Automatically Discerning Power System Dynamics in Synchrophasor Measurements Data Spectra

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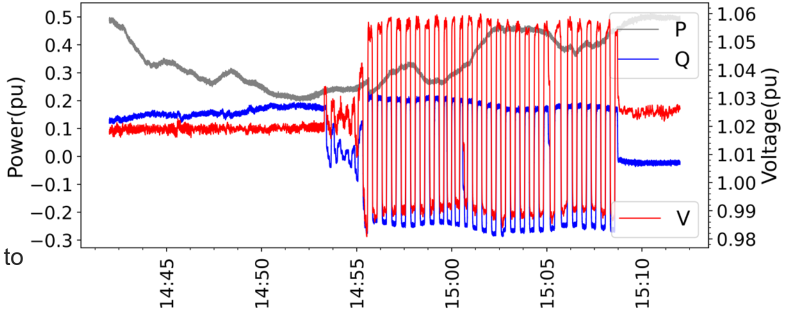
Dominion Energy

Overview

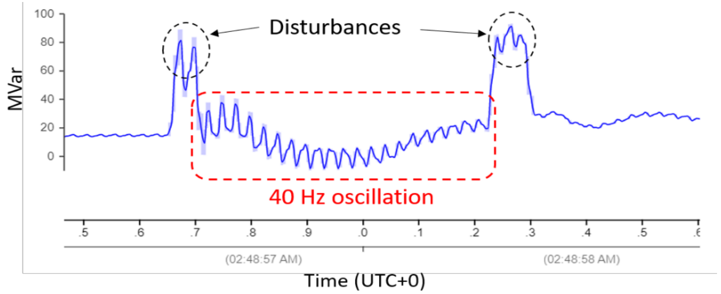
- Value of Measurement Data-Based Analysis
  - Emerging stability issues
  - Historical data analysis
- Towards Labeling Data with Emerging Dynamics
  - Time-frequency representation
  - Thresholding
  - Labeling
- Takeaways

Emerging Stability Issues in Dominion's Grid
(Value of Data-Based Analysis)

- **Controller design and testing**
  - Decentralized control designed against a range of Thevenin equivalents, simulations with PSS/E planning model
  - Set it and forget it (wait for the next time it goes rogue or trips)
- **Inadequate modeling**
  - Absence of models for non-utility owned assets
  - Inaccuracy - absence of control limiters, averaging fast dynamics, not updated to reflect changes
- **Result** – unprecedented local oscillations
  - Most noticeable from poorly set controllers during maintenance outage season
- Measurement data is left as only recourse for analysis:
  - Helps explain, *in part*, the nature of emerging dynamics.
- Need to go **beyond** oscillation characterization
  - Determining the frequency, damping and source is only one part of the process
- Insights from data help, *in part,* to explain other aspects of emerging dynamics:
  - Could we have anticipated it?
  - How to prevent it?
  - What to do next time it happens?



Unstable Solar Plant AVR During "Planned" Outage [A]



Unmodeled 40 Hz Excitation Dynamics from Hydro

[A] Mishra, L. Vanfretti, J. Delaree 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

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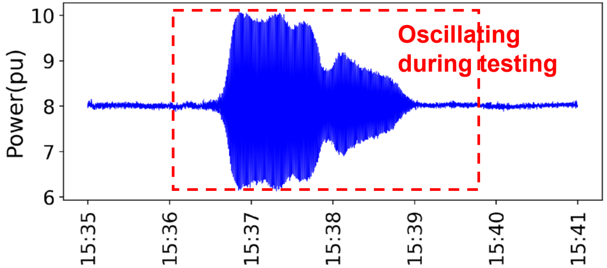
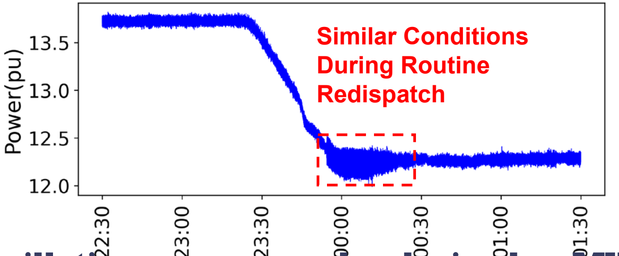
Historical Data Analysis is the Key

(Collecting Enough Data on *“Features”* to Analyze)

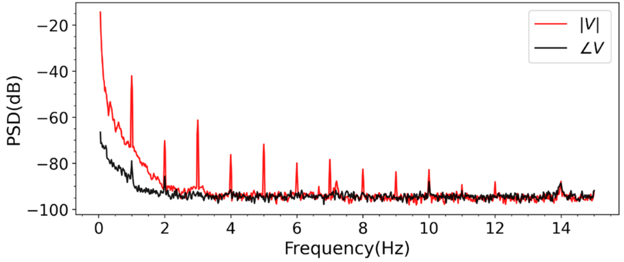
- Most major controller issues leave clues because of a cyclical and largely continuous nature of operation





Oscillations seen everyday during low MW [B]

- Discerning the type of data features:
  - Physical issues (dynamics) vs instrumentation/comm issues vs Controlled Inputs
  - Should *observed* periodic (undamped) motions always trigger alarms? Are they always related to dynamics?
  - *Data features may include artifacts* that are not related to the grid’s dynamics but are product of instrument issues.
  - Long-term behavior could help discern the nature of the features in the data.



Clock-Error Created Periodic Component in Angle [C]

[B] Mishra, Chetan, et al. "Analysis of Generator Forced Oscillations During MOD 25 Testing Exploiting Wavelets." (2024).

[C] Mishra, Chetan, et al. "Analysis of Periodic Clock Errors in Synchrophasor Ambient Data." 2023 IEEE Power & Energy Society General Meeting (PESGM). IEEE, 2023.

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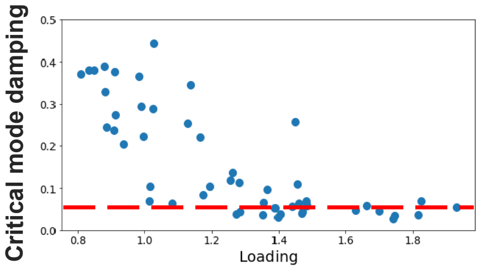
Historical Data Analysis is the Key

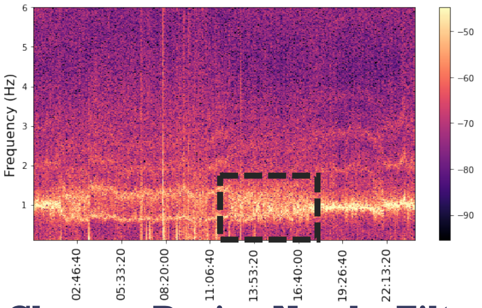
(Collecting Enough Data on "***Similar Dynamics***" to Analyze)

- Preventing future dynamic issues
  - Understanding the **underlying mechanism** (what to fix after the fact?)
- Correcting by learning from the past
  - What **action** to take in real time? (how did an asset respond to past actions?)

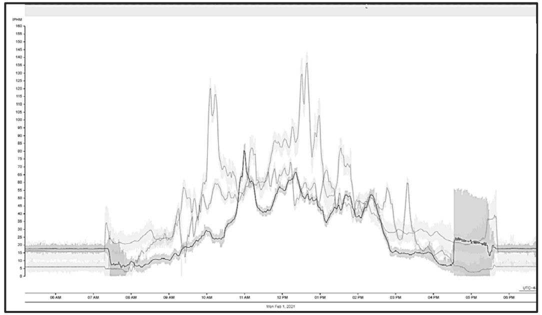
- Looking for ***common patterns*** between issues at different locations
  - Learning from issues at other similar sites and drawing connections (small set of vendors)



Damping Decreased with Loading (2 Months of Data) [D]



Changes During Nearby Filter Bank Switching [D]



Oscillations in Multiple Solar During Low Irradiance Periods

[D] 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, Feb. 21-24, 2022, Washington D.C., USA.

Thresholding Time-Frequency Representation

An Image Segmentation Based Approach [F]

[F] C. Mishra, L. Vanfretti, J. de la Ree Jr., and K. D. Jones, “Automatically Discerning Power System Dynamics in Synchrophasor Measurements Data Spectra,” 2023 IEEE Power & Energy Society (PES) General Meeting (GM) Orlando, Florida, 16 – 20 July 2023.

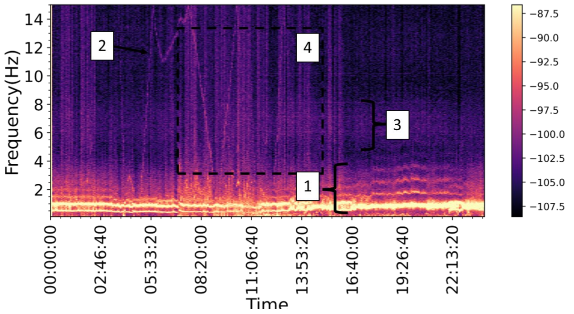
Towards Labeling Data for Unique Dynamics

- System is full of unaccounted for / difficult to explain oscillatory dynamic behaviors
  - Need a way to discover them and track them
  - No simulation model to guide the search
- System mostly in ambient conditions
  - Frequency domain to separate underlying processes
- Non-stationary nature of local modes (adding temporal aspect)
  - Sensitive to system changes, switching on-off, internal changes in control modes
- **Approach:** time-frequency characterization of ambient data

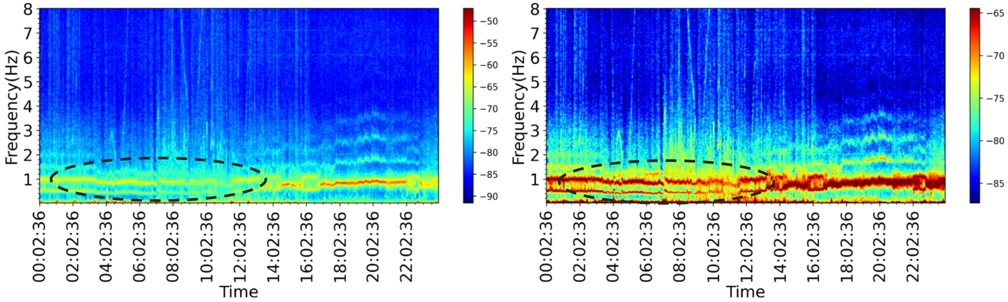
$$\boxed{x(t) = \int e^{j2\pi ft} H(t,f)dz(f)}$$

  - Time varying spectrum $S(t,f) = |H(t,f)|^2$
  - Modes represent set of local maxima at each time

$$\boxed{P = \{(t^*, f^*) \in R^2 | \partial_f S\big|_{t^*,f^*} = 0, \partial_f^2 S\big|_{t^*,f^*} < 0\}}$$



Labelling Unique Dynamics

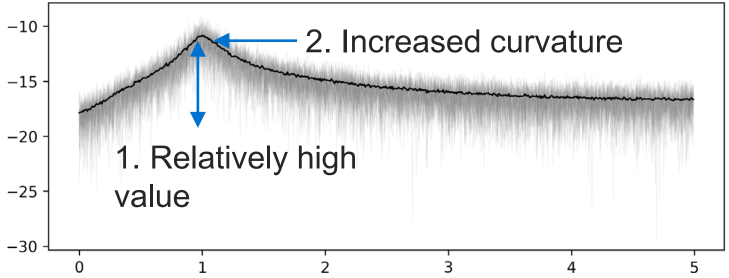


Improperly Set Color Range

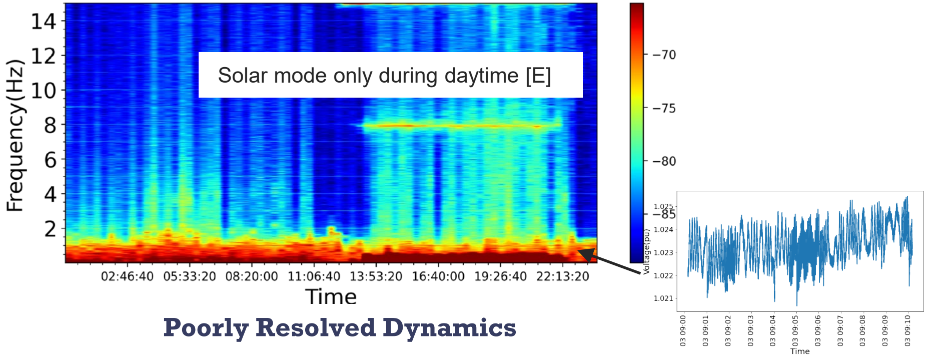
(Analysis Based on Visual Inspection Can be Deceptive)

Problem Formulation and Practical Challenges

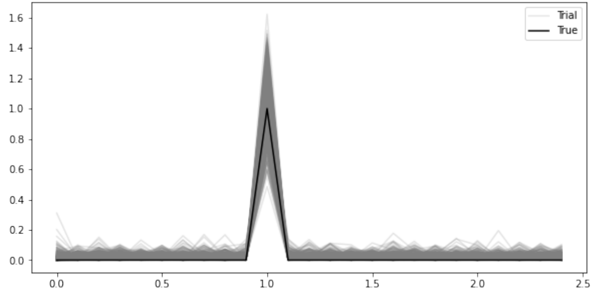
- **Challenges**
  - Stochastic system ⇒ estimation noise in $\hat{S}(t, f)$ makes it difficult to capture low power dynamics
    - Bias-variance tradeoff – goal to estimate peaks and not precision in $S(t, f)$ ⇒ more margin of sacrificing bias
  - Time-frequency resolution tradeoff
    - Cannot find an isolated peak
- **Constraint** – simple to use it in practice (few hyperparameters to tune)



Two Family of Approaches:
1. Threshold vs 2. Pattern Matching



Poorly Resolved Dynamics

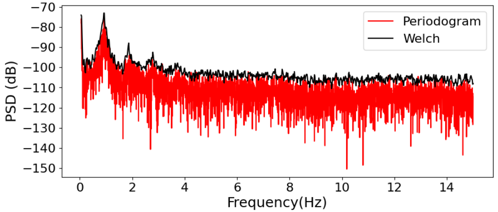


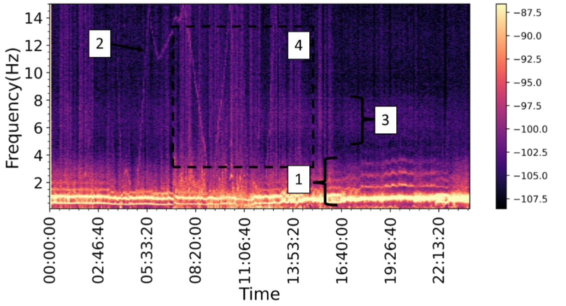
Estimation Noise In $\hat{S}(f)$

[E] 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.

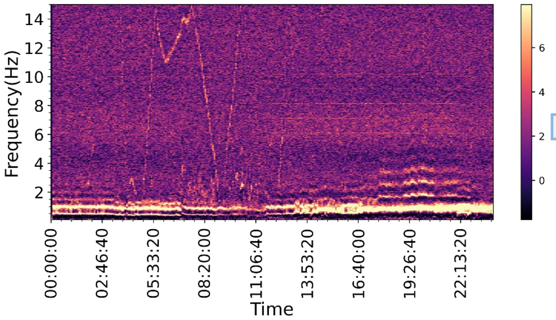
Proposed Approach

Step 1: Good Starting Time-Varying Spectral Estimate

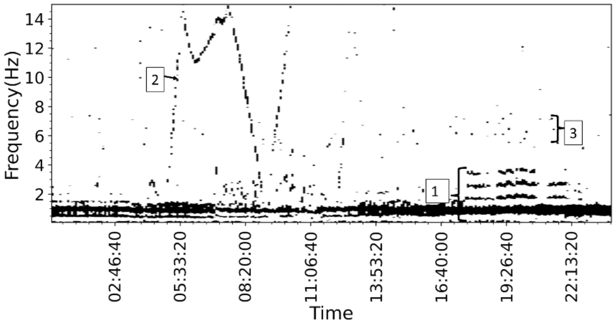




Step 2: Pre-processing (to enhance features)



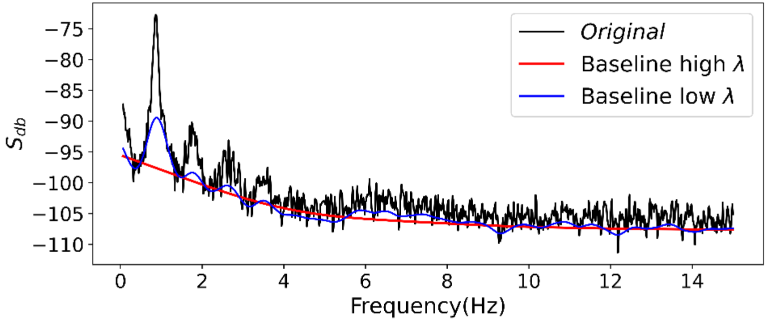
Step 3: Thresholding



Work with $\log(\hat{S})$ as opposed to $\hat{S}$ to get additive estimation noise (yields to linear smoothing)

Pre-Processing

- Dynamics in addition to oscillatory behaviors
  - Slow trends:
    - Arise from changing operating conditions (contributing to low frequency range)
    - Require **detrending** prior to spectral estimate
  - Broad-band:
    - Random inputs, e.g. arc furnace
    - Or from transients/ discontinuous changes in operation
- Can address these by estimating and removing spectral **baseline**
  - Removing longer scale (in frequency) dynamics
  - Allows for **global threshold** (across time)



Baseline $logS(t,f)_b$ defined as a smooth under-approximation to the spectrum

$$logS(t,f)_b = argmin_{b(f)} \sum_f \underbrace{w(err(f))}_{\substack{skew\ towards \\ underapprox}} \underbrace{err^2(f)}_{\substack{fit\ error \\ \log\left(\hat{S}(t,f)\right)-b(f)}} + \underbrace{\lambda}_{\substack{penalizes \\ curvature}} \sum_f \left(\nabla_f^2 b(f)\right)^2$$

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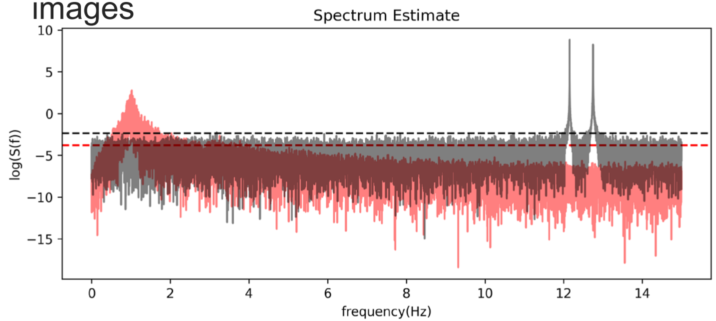
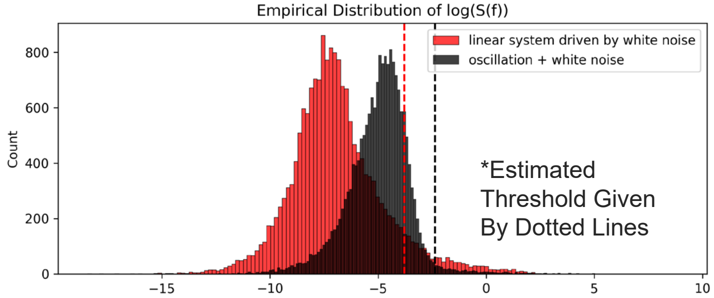
Spectrogram Properties and Thresholding

- **Thresholding** spectrogram (for relatively high value regions) equivalent to image thresholding on grayscale images (intensity of $(t,f)^{th}$ pixel given by $\log(\hat{S}(t,f))$
- **Histogram** based approaches take advantage of pixel intensity distribution, of special relevance in terms of simplicity
  - $\mu(z)$ represents number of pixels with intensity below z
- No technique universally applicable to all kinds of images $\Rightarrow$ need to understand the pixel intensity distribution $\frac{d\mu}{dz}$ of ambient data spectrograms
  - Largely unimodal (few modes or oscillations (small measure of prominent frequencies at unequal intensities), estimation noise $\log(\chi_2^2)$ unimodal)
    - **Baseline removal further ensures this**
  - Finding dynamics equivalent to finding the **right tail**
- **Rosin's method** widely used for unimodal images





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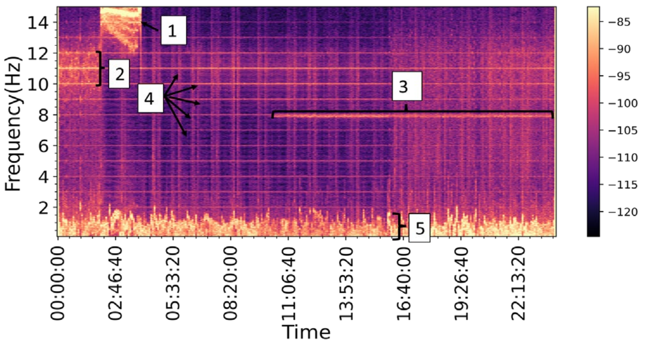
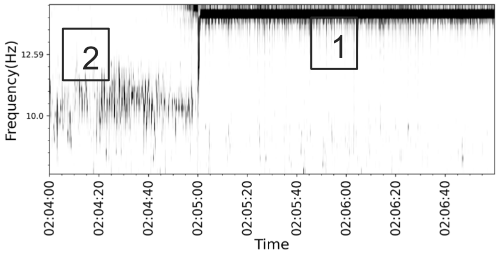
Results

Fast Oscillations from Load [F]

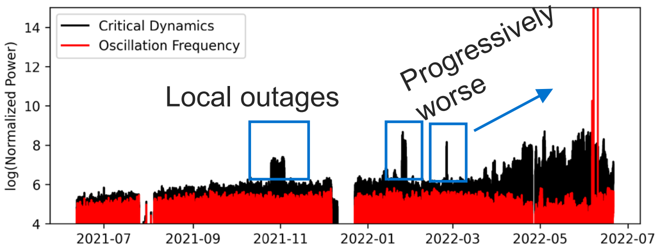
1. 14 Hz oscillation from 2-4 AM.
2. Difficult to characterize dynamics visible blurred region in 10-12 Hz range
3. Mode from nearby solar (only during day time) [E]
4. Repeating and persistent peaks at 1 Hz and its multiples resulting from a periodic voltage sag [H]
5. Poor frequency resolution (fast varying mode)

- Around 16:00 Hrs, the spectral baseline shifts up, likely due to nearby device connecting/disconnecting.

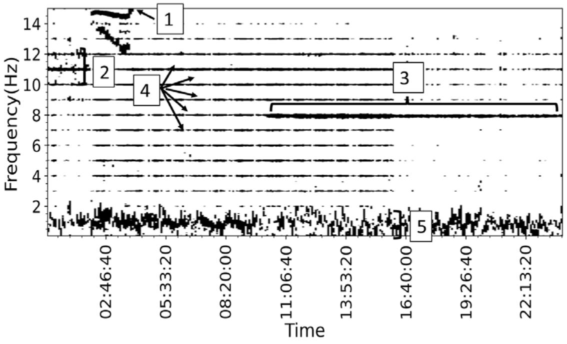




Seemingly Unrelated Dynamics (2) Destabilizing to (1)



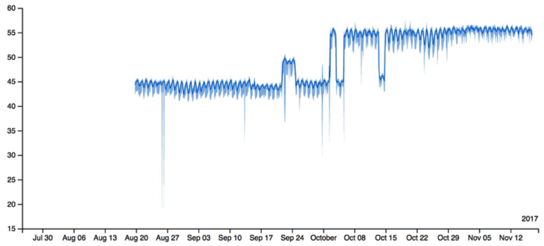
Critical Dynamics (2) Power Progressively Increased over Long Term



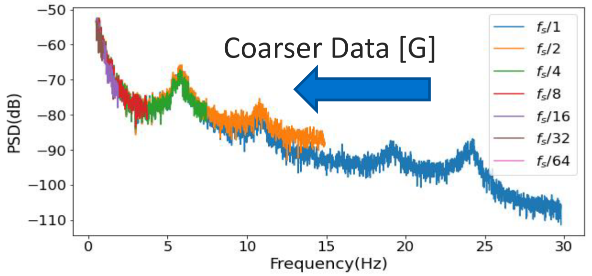
[H] X. Xu, C. Mishra, L. Vanfretti, C. Wang, K.D. Jones, J. Brian Starling, and R. M. Gardner, "Tracking Periodic Voltage Sags via Synchrophasor Data in a Geographically Bounded Service Territory," 2023 IEEE Grid Edge Technologies Conference & Exposition, April 10-13, 2023, San Diego, California, USA.

Tooling PingThings + Customizable Workflows in Python

- Speed of data extraction is the biggest bottleneck for historical data analysis
- No tool solves all the problems
  - Essential to have a good understanding of the underlying theory to use/tune pre-built tool
  - Or better, build what is needed with full access/control on all the algorithms and workflows
- Best - a customizable environment to do whatever you want
  - Requires to have access to an API to pull data/results
- Python support – rich data science libraries
  - We leverage many signal processing libraries to build our own workflows.
- The analyst is the key, not the tool
  - **Tools can be replaced, human experience, insight and understanding cannot.**
- Developing analysts is challenging
  - Incentives not aligned between universities and industry
  - Power engineering knowledge is required to derive insights on data analysis results.



Multiresolution Data Allows for Faster Queries to Analyze Dynamics



[G] X. Xu, C. Mishra, L. Vanfretti, C. Wang, K. D. Jones, M. R. Gardner, and S. Murphy, “Fast Oscillation Detection and Labeling via Coarse Grained Time Series Data for ML Applications,” 2022 IEEE Power & Energy Society Innovative Smart Grid Technologies Conf., Feb. 21-24, 2022, Washington D.C., USA.

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Takeaways

- Need to go beyond basic oscillation characterizations (frequency, damping, source) to prevent stability issues
  - Requires collecting enough evidence to draw inference, efficient access to large scale data is a must.
  - *The analyst is the key:* the tool can be replaced, while human experience, insight and understanding, cannot.
    - Understanding underlying mechanism is essential, need a strong foundation in power systems to interpret the results.
    - Universities should consider expanding the curriculum to cover how to apply digital signal processing for power engineering problems that require both power insight and signals knowledge.

- System is full of unaccounted for / difficult to explain dynamic behaviors
  - Need a way to discover them and track them to prevent stability problems
  - Conventional simulation models to guide the search are not available, would be nice to have (compliment the analysis)
  - Local dynamics can be fairly non-stationary (in terms of spectral characteristics)

- The present work explores automatically identifying prominent dynamics in synchrophasor data spectra – you can find more details in:
    - C. Mishra, L. Vanfretti, J. de la Ree Jr., and K. D. Jones, "Automatically Discerning Power System Dynamics in Synchrophasor Measurements Data Spectra," 2023 IEEE Power & Energy Society (PES) General Meeting (GM) Orlando, Florida, 16 – 20 July 2023. Online: here

References

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[B] 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

[C] C. Mishra, L. Vanfretti, J. de la Ree Jr., T.J. Purcell, R. Orndorff, K. D. Jones, “Analysis of Periodic Clock Errors in Synchrophasor Ambient Data,” 2023 IEEE Power & Energy Society (PES) General Meeting (GM) Orlando, Florida, 16 – 20 July 2023. Author’s copy: here

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Thank You
Questions ?

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