Dissipating energy flow method for locating the source of sustained oscillations

Slava Maslennikov\textsuperscript{a,}\textsuperscript{*}, Bin Wang\textsuperscript{b}, Eugene Litvinov\textsuperscript{a}

\textsuperscript{a}ISO New England, 1 Sullivan Road, Holyoke, MA 01040, USA
\textsuperscript{b}Department of EECS, University of Tennessee, Knoxville, TN 37996, USA

\textbf{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.

\* Corresponding author.

E-mail addresses: smaslennikov@iso-ne.com (S. Maslennikov), bwang@utk.edu (B. Wang), elitvinov@iso-ne.com (E. Litvinov).

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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:

$$ W^D_{ij} = \int \left( AP_i d\Delta\theta_i + AQ_i d(\Delta \ln V_i) \right) $$

$$ = \int \left( 2\pi AP_i Af_{dt} + AQ_i d(\Delta \ln V_i) \right) $$

(1)

where $\Delta P_i$ and $\Delta Q_i$ are deviations from the steady-state values of the active and reactive power flow in branch $ij$; $\Delta\theta_i$ and $Af_{dt}$ 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 $W^D_{ij}$ 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 $\Delta V_i$ 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 $\Delta V_i$. Impossible. To address this problem, the term $d(\Delta \ln V_i)$ is replaced by approximately the equivalent one $d(\Delta V_i)^2/V_i^*$. accounting for a single oscillatory mode only

$$ W^D_{ij} \approx \int \left( AP_i d\Delta\theta_i + AQ_i d(\Delta V_i) \right) $$

$$ = \int \left( 2\pi AP_i Af_{dt} + AQ_i d(\Delta V_i) \right) $$

(2)

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

$$ W^D_{ij,t} = W^D_{ij,t-1} + 2\pi AP_i Af_{dt} \cdot t_s + AQ_i \Delta V_{ij,t-1} - \Delta V_{ij,t-1}^2$$

(3)

Quantities with $\Delta$ 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.
2.4.3. PMU data pre-processing

PMU angles for voltages and currents should be unwrapped. Replace missing PMU data (NaN) and outliers with interpolated data. Do unwrapping before interpolation.

2.4.4. Frequency identification of sustained oscillations

Apply Fast Fourier Transformation (FFT) to identify the frequency of sustained oscillations $f_i$, which is the mode of interest. Be aware that accuracy of numerical results of FFT for oscillations with frequencies below 0.1–0.15 Hz could be impacted by trends in measured signals. Use of MW flow in monitored lines for FFT is preferable because active power signal has less trend in the frequency range below 0.1–0.15 Hz compared to other signals and particularly compared to bus voltage angle. Additionally, the magnitude of power spectral density for MW signal calculated in multiple transmission elements across a power system reflects the MW magnitude of oscillations, which is meaningful for operations.

2.4.5. Filtering the mode of interest

The filtering process must satisfy the following conditions for a filtered mode with frequency $f_i$: (a) preserves phases among all quantities, i.e. active and reactive power, voltage magnitude, angle and frequency; (b) preserves magnitudes for all filtered quantities.

Reasonably good filtering is achieved by applying a 4th to 6th order Butterworth band pass filter with the pass frequencies $f_p = (1 \pm \varepsilon) \cdot f_i$, where $\varepsilon = 0.05$; cutoff frequencies $f_c = (1 \pm 2\varepsilon) \cdot f_i$; 1 dB of ripple allowed and 10–15 dB attenuation at both sides of the pass band. A filter could be designed, for example, using the Matlab functions fdesign.bandpass and design for known frequency of interest $f_i$ and utilizing the above described parameters. Zero-phase distortion is achieved by applying filtering in both forward and reverse directions for all signals by using the filtfilt Matlab function. Filtering typically creates significant deviations of the filtered signals at the edges of the interval. Keeping 30–50% of the middle part of filtered signal only works best in formula (3).

3. Properties of the DEF method

The method assumes a lossless network and the constant power model of the load, which do not hold in real power systems. The impact of these assumptions is evaluated below for DE calculation by using bus voltage angle. Main conclusions of the analysis hold also for the use of bus frequency instead of angle.

3.1. Analysis of dissipating energy components

Assume the deviations of all branch $ij$ components in (2) are single mode sinusoidal functions in time:

$$\begin{align*}
\Delta P_{ij} &= A_p \sin(\omega t + \varphi_p) \\
\Delta Q_{ij} &= A_q \sin(\omega t + \varphi_q) \\
\Delta h_i &= A_h \sin(\omega t + \varphi_h) \\
\Delta V_i &= A_v \sin(\omega t + \varphi_v)
\end{align*}$$

(6)

where $A_p, \ldots, A_v$ are constant amplitudes and $\varphi_p, \ldots, \varphi_v$ are phases of oscillations.

Substituting (6) into (2), the net energy flow is:

$$W_{ij}^D \approx DE_{ij} \cdot t$$

(7)

$$W_{ij}^D = \frac{\alpha A_p A_h \sin(\varphi_p - \varphi_h) + \alpha A_p A_v \sin(\varphi_v - \varphi_h)}{2}$$

(8)

The net energy flow consists of periodic and monotonic over time components. Coefficient $DE_{ij}$ in (7) and (4) represents the slope or rate of change of dissipating energy flow. If $DE_{ij}$ is positive (or negative), the dissipating energy flows from bus $i$ (or $j$) to bus $j$ (or $i$). When multiplied by a period of time, the $DE_{ij}$ coefficient can give the total dissipating energy that has been transferred from bus $i$ to bus $j$ during that period.

The sign and value of $DE_{ij}$ per (8) depends on magnitudes of the active and reactive power, voltage magnitude and angle and phase relation between oscillations of these parameters. That illustrates the importance in preserving magnitudes and phase relation between all parameters during PMU data processing for the accurate DE calculation.

3.2. Simulated test cases

A test case library for testing different methods, locating the source of sustained oscillations was developed in [13]. Test cases are based on a simplified Western Electricity Coordination Council (WECC) 179-bus, 29-generator system model. The library was used to numerically estimate the impact of network losses and the variability of load model on DE values.

For convenience, the sum of DE coefficients calculated for all system components of the same type (generators, loads, branches) is denoted as $DE$. For branches, $DE_i$ includes DE values calculated from both ends. Positive $DE$ value means injection of energy and negative means consumption.

3.3. Impact of network losses

In the case F1 of the forced oscillation cases from [13], all loads are represented by constant power. If all resistances are changed to be zeros, the normalized $DE$, (max of $DE$, is taken as the base) from each type of element are summarized in Table 1 and compared to those of the original network with losses.

From Table 1, it can be seen that:
Table 1

<table>
<thead>
<tr>
<th>Networks</th>
<th>Source generator</th>
<th>All Sink generators</th>
<th>All loads</th>
<th>All branches</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lossless</td>
<td>1.000</td>
<td>–0.985</td>
<td>0.000</td>
<td>0.001</td>
<td>0.016</td>
</tr>
<tr>
<td>With losses</td>
<td>0.806</td>
<td>–1.000</td>
<td>0.000</td>
<td>0.209</td>
<td>0.015</td>
</tr>
</tbody>
</table>

* Source generator is the generator at bus 4 and the rest are sink generators.

Section 3.4, are compared for three other static load models in Table 2.

For each of the last three load models, the DE from loads is much greater than that from the source. DE produced by individual load can be comparable or even larger than DE produced by the source generator. That means the loads in DE results might look like the sources or sinks of energy. DE produced by loads also impacts the DE flow in transmission lines. Significant deviation of the load model from constant power can impact the accuracy of DE values in transmission elements and complicate the locating of the source. Nevertheless, regardless of load model, DE values can still be used to identify a generator-source of oscillations by analyzing DE flows only in the branches connecting generators to the network. DE values in these branches are less affected by load model uncertainty.

Table 2

<table>
<thead>
<tr>
<th>Load models</th>
<th>Source generator</th>
<th>All Sink generators</th>
<th>All loads</th>
<th>All branches</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Const. PQ</td>
<td>0.806</td>
<td>–1.000</td>
<td>0.000</td>
<td>0.209</td>
<td>0.015</td>
</tr>
<tr>
<td>Const. I</td>
<td>0.141</td>
<td>–1.000</td>
<td>0.785</td>
<td>0.074</td>
<td>0.000</td>
</tr>
<tr>
<td>Const. Z</td>
<td>0.031</td>
<td>–1.000</td>
<td>0.918</td>
<td>0.050</td>
<td>0.001</td>
</tr>
<tr>
<td>Default</td>
<td>0.140</td>
<td>–1.000</td>
<td>0.787</td>
<td>0.074</td>
<td>0.001</td>
</tr>
</tbody>
</table>

* In the default model, active and reactive power loads are respectively represented by the constant currents and constant impedances.

3.4. Impact of load model

The normalized DE of the system with losses, considered in Section 3.3, are compared for three other static load models in Table 2.

3.4. Impact of load model

The normalized DE of the system with losses, considered in Section 3.3, are compared for three other static load models in Table 2.

Table 3

<table>
<thead>
<tr>
<th>Case</th>
<th>Frequency (Hz)</th>
<th>Damping (%)</th>
<th>Actual source Gen</th>
<th>Δx (p.u.)</th>
<th>DE results</th>
</tr>
</thead>
<tbody>
<tr>
<td>ND1</td>
<td>1.41</td>
<td>0.01</td>
<td>45</td>
<td>1.0</td>
<td>45</td>
</tr>
<tr>
<td>ND2</td>
<td>0.37</td>
<td>0.02</td>
<td>65</td>
<td>1.0</td>
<td>65</td>
</tr>
<tr>
<td>ND3</td>
<td>0.46</td>
<td>2.22</td>
<td>11</td>
<td>1.0</td>
<td>11</td>
</tr>
<tr>
<td>ND4</td>
<td>0.46</td>
<td>0.68</td>
<td>11</td>
<td>1.0</td>
<td>11</td>
</tr>
<tr>
<td>ND5</td>
<td>0.46</td>
<td>0.69</td>
<td>11</td>
<td>1.0</td>
<td>11</td>
</tr>
<tr>
<td>ND6</td>
<td>0.46</td>
<td>0.93</td>
<td>45</td>
<td>1.0</td>
<td>45</td>
</tr>
<tr>
<td>ND7</td>
<td>1.41</td>
<td>–0.4</td>
<td>45</td>
<td>0.55</td>
<td>45</td>
</tr>
<tr>
<td>ND8</td>
<td>1.27</td>
<td>–1.06</td>
<td>36</td>
<td>1.0</td>
<td>36</td>
</tr>
<tr>
<td>ND9</td>
<td>0.46</td>
<td>–0.86</td>
<td>11</td>
<td>1.0</td>
<td>11</td>
</tr>
</tbody>
</table>

4. The DEF method verification

The results described below were obtained by using Matlab version of the DEF method.

4.1. Simulated cases

The test case library [13] was specifically designed for testing algorithms locating the source of sustained oscillations and contains nine cases of poor damped natural modes and twelve cases of forced oscillations. Test cases are representative of electromechanical oscillations which are observed and could be observed in actual systems including (a) undamped local and interarea modes and their combinations, (b) single and multiple sources of oscillations, (c) forced periodic and harmonic injection signals creating resonance and near resonance with local and interarea modes. All cases in [13] have network with losses and constant power load model.

Table 3 shows the DEF method test results with cases of poorly damped natural oscillations. The method was applied to the transient from 5 s to 40 s. Negative damping in [13] is created by setting the negative value of the damping coefficient D of a specific generator. Contribution of a generator with classical model into negative damping, shown in column 5, is evaluated by using the following linear approximation: Δx = δx0/D, where δx0/D is the sensitivity of the real part of the eigenvalue w.r.t. the parameter D. DE value in the last column is normalized per the largest DE value of the generator branches. The column lists only positive values greater than 0.01 indicating the sources of energy. The DEF method reliably identifies the main source of oscillations for all poorly damped oscillations and oscillations with negative damping. In ND6, ND7, ND8 cases, where multiple sources impact the same mode, DE value qualitatively reflects the contribution of individual generator into negative damping. Generators 6 and 30 in ND3 case have slightly positive DE while not being the sources of negative damping.
Cases ND3, ND5 and ND9 in [13] contain poorly damped 1.63 Hz mode, however this mode was not excited by the selected disturbances and practically is not observed in the transient. That is why this mode is not listed on Table 3.

Table 4 contains results for the cases of forced oscillations. Forced oscillations in [13] were created by adding a periodic forced signal into the excitation system of specific generator(s). In case F6-2, the forced signal is applied to generator 79 and has rectangular shape creating odd harmonics with the lowest frequency of 0.2 Hz. In other cases, the forced signal has sinusoidal shape at specific frequency listed in column 3. Forced signal in cases F4-F6 has a frequency equal to the frequency of certain natural modes and thus creating resonances. Frequencies of the forced signal in cases F4-2 and F5-2 are respectively in between of two close frequencies of natural local and inter-area modes. Case F7-1 has two simultaneous sources at different generators creating resonance conditions with two different natural modes. Case F7-2 has two sources at different generators but creating resonance conditions with the same natural mode. Results for some of the tested cases from [13] are not shown in the table because they represent small variations of the F4-F6 cases. The DEF method reliably identifies the source of oscillations for all cases.

Fig. 1 shows the power spectral density of oscillations excited in the F6-2 case. Fig. 2 shows $W_D$ of all 29 generators as a function of time for the first four harmonics on the forced signal. Red1 curve representing the generator 79 clearly indicates this generator as the source for all harmonics.

### 4.2. Actual events in the ISO New England system

ISO-NE has PMU infrastructure collecting PMU measurements since 2012 from about 80 PMUs located across the system. Multiple instances of oscillations with significant magnitude have been detected since the PMU installation. The majority of these oscillations, as we believe, have a forced nature. The DEF method was tested with more than 30 instances of actual events for oscillation frequencies in the range from 0.05 Hz to 1.7 Hz where the actual source of oscillation was known with a high confidence level based on operational information, analysis of multiple data sources and communication with power plants.

The set of PMU data includes frequency and voltage measurements from 24 locations and currents from 102 branches (lines and transformers) of the 345 kV network. Each location has more than one branch monitored by PMU.

The DEF method has demonstrated high efficiency for all tested cases in identifying the source of forced oscillations. Calculated dissipating energy flow in transmission elements also demonstrates high consistency with the expected direction of flow from the source to sinks. The unknown actual load model and network losses discussed in Section 3 did not significantly impact results in the actual system.

Below are some examples of actual events.

- **April 5, 2013 event.** Rapidly growing in magnitude oscillations of 0.12 Hz were observed in a significant part of the system. The magnitude of oscillations reached up to 100 MW peak-to-peak in some transmission lines. Oscillations gradually disappeared in 3 min. Fig. 3a shows MW flow in one of the lines.

The DEF method has clearly identified one power plant as a source of the oscillations and Fig. 3c illustrates the dissipating energy flow in the 345 kV network around that power plant. Fig. 3b shows the flow of dissipating energy over time at the connection point of the power plant to network. Note that the energy coming from the generator practically equals to the sum of energy flowing over lines A and B and provides reasonable nodal balance:

$$DE_{Gen} + DE_{A} + DE_{B} = 1.000 - 0.636 - 0.397 = -0.032$$

That demonstrates practical applicability of the DEF method for actual systems.

- **June 17, 2016 oscillations.** Oscillations with magnitude up to RMS = 11 MW and frequency fluctuating from 0.22 Hz to 0.28 Hz have been detected in multiple locations of ISO-NE lasting 45 min. Fig. 4a shows the active power flow in one of the two 345 kV lines connecting ISO-NE and New York ISO (NYISO) during the initial stage of the event. The mode shape showed that the majority of ISO-NE generators were oscillating in phase, suggesting...
that ISO-NE PMUs allow the observation of only a part of the system wide event. Control room operators in this situation need to know whether the source of oscillations located inside or outside of control area in order to take proper course or actions. The DEF method was applied for this event by using available PMU data from ISO-NE. Fig. 4b shows the DE values for the 345 kV part of network connecting ISO-NE and NYISO and Table 5 contains these DE values. DE flow clearly indicates that the source of oscillations was located outside ISO-NE.

On June 30, 2016 three generators G1, G2 and G3 at one of the power plants were operating in the same conditions producing 237 MW each. A failure suddenly occurred at the excitation system of G3 resulted in 1.3 Hz oscillations with RMS magnitude of 18 MW and consequential tripping of this unit. Fig. 5 shows power plant terminal voltage. Excitation failure at G3 started at t = 5 s and the unit was disconnected at t = 24 s. All three units were monitored by PMU and Table 6 shows the results of the DE results. Unit G3 is reliably identified as the source of oscillations producing energy while other two units were contributing into damping by dissipating energy. Note that the G3 has the highest DE flow in the network. This example illustrates the ability of the DEF method to identify a specific unit as the source from multiple units within a power plant.

The entire time for applying the DEF method for the ISO-NE grid takes less than 5 s by using Intel i7 CPU@ 2.1 GHz and 8 GB RAM. Total time from the detection of oscillations to identification of the source for online application should include also a possible artificial delay necessary to collect data during a time interval sufficiently long for the DEF method per Section 2.4.2 requirements and time for loading PMU data. Even with these delays, the DEF method is fully suitable for online application.

### 4.3. Actual events in WECC

The DEF method was tested with two events where the wide spread forced oscillations with significant MW magnitude were observed in the WECC system respectively in March 10 (1.48 Hz

<table>
<thead>
<tr>
<th>Table 5</th>
<th>DE in 345 kV lines for June 17, 2016 event.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line</td>
<td>DE</td>
</tr>
<tr>
<td>A</td>
<td>0.635</td>
</tr>
<tr>
<td>B</td>
<td>0.851</td>
</tr>
<tr>
<td>C</td>
<td>-0.525</td>
</tr>
<tr>
<td>D</td>
<td>-0.007</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 6</th>
<th>DE of generators for June 30, 2016 event.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator</td>
<td>G1</td>
</tr>
<tr>
<td>DE</td>
<td>-0.01</td>
</tr>
</tbody>
</table>

Fig. 3. Oscillation source location for April 5, 2013 event.

Fig. 4. Locating the source of oscillations for June 17, 2016 event.

Fig. 5. Power plant terminal voltage during June 30, 2016 event.
event) and in November 17, 2015 (1.17 Hz event). PMU from 55 locations metering flow in 271 transmission elements were kindly provided by Bonneville Power Administration (BPA) for testing. Mapping of PMU data with the system topology was not known during the test. Results of the DEF method in the form of DE values for 20 transmission elements with the largest DE values were sent back to BPE. As an example, Table 7 shows some of DE values for the November 17, 2015 event. BPA personnel have mapped DE values with the system topology and confirmed that DE values correctly trace the source of forced oscillation in both cases.

5. Evaluation of damping properties of power system components

The DEF method potentially enables the estimation of contribution of system components (generators, HVDC lines, FACTS) to the damping of a specific oscillation mode. Flow of dissipating energy calculated for a generator in a low damped process can be viewed as the net damping contribution of this generator. The same is true for any system element contributing into damping. It is important that such an evaluation can be done in a distributed manner by using local PMU measurements only. Single PMU metering output of a generator is sufficient to at least qualitatively identify whether this generator produces positive or negative damping for a specific mode.

Refs. [11,12] demonstrate that for a single machine linear system, dissipating energy rate for a specific mode is approximately proportional to the real part of eigenvalue for that mode. It was assumed also in [11] that this property is valid for multi-machine system and the numerical illustration was provided for a four-machine two-area system. This property can potentially open a door for new class of PMU-based applications. The efficiency and limitations of these new opportunities for real-life systems should be carefully evaluated because the assumptions of the DEF method, strictly speaking, do not hold in actual systems. Details of PMU processing steps, described in Section 2 can also impact the accuracy of results. This section provides numerical estimation of the DEF method in identifying of specific generator’s contribution into damping of a poorly damped mode for simulated case in 29-machine WECC system and for actual event in ISO-NE system. Application of the DEF method for actual events indicates that the method can be successfully used in most of practical situations.

Let us illustrate the capability of the DEF method to detect the negative damping contribution of a generator into a poorly damped mode in 29-machine WECC system. For that purpose, the damping coefficients of three generators in the base case system from [13] were modified (D35 = 1, D65 = −1, D77 = 0.2) to create two low damped modes, i.e. −0.034 ± j2π × 0.37 Hz and −0.096 ± j2π × 0.47 Hz. Generator 65 contributes negative damping here. The rest of generators have D = 4. Linear analysis and simulated PMU data were produced by using SSAT and TSAT software [14].

Linear estimate of damping contribution of a classical model generator i to the mode is a product of eigenvalue sensitivity and damping coefficient, i.e., ∆p = D·∂e/∂Di. Columns 3 and 5 of Table 8 contain ∆p contributions of the generators most impacting damping of the 0.37 Hz and 0.47 Hz modes. Columns 4 and 6 contain corresponding DE values. These results demonstrate that the DEF method allows to identify the generator negatively contributing into damping of poorly damped modes. Additionally, DE values can also be qualitatively used for estimation of positive damping contribution of generators.

The January 25, 2016 event in ISO-NE system allows to evaluate the ability of the DEF method to detect the generator-source of negative damping in a low damped transient. That day, the tripping of a large generator initiated very poorly damped 0.98 Hz oscillations observed in the significant part of the system. The DEF method applied to this process clearly indicates that one of the power plants served as the source of negative damping for these oscillations, as shown in Fig. 6. This result is consistent with the facts historically known to ISO-NE that this power plant can contribute negative damping into about 1 Hz mode under specific operating conditions. Following communication with the power plant personnel and the investigation of the source of the negative damping within the power plant has resulted in a discovery of incorrect setting in the excitation system.

Table 8
Comparison of generators’ contribution into damping.

<table>
<thead>
<tr>
<th>Gen</th>
<th>D</th>
<th>Mode 0.37 Hz Δp</th>
<th>Mode 0.47 Hz Δp</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Di</td>
<td>DE</td>
</tr>
<tr>
<td>35</td>
<td>1</td>
<td>−0.0413 0.915</td>
<td>−0.0214 0.342</td>
</tr>
<tr>
<td>79</td>
<td>4</td>
<td>−0.0136 0.369</td>
<td>−0.0512 0.710</td>
</tr>
<tr>
<td>15</td>
<td>4</td>
<td>−0.0008 0.024</td>
<td>0.0004 0.188</td>
</tr>
<tr>
<td>77</td>
<td>0.2</td>
<td>0.0003 0.084</td>
<td>0.0009 0.127</td>
</tr>
<tr>
<td>30</td>
<td>4</td>
<td>0.0004 0.023</td>
<td>−0.0188 0.025</td>
</tr>
<tr>
<td>65</td>
<td>−1</td>
<td>0.0322 1.000</td>
<td>0.0309 1.000</td>
</tr>
</tbody>
</table>

Fig. 6. Locating the generator contributing negative damping in the January 25, 2016 event in ISO-NE system.

6. Conclusion

Modification of the energy-based method named dissipating energy flow (DEF) method has been proposed. The DEF method allows locating the source of poorly damped natural or forced oscillations in a power system by using PMU data. In testing, the method has correctly identified the source of sustained oscillations in all simulated cases from [13] (9 cases of natural and 12 cases of forced oscillations) and demonstrated high efficiency for all 30+ tested actual events from ISO-NE and for two cases from WECC systems.
The method is capable of identifying a specific generator as the source of oscillations by using PMU measurements in the radial connection of a generator to the network. The method is also helpful in identifying whether the source of oscillations is located inside or outside of the control area by using PMU measurements in tie-lines connecting control areas.

Network losses and load characteristics can impact accuracy of the DEF method as it was shown with simulated data. Testing real events, however, demonstrates that the DEF method can be efficiently used for actual systems. Further analysis is required to establish a possible limitation for the use of DEF approach.

The method potentially opens an opportunity to a new type of PMU application – online, decentralized estimation of the contribution of a power system component to the damping of a specific oscillation mode. Possible limitations of this capability related to the DEF assumptions and PMU data processing need further investigation.

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References