

Emerging Challenges from Data Centers in Dominion Energy

Large Electronic Loads Panel

NASPI Hybrid Work Group Meeting and Vendor Show

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Framing the Data Center Dynamics Challenge

In 2018

- 190 data centers connected
- A peak data center load of less than 1GW
- Representing ~ 5% of peak load

Today

- 450 data centers connected
- Peaking a 3.5 GW
- Representing ~ 15% of peak load

Increasing Number of Local Oscillations

- Our system is having to grow quickly to meet demand
- While generation becomes increasingly less synchronous
- And data centers reach for the more rural parts of our system
- No models to anticipate issues

Deteriorating
Grid Stability

Greater need for
upgrades and
taking outages

More loads
behind power
electronic
interfaces

Less
synchronous
generation and
more IBRs

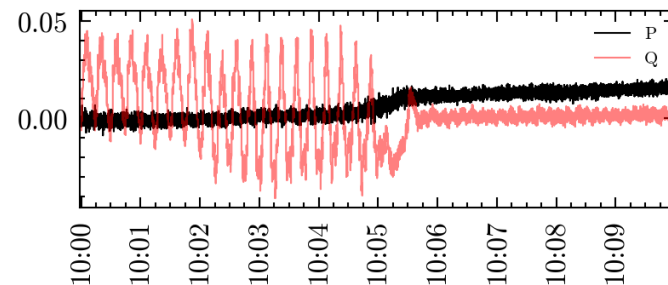
Representing a
larger
percentages of
the system

Greater
propensity for
unwanted
dynamic
responses

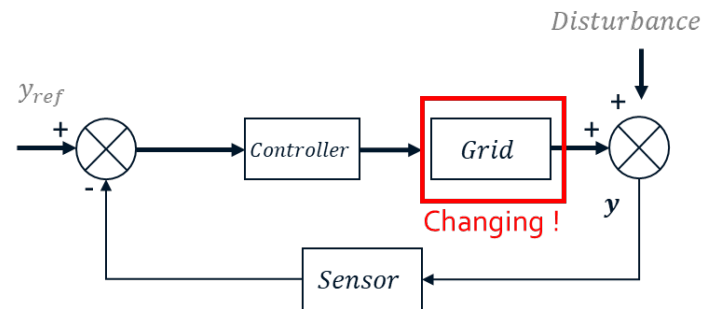
Classifying Local Oscillations

From Data Driven Diagnosis Point of View

- **Type 1: Stemming from Internal Device Dynamics**
 - Often unobservable and unmodeled phenomena
 - Nothing to track/anticipate, the best we can do is detect
- **Type 2: Local “Plant” + Grid Interactions**
 - Controller design does not adapt to changing grid
 - Local control mode often observable
 - Explainable - may be preventable
- **Type 3: Controlled Periodic Inputs**
 - Load cycling of large loads were rare in the past
 - Does not trigger an “oscillation” but drives the system’s response
 - Measured response can be “perceived” as an oscillation, **but it is not!**
- **From understanding to prevention**
 - Requires identifying characteristics beyond frequency and source
 - Requires going beyond “toolbox” mentality - need to custom tools to help derive insights from measurements



Type 1: Unstable Response from PV Plant in Low MW Periods



Type 2: Feedback Control Not Adapting to Grid Conditions

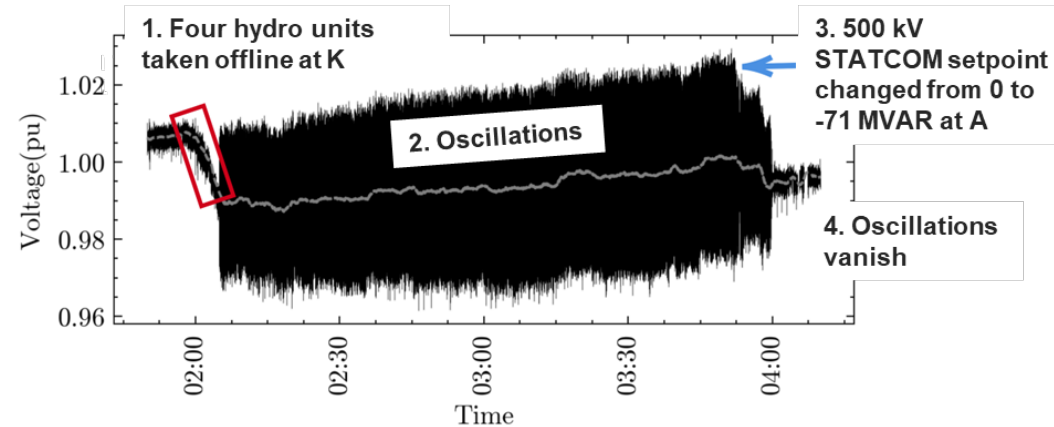
Inception of 14.7 Hz Oscillation at a Data Center

From the paper:

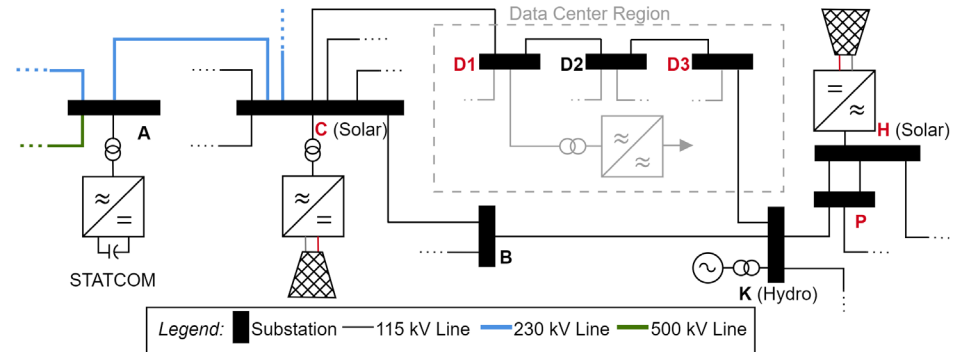
- C. Mishra, L. Vanfretti*, J. de la Ree Jr., T.J. Purcell, K.D. Jones, “Understanding the Inception of 14.7 Hz Oscillations Emerging from a Data Center,” Sustainable Energy, Grids and Networks, Volume 43, 2025, 101735, ISSN 2352-4677, <https://doi.org/10.1016/j.segan.2025.101735>

How We Noticed?

- In June 2022, personnel noticed lights flickering in multiple substations in a data center rich region (115 kV) and reported it to operations.
 - This was the “Event” that brought attention to this issue.
 - However, the mechanism that led to this oscillation (and other instances of this oscillation) was found in our historical data for multiple months.
- Where did it originate from ?
 - Was it the utility or the customer ?
- Oscillation mechanism – forced oscillation ?

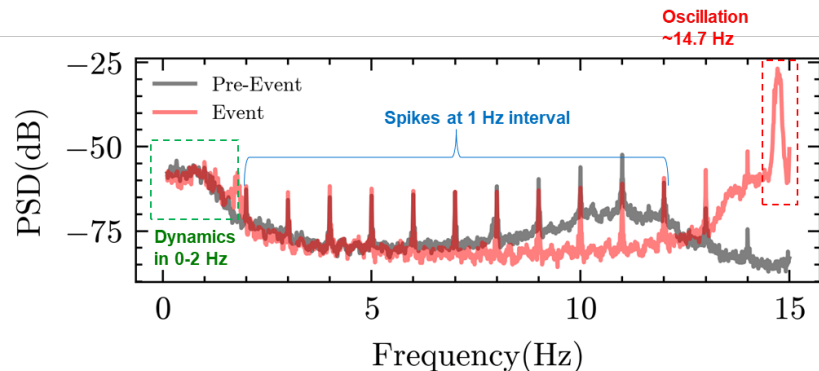


Fast Oscillation Lasting 2 Hrs in Data Center Region



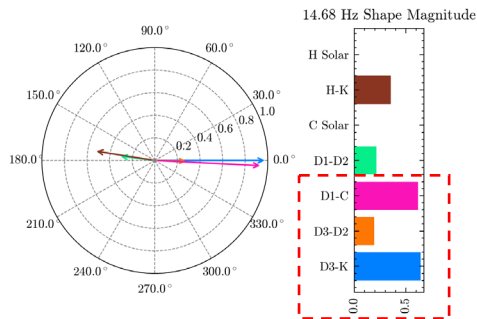
Spectral Characterization, Nature and Localization

(Identifying Relevant Dynamics)

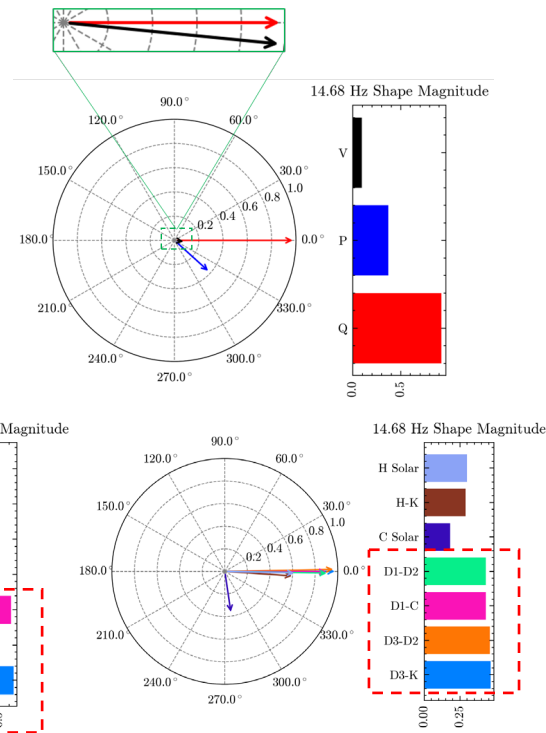


Voltage Magnitude Spectra Pre-Event vs During Event
 14.7 Hz oscillation along with a pulse train (1 Hz fundamental) and some changes in 10-12 Hz range

Volt-VAR Type
 Oscillations localized to Data Center region using Q and V

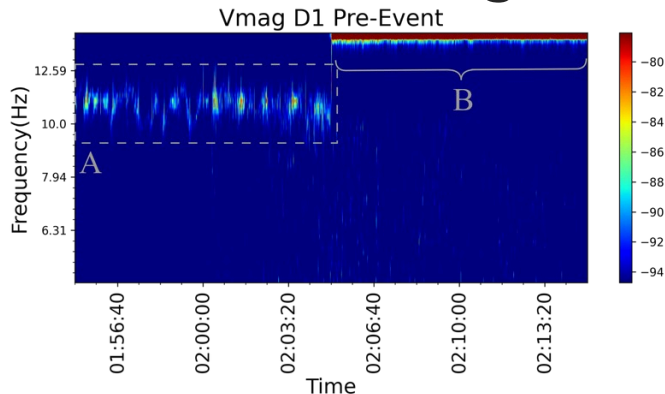


Relative Q Participation

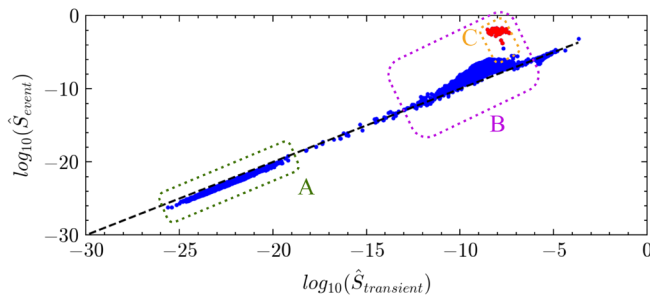


Relative V Participation

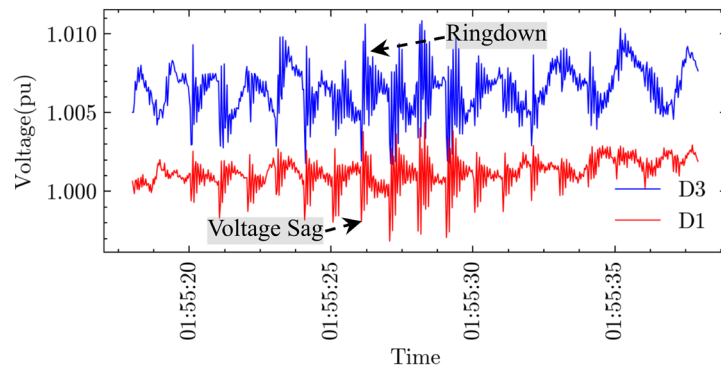
Understanding the Mechanism



Blips (A) Vanish During Oscillation (B)

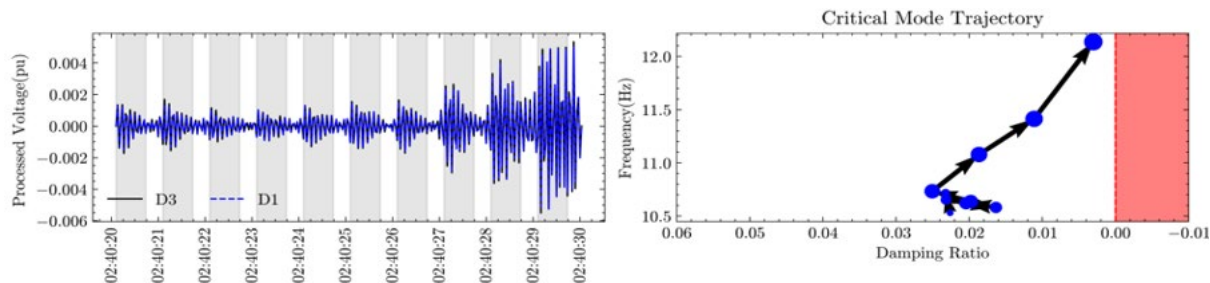


Collecting Similar Events



Blips Due To Periodic Excitation

Exogenous input exciting and enabling to analyze an otherwise very stable mode in 10-11 Hz



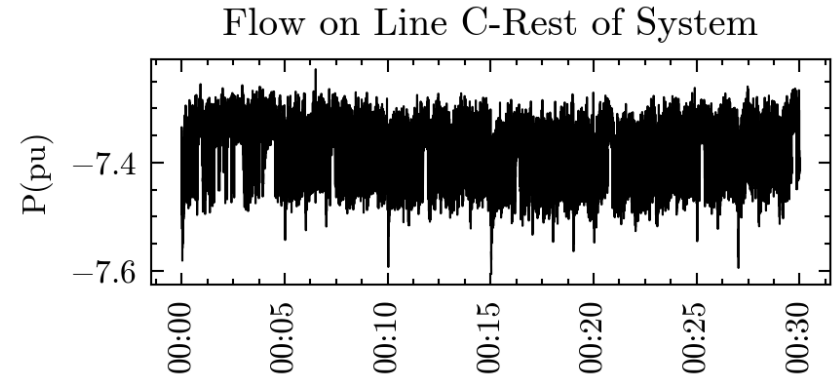
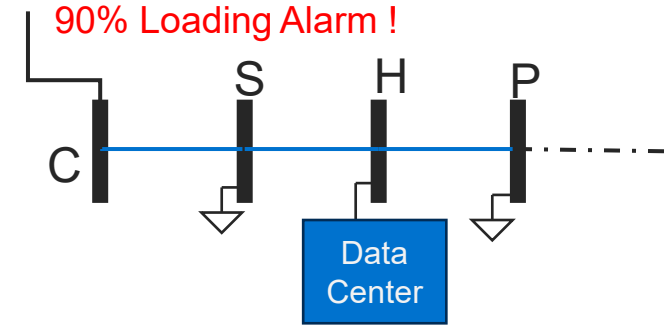
Tracking Damping of 10-11 Hz Mode Leading Up to Oscillation

Oscillation Created from Gradually Destabilizing 10-11 Hz Local Control Mode.
Site Owner confirmed it to be UPS being unstable, no further cooperation.

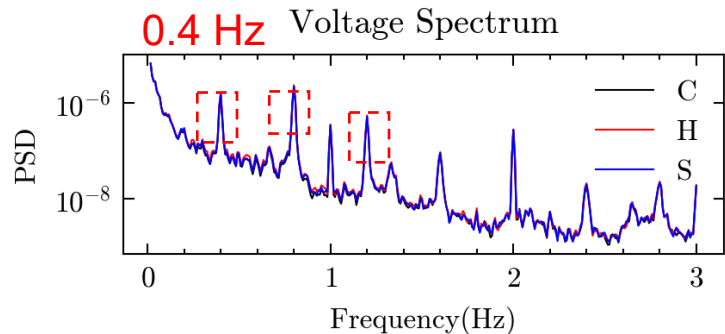
0.4 Hz Data Center Oscillation Triggered By Outage

How We Noticed?

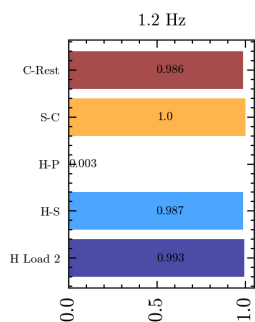
- Observation:
 - In July 2025, outage of line from P to rest of the system triggered 10-15 MW power swings in a data center region
 - Puts data center into a radial configuration
 - 230 kV subsystem
- Discovered because line C-rest of the system hit 90% loading
- Where did it originate from ?
 - Was it the utility or the customer ?
- Oscillation mechanism ?



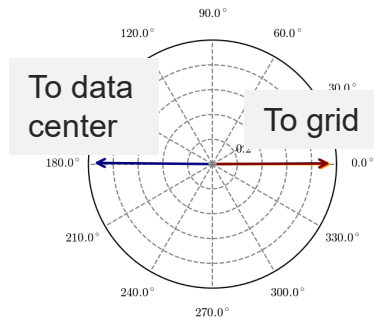
Spectral Characterization, Nature and Localization



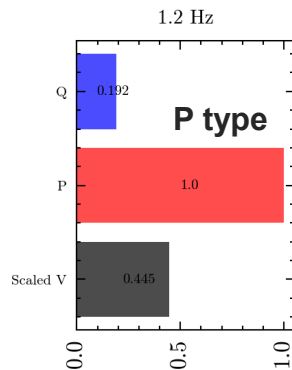
Voltage Magnitude Spectrum



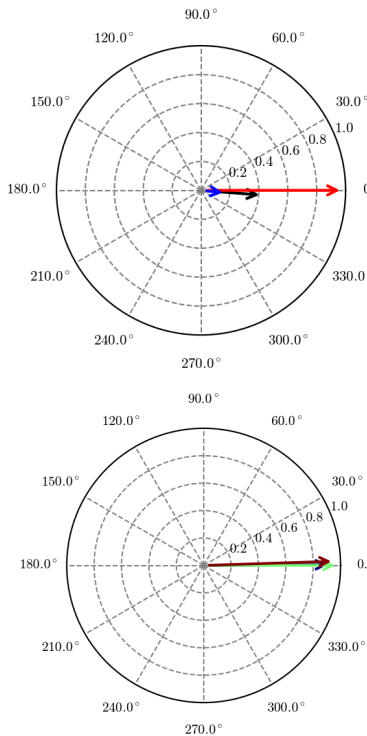
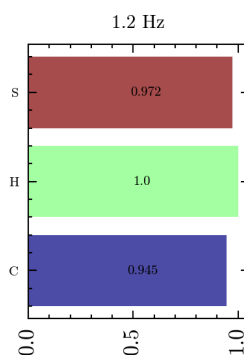
Relative P Participation



P-V Phase Information
Data center injection (P)
oscillating nearly in phase
with response (V,f)

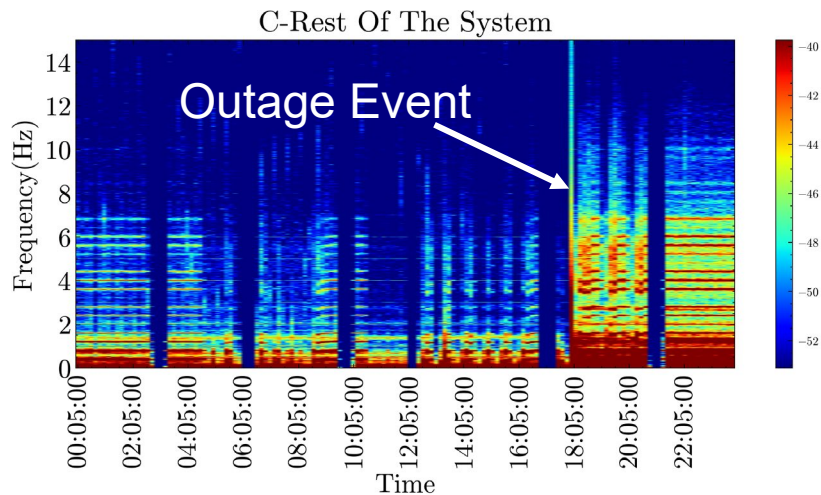


Relative V Participation



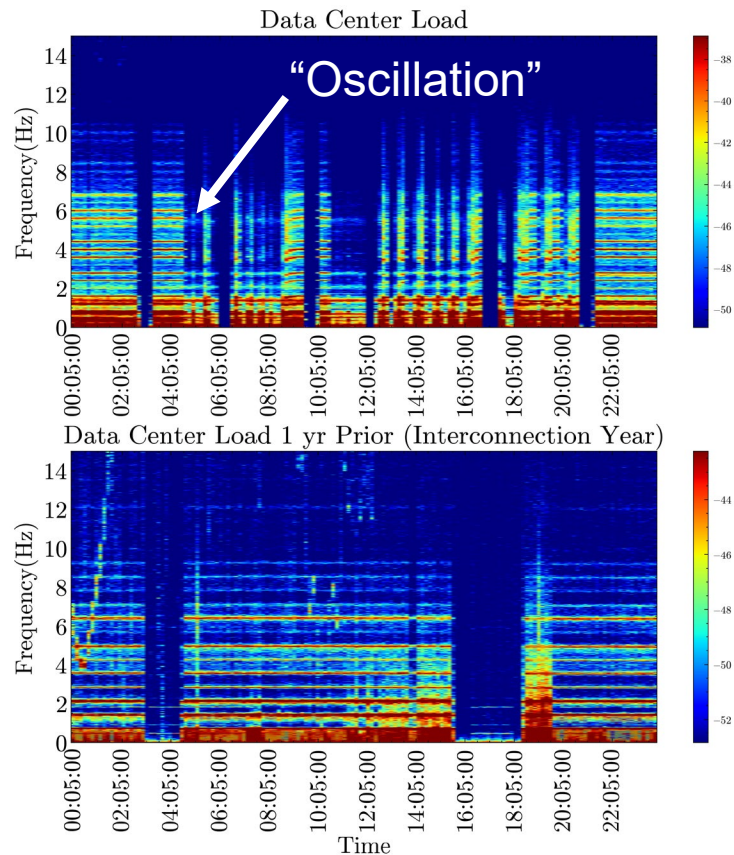
Magnitude Information Inconclusive
Small, radial subsystem

Understanding the Mechanism (Clues in Historical Data)



P Spectrogram of Overloaded Line On the Day Of Outage

Removal of line did not “trigger instability” but merely redirected power (and corresponding oscillation) making it appear “worse”



Periodic Component in Load Always Present
Consistent size. load duty cycle

Key Takeaways

- Investigation of two types of responses from data centers reveal new challenges
 - Different frequencies at 14.7 Hz and 0.4 Hz
 - Similar on the surface level, however, analysis reveals different underlying mechanisms
 - Triggered by local outage
- Type 2: 14.7 Hz – Fast response, result of a local control mode becoming unstable
 - Outage of local synchronous machines triggered oscillations (in one of the 10 events that was noticed)
 - Exogenous excitation helped reveal otherwise unobservable critical dynamics behind it
 - Long term tracking of critical dynamics showed progressively worsening stability over 6 months – chance at anticipating it
- Type 3: 0.4 Hz – Slow response resulting from load cycling
 - Growing data center consumption behavior will likely result in more of these responses
 - Historical data showed periodic behavior from the beginning
 - Outage redirected the flow to a single line making it look worse
 - What operational boundaries should be placed on load behavior?
- Should these two types be treated differently due to differing mechanisms ?
 - Unstable vs stable/controlled input
 - May have the same impact on the system

Other Events from Dominion

- [1] C. Mishra, L. Vanfretti, J. Delaree Jr. and K. D. Jones, "Analyzing a Non-Sinusoidal Response from a Real-World Solar PV," in IEEE Transactions on Power Systems, vol. 39, no. 2, pp. 4771-4774, March 2024, doi: 10.1109/TPWRS.2024.3350377. Author's copy: [here](#)
- [2] X. Xu, C. Mishra, L. Vanfretti, C. Wang, K.D. Jones, J. Brian Starling, and R. M. Gardner, "Tracking Periodic Voltage Sags via Synchrophasor Data in a Geographically Bounded Service Territory," 2023 IEEE Grid Edge Technologies Conference & Exposition, April 10-13, 2023, San Diego, California, USA. Author's copy: [here](#)
- [3] B. Pudasaini, L. Vanfretti, C. Mishra, J. de la Ree Jr., and K. D. Jones, "Dynamic Performance Analysis of an Inverter-Based PV Plant during Sunrises and Sunsets through Synchrophasors," accepted for publication in the 2025 IEEE Power & Energy Society General Meeting, Austin, Texas, USA. Author's copy: [here](#)
- [4] C. Mishra, L. Vanfretti, M. Baldwin, J. de la Ree Jr., and K. D. Jones, "Analysis of Generator Forced Oscillations during MOD 25 Testing Exploiting Wavelets," Hawaii International Conference on System Sciences (HICSS), Hilton Hawaiian Village Waikiki, January 3-6, 2024. Author's copy: [here](#)
- [5] C. Mishra, L. Vanfretti, D. Yang, C. Wang, X. Xu, K.D. Jones and M.R. Gardner, "Analysis of STATCOM Oscillations using Ambient Synchrophasor Data in Dominion Energy," 2022 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT 2022), Feb. 21-24, 2022, Washington D.C., USA. Author's copy: [here](#)
- [6] C. Wang, L. Vanfretti, C. Mishra, K.D. Jones, R.M. Gardener, "Identifying Oscillations Injected by Inverter-Based Solar Energy Sources," 2022 IEEE Power & Energy Society General Meeting, 17-21 July 2022, Denver, Colorado. Author's copy: [here](#)

Thank You Questions ?