Electrical Power and Energy Systems 88 (2017) 55–62

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

Dissipating energy flow method for locating the source of sustained oscillations

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ARTICLE INFO

Article history:
Received 31 October 2016
Received in revised form 29 November 2016
Accepted 13 December 2016

Keywords:
Dissipating energy
Forced oscillations
PMU
Source location
Poorly damped oscillations

ABSTRACT

The modification of an energy-based approach called the dissipating energy flow (DEF) method is proposed, which uses data from phasor measurement units (PMUs) to trace the source of poorly damped natural and forced oscillations in power systems. The original energy-based approach (Chen et al., 2013) assumes the ability to determine steady-state values of variables measured by PMU during the transient process and that prevents the reliable use of the original method with actual PMU data. PMU data processing, proposed in the DEF method, is a key step in converting the energy-based method into a robust and automated tool for use with actual PMU data. The effectiveness of the proposed DEF method is demonstrated by testing multiple simulated cases of sustained oscillations, including both poorly damped natural and forced oscillations and more than 30 actual events in ISO New England (ISO-NE) and two events in Western Electricity Coordination Council (WECC) systems. The study also demonstrates the potential for using the DEF method to estimate the contribution of any generator to the damping of a specific oscillation mode.

1. Introduction

Monitoring actual power system dynamics in the ISO New England (ISO-NE) footprint using phasor measurement units (PMUs) has detected multiple instances of sustained oscillations with significant magnitude in the frequency range from 0.05 Hz to 2 Hz and some instances of oscillations up to 8 Hz. Engineering analyses indicate that most of these oscillations are caused by equipment failures, malfunctioning control systems, or abnormal operating conditions causing periodic disturbances, which together are often referred to as "forced oscillations." Another type, caused by bad tuning of control systems or by significant power transfer over a weak network, is often called "natural oscillations." Regardless of the type of oscillation, sustained oscillations with significant magnitude can potentially cause uncontrolled cascading outages in the system and undesirable mechanical vibrations in its components, which increases the probability of equipment failure, reduces the lifespan of equipment, and results in increased maintenance requirements. The most efficient way to mitigate sustained oscillations is to locate the source and disconnect it from the network, which requires locating the system component causing the oscillations, such as a power plant or a specific generator. Locating the source of oscillations is not a trivial task, however. It must rely on PMU measurements in practice because the model-based approach cannot be reliably used, particularly online, when prior knowledge of the nature and location of the forced signal is not available.

Many methods for locating the source based on different mechanisms have been proposed in the past few years. Here are some of Refs. [1–10]. Each of the proposed methods have advantages and disadvantages and can be successfully used only for some situations. Unfortunately, none of the methods have been demonstrated as being a universal and reliable practical tool applicable for a broad range of possible situations in actual power systems.

Several methods have been evaluated by the authors and the energy-based method [6] is selected as the candidate for a practical use. The method is based on the primary attribute of oscillations, i.e. energy, and thus sets an expectation to be more robust in multiple possible situations while other methods based on other attributes of oscillations (such as magnitude, phase angles, propagation speed and statistical signature) experience difficulties. The implementation of the method requires knowing the steady-state values of PMU measurements during the transient stage which are actually unknown. That is why the use of the original energy-based method [6] with actual PMU data is not robust enough for online environment.

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http://dx.doi.org/10.1016/j.ijepes.2016.12.010
0142-0615/

This paper describes the proposed Dissipating Energy Flow (DEF) method. The main contribution of this paper is the PMU signal processing in the DEF method which is a key step in converting the energy-based method into a robust automated methodology for the use with actual PMU data. Proposed PMU processing also creates an opportunity using the DEF method in a new type of PMU application: a decentralized online estimation of the contribution of any monitored power system component to the damping of a specific oscillation mode.

2. Dissipating energy flow method

2.1. Original energy-based method

An energy-based method [6] calculates the flow of dissipating transient energy in the network and demonstrates that the calculated energy is equivalent to the energy dissipated by a damping torque. The flow of dissipating energy in a branch ij is expressed by using bus voltage angles or bus frequencies as follows:

$$W_{ij}^{D} = \int (\Delta P_{ij} d\Delta\theta_{ij} + \Delta Q_{ij} d(\Delta \ln V_i)) \\ = \int (2\pi \Delta P_{ij} \Delta f_i dt + \Delta Q_{ij} d(\Delta \ln V_i)) \tag{1}$$

where ΔP_{ij} and ΔQ_{ij} are deviations from the steady-state values of the active and reactive power flow in branch ij; $\Delta\theta_i$ and Δf_i are deviations from steady-state values of bus voltage angle and frequency at bus i; V_i is the bus voltage magnitude. $\Delta \ln V_i = \ln V_i - \ln V_{i,s}$, where $V_{i,s}$ is the steady-state voltage magnitude.

The formula (1) was derived by using the assumption of the lossless network and constant power load model.

The flow of dissipating energy by (1) can be considered as a regular power flow and allows the tracing of the source of sustained oscillations. It was demonstrated in [6] that the method also works at varying amplitude of oscillations and with realistic model of generators by extracting the information about the dissipating energy from the slope of W_{ij}^{D} curve rather than from its instantaneous values. It was also demonstrated in [11,12] that in linear single machine system, the rate of dissipated energy calculated by (1) for a specific mode is approximately proportional to the real part of the eigenvalue of that mode. That makes it possible, under above assumptions, the utilization of the dissipated energy approach for the estimation of the damping contribution of each individual generator or any other system element into damping of a specific mode of oscillations.

Standard PMU measurements of bus frequency, voltage and current phasors are sufficient for the estimation of the dissipating energy flow by (1). Note that power quantities, i.e. P and Q, are calculated from voltage and current.

2.2. Challenges in actual power systems

Strictly speaking, the underlying assumptions on the lossless network, system linearity and constant power load model do not hold for actual bulk power systems and the impact of these assumptions needs to be evaluated. The efficiency of the energy-based method, as a robust tool, by using actual PMU data has not been demonstrated either.

The most challenging factor to apply the method proposed in [6] is the need to find the deviations from the steady-state values for all quantities used in (1). Ideal steady-state conditions in actual power systems practically do not exist so the de-trending process is required in order to estimate steady-state quantities. Reasonably accurately de-trending can be done only for a short period of time which is often too short to reliably trace the flow of dissipating energy. A particular difficulty is the de-trending of PMU bus voltage angle measurements. Due to the nature of PMU measurements, the absolute value of an angle may change by several hundred degrees over 10–30 s at off-nominal frequency while deviation of the angle from its steady-state value, which is required in (1), is typically less than one degree. Steady-state values from traditional state estimation (SE) cannot be reliably used here due to time misalignment, accuracy of SE results and absence of bus frequency values.

2.3. Modification of the method for use with actual PMU data

The calculation of deviations for all variables in (1) can be effectively done without the need of de-trending and estimation of steady-state quantities by filtering modes of interest from PMU data in the frequency domain. Filtered mode for any variable has zero steady-state value. Then, dissipating energy flow is calculated for each mode separately.

Formula (1) cannot be directly used for filtered signals because $\ln V_i$ is defined only for positive values of voltage but a filtered signal has both positive and negative values with a zero mean, which makes calculation of $\ln V_i$ impossible. To address this problem, the term $d(\Delta \ln V_i)$ is replaced by approximately the equivalent one $d(\Delta V_i)/V_i^{*}$ accounting for a single oscillatory mode only

$$W_{ij}^{D} \approx \int \left(\Delta P_{ij} d\Delta\theta_{ij} + \Delta Q_{ij} \frac{d(\Delta V_i)}{V_i^{*}} \right) \\ = \int \left(2\pi \Delta P_{ij} \Delta f_i dt + \Delta Q_{ij} \frac{d(\Delta V_i)}{V_i^{*}} \right) \tag{2}$$

where $V_i^{*} = \widetilde{V}_i + \Delta V_i$ and $\widetilde{V}_i$ is the average voltage in the studied period. For discrete PMU signals, a discrete-time version of (2) has the following form:

$$W_{ij,t+1}^{D} = W_{ij,t}^{D} + 2\pi \Delta P_{ij,t} \Delta f_{i,t} \cdot t_s + \Delta Q_{ij,t} \frac{\Delta V_{i,t+1} - \Delta V_{i,t-1}}{2V_{i,t}^{*}} \tag{3}$$

Quantities with Δ in (2) and (3) are the filtered components for a mode; t_s is time interval between PMU samples; index t reflects the time instant. Integration time limits in (2) are determined from the transient when sustained oscillations have significant magnitude larger than noise.

This modification is implemented into a newly designed DEF method/process. Careful implementation of all PMU data processing steps, described below, is crucial in achieving high efficiency and robustness of the DEF method.

2.4. Step by step process

2.4.1. Selection of PMU measurements

The DEF method calculates the flow of dissipating energy in any element. Any transmission line, transformer or generator that has PMU measurements of voltage, current and frequency/angle, can be used to estimate the DEF flow in that element. The most efficient are measurements in transmission elements connecting generators to the system because a generator is usually the most likely source of sustained oscillations.

2.4.2. Selection of transient period for analysis

The time period selected for analysis should have sustained oscillations preferably with dominant magnitude. Duration of the time interval should preferably contain 20–40 periods of oscillations. Smaller interval containing as few as 4–6 periods can also work as well but with less robustness. The time period could be selected manually in offline studies or automatically online. An automatic selection algorithm is beyond the scope of this paper.