Forced Oscillation Location Estimation with Partial Observation of the Power System

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***Abstract*—Forced oscillations are usually excited by external periodical sources, e.g., malfunctions in exciters, power system stabilizers, and governors. Unlike natural oscillations which can be attenuated on their own if the system has sufficient damping, forced oscillations cannot be fully mitigated until the source is identified and removed. Therefore, fast and accurate source location is of importance for forced oscillation mitigation in interconnected power grids. This paper proposes a synthetic approach for forced oscillation source location using synchrophasor measurements. This approach uses three methods, dissipating potential-based, oscillation magnitude-based, and oscillation mode angle-based, to estimate the source location individually, and then provide the final estimation based on the weights of different methods. A tool called Forced Oscillation Localization Tool is developed, which uses voltage synchrophasor measurements for source location without knowing system topology information. The developed tool is tested with the IEEE test case library of power system sustained oscillations, which are simulated forced oscillation events in a reduced 179-bus WECC model with full observation of the system. Also, the tool is tested using an actual forced oscillation event in EI. The test results demonstrate the effectiveness of the tool in forced oscillation source location.**

KEYWORDS— Forced oscillation, source location, synchrophasor, dissipating potential, dissipating energy flow, oscillation mode angle, Forced Oscillation Localization Tool (FOLT), FNET/GridEye

1. Introduction

With more PMUs deployed in power grids, various forced oscillation events have been monitored worldwide. Unlike the natural oscillations, which can be quickly attenuated on their own if the system has sufficient damping, forced oscillations are usually excited by external disturbances, e.g., generator malfunction or cyclic load, and can persist for a few minutes or several hours until the external source is removed [1]. When the frequency of a forced oscillation is close to that of a natural oscillation mode, the resonance can make the forced oscillation observable across the entire interconnection. Therefore, it is critical to identify the source location quickly to fully mitigate forced oscillations.

A general procedure to mitigate forced oscillations in recommended by the North American Electrical Reliability Corporation (NERC). It consists of five steps: Detect the forced oscillation, determine oscillation frequency and magnitude, determine extent of oscillation, determine location or general proximity of oscillation, and determine specific system component causing oscillation. Obviously, the last two steps focus on source location [2]. A comprehensive method to mitigate forced oscillation is presented in [3]. The active control through battery energy storage system can be activated to reduce forced oscillation energy to a safe level to allow sufficient time for system operators to pinpoint the exact source location without risking the bulk power system reliability. However, the forced oscillation cannot be fully mitigated until the source is removed.

Many methods have been proposed for forced oscillation source location. Dissipating energy flow-based method is method is developed and used by Independent System Operator - New England (ISO-NE) [4]-[5]. This method needs system topology and even real-time system topology. Also, many artificial intelligence-based methods have been proposed [6]-[7]. However, they usually require training and validation using massive simulated forced oscillation events.

This paper proposes a composite approach for forced oscillation source location, which includes three methods: dissipating potential-based, oscillation magnitude-based, and oscillation mode angle-based. The uniqueness of this composite approach is that it does not require system topology information. It can locate the source based on voltage magnitude and voltage angle synchrophasor measurements. A forced oscillation source location tool is developed and validated using IEEE test cases library of power system sustained oscillations and an actual forced oscillation event that occurred recently in the US Eastern Interconnection (EI) grid.

2. Forced Oscillation Source Location Methods

2.1 Dissipating potential-based method

The dissipating energy generated by the forced oscillation source flows from the source location to other areas. The direction of the dissipating energy flow can be used for source location. However, the system topology is needed. This method is utilized by ISO-NE for forced oscillation source location.

The paper proposes a modified method based on dissipating potential. The calculated dissipating energy can be used to calculate the dissipating potential. In an electric circuit, the current flows from the high voltage node to the low voltage node. Similarly, the dissipating energy flows from the bus with high dissipating potential to the bus with low dissipating potential. In this way, the source location can be estimated using the calculated dissipating potential without system topology.

2.2 Oscillation magnitude-based method

The second method is based on the oscillation magnitude. Usually, the source location has the highest oscillation magnitude, which make is possible to identify source location. However, it is not always the case. Therefore, this method is usually assigned with the lowest weight.

2.3 Oscillation mode angle-based method

The third method is based on the oscillation mode angle, which is defined as the phase angle of a variable with oscillations. As shown in Figure 1, frequency signals of both PMU1 and PMU2 can reflect the same oscillation mode. The oscillation mode angle of PMU1 is leading that of PMU2 by 35°. Similar to the active power which flows from a power angle leading bus to a power angle lagging bus, the dissipating energy excited by the forced oscillation source flows from a bus with leading oscillation mode angle to a bus with lagging oscillation mode angle. It is noted that this method can be applied to different variables if that variable can observe oscillations. Sometimes, it is tricky to unwrap oscillation mode angle in a large power system, and thus this method is usually assigned with an intermediate weight.

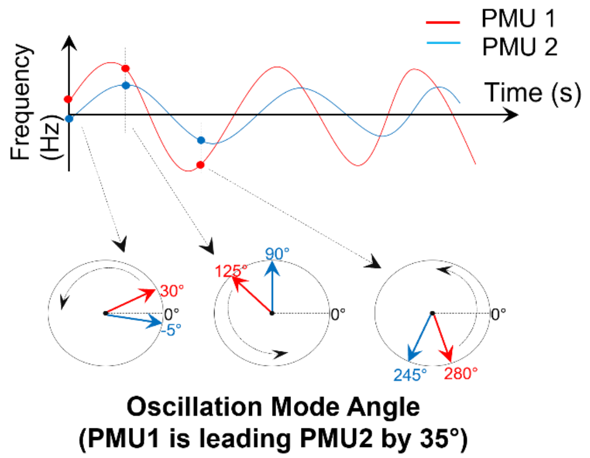


Figure 1. Oscillation mode angle between two PMUs

3. Forced Oscillation Source Location Tool

A Forced Oscillation Localization Tool (FOLT) is developed to identify the source location of a forced oscillation using the three aforementioned methods [8]. The diagram of the tool is given in Figure 2. The inputs of the tool are voltage magnitude, voltage angle, and frequency synchrophasor measurements. Frequency measurements are optional since frequency can be estimated by using the voltage angle measurements. The outputs of the tool are the estimated source location with confidence index. The final estimation result is the synthetic result of each method with given weights. Also, the tool can provide the intermediate results, e.g., FFT analysis results to identify the dominant oscillation mode. The required configurations include PMU location (either GPS coordinates, zip code, or county name), method selection and weight, PMU data reporting rate, and data window selection. One uniqueness of the tool is that it does not require system topology information. The forced oscillation source location estimation is based on synchrophasor measurements and PMU location.

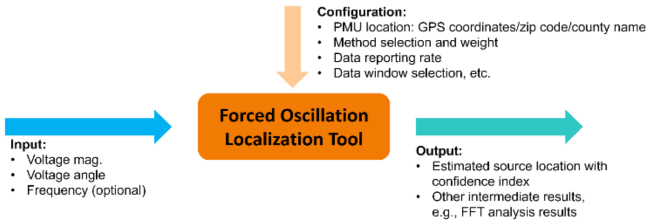


Figure 2. Diagram of the developed Forced Oscillation Localization Tool (FOLT)

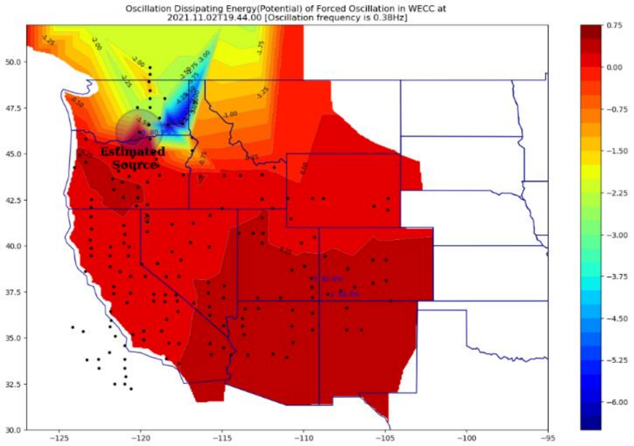
4. Test with IEEE Test Cases Library of Power System Sustained Oscillations

The developed tool is tested with the IEEE test cases library of power system sustained oscillations. These forced oscillations were created by simulation on a 179-bus reduced WECC system model [9]. The 18 test cases are listed in Table 1. The forced signals (sinusoidal or periodic rectangular) are injected into exciter or governor of a synchronous generator. The oscillation frequency varies from 0.1 Hz to 0.86 Hz. The system is fully observable. Voltage magnitude and voltage angle of each bus, current magnitude and current angle of each transmission line or transformer, and rotor speed and angle of each machine are provided. However, the developed tool uses voltage magnitude and voltage angle only to estimate source location.

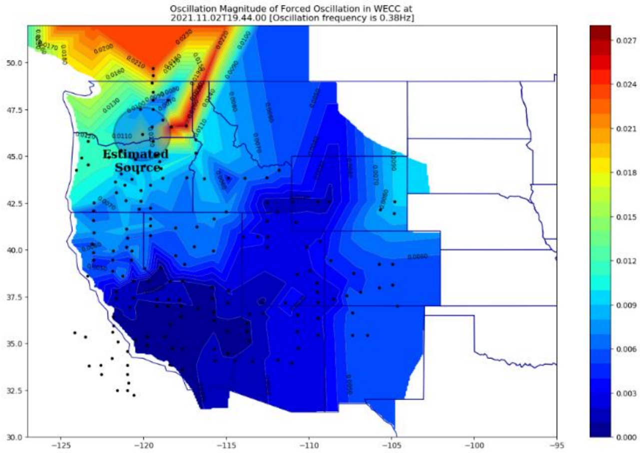
Table 1 Simulated forced oscillations and FOLT estimation results

Case #	Type of injected signal	Disturbance controller	Oscillation Freq. (Hz)	Source Location	FOLT Estimation Result
F_1	Sinusoidal	Exciter	0.86	4	4
F_2	Sinusoidal	Exciter	0.86	79	79
F_3	Sinusoidal	Exciter	0.37	77	77
F_4_1	Sinusoidal	Exciter	0.81	79	79
F_4_2	Sinusoidal	Exciter	0.85	79	79
F_4_3	Sinusoidal	Exciter	0.89	79	79
F_5_1	Sinusoidal	Exciter	0.42	79	79
F_5_2	Sinusoidal	Exciter	0.46	79	79
F_5_3	Sinusoidal	Exciter	0.50	79	79
F_6_1	Periodic, rectangular	Exciter	0.1	79	79
F_6_2	Periodic, rectangular	Exciter	0.2	79	79
F_6_3	Periodic, rectangular	Exciter	0.4	79	79
F_7_1	Sinusoidal	Exciter	0.65 & 0.43	79 & 118	Incorrect (due to multiple modes)
F_7_2	Sinusoidal	Exciter	0.43	70 & 118	Incorrect (due to multiple locations)
FM_1	Sinusoidal	Governor	0.86	4	4
FM_3	Sinusoidal	Governor	0.37	77	77

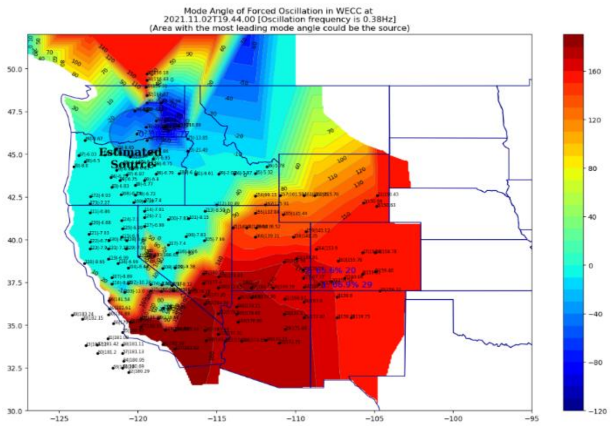
FM_6_2	Periodic, rectangular	Governor	0.2	79	79
FM_7_1	Sinusoidal	Governor	0.65 & 0.43	79 &118	Incorrect (due to multiple modes)



(a) Dissipating potential-based method



(b) Oscillation magnitude-based method



(c) Oscillation mode angle-based method

Figure 3. Results of test case FM_3

Figure 3 shows the results of the test case FM_3 as an example. The color bars represent the dissipating potential, oscillation magnitude, and oscillation mode angle in Figure 3 (a), (b), and (c), respectively. The results of other test cases are listed in Table 1. The FOLT can provide accurate estimation results in 15 cases of total 18 cases. The tool cannot handle forced oscillation with multiple source locations for now.

5. Analysis of Actual Forced Oscillation Events

5.1 Forced oscillation data collection by FNET/GridEye

The measurements of the actual interconnection-wide forced oscillation events are collected by FNET/GridEye. FNET/GridEye is a Global Positioning System (GPS) synchronized power grid dynamic frequency and phase angle monitoring network deployed at the distribution level [10]-[11]. It uses single-phase Phasor Measurement Units (PMUs) to measure synchrophasor at the 110 V or 220 V distribution level and transport data to application servers via Internet. FNET/GridEye is the only monitoring system that provides real-time insights into the dynamic behaviors of all interconnection grids in North America. Various online and offline applications have been implemented on FNET/GridEye to monitor large-scale power grids. It proves to be an effective situational awareness tool for electric utilities, Independent System Operators, and regulatory agencies.

Two types of sensors are deployed at the data collection level, Frequency Disturbance Recorder (FDR) and Universal Grid Analyzer (UGA). FDR is the earlier version of the sensor usually deployed in an office room or at home to collect GPS-synchronized measurements, including frequency, voltage magnitude, and voltage angle, from an ordinary 110 V or 220 V outlet. Universal Grid Analyzers (UGAs) are the advanced version of FDRs with higher sampling and reporting rates, and newly added power quality monitoring functions. Currently, more than 200 FDRs/UGAs have been deployed in North America, as shown in Figure 4.

Figure 4. FDR/UGA deployment in North America

5.2 Actual forced oscillation event in EI

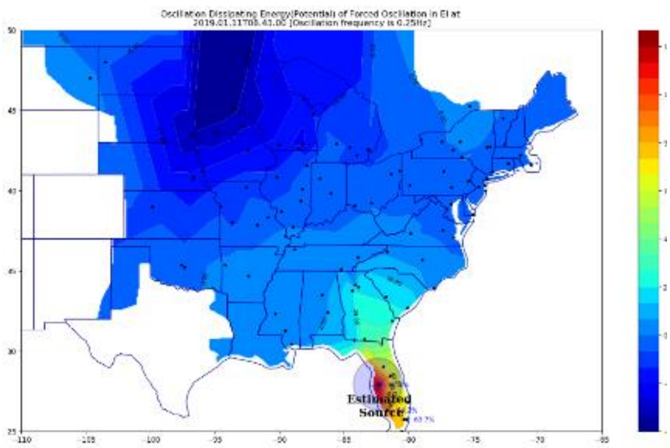
A recent interconnection-wide forced oscillation event in EI is summarized in Table 2. The oscillation frequency is 0.25 Hz, which is close to the frequency of the natural oscillation mode among Florida, MISO, and ISO-NE. This forced oscillation was excited by a generator in Florida due to a failed PT connection and errored voltage measurement. The oscillation lasted 18 minutes before the generator was disconnected from the grid. The entire EI can observe this force oscillation. The disturbance generator injected 200 MW oscillation peak-to-peak, and ISO-NE area can observe 50 MW oscillation peak-to-peak [12].

Table 2 Overview of recent interconnection-wide forced oscillation events

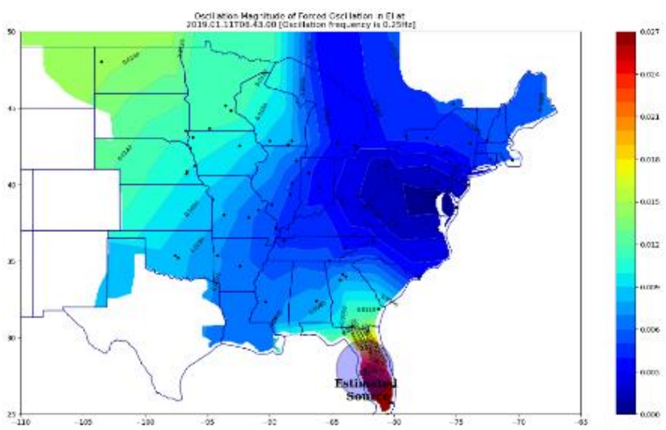
NO.	Inter-connection	Date	Time (UTC)	Oscillation Frequency (Hz)	Verified Source Location
1	EI	01/11/ 2019	08:44 - 09:03	0.25	Tampa, Florida

5.3 Source Location Results

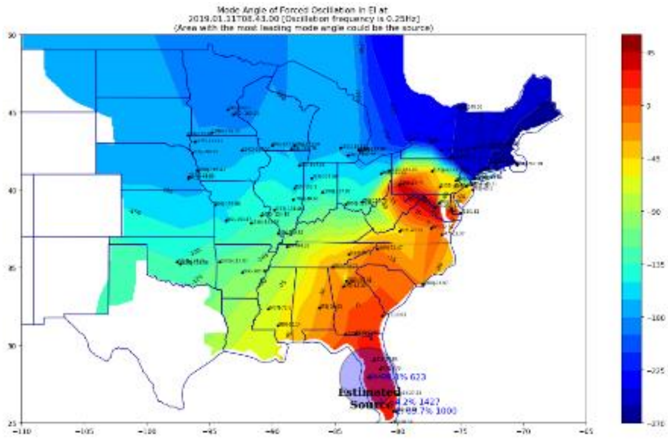
The analysis results of the EI 01/19/2019 forced oscillation event are given in Figure 5. Since there is an FDR/UGA deployed around Tampa, Florida, the source location can be correctly identified. Also, since the source location happens to have the highest oscillation magnitude, the oscillation magnitude-based method can provide a good estimation result as well.



(a) Dissipating potential-based method



(b) Oscillation magnitude-based method



(c) Oscillation mode angle-based method

Figure 5. EI 01/19/2019 forced oscillation event

6. Conclusions

Fast source location identification and removal are critical to mitigate forced oscillation and maintain the reliability of bulk power systems. This paper proposes three methods, dissipating potential-based, oscillation magnitude-based, and oscillation mode angle-based, for forced oscillation source location identification. The final estimated location is the synthetic results of the three methods with different weights. These methods do not require grid topology in source location identification, which make it feasible to quickly identify the source location of an interconnection-wide forced oscillation event. The developed FOLT is tested with the IEEE test cases library of power system sustained oscillations and an actual interconnection-wide forced oscillation event in EI. The test results demonstrate that the tool can quickly identify the rough location of the forced oscillation source with limited PMU coverage.

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