IEEE-NASPI Oscillation Source Location Contest – Case Development and Results

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Power System Oscillations

• A marginal state between stable and unstable
• Potential dynamic risks
• Historic events involving oscillations
  ➢ 1996 Blackout
  ➢ 2003 Blackout
  ➢ 2009 TX SSO
• Should be mitigated timely

Source: https://www.youtube.com/watch?v=TLWvSoBAjOc

0.29Hz oscillations involving PV
IRPWG Meeting on Aug. 19, 2021
Source: TVA

SSO: sub-synchronous oscillations

SSO caused by traditional synchronous machines had been taken care of
SSO & other fast dynamic issues are surging caused by increased IBRs

Source: TVA
Oscillation Source Location (OSL) Contest

• Joint effort by IEEE OSL Task Force and NASPI [1-2].
• Objective: evaluating the efficiency of OSL methods and their applicability for practical implementation.
• Contest Highlights:
  ➢ 60 teams from 11 countries signed up
  ➢ 21 submissions
• Special thanks
  ➢ Contest coordinator: Frankie Zhang (ISO New England)
  ➢ Web support: Kai Sun (UTK), Teresa Carlon (PNNL)
  ➢ WECC-240 bus base case: Jin Tan and the rest of the NREL team
  ➢ TSAT simulation technical and license support: Powertech Labs

[1] https://www.naspi.org/node/890
OSL Methods

• Some existing methods (by 2015) for locating the oscillation source [3]

<table>
<thead>
<tr>
<th>Category</th>
<th>Key Idea</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damping torque</td>
<td>The generator with a negative damping torque coefficient is the source</td>
<td>Possible unavailability of rotor angle and speed data, possible failures under forced oscillation cases.</td>
</tr>
<tr>
<td>Mode shape</td>
<td>Largest magnitude, most leading phase of the mode shape or their combinations may indicate the source</td>
<td>Lack of a theoretical foundation, possible failures for cases having weakly damped/undamped oscillation together with forced oscillation.</td>
</tr>
<tr>
<td>Energy</td>
<td>The device producing dissipation energy is the source</td>
<td>Strong assumption in modeling loads and network, lack of theoretical proofs for multi-mode cases.</td>
</tr>
<tr>
<td>Equivalent circuit</td>
<td>The source of the equivalent circuit is the source of the oscillation</td>
<td>Possible failures when the phasor concept cannot be applied, e.g. non-sinusoidal oscillations. Lack of theoretical proofs for multi-mode oscillation cases.</td>
</tr>
<tr>
<td>Hybrid</td>
<td>A larger difference between simulations and measurements indicates the source</td>
<td>Possible unavailability of the accurate model of the entire system.</td>
</tr>
<tr>
<td>Traveling wave</td>
<td>The closer to the source, the earlier the location will exhibit oscillation</td>
<td>Inaccurate and unreliable detection of the oscillation arrival time, Unavailability of the wave speed map in real-time, lack of investigations on multi-mode cases.</td>
</tr>
<tr>
<td>Machine learning</td>
<td>An offline trained decision tree from model-based simulations to locate the source using online measurements</td>
<td>Possible unavailability of the accurate model of the entire system, can only be applied to forced oscillation cases.</td>
</tr>
</tbody>
</table>

• New methods, e.g. effective gen Z [4], UIO [5], RPCA [6], and harmonics [7].

Energy based OSL


- Calculation and physical meaning

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

- How to get DEF tool?
  - OSLp software by ISO-NE, free of charge at [10]

[10] https://www.iso-ne.com/participate/support/request-software
Data Flow Process

- Input data preparation
- Run TSAT
- Convert results into “test cases library” format
- PMU Emulator to mimic P/M PMU class
- Add “missed” samples
- Synthetic PMU data set

Scenario design:
- High-level description
- Technical implementation

Final verification and benchmarking by OSLp

• What are the desired cases, and the implementation challenges?
• How did we conquer them with DSATools?
Philosophy for Creation of Simulated cases for the OSL Contest

• The cases should be representative for real-life situations
  – Realistic combination of local and interarea natural oscillations with realistic modeling of all components
  – Representative Synthetic PMU measurements as a result of time-domain simulation
    ▪ Partial system observability by PMUs
    ▪ Processing measurements to mimic P/M class of PMU
    ▪ Introduce missed/bad PMU samples, colored noises

• Properties of FO:
  – Located at Generator (Governor & Exciter), Load, HVDC
  – Variable magnitude and frequency
  – Not necessary/clear inception and limited duration
  – Multiple sources and resonance with natural modes

• Do not create bias for any known source locating method
Challenge 1: Adding Power System Stabilizers (PSSs)

- Test system: 240-bus reduced WECC system developed by NREL [12].
- High renewable penetration (~20%).
- Power flow and dynamic data in PSS/E format now available at [13].
- Poorly damped local modes [12].

“Local oscillation modes around 1Hz have low damping ratios...because of the lack of stabilizer models.” [12]

Challenge 1: where and how much to add to make a realistic-looking case?

<table>
<thead>
<tr>
<th>No.</th>
<th>Mode Freq (Hz)</th>
<th>Mode Damping Ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.3069</td>
<td>17.61</td>
</tr>
<tr>
<td>2</td>
<td>0.5225</td>
<td>1.98</td>
</tr>
<tr>
<td>3</td>
<td>0.5080</td>
<td>1.06</td>
</tr>
<tr>
<td>4</td>
<td>0.6927</td>
<td>1.25</td>
</tr>
<tr>
<td>5</td>
<td>0.7282</td>
<td>1.13</td>
</tr>
<tr>
<td>6</td>
<td>0.7624</td>
<td>1.5</td>
</tr>
<tr>
<td>7</td>
<td>0.8448</td>
<td>1.26</td>
</tr>
<tr>
<td>8</td>
<td>0.8998</td>
<td>1.73</td>
</tr>
<tr>
<td>9</td>
<td>0.958</td>
<td>1.42</td>
</tr>
<tr>
<td>10</td>
<td>0.9777</td>
<td>1.81</td>
</tr>
<tr>
<td>11</td>
<td>1.0372</td>
<td>3.07</td>
</tr>
<tr>
<td>12</td>
<td>1.1457</td>
<td>5.33</td>
</tr>
<tr>
<td>13</td>
<td>1.1484</td>
<td>3.07</td>
</tr>
</tbody>
</table>

Dynamic Models: GENROU, SEXS, TGOV1, HYGOV, GAST, REGCA, REECB, REPCA.

Challenge 1: Adding PSSs

- **DSATools/SSAT** – Small signal analysis tool.
- **SSAT** is very efficient: 10-sec runtime for this case with >2000 state variables.
- **Where to add**: Identified 10 critical machines for adding PSSs based on eigenvalues and eigenvectors (mode shape, participation factors) from SSAT.
- Added IEEEST PSS model [14] to the above 10 machines.

- **How much to add**: Sensitivity of eigenvalues to the variation of key IEEEST parameters, e.g. $T_1$ and $K_S$, can be calculated by SSAT. Easy to find parameters for reasonable damping ratios (6%-10% or higher).

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Challenge 2: Adding forced oscillations (FOs)

- Previously [15-16], adding an FO involves MANUALLY preparing a user-defined model (UDM) by DSATools/UDM editor.
- Cases design requires testing FOs at different controls (governor or excitation), different generators, with different forcing frequencies, and at load/HVDC.

Block diagram of the external force used for WECC 179-bus based oscillation test cases library [15-16]

Challenge 2: Adding FOs

- DSATools/Template UDM models.
- Developed by Jeff Bloemink (Powertech Labs)
- FOs at TGOV1, SEXS, load have been implemented as a list of template UDM models: FOINJECT, TGOV1FO, SEXSFO.
- Example: FO at load.

```
'STMLT','FOINJECT',BUS,JD,SBASE,FOP,GNIP,FOQ,GNIQ /
'STMLT','FOINJECT',1002,'IM',1,0.614,25,0.614,0/
```

- Testing different FOs can be easily scripted and automated.
Challenge 2: Adding FOs

- With the new Template UDM models, it is easy to
  - scan thru many (1000+) interesting cases
  - find out cases to fail OSL methods based on (1) largest magnitude (mode shape) and (2) DEF.

9 out of 13 final contest cases have the largest oscillation amplitude in MW flow that is not at the actual source(s).


<table>
<thead>
<tr>
<th>Location of FO</th>
<th>Frequency of FO, Hz</th>
<th>Cases of FO with FO</th>
<th>Correct identification cases</th>
<th>Average success rate</th>
<th>Correct identification cases</th>
<th>Average success rate</th>
<th>Correct identification cases</th>
<th>Average success rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Governor</td>
<td>0.379</td>
<td>31</td>
<td>30</td>
<td>96.8%</td>
<td>30</td>
<td>96.8%</td>
<td>31</td>
<td>100.0%</td>
</tr>
<tr>
<td></td>
<td>0.514</td>
<td>31</td>
<td>31</td>
<td>100.0%</td>
<td>31</td>
<td>100.0%</td>
<td>31</td>
<td>100.0%</td>
</tr>
<tr>
<td></td>
<td>1.27</td>
<td>31</td>
<td>31</td>
<td>100.0%</td>
<td>31</td>
<td>100.0%</td>
<td>31</td>
<td>100.0%</td>
</tr>
<tr>
<td>Exciter</td>
<td>0.379</td>
<td>93</td>
<td>12</td>
<td>12.9%</td>
<td>79</td>
<td>84.9%</td>
<td>83</td>
<td>89.2%</td>
</tr>
<tr>
<td></td>
<td>0.514</td>
<td>96</td>
<td>71</td>
<td>74.0%</td>
<td>76</td>
<td>79.2%</td>
<td>91</td>
<td>94.8%</td>
</tr>
<tr>
<td></td>
<td>1.27</td>
<td>91</td>
<td>85</td>
<td>93.4%</td>
<td>88</td>
<td>96.7%</td>
<td>91</td>
<td>100.0%</td>
</tr>
</tbody>
</table>

Comprehensive statistics of DEF’s effectiveness [18]
Challenge 3: Variable FO frequency and magnitude

- DSATools/Template UDM models.
Challenge 4: Adding Colored Noises

- Colored noises: very small load fluctuations added during time domain simulations.
- DSATools/Template UDM models.

![Diagram with labels: iptimeseries.txt, iqtimeseries.txt, Noise Profile, Simulated voltage magnitude]
Features of Resulting 13 Contest Cases [19]

- It becomes possible or easier with DSATools to achieve these features.

<table>
<thead>
<tr>
<th>Case</th>
<th>Key Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Easy case to “warm up”</td>
</tr>
<tr>
<td>2</td>
<td>Observable source; resonance with local mode</td>
</tr>
<tr>
<td>3</td>
<td>Non-observable source in the exciter resonance with system-wide inter-area mode</td>
</tr>
<tr>
<td>4</td>
<td>Non-observable source in the governor resonance with system-wide inter-area mode</td>
</tr>
<tr>
<td>5</td>
<td>Variable frequency of FO</td>
</tr>
<tr>
<td>6</td>
<td>Non-observable source; resonance with local mode</td>
</tr>
<tr>
<td>7</td>
<td>Source in the exciter; strong interaction with controls</td>
</tr>
<tr>
<td>8</td>
<td>Observable source; resonance with regional inter-area mode</td>
</tr>
<tr>
<td>9</td>
<td>2 sources: (1) FO source in the governor (2) wrong tuning of PSS in another generator</td>
</tr>
<tr>
<td>10</td>
<td>2 sources of FO; resonating with local and inter-area modes</td>
</tr>
<tr>
<td>11</td>
<td>Source of FO in Load</td>
</tr>
<tr>
<td>12</td>
<td>Rectangular shape of forced signal creating wide spectra of oscillations</td>
</tr>
<tr>
<td>13</td>
<td>Source of FO in HVDC</td>
</tr>
</tbody>
</table>

[19] [http://web.eecs.utk.edu/~kaisun/Oscillation/contestcases.html](http://web.eecs.utk.edu/~kaisun/Oscillation/contestcases.html)
## Summary of OSL Contest Results

### Methods
1. Energy-based
2. Oscillation shape and magnitude
3. Machine Learning and Model-based analytic
4. Cross Power Spectra Density

### Energy-based methods are most efficient

| Team | 1/2 | 1/2 | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 |
|------|-----|-----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| Score| 110 | 110 | 99 | 82 | 77 | 76 | 71 | 68 | 62 | 57 | 55 | 44 | 47 | 46 | 45 | 42 | 38 | 37 | 25 | 18 | 17 |

### Details of implementation could be critical

### ML and Model-based method are less efficient
Summary

• DSATools makes the case design process much easier:
  – SSAT efficiently calculates and visualizes eigenvalues/eigenvectors
  – SSAT provides sensitivity analysis
  – Template UDM models for adding a variety of FOs, and colored noises
  – DSAOA built-in Prony analysis, curve statistics table, and DEF analysis