Tracking Periodic Voltage Sags via Synchrophasor Data in a Geographically Bounded Service Territory

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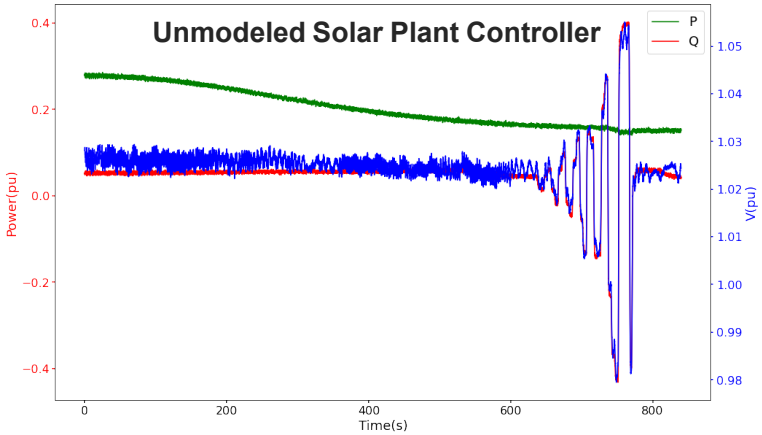
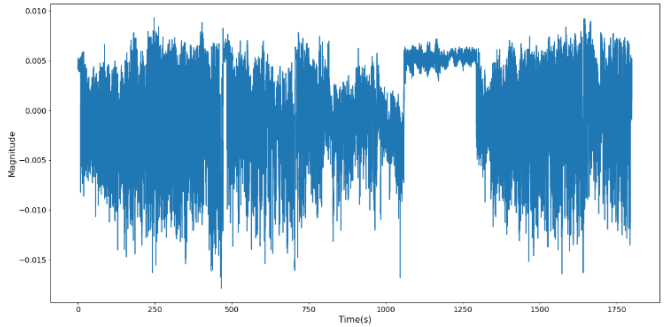
Importance of Data Driven Analysis

- 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 !)



- Power industry heavily relies on models for planning and even control specifications
- Models for real-world FACTS and Renewable Generation
  - Usually not available, Generic models rarely help with troubleshooting
  - Complicated by protection
  - Black box models in EMT software and/or controller replica
  - Not always updated with device changes
- Have to rely on measurements !



Unmodeled Load - Electric Arc Furnace

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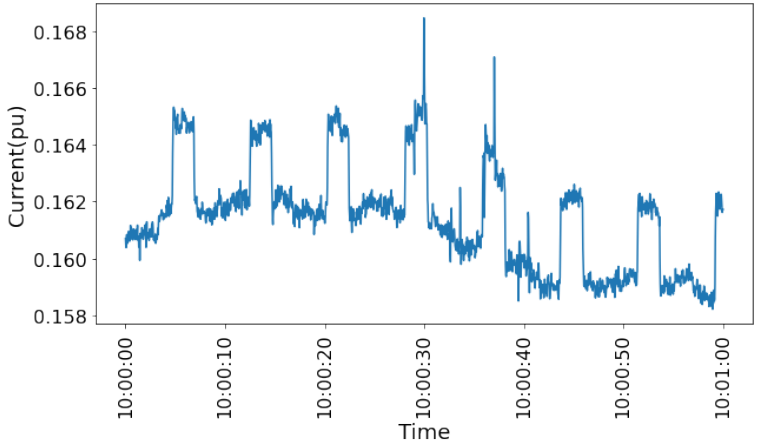
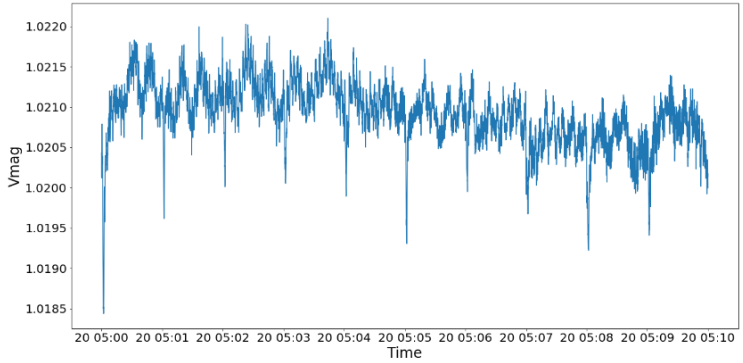
Not All Periodic Behaviors Stem from Instability

- Real world power systems are full of harmless periodic behaviors
  - Usually a result of industrial duty cycle
- Can be confused with stability issues (which also manifest as limit cycles) and trigger alarms
  - Need to locate their source as well as analyze their long term behavior to understand whether an issue
- Can play important role in model estimation
- Dominion observed a voltage sag once a minute in a load dominant area
  - Small enough < 5% to not cause power quality issues
  - STATCOM impedance estimation logic thought to be the source



Auxiliary Load at Power Plant



Voltage Sag Every 1 min

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Spectral Analysis Background

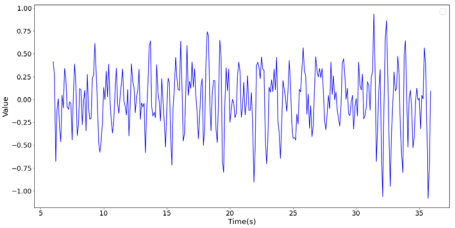
Power spectral density

- Distribution of signal power over frequency

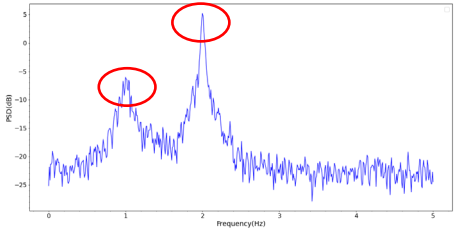
$$\int S(\omega)d\omega = \lim_{T\to\infty} \frac{1}{T} \int E(|x^2(t)|)dt$$

- Can help discern oscillatory dynamics

Oscillatory Behavior



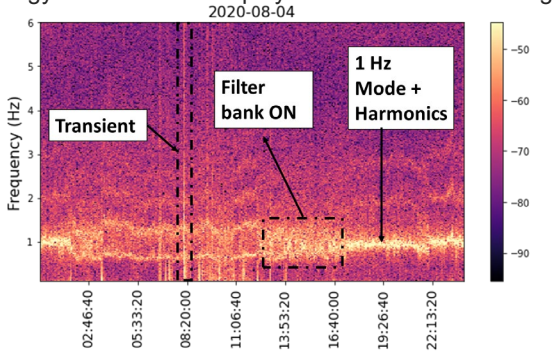
Time Domain



PSD

Time Frequency Analysis

- System changes all the time (topology, load, generation dispatch, setpoints, etc)
  - Time varying spectrum
- Time-frequency analysis techniques decompose the signal using basis (building blocks) that are approximately compact in time and frequency
  - Analogy: what instrument played at what time in a song



24 Hr Spectrogram of STATCOM Voltage

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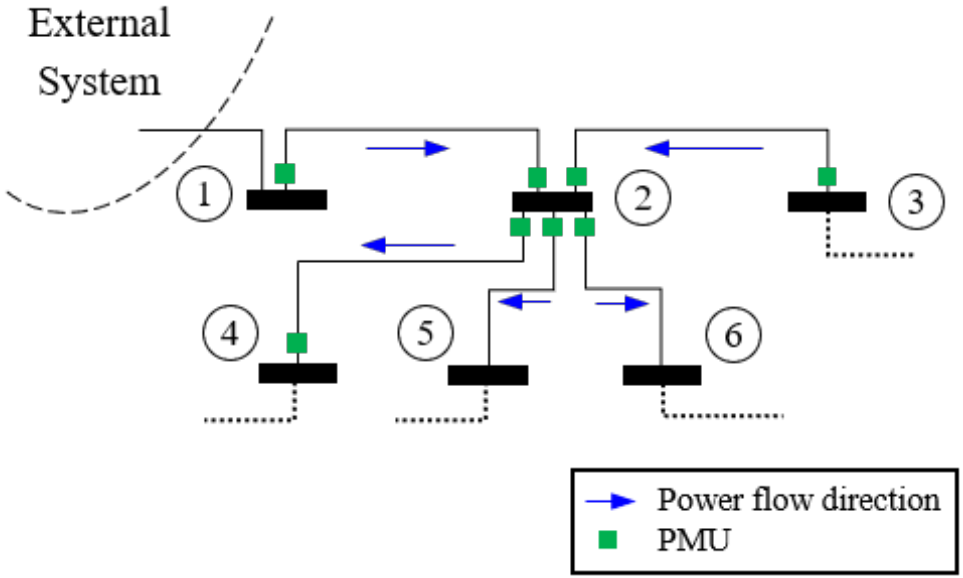
Study System

- 500 kV region where the sags were first observed by the field personnel
- Adjacent to the neighboring utility
  - No measurements in the neighbors
- Sags best observed in voltage and current magnitudes
  - Signals of choice



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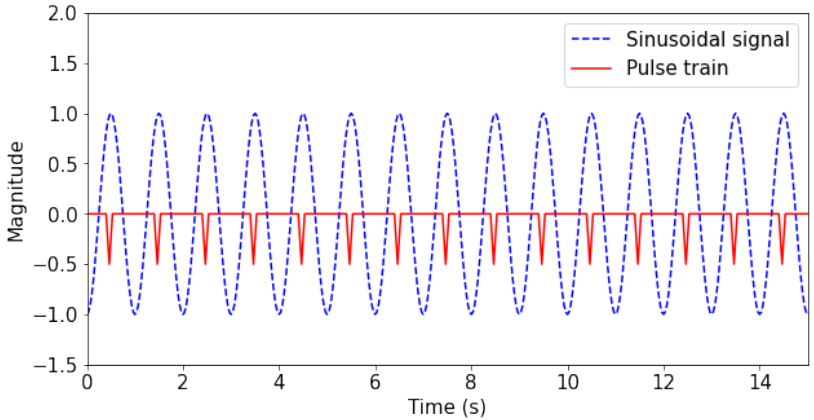
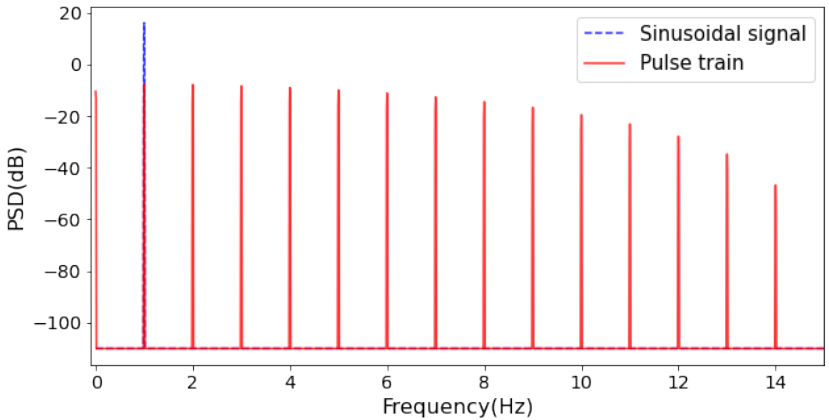
Characterization of Sags

- Periodic voltage sag resembles a pulse train
  - Pulse train in frequency domain as well at intervals of fundamental frequency
- Unlike traditional modal oscillations, not band limited, characterized by family of spectral peaks





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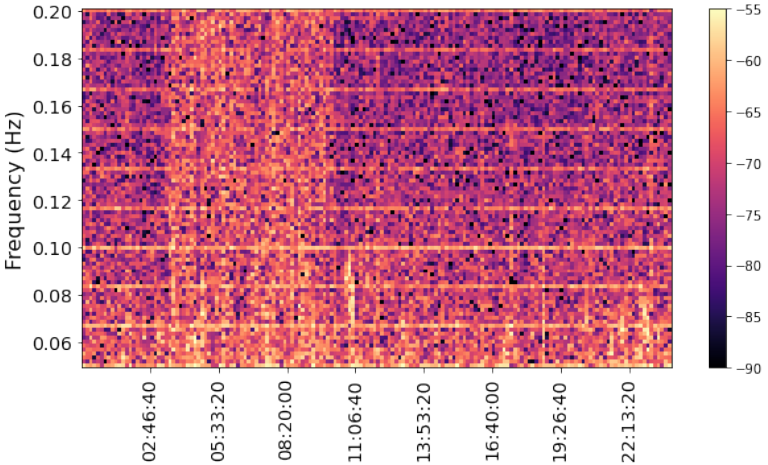
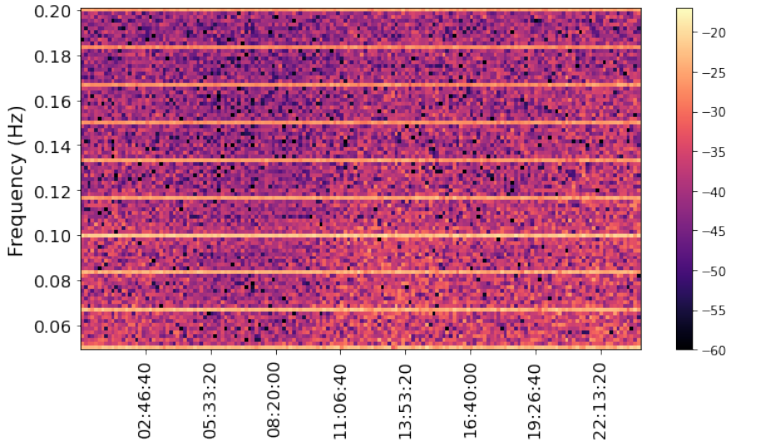
Time-Frequency Characteristics

- Nearly constant spectrum => not impacted by operating conditions
  - Unlikely to evolve into instability



24 Hr Spectrogram of Voltage Magnitude on Line 1-2



24 Hr Spectrogram of Current Magnitude on Line 1-2

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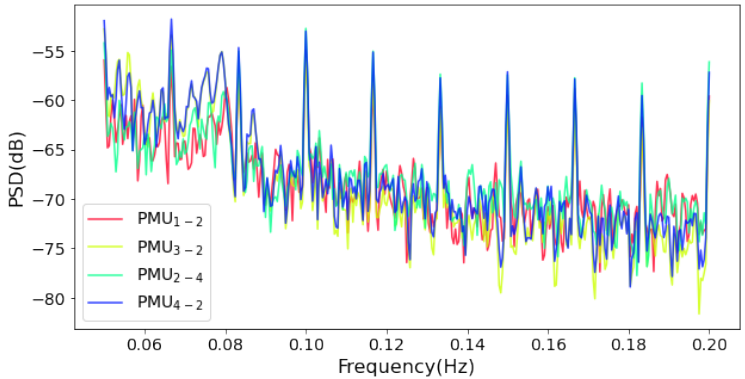
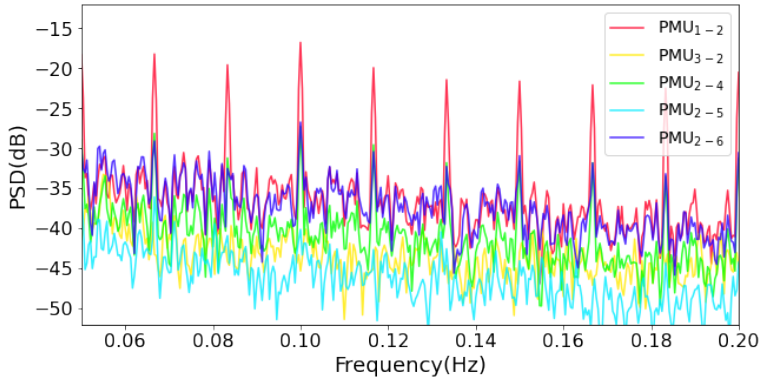
Spectral Analysis

- Owing to tight 500 kV coupling, voltage magnitude is not the best for localizing the source
  - Spectral estimates show no clear source
- Current magnitude spectrum shows line 1-2 as the best observer
  - Connected to the tie line
  - Source could be outside !



Voltage Magnitude Spectrum



Current Magnitude Spectrum

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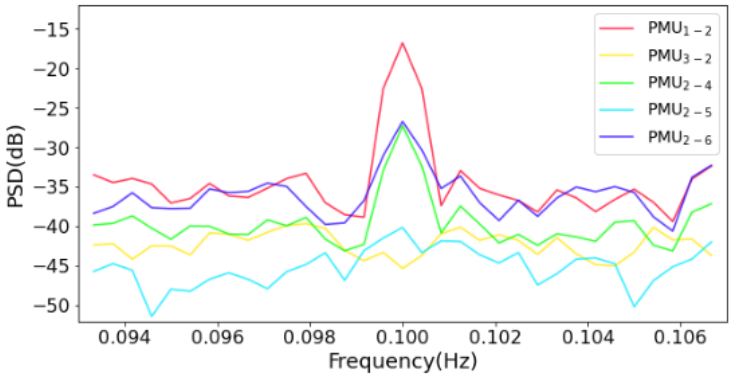
- Certain frequencies are strongly impacted by other irrelevant dynamic behaviors
  - Makes it difficult to isolate the source
- Since the phenomenon results in a family of spectral peaks, have more choices



0.1 Hz is Good for Isolating the Phenomenon

Role of Current Magnitudes

- In the absence of resonance, currents from the source have the maximum power at the corresponding frequency
  - Progressively lower on lines away from the source due to intermediate regulators acting as sinks
- Since the phenomenon impacts multiple frequencies, it is unlikely that all of them resonate with system modes
  - Can analyze the non impacted ones
- Simple ranking of branches by value of current spectra along with network topology can help arrive at a propagation path

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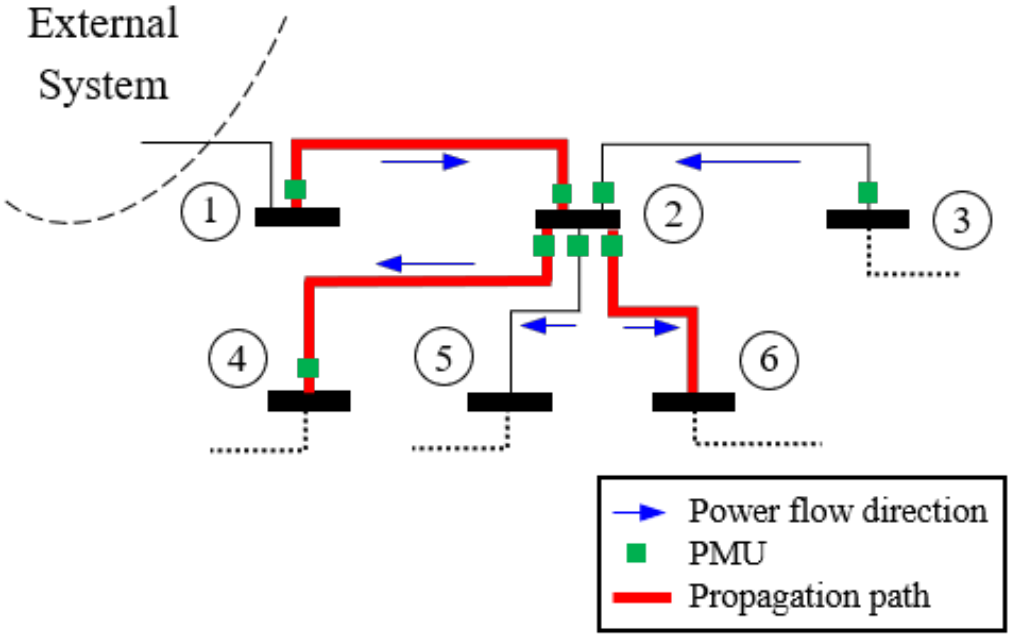
Identified Propagation Path



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Summary

- Spectral analysis based approach to investigate a wide area periodic voltage sag observed in the Dominion Energy system.
- Characterized by a concentration of signal power over a set of frequencies making it easier to analyze in presence of other dynamics
- The impacted area and a likely propagation path is identified through an analysis of current magnitudes which points to a neighboring utility