Localizing Power-Grid Forced Oscillations Based on Harmonic Analysis of Synchrophasor Data

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Background

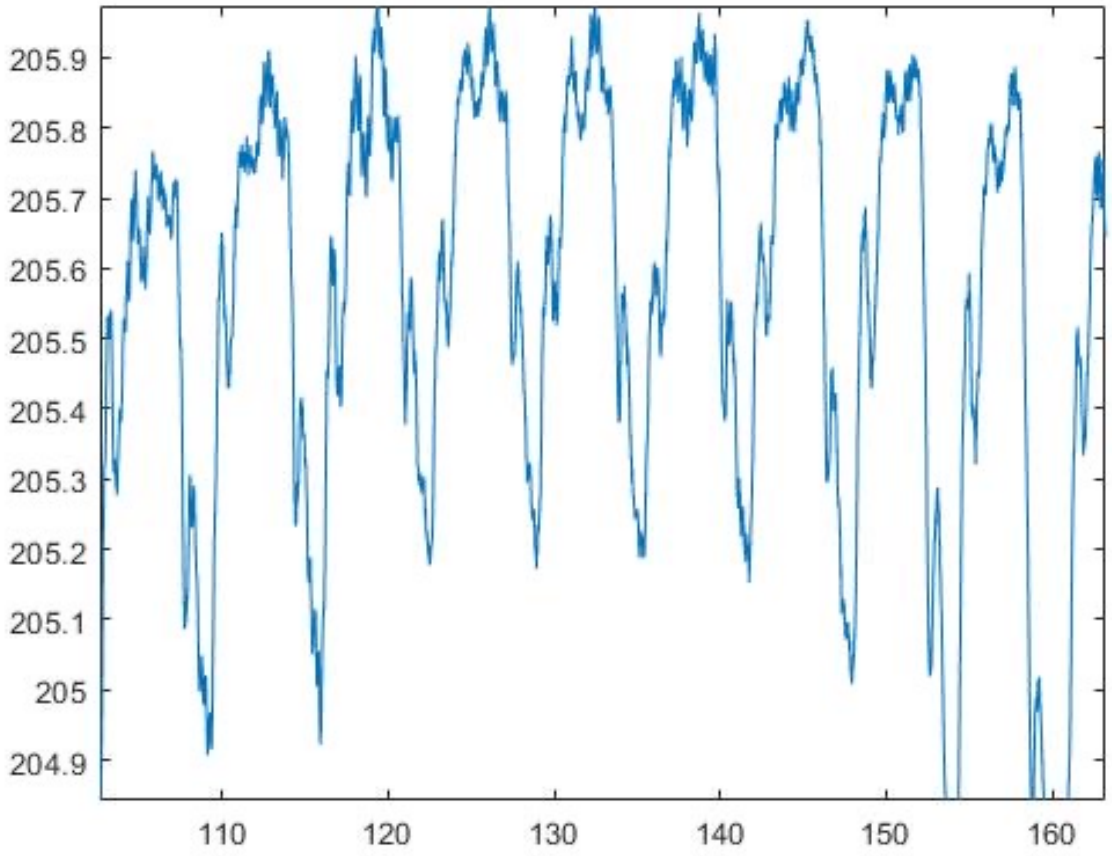
- Wide-area power oscillations are a concern in the bulk grid.
  - Have led to cascading outages, equipment failure, etc.
  - Two types: natural and forced.
- Phasor measurement units (PMUs) allow monitoring of oscillation events.
  - Detection of forced oscillations and poorly-damped natural oscillations.
  - Calculation of damping, modes, mode shapes
- Recent focus on localization of forced oscillations using PMU data.
  - Several heuristics (response amplitudes, phase properties, energy)
  - Localization has proved tricky, because the response pattern depends on the oscillation driver and the natural modes in a complex way.
  - Can also use models together with data, if good models are available.

Our Goal

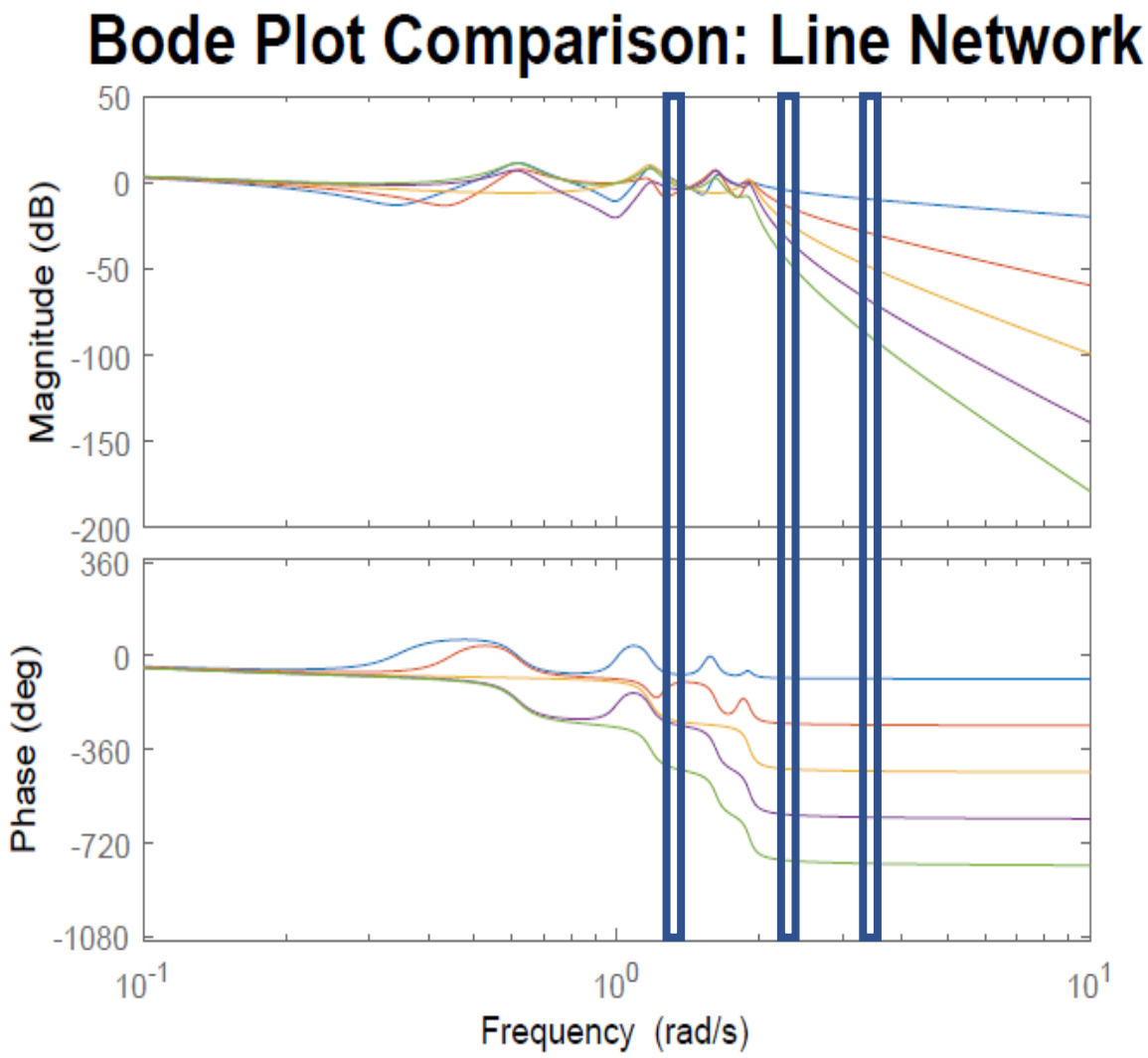
- We explore whether *harmonics* in forced oscillation signals can aid in data-only localization.
  1. Conceptual development.
  2. Case studies.

Conceptual Development: Premises

- Two main ideas underlying our use of harmonics.
    1. Forced oscillation signals are periodic but not purely sinusoidal, hence have harmonics.
    2. Harmonics at high enough frequencies are more strongly filtered by the power network, i.e. they degrade more strongly with distance from the source.
        - Why??



Spatial Degradation of Harmonics: Explanation



Forced oscillation w/ fundamental frequency of 0.2 HZ, applied at edge bus.

- Sketch of proof:
  1. Classical Model: input-output

$$\begin{bmatrix}\dot{\delta}\\ \dot{\omega}\end{bmatrix} = \begin{bmatrix}0 & \mathbf{I}\\ -H^{-1}L(\Gamma) & -H^{-1}D\end{bmatrix}\begin{bmatrix}\delta\\ \omega\end{bmatrix} + \begin{bmatrix}0\\ e_i\end{bmatrix}u$$

$$y = [0 \quad e_j]\begin{bmatrix}\delta\\ \omega\end{bmatrix}$$

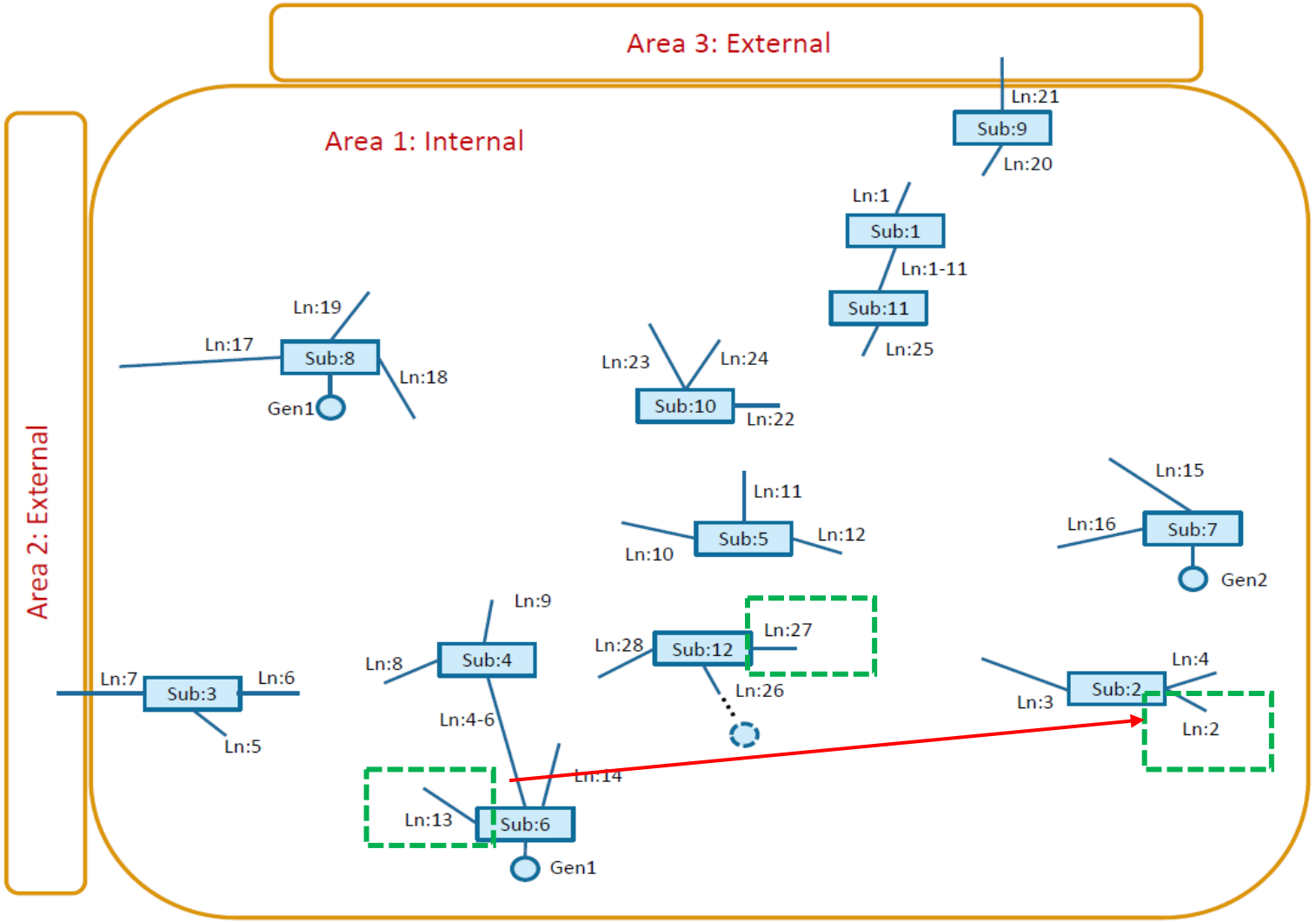
  2. Consider transfer function H(s)=Y(s)/F(s).
     - Key observation: relative degree is 2d+1, where d is the input-output distance in the susceptance graph.
  3. Bode-plot slope at high frequencies is -20(2d+1).
     - Higher frequency inputs are attenuated more strongly with distance.
     - Implies that harmonics degrade more quickly across the network.

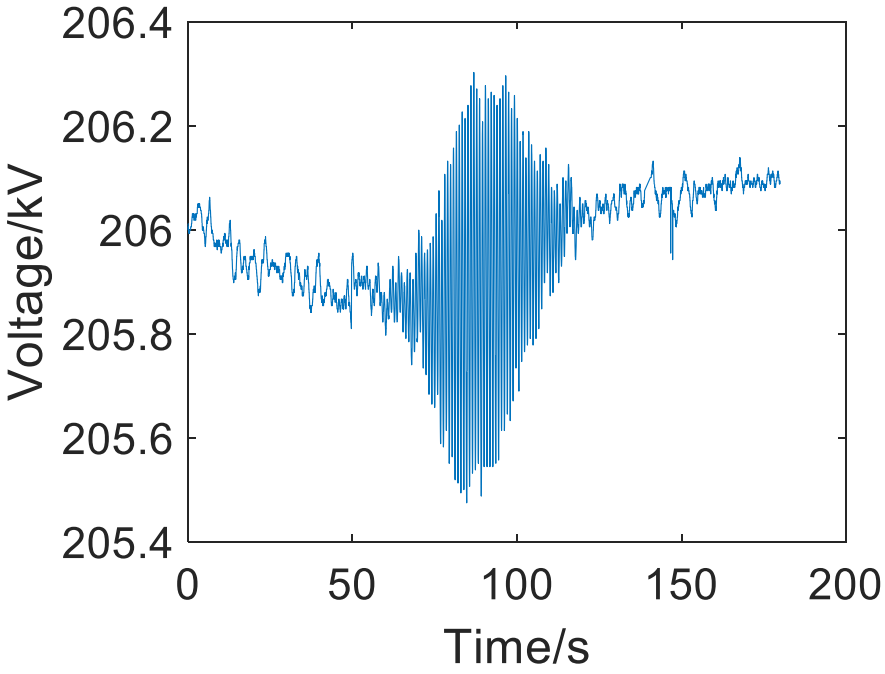
Process for Localizing Forced Oscillations

- The harmonics analysis suggests a procedure for data-only localization:
  1. Determine the fundamental frequency (this is usually easy).
  2. Find the ratio of the signal amplitude at higher harmonics vs at the fundamental frequency, for several PMUs.
  3. PMUs with larger ratios are closer to the source.
     - As a first cut, can use the largest-ratio PMU as a source-location estimation.
     - Improved triangulation using ratios from multiple PMUs.

Test Case 1 (1): ISO-NE

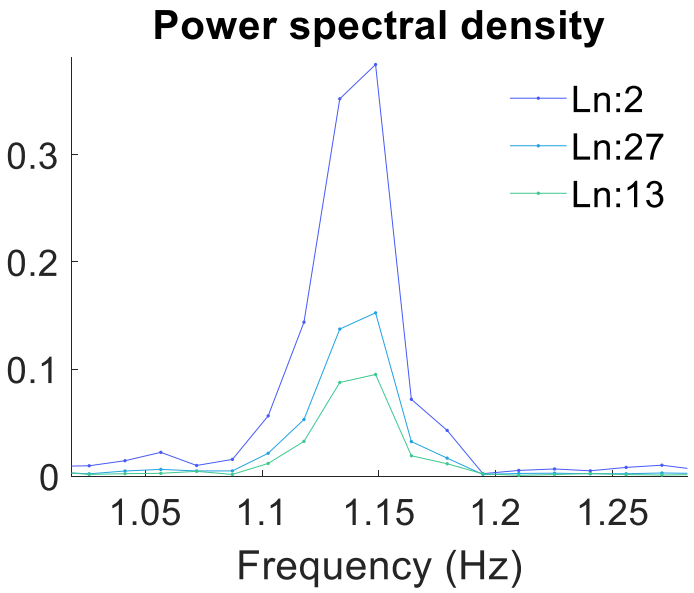
The oscillation frequency is 1.13 Hz. It happened on Jul.20, 2017. Generator located East from Sub:2. Lines Ln:2 and Ln:4 is the source.

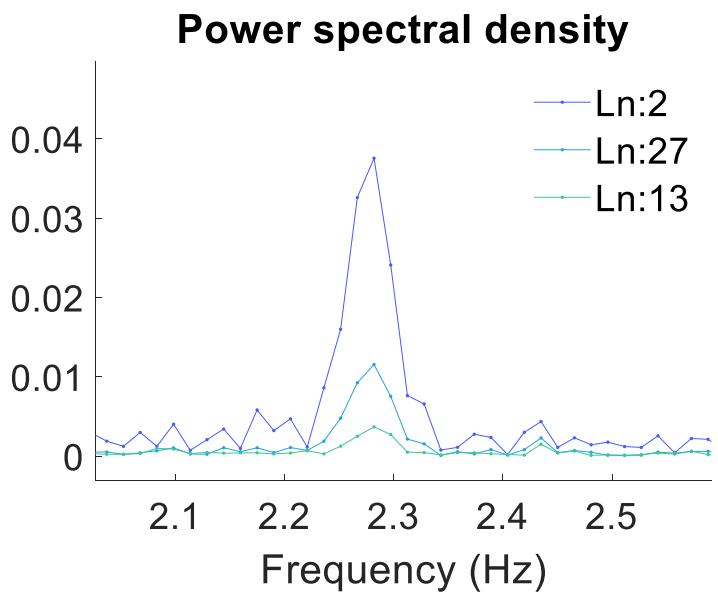


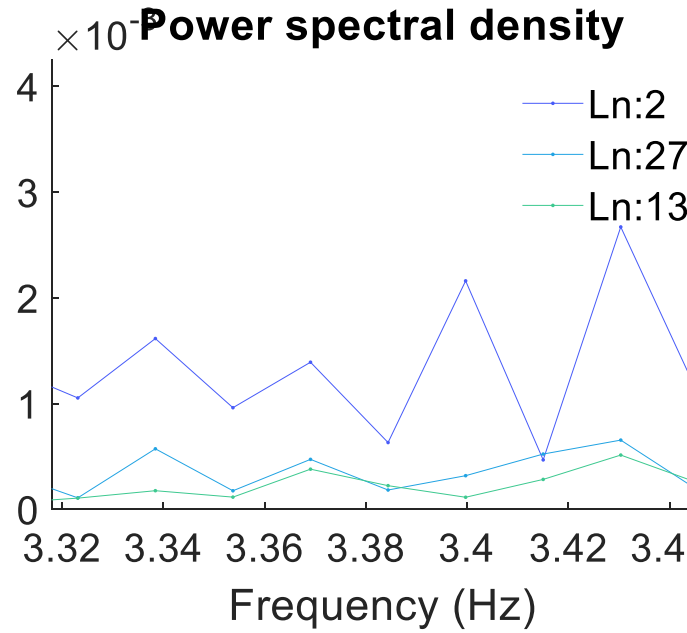


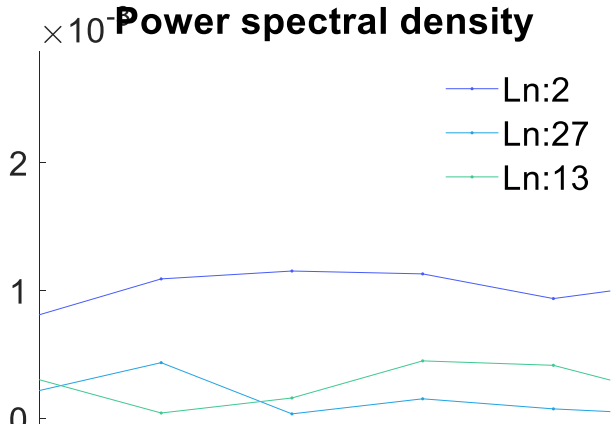
Ratio of the Harmonics

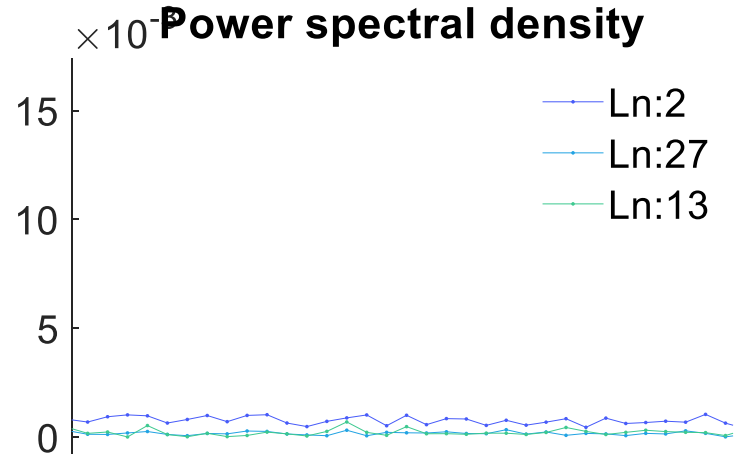
The power spectral density for the fundamental frequency, 2nd, 3rd, 4th and 5th harmonics [1.13Hz, 2.26Hz, 3.39Hz, 4.52Hz, 5.65Hz] are:











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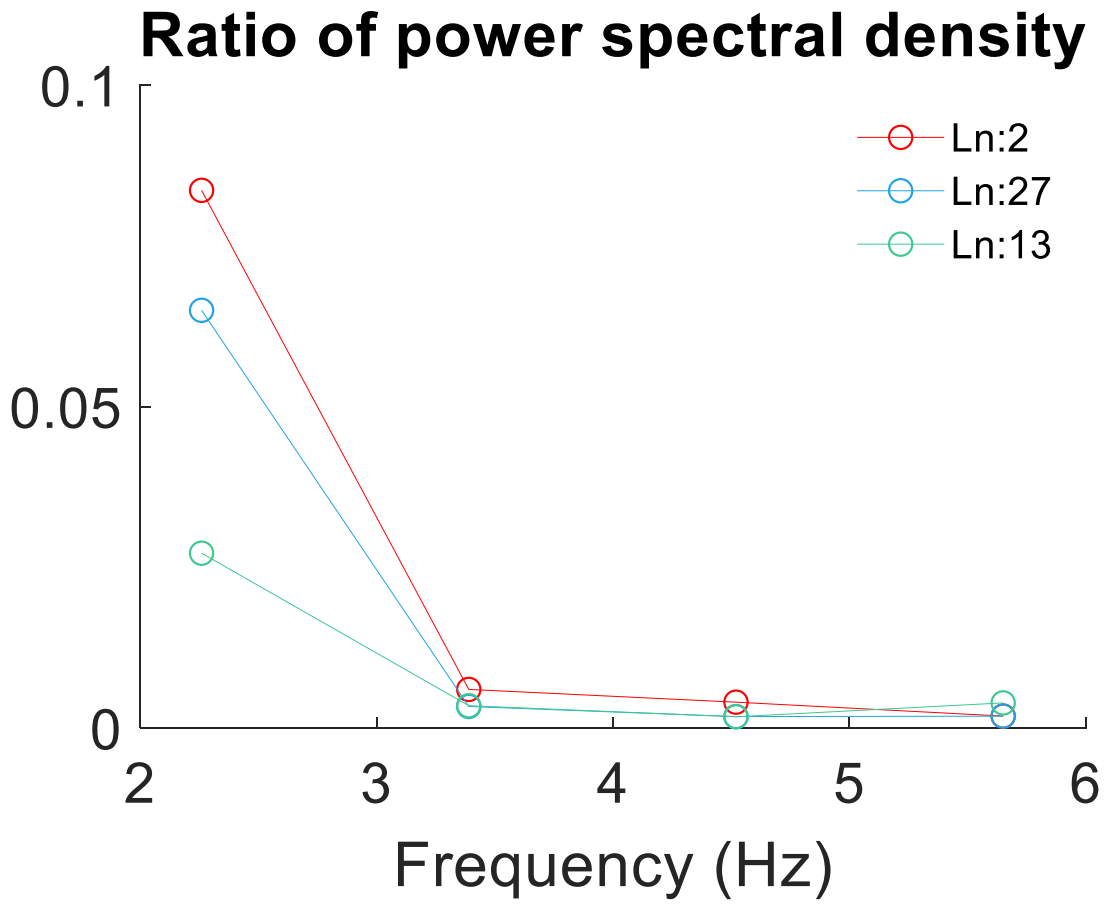
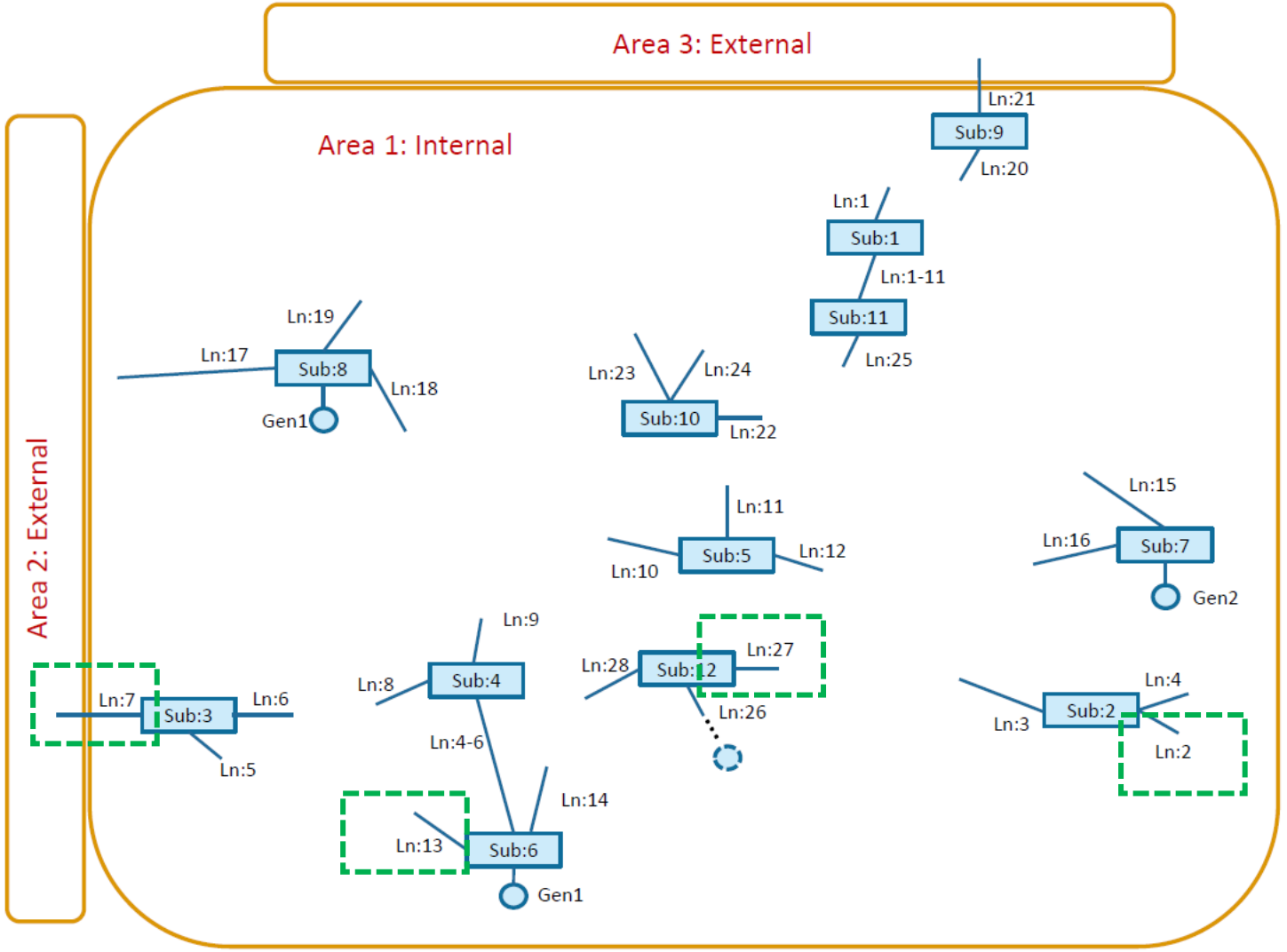
The amplitude of the harmonics in terms of power spectral density is compared to the fundamental frequency component. The ratio values of 2nd, 3rd, 4th and 5th harmonics [2.26Hz, 3.39Hz, 4.52Hz, 5.65Hz] are:



Test Case 1 (addition)



Adding another Signal from Ln:7 (away from source)

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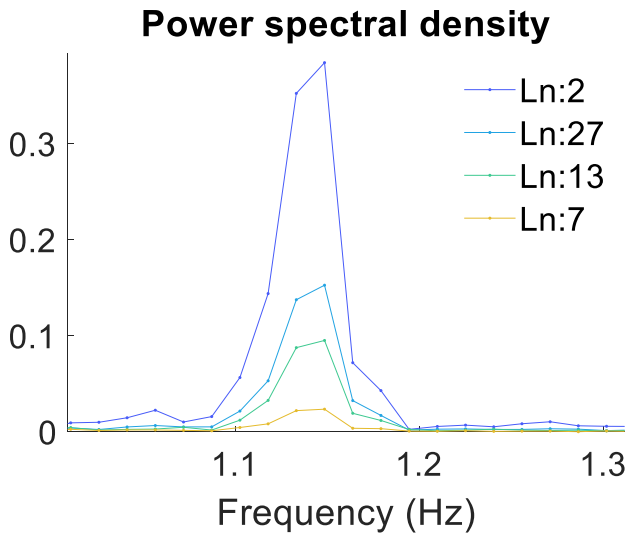

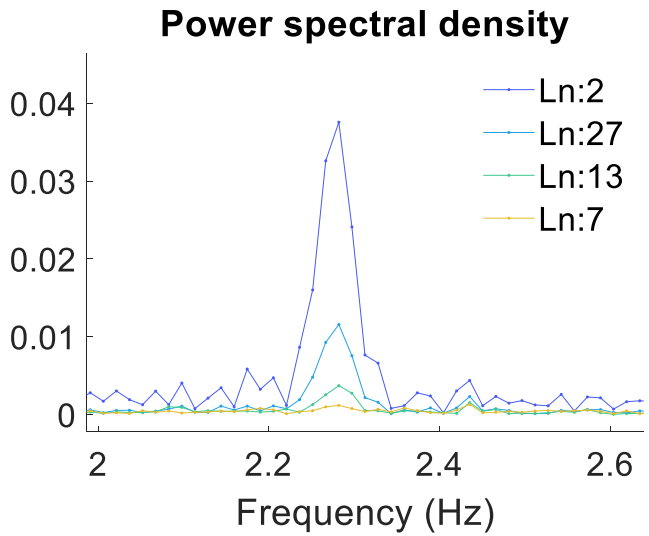

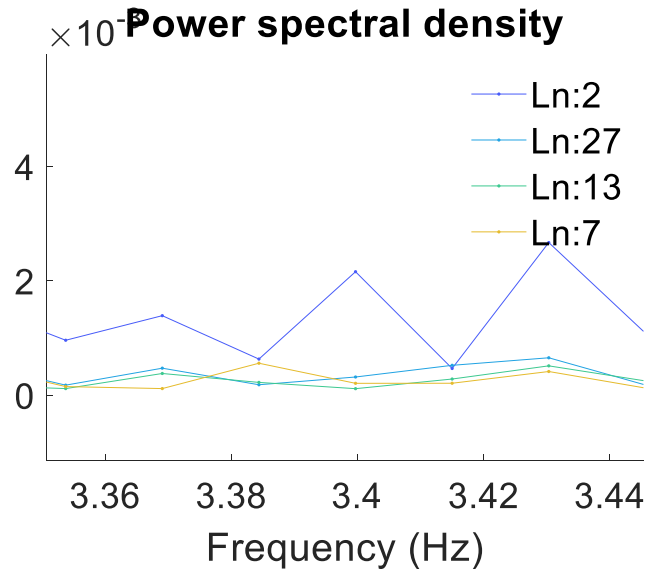

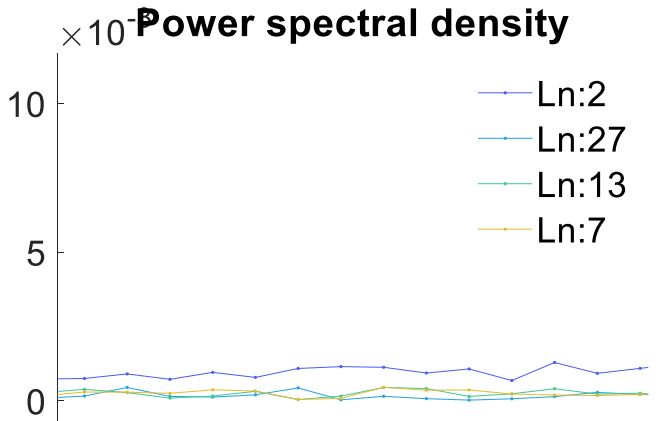

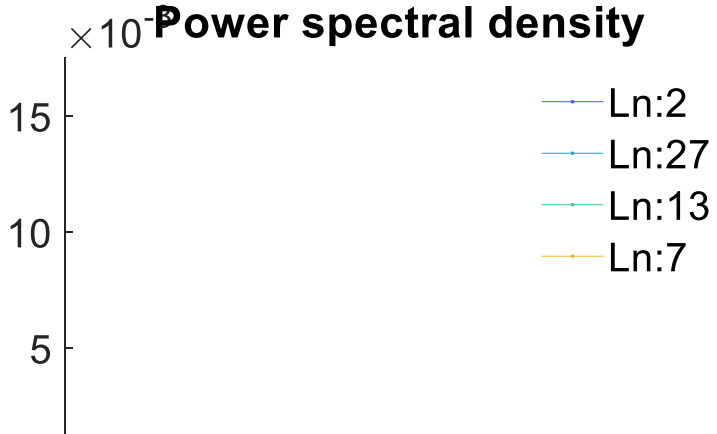

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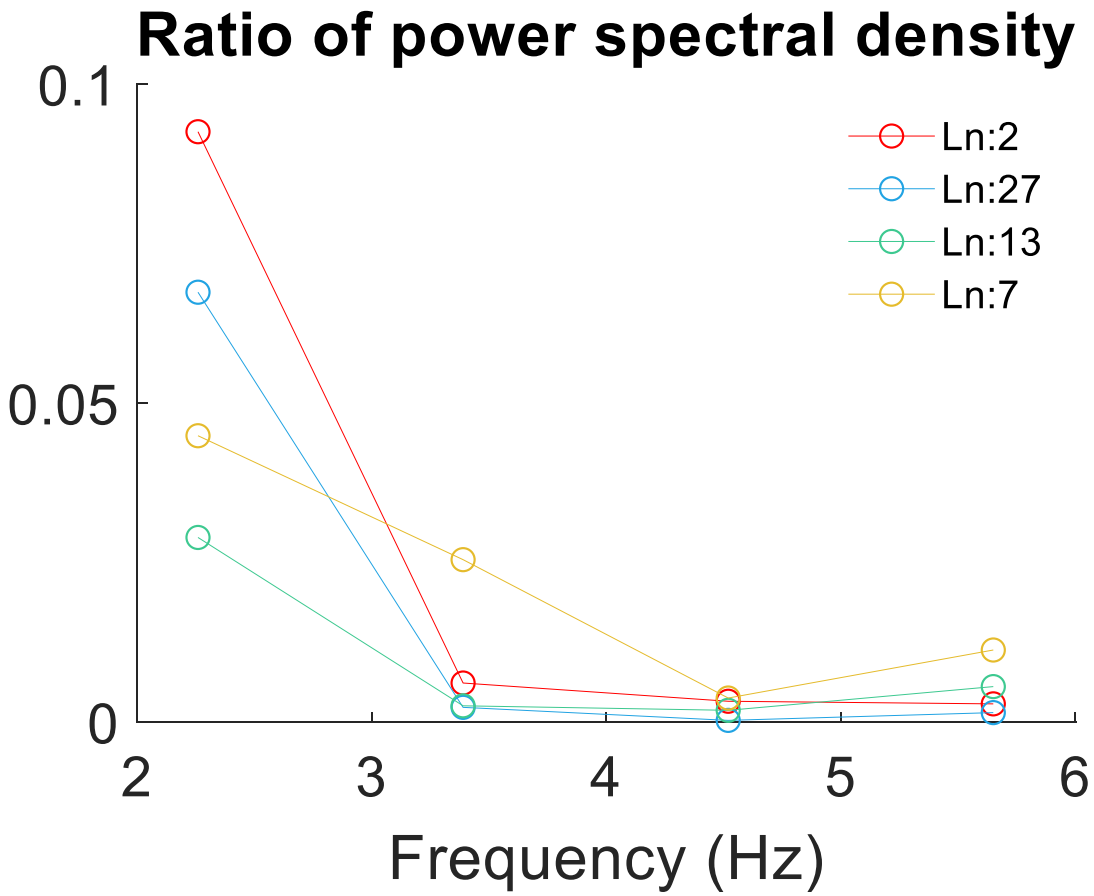
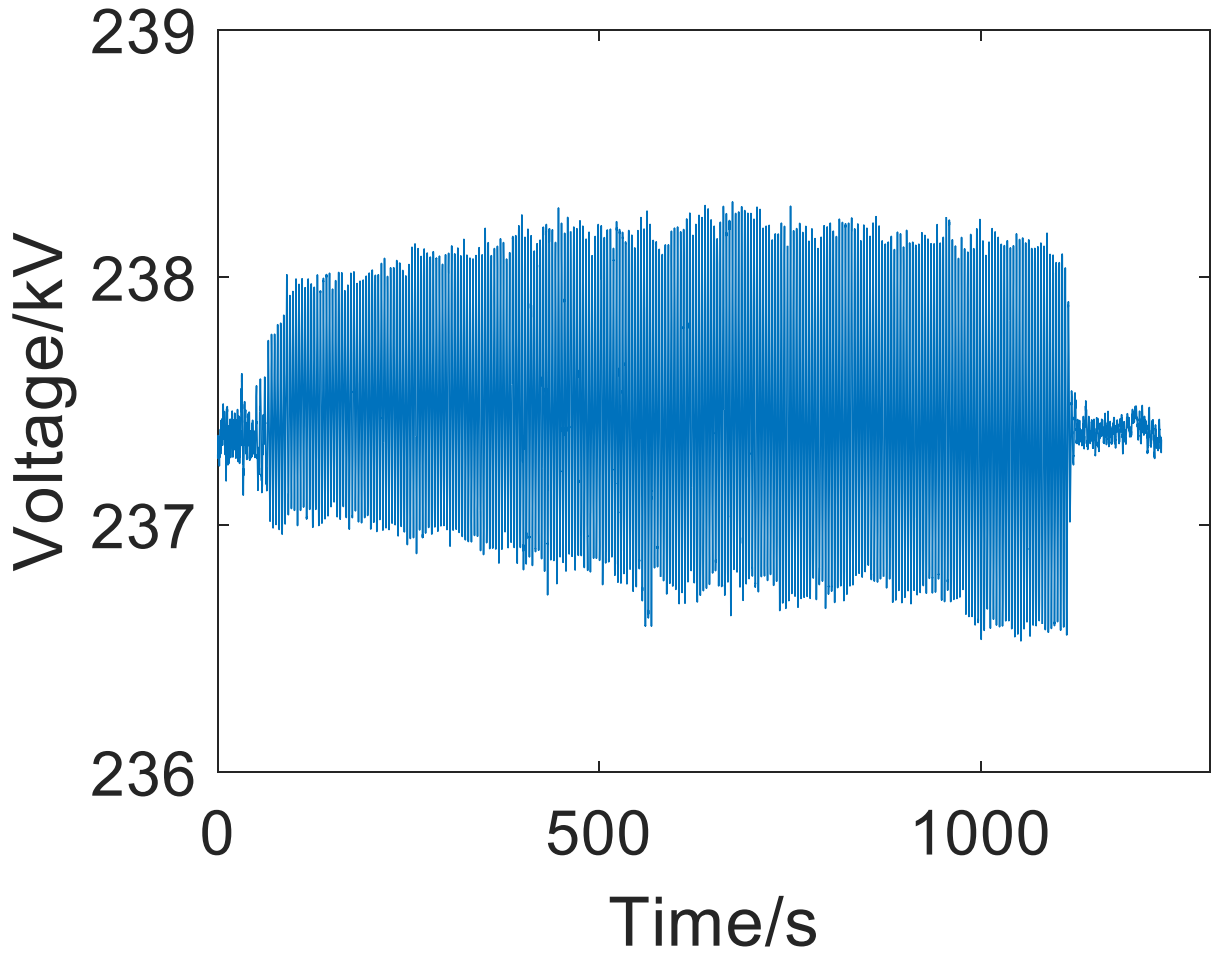


Comment: Results may be inconsistent because the dominant frequency is being blocked (zeroed) at Ln 7.

Test Case 2: Eastern Interconnection

The oscillation frequency is 0.25 Hz. It happened on Jan.11 2019. The oscillation source is close to the South.



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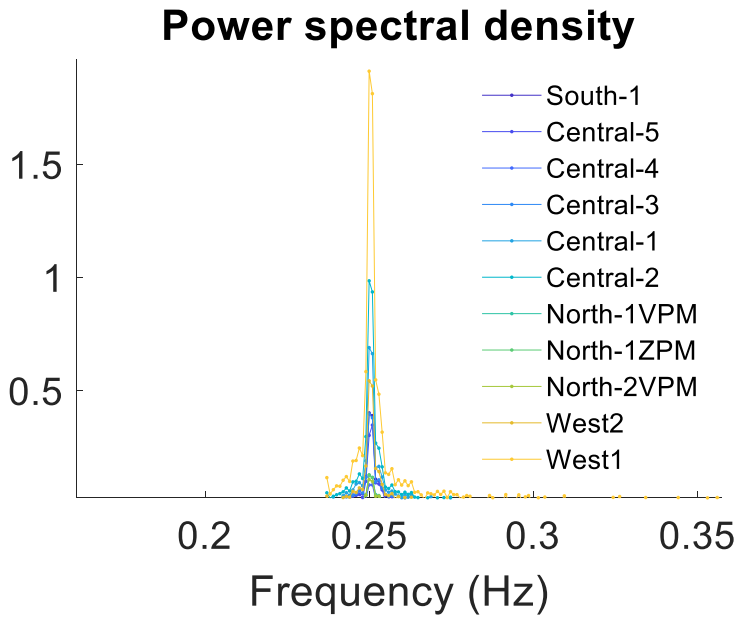

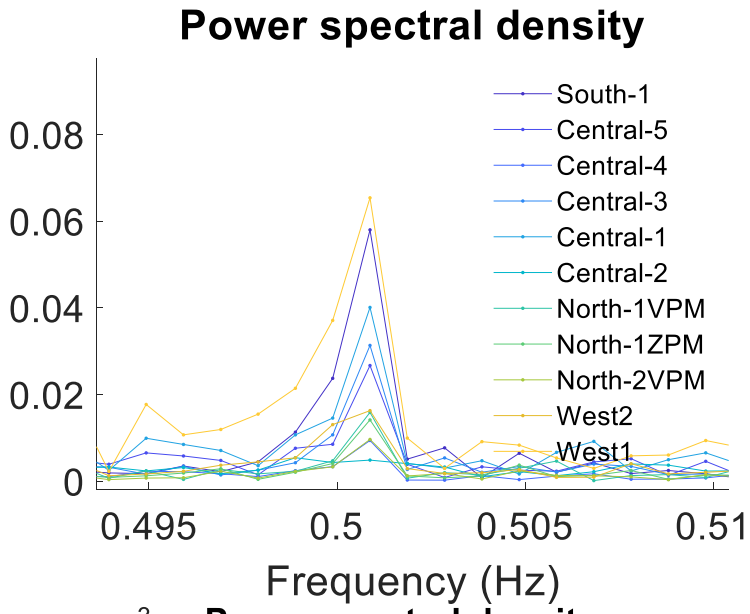

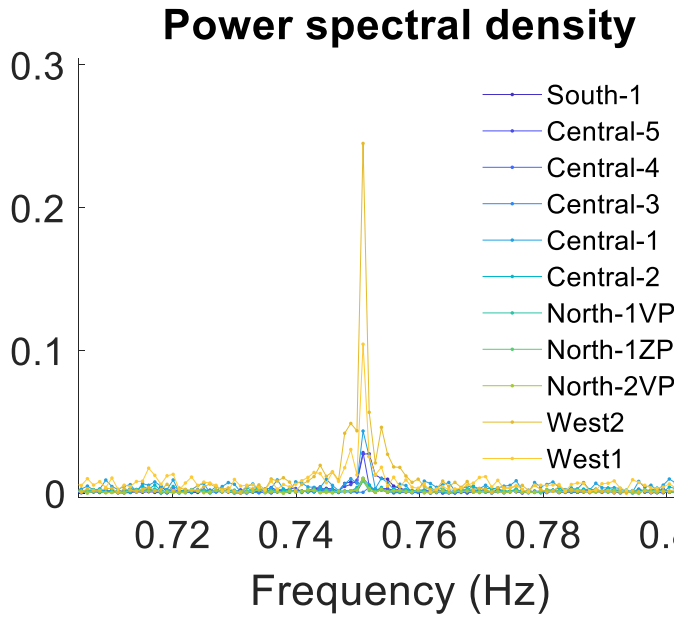

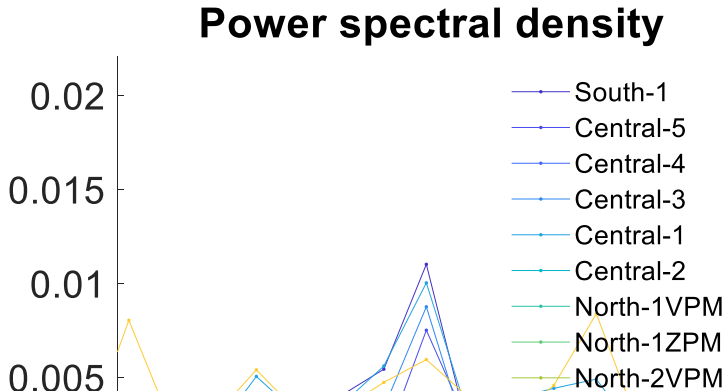

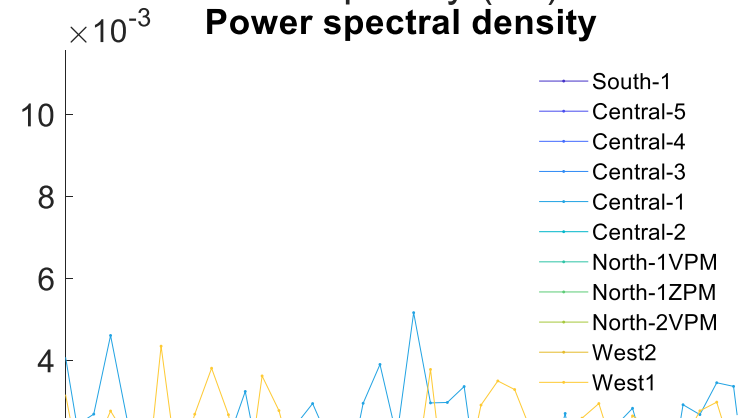

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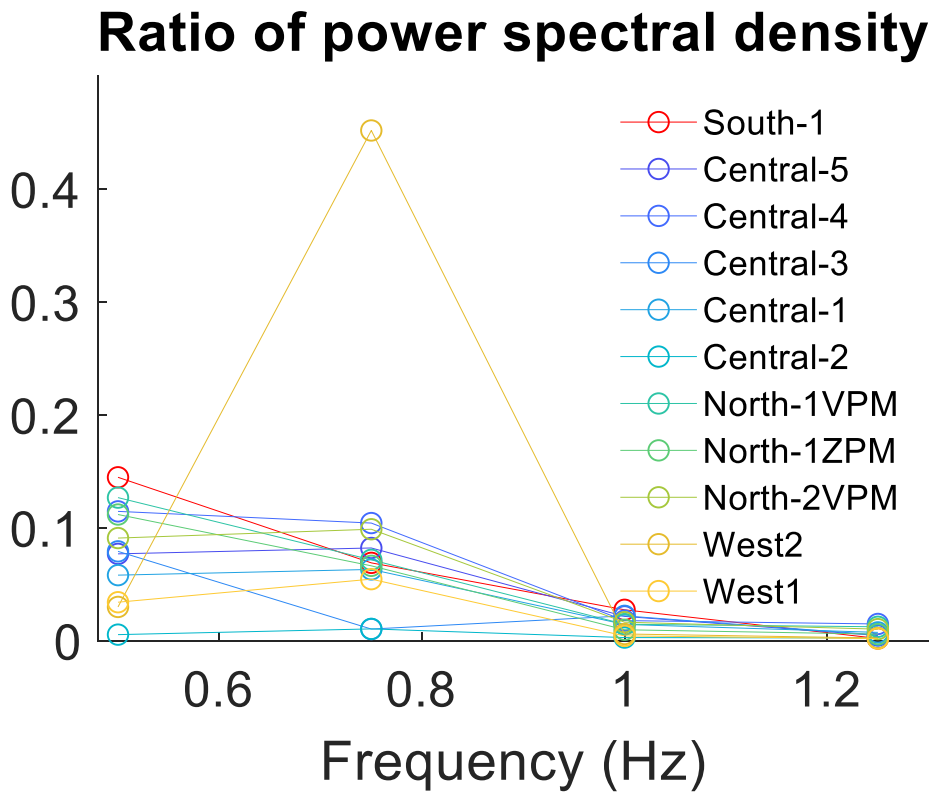


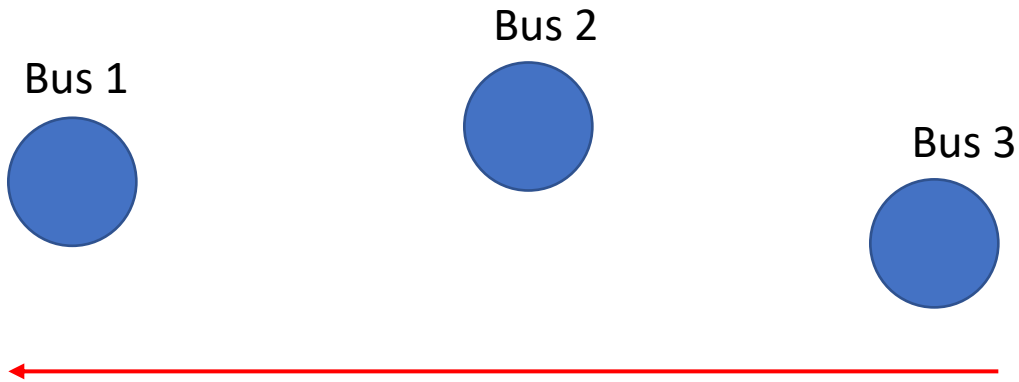
Comments: For 2nd Harmonic, Highest ratio is for signal in the south as expected. However for 3rd harmonic, measurement in West2 shows highest ratio.

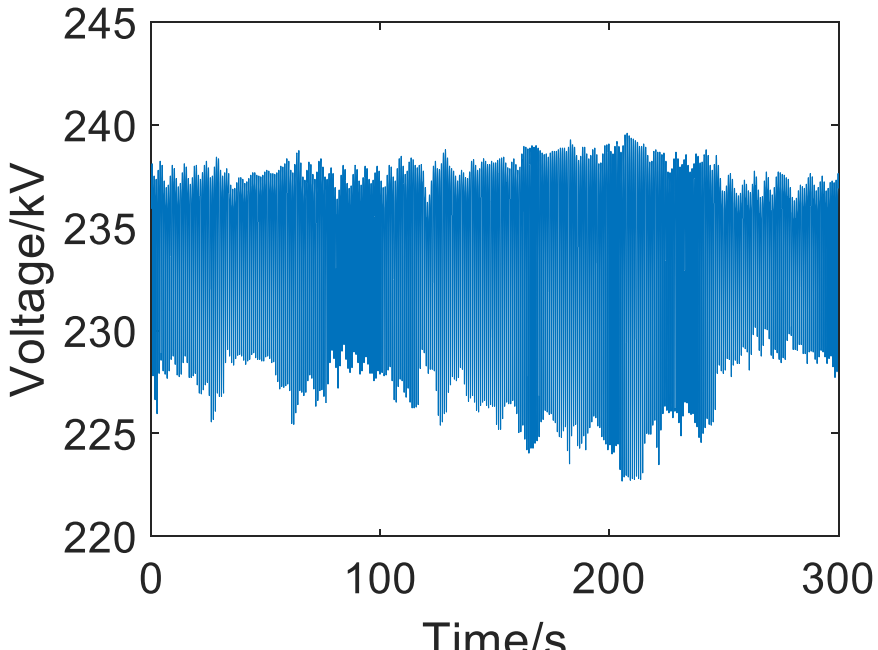
Possible reason: Resonance of the 3rd harmonic with a natural mode at West2; however, this mode is localized.

Test Case 3: Western Interconnection

The oscillation frequency is 1.14 Hz.

Oscillation source





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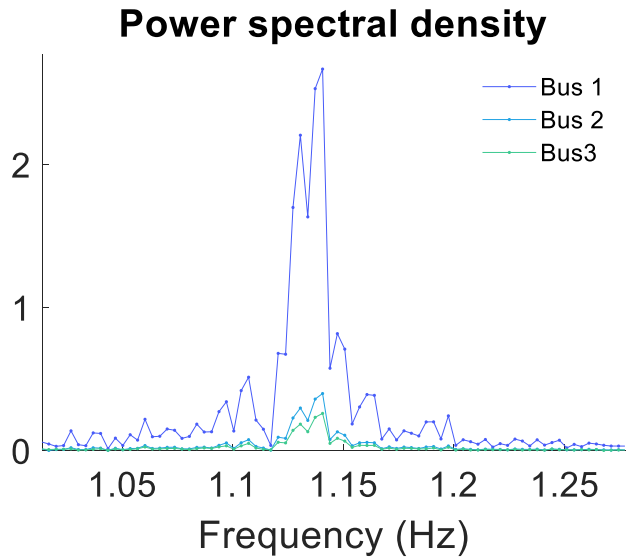

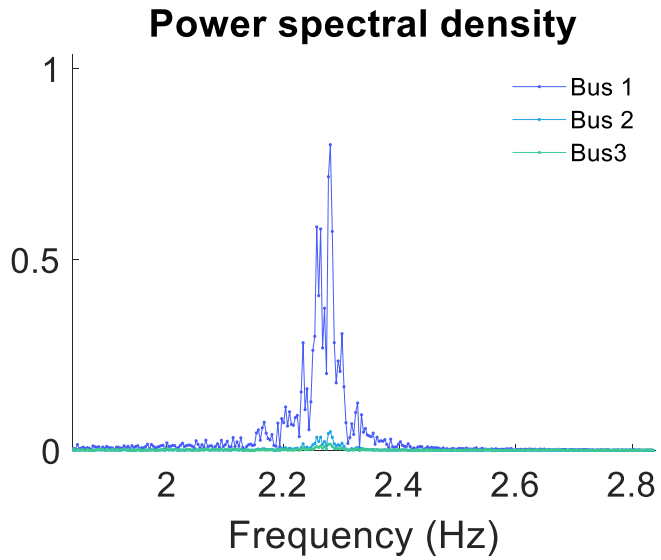

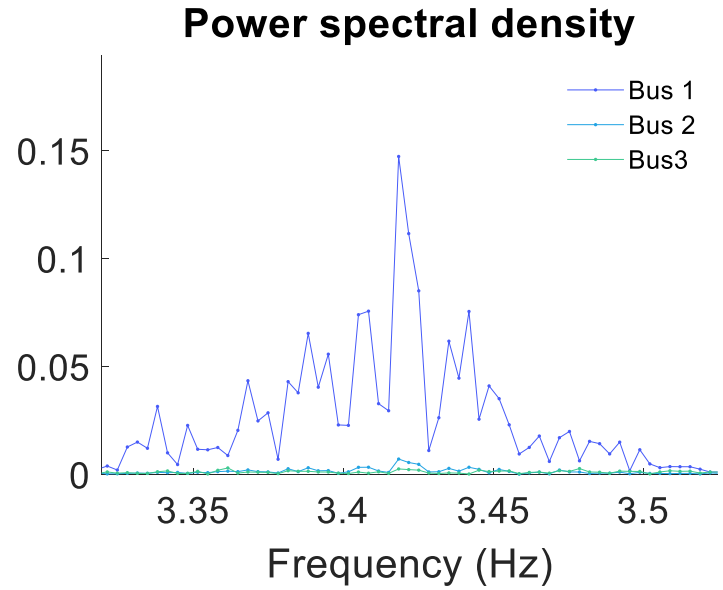

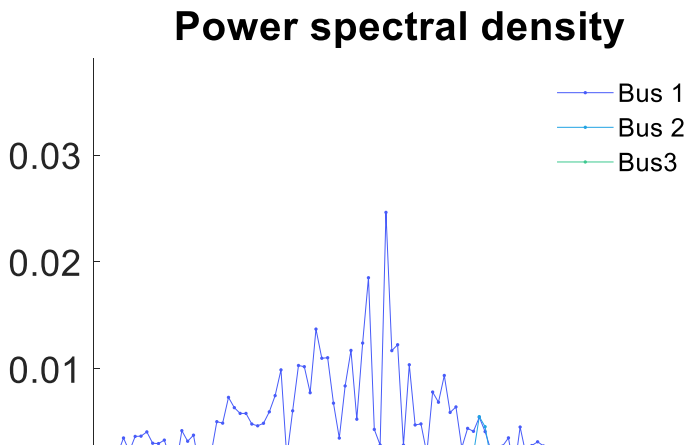

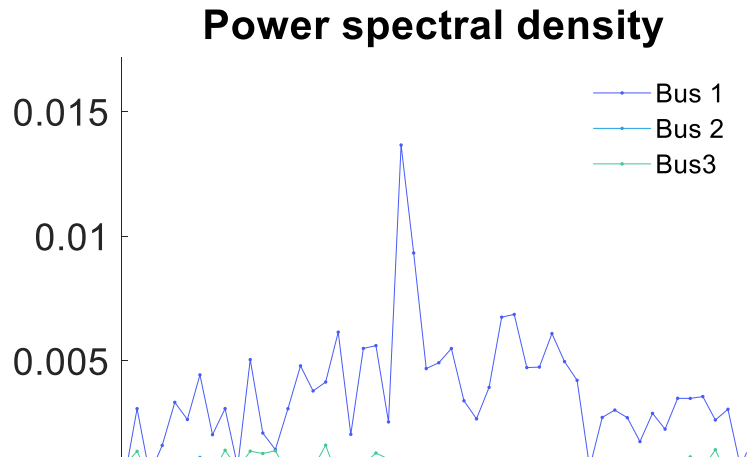

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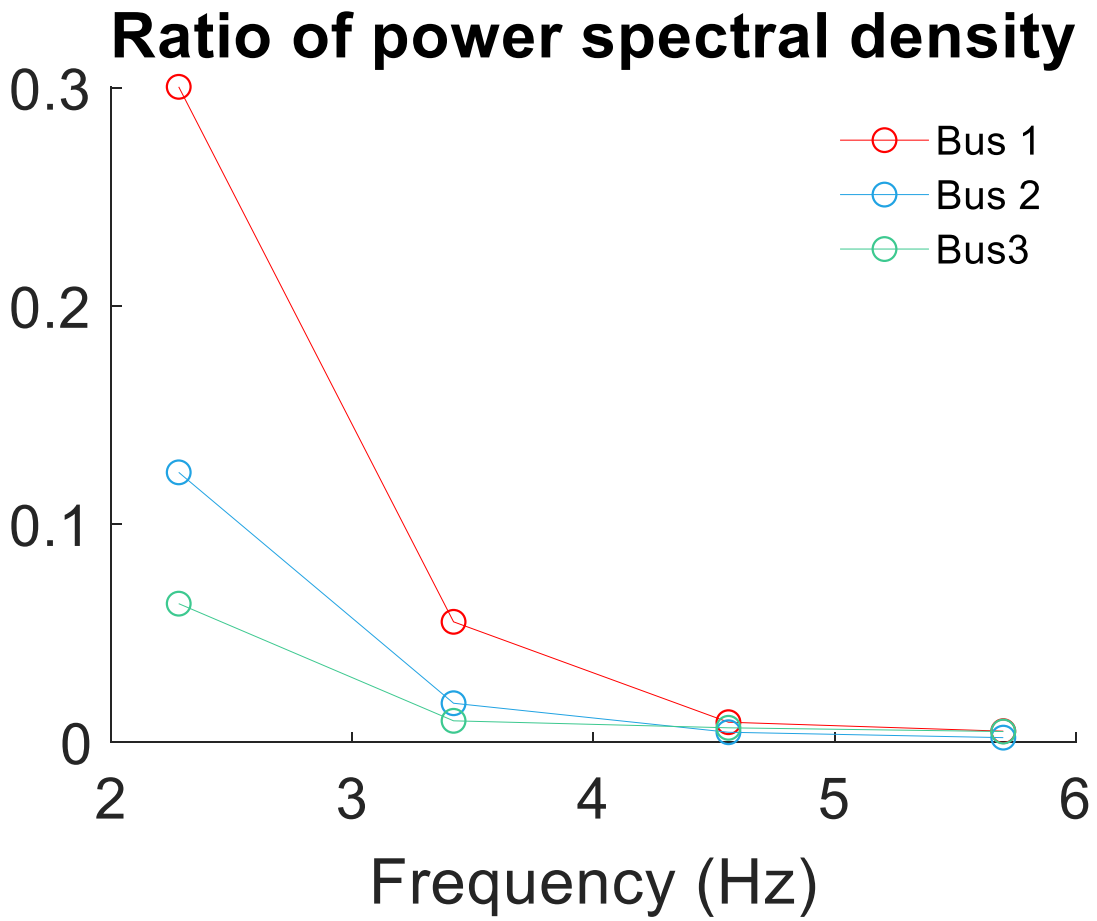

Discussion

- Harmonic content in forced oscillation data can be leveraged for localization:
  - Harmonics can assist in cases where the signal at the fundamental does not show a clear spatial pattern.
  - Network properties (e.g., resonances, zeros) can modify spatial characteristics of harmonics, however these are localized phenomena.

- Future work:
  - Develop procedures which use harmonics along with other metrics.
  - Exploit model knowledge

Thanks!

- Questions?

- Contact: sandip@wsu.edu