Ensuring Successful Decarbonization through Data Driven Grid Dynamics Discovery & Analysis

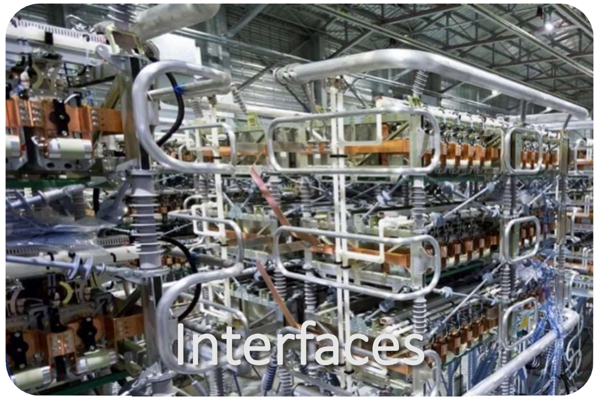
Presented by

Chetan Mishra, Ph.D. - Dominion Energy
Kevin D. Jones, Ph.D. - Dominion Energy

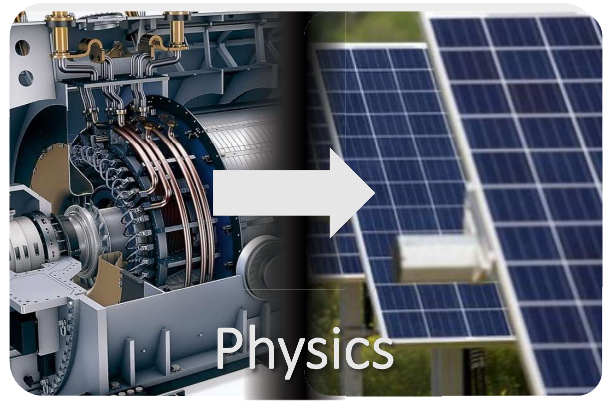
May 24, 2021

Dominion Energy

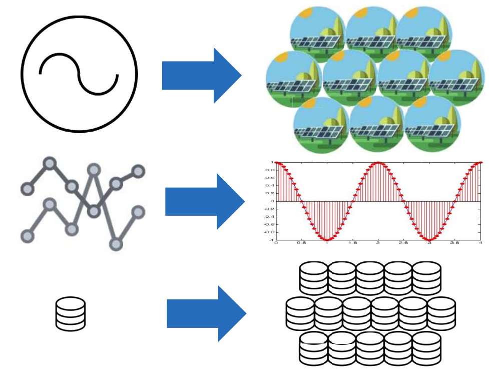
The Grid is Changing….OK, but HOW?



- Power electronics define the interface between the grid and new resources/technologies.
- We must acknowledge the challenge while recognizing the opportunity to use this in our favor



- A "computer" now governs the interactions with the grid with "physics" replaced by frequently changing software.
- Fault current levels, short-circuit strength, inertia
- Oscillations
- Network imbalance



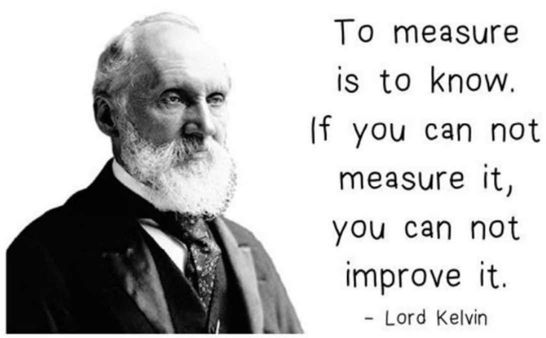
Scale

- 10s of generators become 1000s of solar farms
- <1Hz sampling rates become MHz
- GBs of data become PBs and more
- Increased CapEx to expand the grid
- Increased interconnectedness and infrastructure interdependency

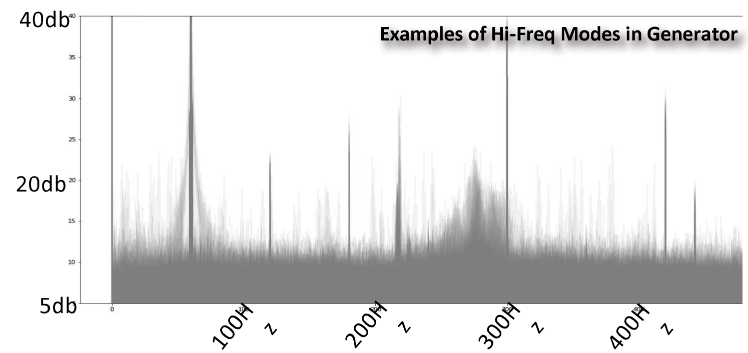
In these ways, *the clean energy transition IS a digital transformation* and we should respond in kind.

A Unifying Philosophy for Data at the Utility

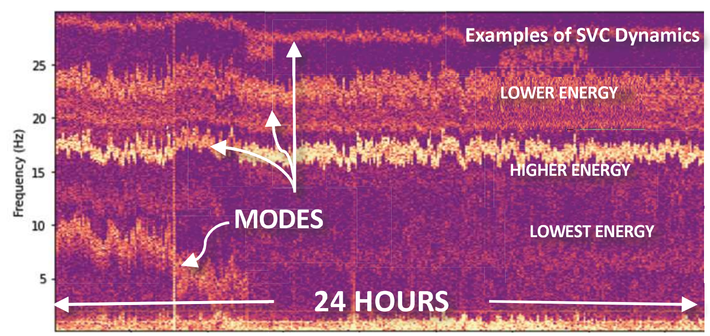
Measurement



- We'll need aggressive sensor deployment
- Measuring everything is not "gold-plating" our system
- Not only WHERE we measure but WHAT and HOW
  - Nyquist says we need higher resolution data

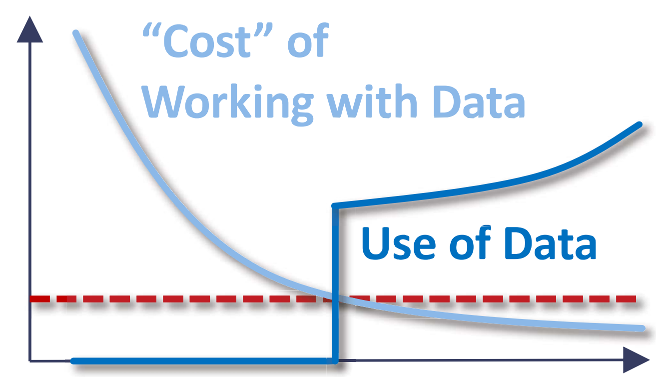


- Important grid phenomena exist a higher frequencies
- Omni-present dynamics show richness of "ambient" data



Follow-Through

- Data doesn't stop at the sensor
- Data Programs require adequate investment into technology, collaboration, staffing, and *follow-through*.
- An organization must still metabolize results of analysis to reap the benefits.
- We have to make it easy!

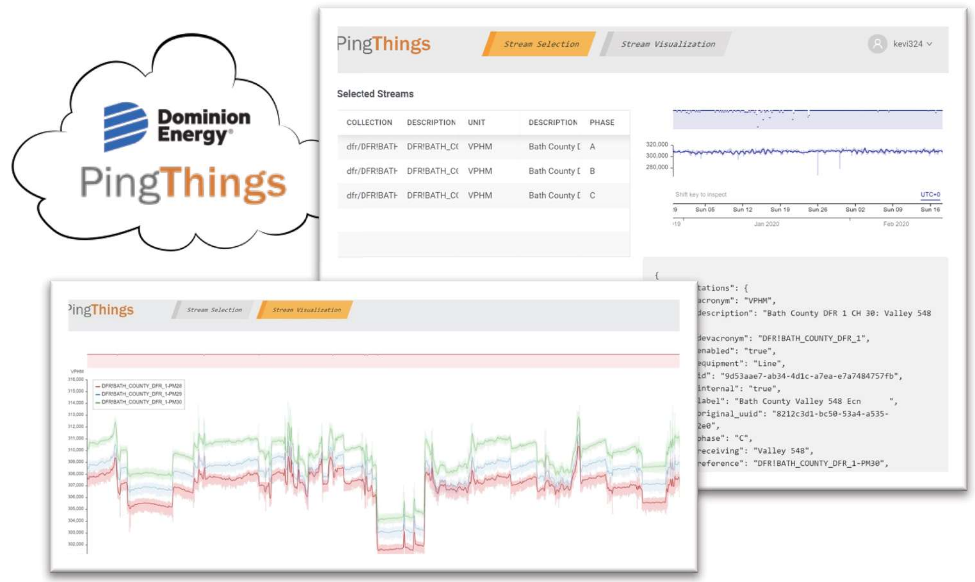


Working with High-Res Data is a Hard Problem

How do we ingest, store, manage, visualize, and analyze of high-res telemetry?

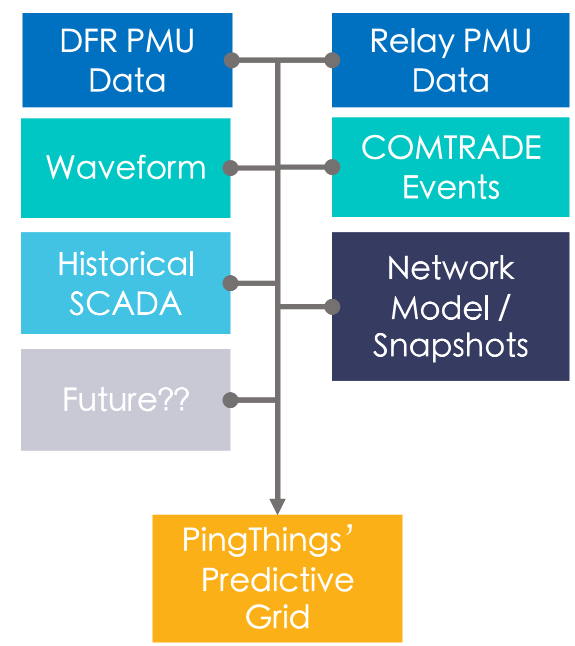
PingThings’ PredictiveGrid

- Human-scale data exploration
- Rich, programmatic access
- Automated event processing
- Streaming analytics
- **Vendor managed** cloud infrastructure, maintenance, scheduled upgrades, security, & services



Zero to streaming data in under 4 months.
We can do more with less [people, time, and resources]
with PingThings & PredictiveGrid.

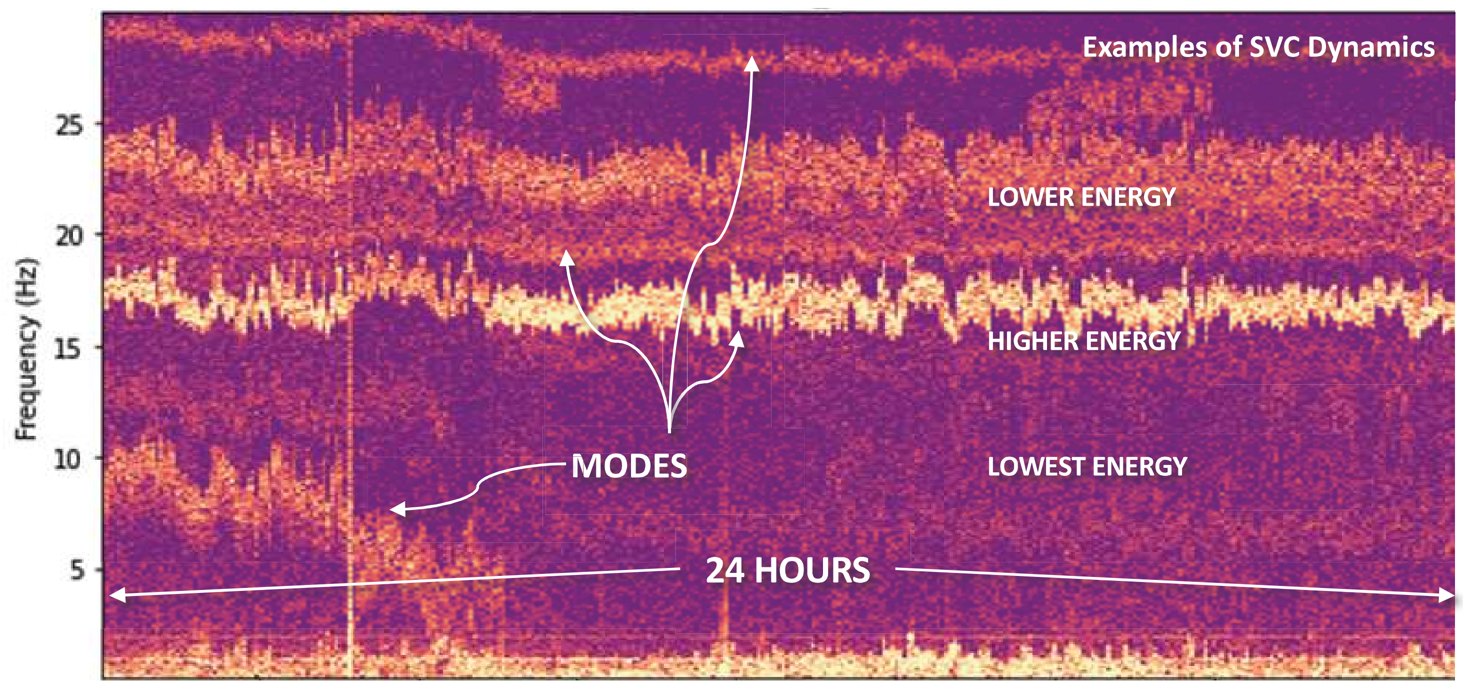
Beyond Synchrophasors



Highlights: Grid Dynamics Discovery & Analysis

Our "killer app(s)": Dominion uses synchrophasor & waveform data to identify and analyze grid dynamics caused by solar, wind, FACTS, loads, and traditional generators.

- Grid dynamics are omnipresent, demonstrating a richness in "ambient" data for understanding the grid
- Many are poorly damped
- Not captured by models
- As sources of oscillations (IBRs, FACTS, etc.) increase so does risk to equipment, customer load, and grid stability
- Must consider grid dynamics under a variety of operating conditions across months of historical data
- This analysis requires working at a scale only made possible by our PredictiveGrid platform



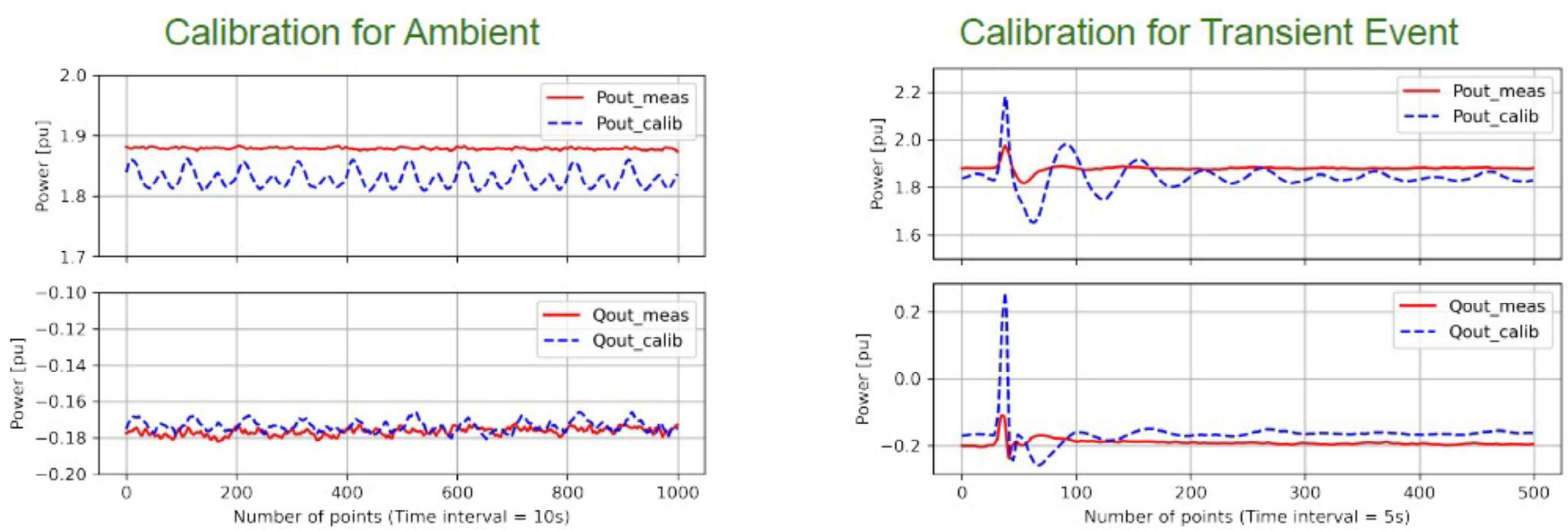
Planning New Dynamic Resources

- Issue identified / anticipated
  - Type of device usually pre-decided
- Simulations to evaluate proposed candidate solution(s)
  - Transmission planning model base case (usually summer peak)
  - Steady state contingency analysis
  - Dynamic simulations for a handful of faults
- If the solution is satisfactory, contact vendor
  - Catalogue of off the shelf solutions
  - Provide design specs (sizing etc)
  - Provide a base case model to work with
    - Vendor does control design based on it
- Eventually deploy in the system
  - If any major event triggers alarms, do root cause analysis

What’ s The Problem ?

Generator Model Validation is Doable

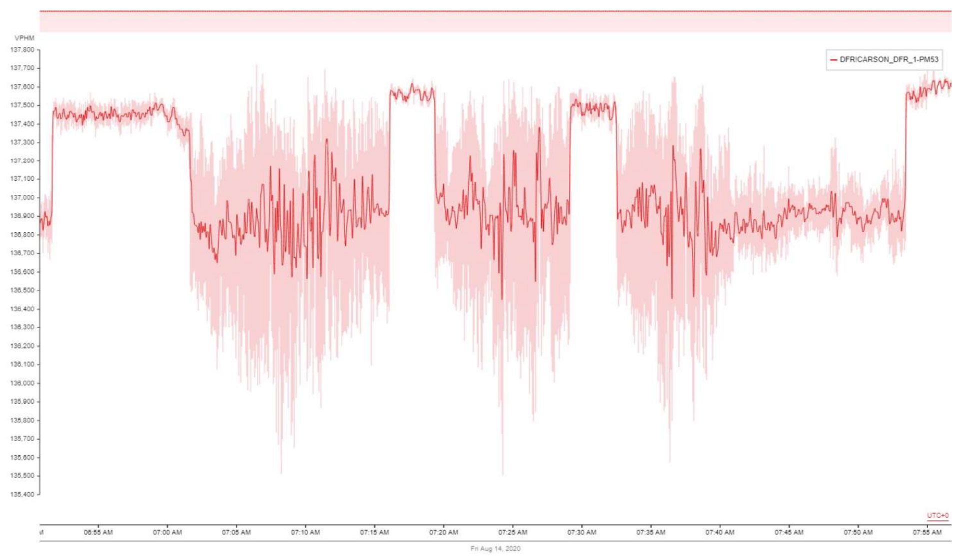
- Traditional generator and associated control models are well understood
  - Can be tuned to match the measurements from event data
  - Tricky from ambient data
- But…..Not all internal components may be modeled in the PSS\E model

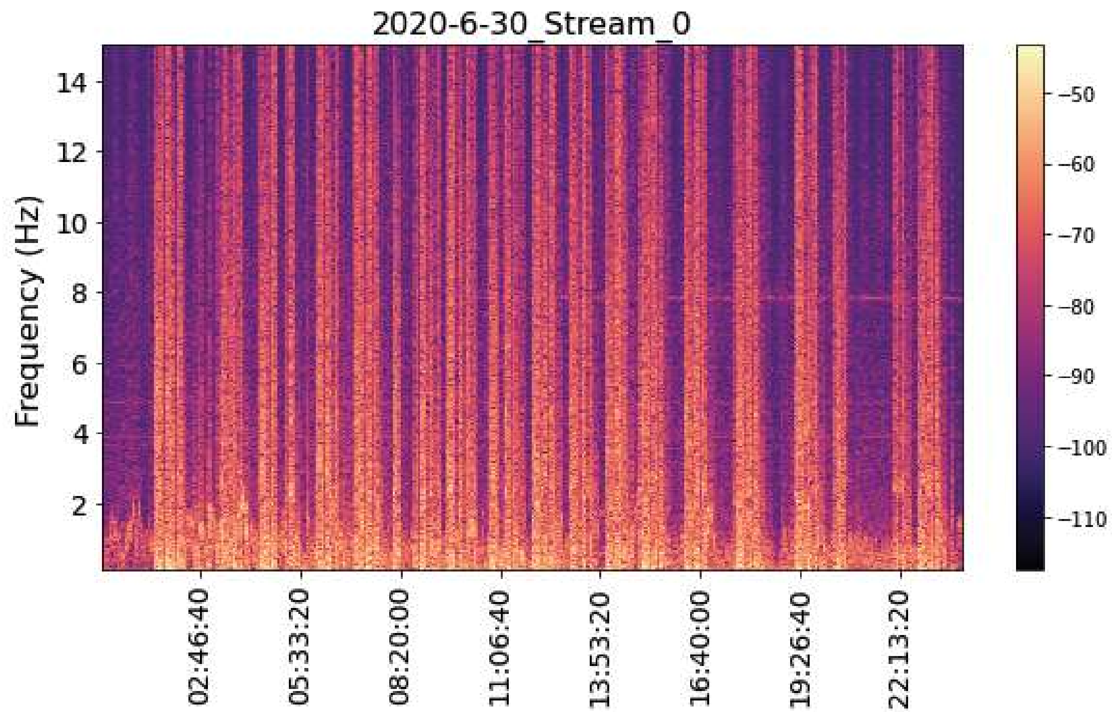


Rensselaer ALSET lab why not change the world?®

Dominion Energy®

But Did We Model Everything Else ?

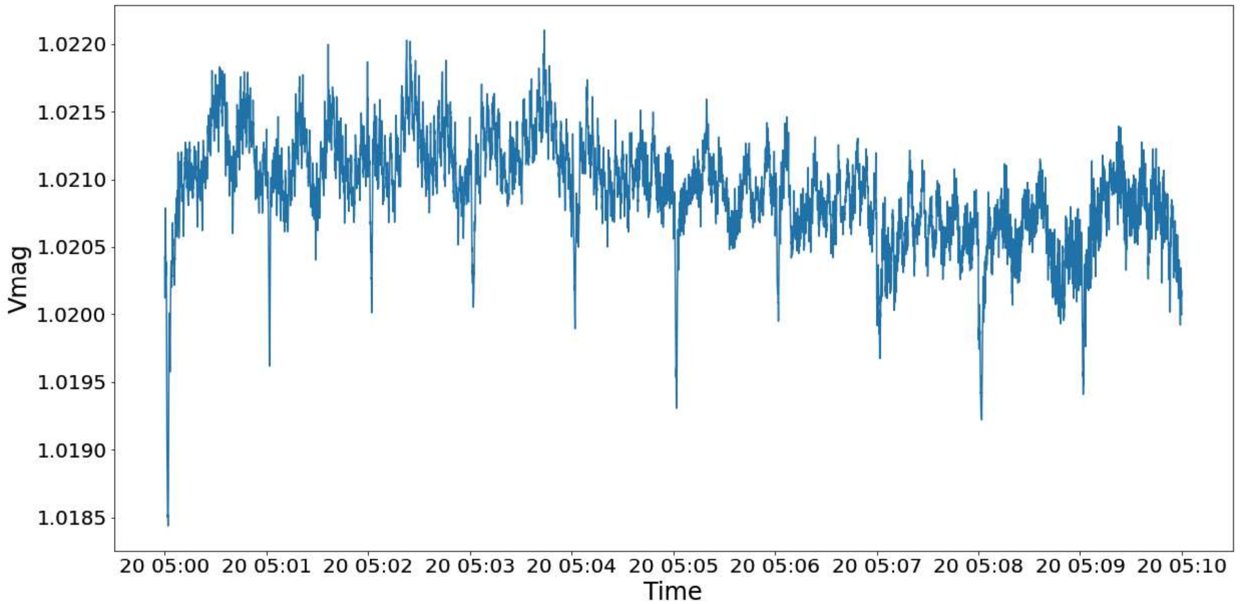




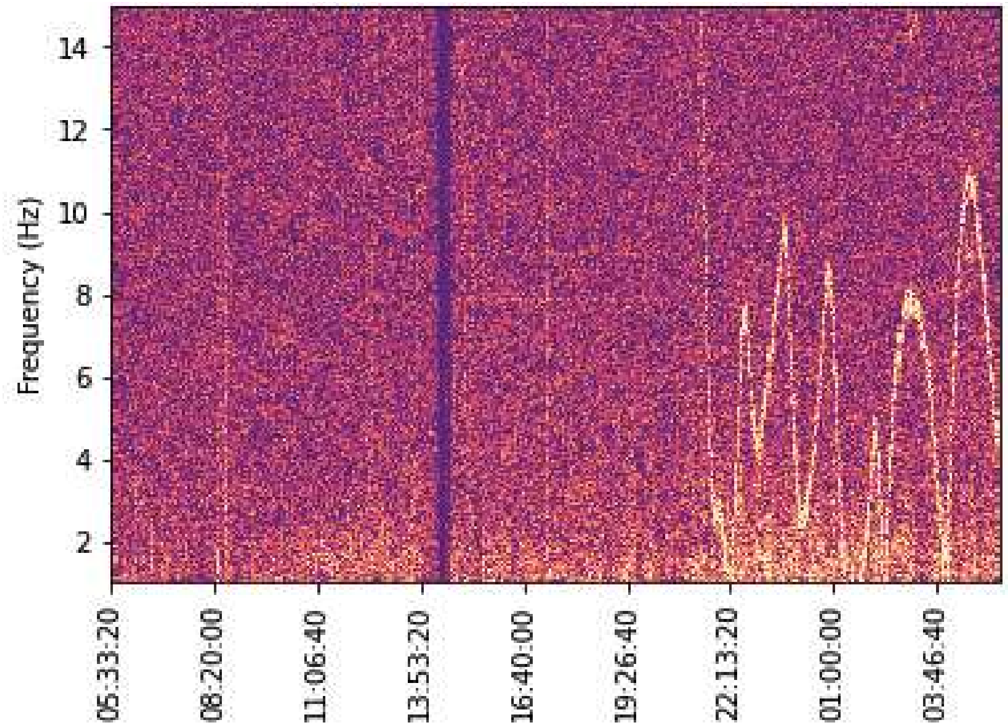
Electric Arc Furnace Operation

- Every 10 mins or so, Large perturbations
- Non-stationary signal
- No well-defined spectral peaks
- Not sure if PMUs process it correctly

Load Dynamics



Periodic Voltage Dips, Couldn't Identify a Source



Suspected Source - Pet Food Manufacturer

FACTS Devices

- Include inverter-based gen, STATCOMs, SVCs, etc
- Power industry is still trying to understand these
- Generic PSS\E models that rarely help anticipate the problems
- Only if we own the resource
  - Black box models in EMTP software
  - Controller replica in RTDS (black box)
- Extremely challenging to “fit” a generic model to unfold dynamics
- But….modeling uncertainties can still not be captured e.g. firmware upgrade reverting to old settings

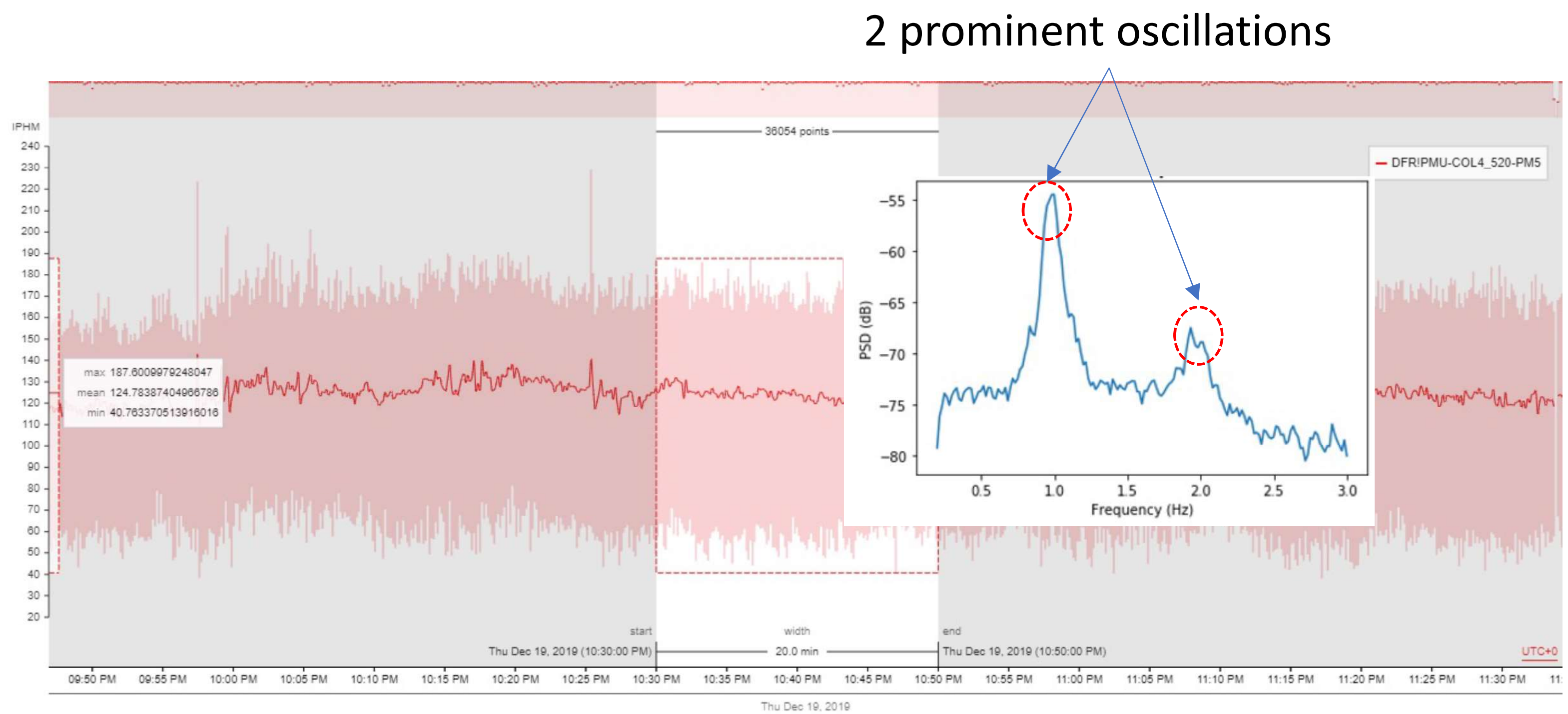
Uncovering Dynamics from Synchrophasor Data

Research Problem

- Aim: Baselining dynamic behavior from measurements
- Motivation -
  - Filling holes in the model up to a certain extent and tuning pre-existing models
  - Identifying problematic controllers and mitigation wherever possible
  - Developing a guide for better operation and planning

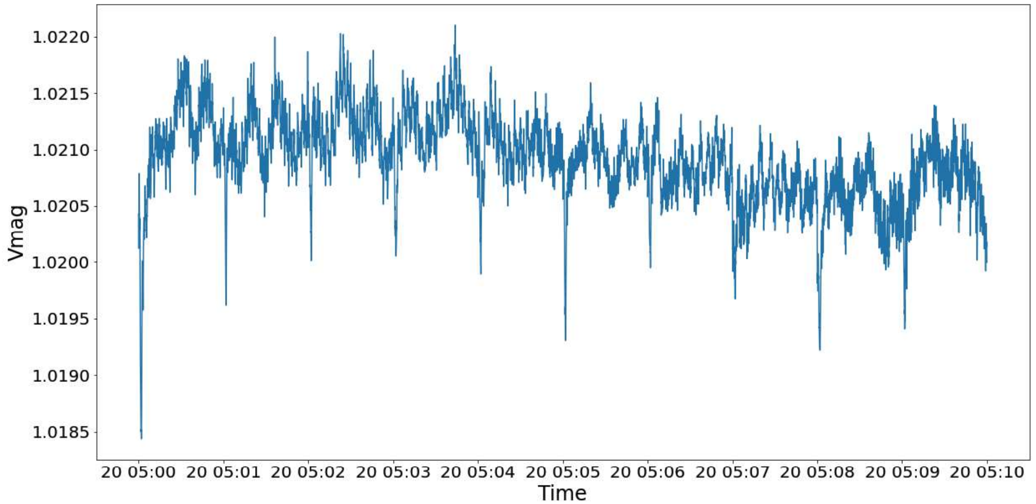
Ambient Data is Rich in Information

- The system is never in steady state but appears to be (ambient conditions)
  - Tiny perturbations like load changes, setpoint changes, etc happen all the time
- Contains information on dynamic signatures
  - Need a different lens to look through (e.g. fourier)



Novelty

- Not only about modes/linear response, interested in generic dynamic behavior/signature from ambient data
  - Existing practice of distilling the whole information into indices loses a lot of valuable information
- Building associations between dynamic signatures and potential sources
  - What are the typical spectral signatures of various sources ?
- Its about combining analytics to fully explain the behavior, e.g. steady state voltage stability metrics can help explain misbehaving voltage regulator



Periodic Dip in Voltage

Challenges

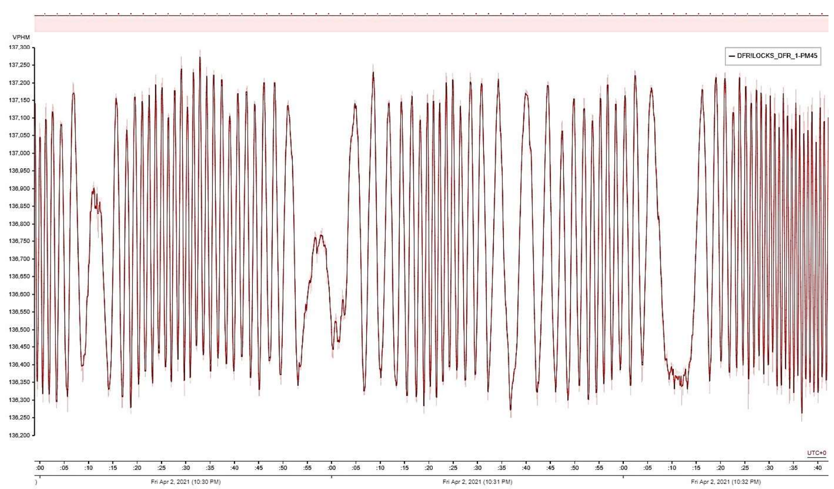
- Large amounts of information to process in space and time
- Synchrophasor data alone is insufficient for root cause analysis, combining information from other measurement sources (even google earth !)
- No textbook recipe, too strong assumptions in the existing literature regarding the underlying dynamic behavior e.g. white noise perturbations on linear system
- Having good tools, figuring out what tools to use (lot of experimentation)

Examples of Challenges from Real Data

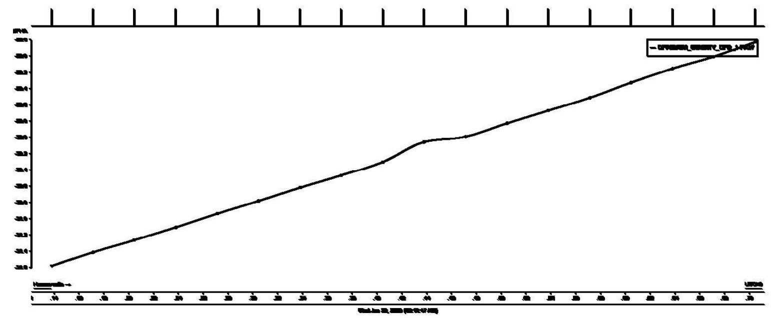
Industrial Loads (Arc Furnace)

Every 10 mins or so, Large perturbations; Non-stationary signal; No well-defined spectral peaks; Not sure if PMUs process it correctly

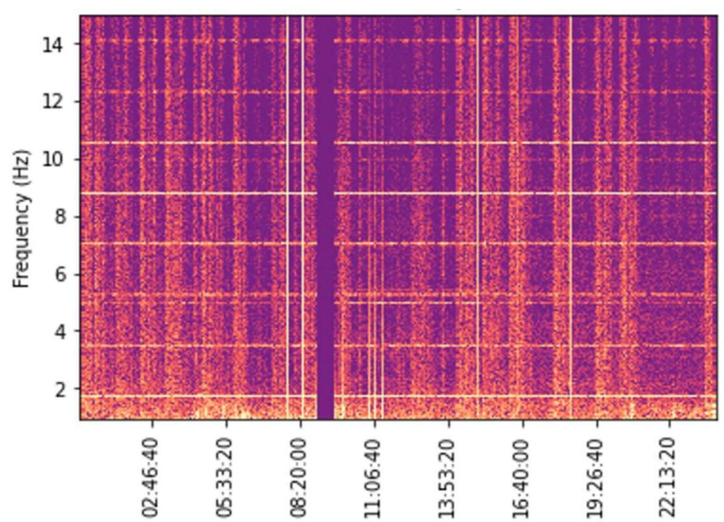
- Unobservability – sparse measurements, not all the internal dynamics are excited sufficiently from the grid side
- Nonlinearities
- Data Quality (especially periodic)



Ambient Conditions ≠ Linearity



Periodic Angle Correction



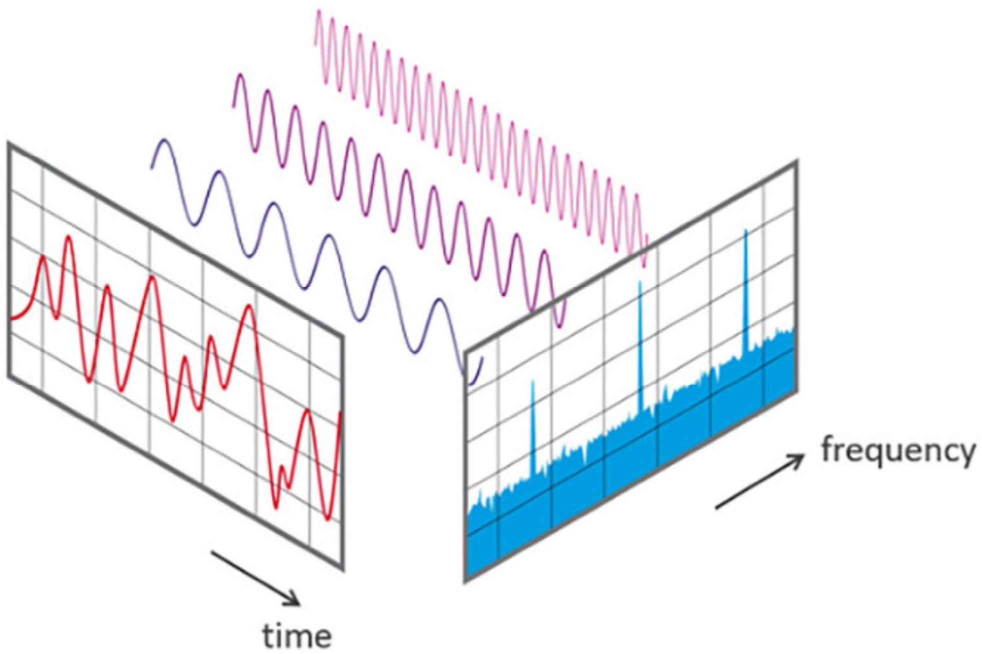
Fourier Transform Review (Frequency Domain Analysis)

- Fourier Transform (analyzing frequency content of a signal)

$$x(t) = \sum_k X(f_k) e^{j2\pi f_k t}$$ $PSD(f_k) = \lvert X(f_k)\rvert^2$ (energy content at each frequency)	(5)

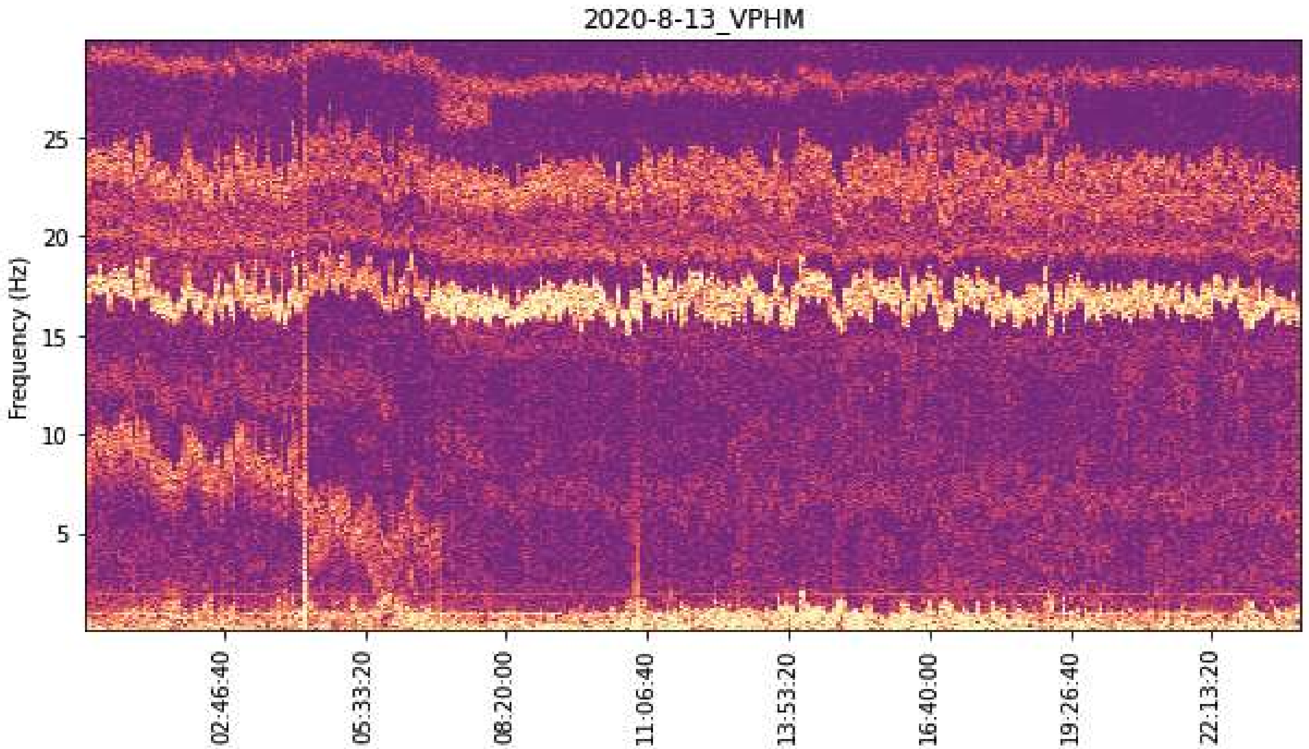
- Advantages
  - Modes appear as clearly defined peaks in measurements
    - Gives insight into noise vs dynamics
  - Nice property for linear systems (differential equation $\xrightarrow{Fourier}$ algebraic equation)

$$\dot{z}_i = \lambda_i z_i + B'\Delta u \xrightarrow{Fourier} (j2\pi f_k - 1)\, Z_i(f_k) = B'U(f_k)$$	(6)



Spectrogram (Time-Frequency Analysis)

- Visual representation of the spectrum of frequencies of a signal as it varies with time (moving window Fourier analysis)
- Modes appear bold colored streaks
  - Sharper the streak, lower the damping
- Useful for analyzing extended periods of time (several hours-days)
  - Allows tracing the evolution and creation/destruction of modes throughout the day
  - Can help distinguish between temporary vs permanent behavior

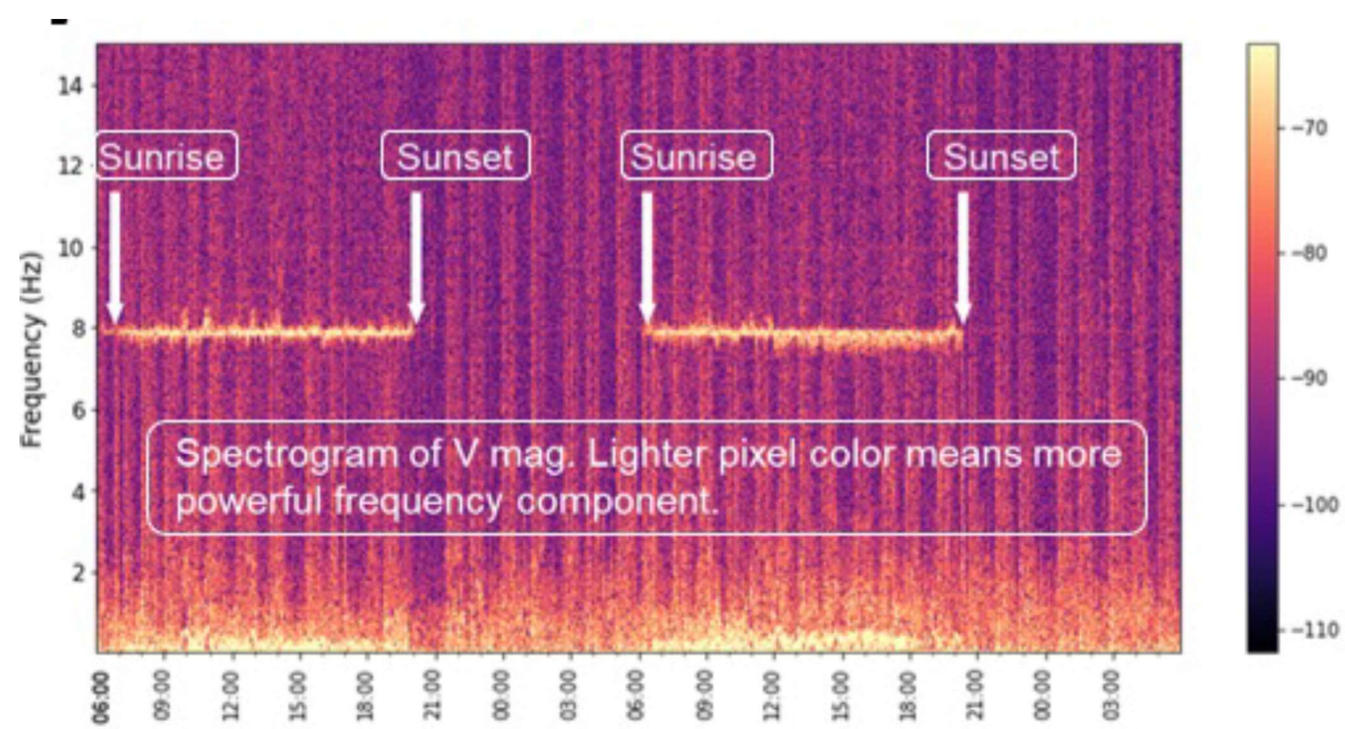


Voltage Magnitude Spectrogram at a Generating Unit

Solar Oscillation

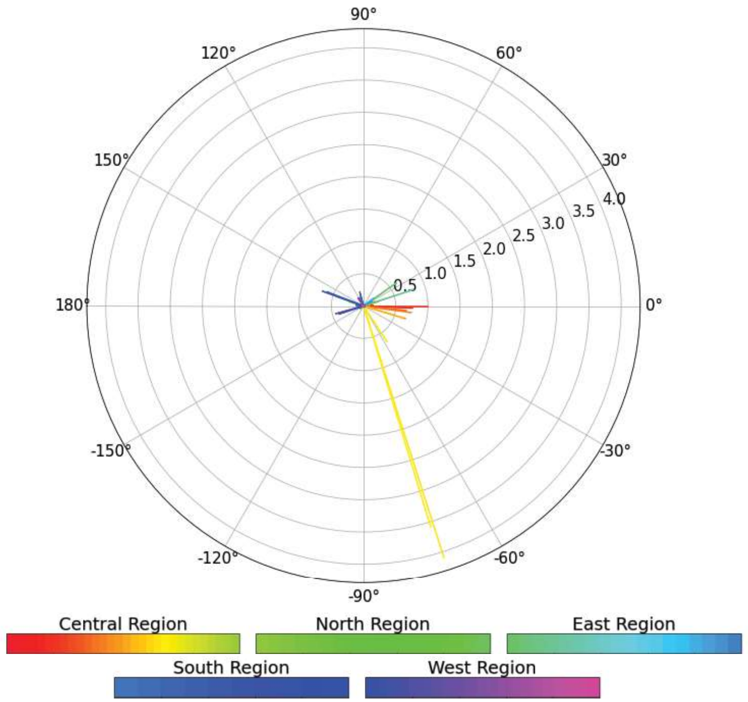
Introduction

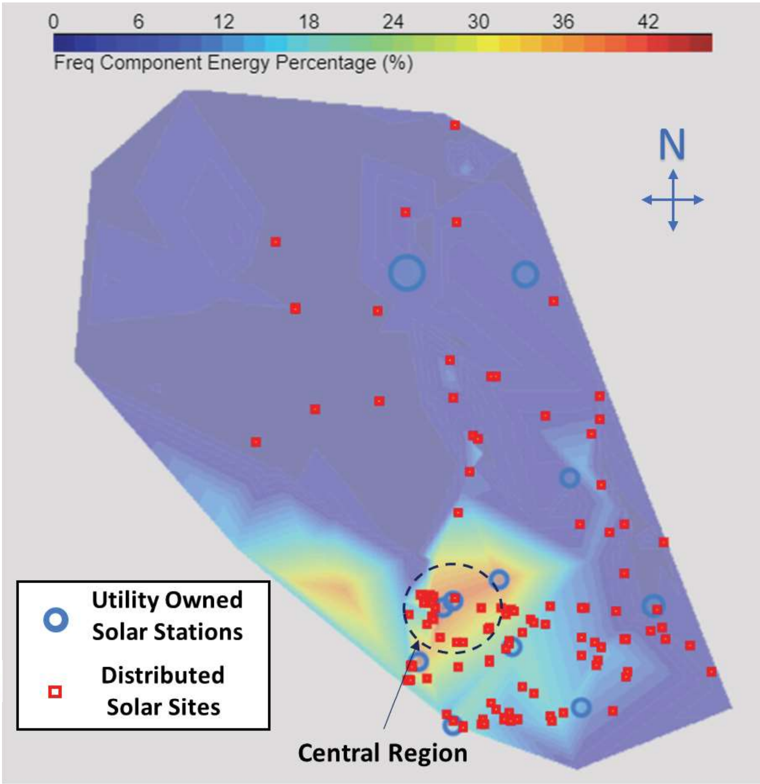
- We first detected an almost constant 8 Hz oscillation when analyzing industrial load dynamics
- Observable everyday during daytime
  - Correlating it with the time of sunrise and sunset was the only clue to identifying its nature…Solar PV !



Source Identification

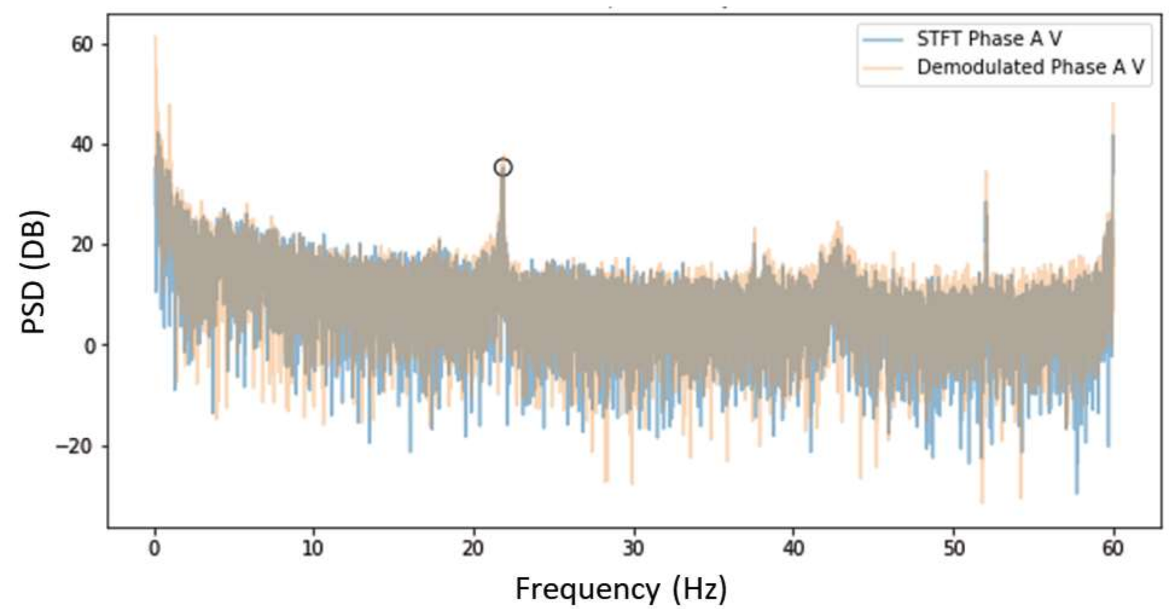
- Observable in only voltage magnitude in ~25 substations
  - Poor observability in current magnitude could be attributed to control mode (unity PF)
- Even though the western region does not have PV, the oscillation propagated there.
- 8 Hz signal energy peak at a single substation with ~ 30 MW solar

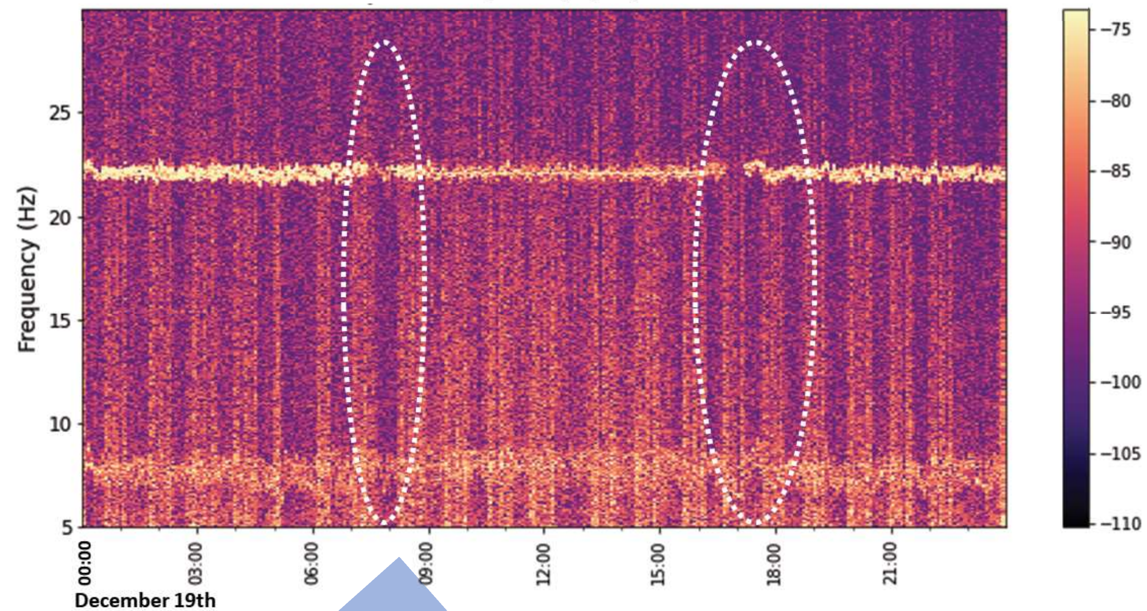




Not 8 Hz !

- PMU data reporting rate is 60 Hz, however, Dominion down samples it to 30 Hz
- Cannot fully trust how PMU processes actual signal content
  - Always good to confirm with point on wave data
- Both STFT and Hilbert Transform showed a spectral peak at 22 Hz
  - Nothing at 8 Hz, aliasing !





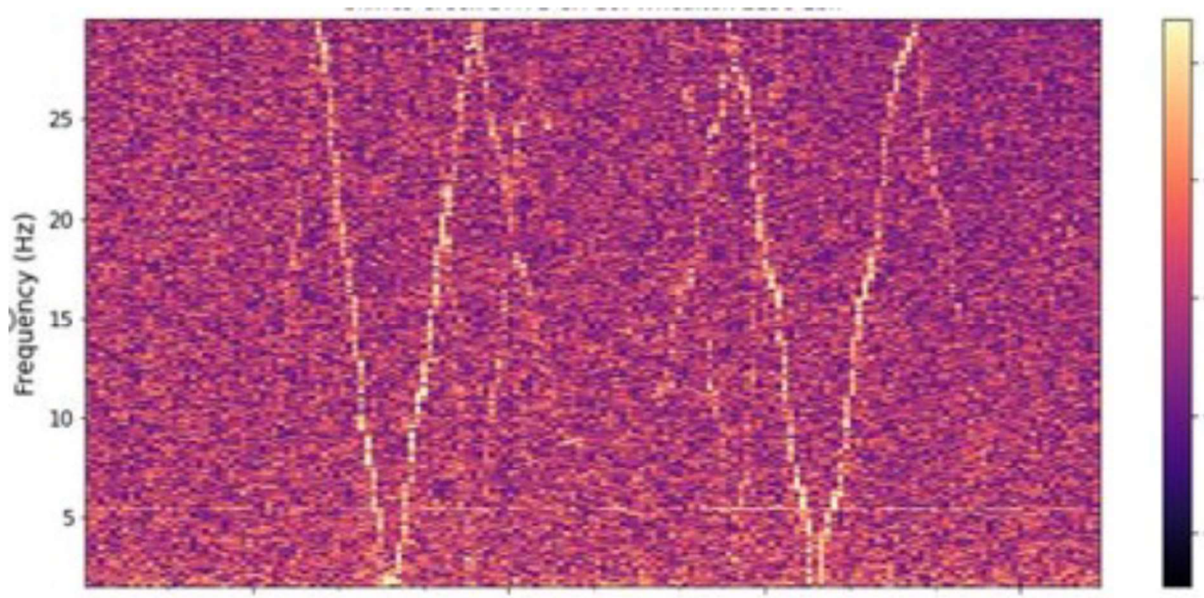
Spectral Folding Due to Aliasing

- Fourier basis vector corresponding to frequency $f = \frac{f_s}{2} + \Delta f$ with sampling rate f_s

$$Z(\theta) = \left[1, e^{j(\pi+\theta)}, e^{2j(\pi+\theta)} \dots\right]^T$$

where $\theta = \frac{\pi \Delta f}{f_s/2}$

- $e^{j(\pi+\theta)} = \cos(\pi+\theta) + 1j sin(\pi + \theta) = \cos(\pi-\theta) - 1j sin(\pi-\theta)$
  - Spectrum (square of fourier amplitude) has symmetry about $n\pi$



Mode with Increasing Frequency + Effect of Aliasing

Dominion Energy

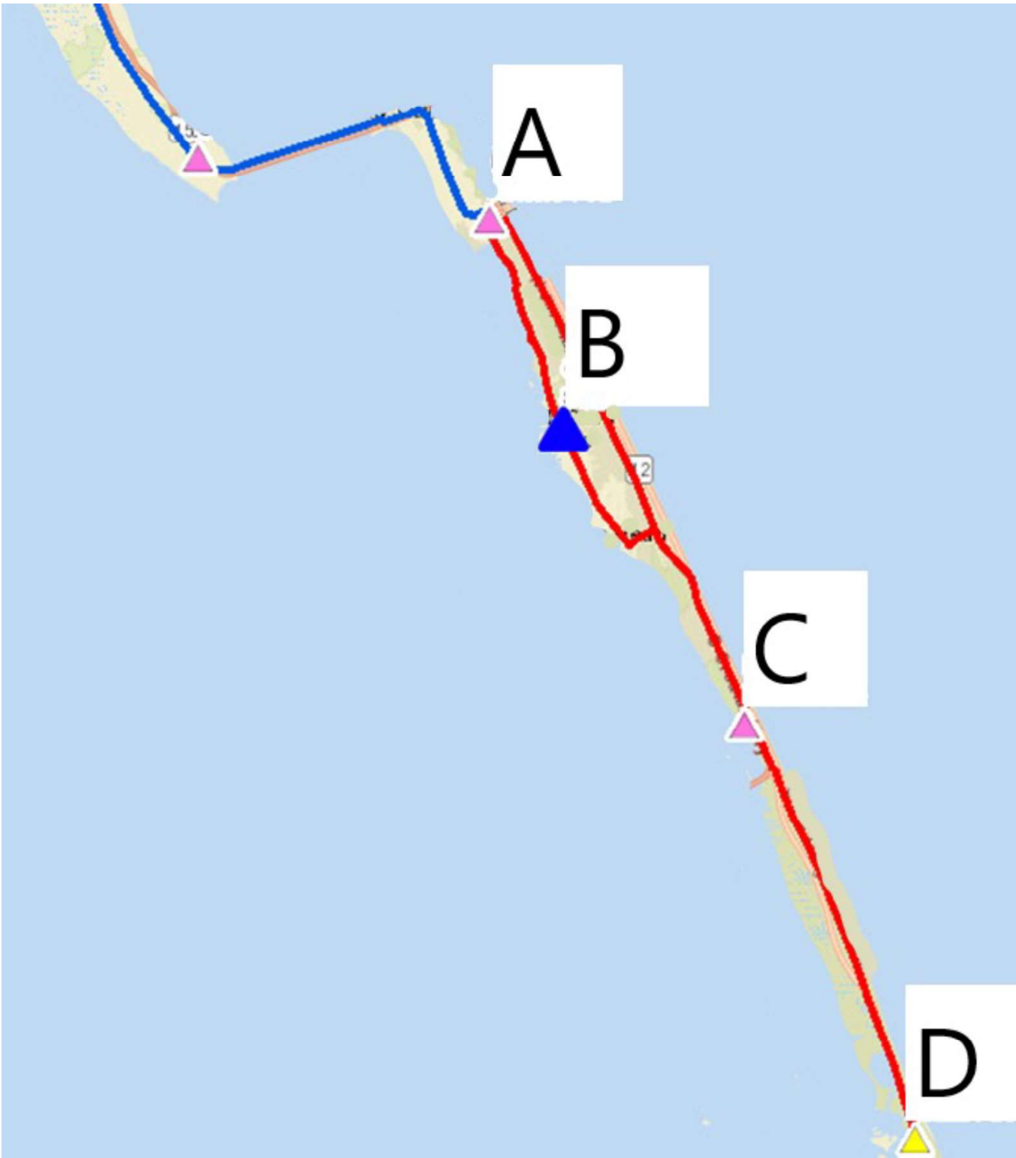
Key Takeaways

- Analyzing the evolution of dynamics over time can provide clues to identifying the potential source
- Sometimes, seemingly harmless processing of the data (down sampling in this case) can hamper the analysis
  - Need to double check against measurements available in the purest form (point on wave)

STATCOM

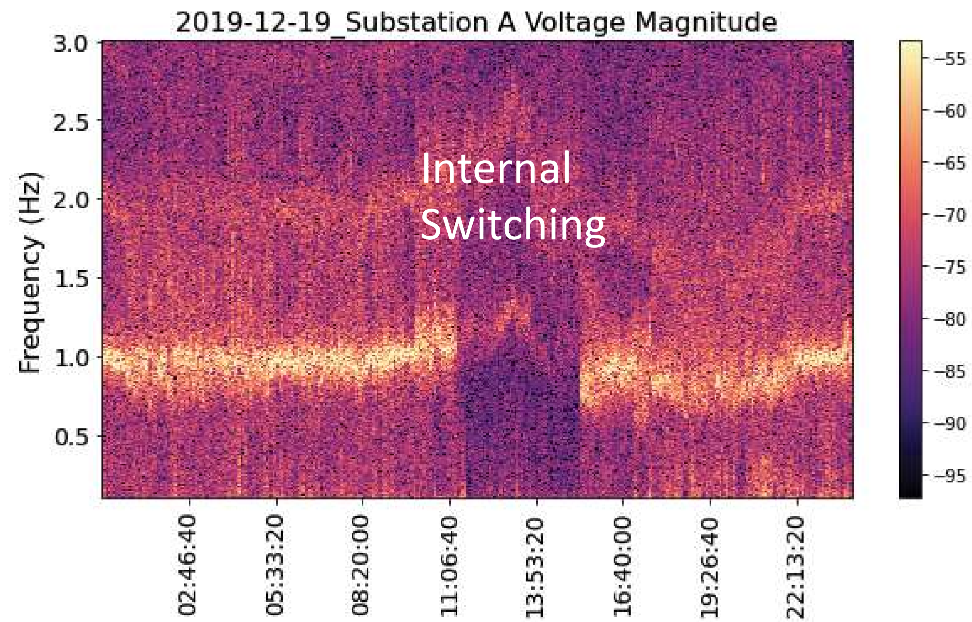
Initiating Event

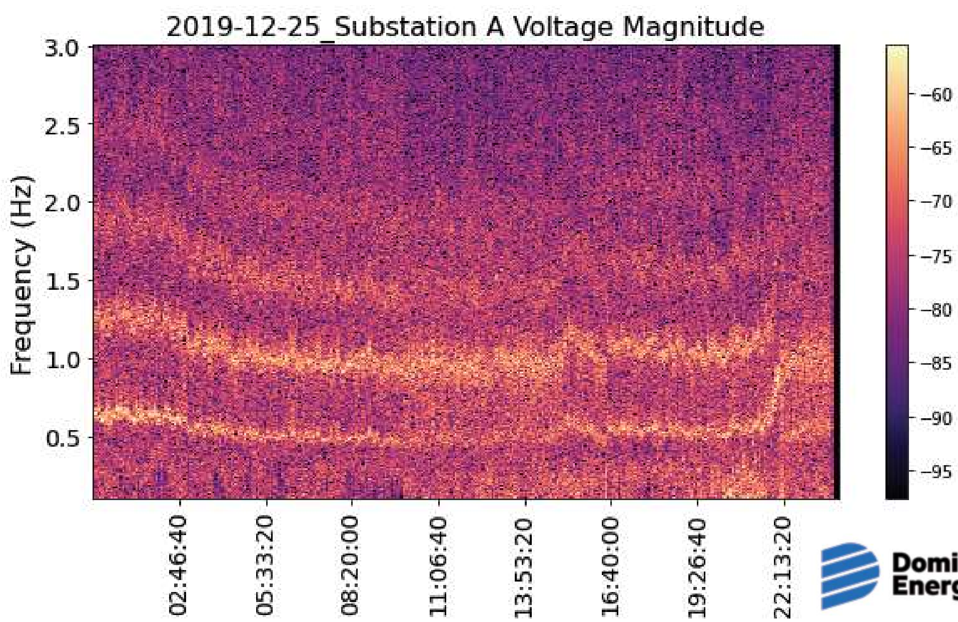
- Almost radial, 115 kV network with no local generation and a 125 MVAR STATCOM at B
- In Feb 2019, opening of line C-D triggered large oscillations
- Vendor conducted root cause analysis using a PSCAD model with a Thevanin Equivalent of the system
  - Recommendations to turn off a control function in weak conditions
  - Brushed off as a one-off event
- What if the issue was always there and no one looked closely ?
  - STATCOMs are supposed to take care of the voltage problems with no adjustments needed

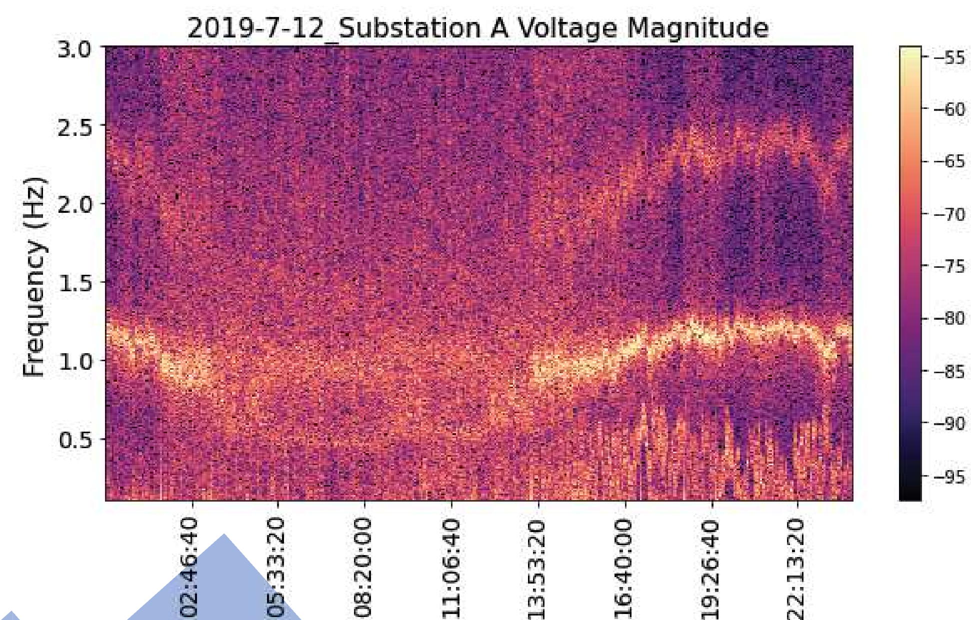


Spectral Analysis of Ambient Historical Data

- Measurements only available at Substations A and C
- 3 modes observable in voltage magnitude
  - Identical eigen trajectories points to a harmonic set
  - Poor damping often observed
- Switching inside the controller makes the mode vanish
  - Could not recreate using model



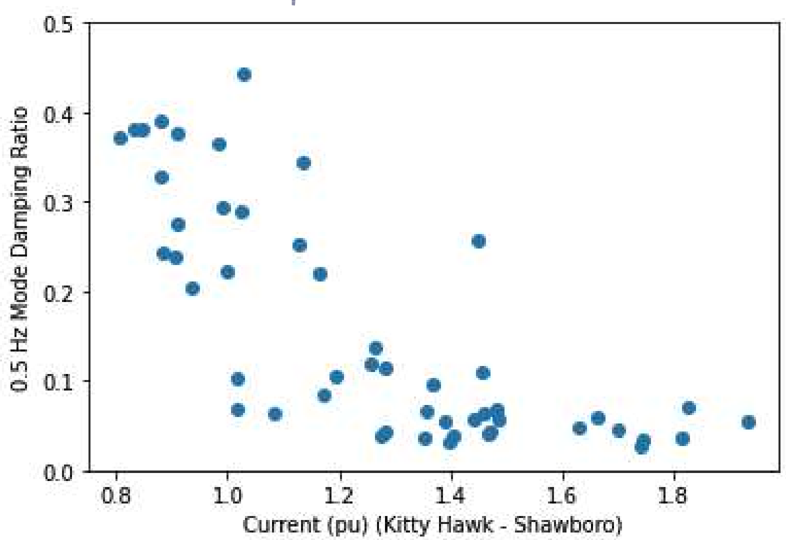


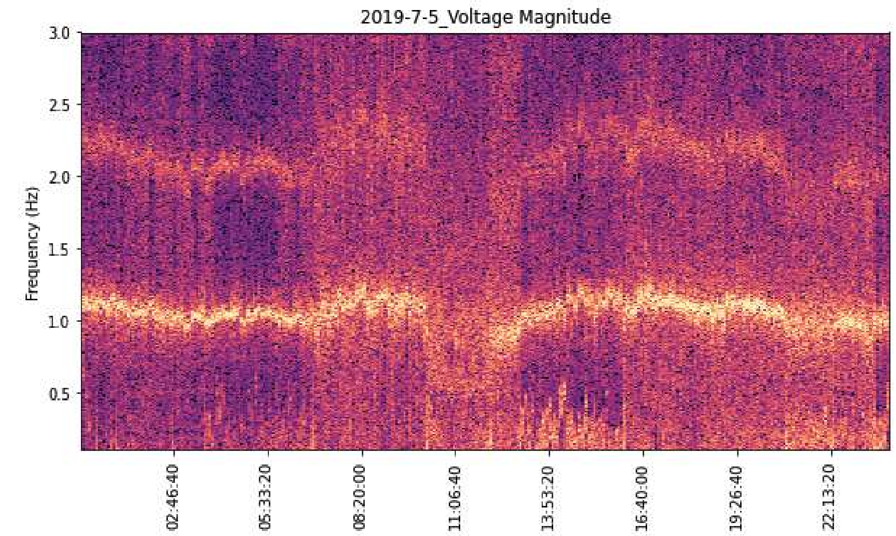


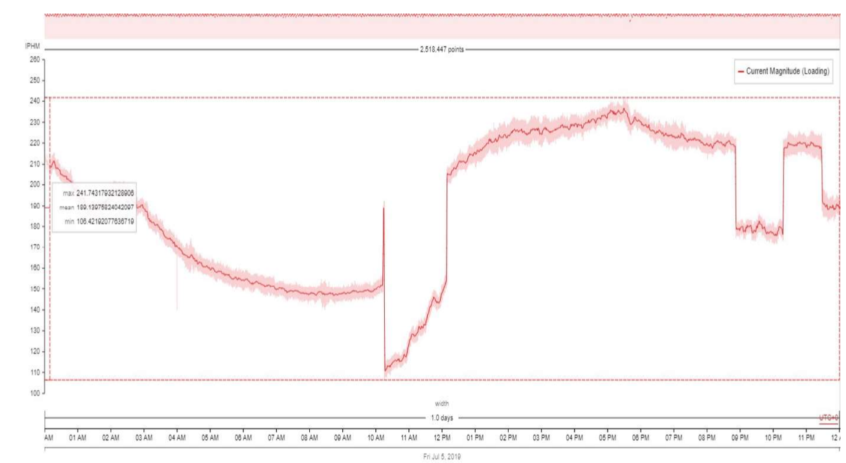
Dominion Energy

Familiar Pattern

- Qualitative behavior (damping and frequency) of dominant oscillations had a close link with system load
- Damping decreased with increasing loading, often went below 5 %
    - Need for adaptive control



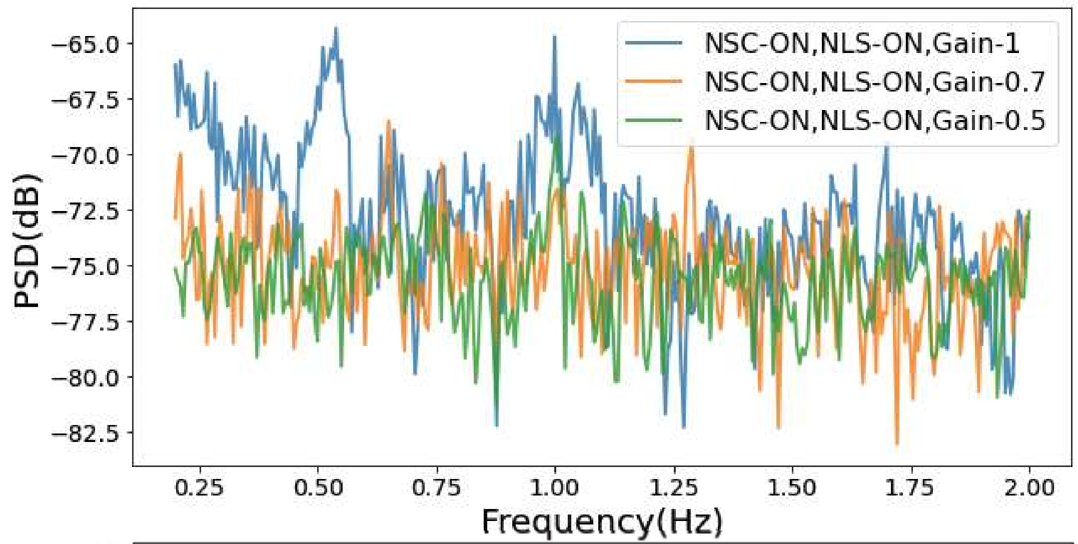


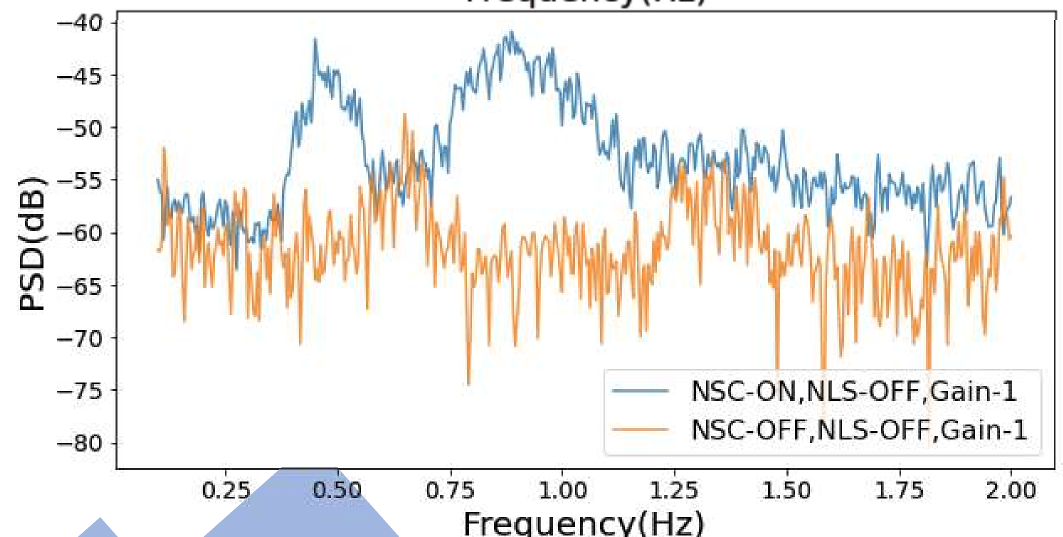


Dominion Energy

Online Test to Identify Specific Cause

- Need an accurate model or controlled experiments in the field to identify the specific component at fault
- STATCOM is run in QV control mode with Q = 0 with V control only during transients
- STATCOM has a negative sequence control (NSC) functionality that helps balance,
  - STATCOM individual submodule voltages (besides circulating current)
  - Transmission system imbalance
- Before scheduled maintenance outage, effect of control gain change and NSC was studied
  - Poorly damped mode associated with NSC ON state
  - NSC confirmed to struggle during weak system conditions and/or large imbalances while maintaining Q = 0





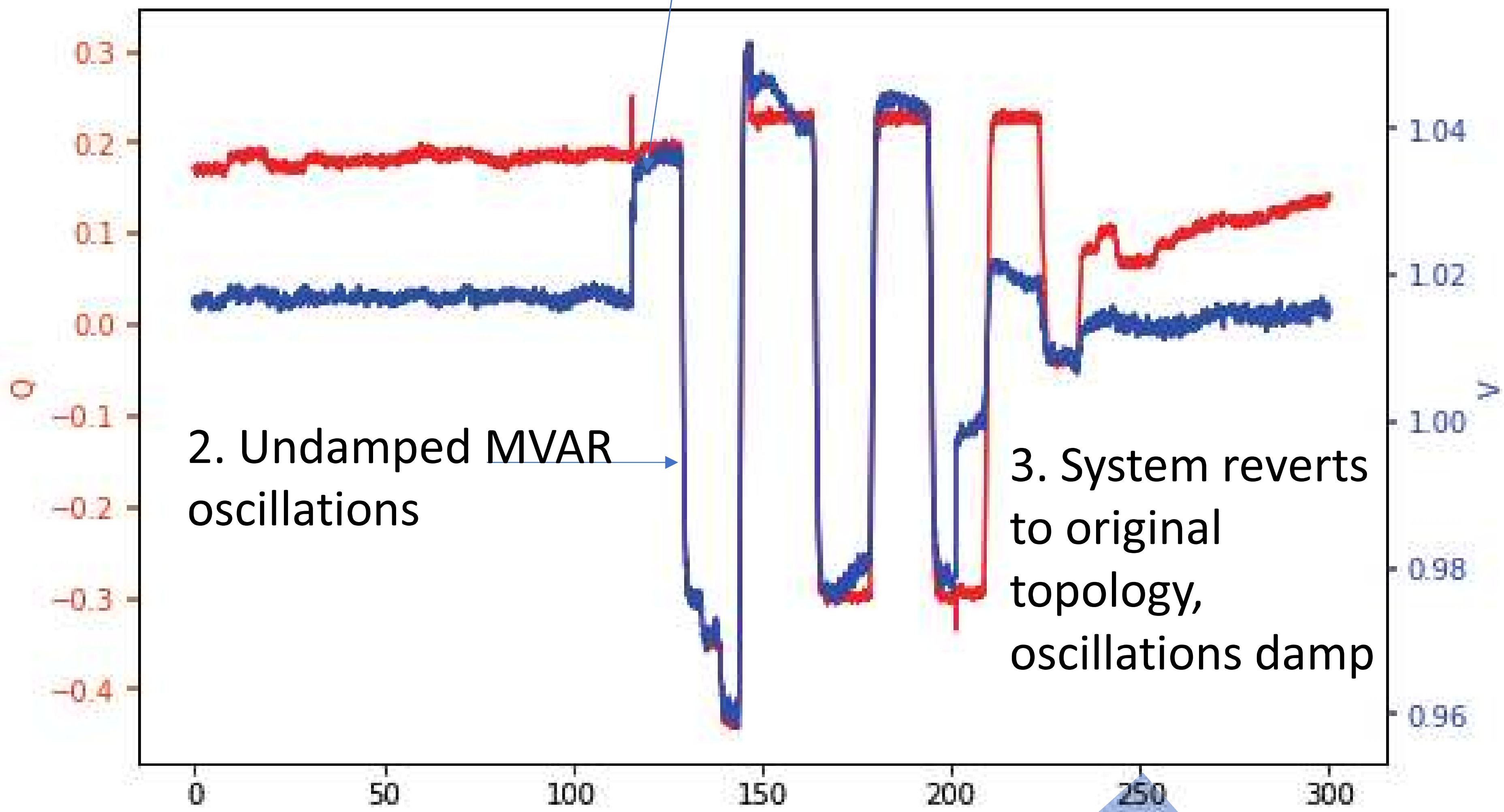
Key Takeaways

- Cannot wait for large events to expose issues in the system
- One set of control settings may not work well for the whole year, need to adapt
- FACTS controls can be complicated with internal switching (hybrid system)
- To fully explain the case, need better models and/or ability to do online experiments
  - Asset owner must work with the vendor to get the models right based on continuous evaluation of performance using measurements

Hierarchical Control Scheme for Solar

PV Oscillation

1. Line opened making the PV plant radially connected, overvoltage observed

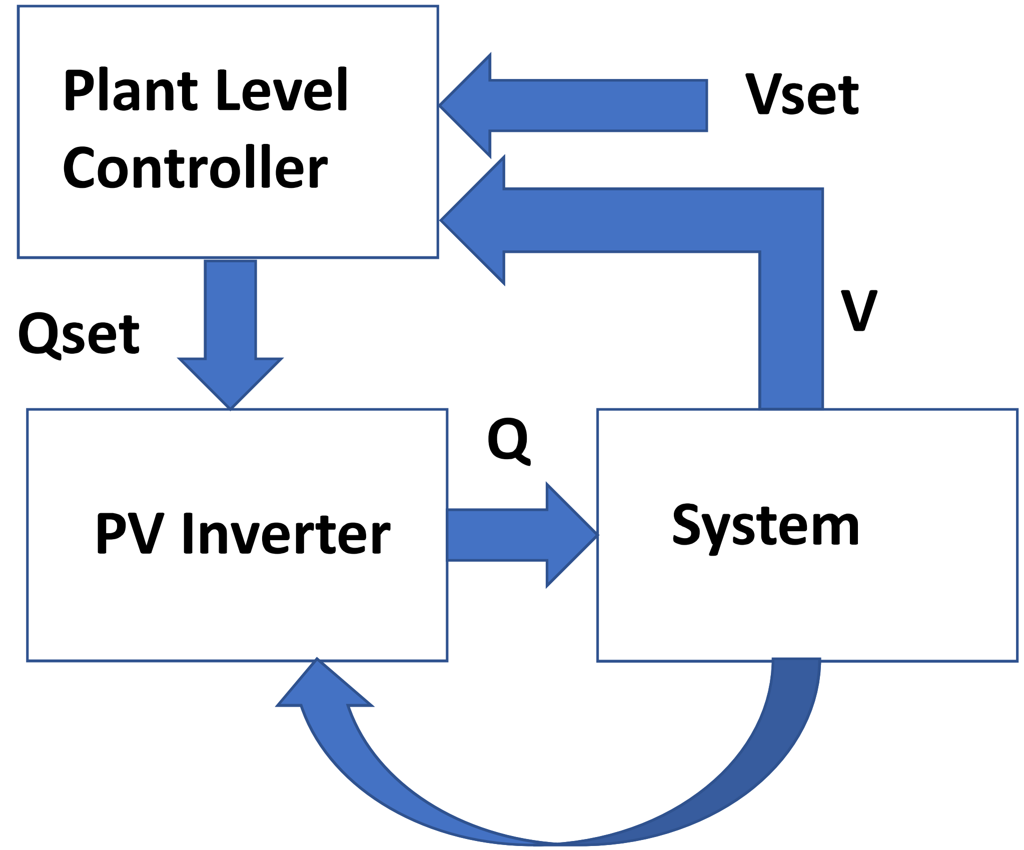


2. Undamped MVAR oscillations

3. System reverts to original topology, oscillations damp

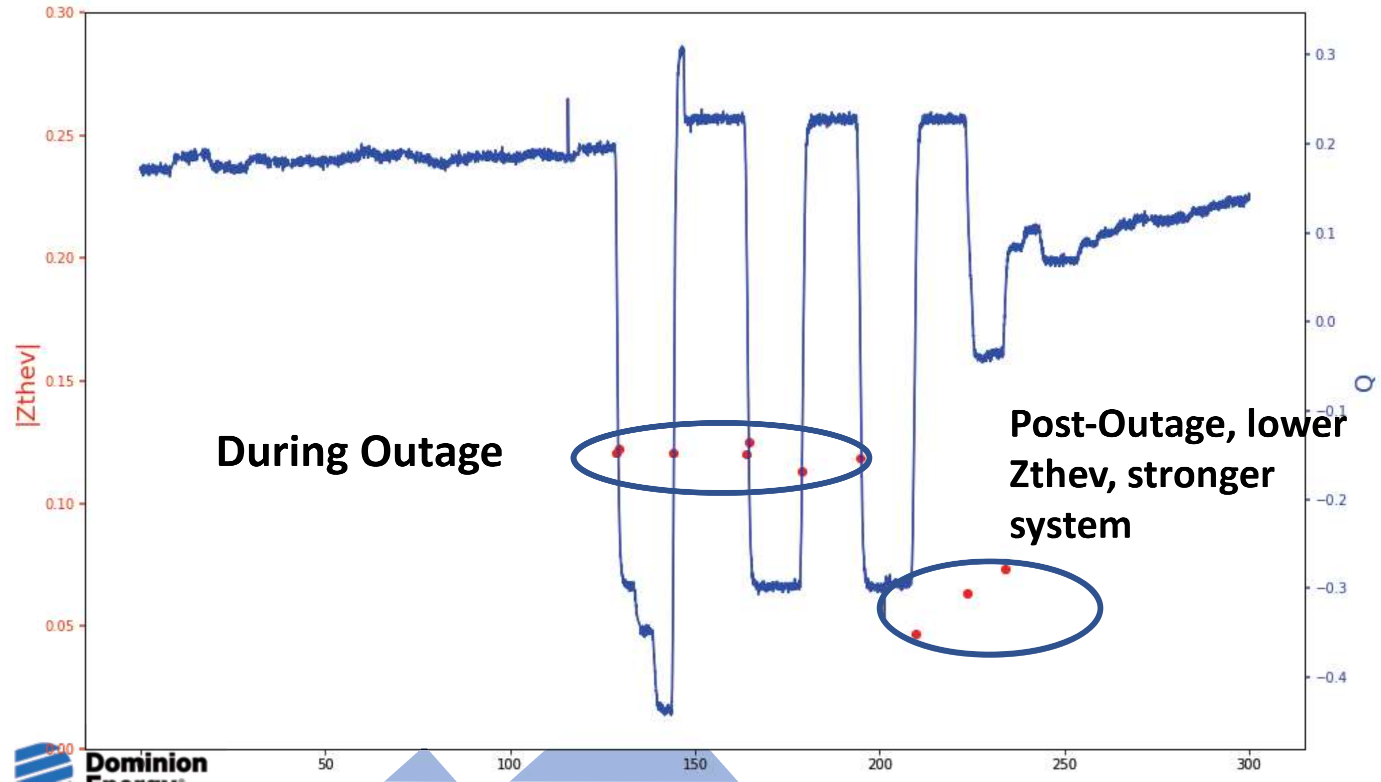
Atypical Control Setup

- Third party plant level PI type voltage controller
  - Feedback signal from POI meter takes 3 s to reach the controller
  - Execution period set to 4 s
  - Runs in V control mode, no deadband
  - Disabled when solar PV output less than 10 %
- PV inverter operating in PQ mode
- Evaluation of controller performance is done during commissioning using normal system conditions
  - No simulation studies
  - Settings revisited if any issues



Closer Look

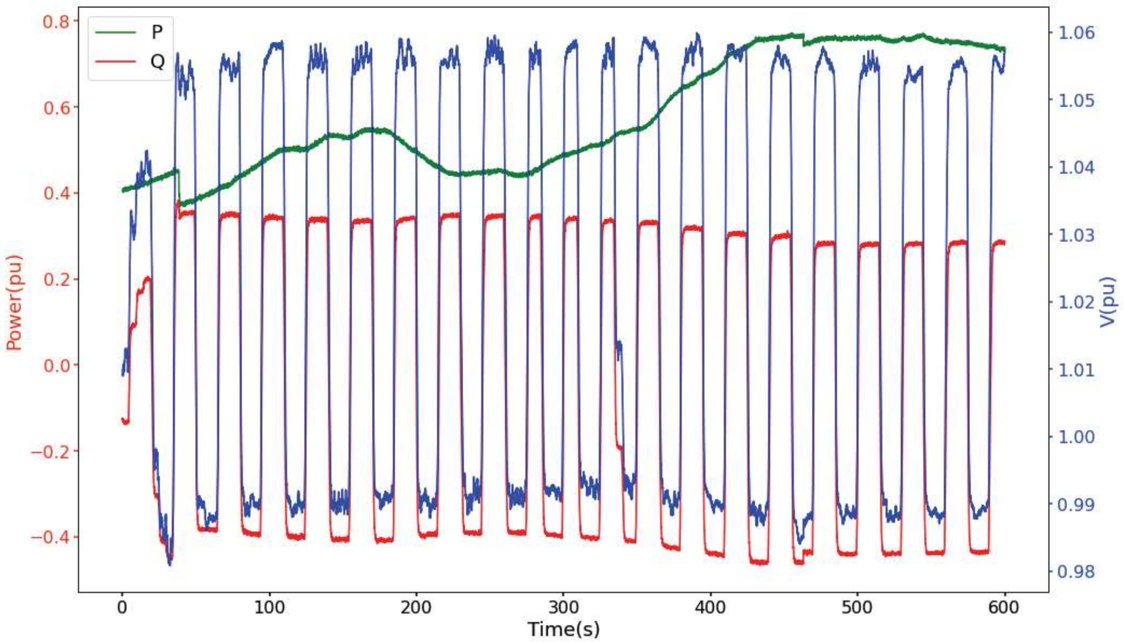
- Thevanin Impedance is a good metric for voltage security
  - Needs a significant change (ideally a step) to estimate correctly
  - Detect change points and estimate Thevanin at them
- A significant increase in Thevanin impedance due to topology change was observed
- Controller was not tuned to work with the new weakened system



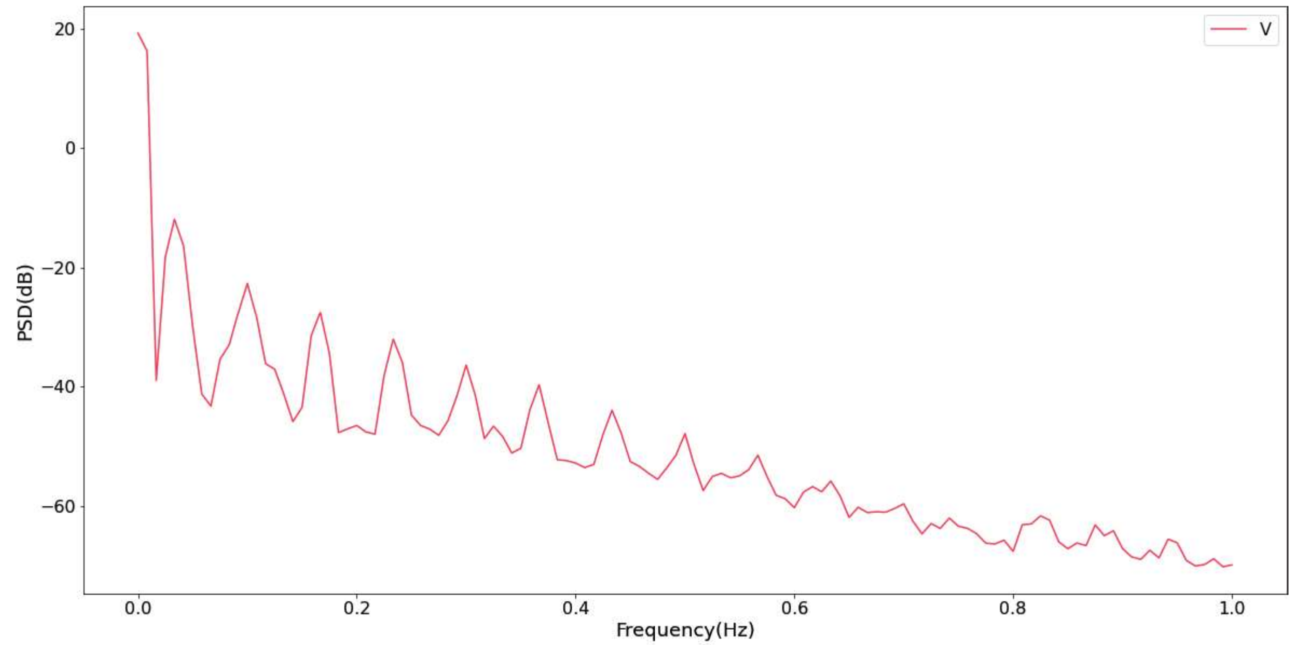
Dominion Energy

Traditional Oscillation ?

- Square wave type oscillations and not exponentially decaying sinusoids
- Sinusoidal basis (Fourier) is not optimal for spectral analysis, shows N different modes



Time Domain



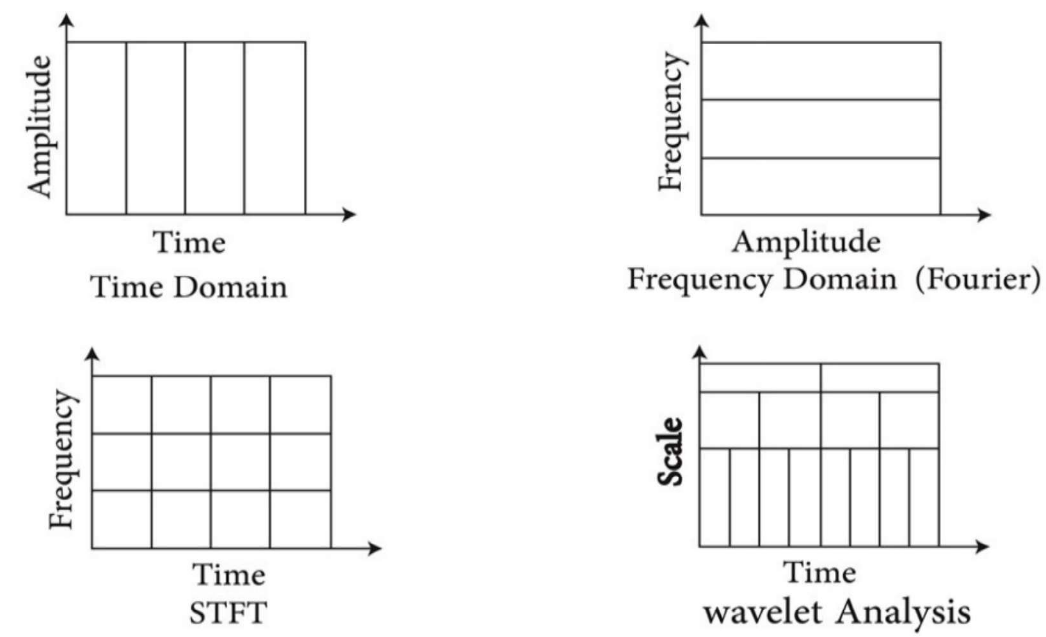
Frequency Domain

Time Frequency Analysis and Wavelet Decomposition

- Spectrogram has a tradeoff between time and frequency resolution
- Idea is to choose window length based on frequency
  - Low time resolution for small frequencies, high time resolution for large frequencies
  - Most signals follow this pattern
- Wavelet decomposition uses non-sinusoidal basis (chosen based on the underlying signal being studied)

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right)$$

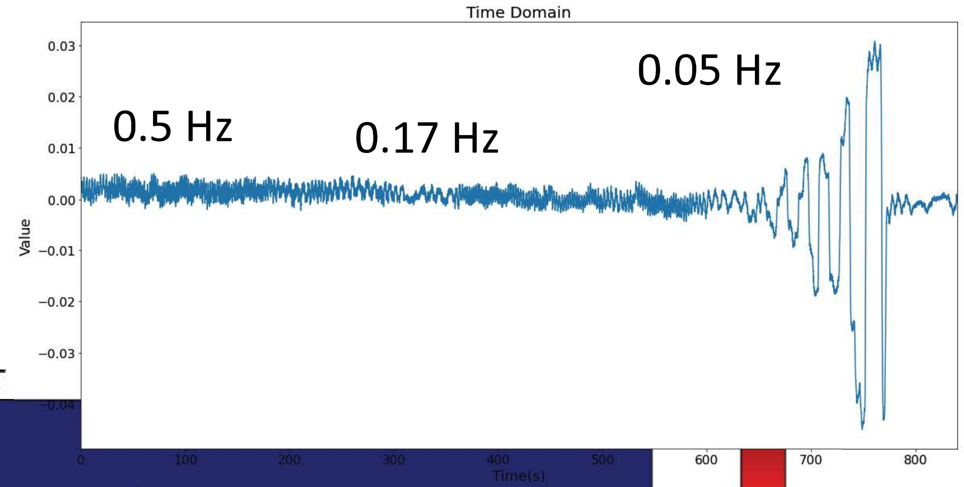
- b shifts, a stretches the mother wavelet ψ

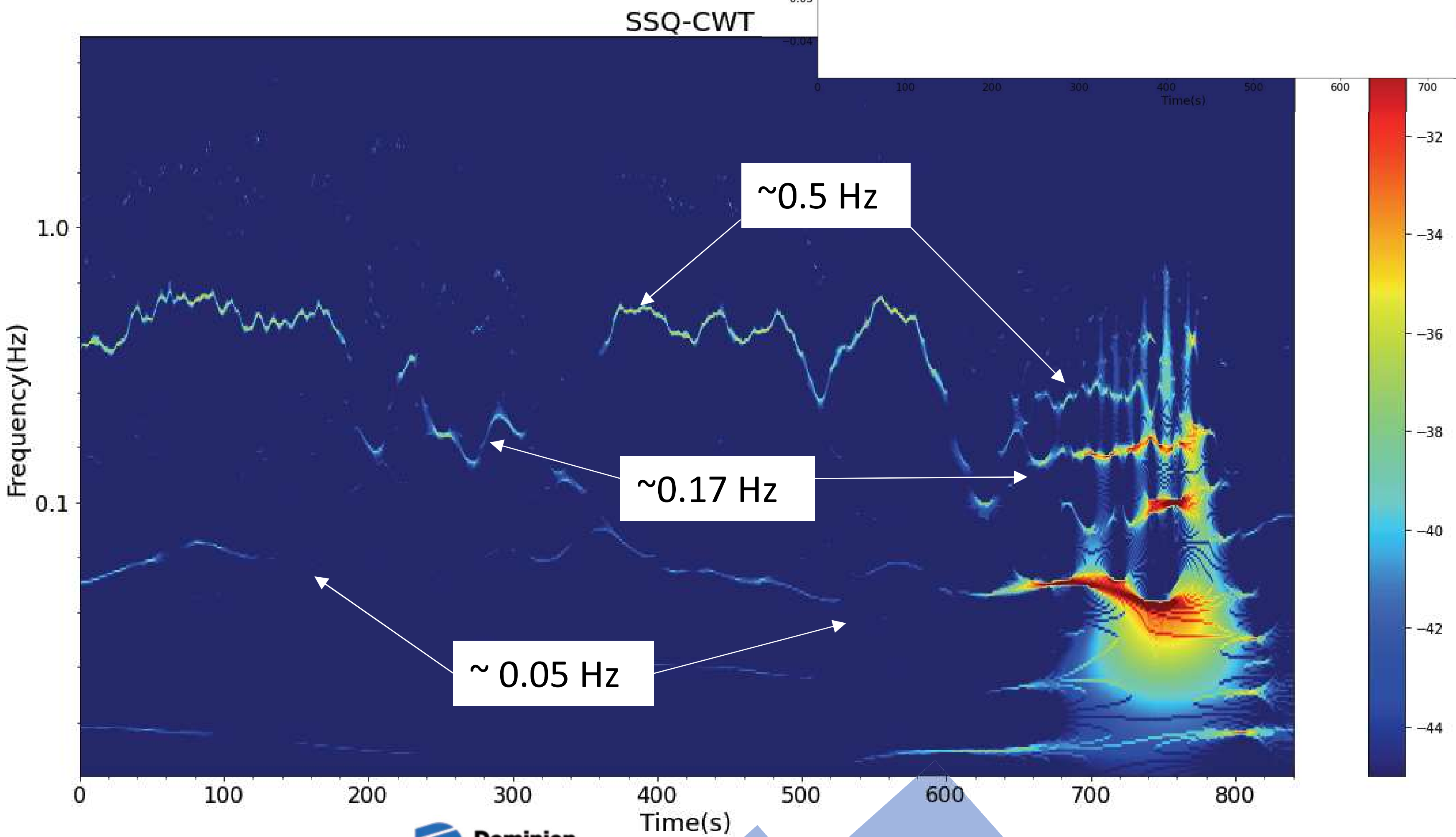


Time Frequency Analysis

Spectral Analysis

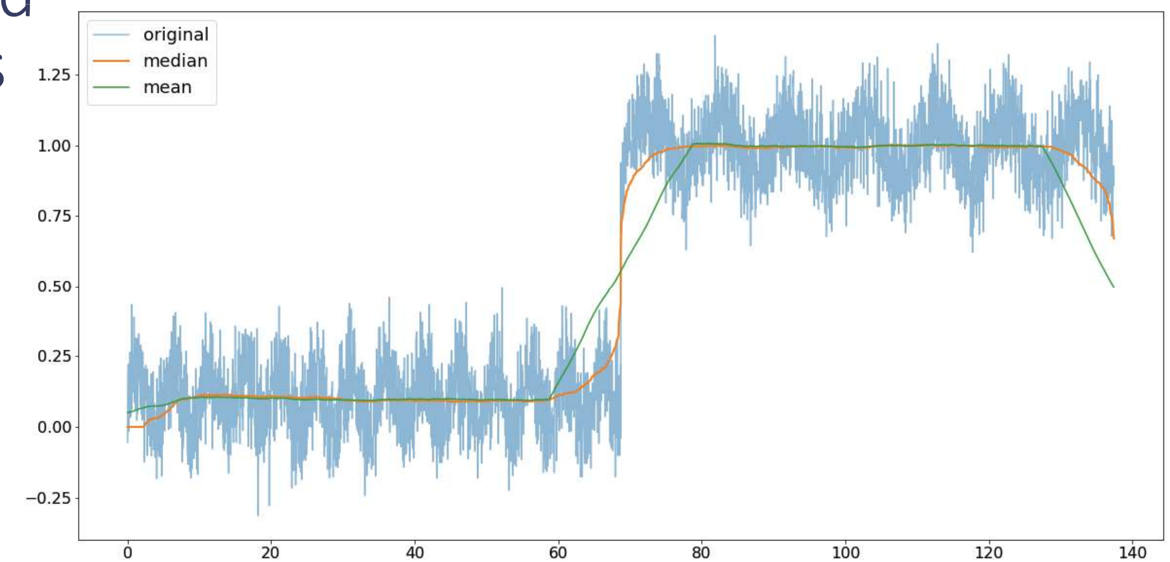
- 3 time scales – 0.05, 0.17 and 0.5 Hz
- 0.5 transitions to 0.17 occasionally
- 0.05 (controller mode)
  - Can be observed during ambient conditions
  - Becomes unstable, effects others due to coupling





Scaling Over Time (Event Detection)

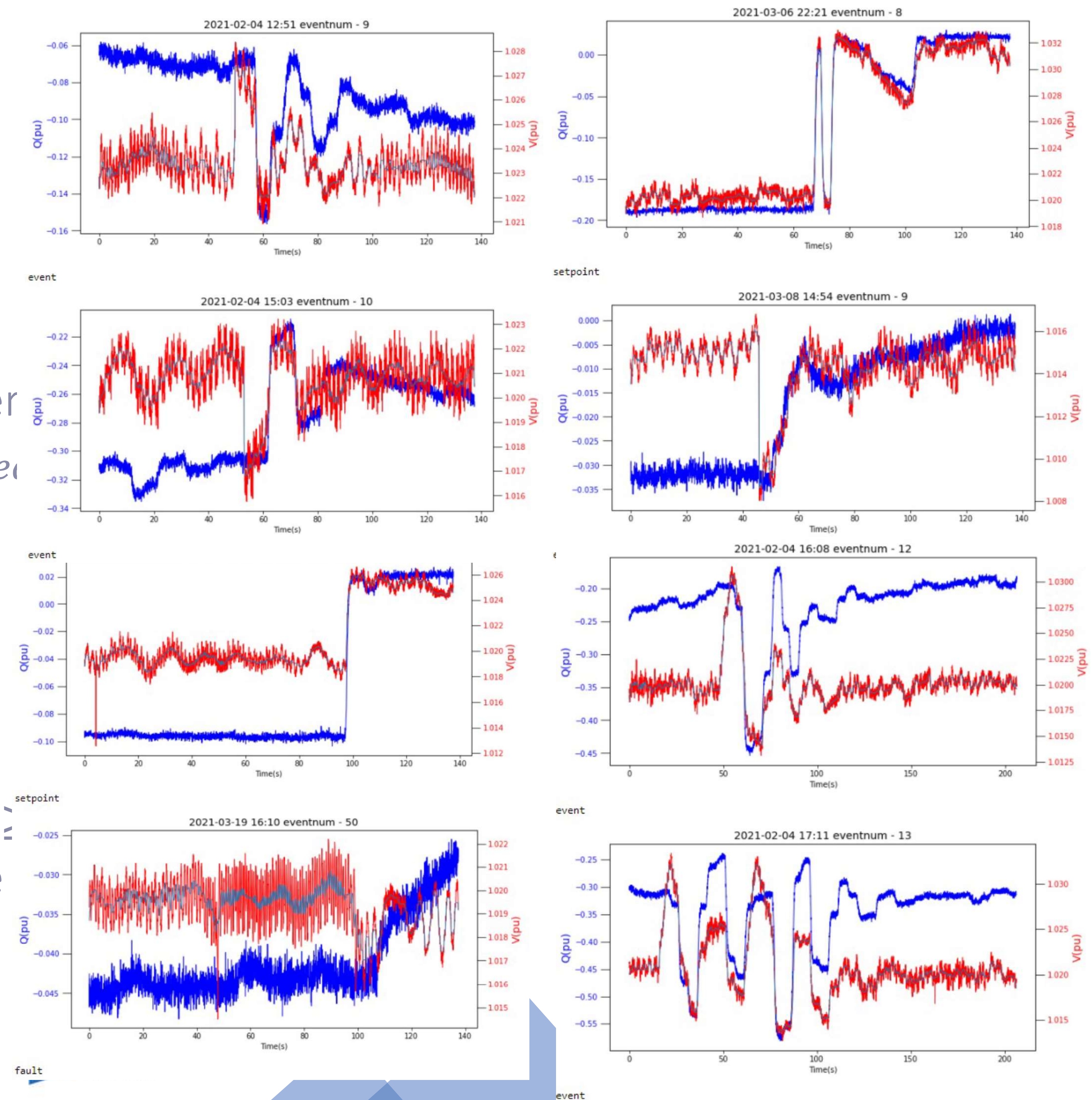
- For baselining controller behavior, need a way to quickly identify time windows where the controller dynamics are observable
  - Further classify into voltage setpoint change vs step response vs transients
- Relevant info
  - Controller acts every 4 s
  - Tiny voltage setpoint changes < 0.005 pu not done
  - Fault effects usually stay for < 2s



Median filter preserves edges better

Results

- Detection and Classification
  - 2 s moving window median filter to voltage magnitude data - V_{med} (smooths out fault)
    - **Label – fault** if If $\max([|\min(V_{med}) - mean(V_{med})|, |\max(V_{med}) - mean(V_{med})|]) \leq 0.003$
  - If not fault, if $\left|mean\left(V(t \leq 3s)\right) - mean\left(V(t \geq T-3)\right)\right| \geq 0.003\ pu$, **Label – setpoint,** Else **Label - Event**



Key Takeaways

- Combining information from different metrics can help with root cause analysis
- Ambient conditions do not automatically imply an underlying continuous linear time invariant system
  - Choice of basis for decomposing the signal is driven by the underlying system dynamics
- There is always an associated event detection/classification problem (usually unsupervised) to identify relevant time windows

Next Steps…

- Unsupervised identification of time periods of interest
- Integrate spatial information
- Learning mapping between operating conditions and dynamic behavior

Thank You !

Baselining Dynamic Behavior

- Not about one mode at one frequency, trying to understand the mechanism
- Traditionally, analysis of dynamics focuses on
- What do problems look like in frequency domain, purely ambient data because baselining, about interpreting

- Theres a lot of things that have been ignored from the point of view of traditional mode estimation
- Not about an index(loss of info), its about characteristics
- Its all about creating customized (which combo of tools needed in each problem)
- Whats New ?
- Having good tools, figuring out what tools to use