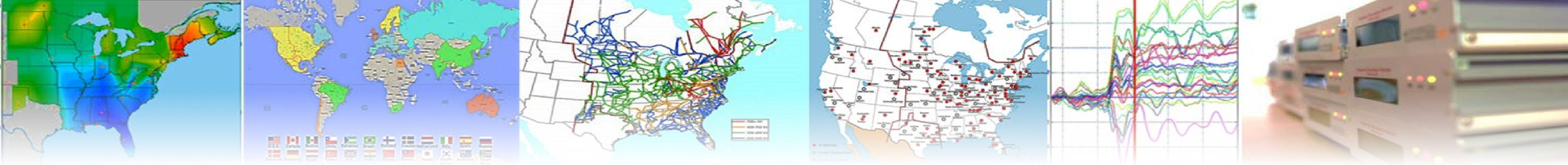


Calculate Center-of-Inertia Frequency and System RoCoF Using PMU Data

Shutang (Steve) You[1], Hongyu Li[1], Yilu Liu[1,2]

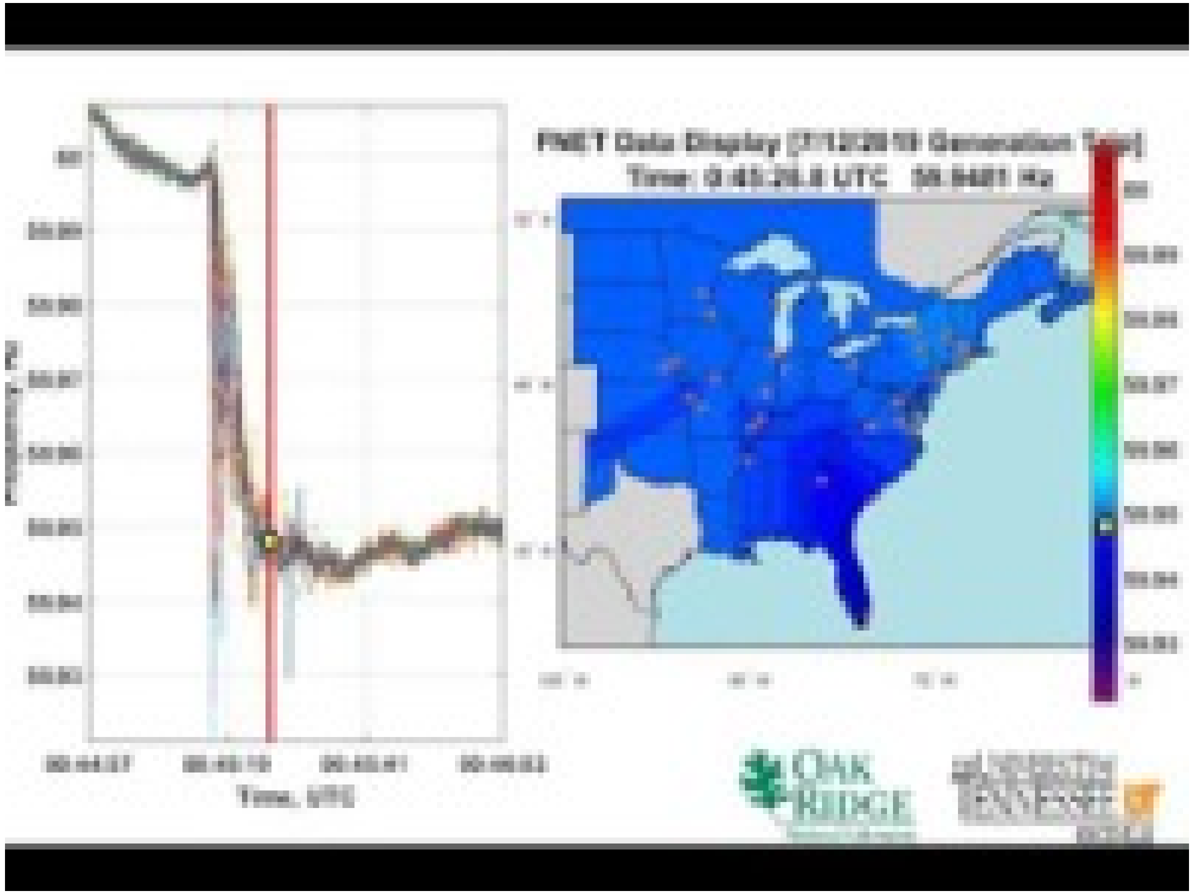
1. The University of Tennessee, Knoxville

2. Oak Ridge National Laboratory

Emails: syou3@utk.edu; liu@utk.edu

What is CoI frequency and why does it matter?

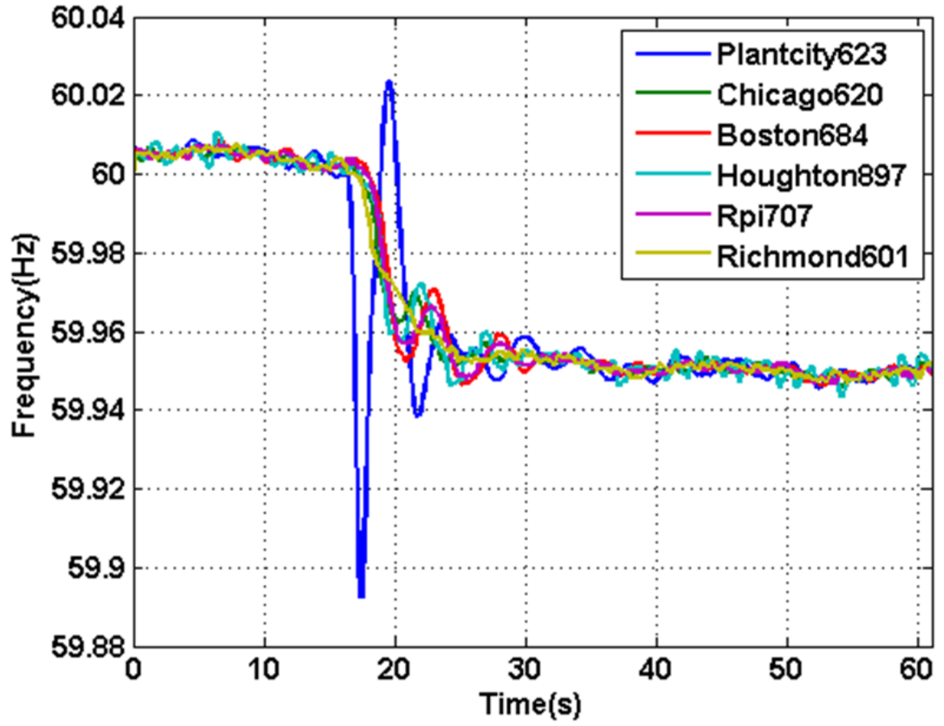
- “What is the system frequency?”
  - This may be an invalid question, like “how deep is the sea?”.
  - The frequency is usually localized measurement data.



- CoI frequency
  - The CoI frequency is the <u>frequency value weighted by inertia at different locations</u> across the geographic distribution of a power grid.
  - It may represent “the system frequency” (if we assume there exists one).

CoI-RoCoF

- RoCoF, the rate of change of the frequency, is useful for
  - Protection relays of distributed resources
  - Islanding detection
  - Control of energy storage
  - Synthetic inertia emulation
  - Frequency control
  - Underfrequency load shedding
  - Inertia estimation
  - Event magnitude estimation

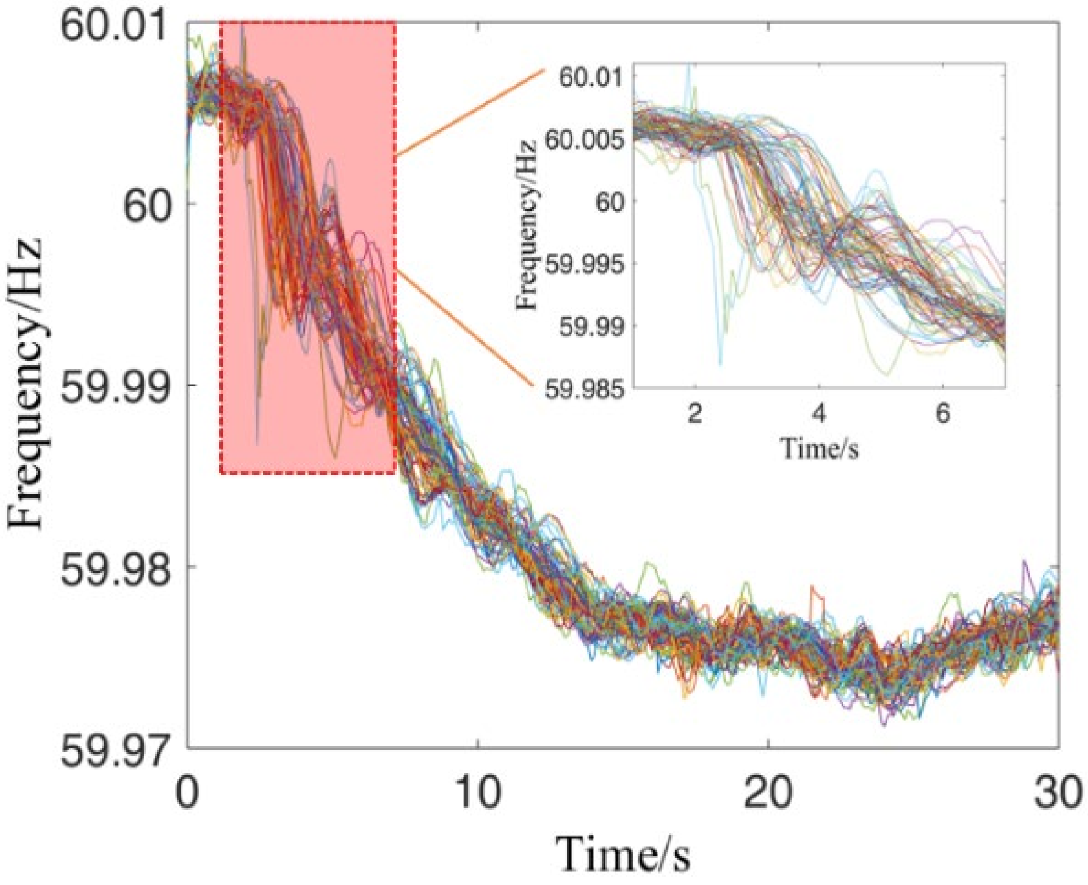


- Once the CoI frequency is known, CoI-RoCoF can be calculated.
- Similar to the CoI frequency, CoI-RoCoF is sometimes more useful than individual RoCoF obtained locally.

CoI frequency and CoI-RoCoF

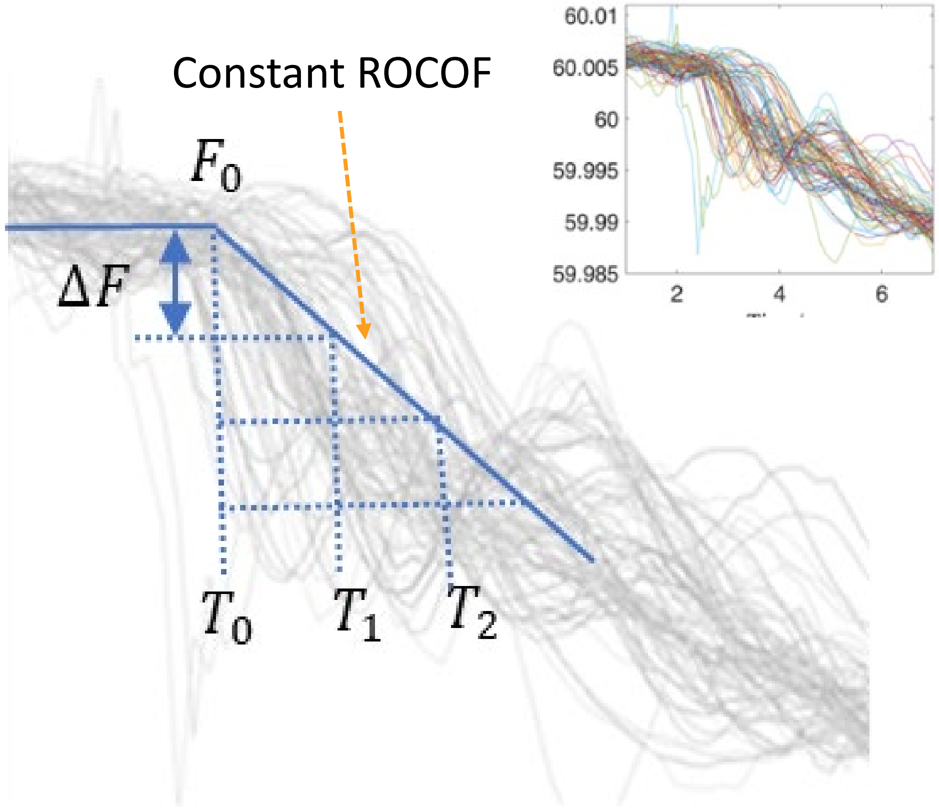
- CoI frequency is difficult to obtain due to:
  - Electromechanical wave propagation and oscillations
  - Inadequate deployment of sensors for localized frequency measurement of all inertia contributors
  - Constantly changing system inertia distribution, such as unit commitment and load inertia contribution

- Conventional methods include using the system medium frequency or average frequency to represent system CoI frequency and calculate RoCoF.



Proposed method – assumptions

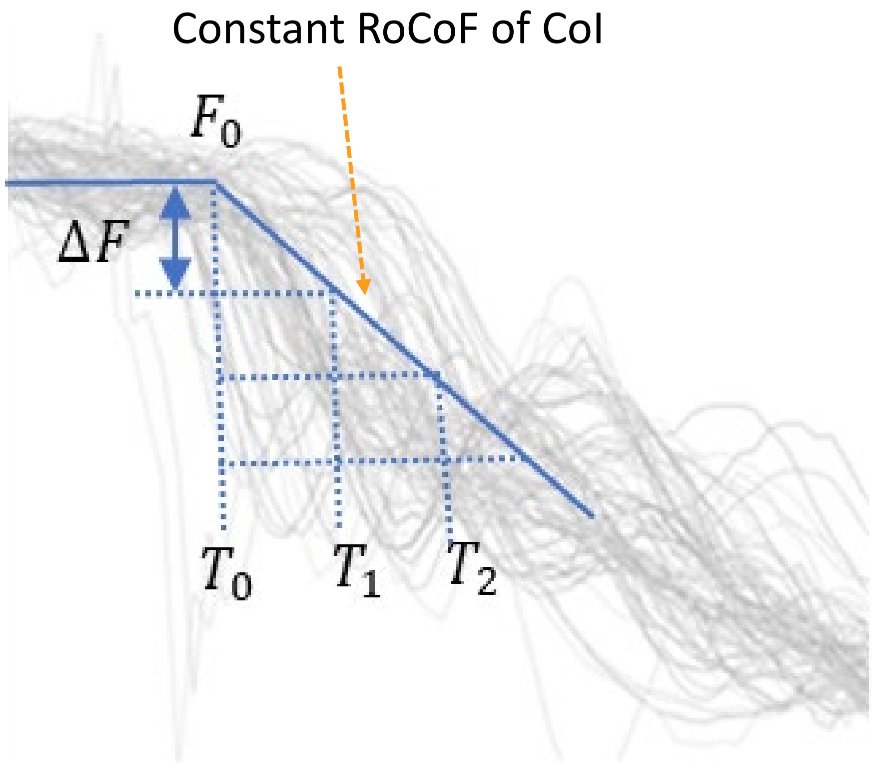
- CoI-RoCoF is influenced by two factors, system inertia and the event MW amount.
- Other factors that may have an impact are simplified
  - Governor response are not considered due to the existence of the governor deadband and the delay of governor response.
  - Load response are not considered due to that the initial frequency deviation is small.
- With these assumptions, CoI-RoCoF is a **<u>constant value in the initial period</u>** (the first 1-2 seconds) after a generation loss.



System frequency after a generation trip

Proposed method – objective

- Borrow the idea of **<u>weighted-average frequency</u>** in the CoI frequency definition. The objective is to find the weighting values for each frequency measurement.
  - How can we find the <u>optimal weighing values using just frequency measurements to make this CoI-RoCoF constant in this time window</u>?



System frequency after a generation trip

Proposed method – formulation

- Each time stamp data point can form an equation.

$$T_K: \quad f_1[T_K]\cdot x_1 + f_2[T_K]\cdot x_2 + f_3[T_K]\cdot x_3 + \cdots + f_N[T_K]\cdot x_N = F_0 + K\cdot \Delta F$$

where $\boldsymbol{x} = [x_1, x_2, \cdots, x_N]^T$ are the weights of different PMU channels, $\sum\{x_1, x_2, x_3, \ldots, x_N\} = 1$

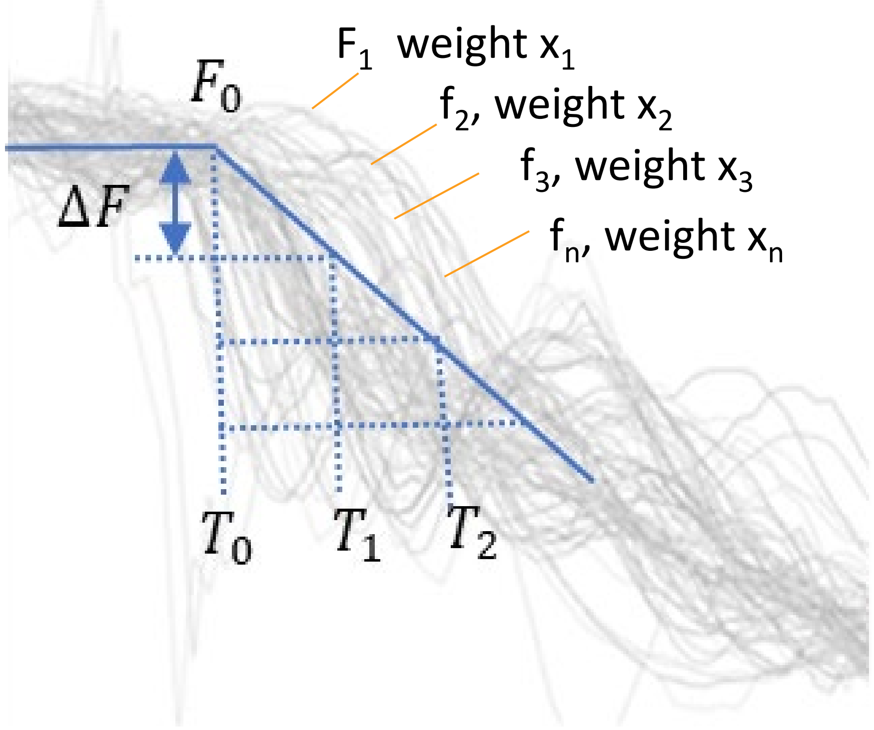
- As the time window includes multiple data points , the problem can be represented by a set of equations.

- The solution can be found using the ordinary least square method.

$$\min \|\boldsymbol{A}\boldsymbol{x}_E - \boldsymbol{b}\|$$

- The solution of weights is

$$\boldsymbol{x}_E = \left(\boldsymbol{A}^T\boldsymbol{A}\right)^{-1}\boldsymbol{A}^T\boldsymbol{b}$$



System frequency after a generation trip

Proposed method – output

- After $\boldsymbol{x}$ is determined, the CoI frequency can be calculated by weighting the frequency values as

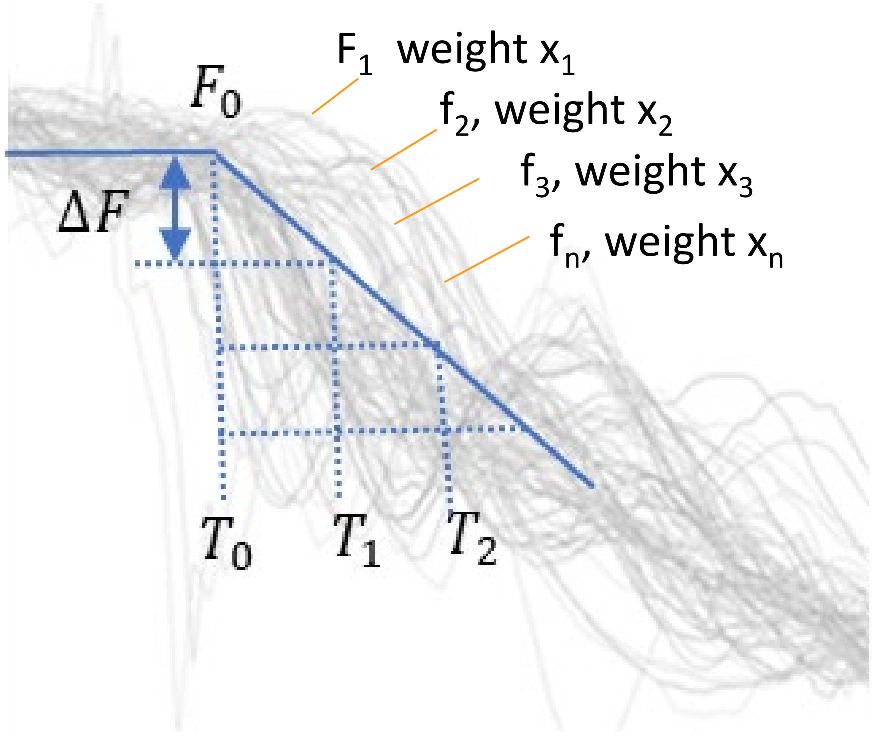
$$f_{\mathrm{CoI}} = (\boldsymbol{f} \cdot \boldsymbol{x}) / \sum_{n=1,\ldots,N} x_n$$

where $\boldsymbol{f}$ is the vector of individual frequency measurement from PMUs.

- The CoI-RoCoF value is the average frequency change in one second and can be denoted as

$$\mathrm{RoCoF} = \Delta F / \Delta T$$

where ΔT is the time duration between two consecutive frequency measurements.

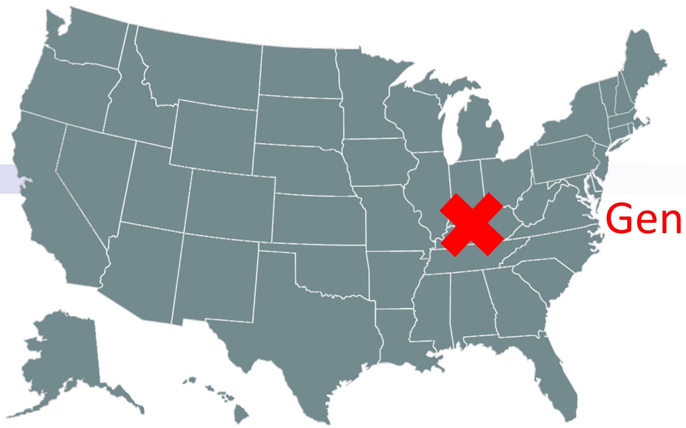


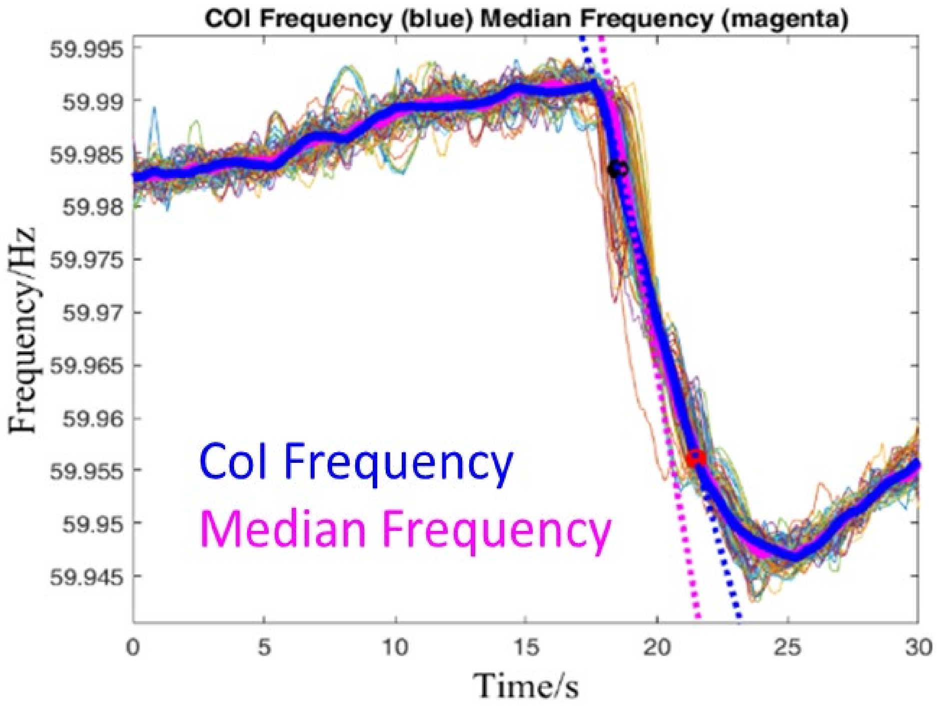
System frequency after a generation trip

Results of actual event measurement in Kentucky

- Two generation trip events at different locations: Florida and Kentucky, are used to compare the RoCoF calculation methods (the proposed CoI-RoCoF method and the RoCoF obtained by the median frequency method).

- When the event happens in the middle of an interconnection grid.
  - Less obvious oscillations and wave propagation
  - Median frequency and calculated CoI frequency almost overlap
  - RoCoF values obtained using different methods are close



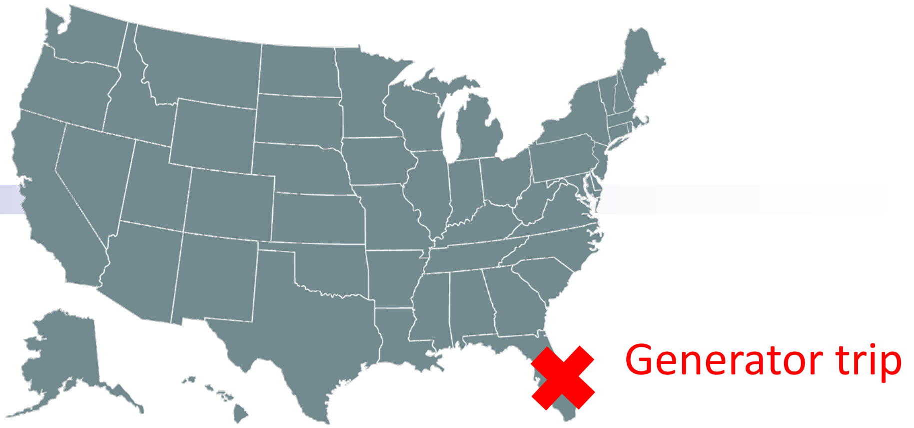


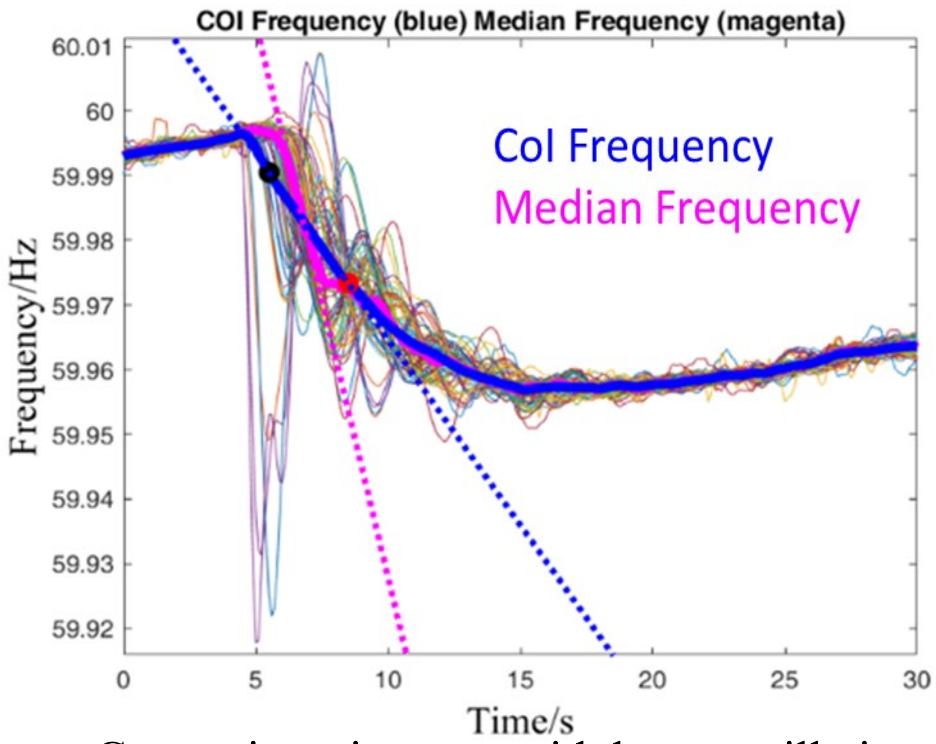
Generation trip event without large oscillation
(Event happened in Kentucky, time: April 2018)

Results of actual event measurement in Florida

- The generation trip happening at the grid edge (i.e., Florida) has large oscillations. It is more challenging to calculate RoCoF when obvious oscillations and wave propagation exist.

- CoI-RoCoF is oscillation-free, smaller than RoCoF based on the median frequency in the frequency decline stage.





Generation trip event with large oscillation
(Event happened in Florida, time: Oct 2017)

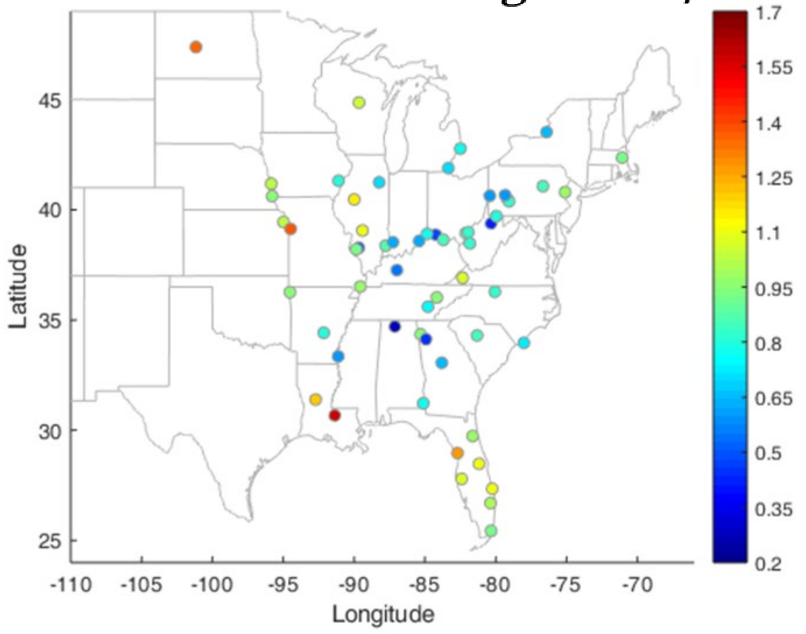
Potential application - monitoring

- Monitoring: event magnitude estimation

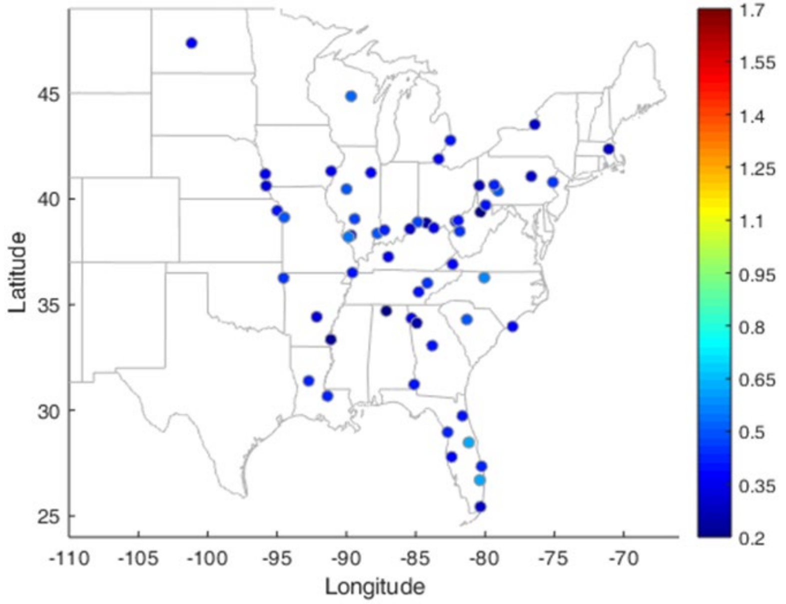
Color value is defined to evaluate the performance of RoCoF in estimating event magnitudes

$$c\ (\text{color value}) = \frac{\mathit{Calculated\ ROCOF}}{\mathit{Event\ magnitude}/\text{EI Inertia}}$$

When events happen in grid edges, RoCoF obtained from system median frequency has a lower accuracy in estimating event MW amounts.



Median frequency based



The proposed method

Potential application - monitoring

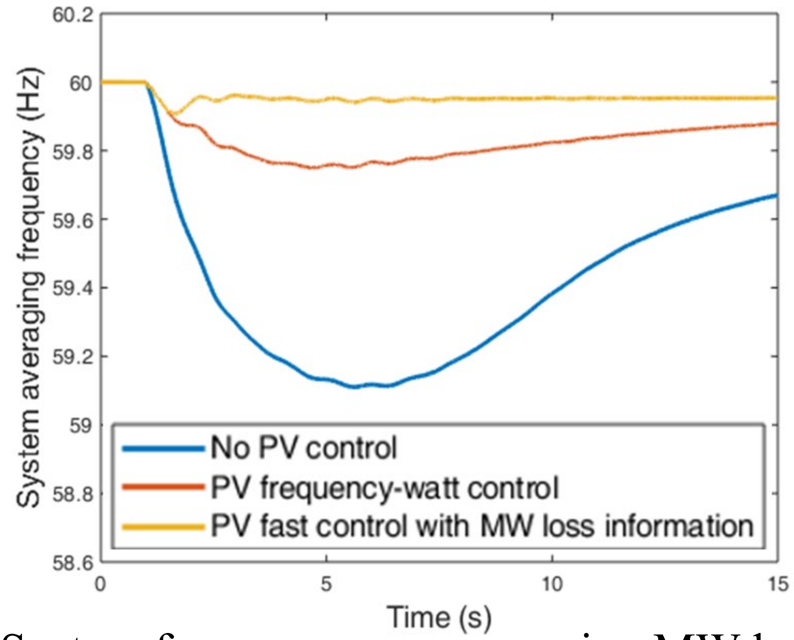
- Event magnitude estimation accuracy

Event Magnitude Estimation Accuracy (100+ events in FNET/GridEye system)

Magnitude Estimation Approach	**Average Error**
Frequency deviation method	30%
Median frequency-based method	24%
Proposed RoCoF	15.6%

Potential application – feedforward frequency control using inverters

- Once we know the MW loss amount based on RoCoF, some feedforward frequency control strategies can probably be designed to leveraging fast response capability of inverters in low-inertia power grids.



System frequency response using MW loss information and PV fast frequency control

Conclusions and future work

- A new method for CoI-RoCoF calculation using PMU data shows better performance in revealing the “true frequency” and “true RoCoF” of large power grids.
- Potential applications: event magnitude estimation, fast control of system frequency.

- Future Work
  - Impact of governor response: what if local governors had responded substantially while the frequency perturbation is still propagating toward remote regions?
  - Time window selection.
  - Impact of load damping.
  - Assign weights using multiple events.

Thanks !

Q&A