillation source [3,8] and evaluate generator damping [4,5,9]. As the energy flow is actually the transfer of transient energy in the network, it is termed as transient energy flow in this paper.

3. Transient energy flow into an impedance

Consider a branch L_{ij} with the admittance $y = \frac{1}{r+\mathrm{j}x} = g + \mathrm{j}b$. The transient energy flow from the two terminals into the branch is:

$$\begin{aligned} W_{inB} &= \int \mathrm{Im}(\boldsymbol{I}_{ij}^{*}\mathrm{d}\boldsymbol{U}_i) + \int \mathrm{Im}(\boldsymbol{I}_{ji}^{*}\mathrm{d}\boldsymbol{U}_j) \\ &= \int \mathrm{Im}(y^{*}(\boldsymbol{U}_i - \boldsymbol{U}_j)^{*}\mathrm{d}(\boldsymbol{U}_i - \boldsymbol{U}_j)) \end{aligned} \tag{4}$$

Denote $\boldsymbol{U}_i - \boldsymbol{U}_j = \Delta U\mathrm{e}^{\mathrm{j}\Delta\theta}$. Then

$$\mathrm{d}(\boldsymbol{U}_i - \boldsymbol{U}_j) = \mathrm{d}(\Delta U\mathrm{e}^{\mathrm{j}\Delta\theta}) = \mathrm{e}^{\mathrm{j}\Delta\theta}\mathrm{d}\Delta U + \mathrm{j}\Delta U\mathrm{e}^{\mathrm{j}\Delta\theta}\mathrm{d}\Delta\theta$$

We can get

$$\begin{aligned} W_{inB} &= \int \mathrm{Im}(y^{*}\Delta U\mathrm{e}^{-\mathrm{j}\Delta\theta}(\mathrm{e}^{\mathrm{j}\Delta\theta}\mathrm{d}\Delta U + \mathrm{j}\Delta U\mathrm{e}^{\mathrm{j}\Delta\theta}\mathrm{d}\Delta\theta)) \\ &= \int \mathrm{Im}((g - \mathrm{j}b)(\Delta U\mathrm{d}\Delta U + \mathrm{j}\Delta U^2\mathrm{d}\Delta\theta)) \\ &= -\frac{1}{2}b\Delta U^2 + g\int \Delta U^2\mathrm{d}\Delta\theta \\ &= -\frac{1}{2}b\Delta U^2 + g\int \Delta U^2\frac{\mathrm{d}\Delta\theta}{\mathrm{d}t}\mathrm{d}t \end{aligned} \tag{5}$$

The term corresponding to the susceptance is conservative.

$$W_b = -\frac{1}{2}b\Delta U^2 = -\frac{1}{2}\frac{-x}{r^2 + x^2}\Delta U^2 = \frac{1}{2}xI_{ij}^2 \tag{6}$$

which is the commonly used transient energy of the reactance.

The term corresponding to the conductance is:

$$W_g = g\int \Delta U^2\mathrm{d}\Delta\theta = g\int \Delta U^2\frac{\mathrm{d}\Delta\theta}{\mathrm{d}t}\mathrm{d}t \tag{7}$$

Generally W_g is non-conservative due to path dependency of the integration, though it may be path independent and conservative in certain conditions. Furthermore, the sign of $\Delta U^2\frac{\mathrm{d}\Delta\theta}{\mathrm{d}t}$ is indefinite, and W_g cannot be identified as a dissipative term. The resistance may dissipate or produce transient energy, which depends on the sign of $\Delta U^2\frac{\mathrm{d}\Delta\theta}{\mathrm{d}t}$.

The above derivation is also applicable to a constant impedance load, with the voltage $\boldsymbol{U}_j = 0$. Then $\Delta U\mathrm{e}^{\mathrm{j}\Delta\theta} = \boldsymbol{U}_i = U_i\mathrm{e}^{\mathrm{j}\varphi_i}$, and

$$W_{inL} = -\frac{1}{2}bU_i^2 + g\int U_i^2\mathrm{d}\varphi_i = -\frac{1}{2}bU_i^2 + g\int U_i^2 2\pi\Delta f_i\mathrm{d}t \tag{8}$$

The above analysis shows the complexity of transient energy dissipation of resistance. The phenomenon found in [9] is reasonable. A resistance in networks or loads may dissipate or produce transient energy, which corresponds to positive or negative damping.

Although transient energy dissipation or production is indefinite, the relationship between energy dissipation and the effect on damping is definite. Transient energy dissipation corresponds to a positive effect on damping. When a resistance dissipates (or produces) transient energy, it has a positive (or negative) effect on power system damping. This will be studied in the following sections.

4. Classical SMIB system with line resistance

In a classical SMIB system, the generator is represented by internal electrical potential $E\angle\delta$ behind reactance x_d'. The impedance of the transmission line is $r + \mathrm{j}x_L$. The equivalent circuit is shown in Fig. 1. Denote $x = x_d' + x_L$. The system equation is (2) where $P_e = -bEU_S\sin\delta + g(E^2 - EU_S\cos\delta)$.

4.1. Transient energy dissipation of resistance

It can be easily obtained that

Fig. 1. Equivalent circuit of the SMIB system.