Advanced Measurements for Resilient Integration of Inverter-Based Resources

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IBRs are vital to the nation's clean energy goals

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Biden Administration Launches Bipartisan Infrastructure Law Initiative to Connect More Clean Energy to the Grid

MAY 31, 2022

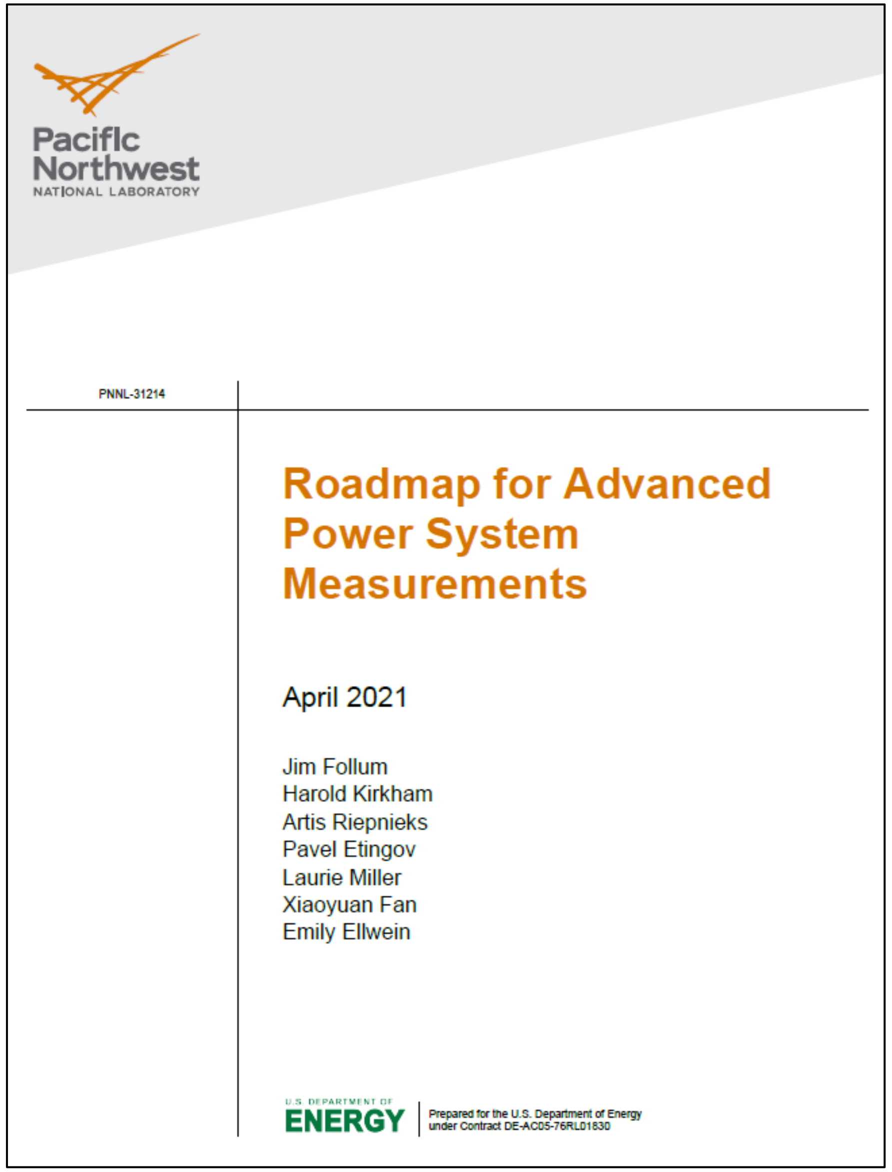
Energy.gov » Biden Administration Launches Bipartisan Infrastructure Law Initiative to Connect More Clean Energy to the Grid

The Interconnection Innovation e-Xchange Engages Utilities, Clean Energy Developers, Regulators, and Others to Enable More Clean, Affordable Electricity While Ensuring Grid Reliability, and Resilience

WASHINGTON, D.C. — The Biden Administration through the U.S. Department of Energy (DOE) today launched the **Interconnection Innovation e-Xchange (i2X)** — a new partnership funded by President Biden's Bipartisan Infrastructure Law that brings together grid operators, utilities, state and tribal governments, clean energy developers, energy justice organizations, and other stakeholders to connect more clean energy to America's power grid by solving challenges facing the power industry. The partnership will help reduce wait times for clean energy sources in interconnection queues and lower costs to connect to the grid. As the Biden Administration ramps up expansion of new renewable energy to reach the President's goal of 100% clean electricity by 2035, i2X partners will develop solutions for faster, simpler, and fairer interconnection of clean energy resources through better data, roadmap development, and technical assistance.

Risk of negative impacts to the bulk power system must be mitigated

Measurements can help mitigate risks



https://doi.org/10.2172/1871292

PROGRESS MATRIX

- Initiated in April 2022
- Jointly funded by DOE’s Office of Electricity (OE) and Solar Energy Technologies Office (SETO)
- Joint effort between PNNL, LBNL, ORNL, and NREL with cost share from McEachern Laboratories
- Objectives:
  - Develop advanced measurement capabilities and analytics
  - Accelerate adoption of IBRs
  - Improve the reliability and resilience of the BPS

Project Structure

Year 1

Gap Analysis (PNNL, ORNL, NREL)

- Survey of utility partners' measurement capabilities: BPA, WAPA, KIUC (Kaua'i, Hawaii)
- Review of measurement-based IBR application requirements

GridSweep Instrument (LBNL)

- System probing and waveform measurement with unprecedented precision
- Data collection and processing from two sites

Year 2

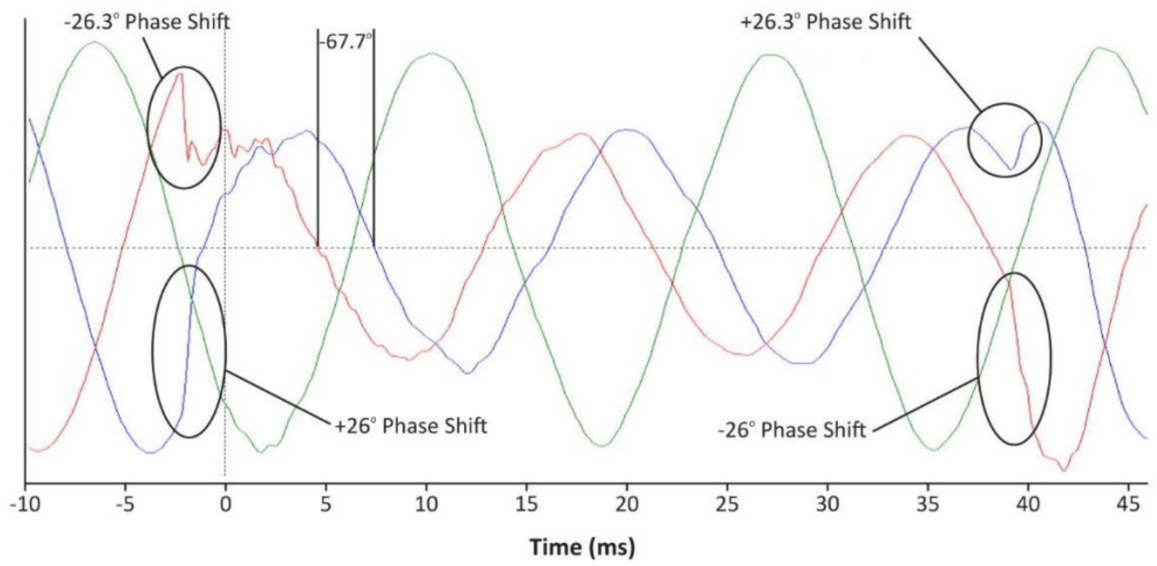
Application Development and Demonstration

- Develop nine measurement-based applications to support integration of IBRs
  - Field demonstration of a synchrophasor-based application
  - Testbed demonstrations of two waveform-based applications
- Release software tools for GridSweep analysis

Gap Analysis

Survey of Utility Measurement Capabilities

- Synchrophasors
  - Systems are mature and readily accessible
  - Information about system limitations is scarce, or at least not readily available to the measurement users
- Waveforms
  - Accessibility varies widely among Transmission System Operators (TSOs)
  - Conventional use will continue to dominate (trigger-based recording)
  - Value proposition for highly accessible (e.g., streaming) waveform measurements is not strong enough yet to justify expenses: bandwidth, network management, security, storage
  - Labeled event data to support AI/ML is lacking (for now)
- Plant owners are hesitant to share measurements
  - Concerns similar to those surrounding models: IP, liability
  - No requirements to justify expense



Source: NERC

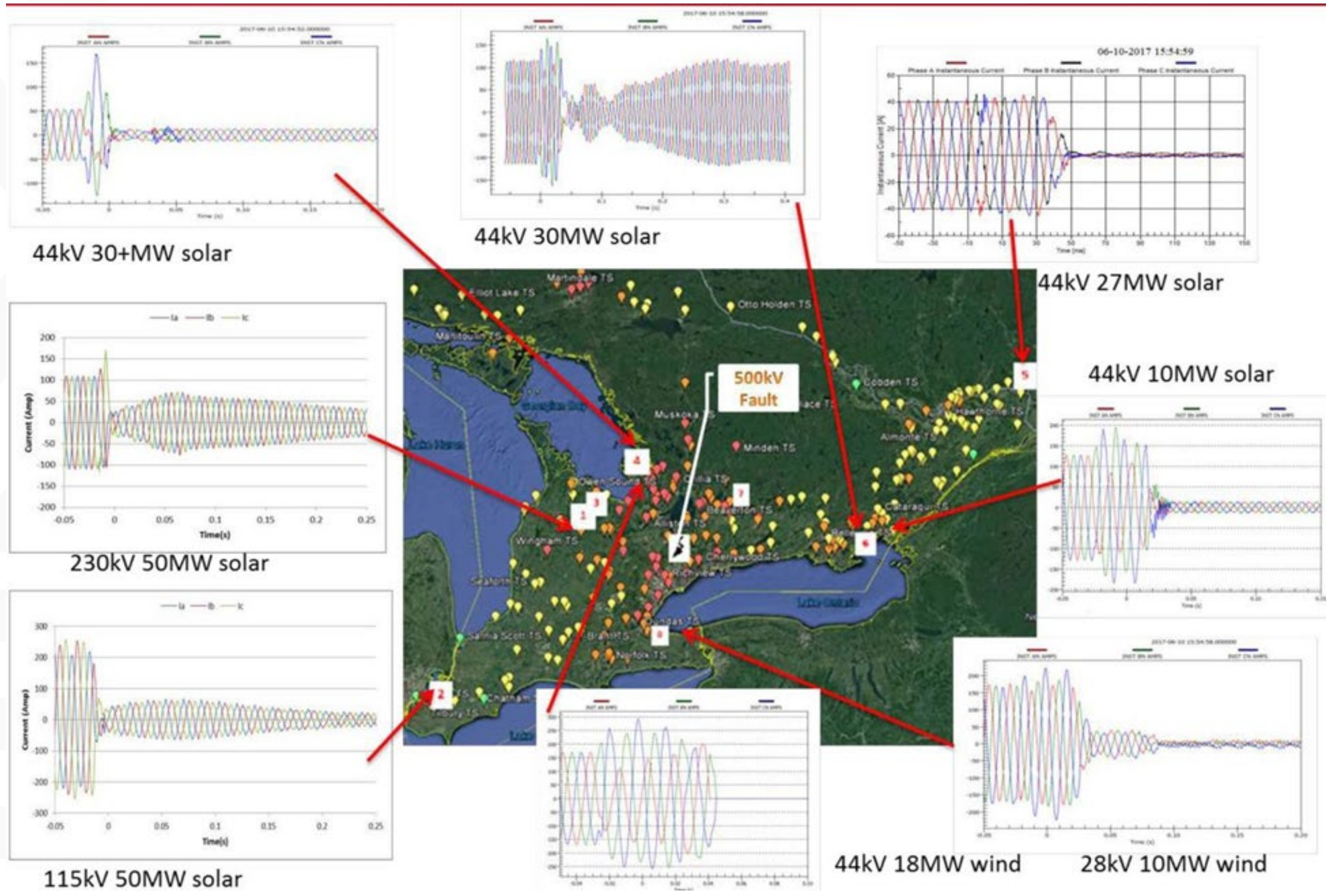
Review of IBR Application Requirements

Application Family	Applications	IEEE Std 2800 Compliance	Measurement Type	Measurement Location or RPA	Meas. RR[a]	TRL	References
Monitoring	Inertia Estimation (Transient)	NR[b]	Synchrophasors	Multiple locations in TS	30Hz	8	[Ashton et al., 2015]
	Inertia Estimation (Ambient)	NR	POW GridMetrix Meas.	Multiple locations in TS	kHz (for GridMetrix)	9	[Kimm
			Synchrophasors	Tie lines, SGs, and IBRs	30 Hz	2	[T
	SSO Metering	NR	POW	POI	120 Hz	9	[Cheng et
	SSO Source Localization	NR	POW	POI	120 Hz	2	
	Impedance-based Stability Analysis	NR	POW	POI	20kHz	7	[Shah et a
	Harmonic Stability Analysis	R	POW	POM, POI	2.75kHz	5	[Mat [War
	Electromagnetic Stability Analysis	R	POW	POI	1Hz-10kHz	5	[ESIG, 2 [NERC,
	Inverter Synchronization Stability Analysis	R	Synchrophasors POW	POM, POC	60Hz, 10kHz	3	[Globa
	Disturbance Monitoring	NR	Synchrophasors, POW, Oscillography	POM,POI,POC	Many kHz	2-9	[NER
	Power Quality Monitoring	R	POW	POM, POI	8 kHz	7	[Ent
Modeling	Data-driven Modeling – Reduced Order Model	NR	Synchrophasors	POI, POM, POC	60 Hz	4	
	Data-driven Modeling – Impedance Spectrum Model	NR	POW	POC	20kHz	2-9	
	EMT Model Calibration and Validation	NR	POW	POC	20kHz	9	[AECOM [DOE, 201 [Badr
	Admittance Model Identification for SSR Screening	NR	POW, Synchrophasors	POM	2kHz	1	[Fan et al., 2022b]
	dq Admittance Model Identification	NR	POW	POM, POI	2kHz	3-4	[Fan and Miao, 2020]

Application Family	Applications	IEEE Std 2800 Compliance	Measurement Type	Measurement Location or RPA	Meas. RR	TRL	References
Control	Plant Level Control Design	R	POW, Synchrophasors	POI,POM	4 kHz	3-9	[Baker et al., 2021]
	Fast or Primary Frequency Response	R	POW, Synchrophasors	POM	20kHz	5	[NERC, 2020a]
	Virtual Inertia Based Control	NR	POW, Synchrophasors	POC	3-20kHz	2	[Yap et al., 2019]
	Reactive Power Control	R	POW, Synchrophasors	POI, POM	3-20kHz	3-4	[Entergy, 2022] [Brown, 2020] [WECC, 2020]
	Automatic Voltage Regulation	R	POW, Synchrophasors	POC and/ POM	3-20kHz	3-4	[Entergy, 2022, Guo et al., 2021]
	Ride-through Controls	R	POW, Synchrophasors	POI	3-20kHz	1-3	[Baker et al., 2021] [ESIG, 2020] [Hart et al., 2022]
Protection	Anti Islanding	R	Synchrophasors POW	POI, POM	3-20kHz	3-8	[Kroposki, 2016], [da Cunha Lima et al., 2021] [Solectria, 2016] [Nassif et al., 2022] [Haddadi et al., 2021], [Mills-Price et al., 2011]
	Line Current Differential Protection with IBRs	R	POW	POC, POI	1kHz	2	[Haddadi et al., 2021] [Chowdhury et al., 2022]
	Utility end distance Protection	R	POW	POC, POI	1MHz	2	[Paladhi and Pradhan, 2020] [Nagpal et al., 2020] [Bini, 2022]
	Sequence Current Limiting Protection	R	POW	POM, POI	3-20kHz	2	[Mahamedi et al., 2018]
Planning	Weak Grid Studies	R	POW, Synchrophasors	POM, POI	Many kHz	2	[Nordgård et al., 2011] [Muljadi, 2016]

Recommendations

- Develop a stronger value proposition for expanding the use of waveform measurements
  - Identify cost effective approaches for improving accessibility
    - Synchrophasor-first architectures
    - Automated polling from local storage
    - Distributed solutions
  - As barriers to model sharing are addressed, consider plant-level measurements as well

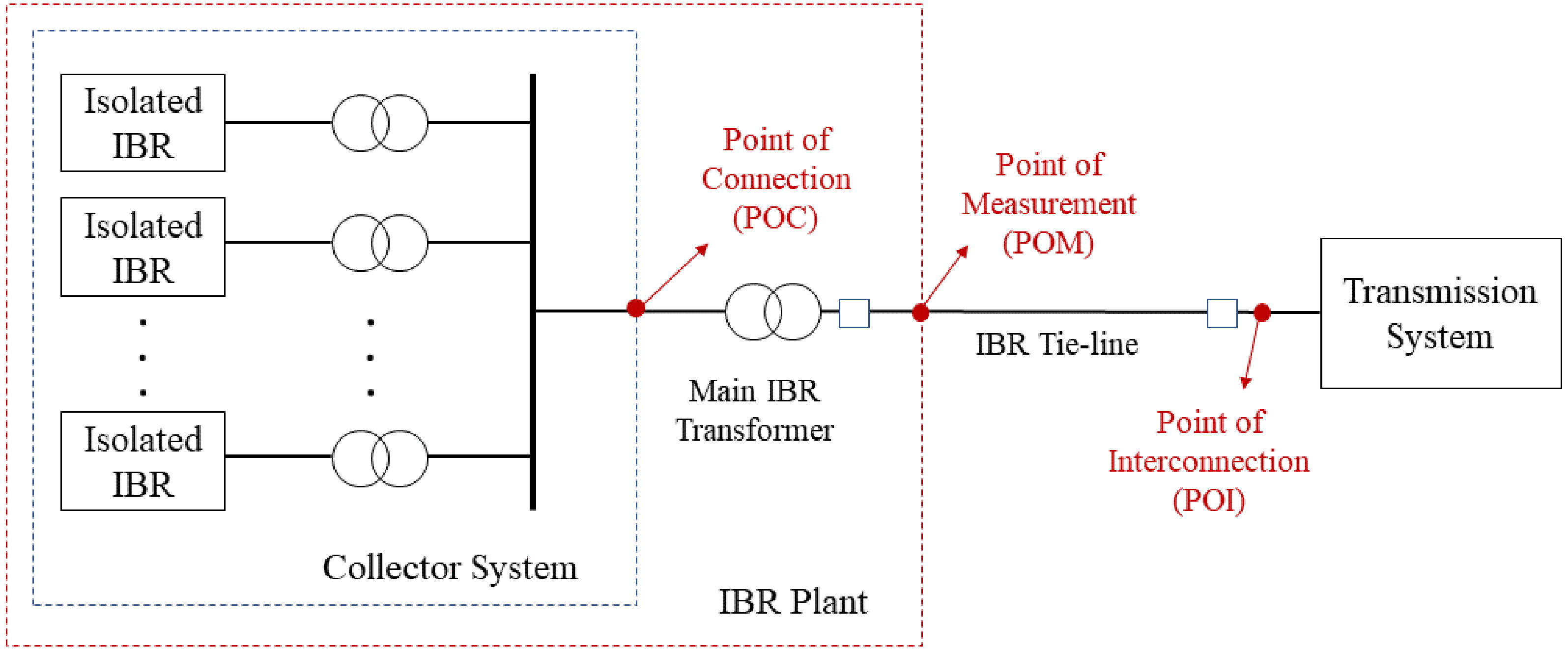


HydroOne Renewable Monitoring

Li, C. (2019). Inverter-Based Resource Monitoring and Event Investigations. Paper presented at the NATF/EPRI/NERC Power System Modeling Conference, Novi, MI.

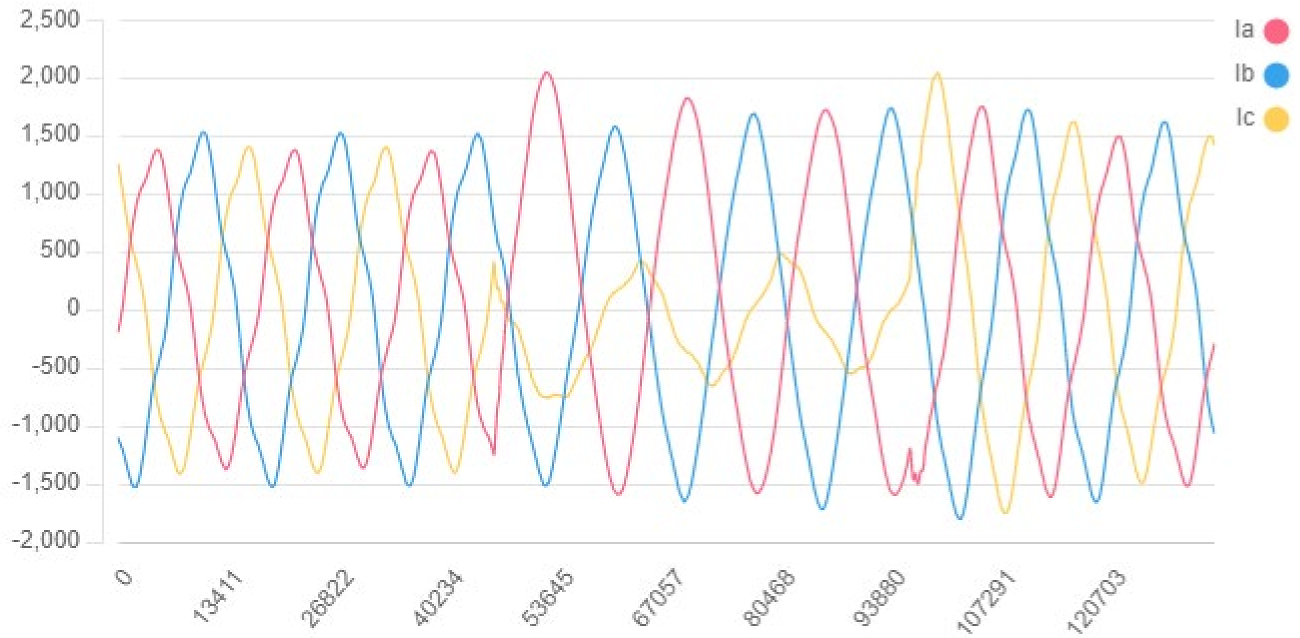
Recommendations

- Clearly identify the user for proposed applications
  - Who does the value proposition apply to?
  - Do they have access to the necessary measurements?



Recommendations

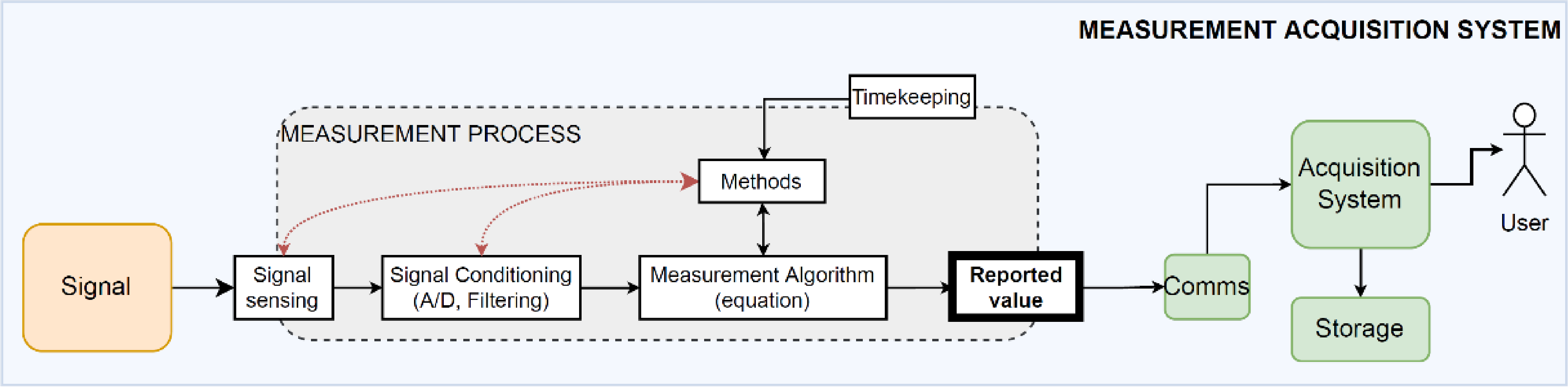
- Address the need for event records with high-quality labels
  - Show the value of existing signature libraries by using them in your research
    - https://pqmon.epri.com/
    - https://gsl.ornl.gov/
  - If your organization sees potential in AI/ML applications, be strategic in how you store and label event data
    - Develop tools to make labeling and organization easier for these utilities
    - Contribute events to existing libraries



Grid Signature Library (GSL) label: "While attempting to close back in transmission line a fault occurred tripping the breaker at substation."

Recommendations

- ► Be aware of the measurement system's limitations
  - Environmental conditions
  - Frequency response
  - Calibration
  - Accuracy class
- ► PNNL report with limitation checklist coming April 2023



GridSweep

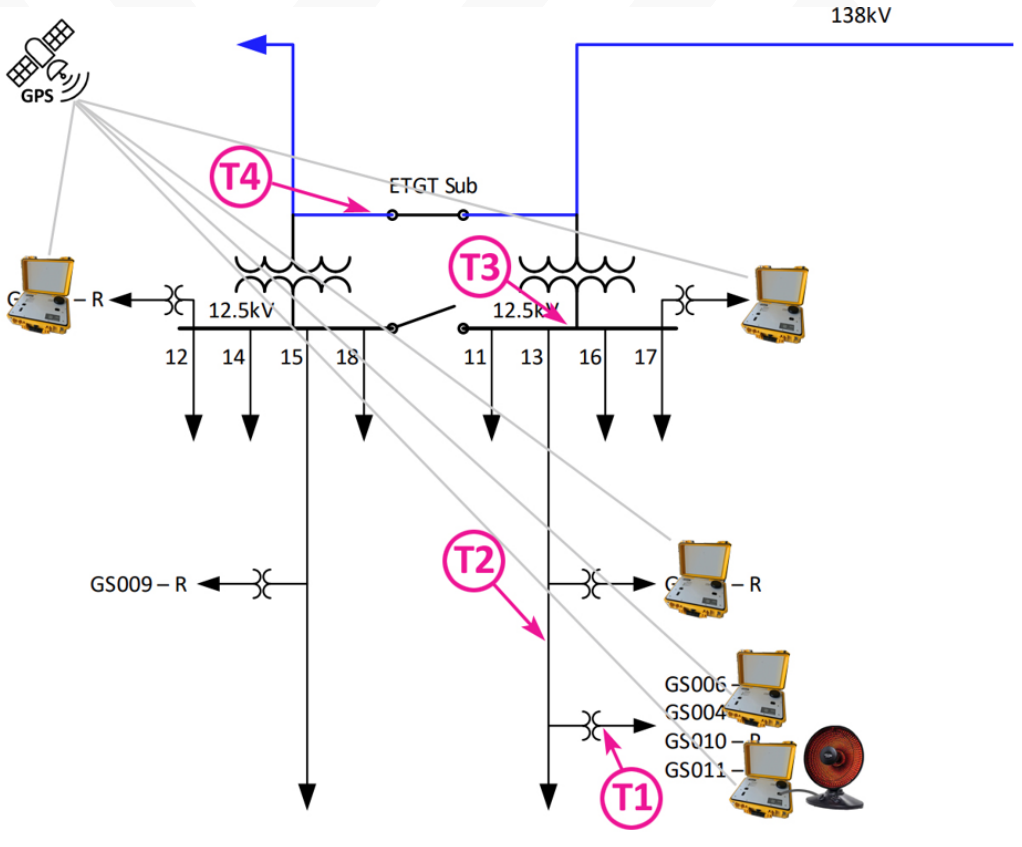
IBR Population – Subsynchronous Resonance Risk

- Individual inverters are stable when connected to a strong grid.
- But what happens with [a] an interconnected population of inverters that [b] have diverse PID weights and diverse control loop speeds and are [c] weakly connected to each other?
- Resonance, Damping, and Inertia
  - IBR's are generally worse than rotating generators.
- How much energy required to initiate oscillation?
  - Much less for IBR's than rotating generators…
- Accidental vs Intentional (hostile act) oscillations
  - Intentional requires knowledge of
    - Subsynchronous resonant frequency
    - Subsynchronous phase angle
    - Bulk grid parameters may be covertly visible from outlets.

Credit: commons.WikiMedia.org Tradycyjna, drewniana huśtawka w Viljandi, Estonia.

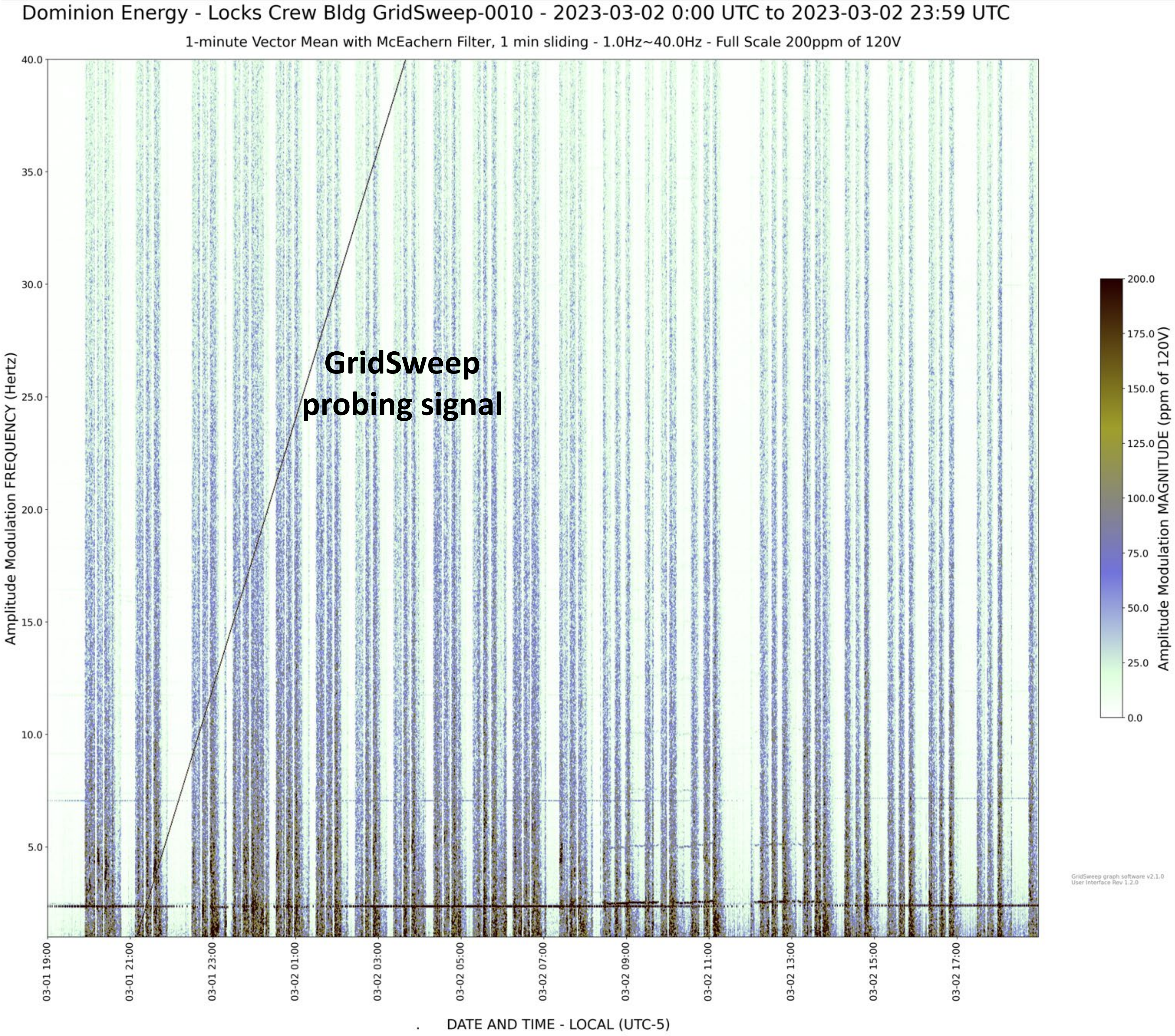
New DOE GridSweep® Instrument

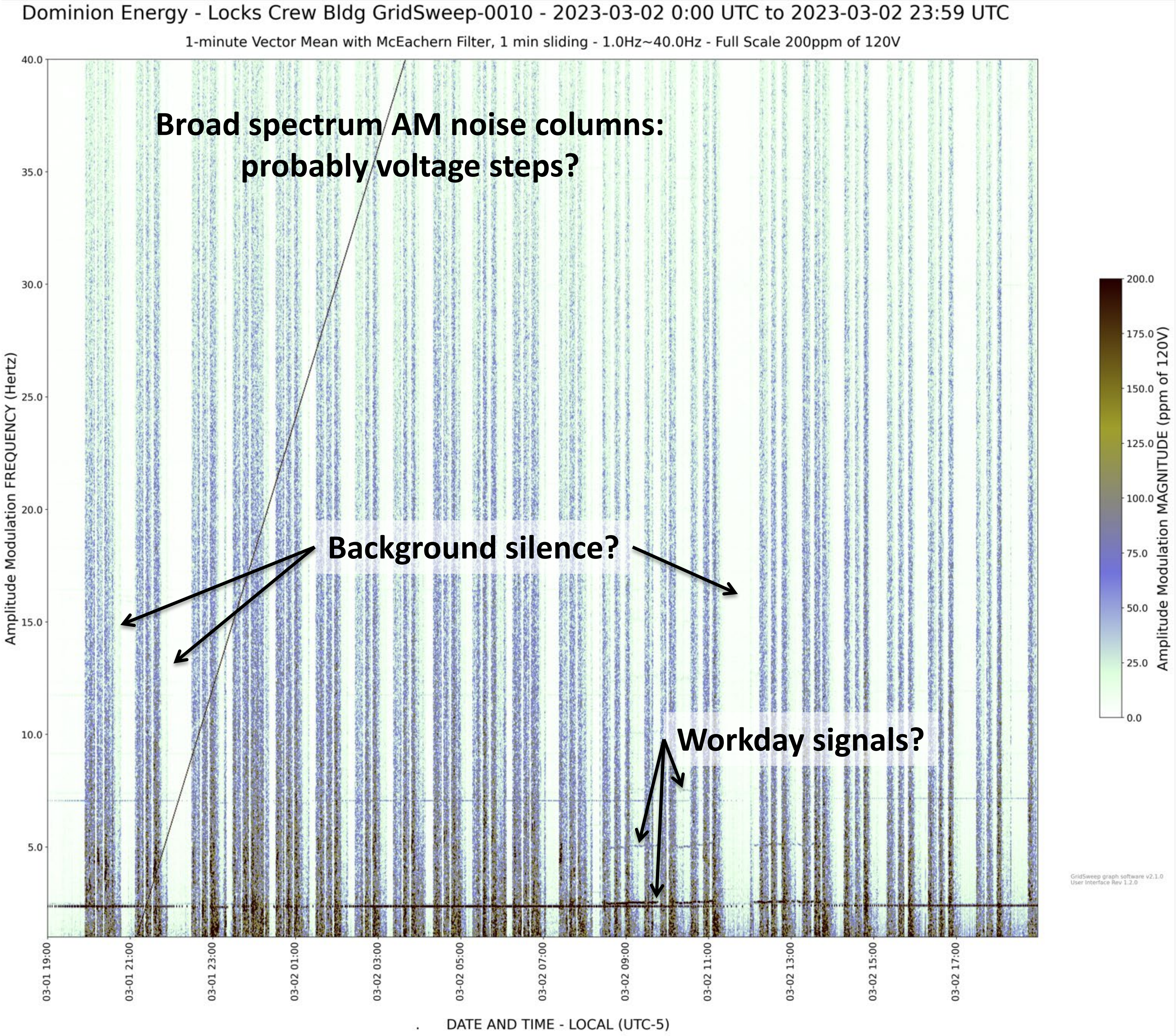
- Research instrument for **subsynchronous resonance risk** on grids.
- Probes grid with current: 0.1Hz – 40.0 Hz amplitude-modulated 60 Hz.
- Measures voltage response at a different location on the grid.
- Parts-per-billion voltage resolution (100,000 times more precise than the very best meters)



Derived from original drawing by Paul Ortmann, Idaho Power

Early stage deployments at Hawaiian Electric, Idaho Power, Dominion Energy, etc.


Dominion Energy - Locks Crew Bldg GridSweep-0010 - 2023-03-02 0:00 UTC to 2023-03-02 23:59 UTC
1-minute Vector Mean with McEachern Filter, 1 min sliding - 1.0Hz~40.0Hz - Full Scale 200ppm of 120V
Amplitude Modulation FREQUENCY (Hertz)
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
GridSweep
probing signal
03-01 19:00
03-01 21:00
03-01 23:00
03-02 01:00
03-02 03:00
03-02 05:00
03-02 07:00
03-02 09:00
03-02 11:00
03-02 13:00
03-02 15:00
03-02 17:00
DATE AND TIME - LOCAL (UTC-5)
Amplitude Modulation MAGNITUDE (ppm of 120V)
200.0
175.0
150.0
125.0
100.0
75.0
50.0
25.0
0.0
GridSweep graph software v2.1.0
User Interface Rev 1.2.0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1-minute Vector Mean with McEachern Filter, 1 min sliding - 1.0Hz~40.0Hz - Full Scale 200ppm of 120V
Broad spectrum AM noise columns: probably voltage steps?
Background silence?
Workday signals?
Amplitude Modulation FREQUENCY (Hertz)
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
03-01 19:00
03-01 21:00
03-01 23:00
03-02 01:00
03-02 03:00
03-02 05:00
03-02 07:00
03-02 09:00
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200.0
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User Interface Rev 1.2.0

Early Practical Takeaways: GridSweep® Project

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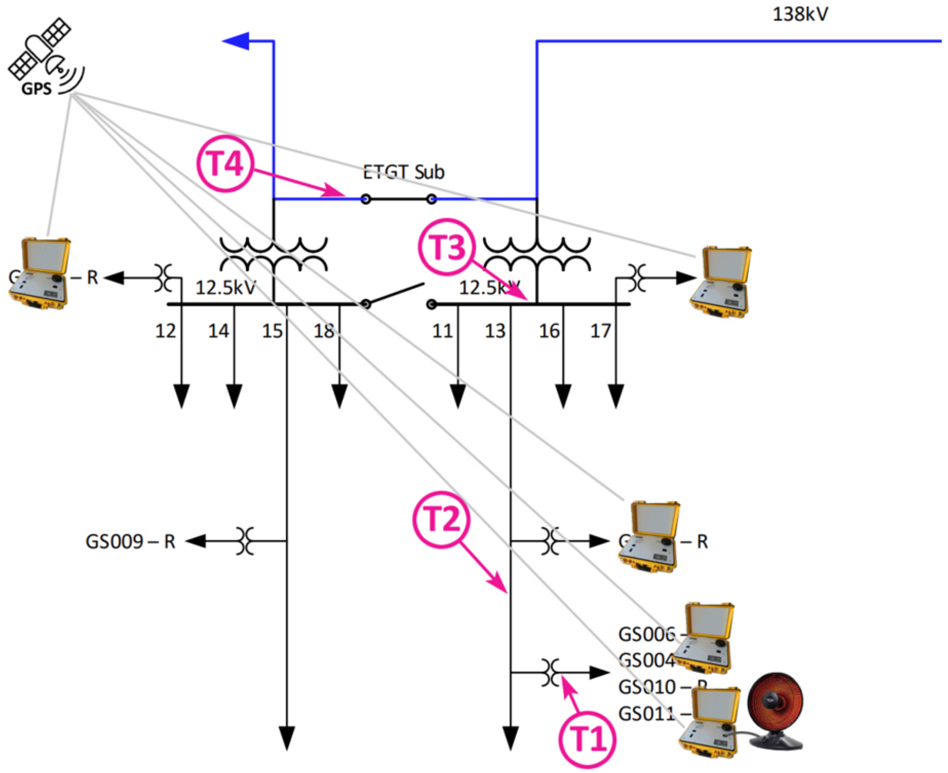
U.S. Department of Energy

- Research in progress now.
- IBR population oscillation risks need to be understood.
- Risk of sub-60-Hz oscillation can be measured via frequency source impedance
- Distribution grid characteristics can be measured from 120V outlets.
  - Real-time Bulk grid parameters may be measurable from 120V outlets...
- Consider this population stability risk in IBR standards?
- Awareness of risk: intentionally-provoked oscillations
  - Population-of-loads vector?
  - Phase related defenses



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Questions?