Unlimited Benefit from Grid Edge Synchronized Measurement Data

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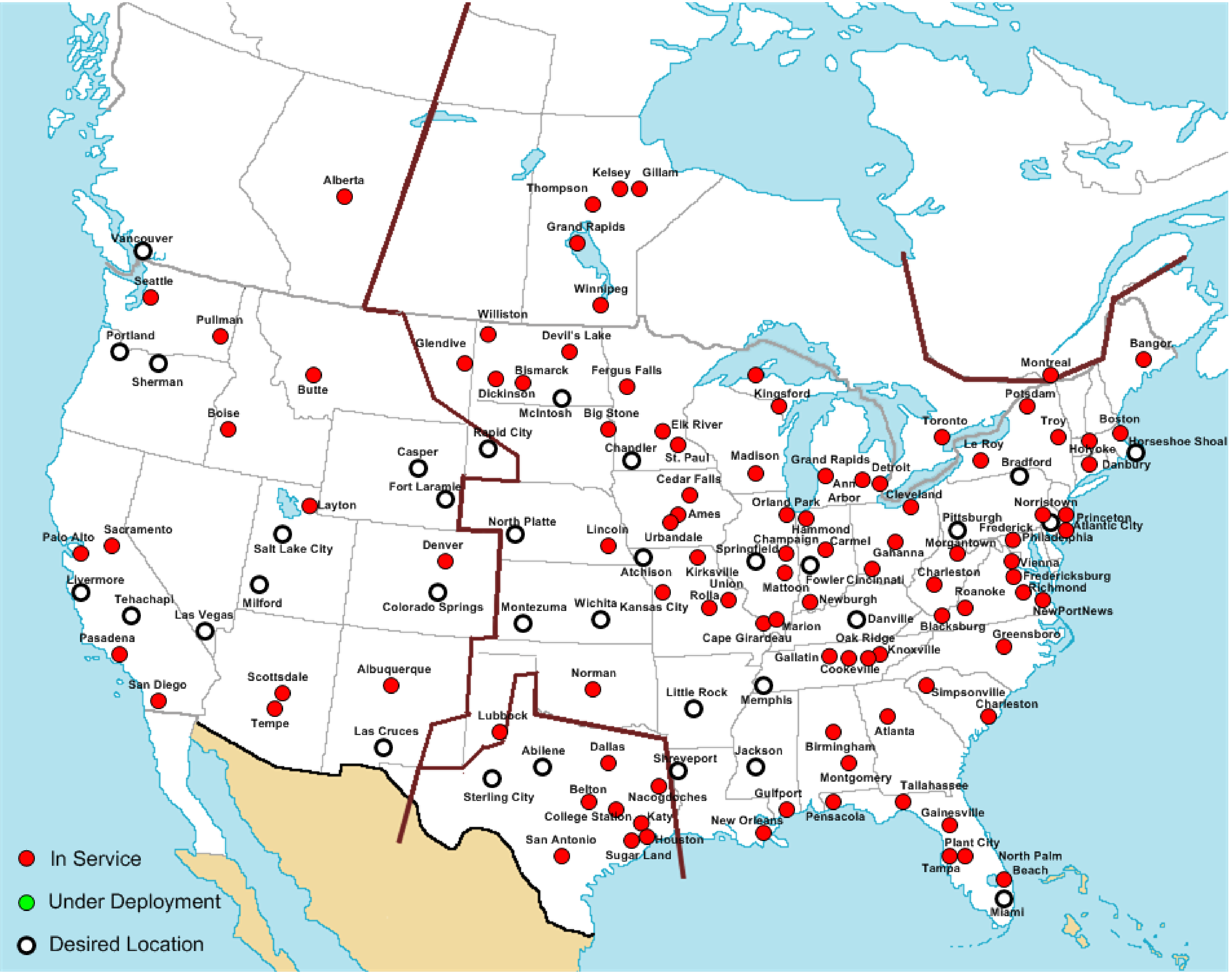
University of Tennessee and Oak Ridge National Laboratory

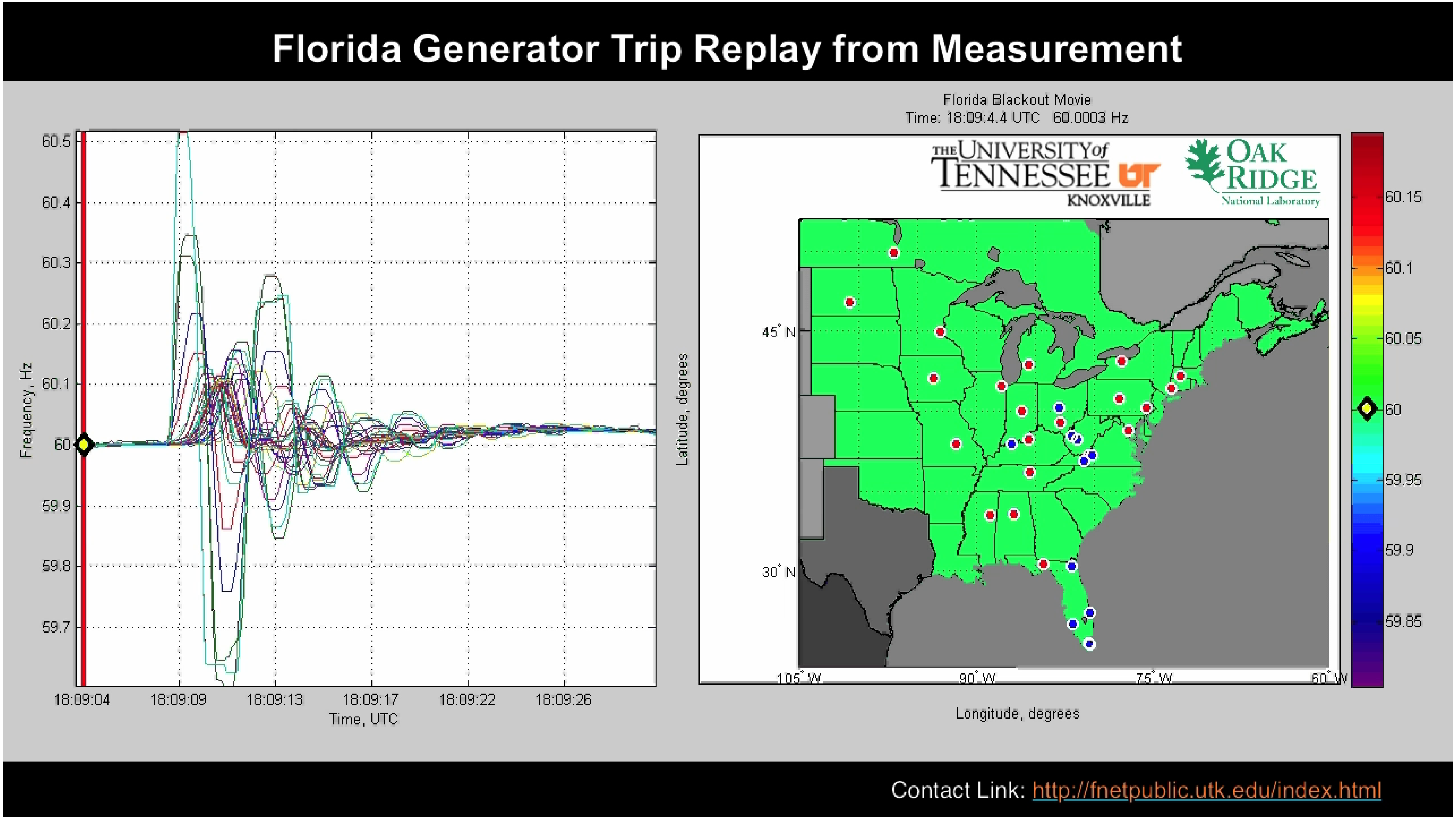
Partial list of UTK/ORNL sensor locations in US/Canada



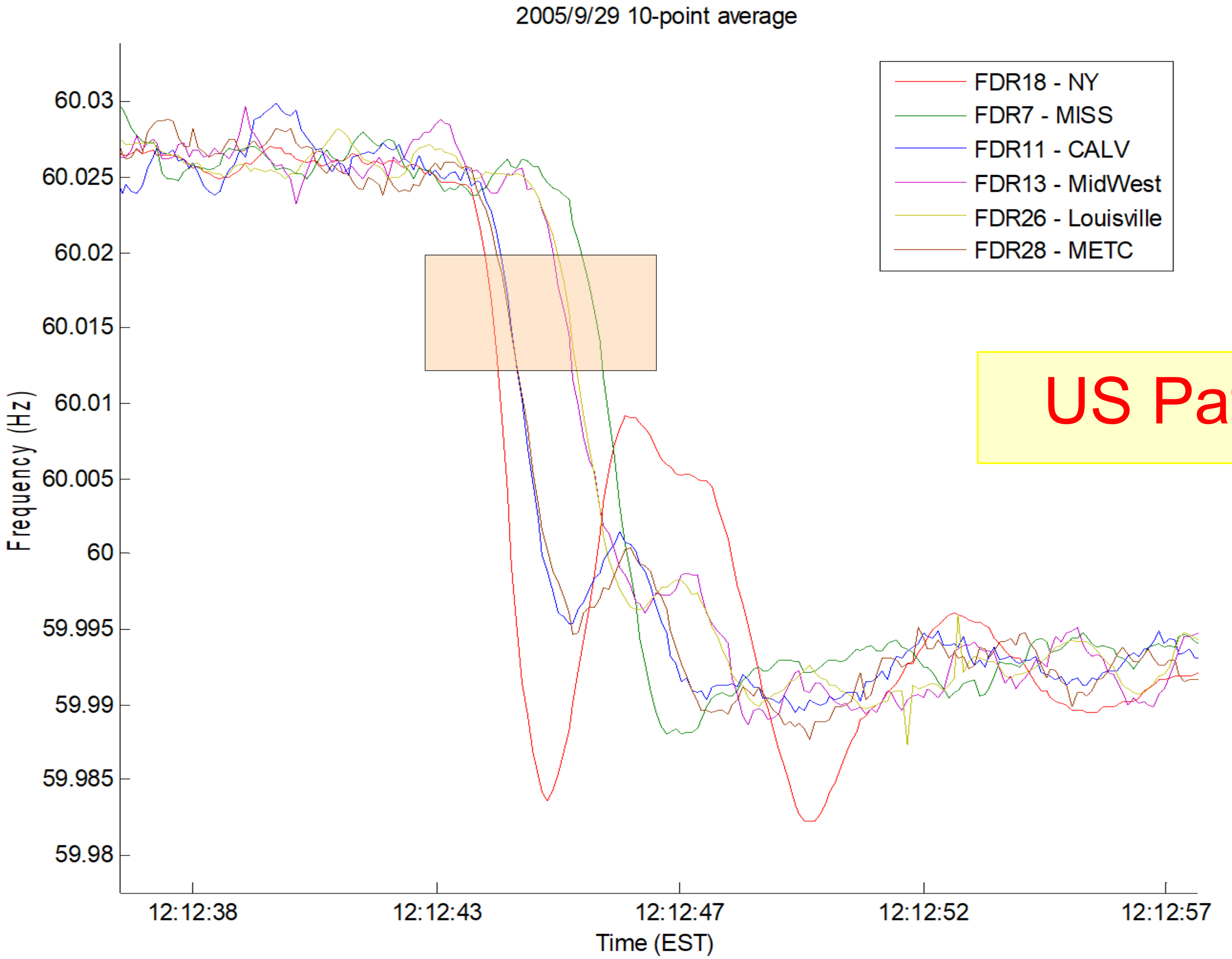
FNET GridEye

Worldwide Monitor Deployment Map (UTK)

Disturbance Propagation Playback 2-26-08



On-line Event Location -TDOA

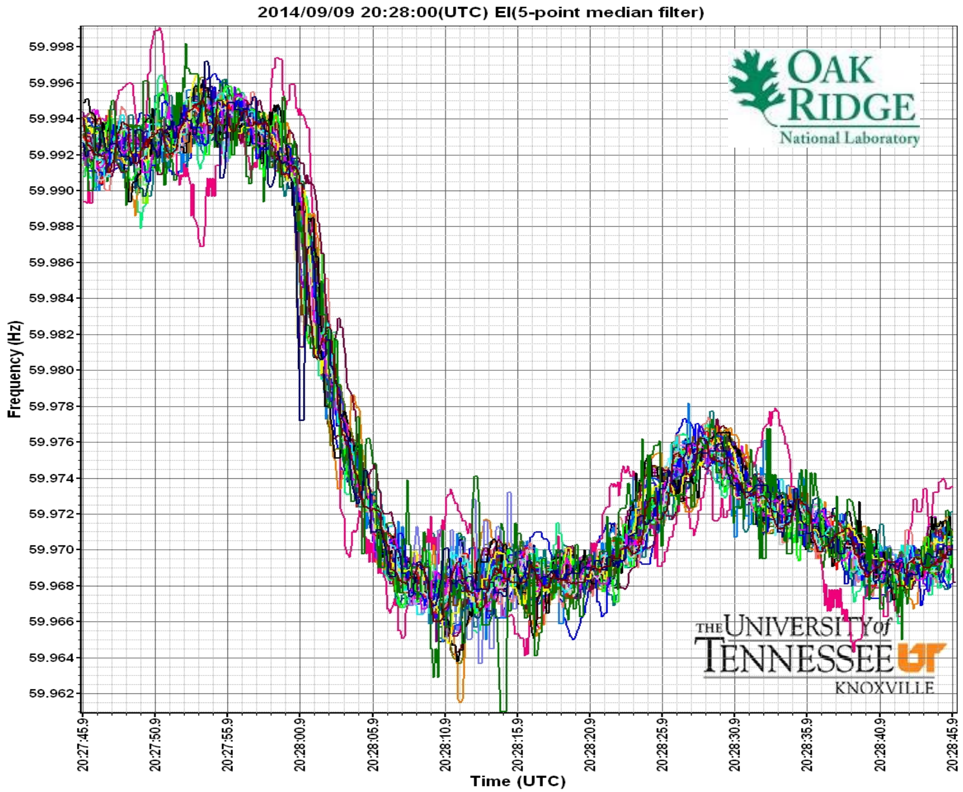


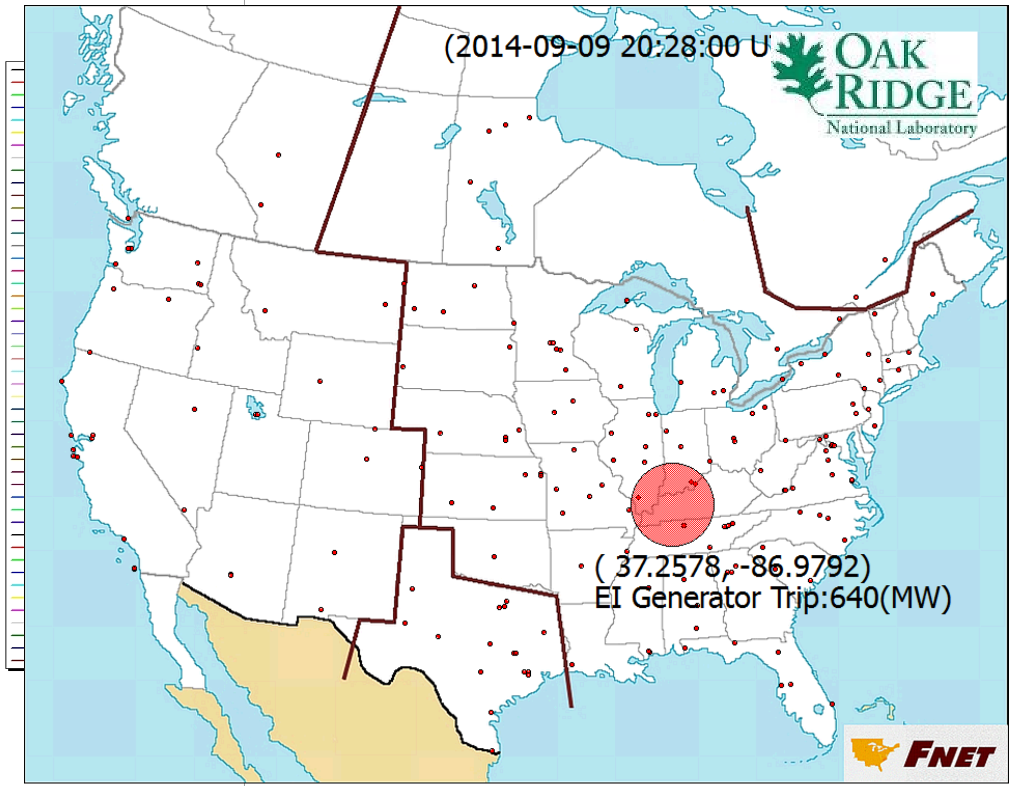
US Patent: 7519454,7765034

Sample automatic event alert

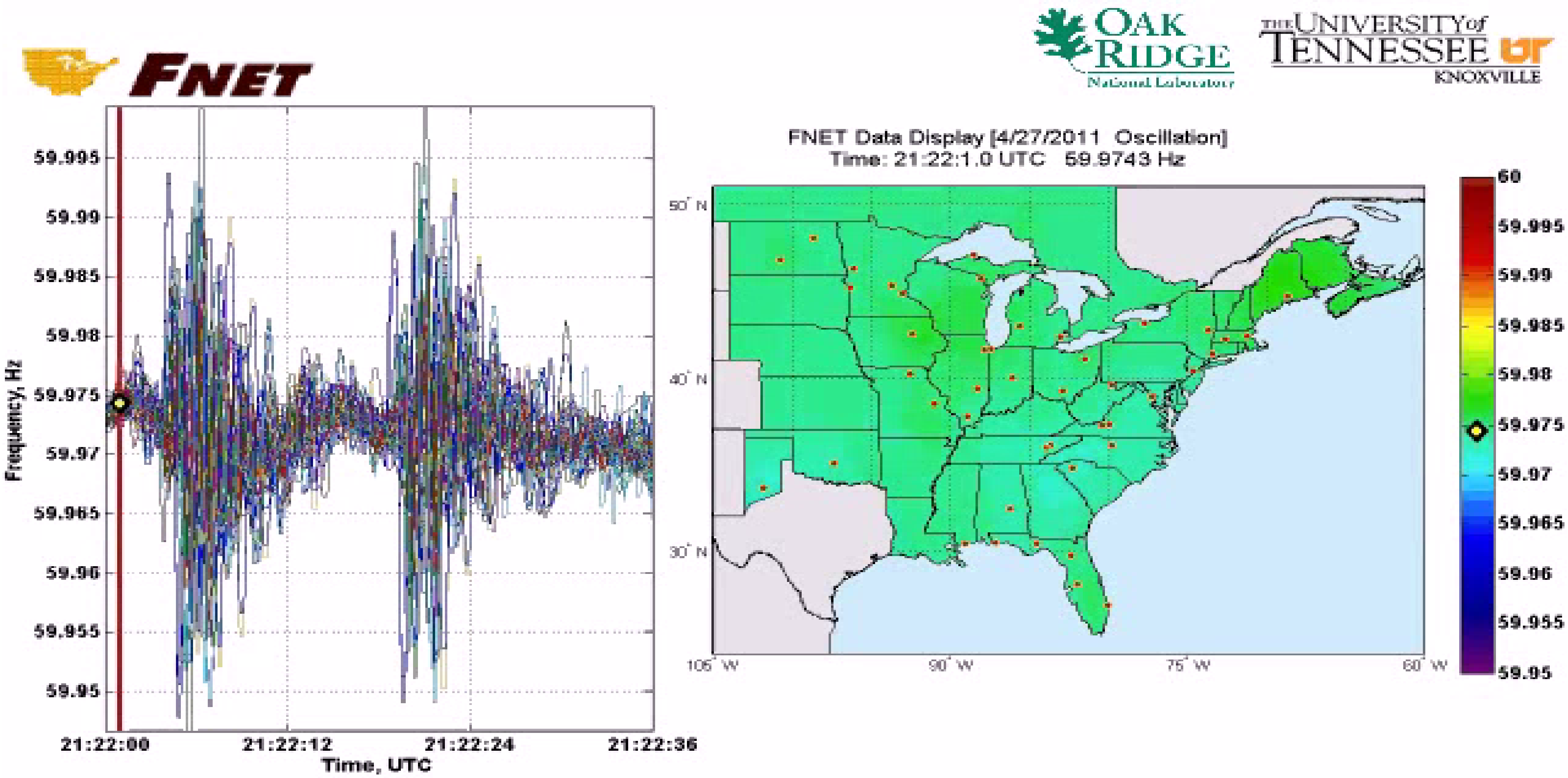
Event Estimation:
640MW EI Generator Trip at 20:28:00UTC, on 09/09/2014 near Paradise power plant (SERC) ((Muhlenberg,KY,42337; Latitude: 37.2578, Longitude: -86.9792)

PLEASE KEEP THIS INFORMATION CONFIDENTIAL.



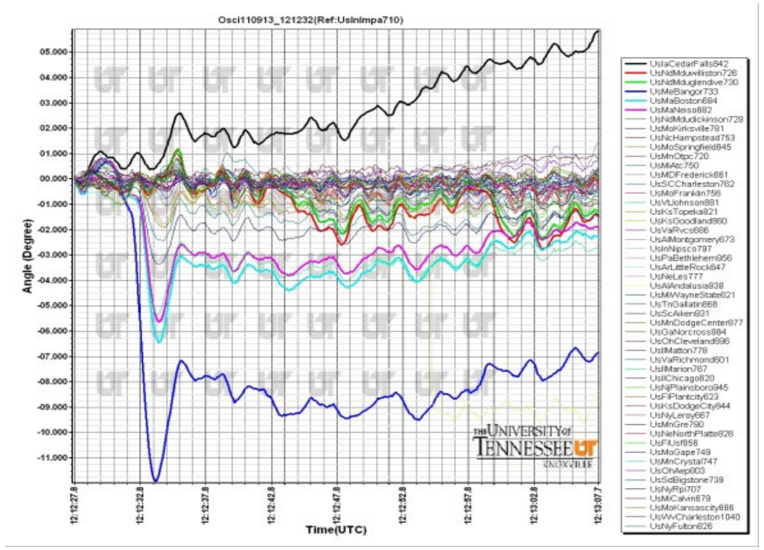


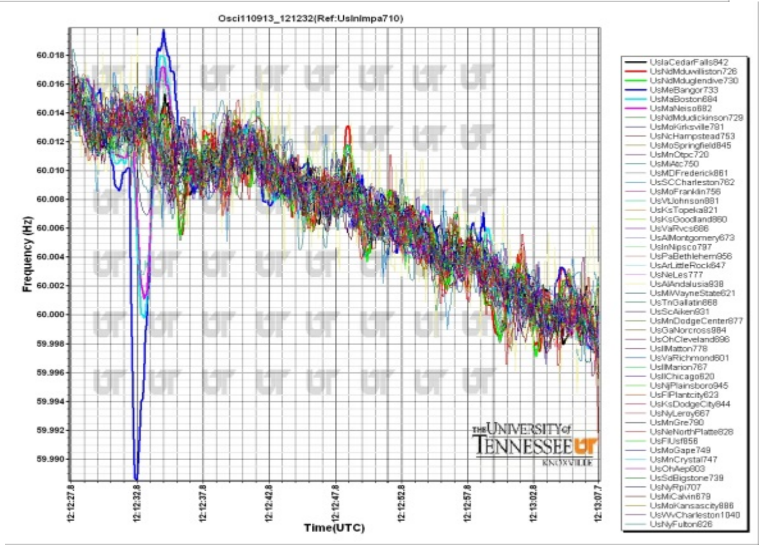
Frequency Disturbance and Oscillations

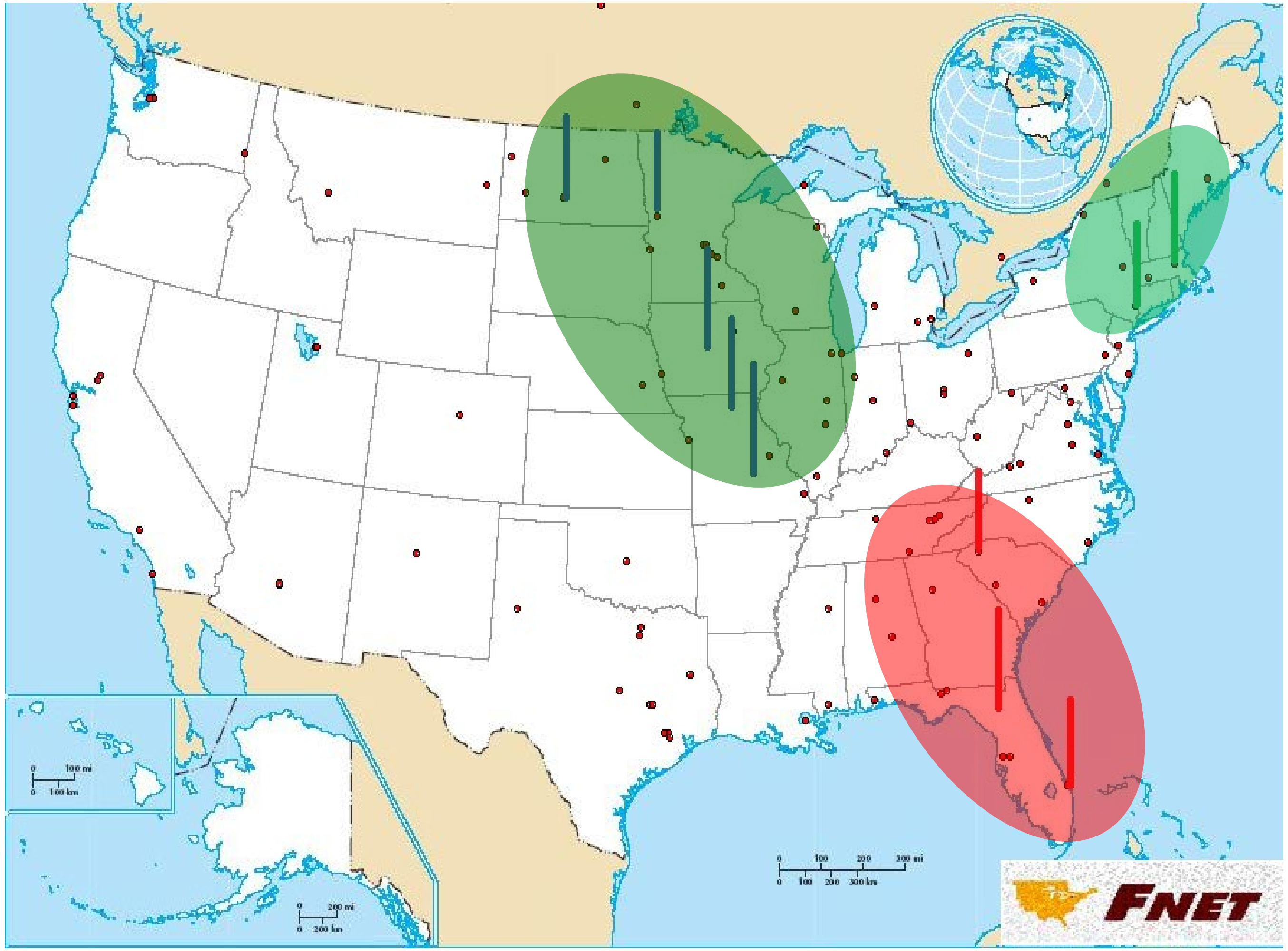


Typical Three area oscillates in EI

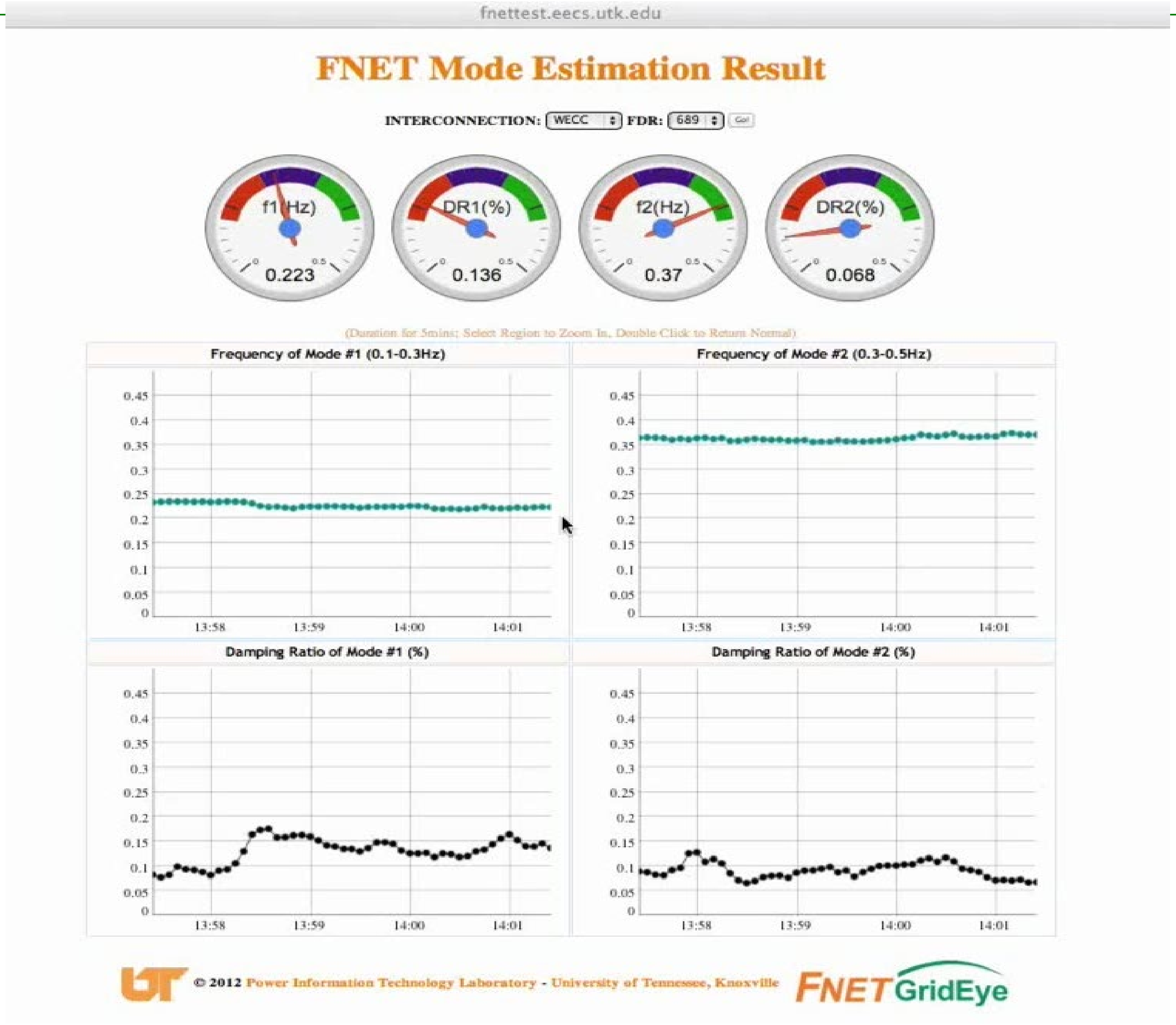
11/09/2013 12:12:32 UTC *Frequency: 0.217Hz*





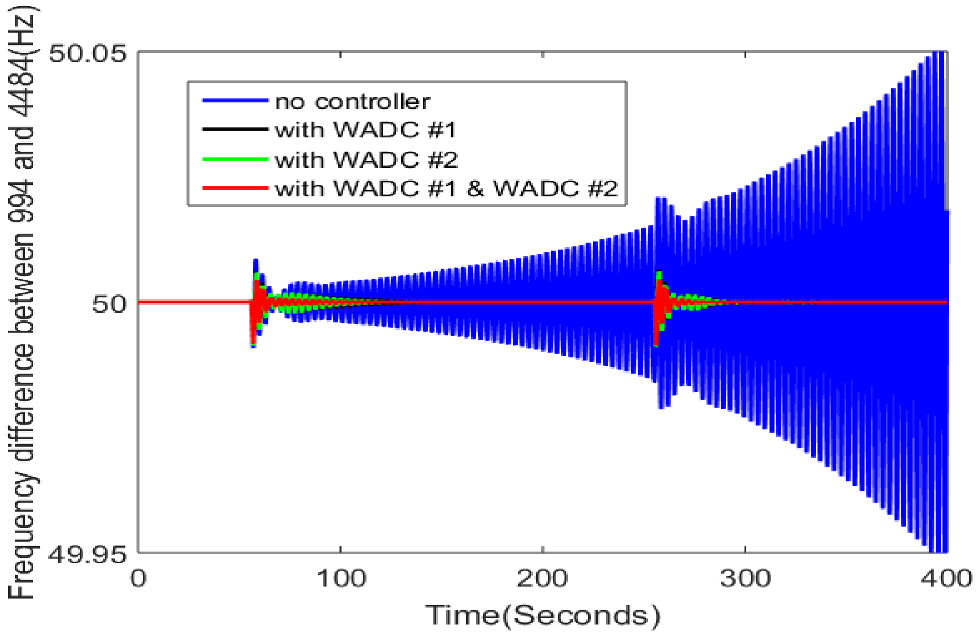


Ambient Online Oscillation Monitor

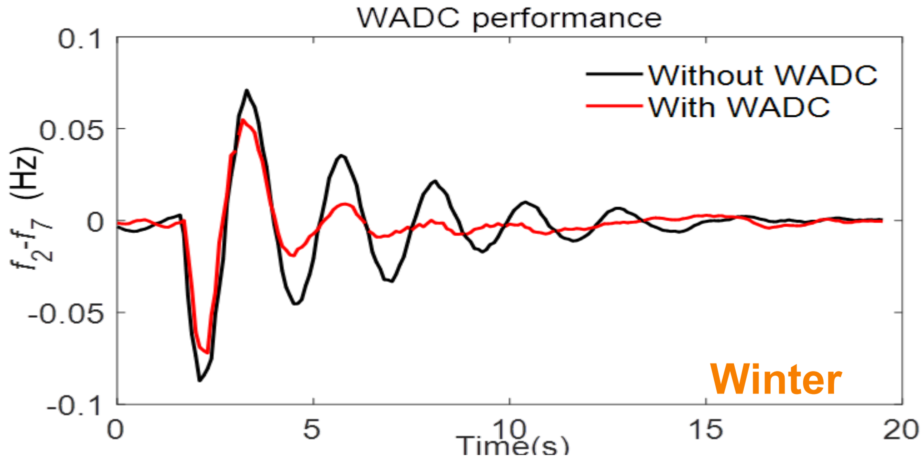


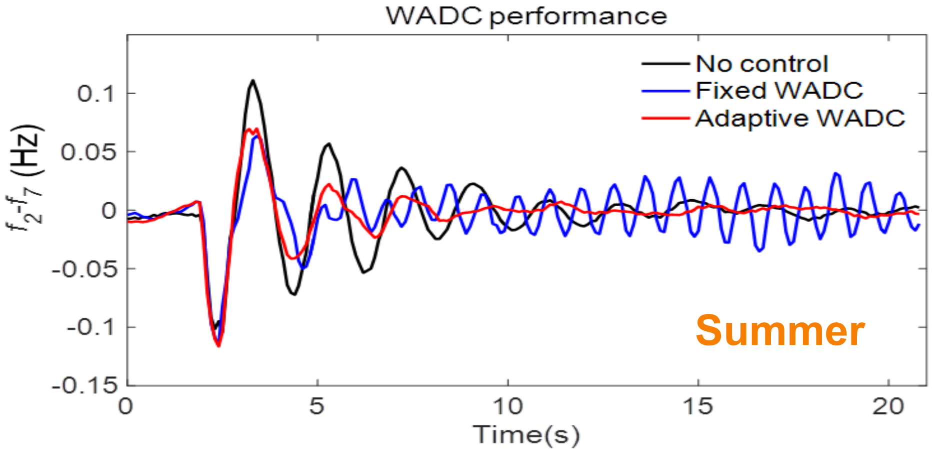
Measurement Derived Grid Model for Oscillation Damping

- Real-time data-driven model based oscillatory mode representation
- Apply to NAPA, TERNA, and Saudi Grids
- Demonstrate on CURENT HTB



Control effect in Terna Grid



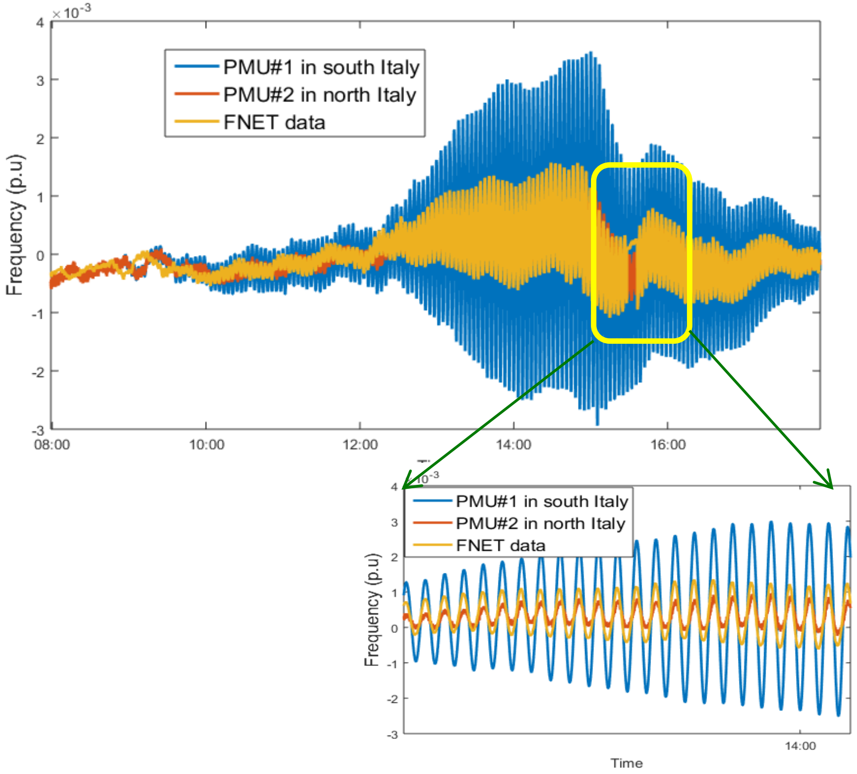


Realtime update Grid transfer functions

Control effect on CURENT HTB

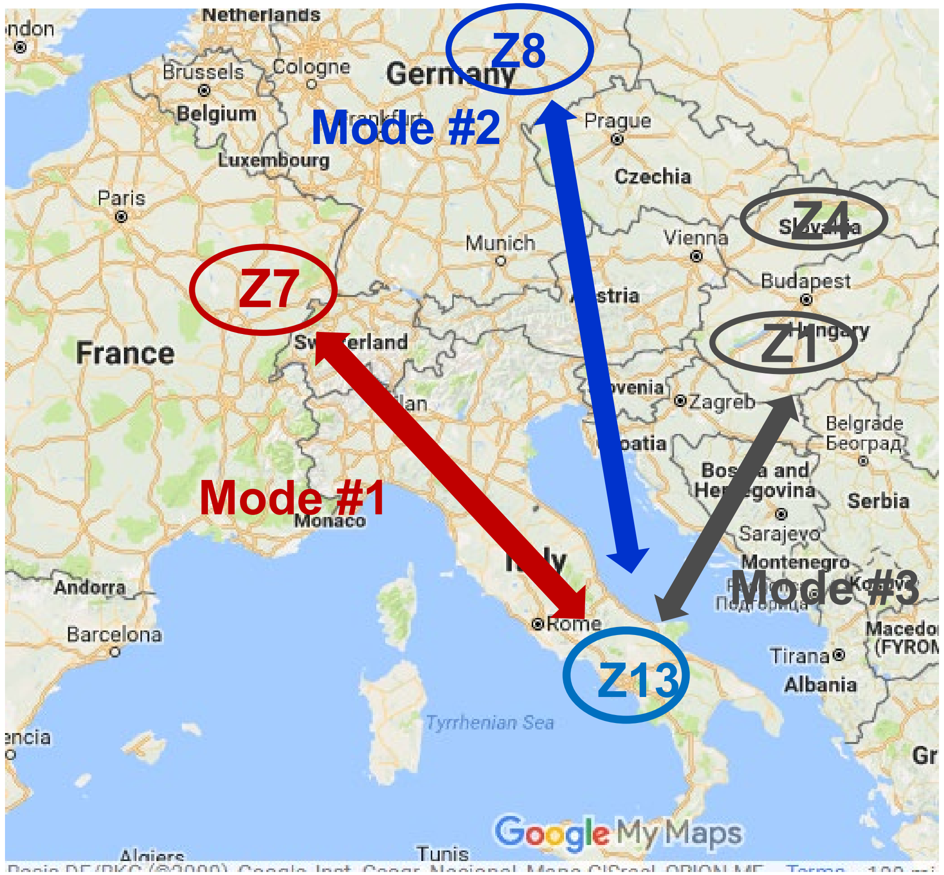
Case Study - Terna Grid Oscillations

- Developed the controller using measurement-driven model
- Terna: TSO in Italy



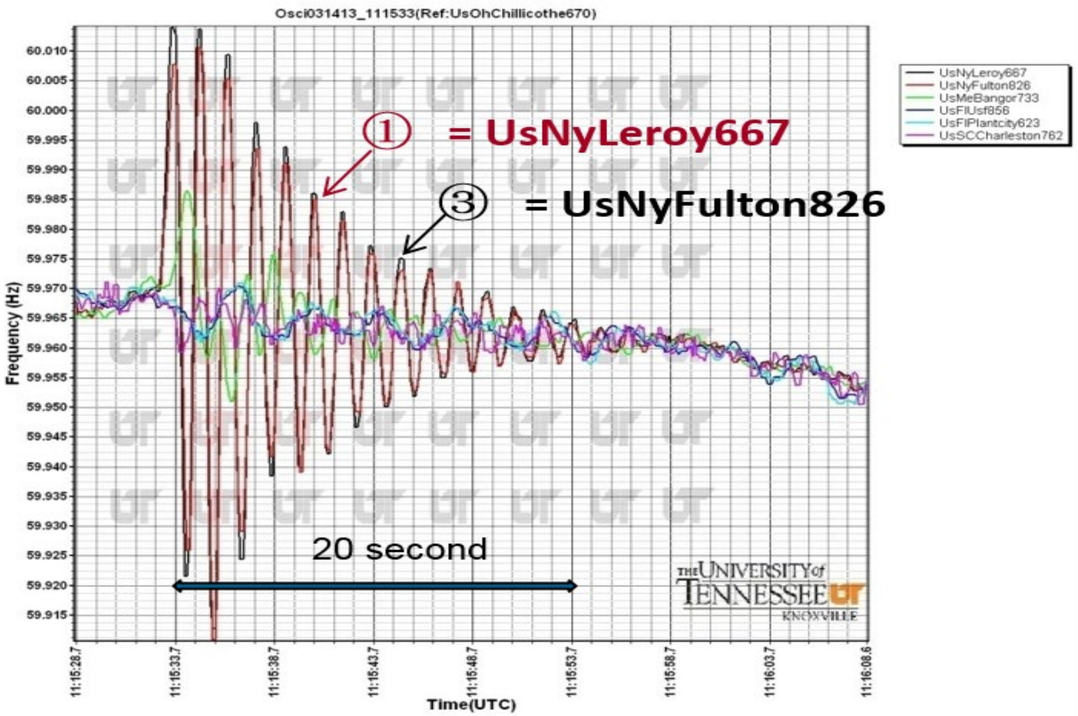
0.25Hz oscillation detected by FNET/GridEye on May 21, 2018

Z1: Bosnia & Herzegovina
Z4: Hungary, Z7: France
Z8: Germany,
Z13: Italy - Palermo

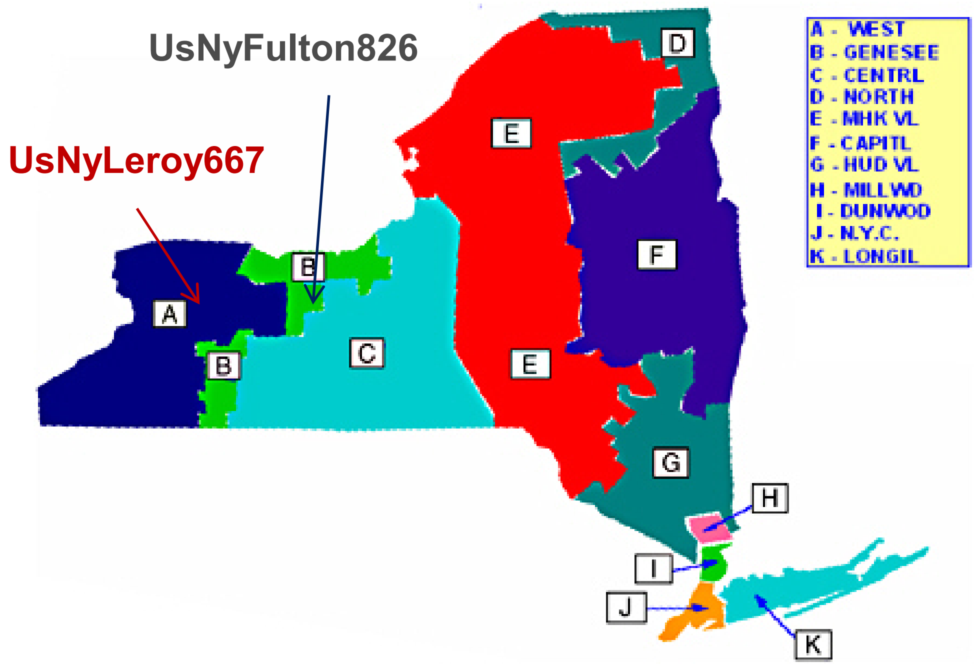


Case Study - NYPA Grid

- Transfer function model was constructed by utilizing measurements.
- Utilized the measurement-driven model to design oscillation damping controller.



Oscillation detected by FNET/GridEye

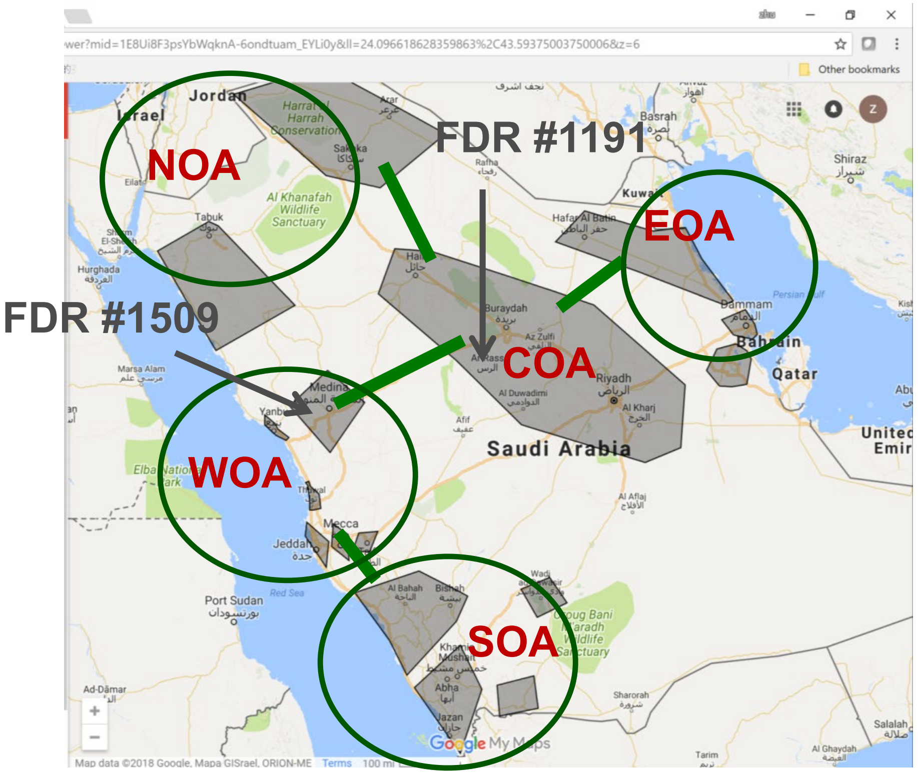


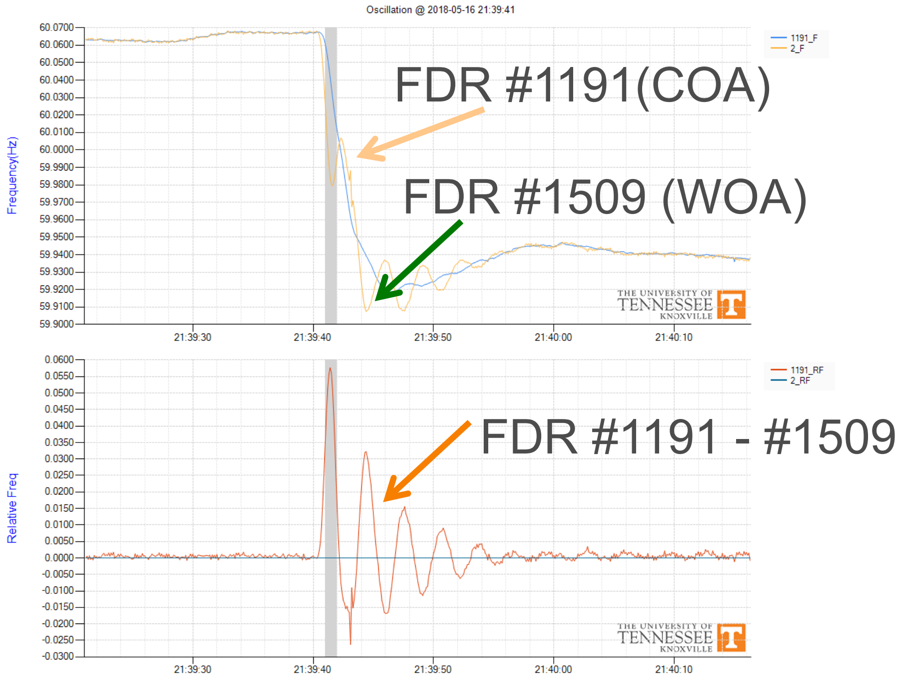
Area map of New York State grid

Source: NYISO

Case Study - SEC Grid

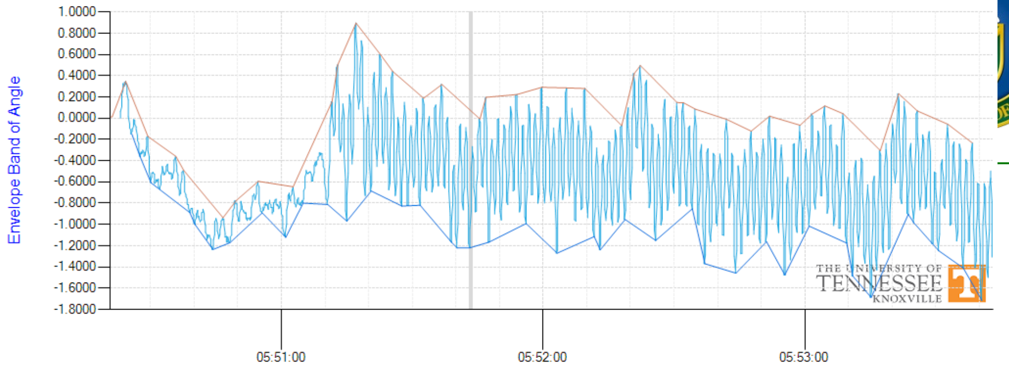
- Modal analysis (five operation areas)
- Transfer function model development & controller design





0.32Hz oscillation detected by FNET/GridEye on May 16, 2018

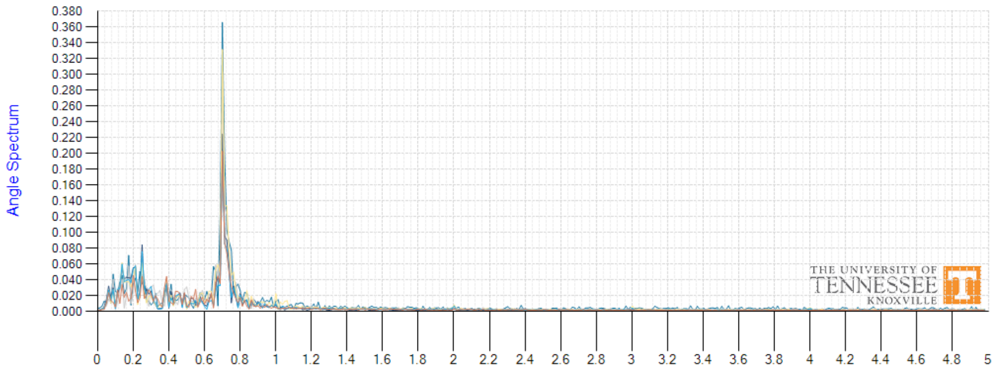
Forced Oscillation Detection



- ✓ **Detection of forced oscillation**

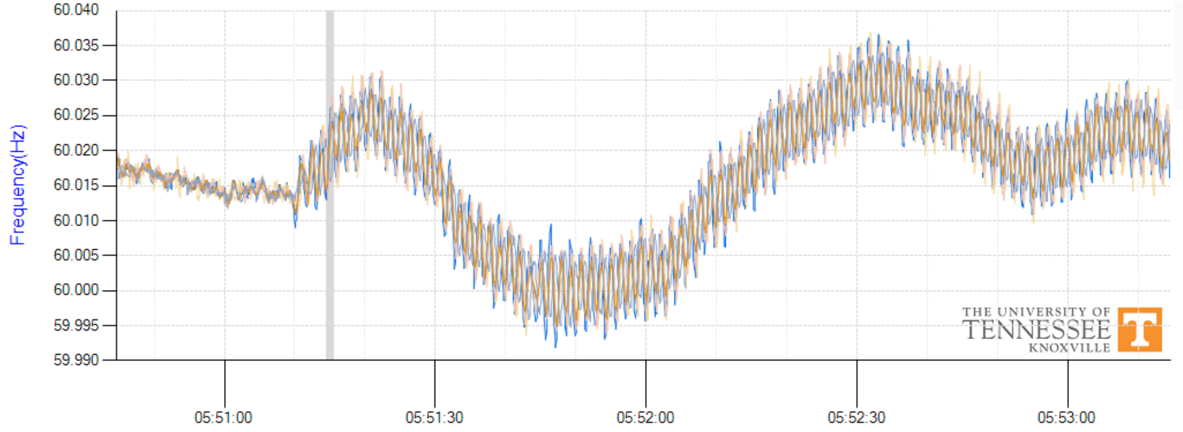
  Step 1) Detection of abnormal envelope height of phase angle

  Step 2) Find the dominant mode.

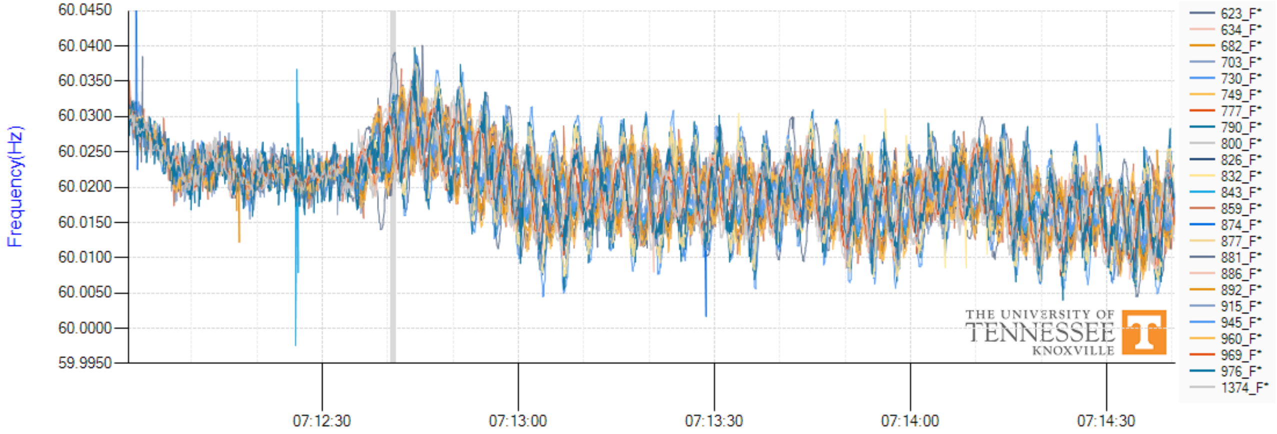


- ✓ **Confirmed Forced Oscillation Cases**

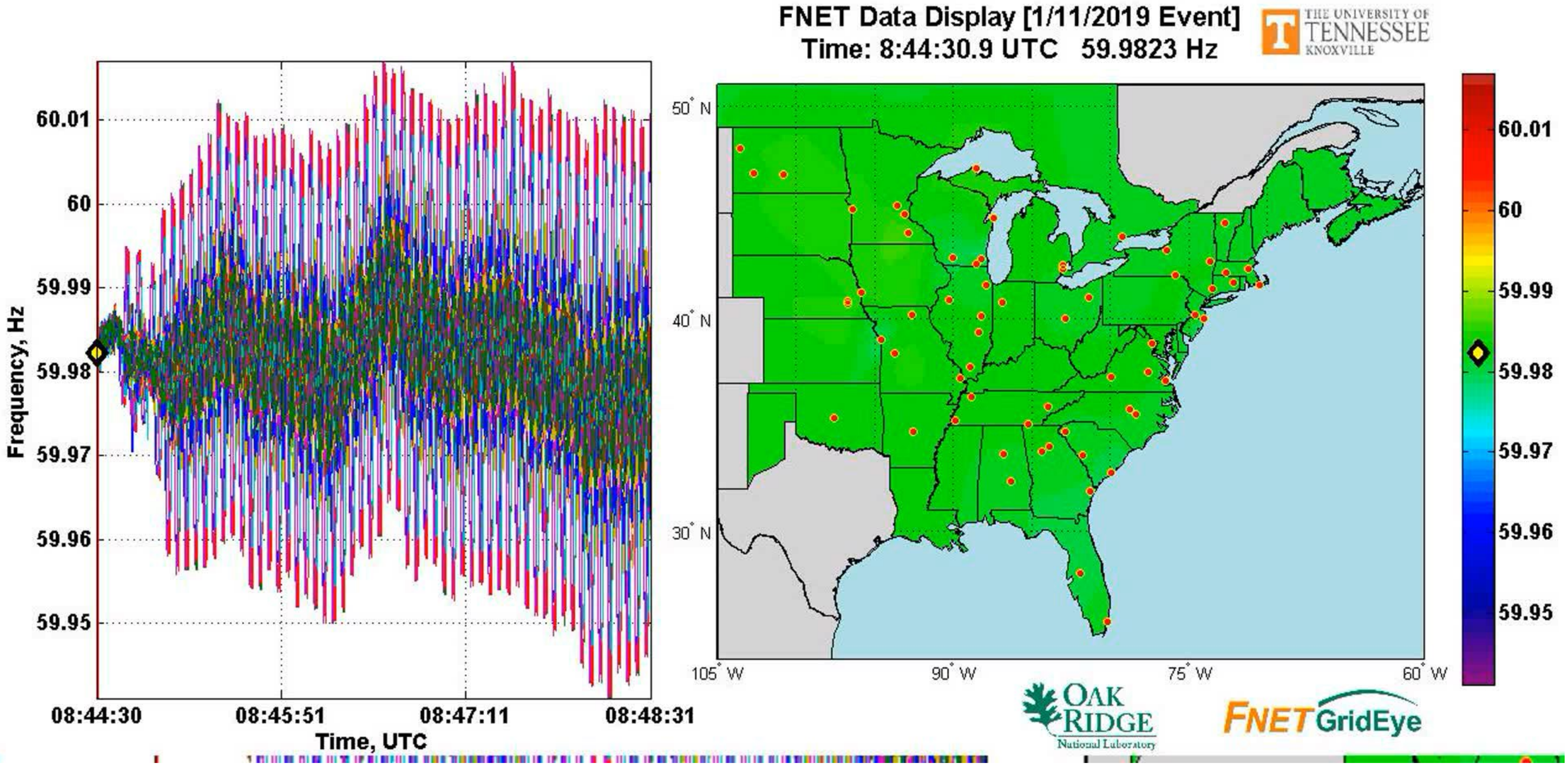
A. Start from 2016-11-27 05.51, EI



B. Start from 2016-06-17 07.12.40, EI

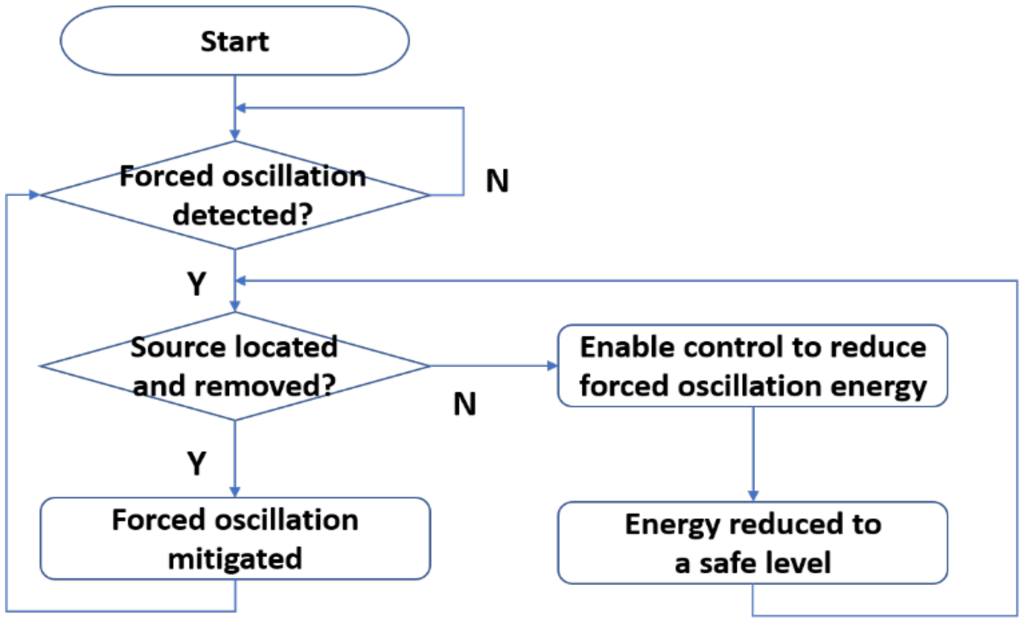


Recent Major Forced Oscillations



A Comprehensive Method to Mitigate Forced Oscillations

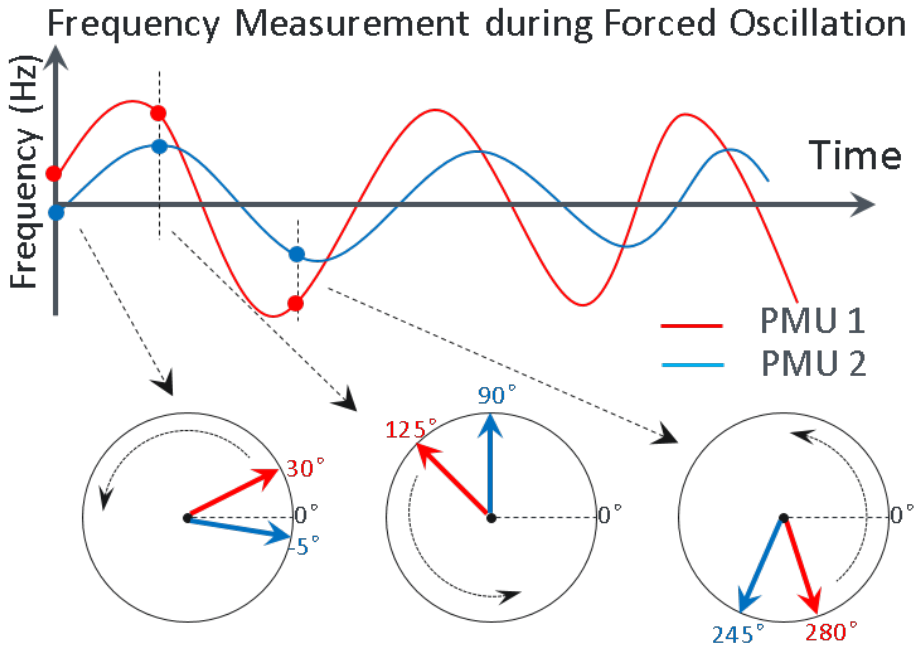
- Source Location + Forced Oscillation Control
  - A new source location algorithm based on mode angle: Not require system topology information and power/current measurements, easy for implementation.
  - Modulate active power of utility-scale BESSs to reduce the forced oscillation energy to a safe level, leave sufficient time for source location.



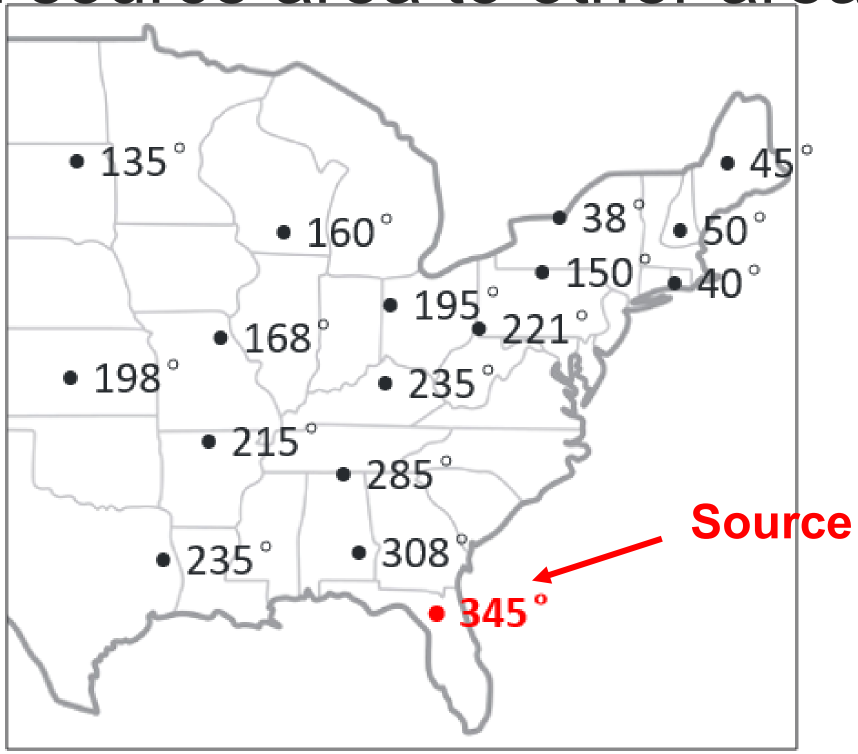
Procedure to mitigate forced oscillation

Source Location Algorithm Based on Mode Angle

- Mode angle: Angle of the oscillating phasor at a specific time.
- The source area usually has the most leading mode angle, and mode angle gradually decrease from source area to other areas.

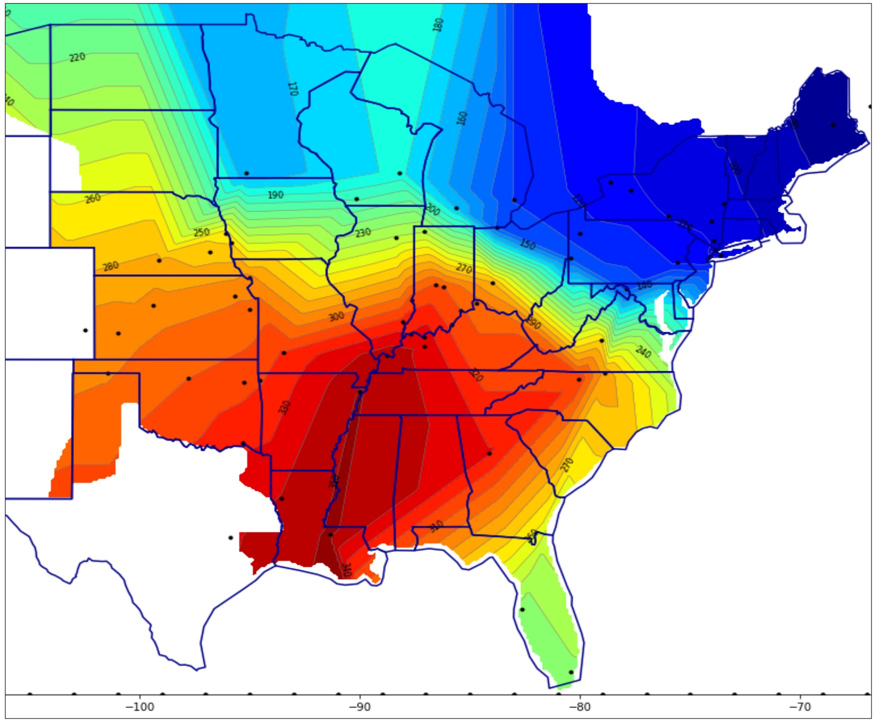


Mode angle: PMU1(red) is leading PMU2(blue) by 35°

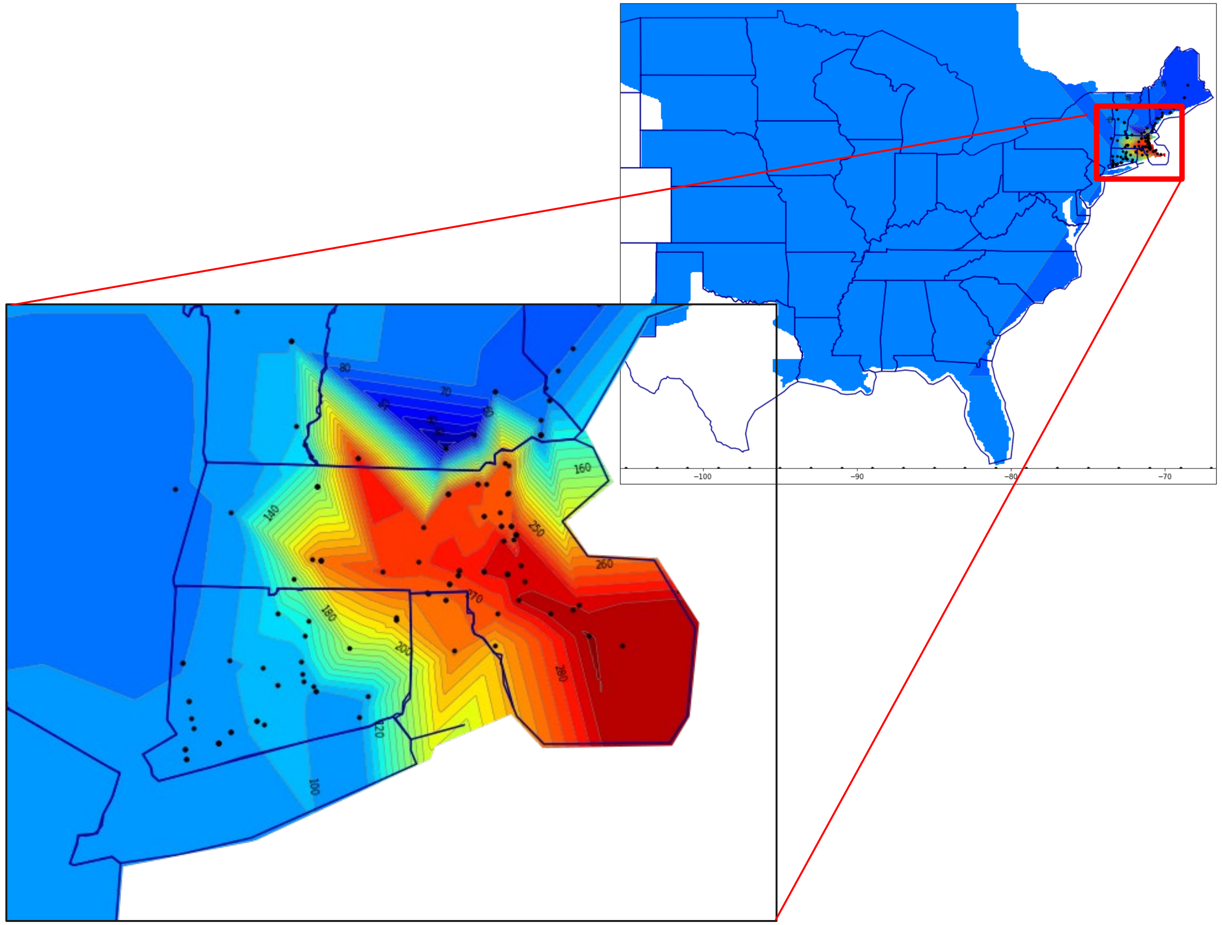


Validation Using Simulated Forced Oscillation Events

- Simulation examples (**Dark red** area has most leading mode angle.



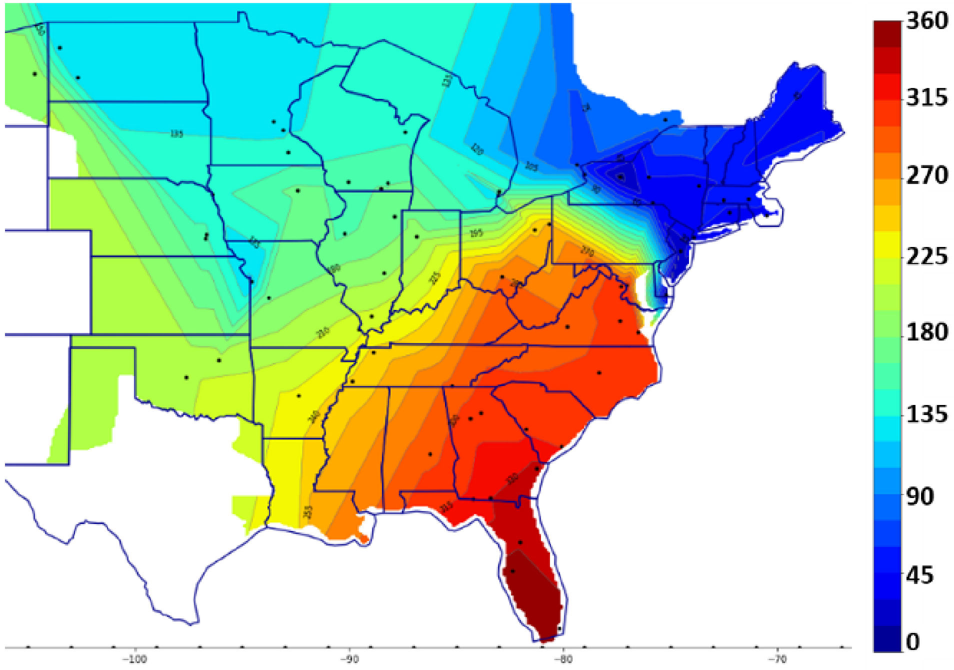
Source locates in TVA area



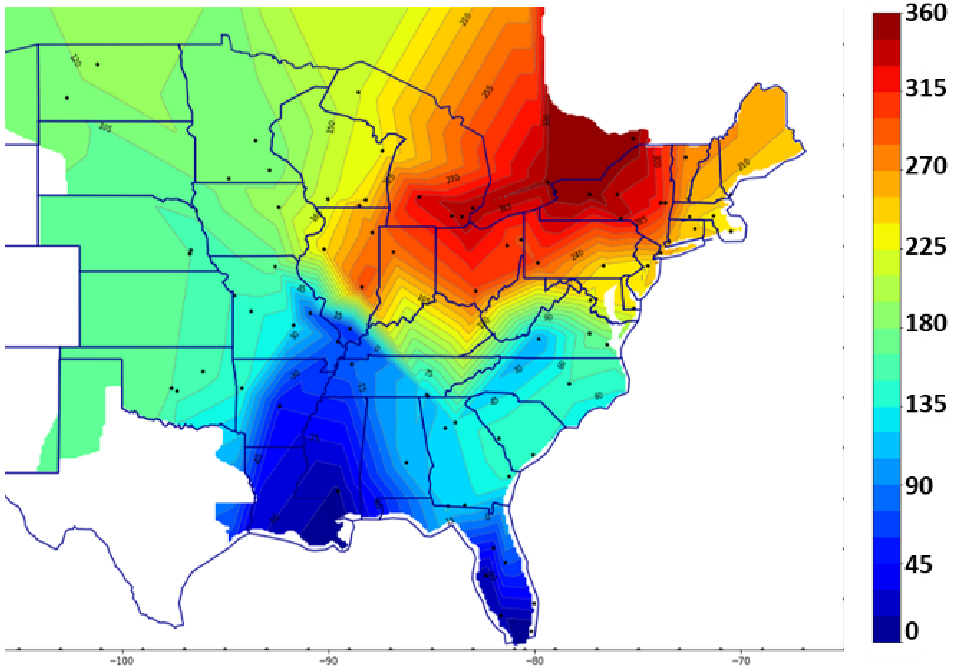
Local forced oscillation

Validation Using Actual Forced Oscillation Events

- EI forced oscillation examples (**Dark red** area has most leading mode angle.



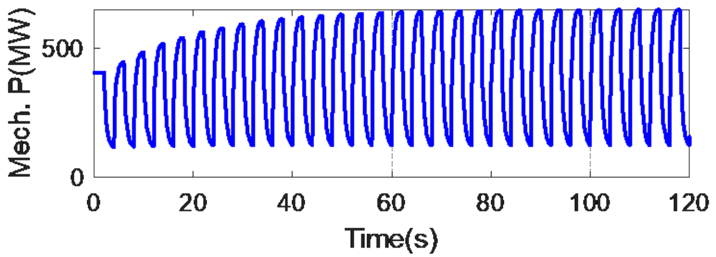
01/11/2019 08:44 Florida



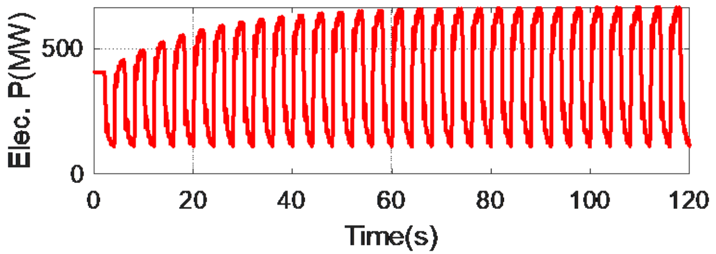
04/07/2020 09:36 NYISO

Replication of January 11, 2019 Forced Oscillation

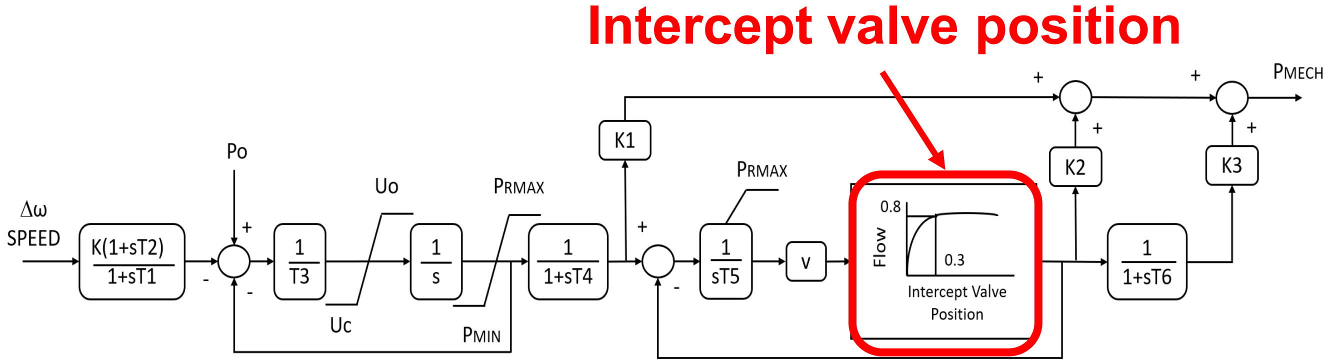
- 70k-bus EI planning model: Light load
- Fast valving feature of TGOV3 model was used to excite forced oscillation
- Forced oscillation magnitudes in bus frequency are consistent with event report



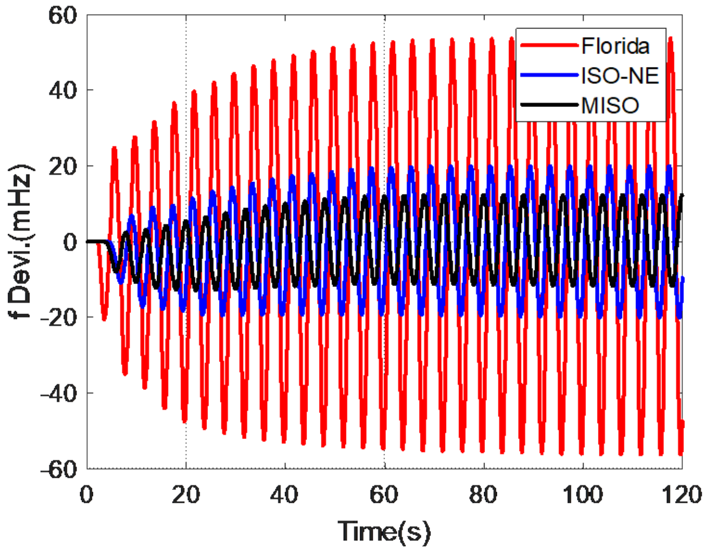
Generator Mech. power



Generator Elec. power



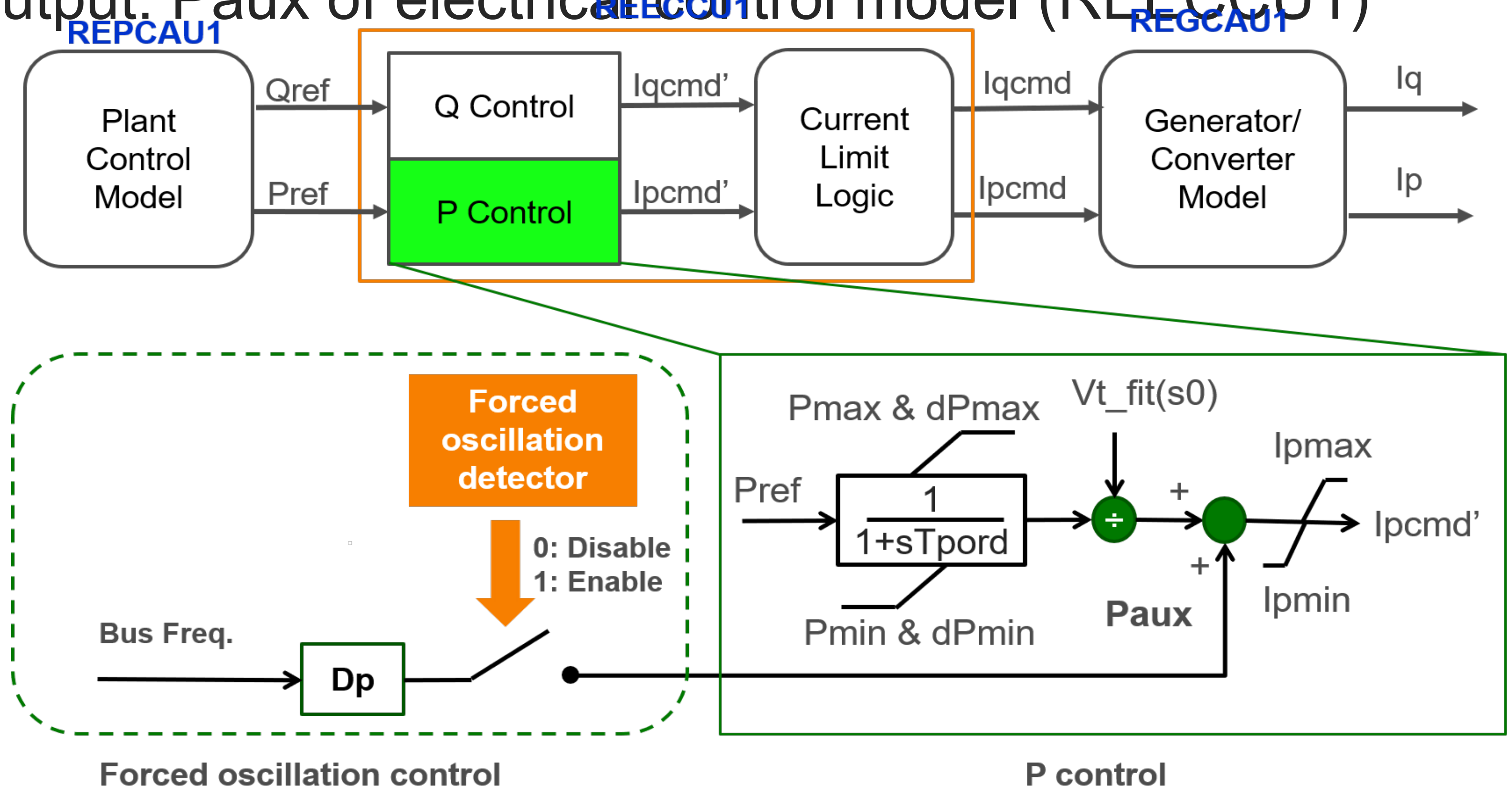
TGOV3 governor model (Source: PSS/e manual)



Bus Frequency

Forced Oscillation Control Strategy

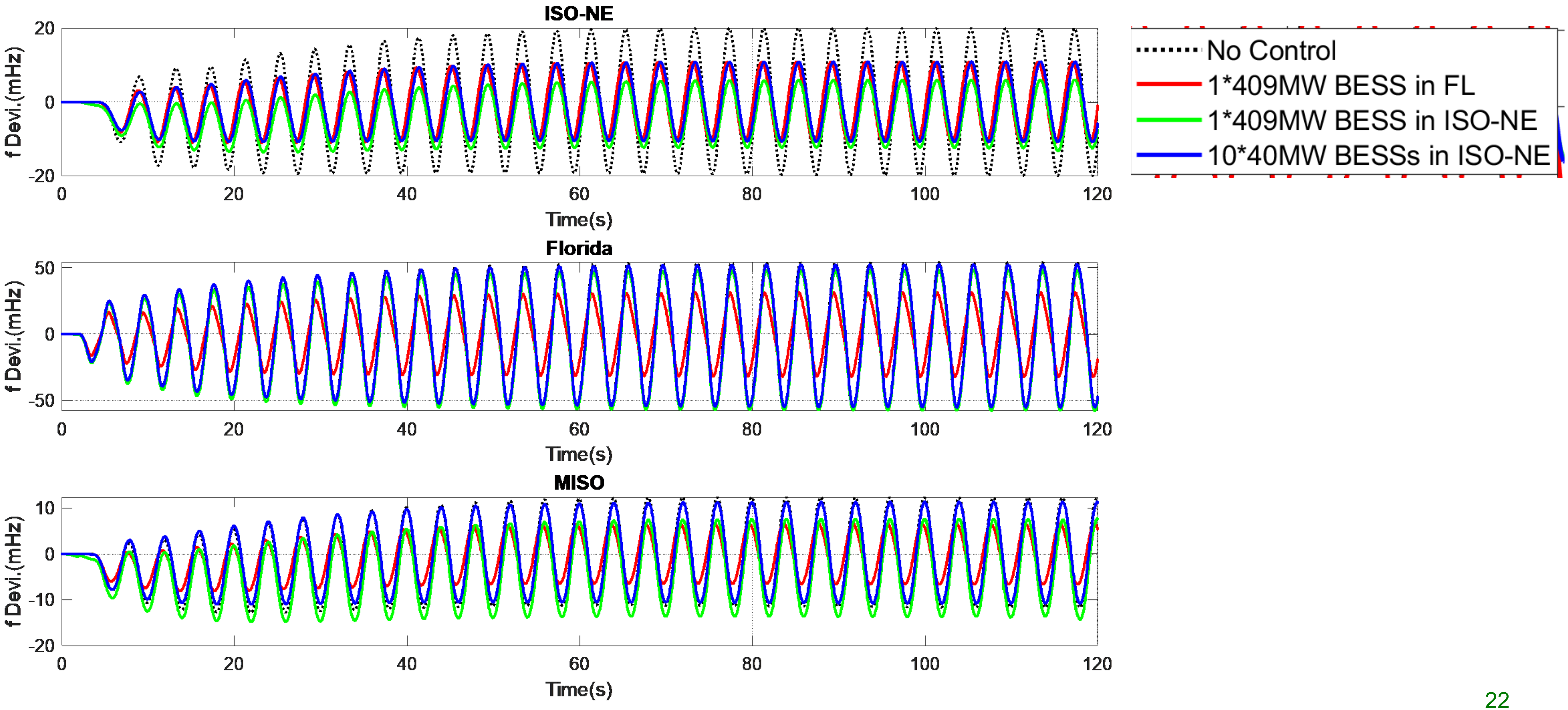
- Simply based on droop control
- Controller input: Local bus frequency
- Controller output: Paux of electrical control model (REECCU1)



Utility-scale BESS model and proposed control strategy

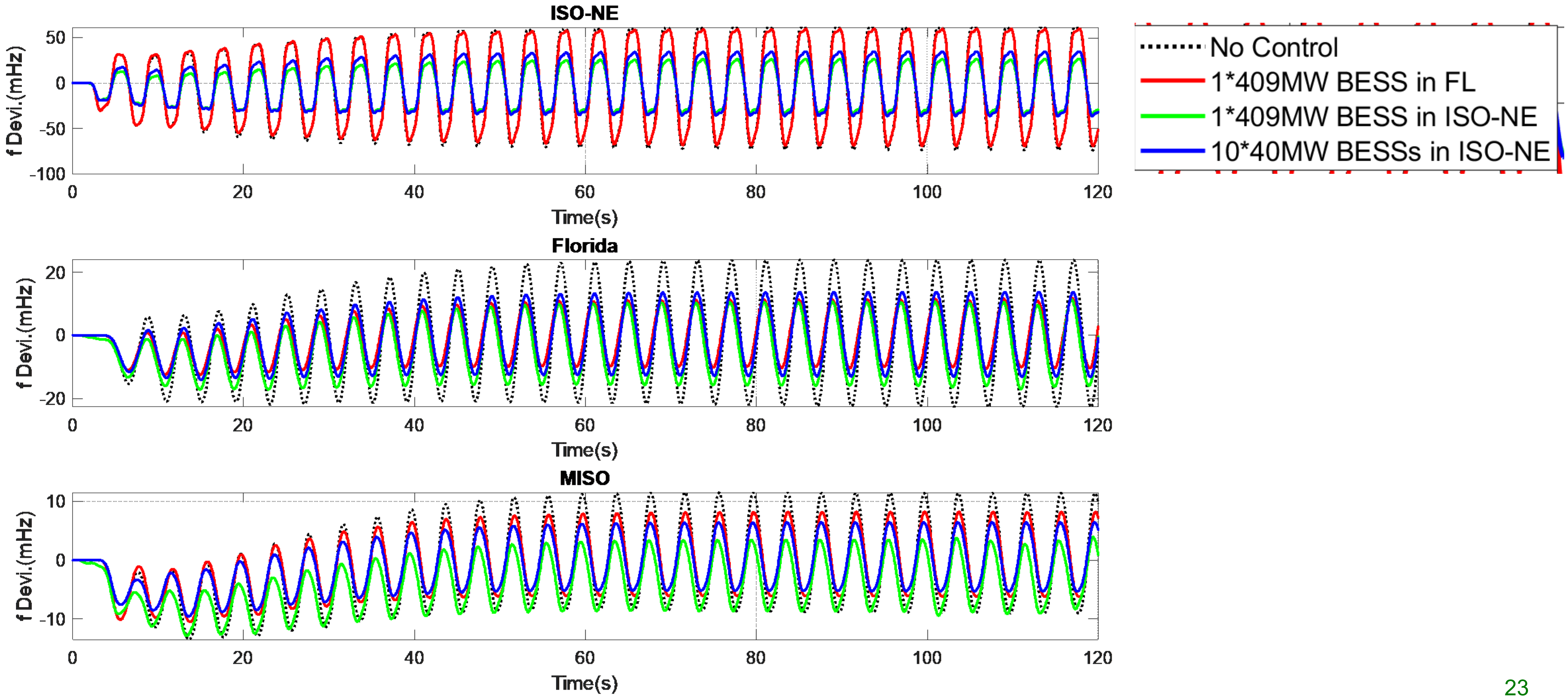
Simulation in 70k-bus EI Model

- Scenario 1: Source in Florida (Jan. 11, 2019 event)

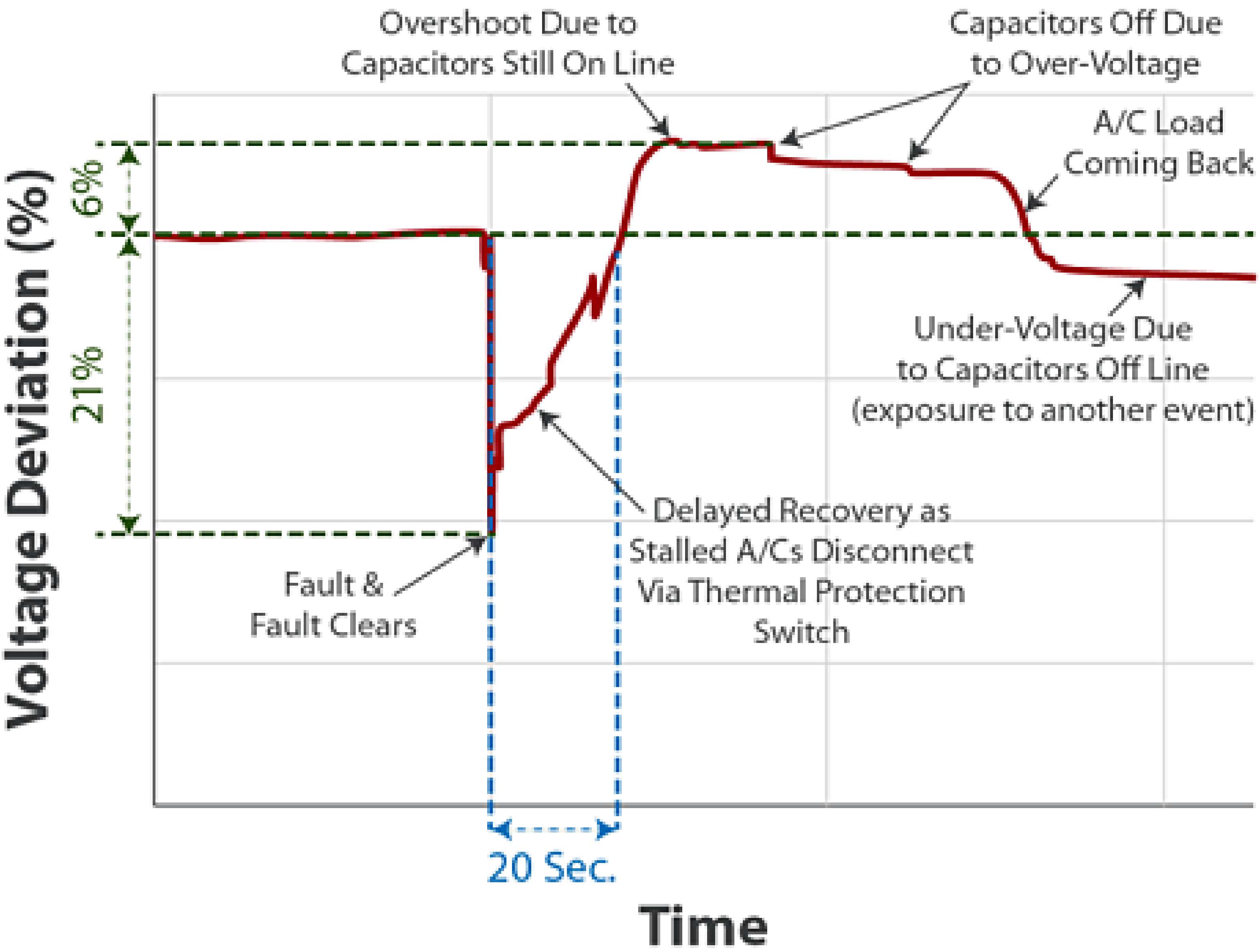


Simulation in 70k-bus EI Model

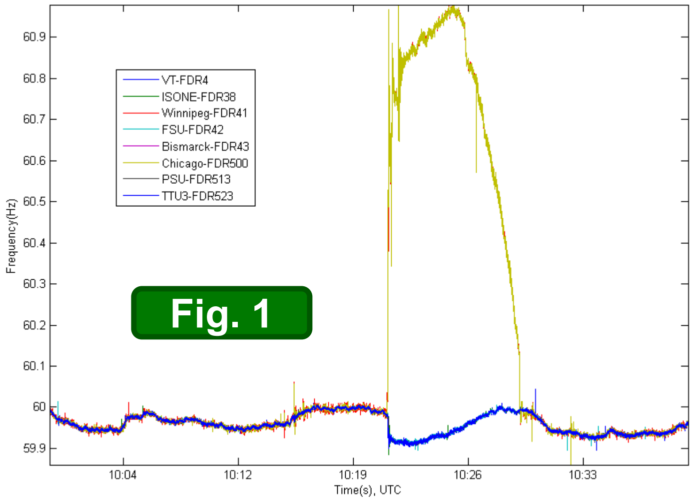
- Scenario 2: Source in ISO-NE

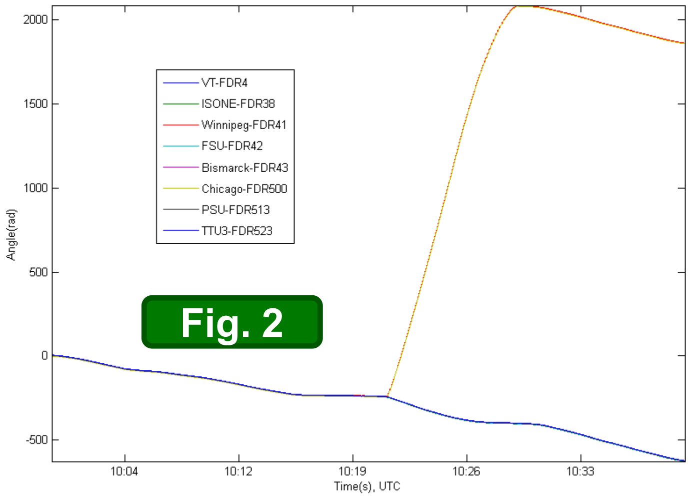


Detect FIDVR (Fault Induced Delay of Voltage Recovery)

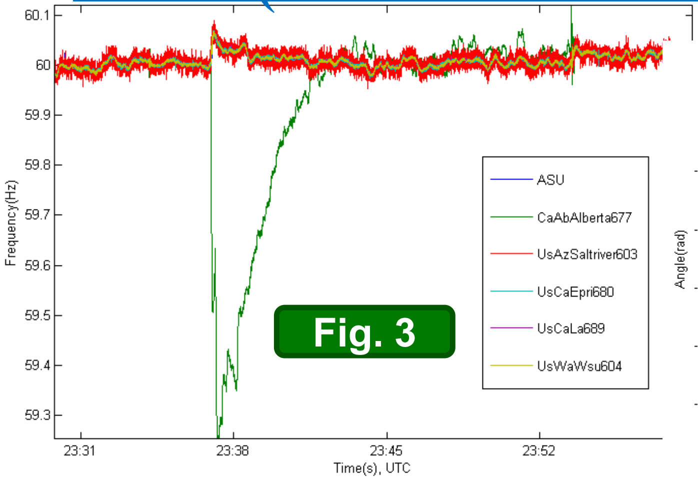


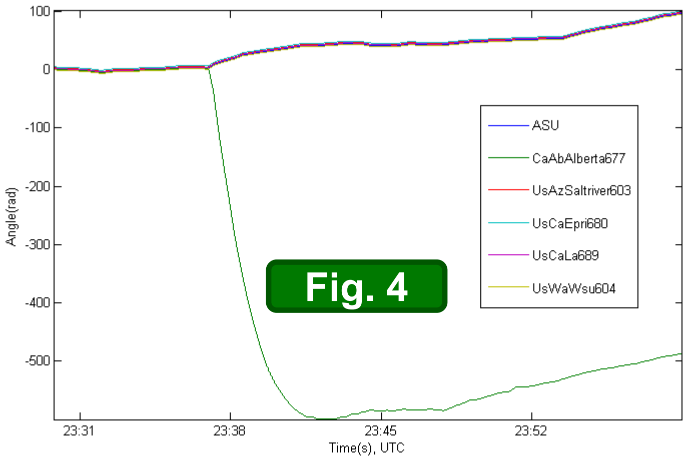
EI 09/18/2007 10:21:23 UTC)





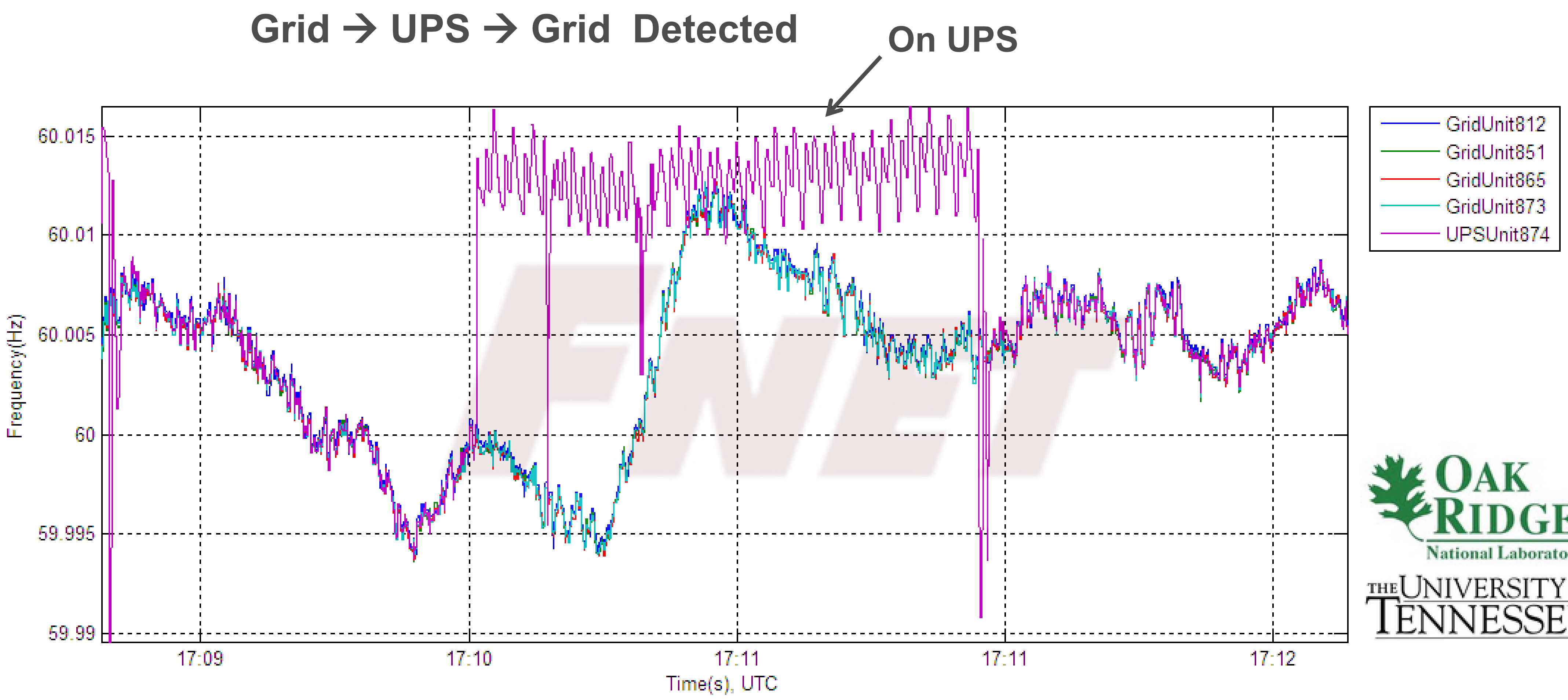
- Case 2 (WECC 06/01/2010 23:37:32 UTC)





Islanding Detection of Bulk Grid & Micro Grid

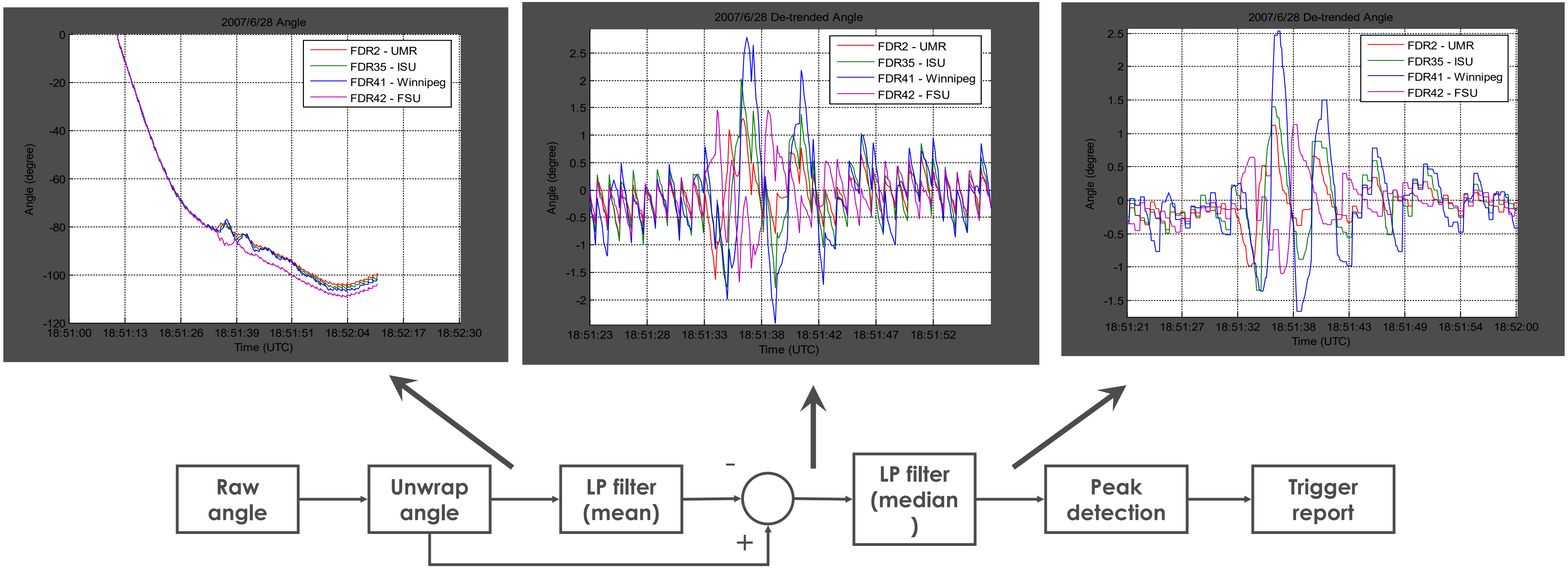
Off Grid Detection for Hospitals and Data Centers



Oak Ridge National Laboratory

The University of Tennessee

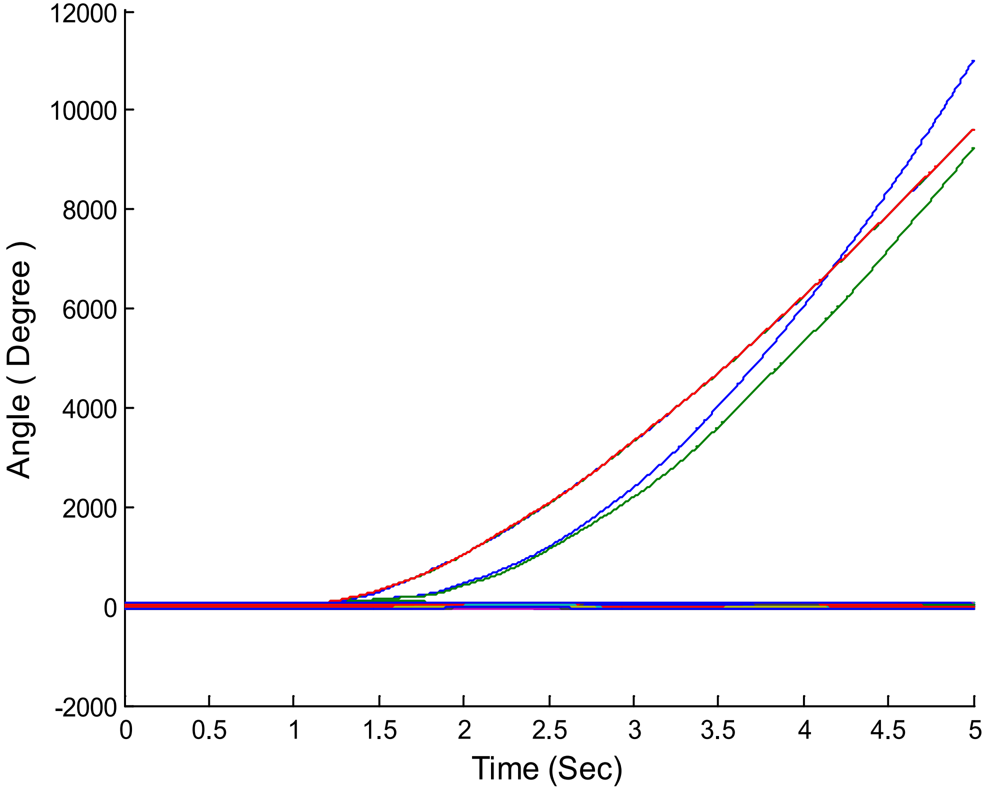
Line Trip Detection and Location

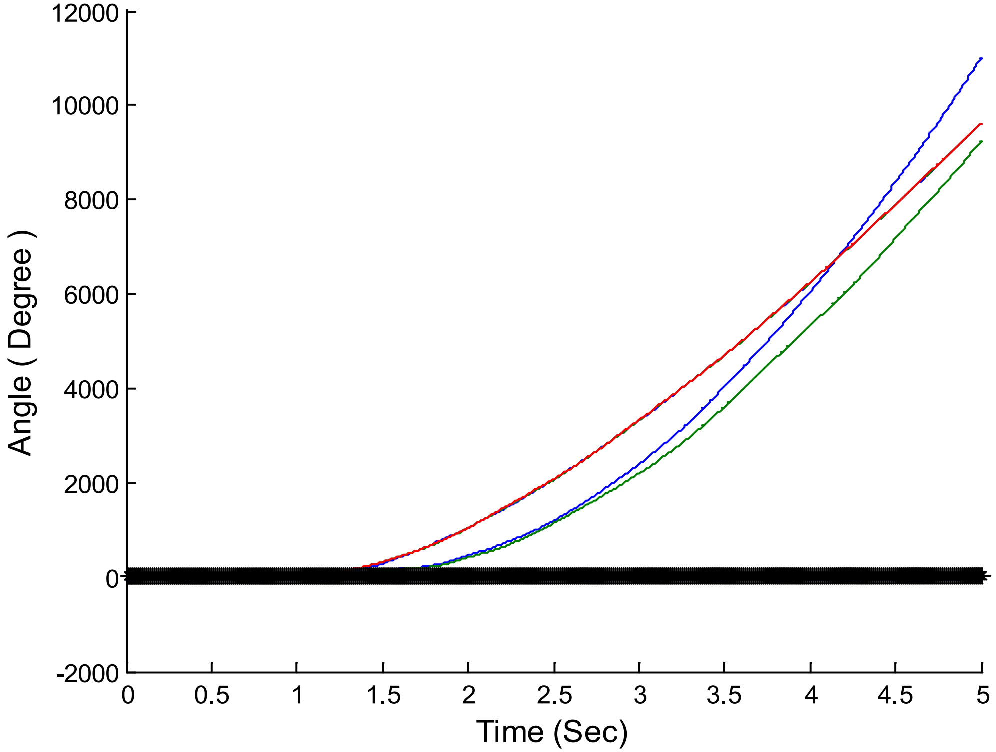


Angle Stability using Relative Angles

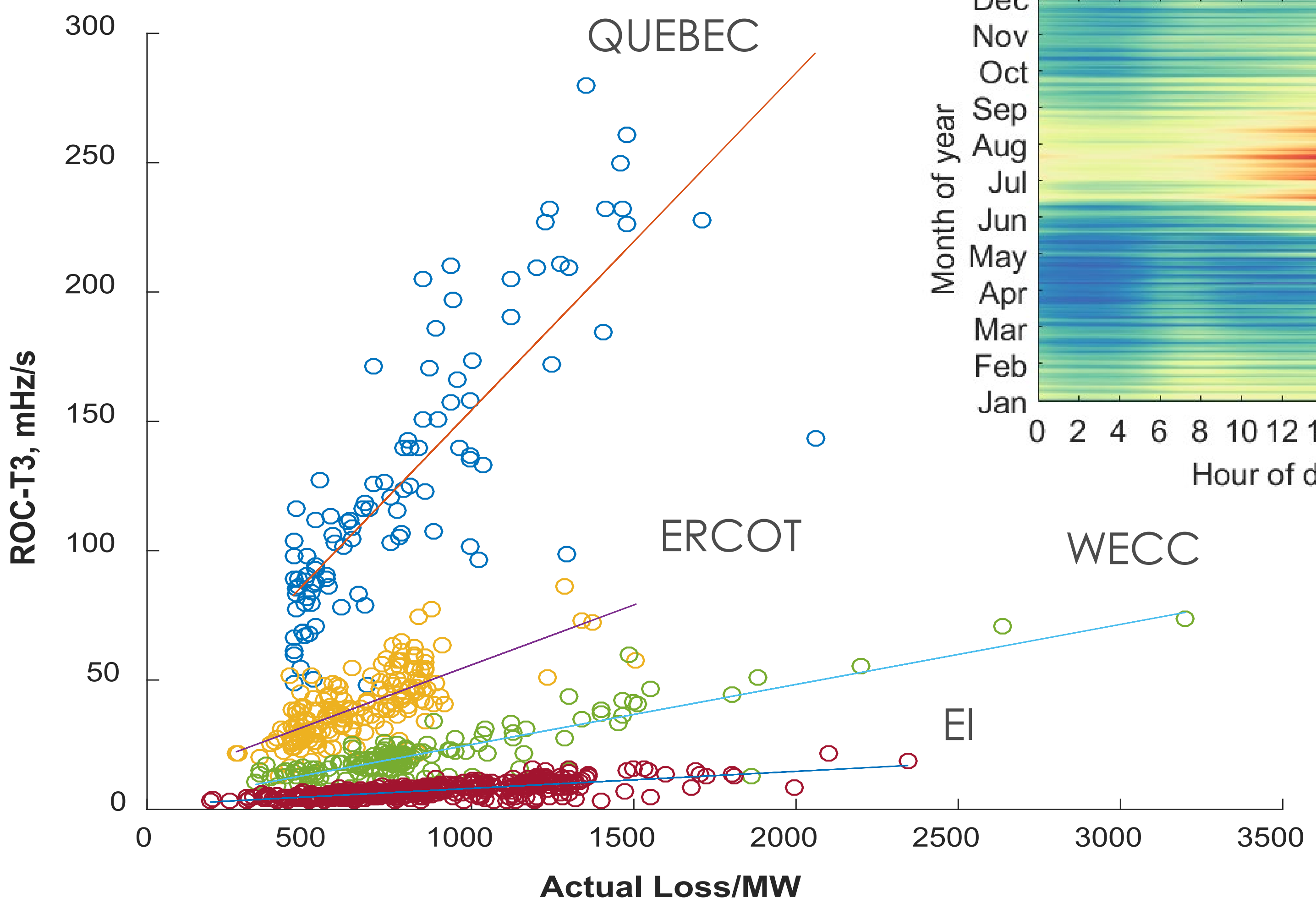
Center-of-Inertia (COI) angle vs the rest of the bus angles

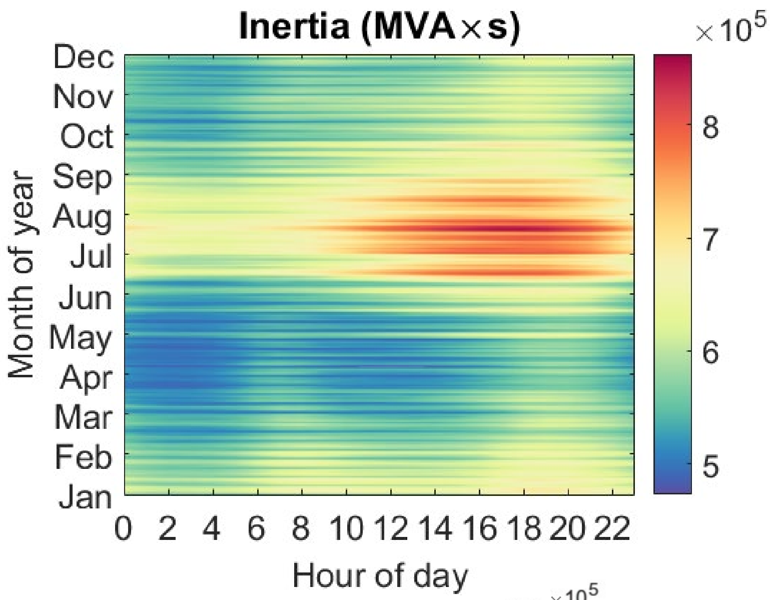
$$\delta_{COI} = \frac{1}{H_T}\sum_{i=1}^{n} H_i\delta_i \Rightarrow \delta_{CBA} = \frac{1}{H_T}\sum_{i=1}^{n} H\delta_{bi} = \frac{H}{nH}\sum_{i=1}^{n}\delta_{bi} = \frac{\delta_{bT}}{n}$$



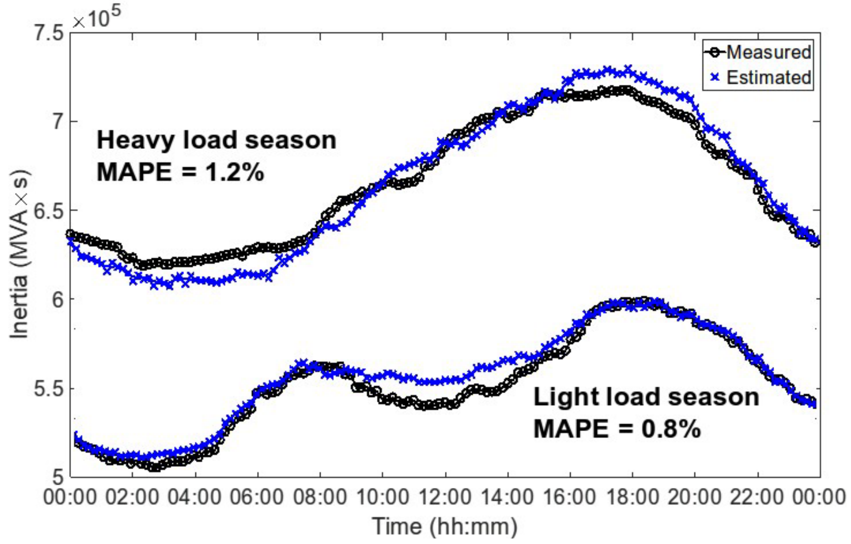


Interconnection Inertia Monitoring





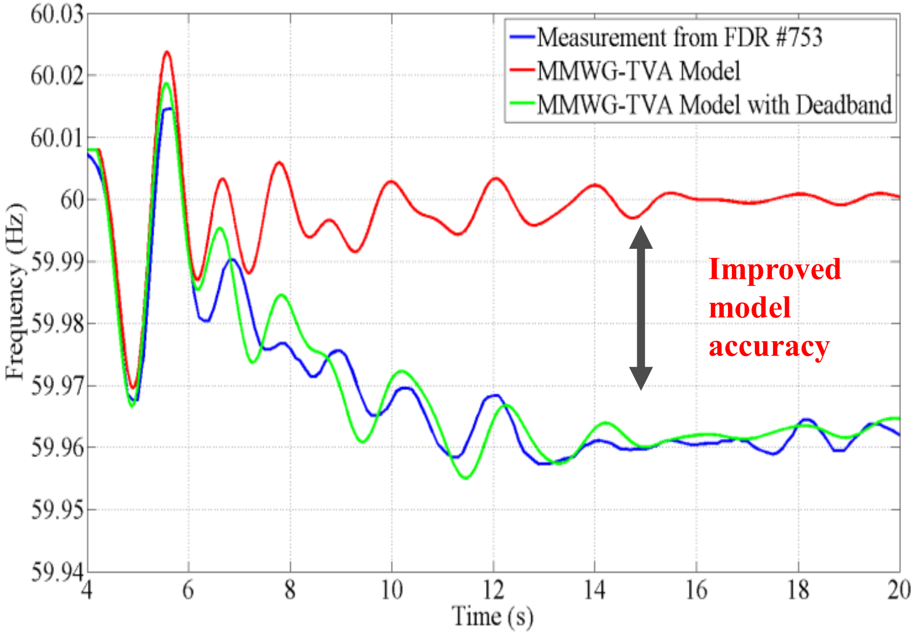
Inertia estimation From local frequency!

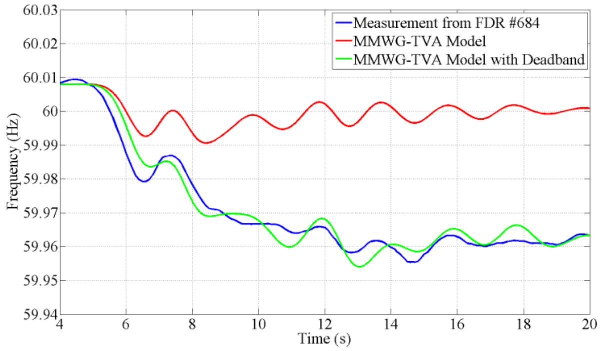


Dynamic Model Validation - Eastern Interconnection

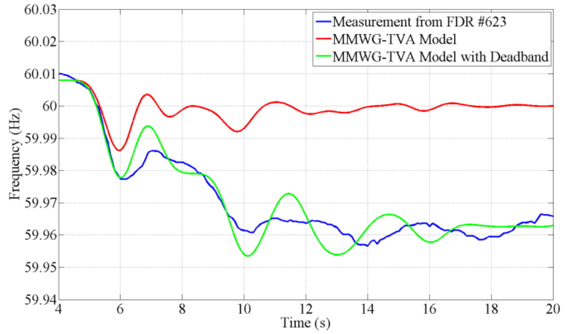
- Synchrophasor measurement collected by FNET/GridEye is used to calibrate the simulated frequency response.
- Governor deadband is adjusted to reflect the actual system performance.

Case Study: a 1100 MW Generation Trip in North Carolina

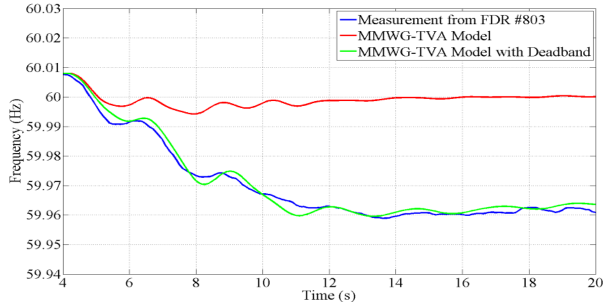




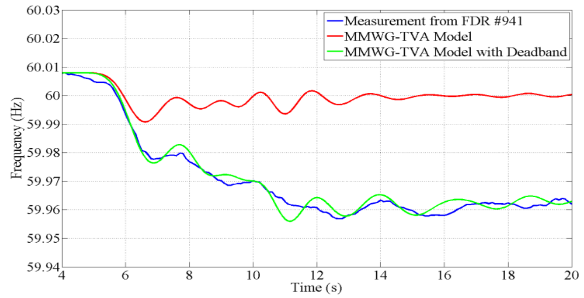
Measurement in MA



Measurement in FL



Measurement in OH



Measurement in KS

Dynamic Response Estimation by Transfer Function

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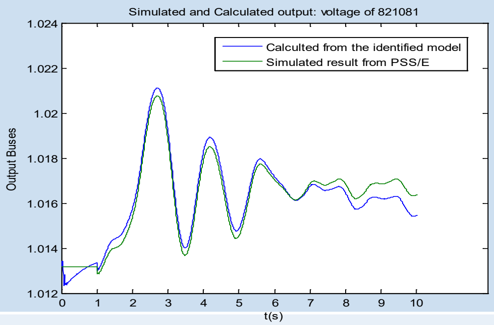
<tr><td>Voltage</td>
<td>
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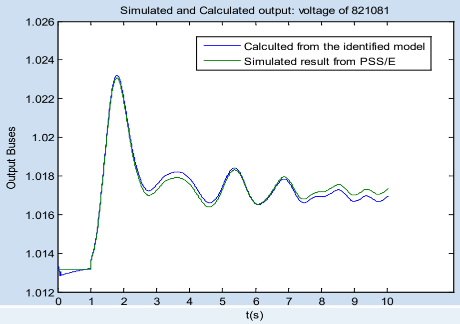
<td>
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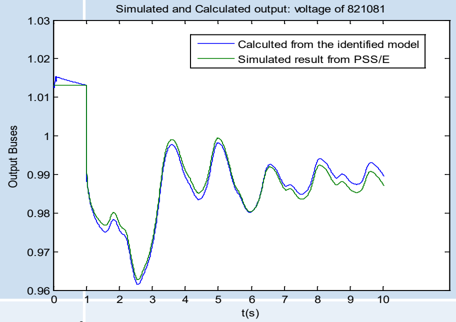
<td>
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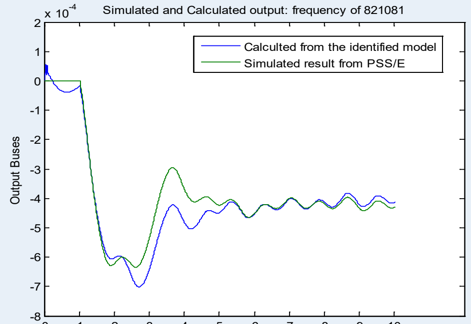
<tr><td>Frequency</td>
<td>
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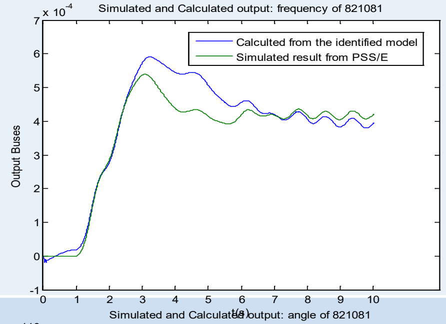
<td>
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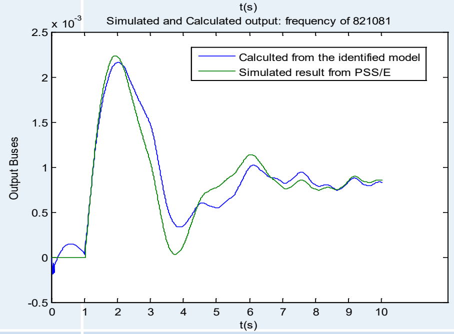
<td>
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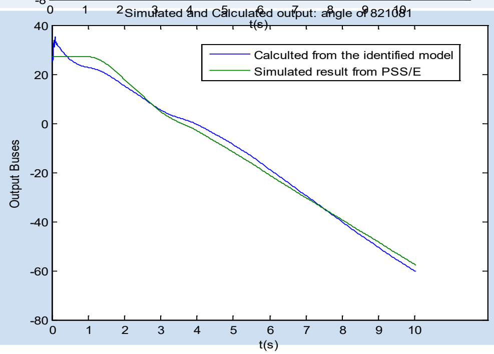
<tr><td>Angle</td>
<td>
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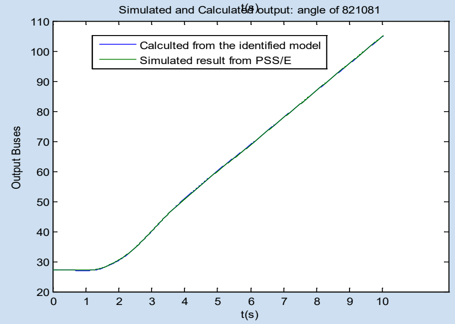
<td>
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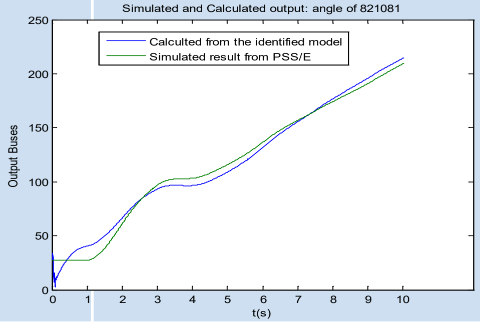
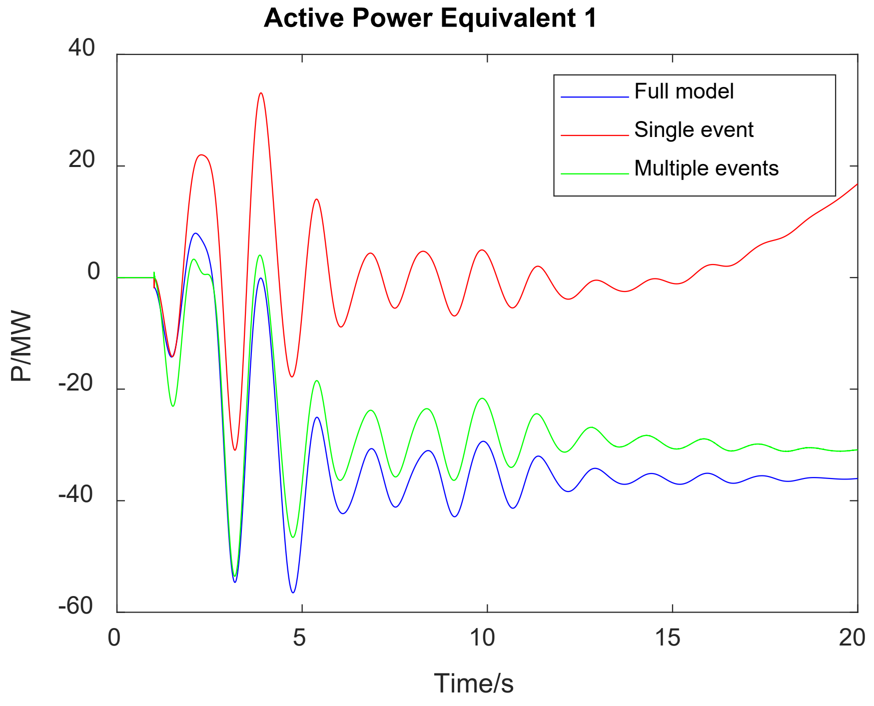
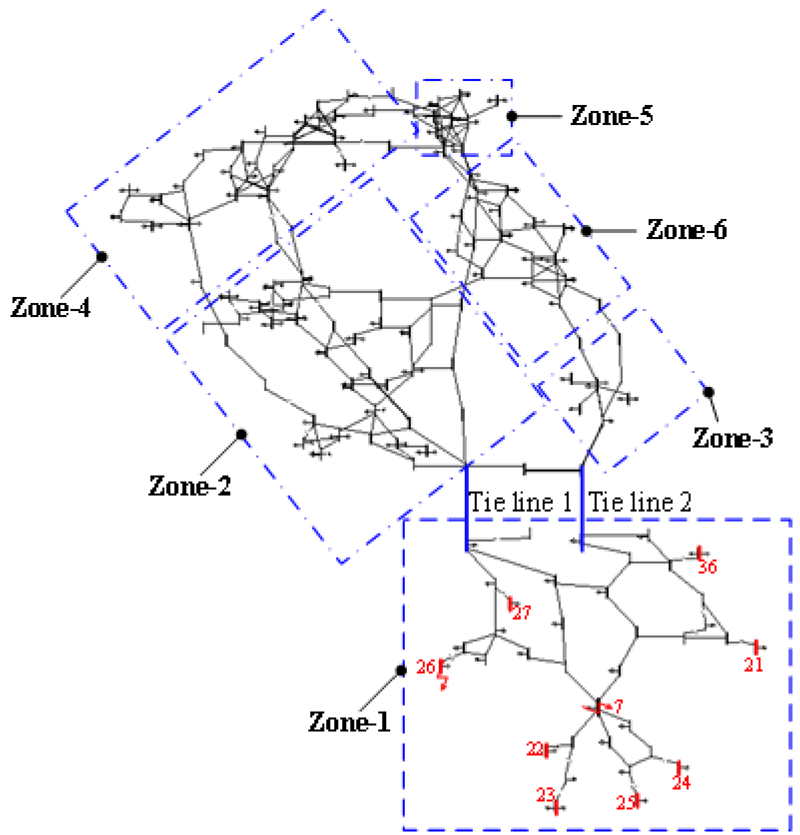
<td>
</td></tr>
</table>

Dynamic Equivalent Identification Method of Large-Scale Power Systems Using Multiple Events

Technical approach

- Derive dynamic equivalents based on transfer function between tie line flow and boundary PMU measurements
- Improve robustness of equivalents by involving multiple events in the parameterization process





NPCC to be reduced

Merits

- Derive dynamic equivalents using measurements without knowledge of external system
- Tracking the dynamic equivalents under changing system conditions

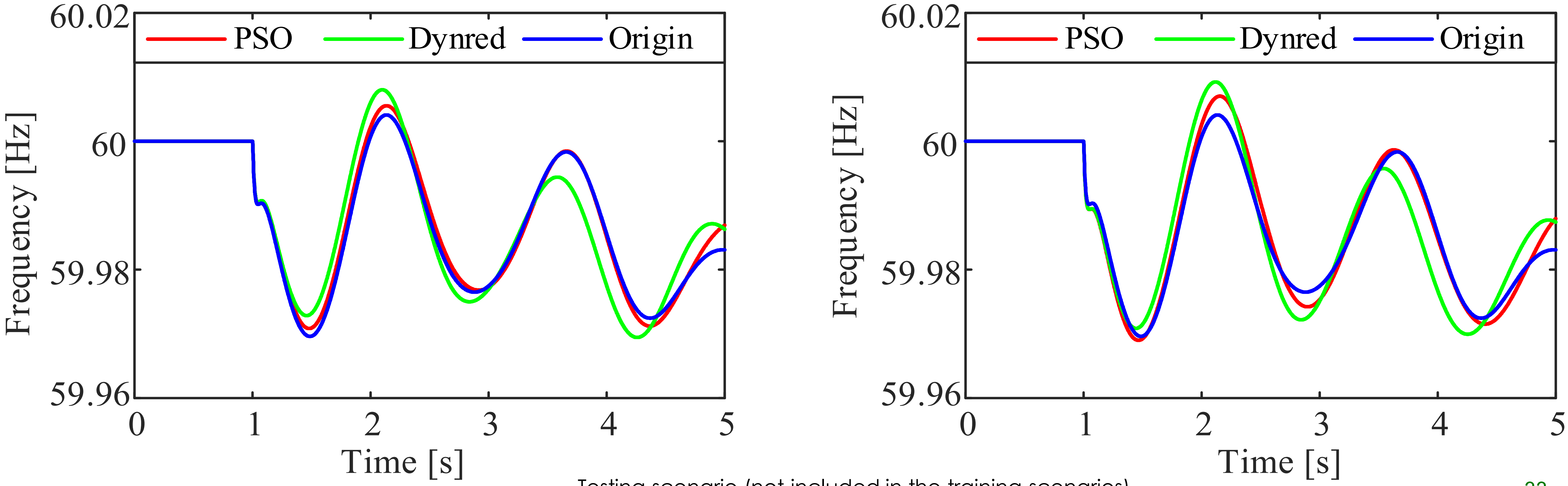
AI-Based Tuning of Dynamic Equivalents

Technical approach

- Derive the structure of the equivalents using DYNRED
- Apply AI algorithm to tune the parameters of the equivalents to match dynamic responses with measurements

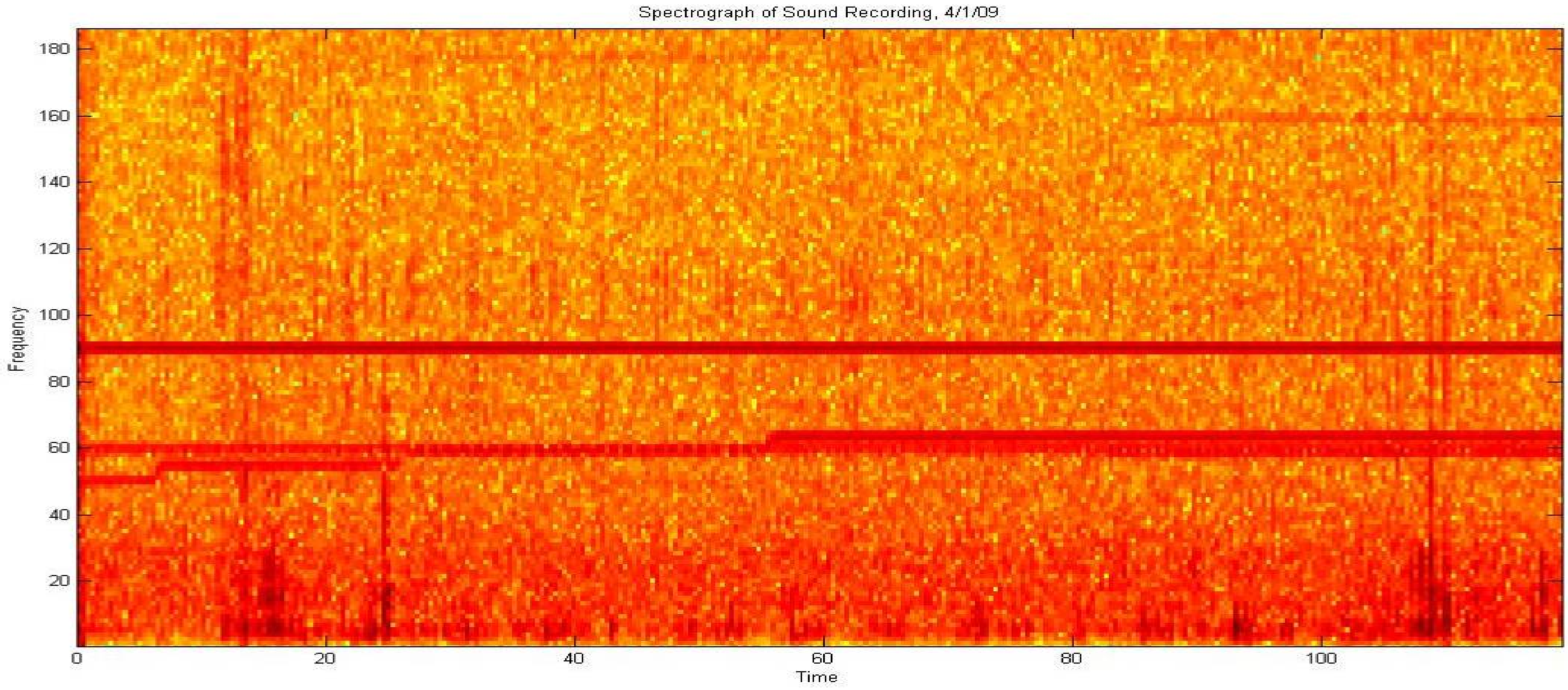
Merits

- Improved the accuracy of the DYNRED based equivalents in representing dynamics of the study area



Testing scenario (not included in the training scenarios)

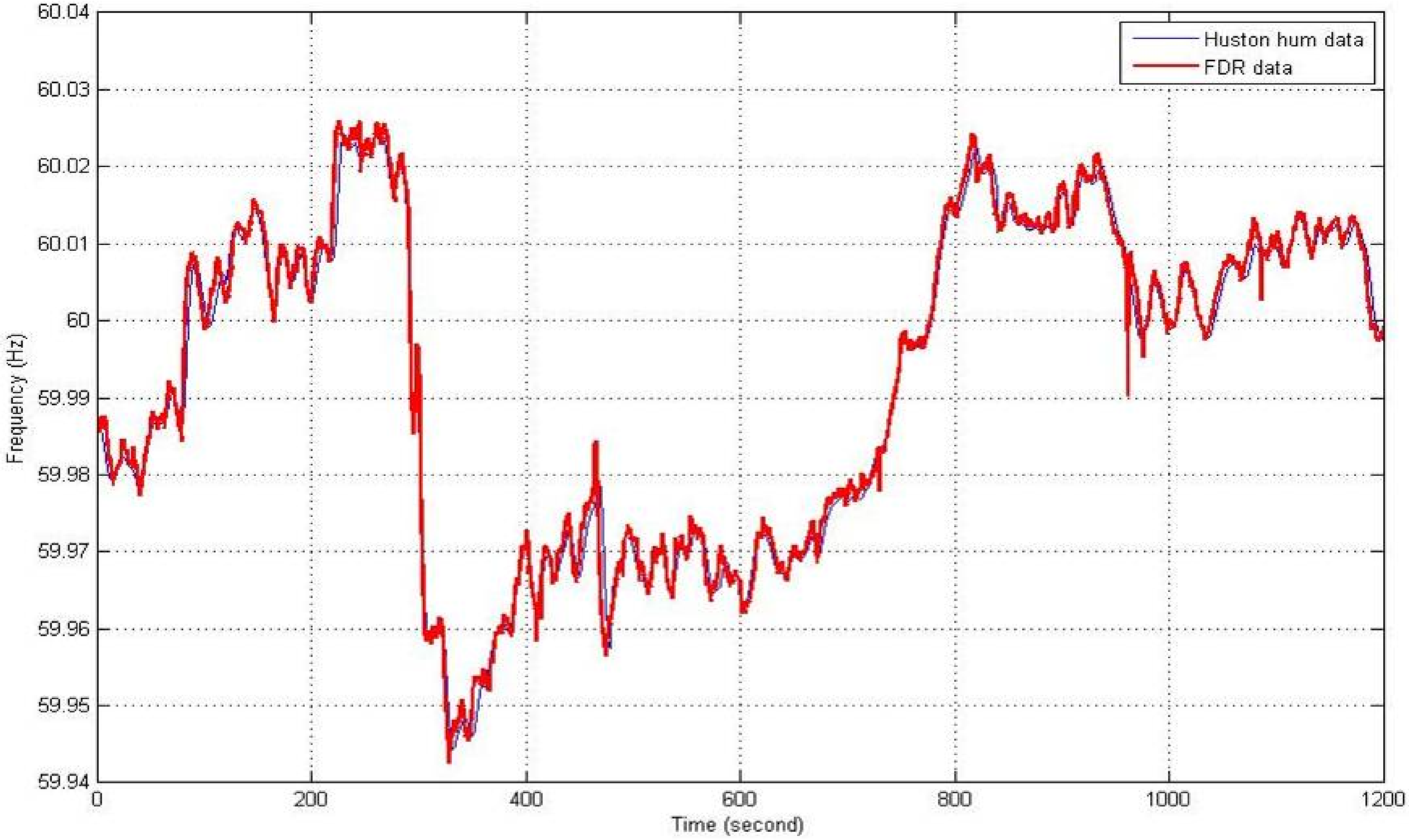
Grid Frequency for Digital Audio Authentication



- Recorded by PC sound card (only background noise)
- 60Hz component is clearly visible

Compared Huston Police Department Data with FDR

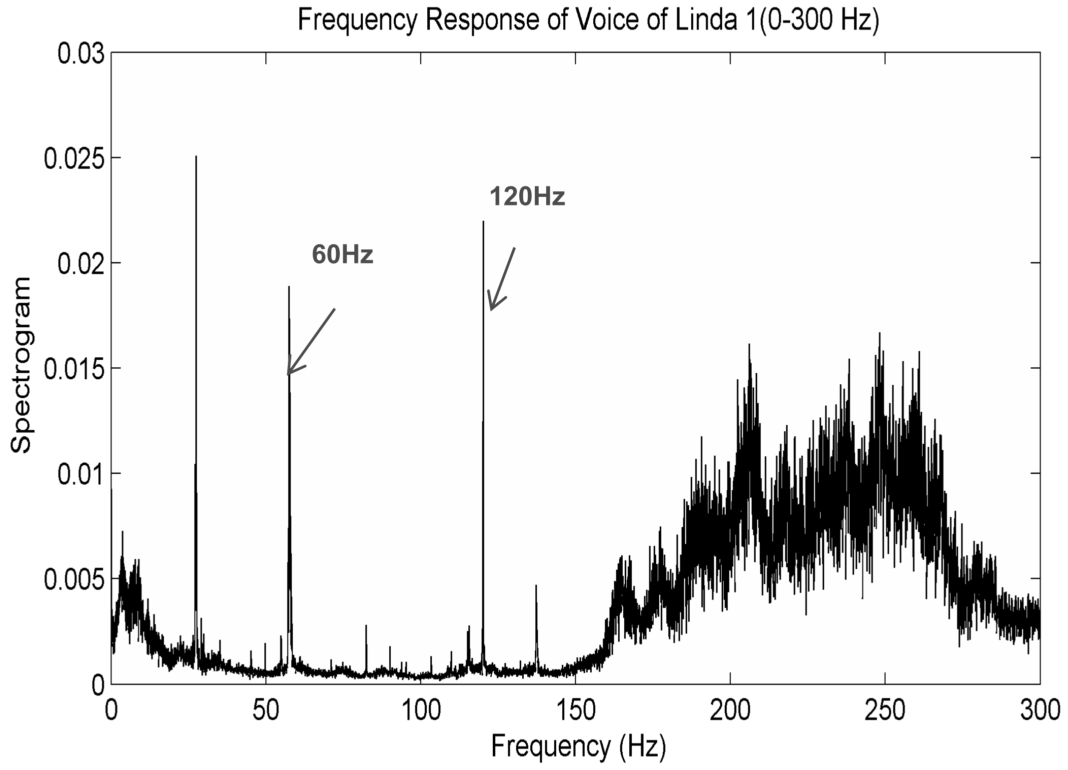
- **Audio record: Houston 05-07-2009,11:00-11:20 CDT**
- **Sample rate: 11kHz**
- **Recorded from equipment ground loop hum**



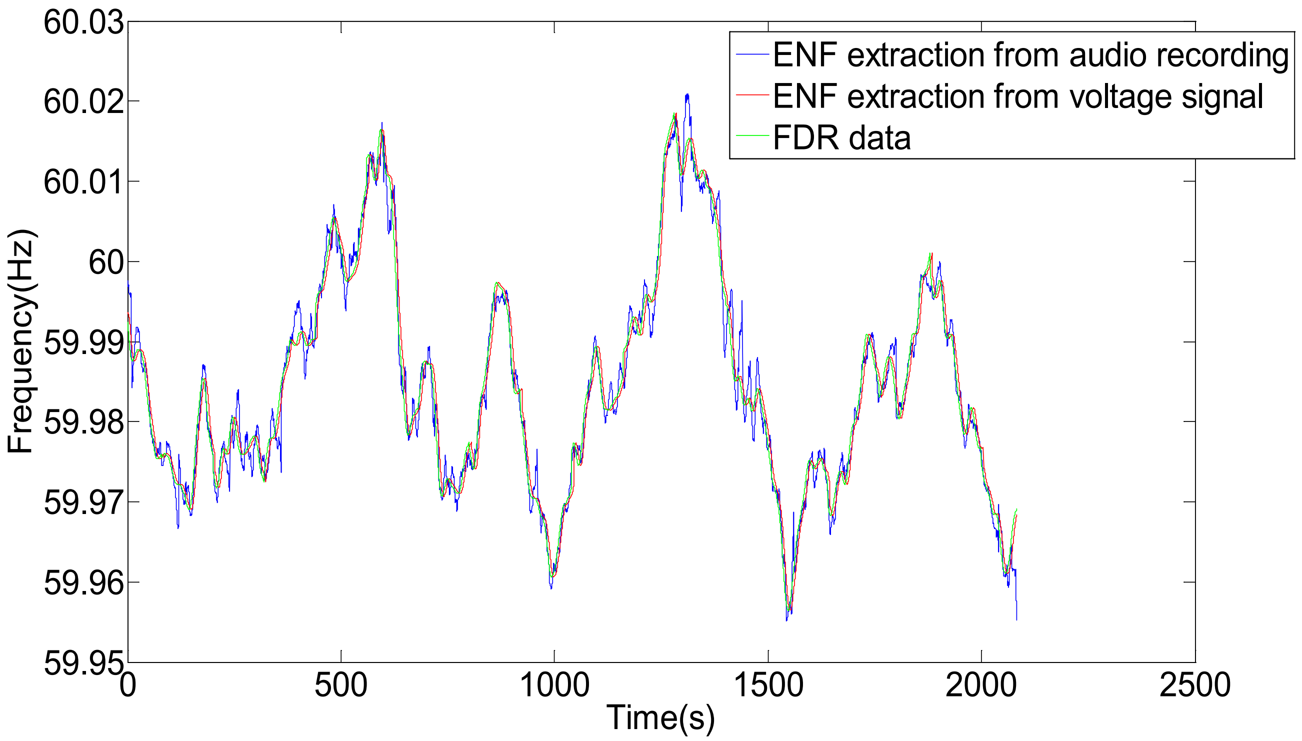
Digital Recording Authentication using Power System Frequency

Power system frequency can be extracted from digital recordings and compared with FNET reference database to authenticate the recordings.

Frequency Spectrum of Audio



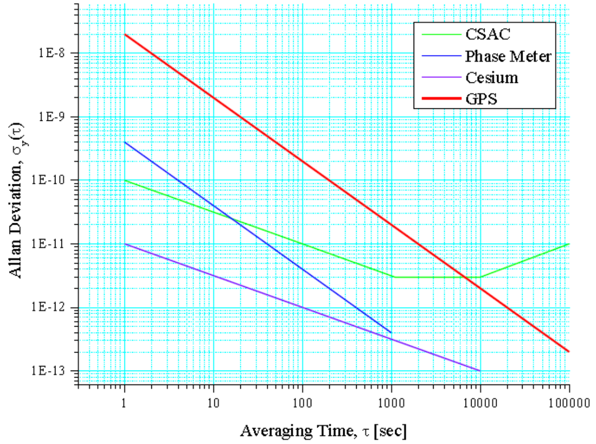
ENF Extraction

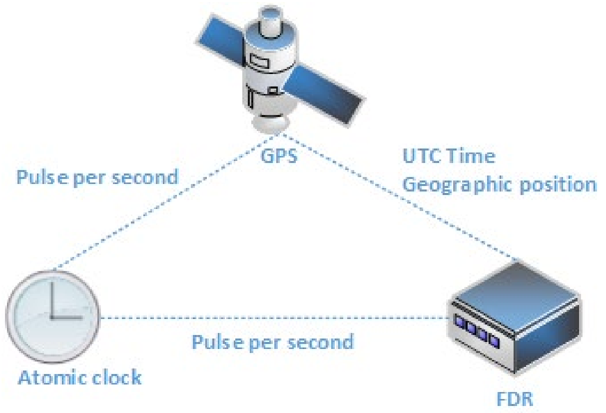


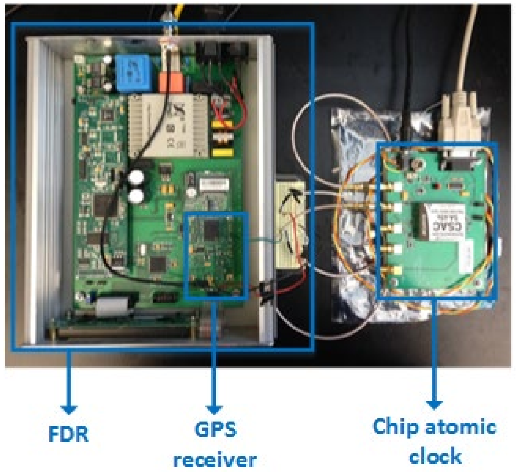
Timing Assistance by Chip Scale Atomic Clock

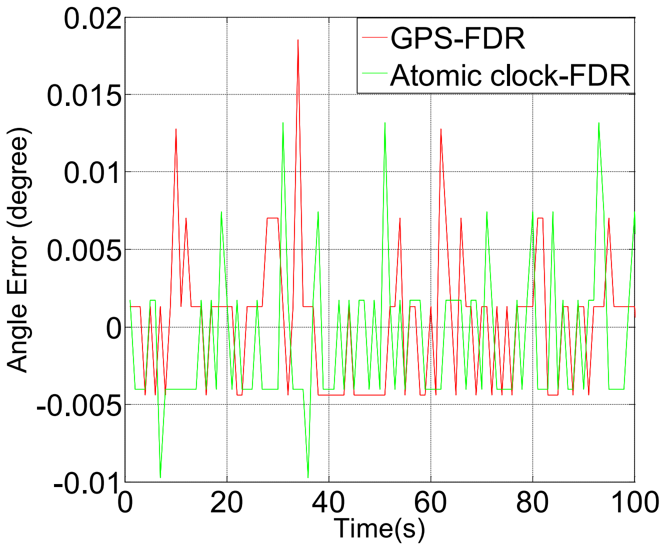
SA. 45s Chip-Scale Atomic Clock

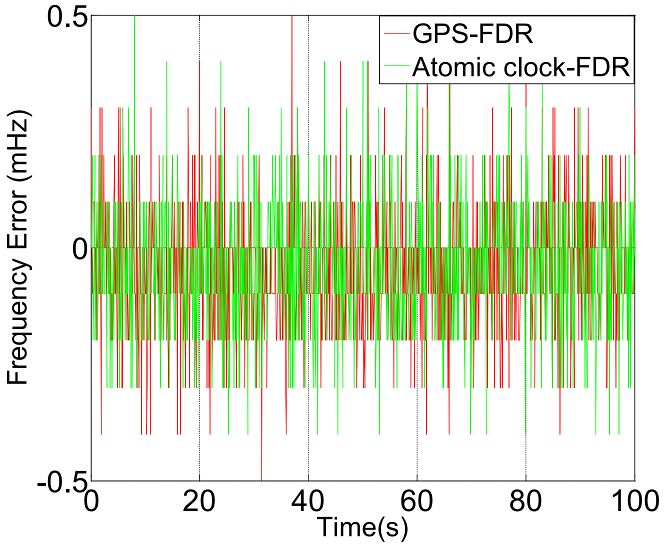
- World's first commercially available chip scale atomic clock
- GPS is noisier than CSAC for averaging time < 5000 seconds







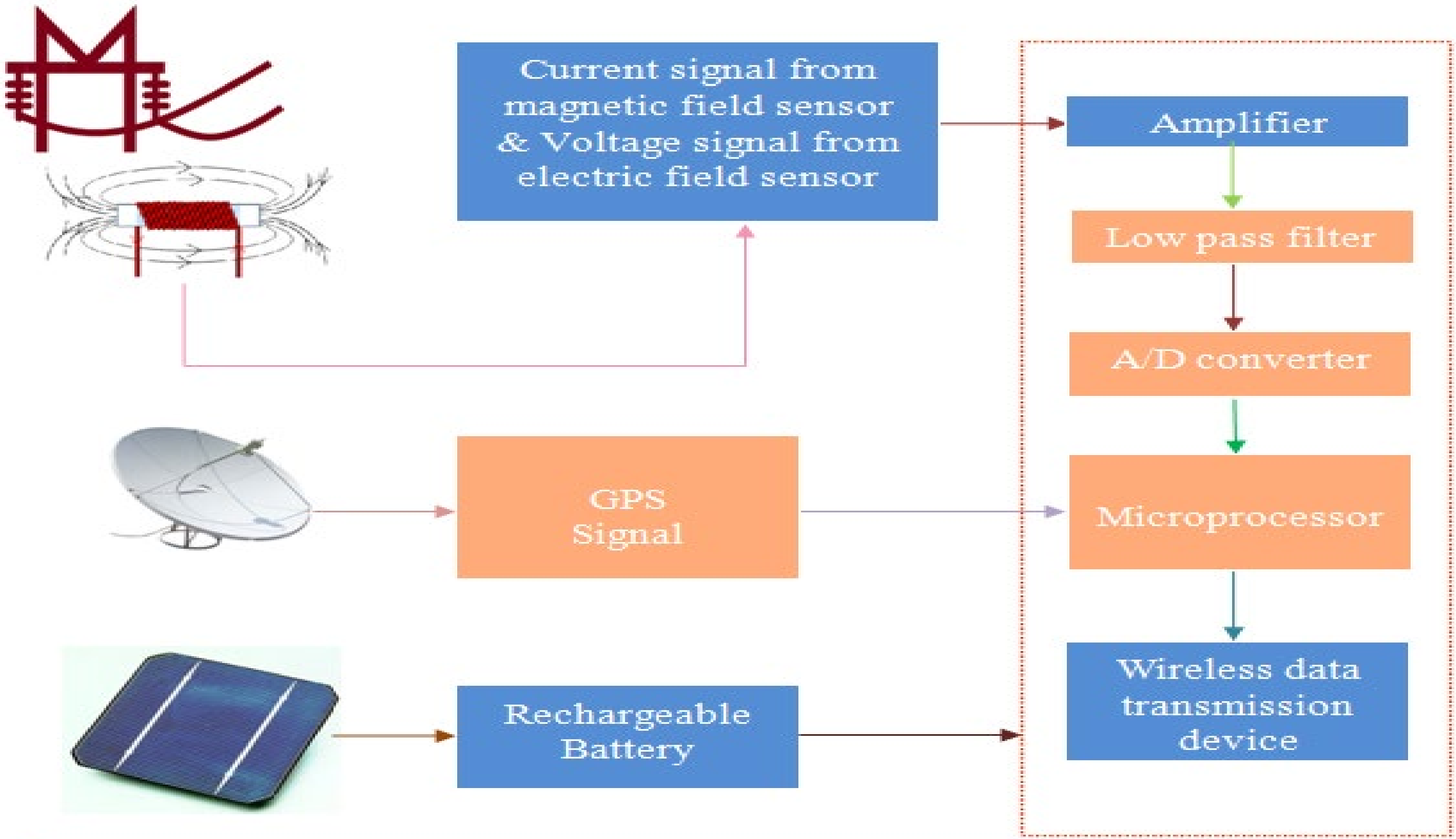




Stand deviation of frequency and angle errors

	GPS-FDR	Atomic clock-FDR
Angle	0.0041	0.0046
Frequency	1.45e-4	1.42e-4

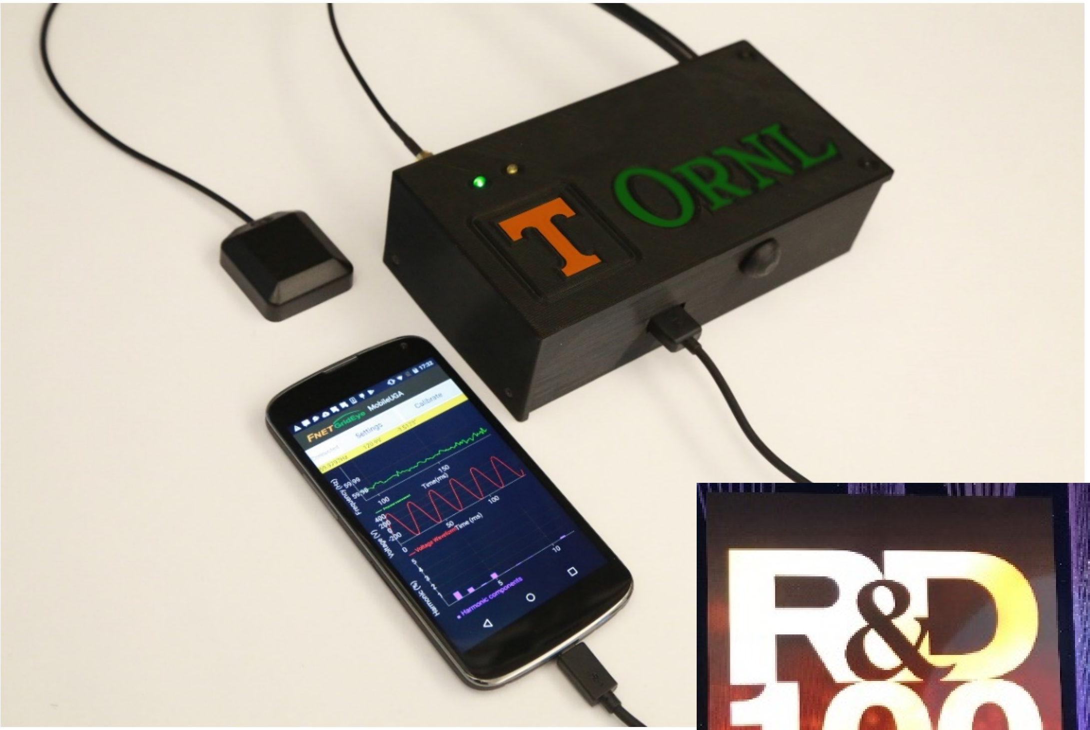
Magnetic and Electric Fields based measurements - contactless

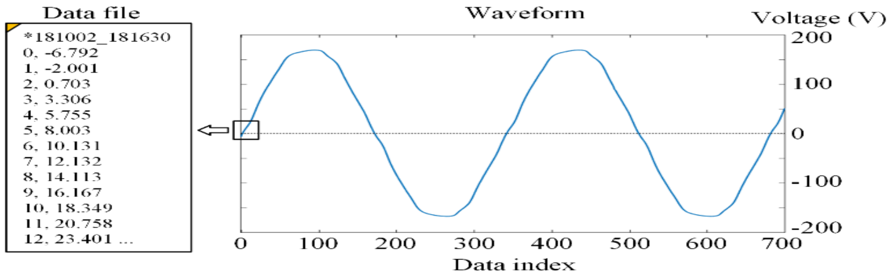


Phase One EPRI project is to complete the current sensor frequency measurement feasibility study

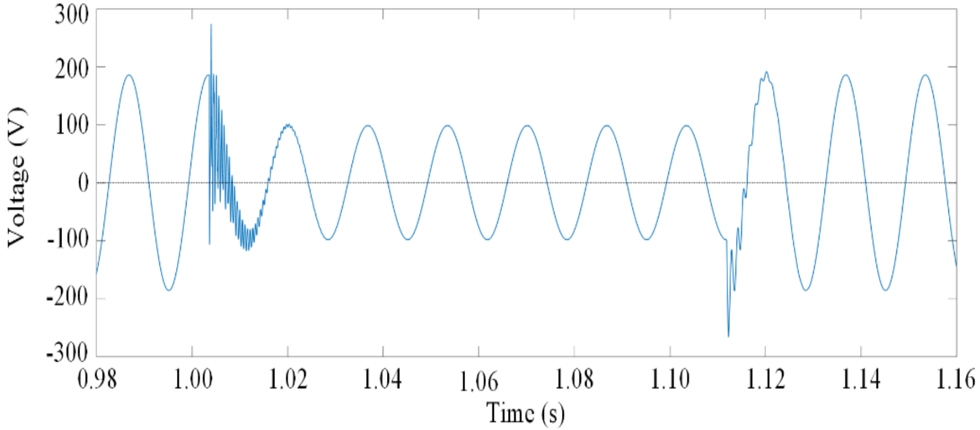
Synchronized Point-on-Wave (SPOW) from Mobile UGA

Mobile Universal Grid Analyzer





GPS time-indexed sample data

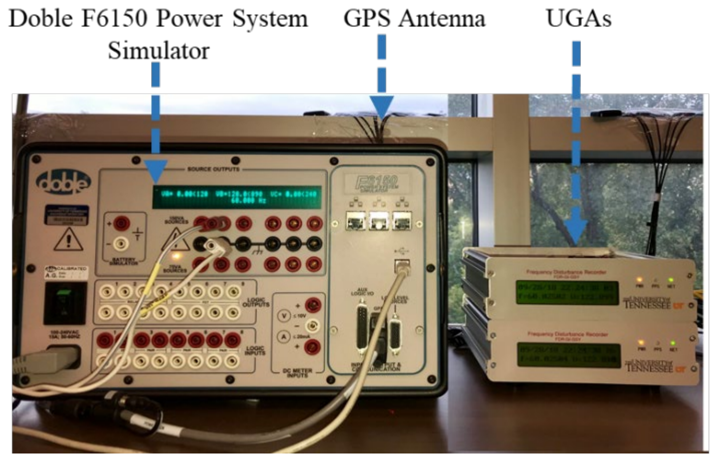


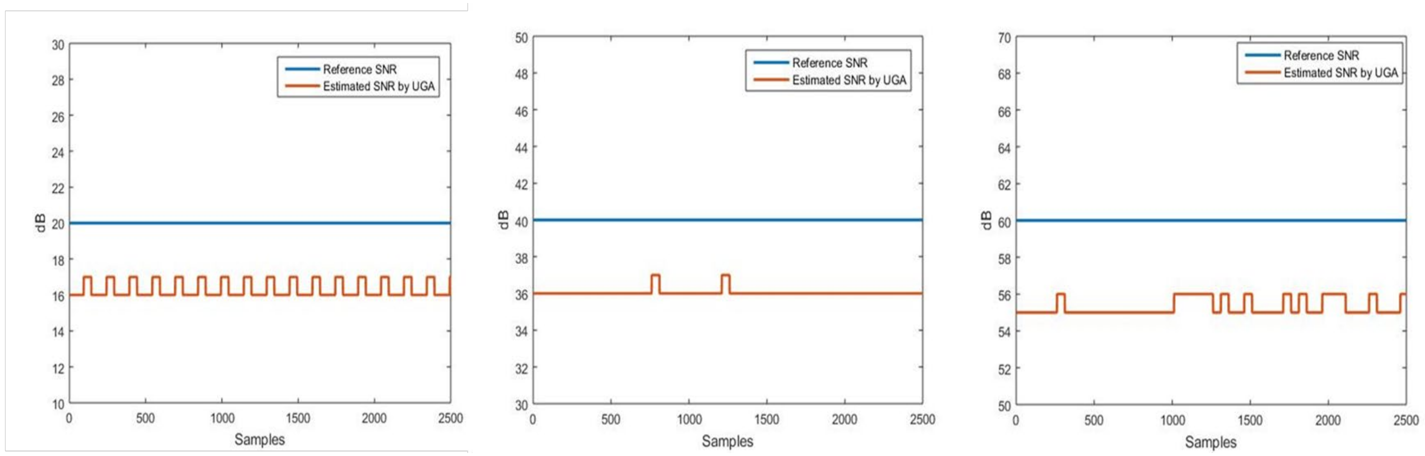
Voltage from phase-to-ground fault

Real-Time Signal-to-Noise Ratio Estimation

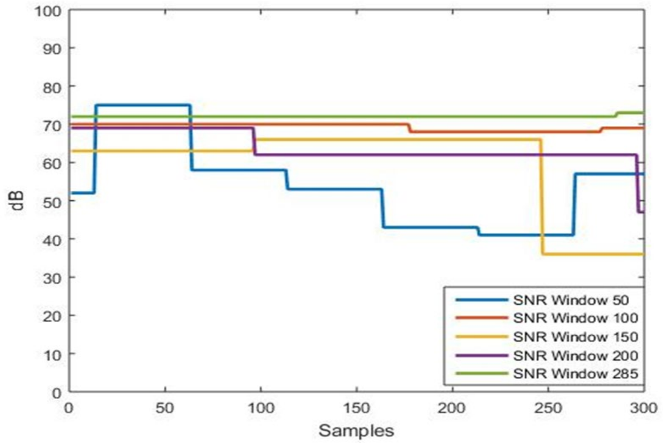
Project Goals:

- Implement SNR algorithm in the UGA for real-time SNR estimation
- HTB needs driven





Real time SNR measurement with Signal generator
(a) 20dB reference; (b) 40dB reference (b) 60dB reference



Real-time SNR estimation with wall signal at different SNR window sizes

Extended UGA functions

- Normal UGA
  - Synchrophasor measurement
  - Power quality parameter measurement
- Extended UGA
  - Synchrophasor measurement
  - Power quality parameter measurement
  - **Point on Wave (POW) data record**

Normal UGA

Synchrophasors
- Frequency
- Phase angle
- Voltage magnitude

Power quality parameters
- Harmonics,
- Sag, Swall,
- SNR,
- Voltage flickers

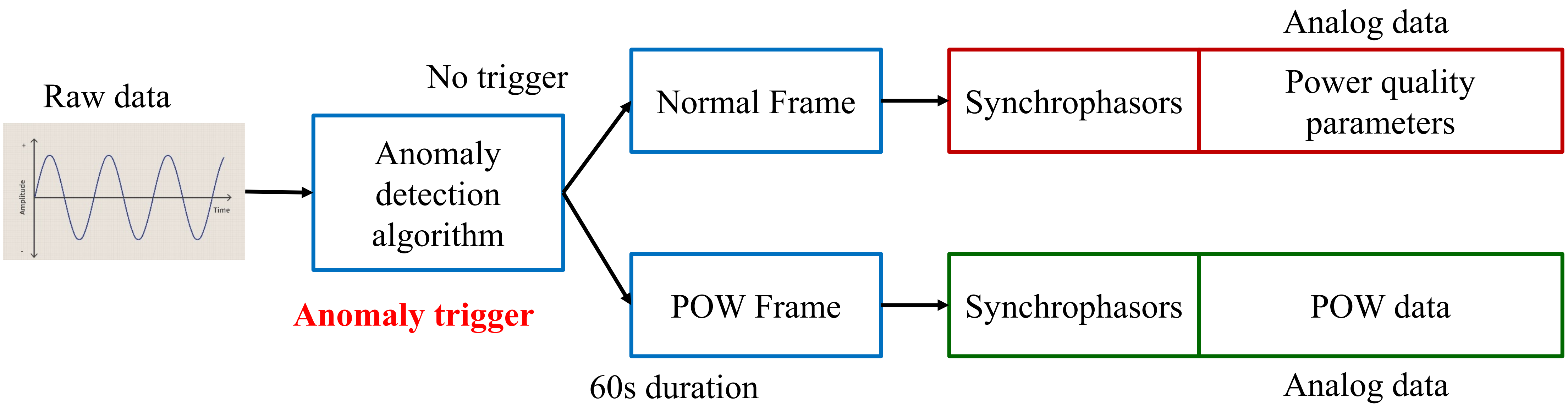
Extended UGA

POW
- 1440Hz POW data continuous streaming, 64kHz burst

Anomaly detection
- Real time waveform trigger

Anomaly detection and POW record

- Anomaly detection
  - Time domain real time anomaly detection
  - 30s POW record before and after anomaly trigger
- Frame types
  - Two kinds of data / configuration frame following IEEE C37.118.2 protocol
  - The power quality parameters and POW data are put in analog data sections



Anomaly detection algorithm can be found:
Zhan L, Xiao B, Li F, Yin H, Yao W, Li Z, Liu Y. Fault-tolerant grid frequency measurement algorithm during transients. Oak Ridge National Lab.(ORNL), Oak Ridge, TN (United States); 2020 Jan 10.

Anomaly detection algorithm

- Anomaly detection algorithm
  - Capable to detect
    - Phase shift
    - Temporary voltage drop / increase
    - Voltage RMS drop / increase

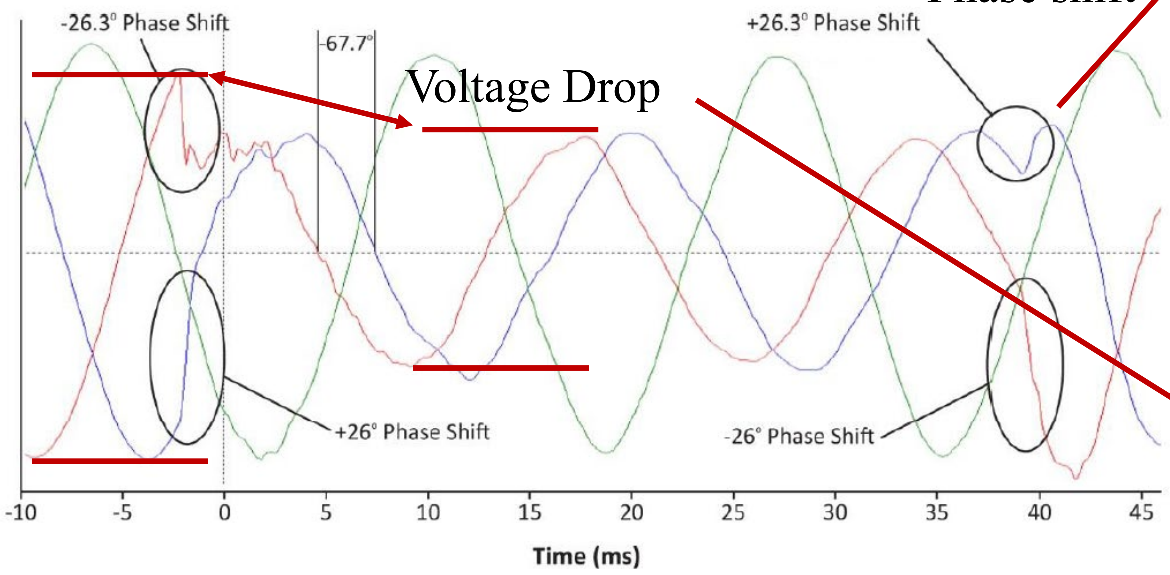
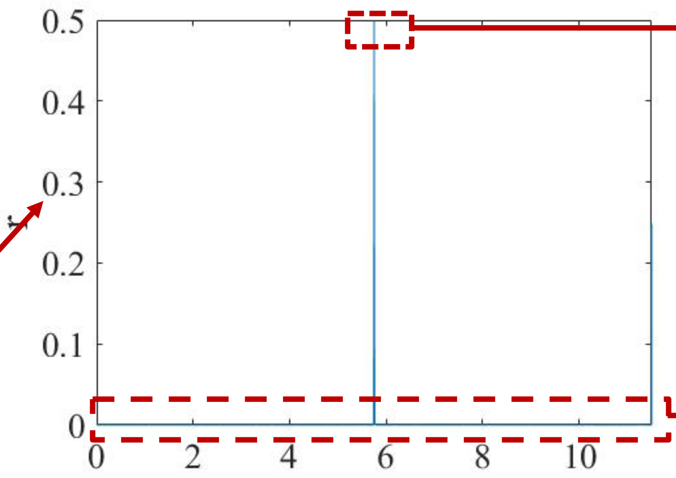


Figure comes from: 1,200 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance Report

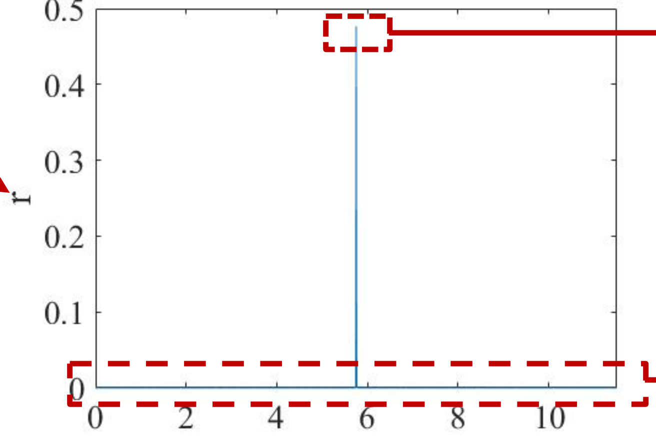
Minimum detectable Phase shift (0.6 degree)



Trigger value under fault case

Trigger value under Normal cases

Minimum detectable Temporary Voltage drop (1.2% reduction)



Trigger value under fault case

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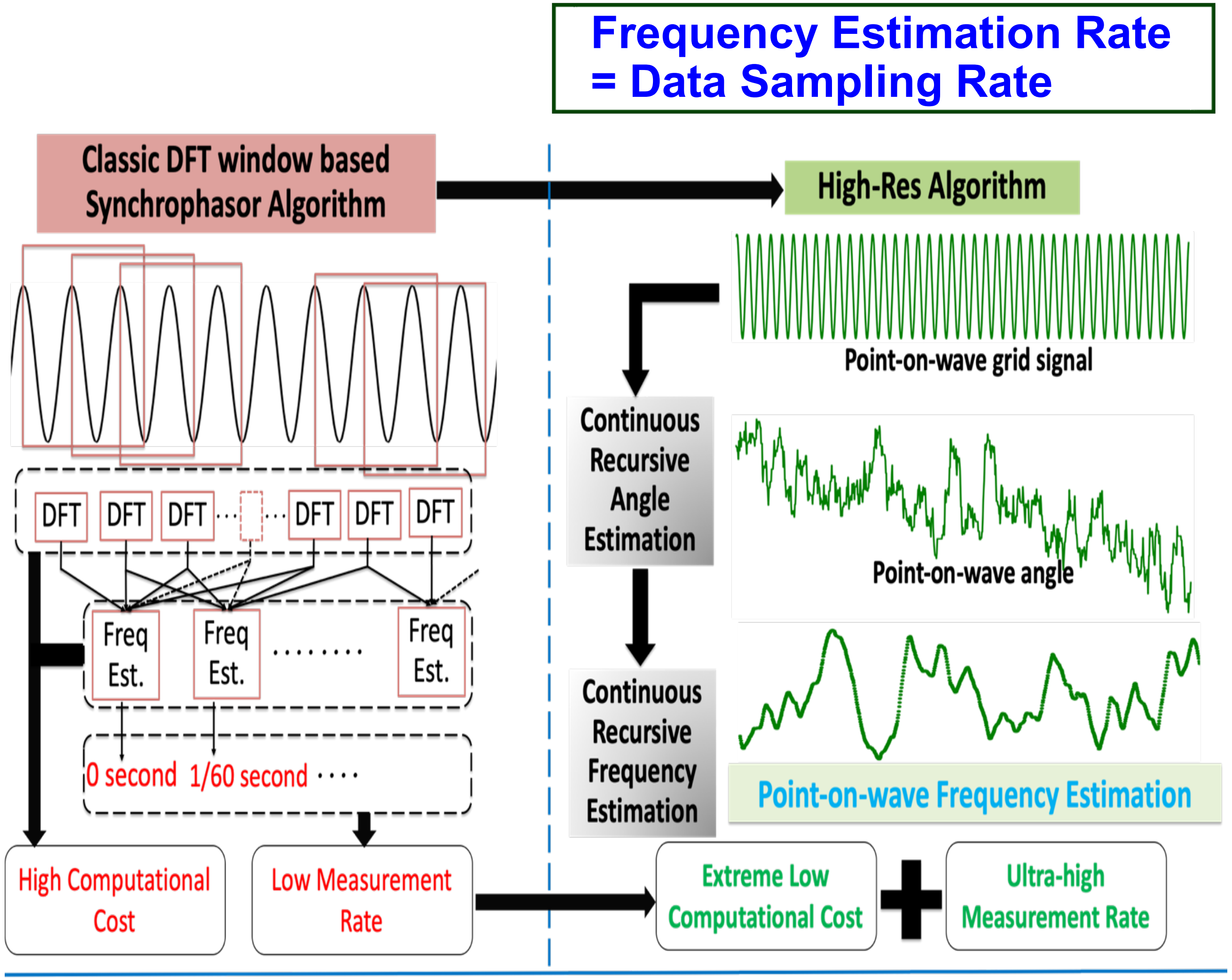
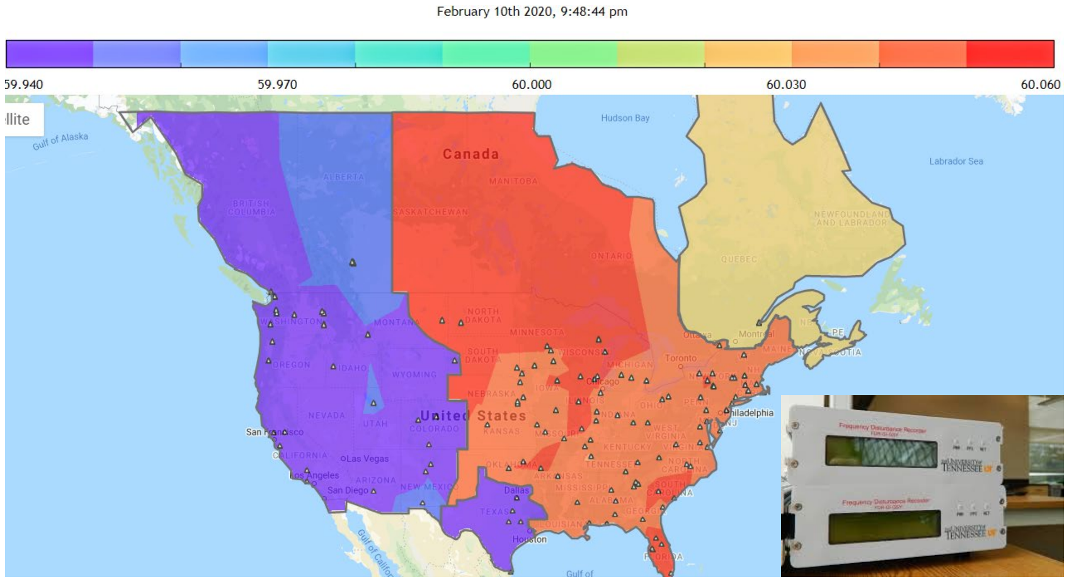
Zhan L, Xiao B, Li F, Yin H, Yao W, Li Z, Liu Y. Fault-tolerant grid frequency measurement algorithm during transients. Oak Ridge National Lab.(ORNL), Oak Ridge, TN (United States); 2020 Jan 10.

High-speed Frequency Measurement-Recursive Computation



Ultra-High-Rate Algorithm evolves from the measurement algorithm used by FNET/GridEye Frequency Disturbance Recorders (FDRs) whose measurement accuracies and reliability have been proven by ~300 units deployment across the nation's grid and over 15 years field operation.



High-speed Grid Frequency Measurement Advantage

Extremely low computation

~ 3 orders of computation time reduction compared to popular DFT based algorithms.

Benefits

- ✓ **Measurement rate**: Orders of higher grid measurement rate (kHz vs typical 60 Hz)
- ✓ **Hardware friendly**: easy hardware integration into grid edge devices.
- ✓ **Grid Applications**: enhanced grid visibility, high-frequency event detection, accurate oscillation source location, accurate RoCOF estimation, fast DER control/protection, stability predication, etc.

Extremely Low Computation Cost

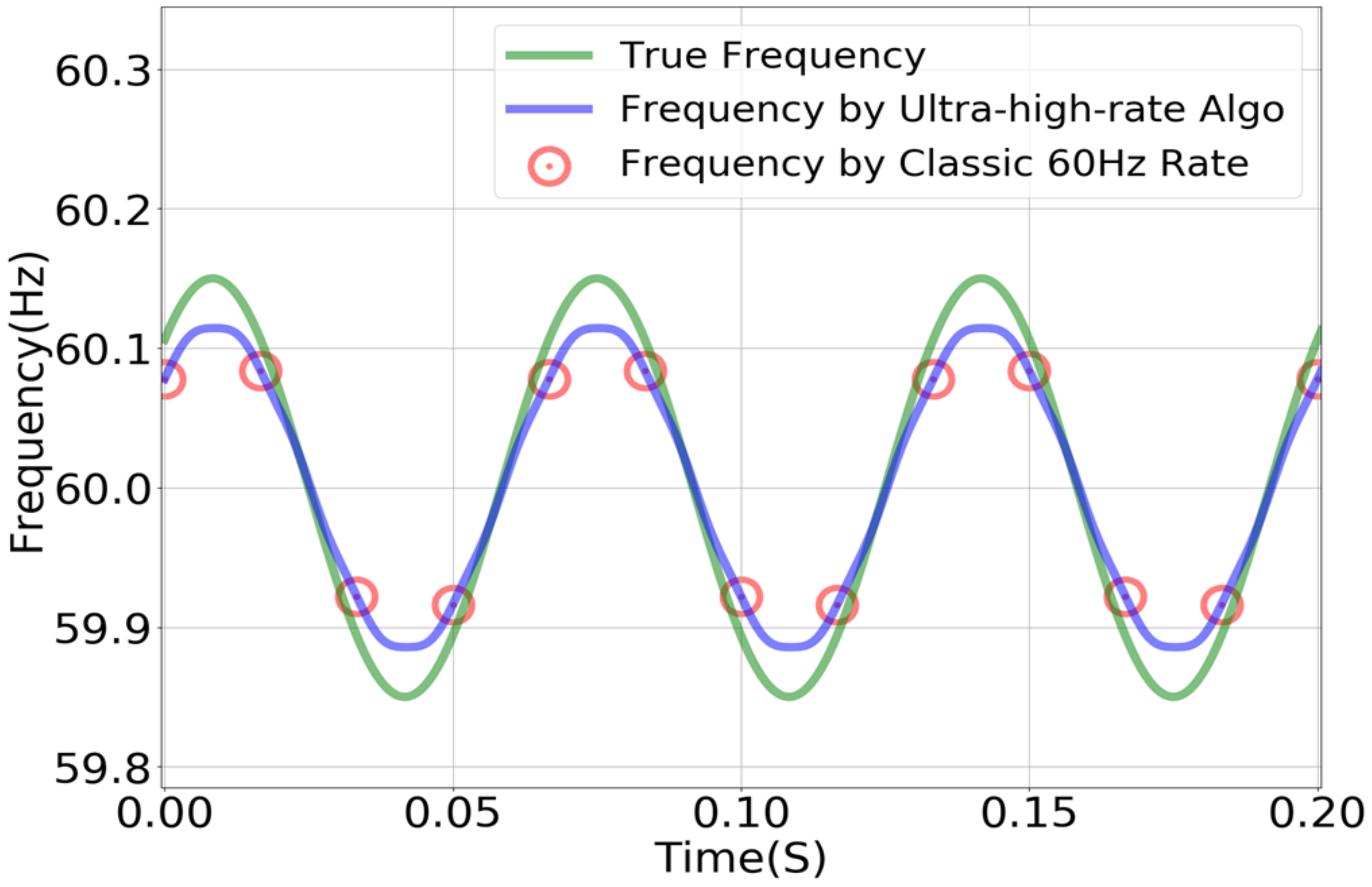
Sampling Rate	Window Size (cycle)	Computation Time (second)		Faster
		DFT Algorithm	Proposed Algorithm	
1440 Hz	5	1.279	0.002	650x
	10	2.396	0.002	1200x
	20	4.611	0.002	2300x
2880 Hz	5	2.590	0.002	1300x
	10	4.870	0.002	2400x
	20	9.240	0.002	4600x

Application Example: **High-Frequency Event Detection**

× Traditional 60 measurements per second could not capture the high-frequency oscillation due to low measurement rate.

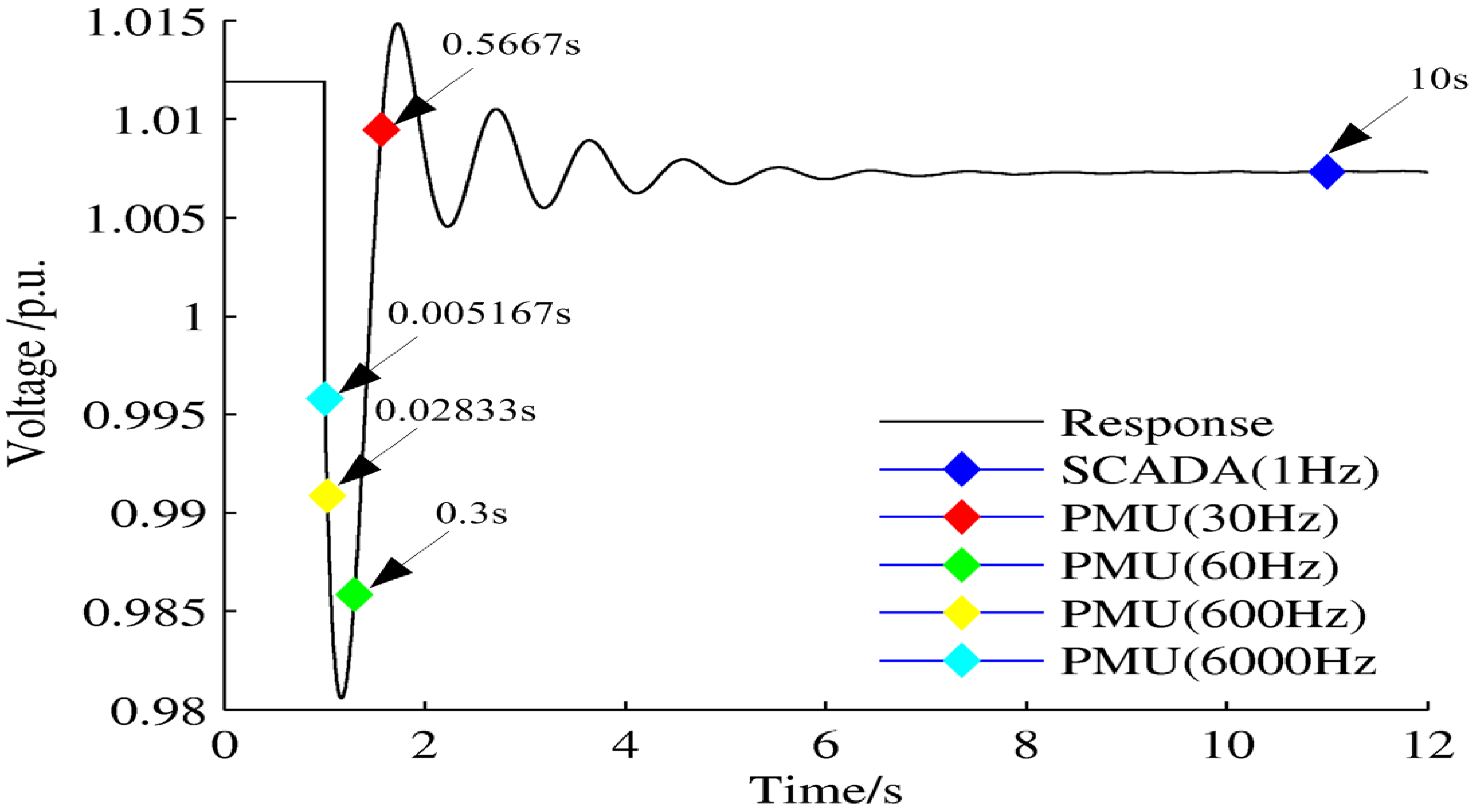
✓ Ultra-high-rate frequency measurement algo successfully captured the high-frequency oscillation.

15 Hz sub-synchronous oscillation



Window size: 1.5 cycles

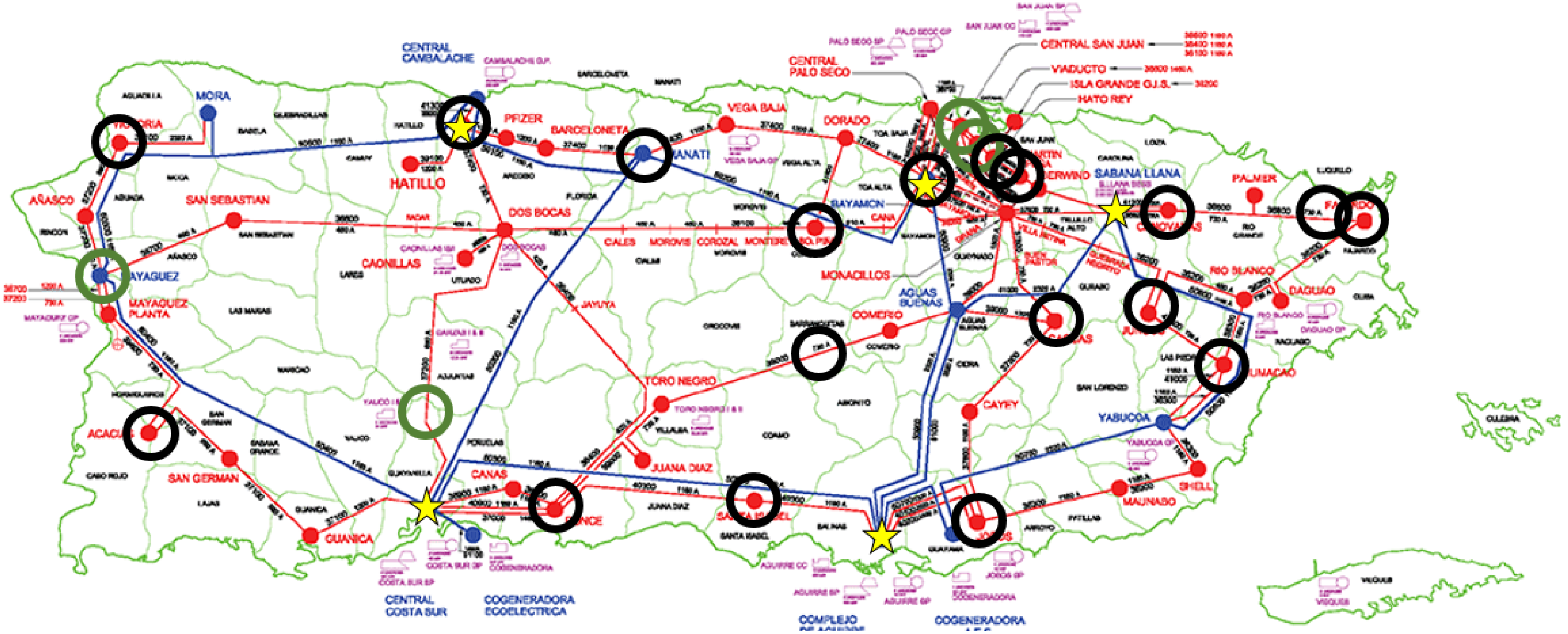
Prediction starts sooner with data rate increase



New Deployment - Puerto Rico Grid

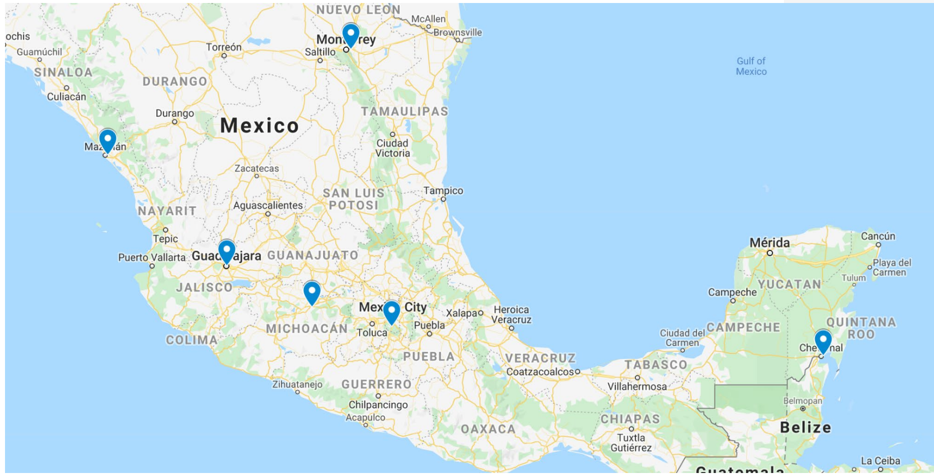
Recommended and Existing UGA Locations

Green Circle – Existing Locations
Black Circle – Proposed Locations with Telecommunication
★ – Recommendations from PNNL



FNET monitoring system operated by other countries

Some figures are illustrative only



Related web links:

FNET Live Display : http://fnetpublic.utk.edu/gradientmap.html

How to install FDR: http://www.youtube.com/watch?v=9Vt2OlVoBJc&NR=1

Sample oscillation alert:
http://fnetapp.eecs.utk.edu/FNETOsciEventReport/20120110_202749_EI_OsciSummary.html

FL Event Movie; http://www.youtube.com/watch?v=bdBB4byrZ6U&feature=related

CA Blackout Movie: http://www.youtube.com/watch?v=YsksUyeLu2Y

April 27 Storm TVA line trip Movie: http://www.youtube.com/watch?v=KmK2VMG57gw&feature=related

2011 Virginia Earthquake Movie: http://www.youtube.com/watch?v=XUN_h-k8kBg&feature=related

2003 blackout movie: http://www.youtube.com/watch?v=eBucg1tX2Q4&feature=related

Worldwide Measurement Map: http://powerit.utk.edu/worldmap/

UTK PowerIt Lab: http://powerit.utk.edu

NSF/DOE Center: http://curent.utk.edu

FNET GridEye