NREL
Transforming ENERGY

Demystifying Power System Oscillations – Recent and Ongoing Efforts

Bin Wang

Grid Planning and Analysis Center

National Renewable Energy Laboratory (NREL)

2021 Joint Synchronized Information Subcommittee (JSIS) Meeting

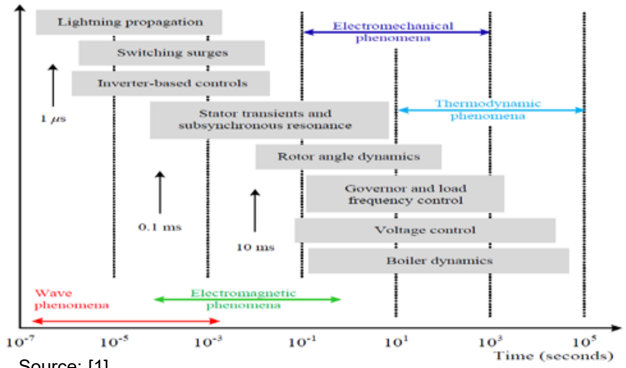
May 13, 2021

Disclaimer

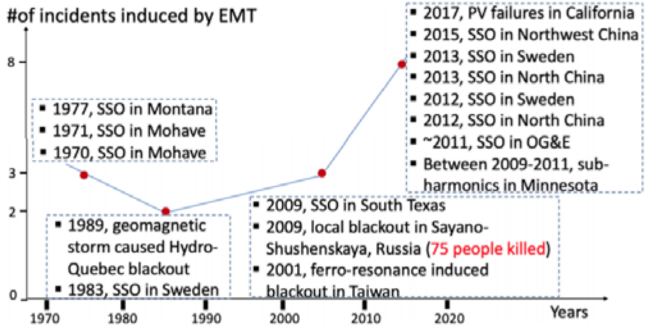
The views expressed in the presentation do not necessarily represent the views of the DOE, the U.S. Government or NREL.

Power System Oscillations

- Power system oscillations
  - ➢ is a phenomenon of periodic energy exchange
  - ➢ represent dynamic risks
- PMU/FDR and AMI provide better observability
- Some historic events involving oscillations
  - ➢ 1996 Blackouts
  - ➢ 2003 Blackout
  - ➢ 2009 TX sub-synchronous oscillation (SSO)
- This talk only covers electromechanical, and up to electromagnetic oscillations
- Most relevant research aim to (i) **better understand** mechanisms and (ii) **mitigate properly**



Source: [1]



Source: [2]

[1] L. Xiong, X. Liu, Y. Liu and F. Zhuo, "Modeling and stability issues of voltage-source converter dominated power systems: A review," in CSEE Journal of Power and Energy Systems, 2020

[2] L. Zhang, **B. Wang**, X. Zheng, W. Shi, P. R. Kumar and L. Xie, "A Hierarchical Low-Rank Approximation Based Network Solver for EMT Simulation," in IEEE Transactions on Power Delivery, vol. 36, no. 1, pp. 280-288, Feb. 2021

Causes of Power System Oscillations

- Poorly-damped natural mode oscillation: bad control parameter, high loading

$$\dot{x} = f(x) \approx Ax \xrightarrow{x = Py} \dot{y} = \begin{bmatrix} \lambda_1 & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & \lambda_n \end{bmatrix} y$$

$if\ \exists i \in \{1,2,\dots,n\}, s.t. Re\{\lambda_i\} \approx 0$

$Then, \omega_i = Im\{\lambda_i\}/2\pi$ *is a poorly damped mode*

- Forced oscillation: external periodic input, e.g. cyclic load

$$\dot{x} = f(x) + Bu(t) \approx Ax + Bu(t)$$
$$u(t) = Acos(\omega t + \theta)$$
$$\Rightarrow x(t) = Bcos(\omega t + \emptyset)$$

- **New:** Modulated oscillation – “nonlinear forced oscillation”

$$\dot{x} = f(x) + Bu(t)$$
$$u(t) = Acos(\omega t + \theta)$$
$$\Rightarrow x(t) = Bcos(\omega t + \emptyset) + Ccos(\omega' t + \varphi)$$

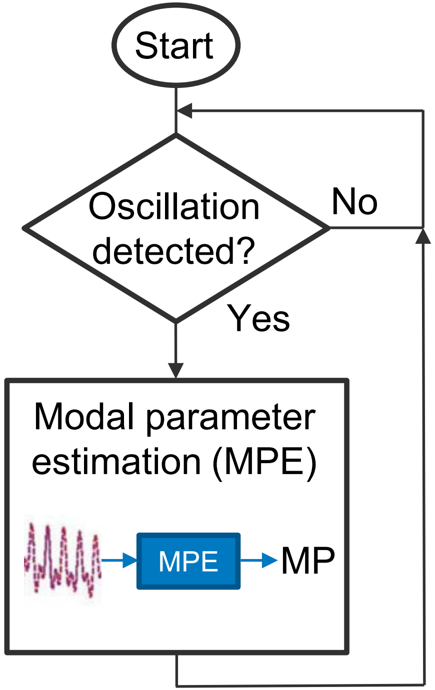
Traditional Oscillation Analysis

- Traditional oscillation analysis aim at the detection, modal parameter estimation, and classification of oscillations.
  - ➢ Oscillation frequency, damping and mode shape

$$\hat{y}(t) = \sum_{i=1}^{n} A_i e^{\sigma_i t} \cos(\omega_i t + \theta_i)$$

- Model-based approach – small-signal analysis
  - ➢ Linearization → Eigen-analysis → modal parameters
- Measurement-based approaches [3]
  - ➢ Linear ring-down analysis: Prony, Matrix Pencil, ERA
  - ➢ Mode-meter analysis: R3LS, N4SID
  - ➢ Nonlinear methods: HHT, Energy tracker
- In current practice, oscillation analysis results are mostly used for monitoring purpose, while not much actionable info.

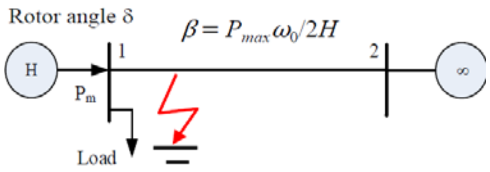
A typical oscillation monitoring application



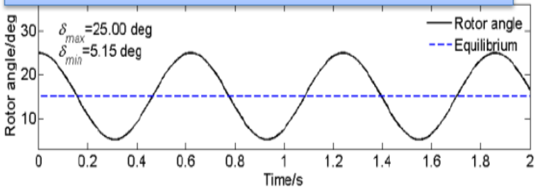
[3] IEEE Task Force on Identification of Electromechanical Modes, Identification of Electromechanical Modes in Power Systems, PES-TR15 (formerly TP462), 2012

Recent Efforts on Nonlinear Oscillations

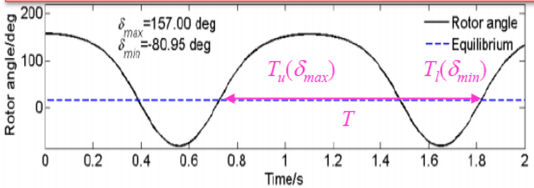
- Frequency-amplitude (F-A) curve [4-5]



Small amplitude (very stable)



Large amplitude (marginally stable)



Formulation of F-A curve

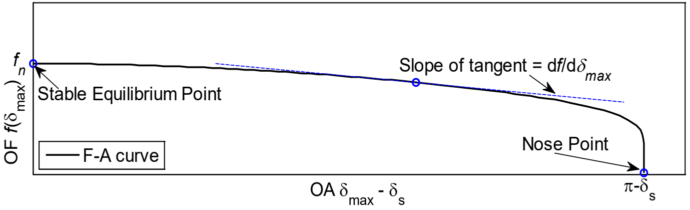
Needs to solve 2 elliptic integrals of the first kind

$$OF = \frac{1}{2(t_{\max} - t_{\min})} = \sqrt{\frac{\beta}{2}} \Big/ \left[\int_0^{\delta_{max}} \frac{d\delta}{\sqrt{\cos(\delta_s+\delta) - \cos(\delta_s+\delta_{max}) + (\delta-\delta_{max})\sin\delta_s}} + \int_{\delta_{min}}^{0} \frac{d\delta}{\sqrt{\cos(\delta_s+\delta) - \cos(\delta_s+\delta_{min}) + (\delta-\delta_{min})\sin\delta_s}} \right]$$

$$\approx \frac{\sqrt{\beta}}{\sqrt{2}\pi} \left(\frac{\sin(\delta_{max}/2)}{m(\delta_{max})} + \frac{\sin(-\delta_{min}/2)}{m(\delta_{min})} \right)^{-1}$$

where $m(x) = \sqrt{\cos\delta_s - \cos(\delta_s + x) - x\sin\delta_s}$

Properties of F-A curve

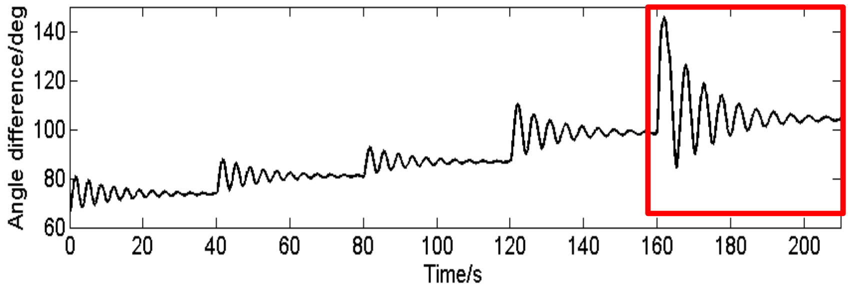


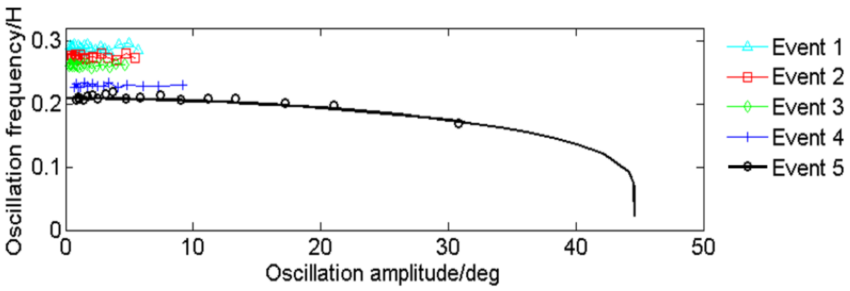
Quantification of the F-A characteristic indicates the margin to instability

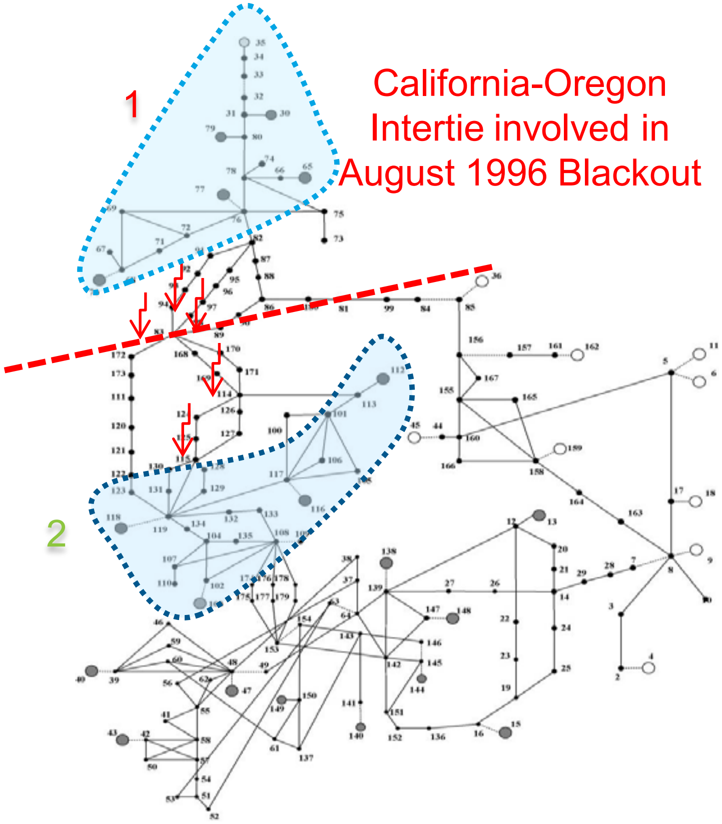
[4] **B. Wang**, K Sun, "Formulation and characterization of power system electromechanical oscillations," IEEE Trans. on Power Systems, vol.31, no.6, pp.5082-5093, Nov. 2016
[5] **B. Wang**, X Su, K Sun, "Properties of the frequency-amplitude curve," IEEE Trans. on Power Systems, vol.32, no.1, pp.826-827, Jan. 2017

Recent Efforts on Nonlinear Oscillations

- Test of F-A curve on the WECC 179-bus system





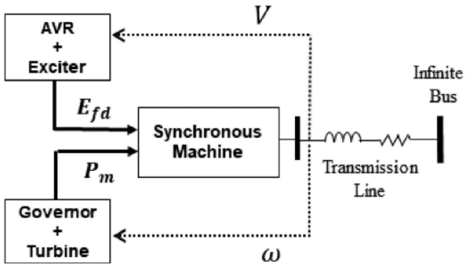


Recent Efforts on Nonlinear Oscillations

- Modulated oscillation [6]

Forced oscillation with a frequency ω_{so} added to the magnitude of infinite bus

$$V_m = V_0 + \eta_{so} \sin(\omega_{so} t)$$



Synchronous-Machine-Infinite-Bus System.

~0.03Hz oscillations occurs in addition to the forcing frequency at ~2Hz.

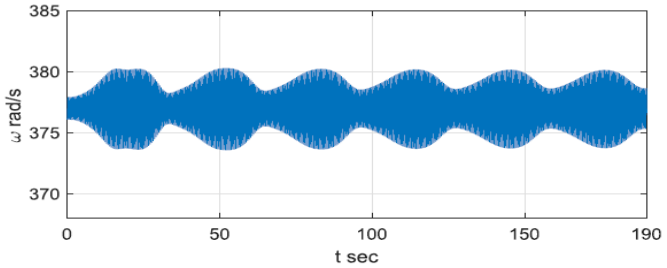


Fig. 4. Modulated Oscillation under Forced Oscillation at $\omega_{so} = 12.76$ rad/s and $\eta_{so} = 0.03$ p.u.

A closer look using bifurcation analysis

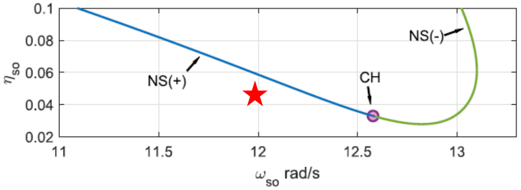


Fig. 6. Full Model Neimark-Sacker Bifurcation Diagram.

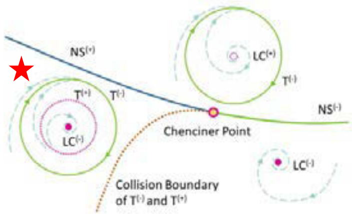
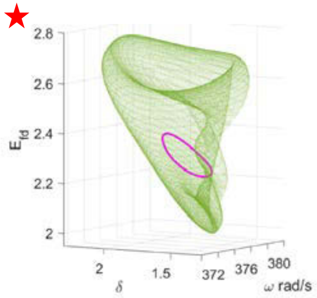
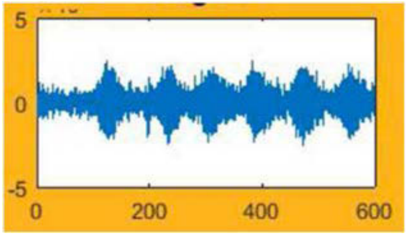


Fig. 7. Chenciner Bifurcation Local Structure.



(a) Attractors at $\omega_{so} = 12$ rad/s and $\eta_{so} = 0.045$ p.u.

Modulated oscillations from PMU measurements in Apr. 2017.



[6] D. Wu, P. Vorobev, S. C. Chevalier and K. Turitsyn, "Modulated Oscillations of Synchronous Machine Nonlinear Dynamics With Saturation," in IEEE Transactions on Power Systems, vol. 35, no. 4, pp. 2915-2925, July 2020.

Recent Efforts on Oscillation Source Location (OSL)

- Some existing methods (by 2015) for locating the oscillation source [7]

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

- New methods, e.g. effective gen Z [8], UIO [9], RPCA [10], and harmonics [11].

[7] **Bin Wang**, Kai Sun, "Location Methods of Oscillation Sources in Power Systems: A Survey," Journal of Modern Power Systems and Clean Energy, 2017
[8] S. C. Chevalier, P. Vorobev and K. Turitsyn, "Using Effective Generator Impedance for Forced Oscillation Source Location," in IEEE Transactions on Power Systems, vol. 33, no. 6, pp. 6264-6277, Nov. 2018
[9] M Luan, D Gan, Z Wang, H Xin, "Application of unknown input observers to locate forced oscillation source," Int Trans Electr Energ Syst., 2019
[10] T. Huang, N. M. Freris, P. R. Kumar and L. Xie, "A Synchrophasor Data-Driven Method for Forced Oscillation Localization Under Resonance Conditions," in IEEE Transactions on Power Systems, vol. 35, no. 5, pp. 3927-3939, Sept. 2020
[11] S. Roy, W. Ju, N. Nayak and B. Lesieutre, "Localizing Power-Grid Forced Oscillations Based on Harmonic Analysis of Synchrophasor Data," 2021 55th Annual Conference on Information Sciences and Systems (CISS), 2021

Recent Efforts on OSL

- Energy method [12] → Dissipating energy flow (DEF) [13] for locating the source

- How DEF works?
  - Given measured U, θ (or freq), P and Q at one end of the line
  - Calculate DEFij by

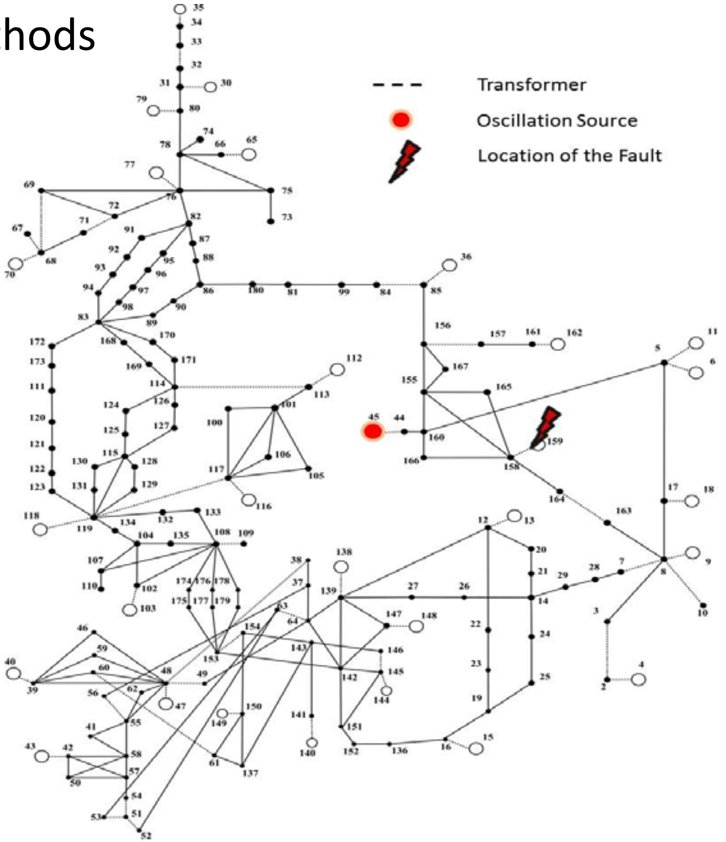
$$\mathrm{DEF}_{ij}(t) = \int \left(\Delta P_{ij}\mathrm{d}\theta_i + \frac{\Delta Q_{ij}}{V_i}\mathrm{d}V_i\right) = \int \left(2\pi\Delta P_{ij}\Delta f_i\mathrm{d}t + \frac{\Delta Q_{ij}}{V_i}\mathrm{d}V_i\right)$$

  - If DE is increasing, then oscillation source is behind Bus i; otherwise, oscillation source is behind Bus j.
- How to get DEF tool?
  - OSLp software by ISO-NE can be requested free of charge at [14]

[12] L Chen, Y Min, W Hu, "An energy-based method for location of power system oscillation source," IEEE Transaction on Power Systems, 28(2):828-836, 2013
[13] S Maslennikov, **B Wang**, E Litvinov, "Dissipating energy flow method for locating the source of sustained oscillations," International Journal of Electrical Power and Energy Systems, 2017
[14] https://www.iso-ne.com/participate/support/request-software

Recent Efforts on OSL

- Test Cases Library [15-16] for evaluating OSL methods
- WECC 179-bus system
  - ➢ 179 buses, 29 machines (**classical model**)
  - ➢ Electromechanical modes: 0.26-1.88Hz
- 27 simulated cases
  - ➢ 9 poorly-damped natural oscillation cases
  - ➢ 18 forced oscillation cases
- Coverage
  - ➢ Linear/non-linear
  - ➢ Resonance/non-resonance
  - ➢ Sinusoidal/non-sinusoidal force
  - ➢ Force at excitation/governor
- 6 actual cases from ISO New England



[15] http://curent.utk.edu/research/test-cases/
[16] S Maslennikov, **B Wang**, Q Zhang, F Ma, X Luo, **K Sun**, E Litvinov, "A test cases library for methods locating the sources of sustained oscillations" accepted by IEEE PES General Meeting, 2016

Recent Efforts on OSL

- DEF's effectiveness
  - ➢ Testing results on Test Cases Library [17] (right tables)
  - ➢ Performance at ISO-NE [18] (below)
    - Since 2017, online OSL has automatically processed 1200+ oscillatory. Alerts and Alarms generated by the PhasorPoint application
    - Correctly identified the source (generator and area) for all instances of oscillations with known sources **inside** and **outside** of ISO-NE

Results for simulated forced oscillations.

Case	Injected signal			DE results	
	Type	Frequency (Hz)	Actual source	Detected source	DE
F1	sin	0.86	4	4	1.0
F2	sin	0.86	79	79	1.0
F3	sin	0.37	77	77	1.0
F4-2	sin	0.85	79	79	1.0
F5-2	sin	0.46	79	79	1.0
F6-2	Periodic rectangular creating odd harmonics	0.2	79	79	1.0
			-	77	0.02
		0.6	79	79	1.0
		1.0	79	79	1.0
		1.4	79	79	1.0
F7-1	sin	0.65	79	79	1.0
		0.43	118	118	1.0
F7-2	sin	0.43	70	70	0.14
		0.43	118	118	1.0

Results for simulated natural oscillations.

Case	Natural modes		Actual source		DE results	
	Frequency (Hz)	Damping (%)	Gen	$\Delta\alpha$ (p.u.)	Detected source	DE
ND1	1.41	0.01	45	1.0	45	1.0
ND2	0.37	0.02	65	1.0	65	1.0
ND3	0.46	2.22	11	1.0	11	1.0
			–	–	6	0.05
			–	–	30	0.03
	0.70	1.15	11	1.0	11	1.0
ND4	0.46	0.68	11	1.0	11	1.0
	0.70	−0.58	11	1.0	11	1.0
	1.63	0.54	11	1.0	11	1.0
ND5	0.46	0.69	11	1.0	11	1.0
			–	–	112	0.02
	0.70	−0.19	11	1.0	11	1.0
ND6	1.41	−0.93	45	1.0	45	1.0
			159	0.45	159	0.38[a]
ND7	1.41	−0.4	45	0.55	45	0.55
			159	1.0	159	1.0
ND8	1.27	−1.06	36	1.0	36	1.0
	1.41	−0.22	45	0.10	45	0.27
			36	0.01	36	0.02
			45	1.0	45	1.0
ND9	0.46	−0.86	11	1.0	11	1.0
	0.69	−1.81	11	1.0	11	1.0

[a] Time interval of transient from 34 to 40 s was used. For the time interval from 5 to 40 s, generator 159 is not detected as the source.

- ➢ Testing results on recent simulated cases on a 240-bus WECC system [18]

[17] S. Maslennikov and E. Litvinov, "ISO New England Experience in Locating the Source of Oscillations Online," in IEEE Transactions on Power Systems, Vol.36,NO.1, January 2021,
[18] S. Maslennikov, "Efficiency of the DEF method for locating the source of oscillation," OAWG, March 18, 2021

Recent Efforts on OSL

- Cases leading to DEF's failure [19]
- Incremental Energy in One Period (IEOP): net energy (negative when dissipated) in one period of the forced oscillation, calculated as follows.

$$E_{Gi}^{D} = E_{E_{fd}\ i}^{D} + E_{P_m\ i}^{D} + E_{E'_{qi}} + E_{E'_{di}}$$

$$E_{E_{fd}\ i}^{D} = \frac{\omega_F \left|\Delta E_{fdi}(\omega_F)\right| \left|\Delta E'_{qi}(\omega_F)\right|}{2\left(X_{di} - X'_{di}\right)} \times \underline{\sin\left[\angle\Delta E_{fdi}(\omega_F) - \angle\Delta E'_{qi}(\omega_F)\right]}$$

$$E_{P_m\ i}^{D} = \frac{\omega_F \left|\Delta P_{mi}(\omega_F)\right| \left|\Delta\delta_i(\omega_F)\right|}{2} \times \underline{\sin\left[\angle\Delta P_{mi}(\omega_F) - \angle\Delta\delta_i(\omega_F)\right]}$$

$$E_{E'_{qi}} = -\frac{T'_{di}\omega_F^2 \left|\Delta E'_{qi}(\omega_F)\right|^2}{2\left(X_{di} - X'_{di}\right)} \qquad E_{E'_{di}} = -\frac{T'_{qi}\omega_F^2 \left|\Delta E'_{di}(\omega_F)\right|^2}{2\left(X_{qi} - X'_{qi}\right)}$$

These control-related terms may change the sign of E_{Gi}^{D}, leading to the DEF's failure.

[19] Y. Zhi and V. Venkatasubramanian , "Analysis of Energy Flow Method for Oscillation Source Location," in IEEE Transactions on Power Systems, vol. 36, no. 2, pp. 1338 1349, March 2021

Ongoing Efforts on OSL

- The first OSL Contest co-hosted by NASPI and IEEE OSL Task Force [20].
  - ➢ Goal: help develop & improve OSL tools, and help utilities identify & evaluate OSL tools for real-time use.
  - ➢ Important dates:
    - Apr. 19, 2021: Test cases released [21], contest begins
    - May 28, 2021: Registration deadline
    - Jun. 11, 2021: Result submission deadline
    - Jul. 28, 2021: Awards announced

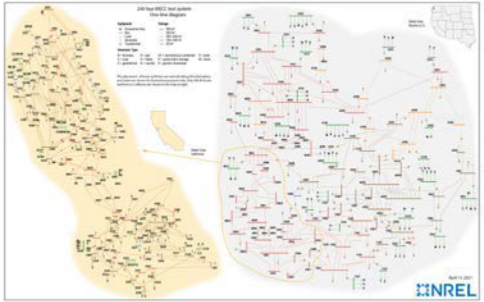
2021 IEEE-NASPI Oscillation Source Location Contest

[20] https://www.naspi.org/node/890
[21] http://web.eecs.utk.edu/~kaisun/Oscillation/2021Contest/

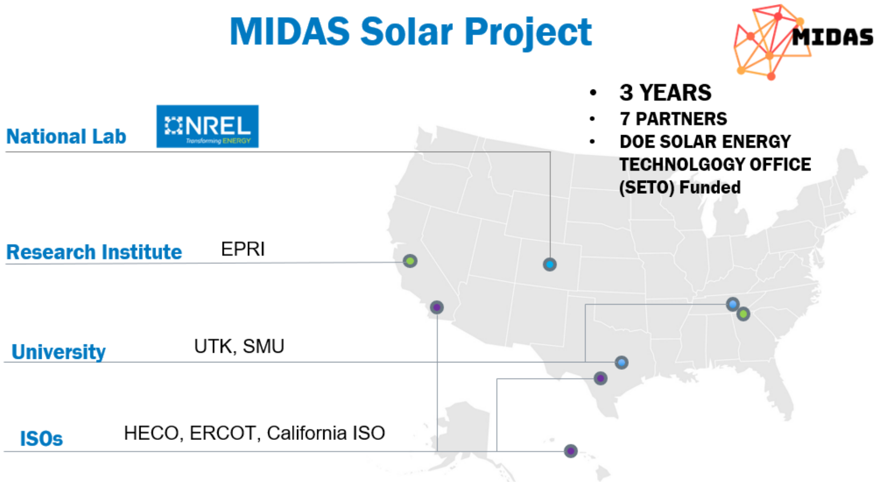
Ongoing Efforts on OSL

- Test system used for OSL Contest
  - ➢ 240-bus reduced WECC system (**109 machines with detail model + exc + gov**)
  - ➢ High renewable penetration (~20%)
  - ➢ Power flow and dynamic data in PSS/E format now available (free of charge) at [22]
  - ➢ Developed by NREL [23] under **MIDAS-Solar project**.

240-bus WECC test system



MIDAS-Solar: help operators understand the interaction of system scheduling and dynamics.



[22] https://www.nrel.gov/grid/test-case-repository.html
[23] H. Yuan, R. Sen biswas, J. Tan, Y. Zhang, "Developing a Reduced 240-Bus WECC Dynamic Model for Frequency Response Study of High Renewable Integration," 2020 T&D

Ongoing Efforts on OSL

- Testing DEF by cases simulated on 240-bus WECC system [18]
  - ➢ Resonance condition, interacting with local or inter-area modes
  - ➢ Forced signal added to generator controls (one per each case), either at exciter or governor

			Identification of Source Generator			Identification of Source Power Plant			Identification of Source Area		
Location of FO	Frequency of FO, Hz	Cases of generators with FO	Correct identifi-cation cases	Success rate	Average success rate	Correct identifi-cation cases	Success rate	Average success rate	Correct identifi-cation cases	Success rate	Average success rate
Governor	0.379	31	30	96.8%	98.9%	30	96.8%	98.9%	31	100.0%	100.0%
	0.614	31	31	100.0%		31	100.0%		31	100.0%	
	1.27	31	31	100.0%		31	100.0%		31	100.0%	
Exciter	0.379	93	12	12.9%	60.1%	79	84.9%	86.9%	83	89.2%	94.7%
	0.614	96	71	74.0%		76	79.2%		91	94.8%	
	1.27	91	85	93.4%		88	96.7%		91	100.0%	

Industry experience:

- "The vast majority of practically observed FO have the source in the governor of traditional generators
- The DEF method is the only method practically used today for online locating the source of oscillation in actual power system" [18]

- ➢ DEF identifies correct oscillation source(s) in governor for almost all cases
- ➢ DEF may potentially fail if the forced signal is in exciter

[18] S. Maslennikov, "Efficiency of the DEF method for locating the source of oscillation," OAWG, March 18, 2021

Potential Research on Power System Oscillations

- Additional efforts are still needed to explore other potential cause(s) of oscillations, including the nonlinearity-induced ones.
- A proper definition of oscillation source for poorly-damped natural oscillations is needed, or at least thoroughly discussed, if not exists.
- Investigation oscillations exist in a system with renewables, HVDC and other power electronics interfaced equipment.
- Oscillation management in distribution systems.
- More capable OSL methods with **desired properties** [7].

1. A **rigorous theoretical foundation**
2. The **adaptability** to different network topologies, different causes of oscillations and different models of dynamic elements that exist in reality
3. **Reliability** of locating the source of oscillation without any false alarm
4. Fully **measurement-based**, i.e. free of the system model
5. Free of additional equipment or only **requiring the minimum equipment** to be installed that are inevitably necessary
6. **Useful even with partial observability**, i.e. when only partial system states are monitored
7. **Robustness** against measurement noises and even missing data
8. **Computationally efficient**
9. Capable of **working continuously in real time**

[7] **Bin Wang**, Kai Sun, "Location Methods of Oscillation Sources in Power Systems: A Survey," Journal of Modern Power Systems and Clean Energy, 2017

Thank you!

www.nrel.gov

NREL/PR-5C00-79994

NREL Contact
Bin Wang
Postdoctoral Researcher
Grid Planning and Analysis Center
National Renewable Energy Laboratory
bin.wang@nrel.gov

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office #34224. The views expressed in the presentation do not necessarily represent the views of the DOE or the U.S. Government.

NREL Transforming ENERGY