IBR Oscillations in the Dominion Energy System

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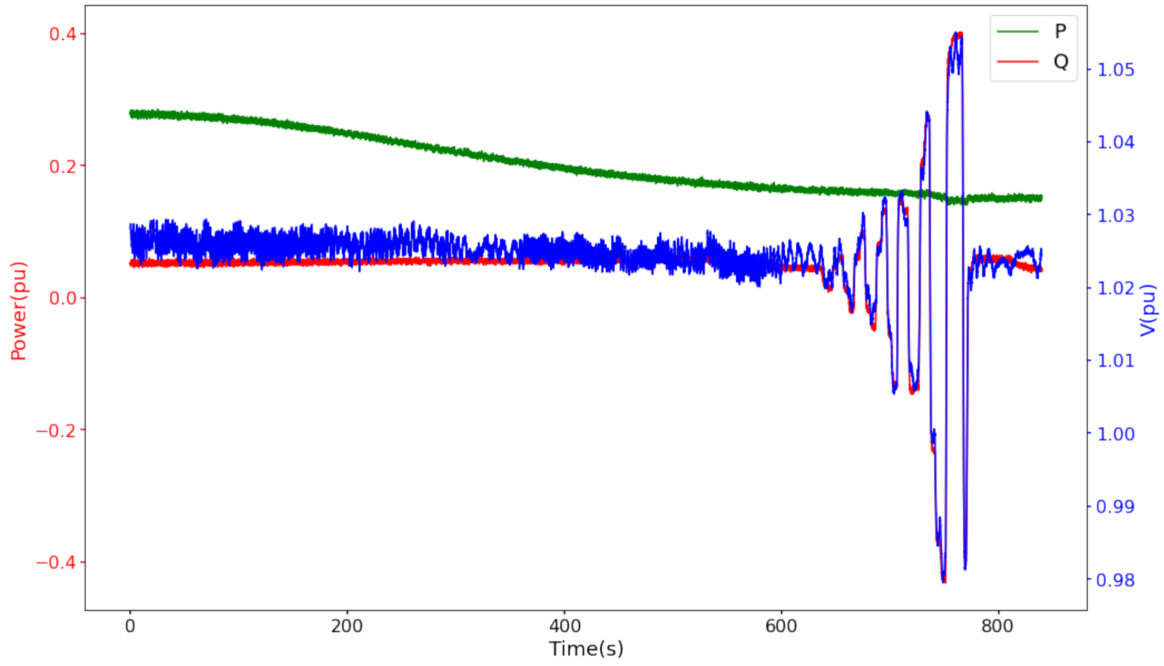
Changing Grid and Stability Issues

- For traditional power systems, stability is mainly about how tightly coupled are the synchronous machines
  - Not been an issue for Dominion (500 kV backbone)
- Emerging control related issues (mostly black box/unmodeled dynamics !)



Unstable Voltage Controller at Transmission Solar

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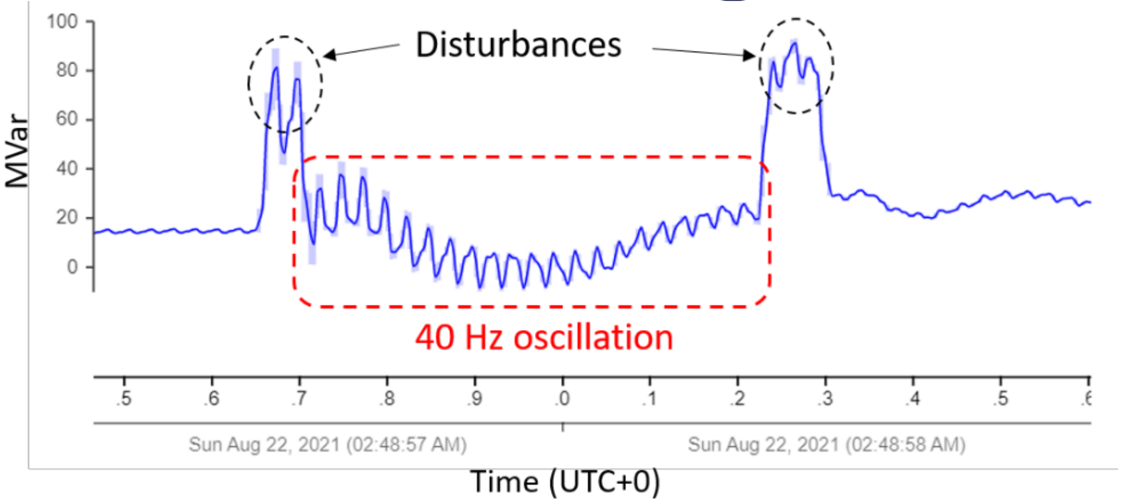
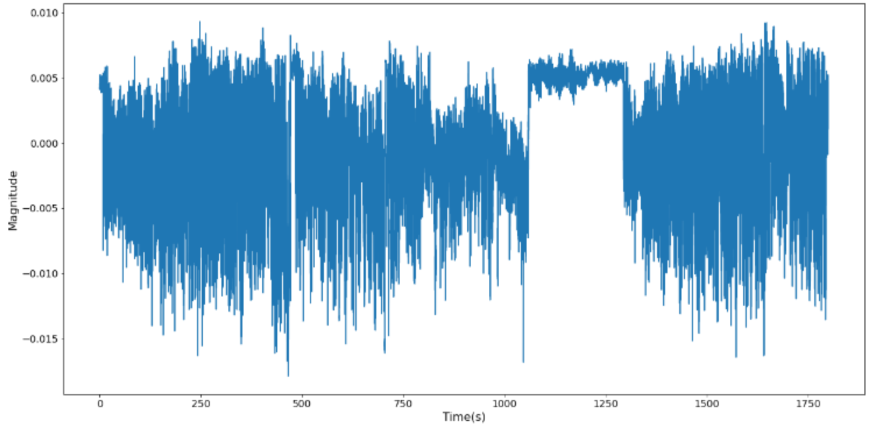
Why Data Driven Analysis ? (Modeling Challenges)

- Power industry heavily relies on models for planning and even control specifications
  - Traditional generator and associated control models are well understood
  - BUT not all internal components are modeled in PSS\E ! Loss of information !
- Detailed dynamic load models are hard to build and/or validate
  - Require events happening everywhere, at multiple times
  - Are the generic models actually useful ?



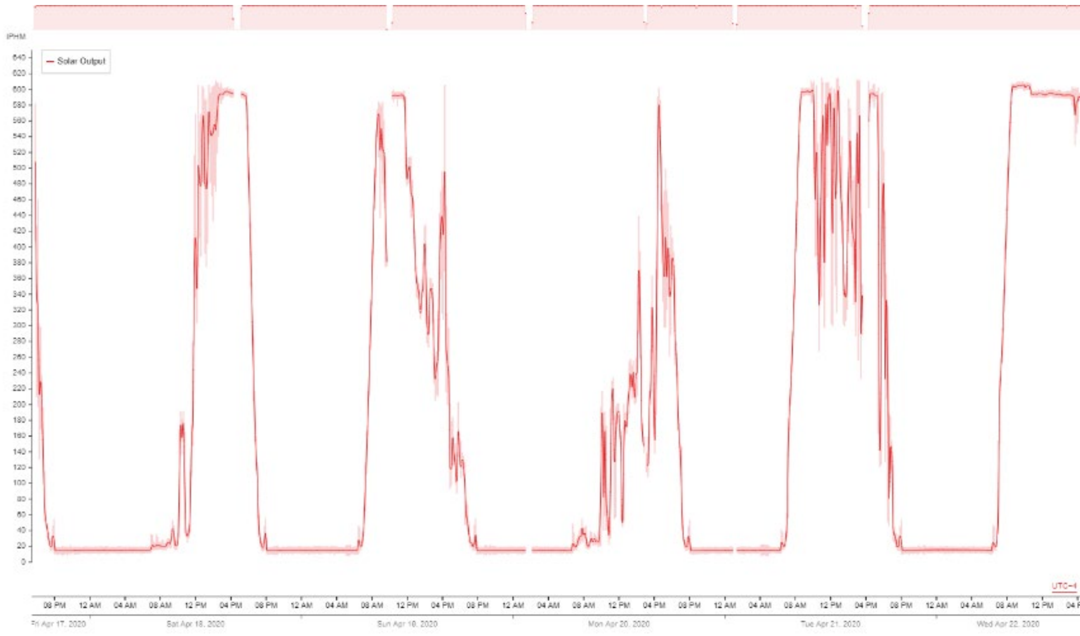
Unmodeled 40 Hz Excitation Dynamics from Hydro



Load - Electric Arc Furnace

Modeling Challenges

- Models for real-world FACTS
  - Black box models in EMT software
  - Controller replica in RTDS (black box)
  - Not always updated with device changes
  - Inaccurate representation of rest of the system
- Renewable Gen Models
  - Usually not available
  - Generic models rarely help with troubleshooting
  - Complicated by protection
  - Short term uncertainty is not modeled in system dynamic models



Typical Solar Output

Research Problem

- Goal: Inferring Dynamic Behavior from Measurements
- Motivation
  - Identifying problematic controllers that models fail to capture
  - Address emerging issues before they become widespread
  - Gaining intelligence on operation and planning in the “new grid”
  - Tuning pre-existing models
  - Augmenting models with new information

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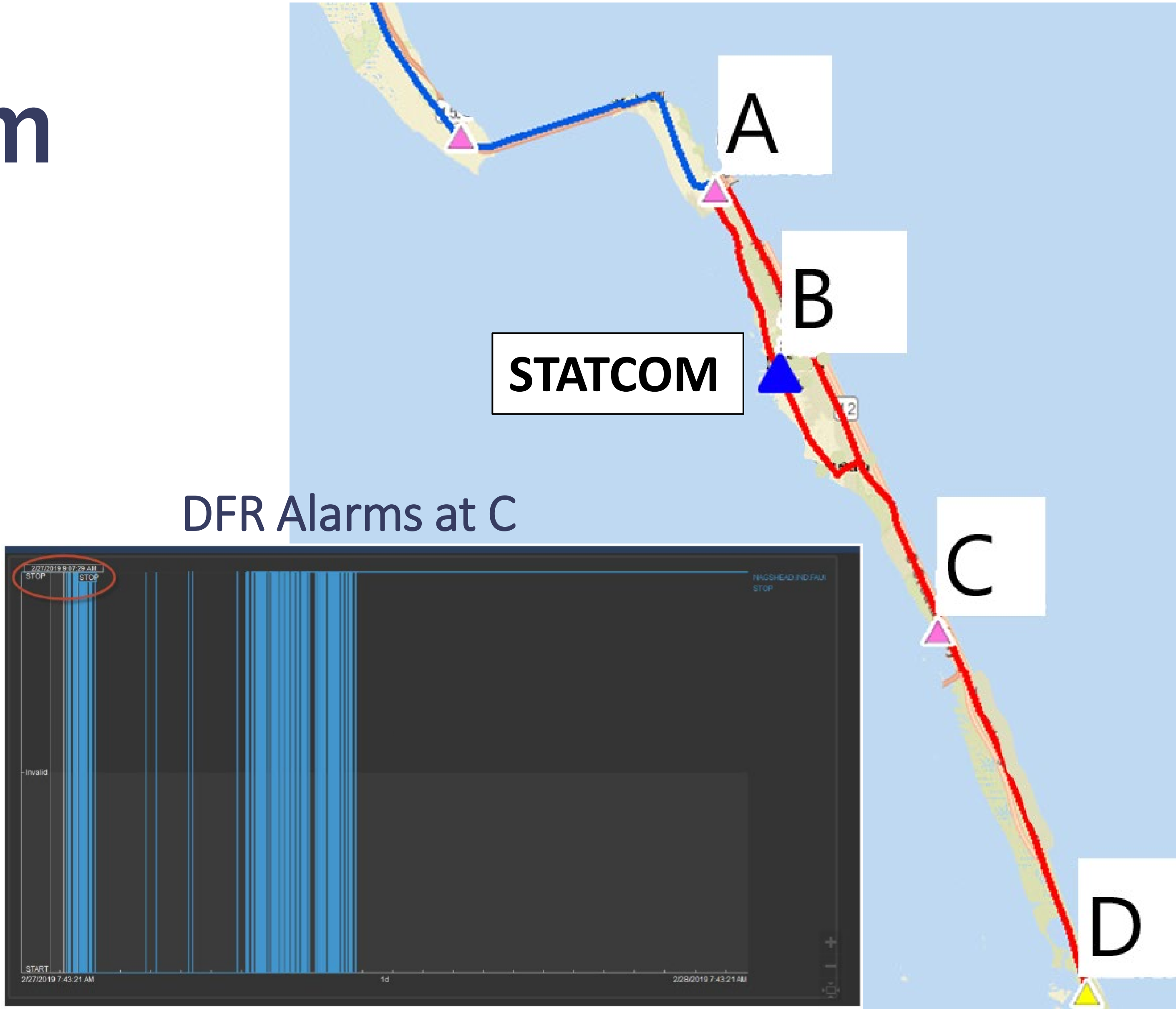
Example Problem

- In Feb 2019, opening of line C-D triggered Digital Fault Recorder (DFR) alarms due to Harmonic Distortion
  - Stopped on reconnecting
- Source(s) ?
- Was the issue always there ?
  - If yes, when does it flare up ?



DFR Alarms at C

Identification of Oscillations from Solar Inverter

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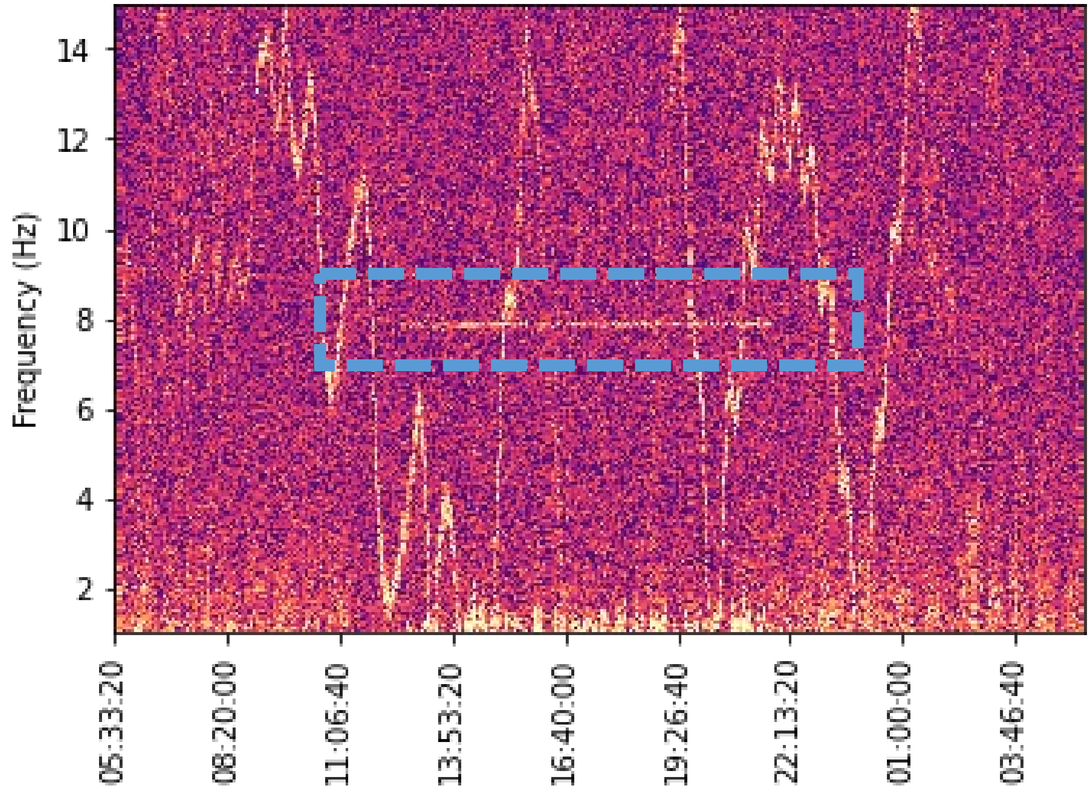
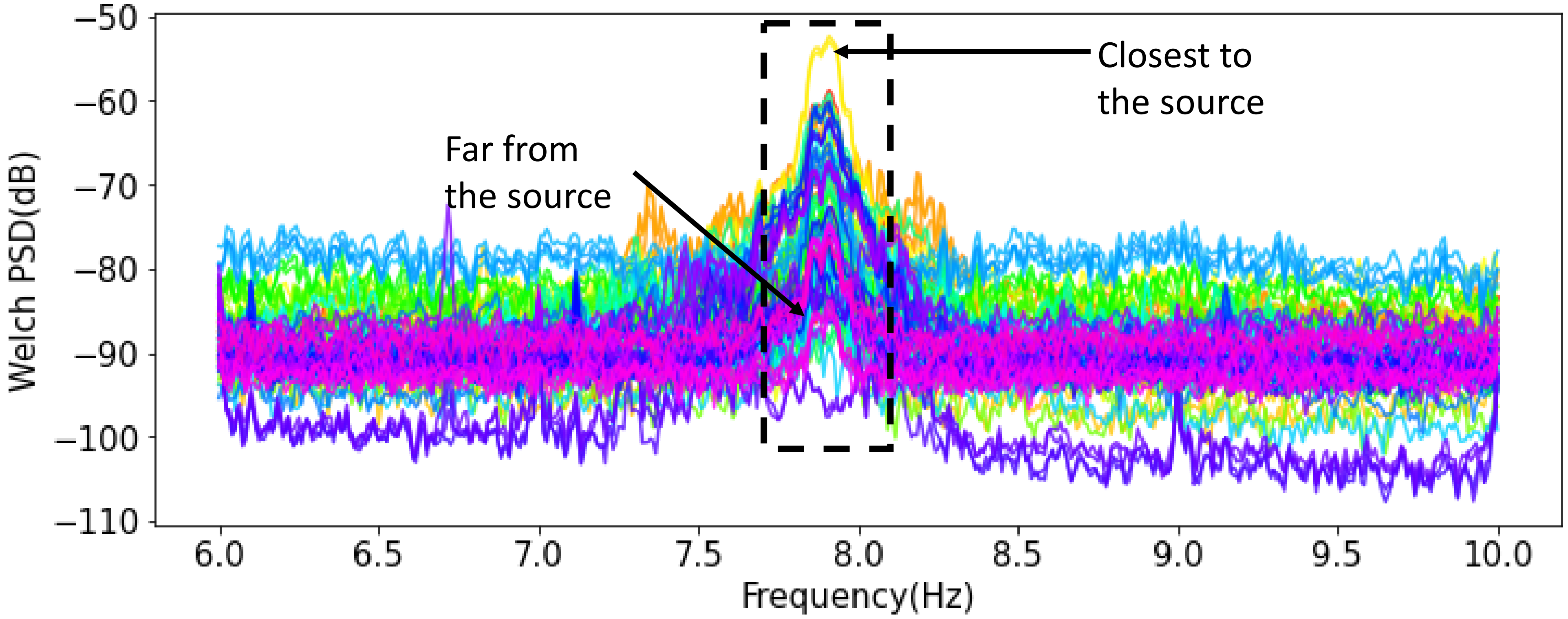
Introduction

- Randomly encountered an 8 Hz oscillation when analyzing industrial load dynamics at another location
- Observable everyday only during daytime
  - Correlating it with the time of sunrise and sunset was the only clue to identifying its nature…Solar PV !



Summer Day V magnitude 24 Hr Spectrogram at Industrial Load

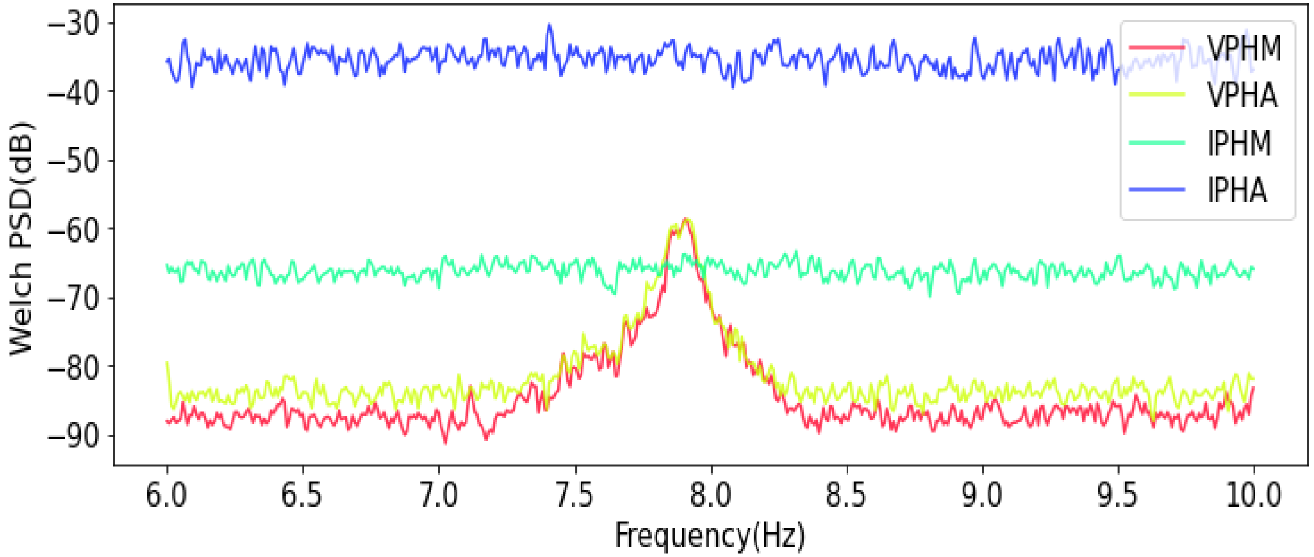
System Wide Spectrum



Summer Day V Magnitude Spectrum across 25 Substations

Signal Selection

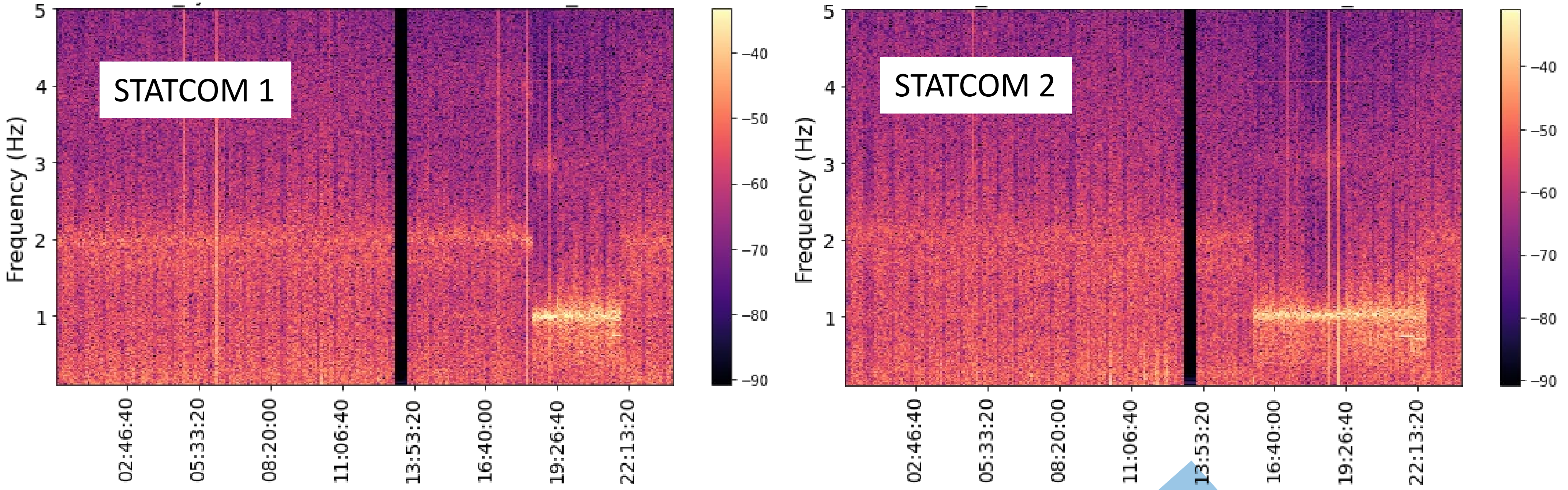
- Mode was observed in voltages at most substations
- Observed in currents at only a few
  - Most solar PVs operate in PQ mode and not PV
  - In IBRs, current is regulated making it a poor observer
- Goal was to locate the source as well as understand how widespread the impact is
  - Voltage magnitude chosen for analysis



V,I Spectrum

Single or Multiple Modes ?

- Multiple modes at nearly same frequencies are fairly common,
  - Devices coming from same manufacturer
  - Connected in similar regions



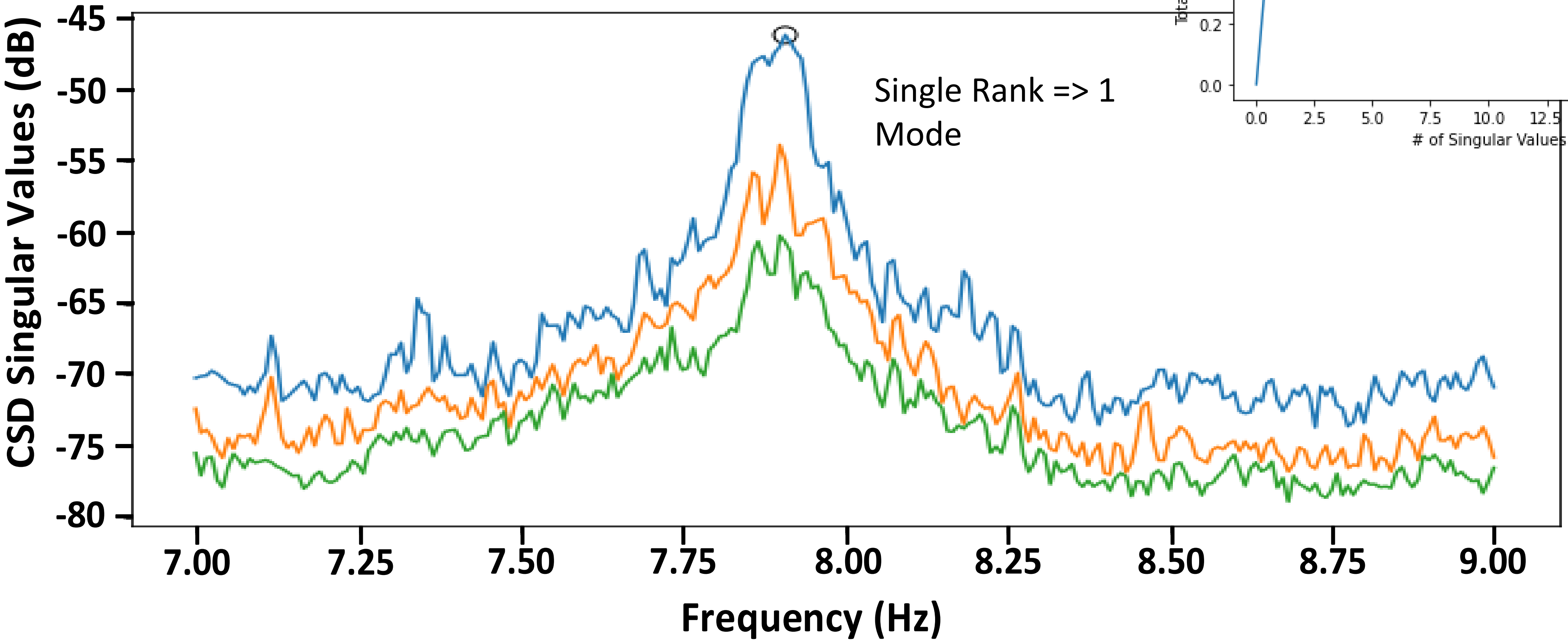
Example - Nearly Identical 1 Hz Control Modes from STATCOMs from Same Manufacturer

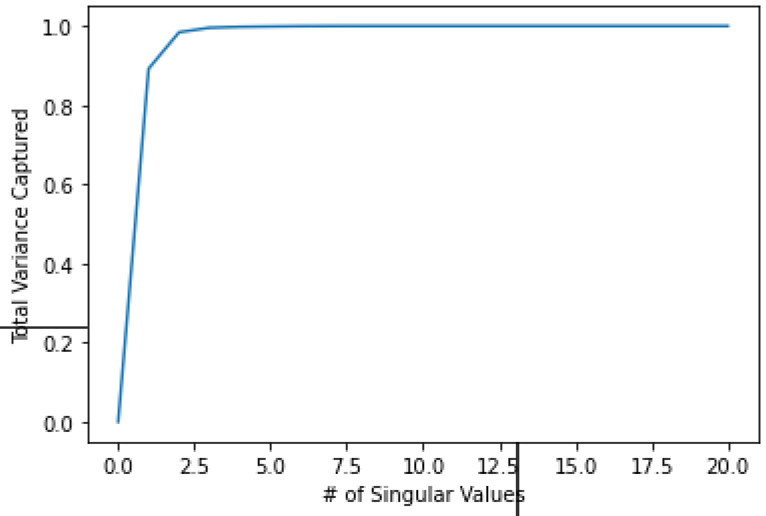
Multiplicity and Shape using Frequency Domain Decomposition

- Power spectral density matrix $S_{yy}(\omega)$ of outputs of a MIMO linear time invariant system can be written as,

$$S_{yy}(\omega) = G(j\omega)S_{uu}(\omega)G^H(j\omega)$$

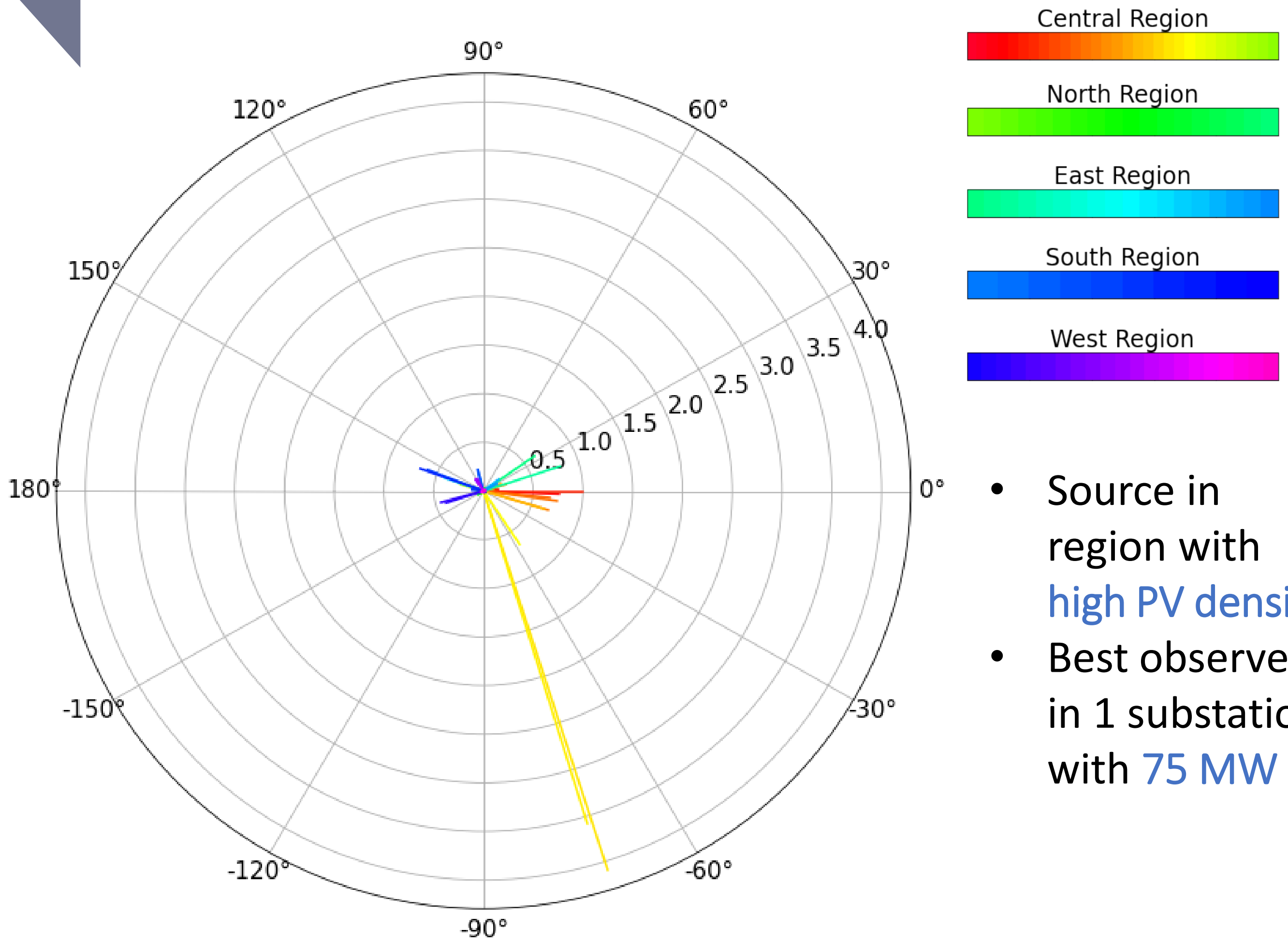
  - $G(j\omega)$ is the transfer function and $S_{uu}(\omega)$ is the PSD matrix of inputs
- Rank of $S_{yy}(\omega)$ gives insight into number of strongly observed + excited modes at ω
  - Singular values give the scaled PSD of underlying modes
  - Singular vectors of S_{yy} can give the mode shapes of those modes (iff they are orthogonal in shape)



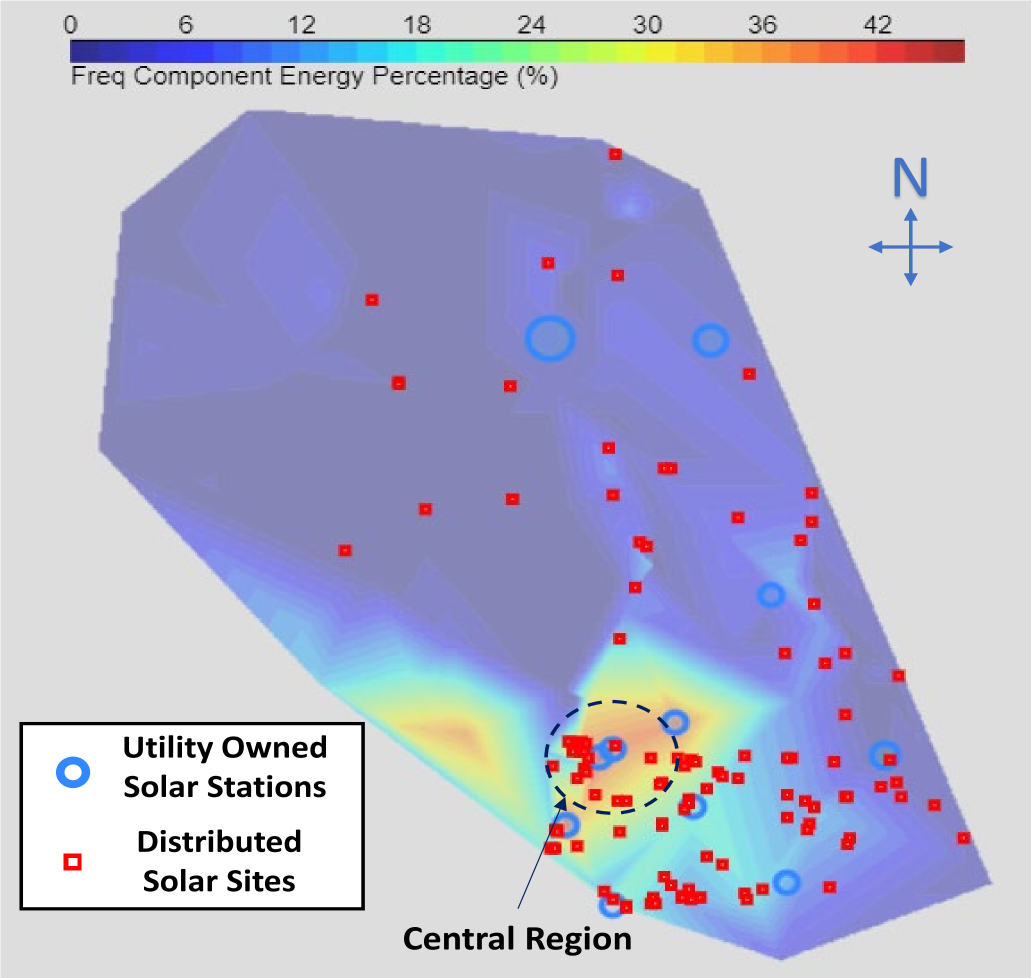


Top Three Singular Values of $G_{yy}(\omega)$

Regional Mode Shape



- Source in region with high PV density
- Best observed in 1 substation with 75 MW PV



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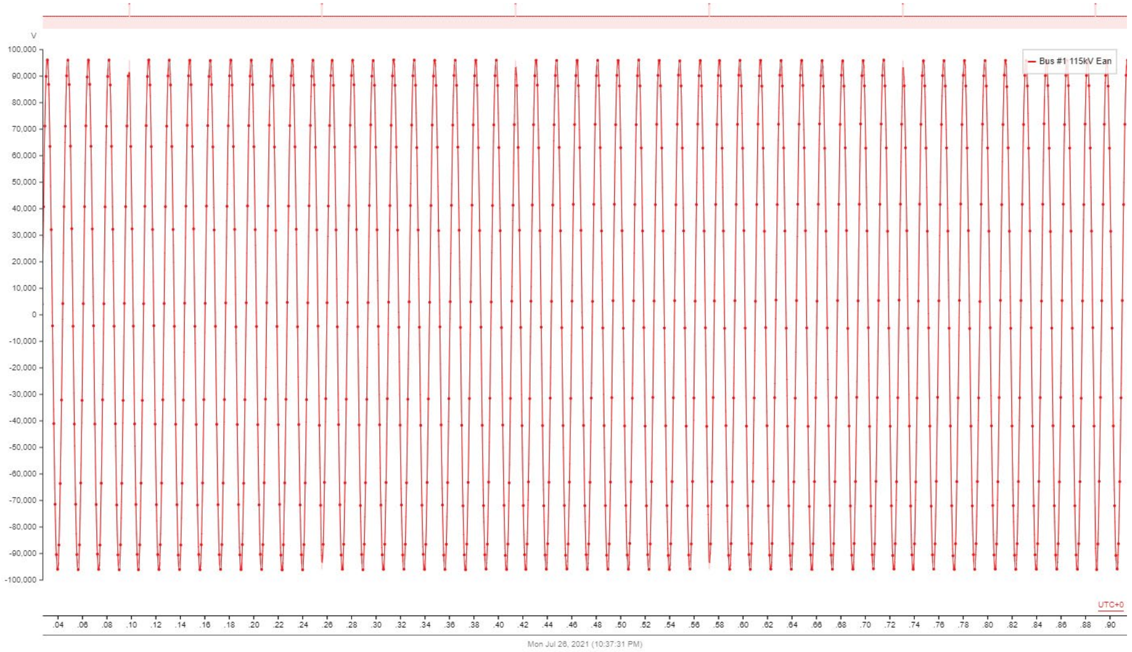
Verification Using Point of Wave (PoW) Data

Introduction

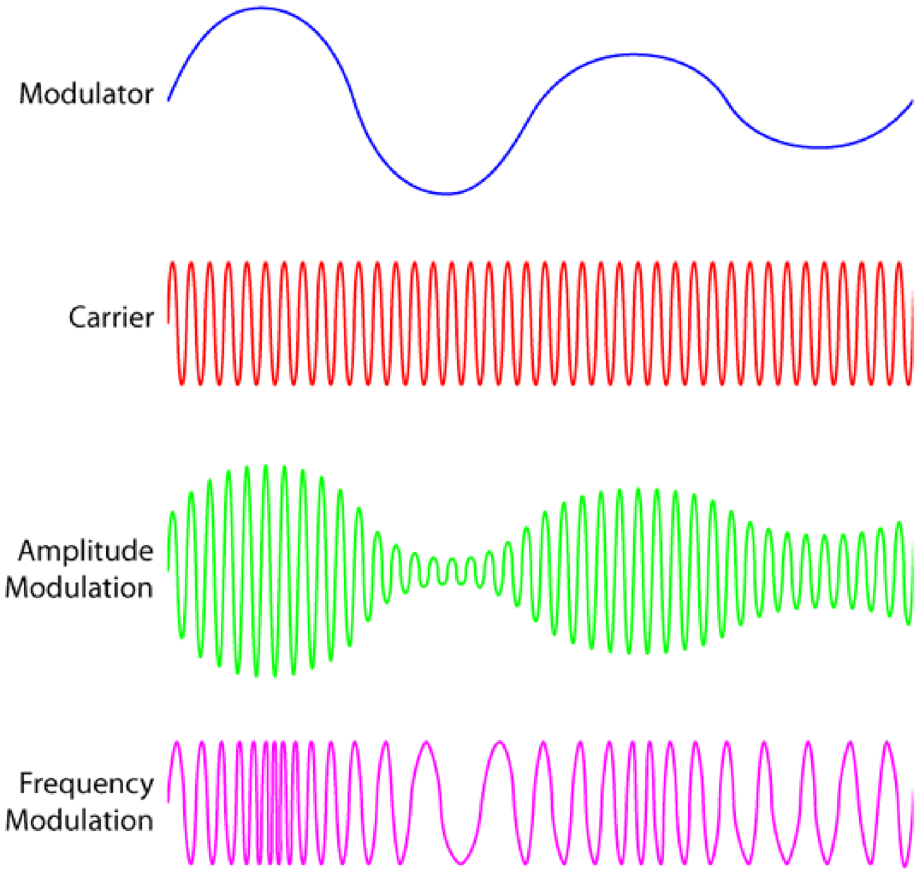
- Important to verify results using PoW data for power electronic equipment
  - Infeasible to conduct entire analysis with PoW data – storage challenges + a lot of irrelevant information content
- Need to map PoW observations to relevant observations in PMU data
- In Dominion System, digital fault recorders (DFRs) sample point on wave data at 4800 Hz, which is filtered + down-sampled to 960 Hz for phasor estimation
  - Temporarily stored at the substation
  - Can be collected on demand, however network bottleneck



Typical PoW

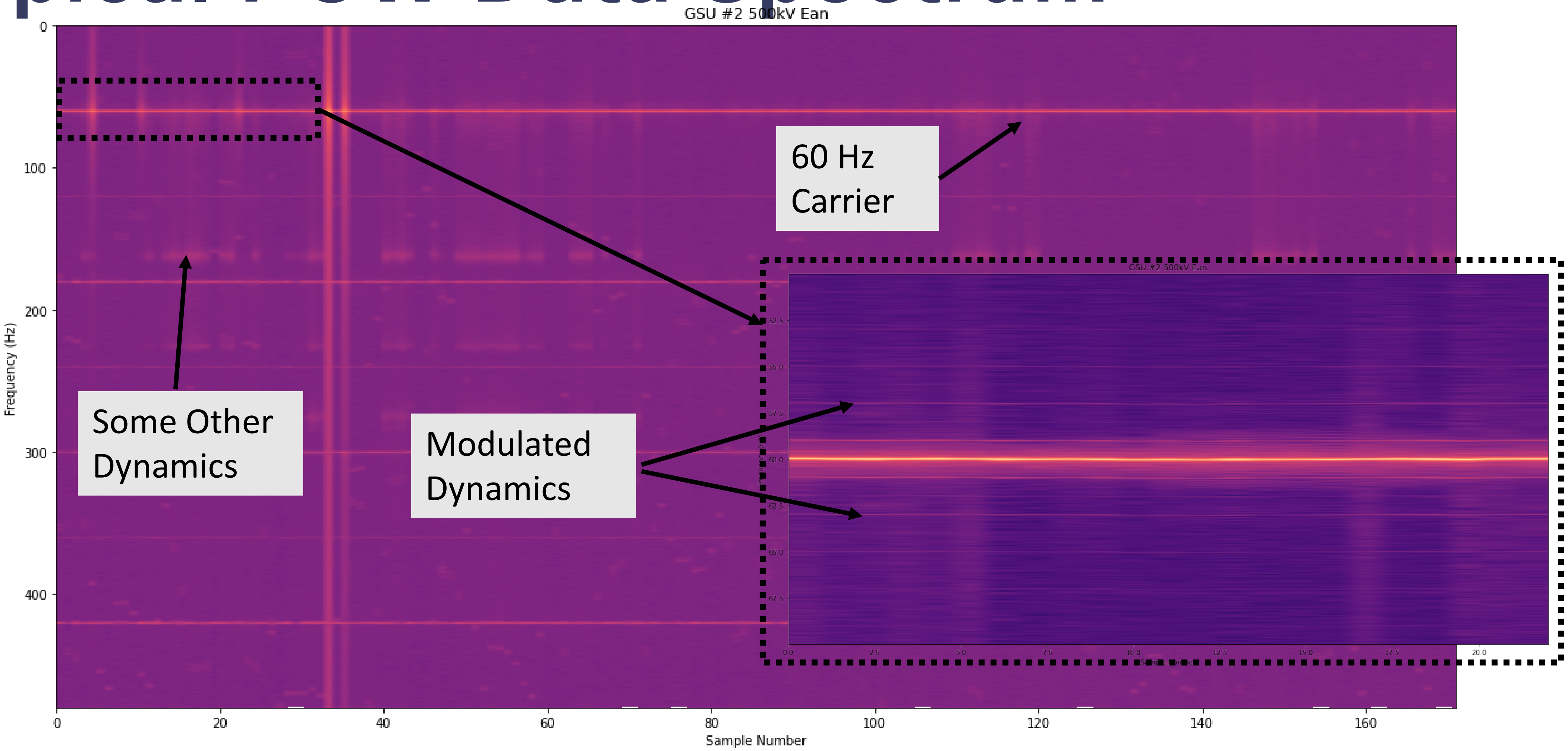
Information in PoW Data

- System operating around 60 Hz
  - Think of it as carrier wave for traditional power system dynamics
- Dynamics encoded into the carrier signal through modulation (governed by device physics)
- Other dynamics (not modulated) also present e.g. harmonics from converter, arc furnace



Modulation

Typical POW Data Spectrum



Point on Wave Spectrogram @960 Hz

Demodulation (Recovering Phasor)

- Modulated signal,

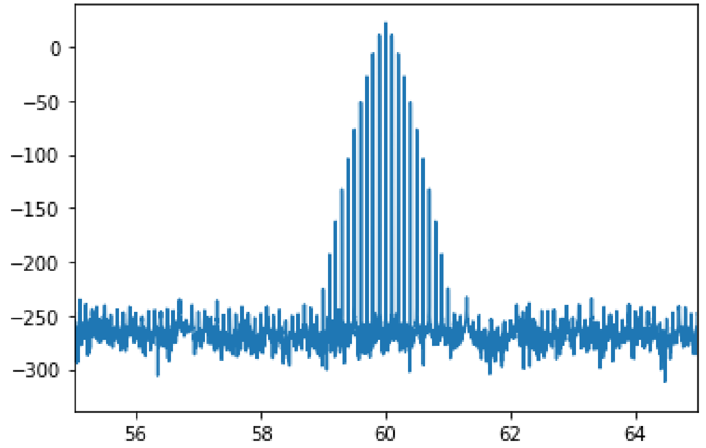
$$x(t) = real(A(t)e^{j(2\pi f_c t + \theta(t))})$$

- Hilbert Transform derives a complex valued signal,

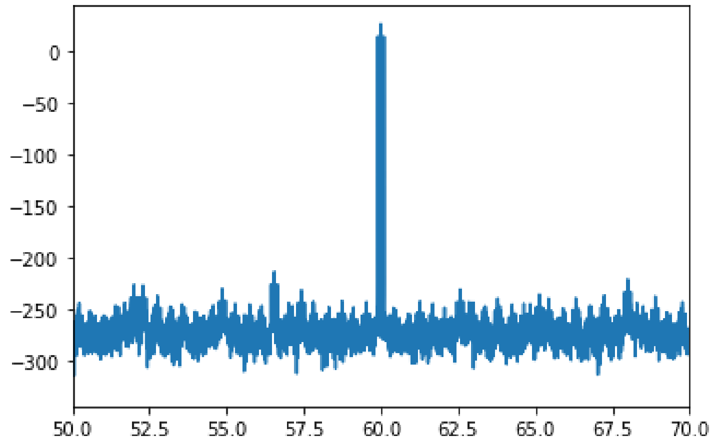
$$x_c(t) = x(t) + jy(t) = a(t)e^{j\phi(t)}$$

$$s.t.\ Y(\omega) = -jX(\omega) \rightarrow -\frac{\pi}{2}\ shift$$

  - Achieved by convolving $x(t)$ with $\frac{1}{\pi t}$

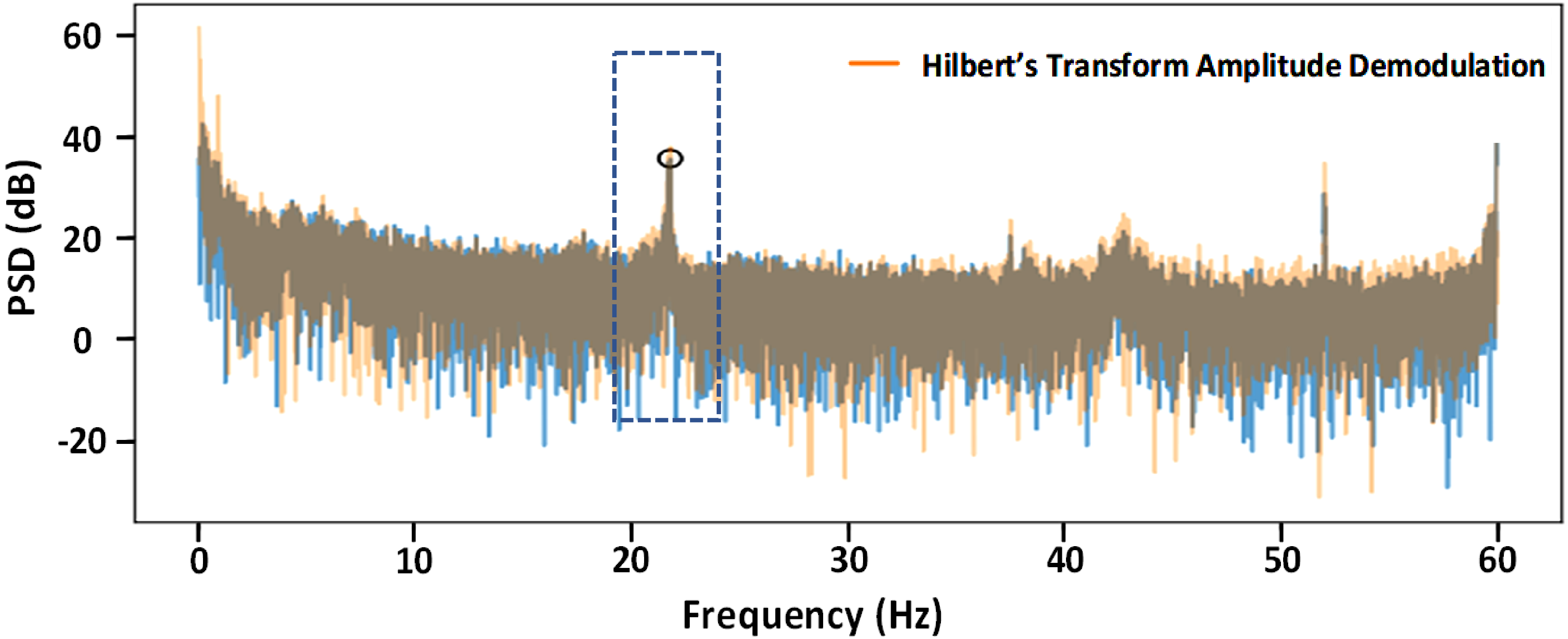


$\theta(t)$ oscillating at 0.1 Hz, amp = pi/6



$A(t)$ oscillating at 0.1 Hz, amp = 0.5

22 Hz not 8 Hz



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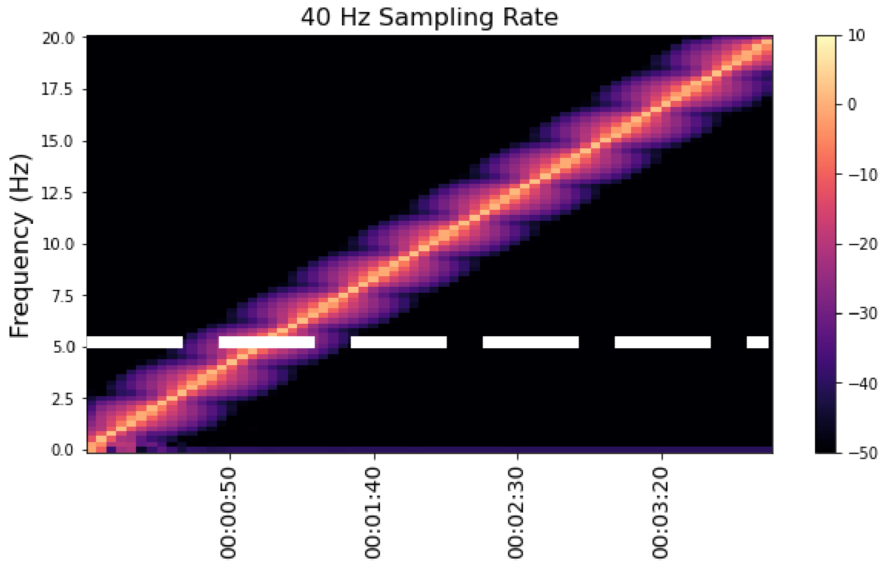
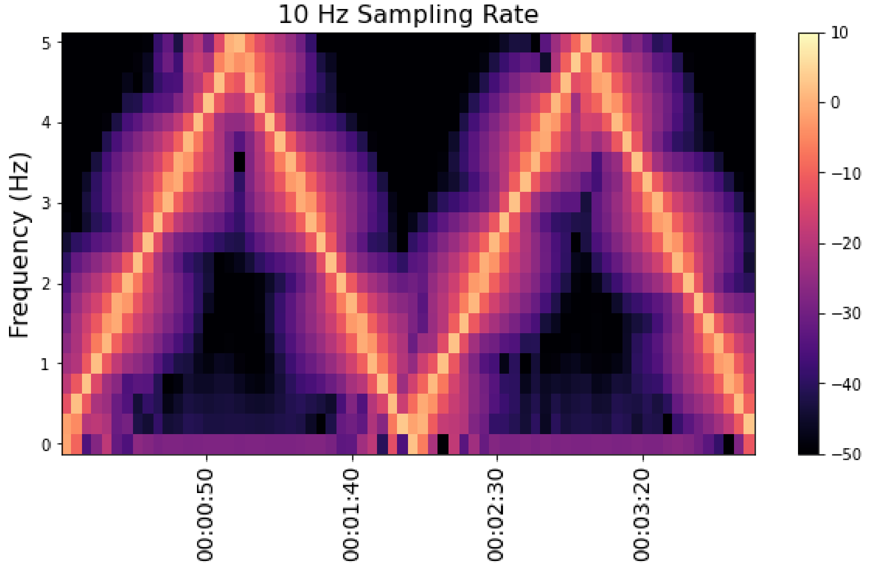
Aliasing

- PMU reporting rate is 60 Hz, Dominion down samples to 30 Hz to optimize storage
- Nyquist theorem – Sample at least twice the maximum frequency component

$$PSD\left(\frac{\omega_s}{2}+\Delta\omega\right)=\left|X\left(\frac{\omega_s}{2}+\Delta\omega\right)\right|^2$$
$$=\left|\sum_k x\left(\frac{2\pi k}{\omega_s}\right)e^{j2\pi\frac{\frac{\omega_s}{2}+\Delta\omega}{\omega_s}k}\right|^2=\left|\sum_k x\left(\frac{2\pi k}{\omega_s}\right)e^{j\left(\pi+\frac{\Delta\omega}{\omega_s}\right)k}\right|^2$$
$$=\left|\sum_k x\left(\frac{2\pi k}{\omega_s}\right)e^{j\left(\pi-\frac{\Delta\omega}{\omega_s}\right)k}\right|^2 \; **$$



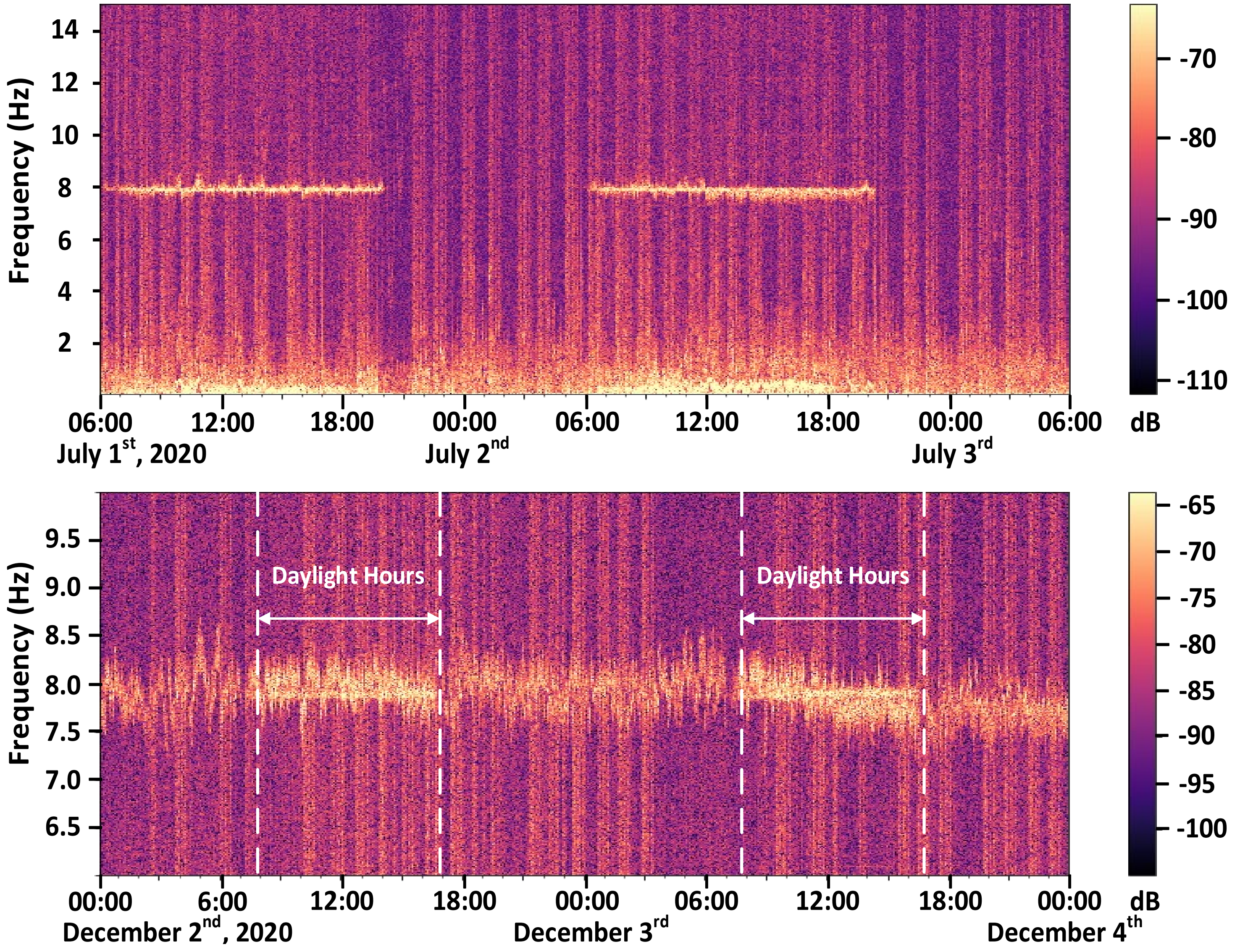


$$**|a\cos(\theta)+1j\,a\sin(\theta)|^2=|a\cos(\theta)-1j\,a\sin(\theta)|^2$$

Changing Controller Behavior

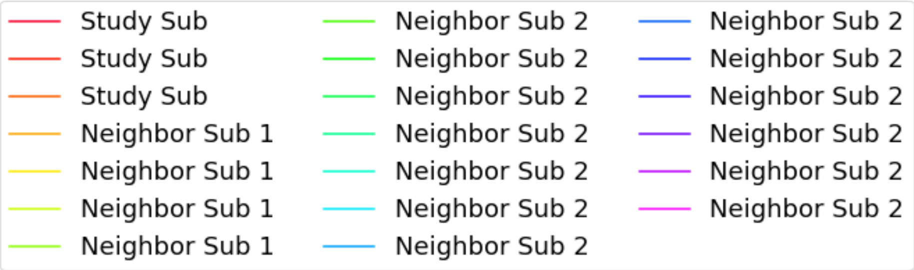
8 Hz Activity

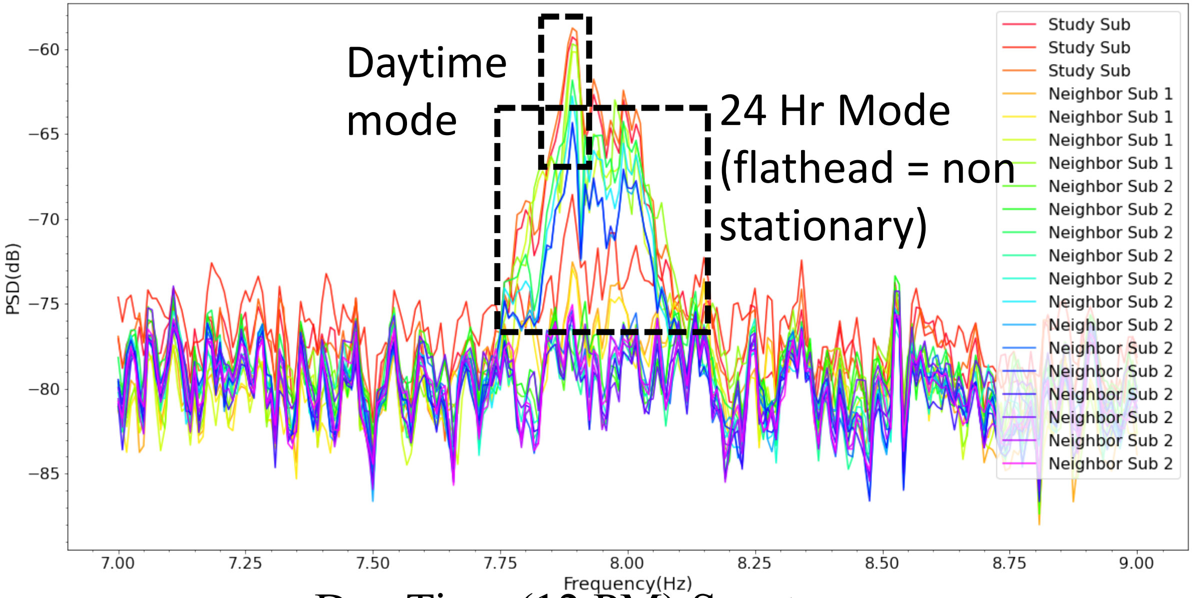
- Usually, only a single mode at 8 Hz during daytime
- On certain days, 2 modes are observed around 8 Hz
  - Day time mode, nearly fixed frequency (similar to above)
  - 24 Hr mode, frequency varies around 8 Hz



Changes in Voltage Magnitude Spectrogram at Identified Source

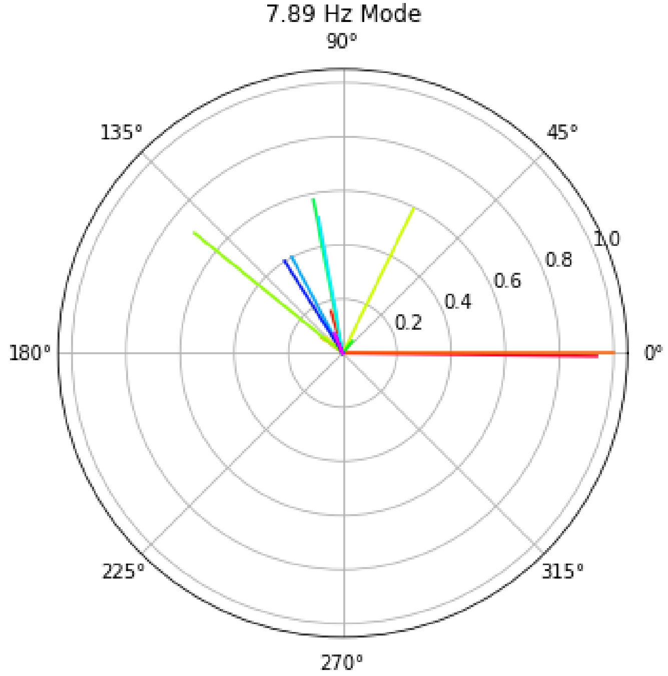
Mode Shape of Daytime vs 24 Hr Mode (Dec 2, 2020, Similar Energy Modes)





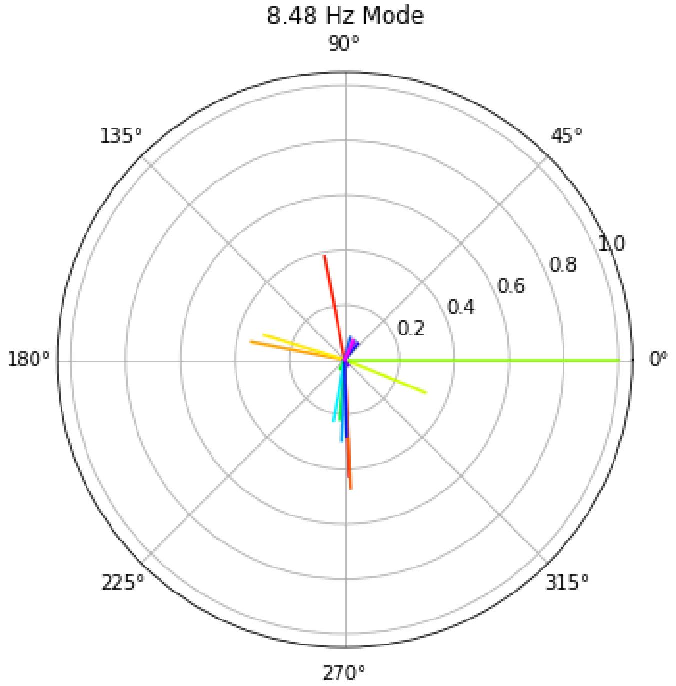
Day Time (12 PM) Spectrum

Day Time Mode Shape



- Local to Identified PV plant

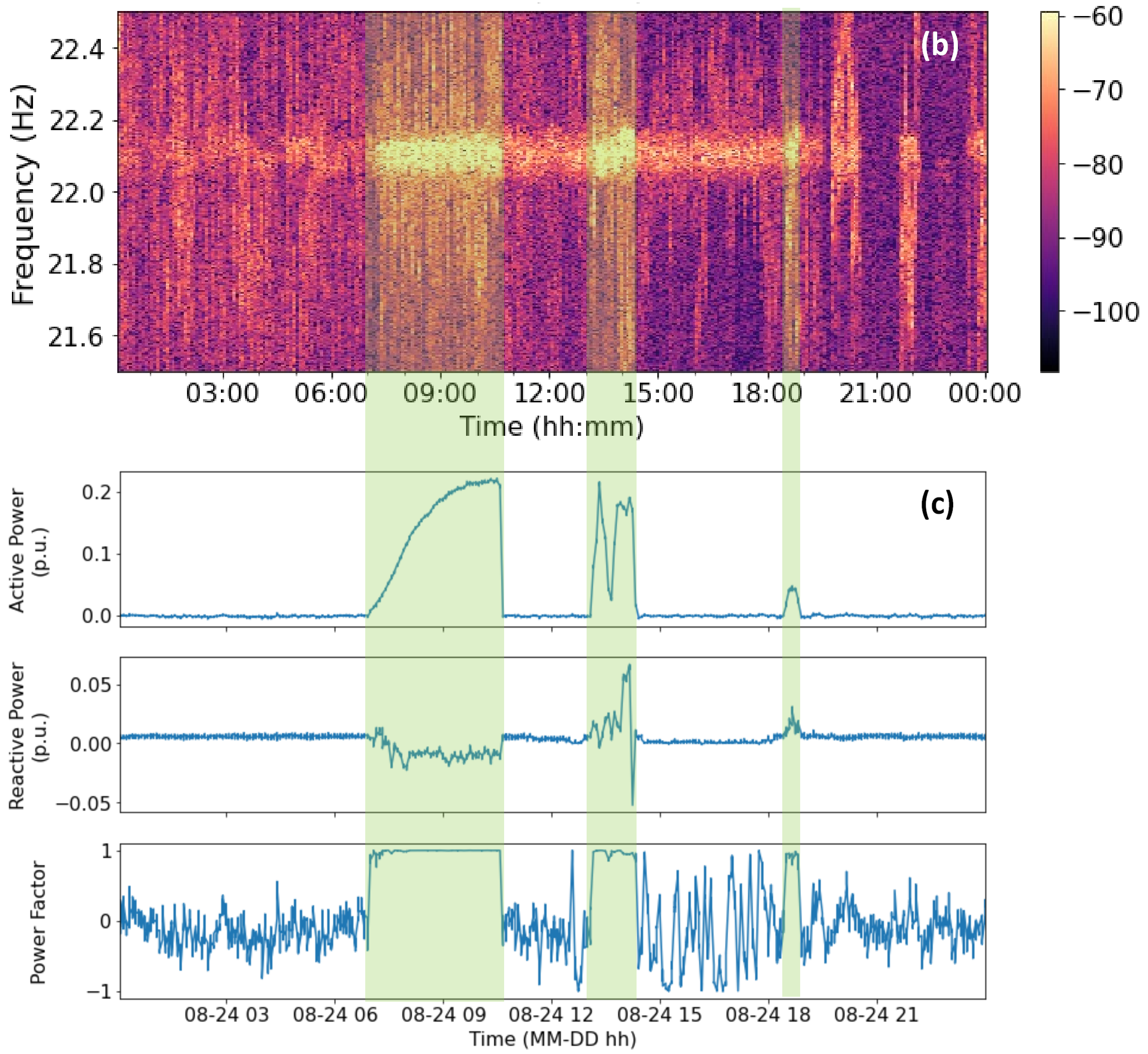
24 Hr Mode Shape (sampled at late night)



- From neighboring PV plant

Spectrum vs PQ Output of Solar Plant

- Most PVs at Dominion are operated in PQ mode with separate V control
  - There are several other auxiliary controls inside converter e.g. negative sequence current control
- Hypothesis - Daytime mode likely from PQ control, only active during significant irradiance
- Online tests to further understand the nature of the oscillations



Voltage Magnitude Spectrogram vs PQ Output on Cloudy Day (24th August 2021)

Key Takeaways

- Transparent models for IBRs are usually unavailable, need to rely on data driven analysis (often the only choice)
- Regardless of the magnitude of the issue, need to prepare for the changing grid
- Analyzing the operating cycle (hourly, daily, seasonal) can help in identifying the nature of the source
  - Events provide an incomplete picture
  - Ambient data is important for inference
- In the present case, IBR oscillations emerged from a PV rich area
- Nearly identical IBRs from the same manufacturer can give rise to mode multiplicity
  - Careful analysis is required
- Difficult to analyze non-stationary modes (recall flathead)
- Sometimes, harmless processing of the data (down sampling in this case) can lead to wrong conclusions
  - Need to very against measurements available in the purest form (point on wave)

Thank You !