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Oscillation Detection and Source Location Based on Synchronized Point-on-Wave Measurements

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1st Point-on-Wave Application Conference

Chattanooga, TN
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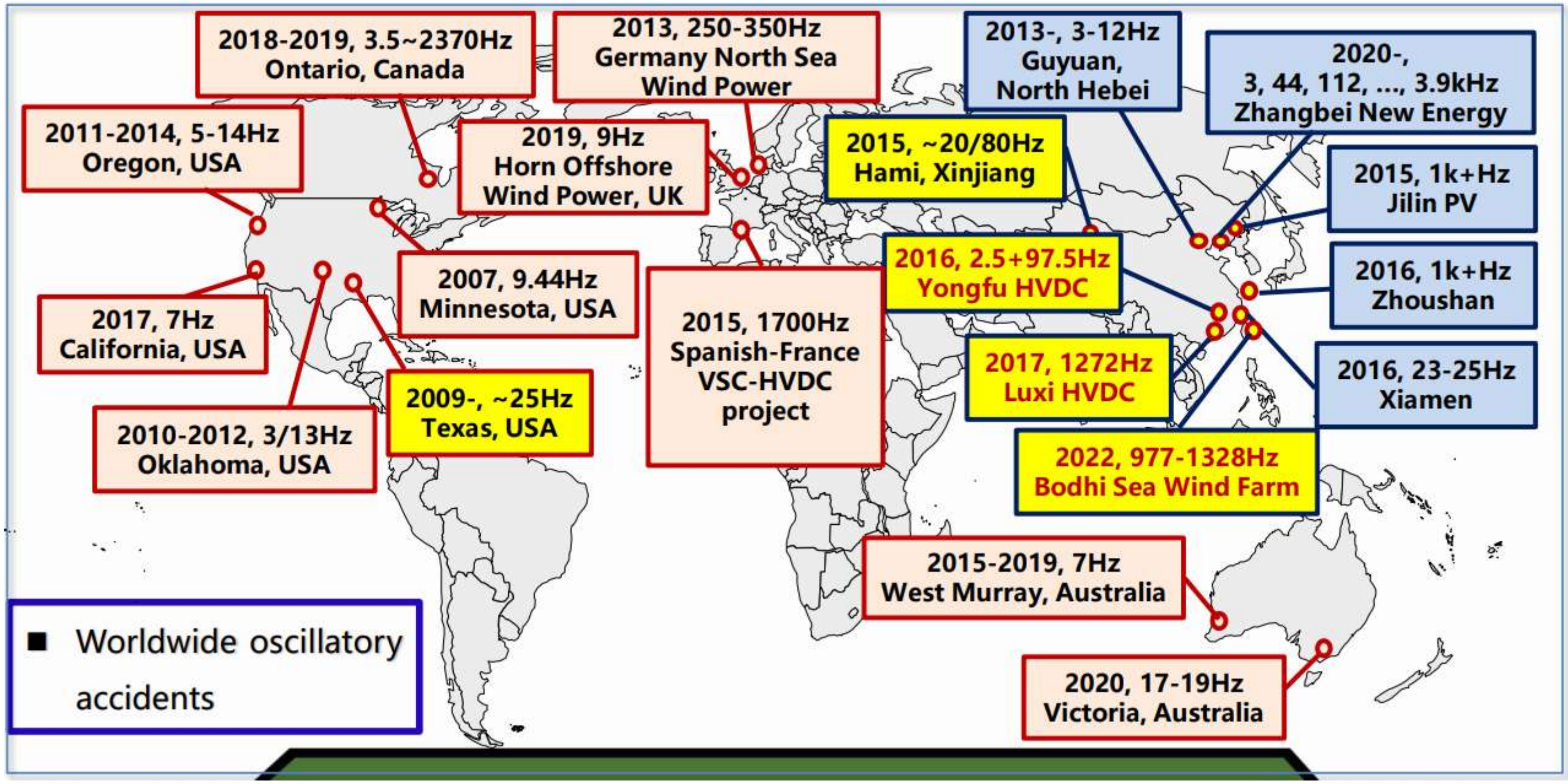
Background

- Increasing number of reported inverter-induced oscillation events
- Wide-band high-frequency oscillations

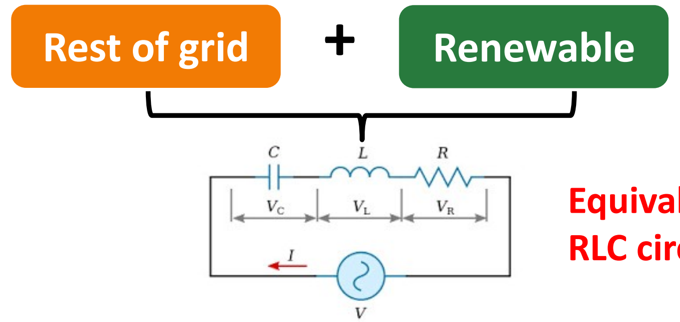


Recent worldwide oscillation incidents

Source: IEEE PELS seminar: Analysis and control of oscillatory stability in renewable power systems: China’s Experience

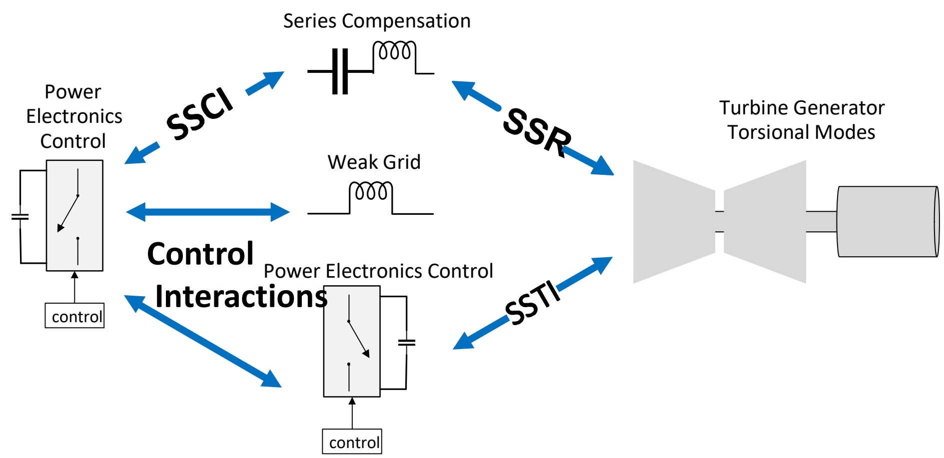
Sub-Synchronous Oscillations (SSOs)

- Adverse interactions between power system components resulting in oscillations in sub-synchronous range (e.g., < 60 Hz)
- **Torsional mode interactions**
  - Sub synchronous resonance (**SSR**)
  - Sub-synchronous torsional interactions (**SSTI**)
- **Control interactions**
  - Resonant interactions between series compensated lines and Type 3 wind plants due to IGE (also known as sub-synchronous control interactions or **SSCI**)
  - Non-resonant interactions due to **weak grid**
  - Other **control interactions** (non-resonant) among power electronic devices – *not limited to sub-synchronous frequencies*



Equivalent RLC circuit

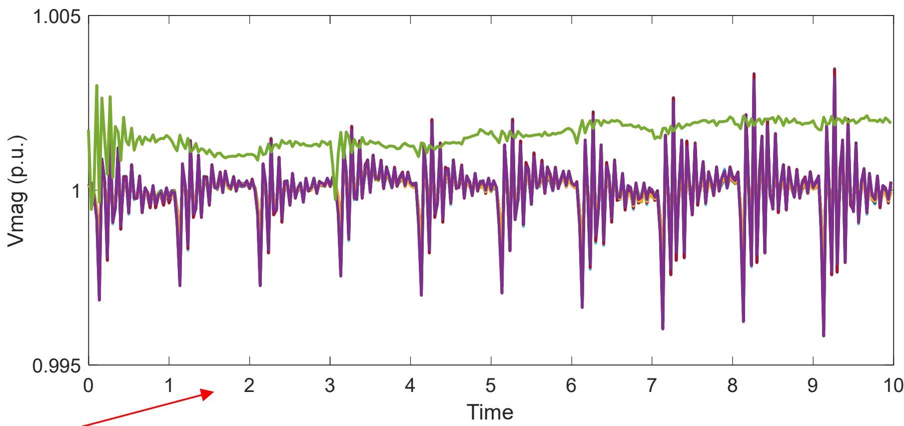
- **R <= 0 to excite oscillation**
- **Frequency:** $f_o = \frac{1}{2\pi\sqrt{LC}}$

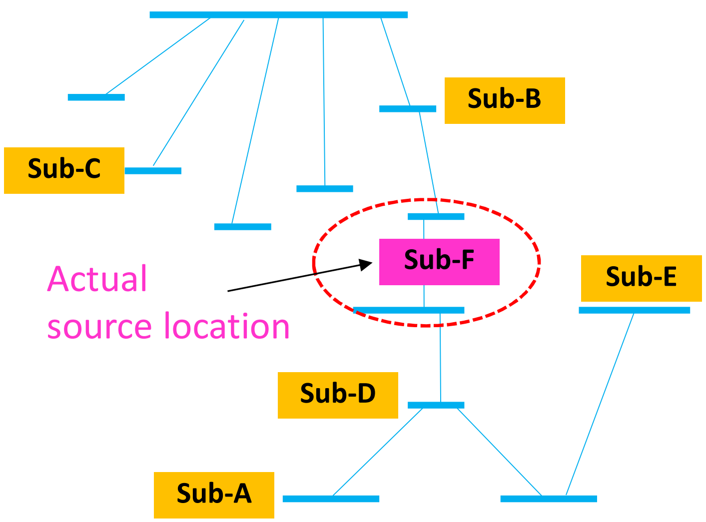


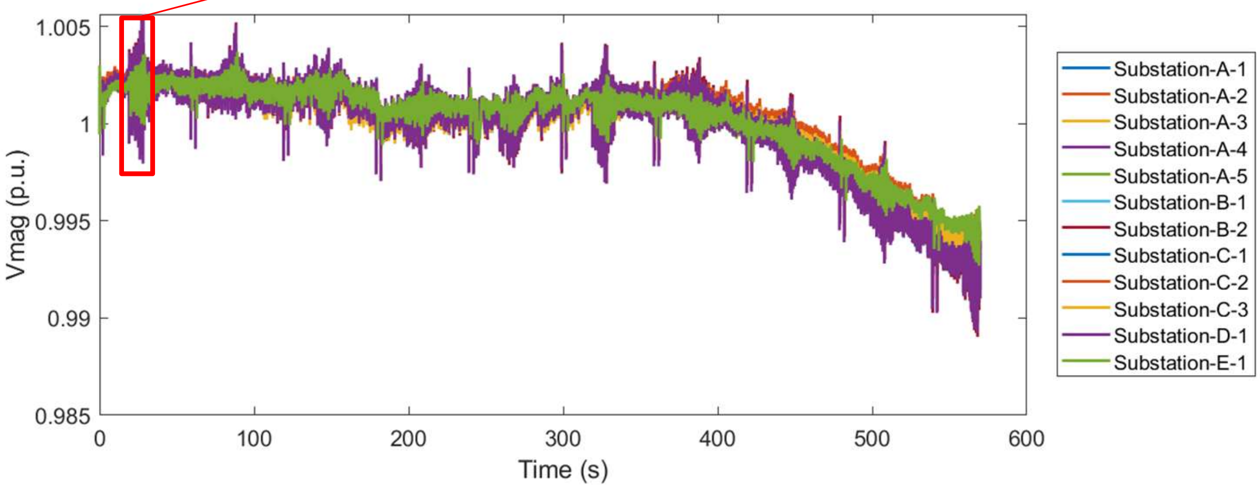
SSO encompasses many different types of inter-element interactions within power system

SSO Event in Dominion Territory

- Oscillation observed by PMUs in 5 substations
- Voltage oscillation mag: ~0.01 pu peak-to-peak
- ~ 11 Hz, ~5% damping ratio
- Reinitiated every 1s: Load synchronized to GPS
- Actual source: Data center





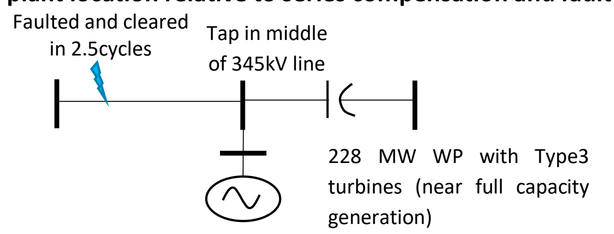


Substations with PMUs

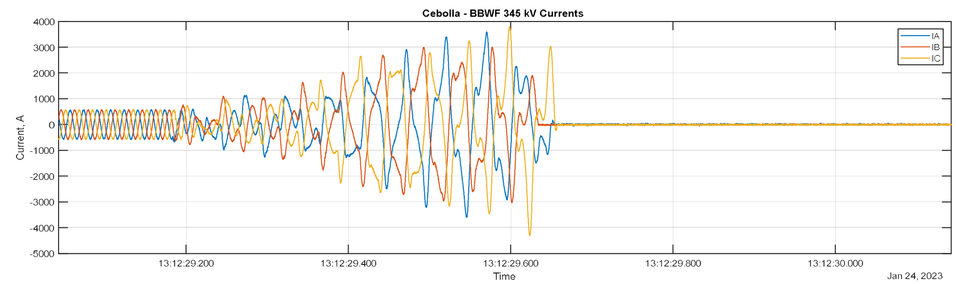
SSO Event in AEP Territory

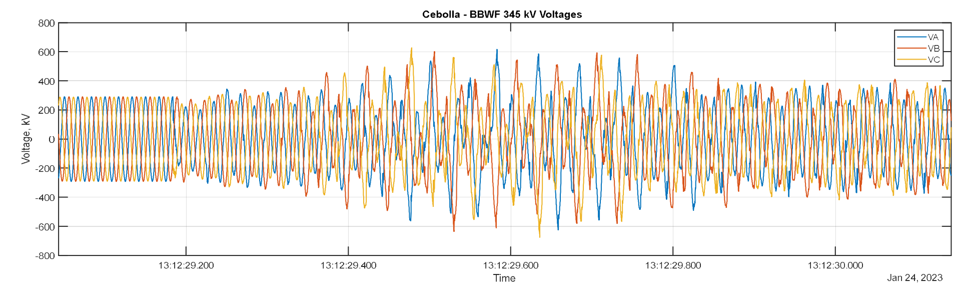
- **<u>Cause:</u>** Fault caused Type 3 Wind Plant to go radial to series compensated transmission line
- **<u>Effect:</u>**
  - High peak magnitude line currents (4000+ Amp peak)
  - High peak magnitude line voltages (600+ kV peak)
  - Dominant sub-synchronous frequency of 21 Hz obtained from frequency spectrum of wind plant phase currents while radial through series cap
  - Wind plant tripped in slightly less than 0.5 seconds due to high main power transformer differential current

Schematic of wind plant location relative to series compensation and fault location



Recorded ABC phase currents and voltages during event at the Wind Plant

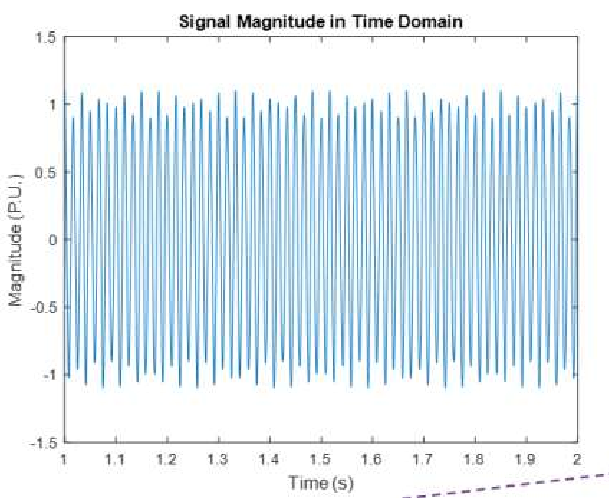




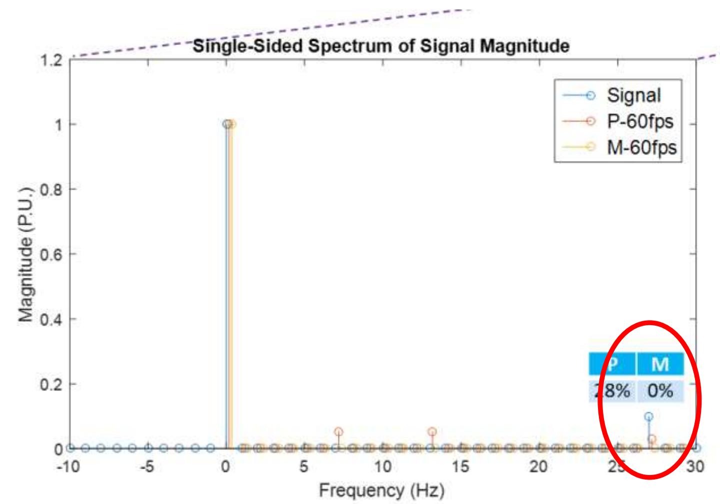
Rob O Keefe, "January 24 & March 10, 2023 SSO Events in AEP," EPRI SSO Workshop, Charlotte, April20, 2023

PMU Limitations in Monitoring High-Frequency Oscillations

- PMU was originally designed to report phasor of fundamental frequency
- Limitations in monitoring fast dynamics: PMU reporting rate, PMU nonideal digital low-pass filter, etc. -> Far below the theoretical Nyquist frequency
- High-resolution synchronized waveform measurements are required



27 Hz dynamic added to the fundamental frequency

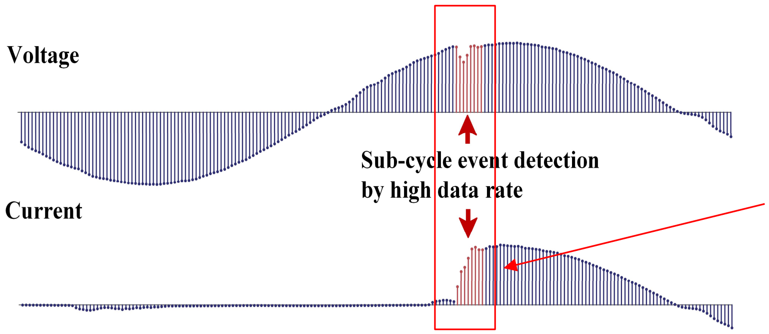


27 Hz dynamic is **NOT** visible with 60 Hz PMU

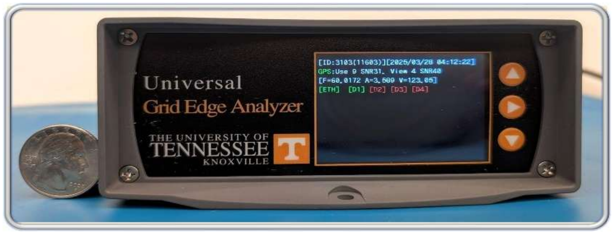
Source: H. Hooshyar, A. Haddadi, E. Farantatos and M. Patel, "Investigation of PMU Limitations in Monitoring Fast Dynamics Through Real-Time Hardware-In-The-Loop Experiments," *2022 SGSMA*, Split, Croatia, 2022.

Waveform Measurement Unit: Universal Grid Analyzer (UGA)

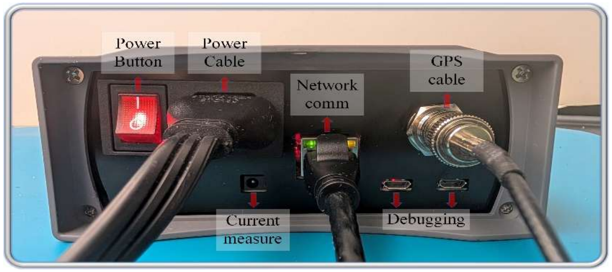
- Real-time synchronized waveform
  - Sampling/Resolution: 1440 per second (240 per cycle)
  - Reporting rate: 10 Hz (144 data points per package)
- Local anomaly detection: Sub-cycle event detection
- Monitoring for various scenarios
  - Solar farm, data center, power cable, islanded grid, microgrid, etc.



Sub-cycle event detection



Front Panel



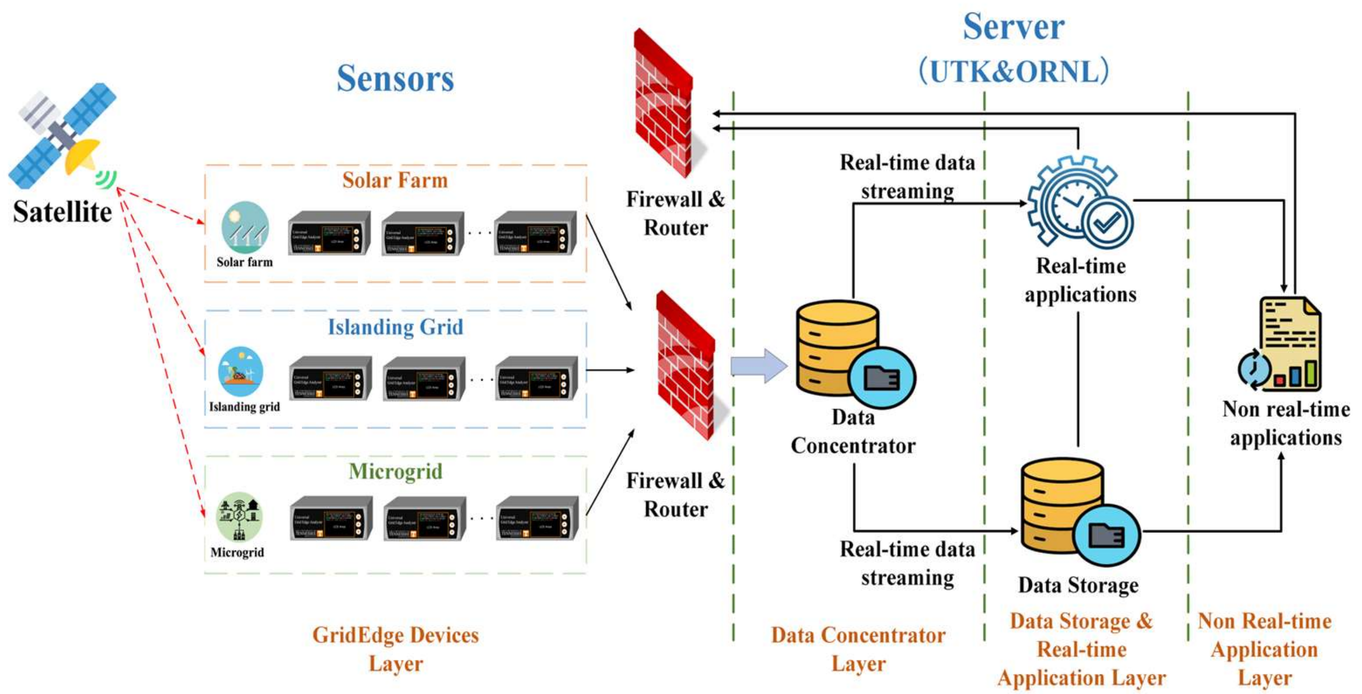
Back Panel

Universal Grid Analyzer (UGA)

Continuous, High-Resolution Insights Into Power Grid Dynamics

Wide-Area Synchronized Waveform System

- Sensor: UGA
- Communication: Internet
- Advanced applications: e.g., sub-synchronous oscillations monitoring and analysis

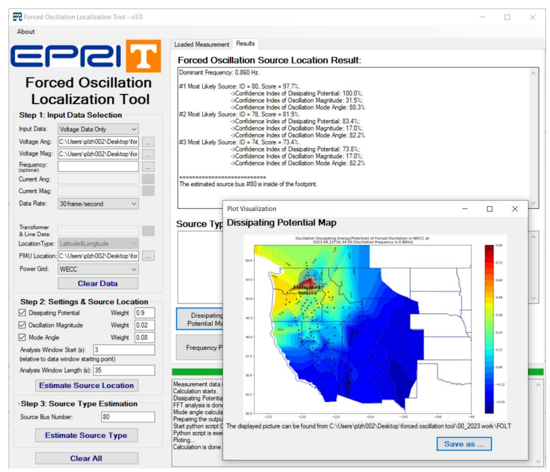


Oscillation Detection and Source Location Tool

- Synthetic or recorded synchronized waveform measurements as input

Configuration:
- Data reporting rate
- Data window selection
- Thresholds, etc.

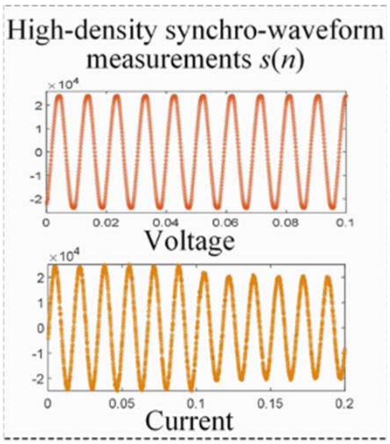
Input:
- Point-On-Wave Measurements
  - Three-phase voltage
  - Three-phase current
- Location: GPS coordinates



Output:
- Estimated oscillation frequency
- Estimated oscillation starting time
- Estimated source location
- Intermediate results, e.g., FFT analysis results

SSO Detection Using Synchronized Waveform

- Step 1: Cycle-to-cycle comparison (Time domain)
- Step 2: FFT analysis (Frequency domain), compare magnitude to that of fundamental frequency component



Step1: Oscillation Alert Cycle-to-Cycle Waveform Comparison

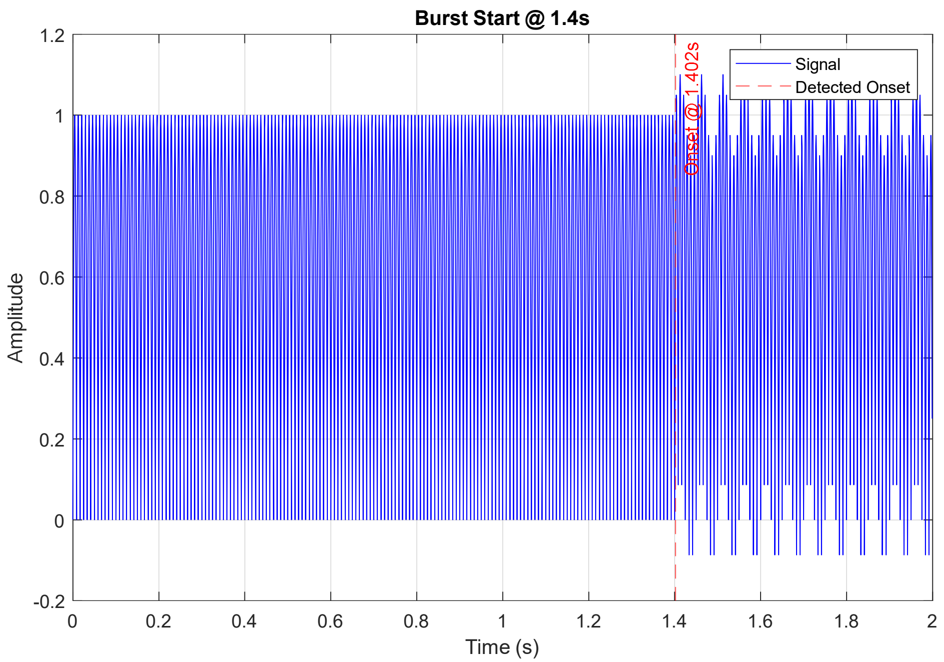
- Compute CycleDiff(t) over sliding windows
- Compare to threshold ➔ set anomalyFlag(t)
- Detect first anomalyFlag ➔ Record t_alert
- Compute onset time: t_onset

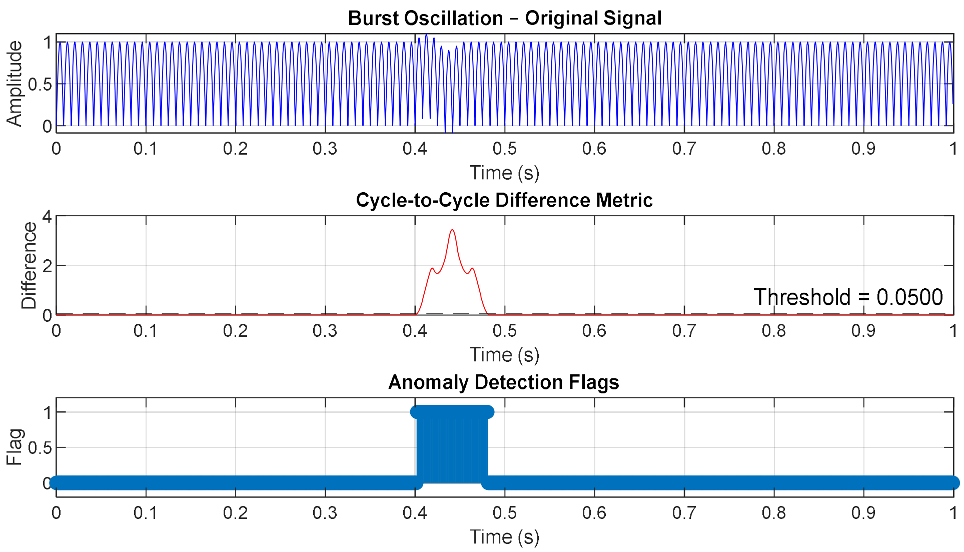
Step2: Oscillation Verification Sideband Detection using FFT Analysis

- Initial SSO Frequency Estimation (FFT)
- Identify Sidebands: *f_lower* & *f_upper* Hz
- Estimate FO: (*f_upper* – *f_lower*)/2
- Estimate SSO magnitude

SSO Detection Using Synchronized Waveform

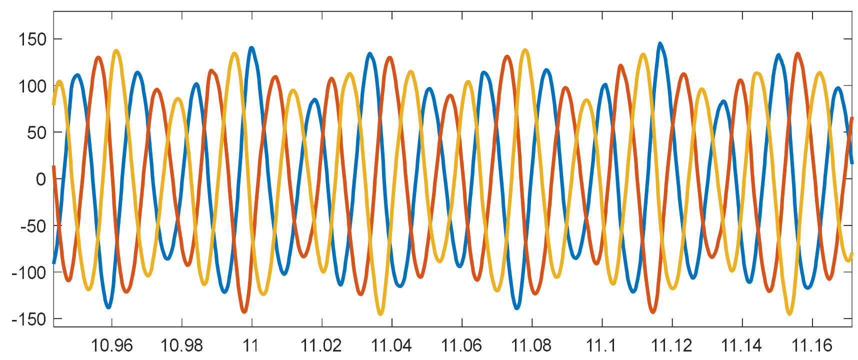
- Synthetic measurements



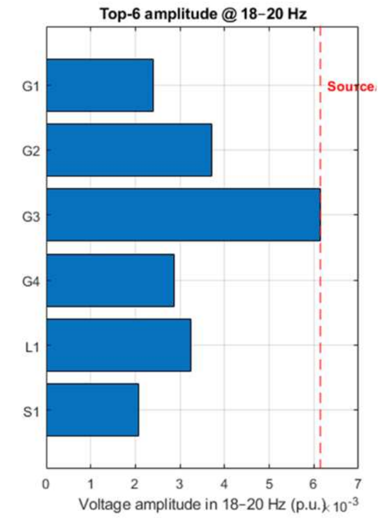


SSO Source/Origin Estimation Using Synchronized Waveform

- Based on oscillation magnitude
  - SSOs are usually local oscillations
  - Location with the highest oscillation magnitude is considered source/origin



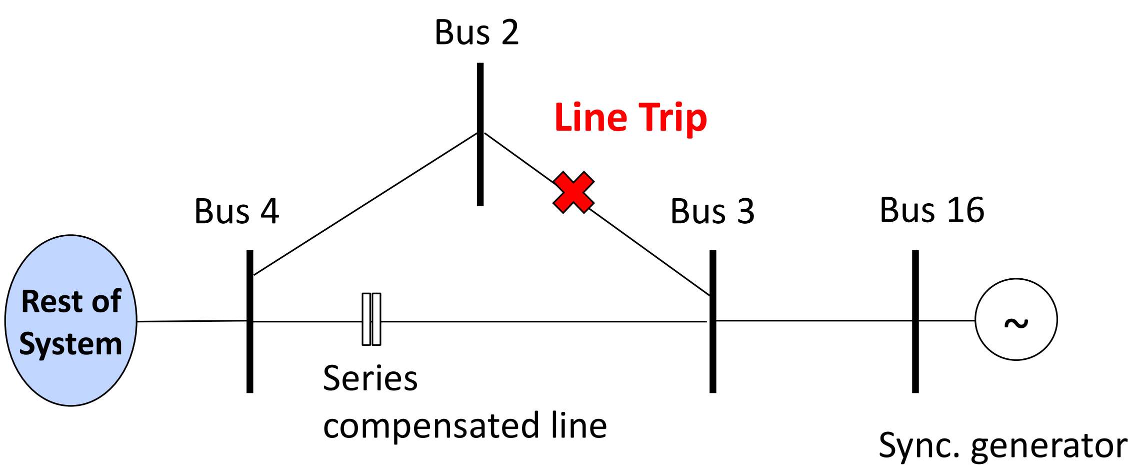
Three-phase voltage or current waveform measurements

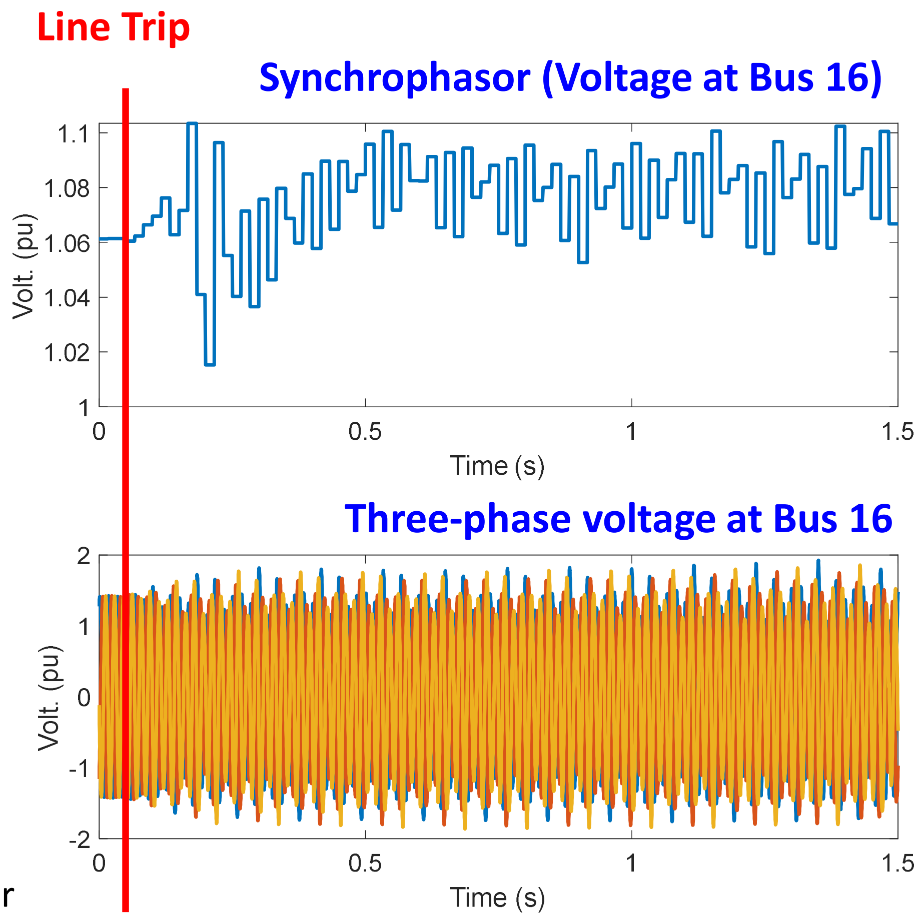


Compare oscillation magnitude at different locations

Case Study on 18-Bus System

- PSCAD model
- Trip line between Bus 2 and Bus 3 (radial topology)
- Sub-synchronous resonance between series compensated line and synchronous generator
- ~25 Hz SSO





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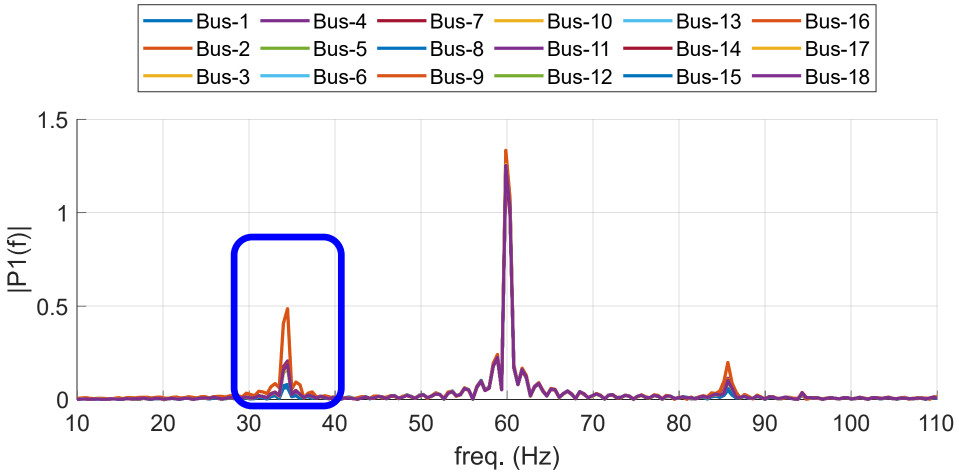
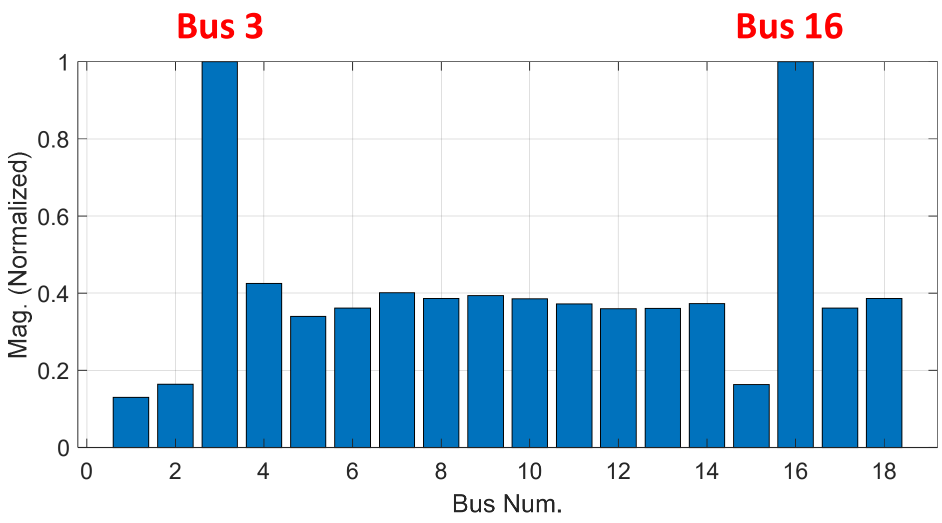
SSO Detection and Source Location

- SSO can be detected: 25.69 Hz
- Bus 3 and Bus 16 can observe the highest magnitude at 25.69 Hz





Summary and Future Work

- Integration of IBRs has led to high-frequency oscillations in power systems
- PMUs/Synchrophasors have limitations in monitoring high-frequency oscillations
- Developed oscillation detection and source location method based on synchronized waveform data
  - Oscillation detection: Cycle-to-cycle comparison + FFT analysis
  - Source location: Oscillation magnitude
- Case study with synthetic measurements of 18-bus system
- Future work:
  - Advanced methods for source location estimation
  - More case studies with actual synchrophasor and synchronized waveform data

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