Creation of Simulated Test Cases for the Oscillation Source Location Contest

Preprint

Slava Maslennikov[1] and Bin Wang[2]

1 ISO New England
2 National Renewable Energy Laboratory

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National Renewable Energy Laboratory
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Creation of Simulated Test Cases for the Oscillation Source Location Contest

Slava Maslennikov
Advanced Technology Solutions
ISO New England
Holyoke, MA, USA
smaslennikov@iso-ne.com

Bin Wang
Grid Planning and Analysis Center
National Renewable Energy Laboratory
Golden, CO, USA
bin.wang@nrel.gov

***Abstract*—This paper describes in detail the design process and creation of 13 oscillatory test cases for the IEEE and NASPI co-hosted Oscillation Source Locating Contest conducted in 2021. The challenges behind the 13 cases are fully explained. Based on the philosophy, implementation considerations, and techniques used for the case design presented in this paper, interested readers can create additional interesting cases for testing the efficiency of their oscillation source location methods.**

***Index Terms*—oscillation, forced oscillation, oscillation source location, oscillation cases, test cases**

I. INTRODUCTION

Sustained power system oscillations, including both forced oscillations (FOs) and poorly damped natural oscillations, represent a threat to power systems, potentially causing instability, reducing the reliability of equipment due to excessive mechanical vibration, and reducing the network transfer capability. The first step in an efficient mitigation strategy is finding the source of oscillation, i.e., finding the component(s) containing the source of the FO (external periodic disturbance), or the system component largely and negatively contributing to the damping of natural modes.

Major methods for locating the source of oscillation are summarized in [1], and their advantages and disadvantages are also discussed. Among the most effective methods is the energy-based method [2], which has been further developed into the dissipating energy flow (DEF) method [3] to adapt to actual power system environments and real PMU data. DEF has been implemented in ISO New England's OSLp software (freely available upon request at [4]), and in Powertech Labs' DSATools/DSAOA [5], mainly due to its practical effectiveness, as shown in [6]. Results (presented in [7]) of the Oscillation Source Location (OSL) Contest [8] also confirm the efficiency of energy-based methods. Nevertheless, a false OSL result is theoretically still possible for DEF when complex interaction of controls is present [9]. In recent years, the topic of OSL has been of high interest, and new methods have been proposed, including those in [10]–[13]. The demonstration of these methods' efficiency is limited to a few simulated cases, which do not fully account for real-life situations. Therefore, their practical applicability and potential limitations for real-life situations are difficult to evaluate.

To comprehensively evaluate the efficiency of existing and new OSL methods and their applicability for practical implementation, IEEE and NASPI co-hosted the first OSL Contest [8]. Thirteen simulated test cases [14] were carefully created and used in the contest. The philosophy adopted for creating the test cases included realism in power system modeling and representative coverage of the FO properties. Each test case contains a set of synthetic PMU measurements, obtained from time domain simulation, for a time period containing FOs with different properties and source locations.

It is worth mentioning that the existing test cases library, created in 2016 [15], is based on a WECC 179-bus power system model, which does not cover all possible practical situations of FOs, such as FOs at load or HVDC. Also, complex control interactions seem difficult to exhibit in the WECC 179-bus system, due to its simplified and idealized model (i.e., classical model for all generators). The new set of simulated test cases presented in this paper complements the existing test cases library by: (i) adopting a test system with detailed modeling of the generator and controls, (ii) adding random fluctuation of loads to represent "colored noise" ambient system dynamics, (ii) including FO cases with complex control interactions, and (iii) including cases with FOs at load and HVDC.

II. PROPERTIES OF DESIRED OSCILLATION CASES

There are several specifics of real-life oscillations that are typically not accounted for in simulated oscillations. To make the cases for OSL Contest more realistic and challenging, the following aspects were considered in the case design process.

- **Reasonably realistic system model.** The size of the test system should be large enough to represent a reasonably realistic spectra of oscillation modes, as in a bulk power system, covering both inter-area and local oscillation modes. Dynamic components are represented by a detailed model with controls, including a generator model and its governor and excitation control systems, with or without a power system stabilizer (PSS). "Colored noise," i.e., ambient system dynamics caused by random load fluctuations, is added in time-domain simulations.
- **Realistic set of PMU measurements.** Quasi-PMU data generated as the output of time-domain simulation provide limited observability. This is to account for the fact that power systems today, and for a significant period in the future, will have only partial observability by PMUs. A realistic sampling rate of 30 samples per second is used. Diversity of P and M class PMUs is reflected in all cases. Data quality issues are present, including missing samples.

- **Realistic properties of FO.** Most real-world FOs are located at generator controls, either in the exciter or the governor, while some FOs are located at a load or at the control of other dynamic components like HVDC. For the vast majority of actual FOs, the source is located in the fuel supply and control system, providing a natural and physical explanation that the failure probability in a mechanical system/governor is higher than in an electrical one/exciter.

  In reality, depending on the nature of the actual forcing signal, the amplitude and frequency of the FO can either remain unchanged or vary significantly over time. The forcing signal can either be an ideal sinusoid or other shapes, like rectangular waveforms, to introduce harmonics. Forcing frequency can either be different from any system natural modes or close to one of them to cause a resonance. The resonance condition is an important practical case where the maximum oscillation magnitude could occur far away from the source, contradicting the first intuition. Single or multiple oscillation sources are also possible.
- **Avoid bias toward any known OSL methods.** Some of the existing OSL methods rely on specific properties of oscillations. One of the objectives in the test cases design was to avoid a situation where cases are biased toward specific OSL methods. Cases with multiple oscillation sources are considered to avoid bias toward methods that can only determine one oscillation source. Disturbances obfuscating the onset of FOs are added to avoid bias toward methods relying on the onset of FOs. A lossy network model and non-constant power load model are adopted to avoid bias toward energy-based methods. The topology and dispatch in the power system model available for the OSL participants were slightly different from those used for designing the test cases, to avoid bias toward methods strongly relying on an accurate model. The resonance condition is used to avoid bias toward methods relying on the mode shape.

III. TECHNICAL IMPLEMENTATION OF DESIRED OSCILLATION CASES

A. *Test System, Simulation Tools, and Setup*

The reduced WECC 240-bus test system developed by the National Renewable Energy Laboratory (NREL) [16]–[17] (see its one-line diagram in [14]) was adopted for creating all cases because it possesses most of the properties discussed in Section II. This test system has 243 buses and 146 generating units at 56 power plants, including 109 synchronous machines, 37 renewable units, and 139 loads. Each generator is represented by the detailed model and equipped with an exciter and governor.

In addition to adding FOs and colored noise, which will be introduced later in this section, another important change we made to this model was adding 10 PSS models for improving the damping ratio of 12 poorly damped local modes, as reported in [17]. Small-signal analysis was conducted in SSAT by Powertech Labs, and the resulting left eigenvectors were used to identify the top 10 machines that have largest controllability over those 12 modes. The IEEEST PSS model was added to each of these 10 machines, and the parameters from [18] were taken as a starting point. Two parameters of the IEEEST model were found to be most influential to mode damping, namely, T1 and KS. A sensitivity table was created by using SSAT to elucidate the relationship between the real part of the eigenvalues associated with these 12 modes and the two parameters. The sensitivity table was used to adjust the damping of system modes as desired by modifying the T1 and KS parameters. The refined IEEEST parameters and the damping ratios of the 12 modes before and after adding PSS are shown in Tables I and II, respectively. Note that KS was modified in some test case(s) for creating a negative damping contribution from the associated machine.

TABLE I. PARAMETERS OF THE 10 ADDED IEEEST PSS MODELS

Machines (Bus-ID)	Parameters of IEEEST Model (Name=Value)
1333-G, 2030-G, 2438-WG, 2630-G, 3931-NH, 4131-H, 6235-H, 6533-C, 8034-G, 7031-G	A1=1.013, A2=0.013, A3=0, A4=0, A5=1.013, A6=0.113, T2=0.02, T3=0, T4=0, T5=1.65, T6=1.65, KS=3, LSMAX=0.1, LSMIN=-0.1, VCU=0, VCL=0
(T1_Machine=Value)	T1_1333G=3, T1_2030G=4, T1_2438WG=11, T1_2630G=4, T1_3931NH=10, T1_4131H=7, T1_6235H=10, T1_6533C=7, T1_8034G=3, T1_7031G=7

TABLE II. SELECTED ELECTROMECHANICAL MODES UNDER 1.5 HZ OF THE 240-BUS TEST SYSTEM WITHOUT AND WITH PSS

Mode Freq* (Hz)	Damping Ratio Without PSS (%)	Damping Ratio With PSS (%)
0.3792	17.61	13.96
0.5225	1.98	8.12
0.598	1.06	10.27
0.6927	1.25	6.7
0.7282	1.13	5.26
0.7624	1.5	6.48
0.8648	1.26	9.4
0.8896	1.73	9.25
0.958	1.42	7.35
0.9777	1.61	6.63
1.0372	3.07	7.21
1.1464	3.97	19.5
1.2729	3.77	4.63

*Frequency of all modes of the system with PSS are slightly different from those without PSS. For each mode, its mode shape was first matched before identifying the change in the damping ratio.

Besides SSAT for small-signal and sensitivity analysis, other simulation tools adopted for implementation include TSAT by Powertech Labs for time-domain simulation, Matlab and Powerworld for data handling and topological analysis, OSLp by ISO New England for verification of data integrity and benchmarking of OSL results, and PMU Emulator by EPRI for implementing P and M class PMUs.

Some remarks on the simulation setup:

- **Load model.** A static ZIP model (Z=40%, I=30%, P=30%) is adopted to represent all 139 loads.
- **Observability setup.** The system consists of four areas: North, South, California and Mexico. Simulated PMU data sets available to OSL participants provide only partial observability of the system in all four areas, including the following: (i) all 23 tie-lines between the four areas; (ii) AC lines connecting HVDC terminals at Celilo and Sylmarla; (iii) 35 transmission lines (mainly 500 kV) within the North, South, and California areas; (iv) step-up transformers connecting 23 power plants to the network (measured at low side) in all four areas (as a result, only 23 of 56 power plants are monitored by PMUs, and no individual generator

within a power plant is monitored by a PMU); and (v) bus voltage and branch current phasors at the rate of 30 samples per second. We intentionally did not provide bus voltage frequency because it is not a state variable in TSAT time domain simulation and practically, it is obtained by numerical differentiation with some filtering. The resulting frequency has some artificially added phase shift, which could be harmful for some OSL methods.

- **Simulation time length.** Each case contains 90 seconds of data, including a 30-second leading window before the event, representing the pre-disturbance ambient condition, and a 60-second time window containing oscillations.

B. *Design Process*

Fig. 1 illustrates data flow of the case design process. Step 1 enumerates many cases possessing properties from Section II, each of which will be processed by steps 2-8. Step 2 prepares input data, including power flow, dynamic, forced oscillation, contingency and monitoring data. Step 3 runs time domain simulation in TSAT. Step 4 converts simulation results into "test cases library" format[1]. Step 5 processes the data by PMU emulator. Step 6 adds "missed" samples. Step 7 packs up and labels the data. Step 8 verifies the data by OSLp.

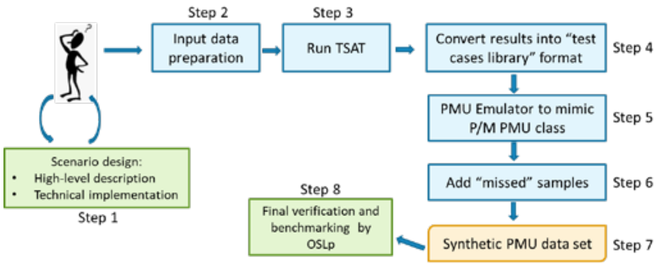

Figure 1. Data flow process of the case design

Additionally, an automated simulation setup was created and used for benchmarking, verification of design results, and selection of the most suitable cases for the contest. This setup includes all necessary steps, including the addition of FO, time-domain simulation, calculation of the DEF in the network by the OSLp application, and scoring of results. The setup was used to exhaustively simulate the cases where the source of FO with desirable frequency was located in the governor of every generator out of the total 31 with the TGOV1 model and in the exciter of every generator out of the total 91 with the SEXS model.

C. *Modeling of Sustained Oscillations*

Sustained oscillations were created by adding FO and by making low damping for natural modes with proper tuning of PSSs. A library of user-defined models (UDM) for TSAT (see [14] for more details) allows the introduction of a periodic forcing signal in the TGOV1 governor model and the SEXS exciter model of generators in the load and in HVDC. A forcing signal is modeled as a sinusoidal signal, with the frequency and magnitude defined as a function of time configured as user-defined profiles. A profile consists of time sequence points of magnitudes/frequencies. Magnitudes and frequencies between two adjacent points are calculated by TSAT by linear interpolation. Proper profiles allow flexible modeling of FO, including variable magnitude and frequency, desired duration, and composition of FO harmonics. Fig. 2 illustrates an example of a rectangular shape of a forcing signal causing harmonics.

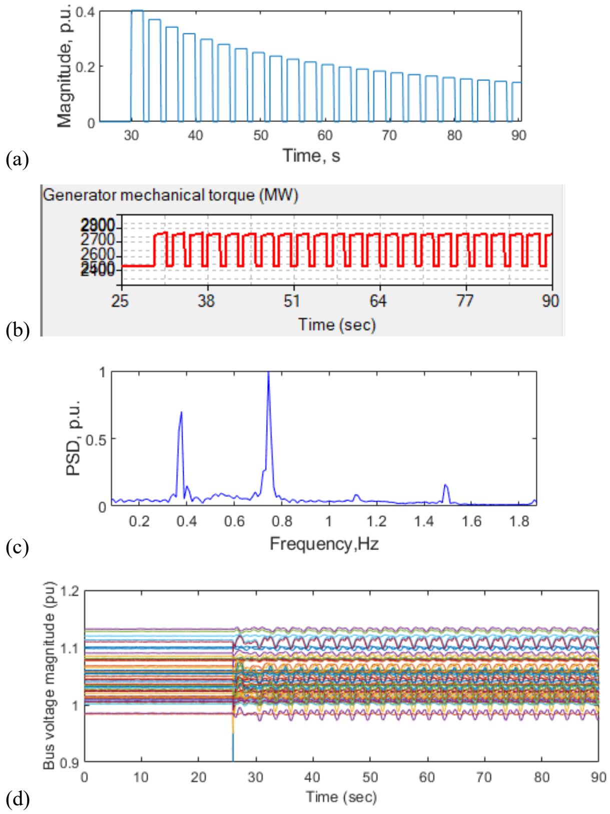

Figure 2. (a) Profile of a forcing signal in UDM for the case 12, (b) resulting rectangular shape mechnical torque, (c) frequency spectrum, and (d) time domain trajectories of bus voltage magnitude

D. *Modeling of "Colored Noise"*

The steady state of any actual power system always exhibits so called "colored noise"—a system dynamic excited by load fluctuation and switching actions. "Colored noise" was modeled by fluctuation of active and reactive power of all loads using the UDM model INJECTCSV, where the power magnitude profile was varied as a sum of two random components with a low and a high frequency (see Fig. 3).

The high-frequency component changes with PMU sampling rate and represents measurement noise. The low-frequency component changes with random time intervals within the 0.5–5.0 s range. Magnitudes of both componets are also random variables in the range from zero to 0.002 p.u. We have created 15 different noise profiles, which were randomly assigned to all loads in each test case. Such noise modeling allows us to create realistic colored noise with a reasonably small size of noise profiles, making sure to avoid a situation where the same noise profile is applied to several closely located loads.

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[1] "Test cases library" format can be found at [19]. PMU Emulator can be found in [20].

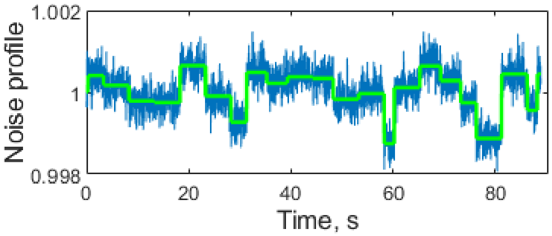

Figure 3. An example of a load noise profile consisting of high-frequency (blue) and low-frequency (green) components

E. Post-Processing – PMU Emulator

Synthetic PMU as a time-domain simulation differs from actual PMU to some extent. Actual PMU, due to internal data processing, creates some signal phase/magnitude distortion and is slightly different depending on the class of PMU (P or M). Allocation of P/M PMU types across actual systems can vary and could be unknown. To account for that factor, the synthetic PMU signals, obtained from time-domain simulation, were processed by EPRI's PMU emulator [20]. The emulator has introduced proper P or M class modification to all voltages and currents at the same PMU. Allocation of PMU class was taken as 70% for M class and 30% for P class, and the allocation was the same for all 13 test cases.

F. Post-Processing – PMU Missing Samples

Actual PMU measurements, due to a variety of reasons, have missing samples. These missing samples are in the form of packets consisting of one or multiple sequential samples. The distribution and size of missing packets can significantly vary over time and between utilities. Thus, it is impossible to model a "typical" distribution of missing samples. Instead, we have modeled a realistic distribution by adding missing samples similar to those actually observed in the ISO New England system, in three 30-minute intervals collected within one week for 500+ phasors, as shown in Fig. 4. Packets of missing samples in synthetic PMU measurements were added according to the distribution in Fig. 4 simultaneously for related current and voltage phasors.

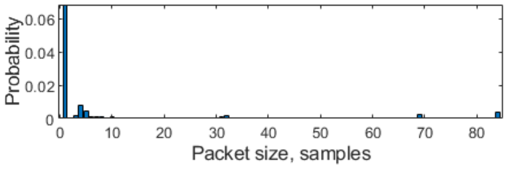

Figure 4. Distribution of missed PMU samples in test cases

IV. TEST CASES

Table III summarizes the main properties of the 13 designed test cases. A few remarks are made below.

- **Resonance.** Resonance exists in almost all 13 cases with either inter-area modes or local modes, causing max oscillation amplitude in MW flow not at the source location, posing a potential challenge for mode shape-based methods.
- **Partial observability**. As stated in Section III-A, only partial observability is provided for each case. Notably, oscillation sources in cases 3, 4, and 5, and one of the two sources in case 10, are not directly measured by PMU. These cases can be challenging for methods requiring direct measurements at the source.
- **Disturbance obfuscating oscillation onset**. In each of cases 2, 3, 4, 7, 8, 10, 11, and 12, a fault is added to mask the onset of FOs. These cases present a challenge for methods relying on the characteristics of FO onset.
- **Case 7**. FO is added to the exciter of a generator, creating a complex interaction [9] between the FO and the generator control, causing potential failures of energy-based methods.
- **Case 10**. Two FOs resonate with two modes at 0.614 Hz and 1.218 Hz, respectively, where the source of 1.218 Hz FO is not directly measured by PMU. This case is challenging because the source of 0.614 Hz FO is directly measured by PMU and can be relatively easily recognized, while the 1.218 Hz FO can be then overlooked, assuming one does not know in advance how many FOs are present.

V. CONCLUSIONS

Detailed design and creation process of 13 oscillatory test cases used for the 2021 IEEE-NASPI co-hosted Oscillation Source Locating (OSL) Contest are presented. The challenges behind these cases are fully explained. Interested readers can not only better understand the challenges behind these 13 cases, but can also design additional interesting cases by using similar thinking, technologies, and provided input data for simulation. For example, (i) TSAT UDM models allow modeling a broad range of FOs by setting a desirable shape of periodic forced signal in one or multiple locations, and (ii) power flow model can be modified to represent a desired topology and dispatch.

Inverter-based resources and HVDC involved high-frequency oscillation events are emerging, which should be considered for evaluating the OSL methods in future.

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TABLE III. 13 DESIGNED TEST CASES AND THEIR MAIN PROPERTIES

#	Oscillation source information	Source monitored by PMU?	Frequency, Hz	Resonance?	Source location, bus/generator	Other key features
1	Generator – Governor	Yes	0.82	No	1431 N	• Easy case of monitored source without resonance
2	Generator – Governor	Yes	1.19	Yes	2634 C	• FO resonates with a local mode at 1.19 Hz • 1.19-Hz natural mode is excited by a fault
3	Generator – Exciter	No	0.379	Yes	1131 G	• The source is in the exciter; FO resonates with the lowest-frequency inter-area mode
4	Generator – Governor	No	0.379	Yes	3831 NN	• The source is in the governor; FO resonates with the lowest-frequency inter-area mode
5	Generator – Governor	No	0.68, 0.76	Almost	4231 C	• Changed the frequency of forced signal from 0.68 Hz before t=58 s to 0.76 Hz after t=61 s without creating resonance. System has modes at: 0.614 Hz, 0.708 Hz, 0.741 Hz and 0.78 Hz
6	Generator – Governor	Yes	1.27	Yes	7031 C	• FO resonates with a local mode in the North area • Line 2604-6404_1 is tripped at t=70 s, slightly changing FO shape
7	Generator – Exciter	Yes	0.379	Yes	2634 C	• FO resonates with the lowest-frequency inter-area mode at 0.379 Hz • Strong FO interaction with controls potentially misleading energy-based methods
8	Generator – Governor	Yes	0.614	Yes	6333 C	• FO resonates with a regional inter-area mode at 0.614 Hz • PMU is available only from the North area, where the source is located
9	Generator – Governor Generator – Exciter	Yes Yes	0.762	Yes Yes	6533 C 4131 H	• FO resonates with a natural mode whose damping is reduced by adjusting PSS gain (KS=–2) in the generator 4131_H, creating negative damping contribution from that generator
10	Generator – Governor Generator – Governor	No Yes	1.218 0.614	Yes Yes	3931 NB 6335 C	• There are two FOs, and each resonates with a natural mode
11	Load	Yes	0.614	Yes	4009	• FO resonates with a regional inter-area mode at 0.614 Hz • The source is the load at Bus 4009. This bus has also connection to HVDC and a generator (neither is a source)
12	Generator – Governor	Yes	0.377, 0.744, 1.11, 1.48	Almost	6335 C	• Rectangular forcing signal (fundamental frequency=0.377 Hz) • The second harmonic resonates with a natural mode
13	HVDC	Yes	0.614	Yes	4010 and 2619	• FO resonates with a regional inter-area mode at 0.614 Hz • Source is in the HVDC controls at California side, while both terminal buses 4010 and 2619 may look like the sources in the AC network

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