Ultrafast Frequency Response of Converter-Dominant Grids Using PMUs

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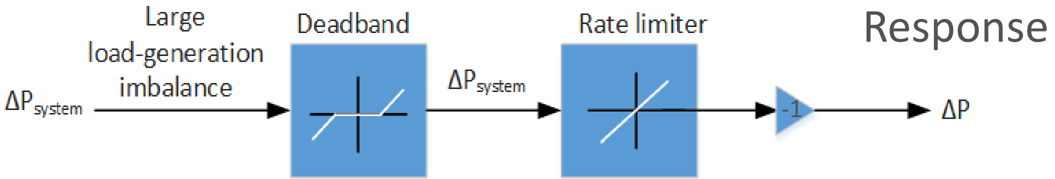
What Is Fast Frequency Response?

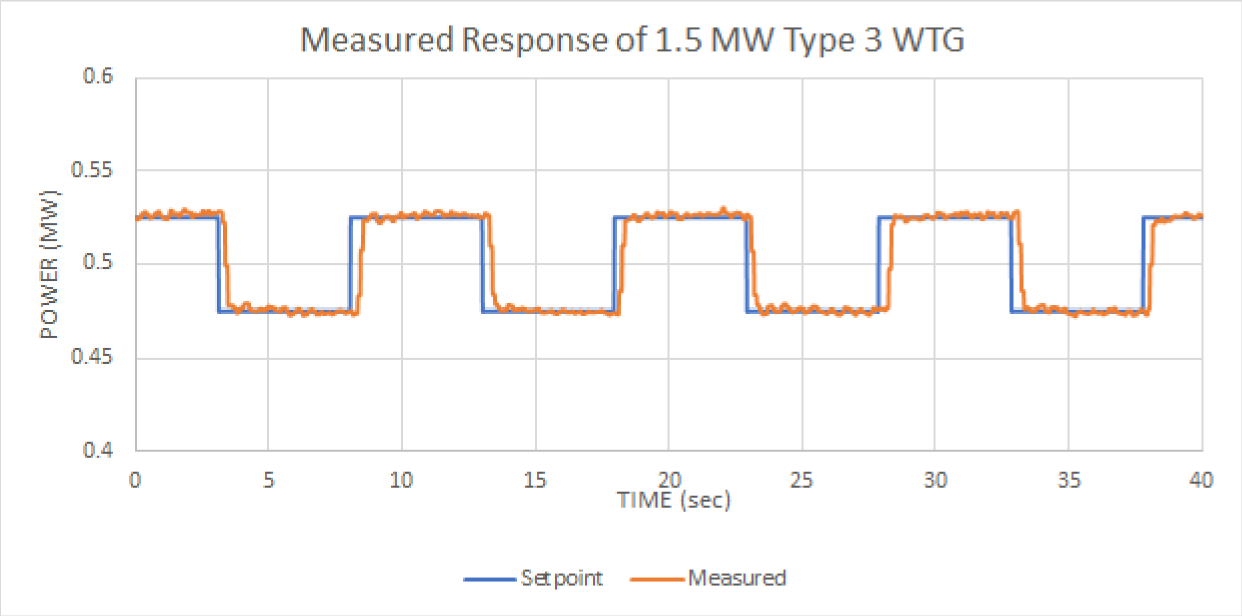
- An alternative method to achieving faster compensation to load-generation imbalances resorts to detecting the amount of a disturbance that triggers a frequency transient.
- We propose a control strategy to deploy ultrafast frequency response (FFR) converter-based assets. The objective is to prevent relatively large frequency transients by counteracting the impact of sudden imbalances on an electric grid.
- FFR: tens of milliseconds.

Inertia | FFR | Droop | AGC

$$P_{bess}(t) = P_o(t) - 2H\frac{df(t)}{dt} + \Delta P_{FFR}(t) - \frac{f_o - f(t)}{droop} + \Delta P_{AGC}(t)$$



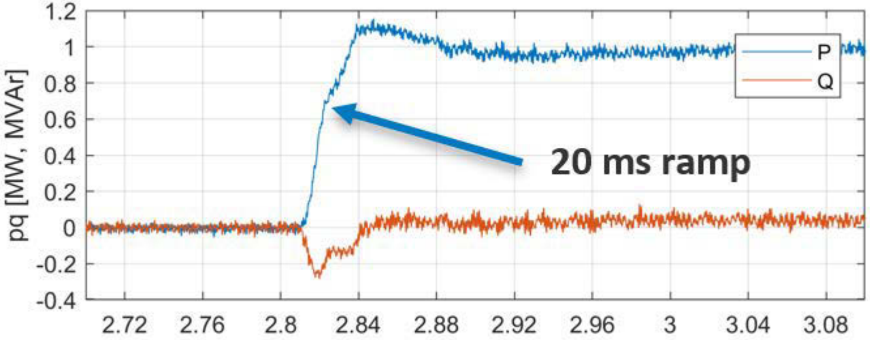
Active Power Response of Type 3 Wind Turbine Generator



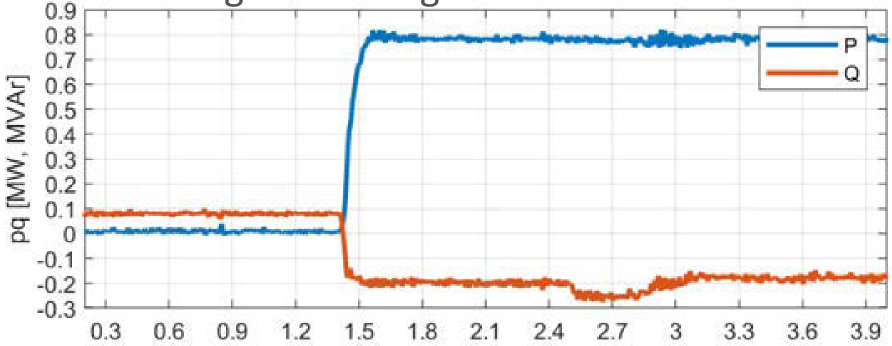
- This test was conducted with a commercial wind power plant controller.
- All plant-level and turbine-level control delays are real.

Ability of Battery Energy Storage System to Provide Fast Frequency Response

Battery energy storage system (BESS) active and reactive power in grid-following mode



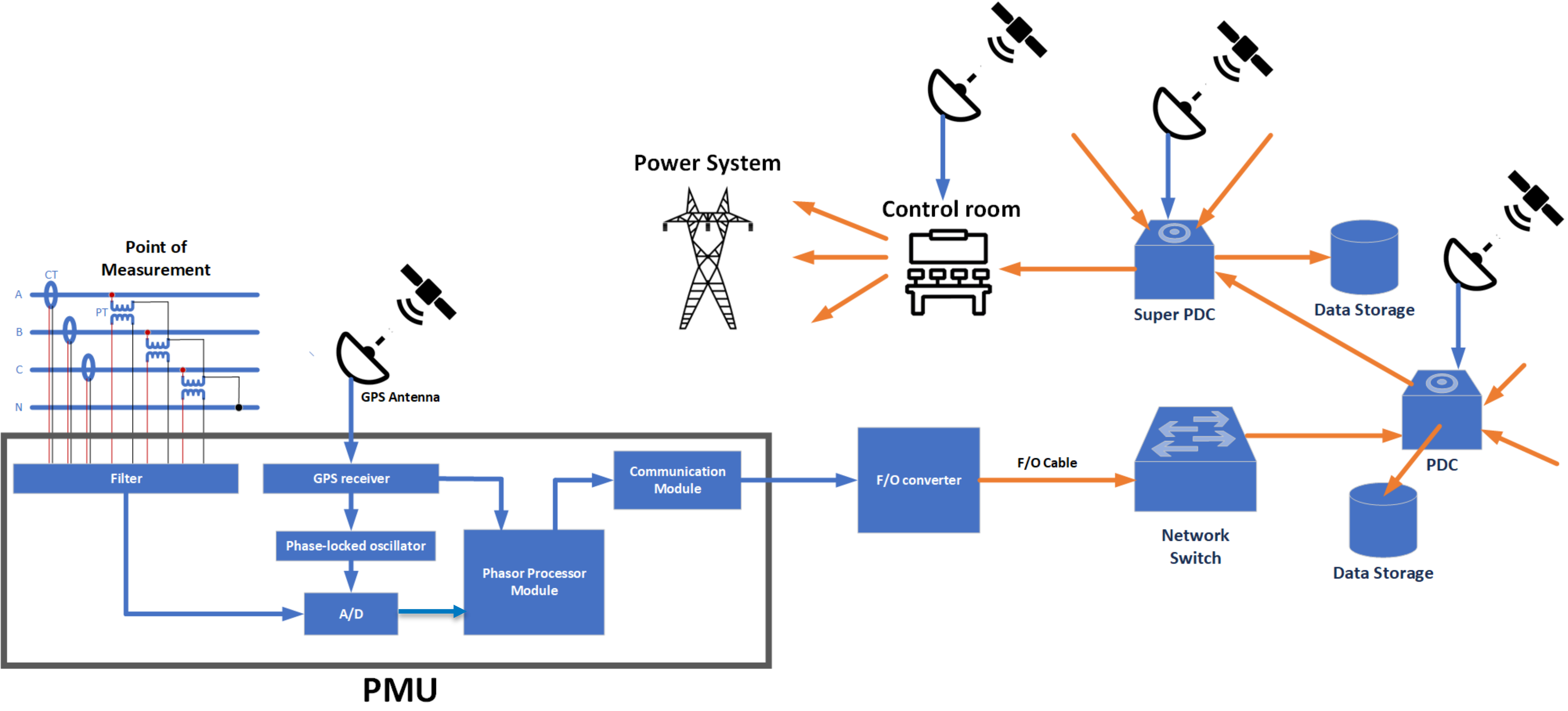
BESS active and reactive power in grid-forming mode



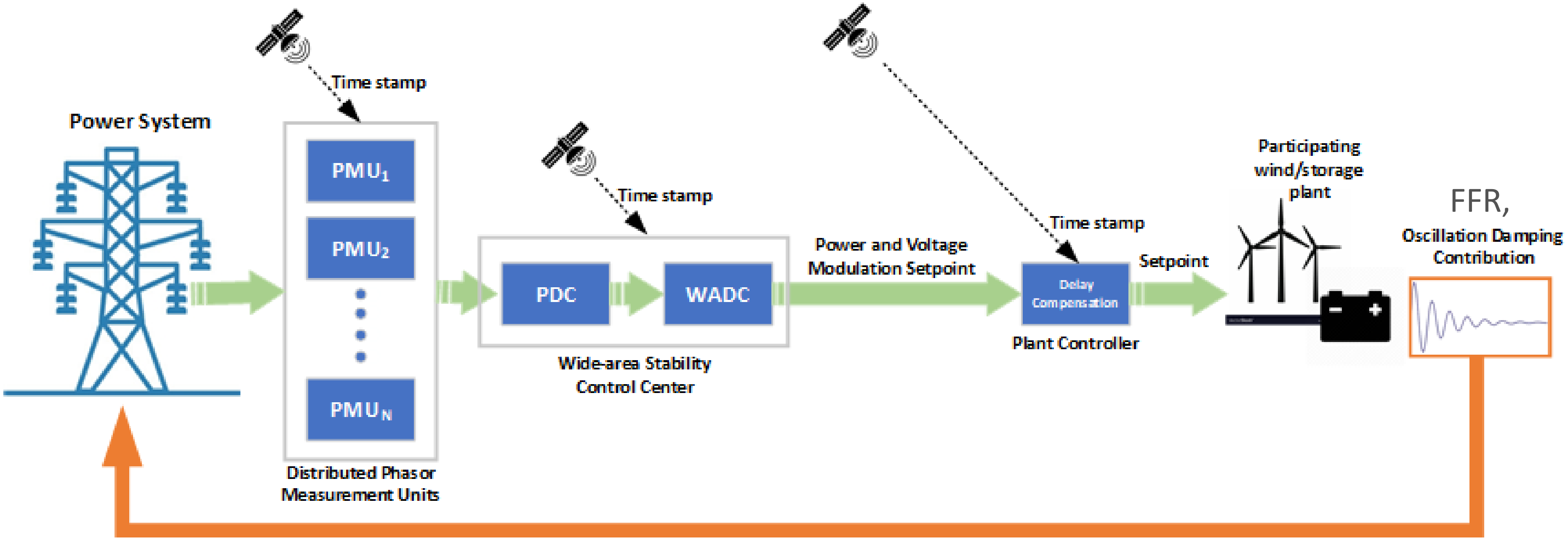
1-MW/1-MWh BESS at NREL test site

Photo by NREL

Phasor Measurement Unit Networks Embedded in Power Systems



Phasor Measurement Unit-Based Wide-Area Stability Control Concept



NREL Flatirons Campus

- Total of 12+ MW variable renewable generation currently
- 7-MVA controllable grid interface (CGI)
- Multimegawatt energy storage test facility
- 2.5-MW and 5-MW dynamometers (industrial motor drives)
- 13.2-kV medium-voltage grid
- 1.5-MW total photovoltaic (PV) capacity.

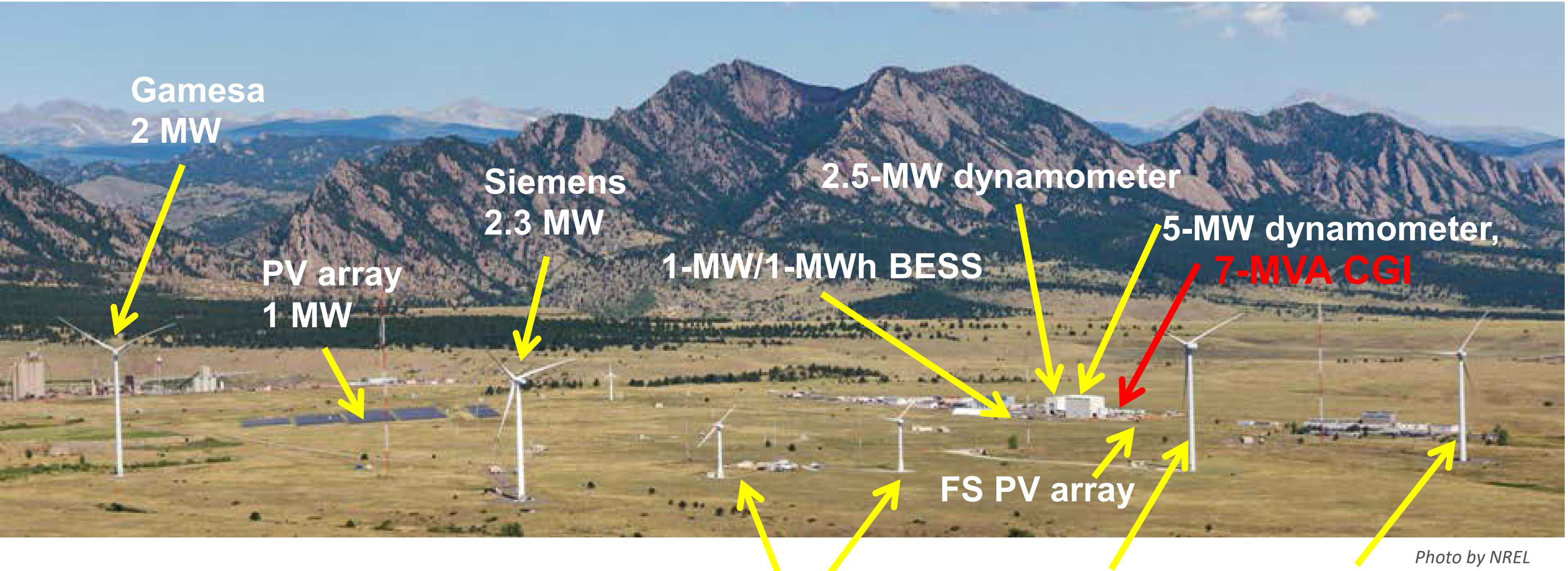


Photo by NREL

National Wind Technology Center Controllable Grid Platform

Flexible test bed for many black-start schemes

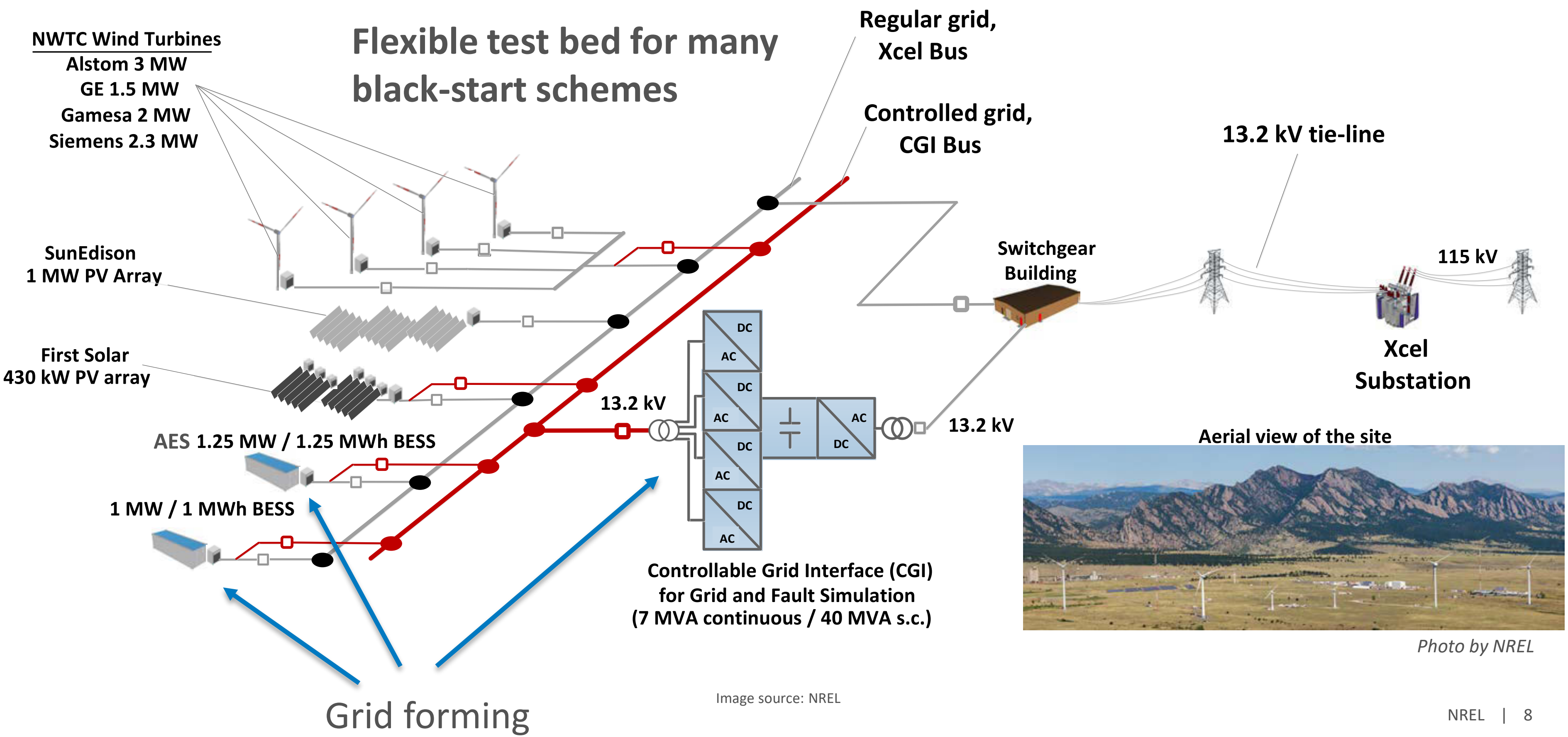
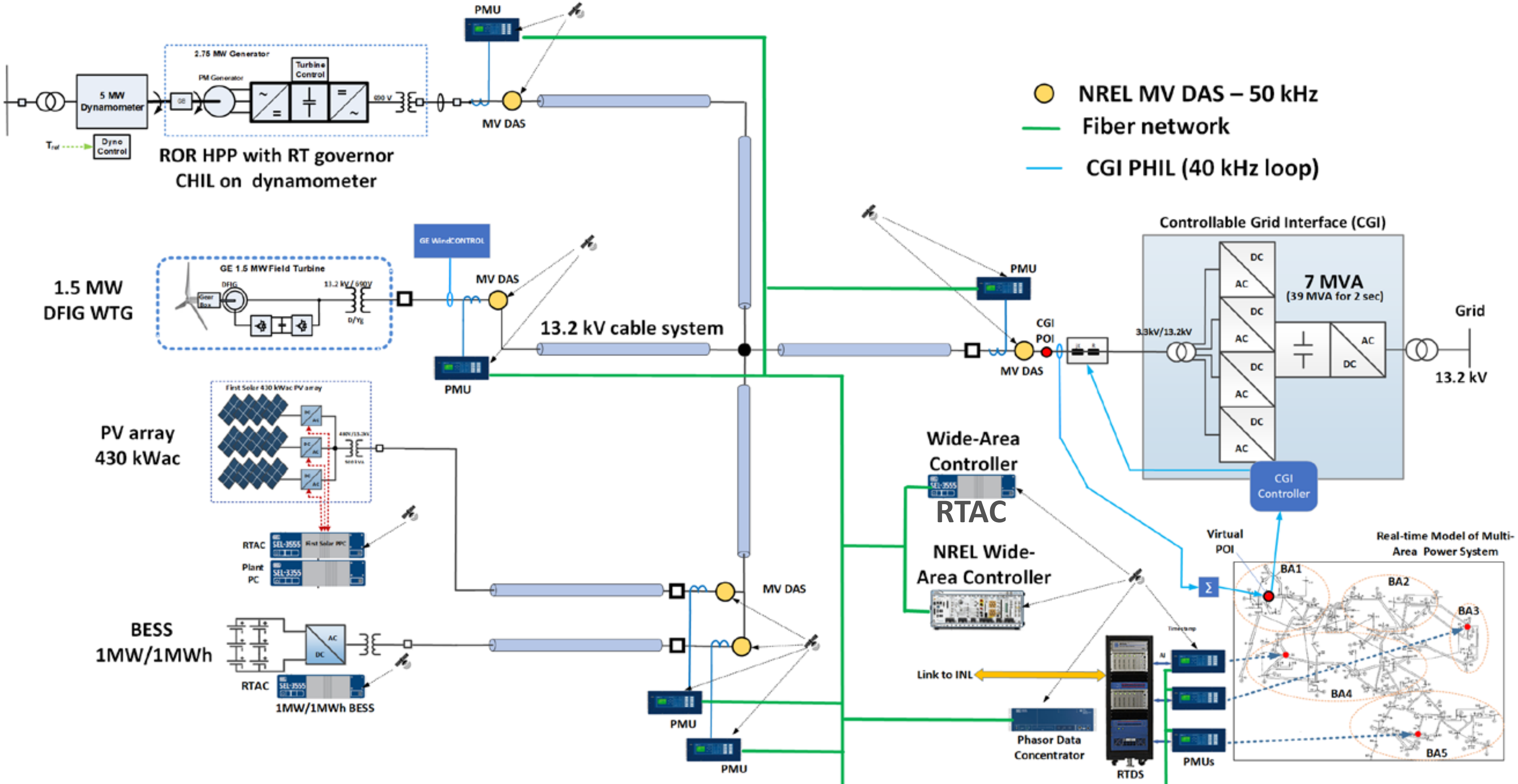


Image source: NREL

Aerial view of the site

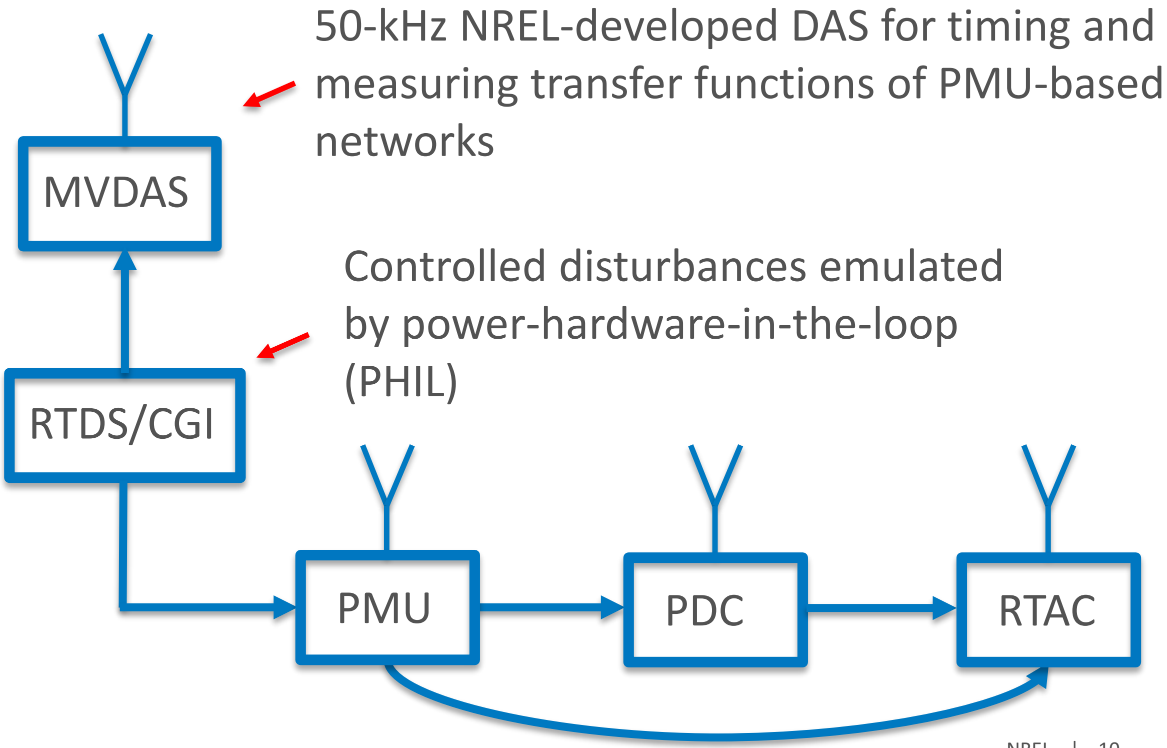
Photo by NREL

NREL's Advanced Test Bed for Wide-Area Stability Controls Validation

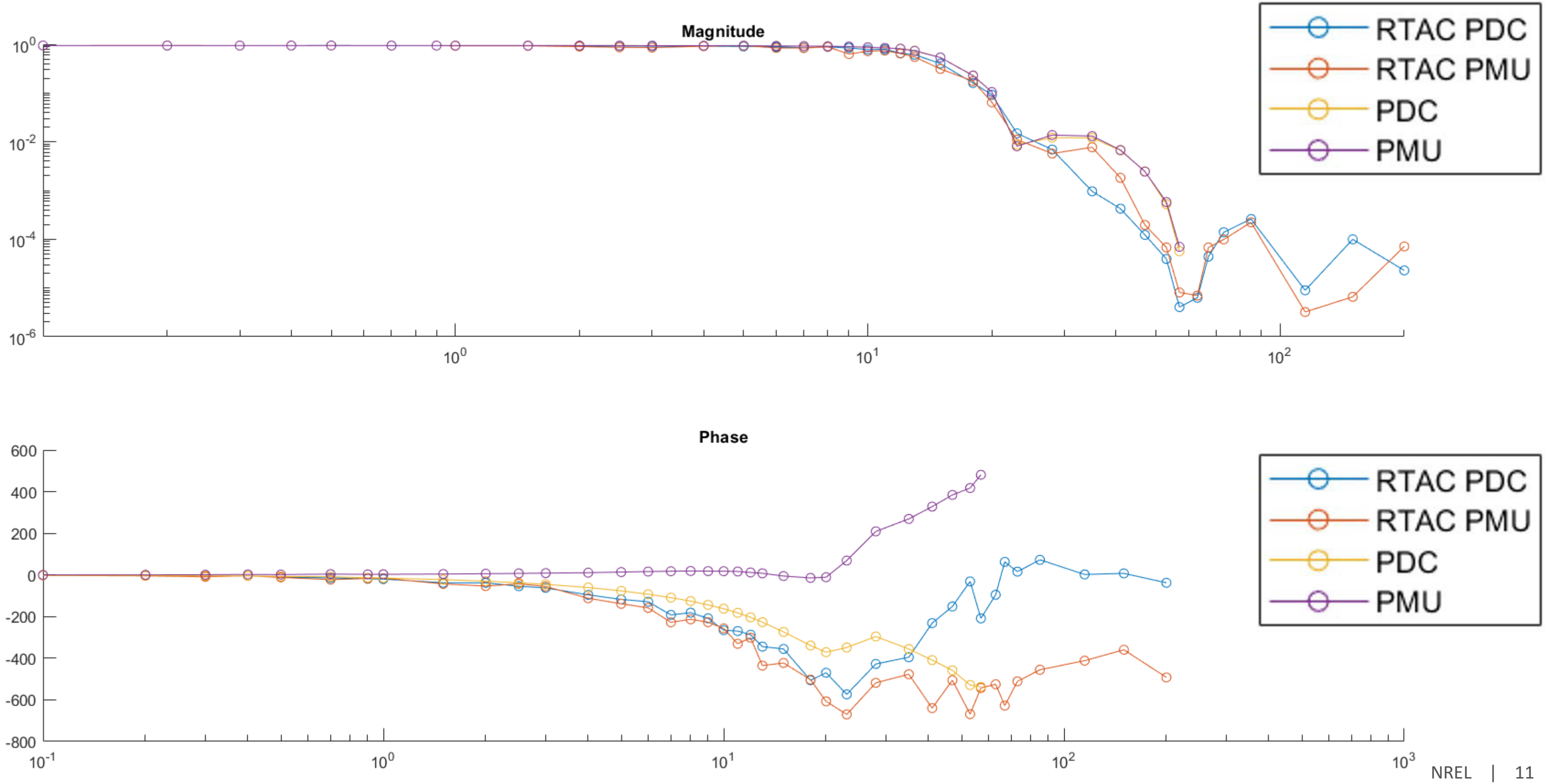


Phasor Measurement Unit-Based System Characterization Test Setup

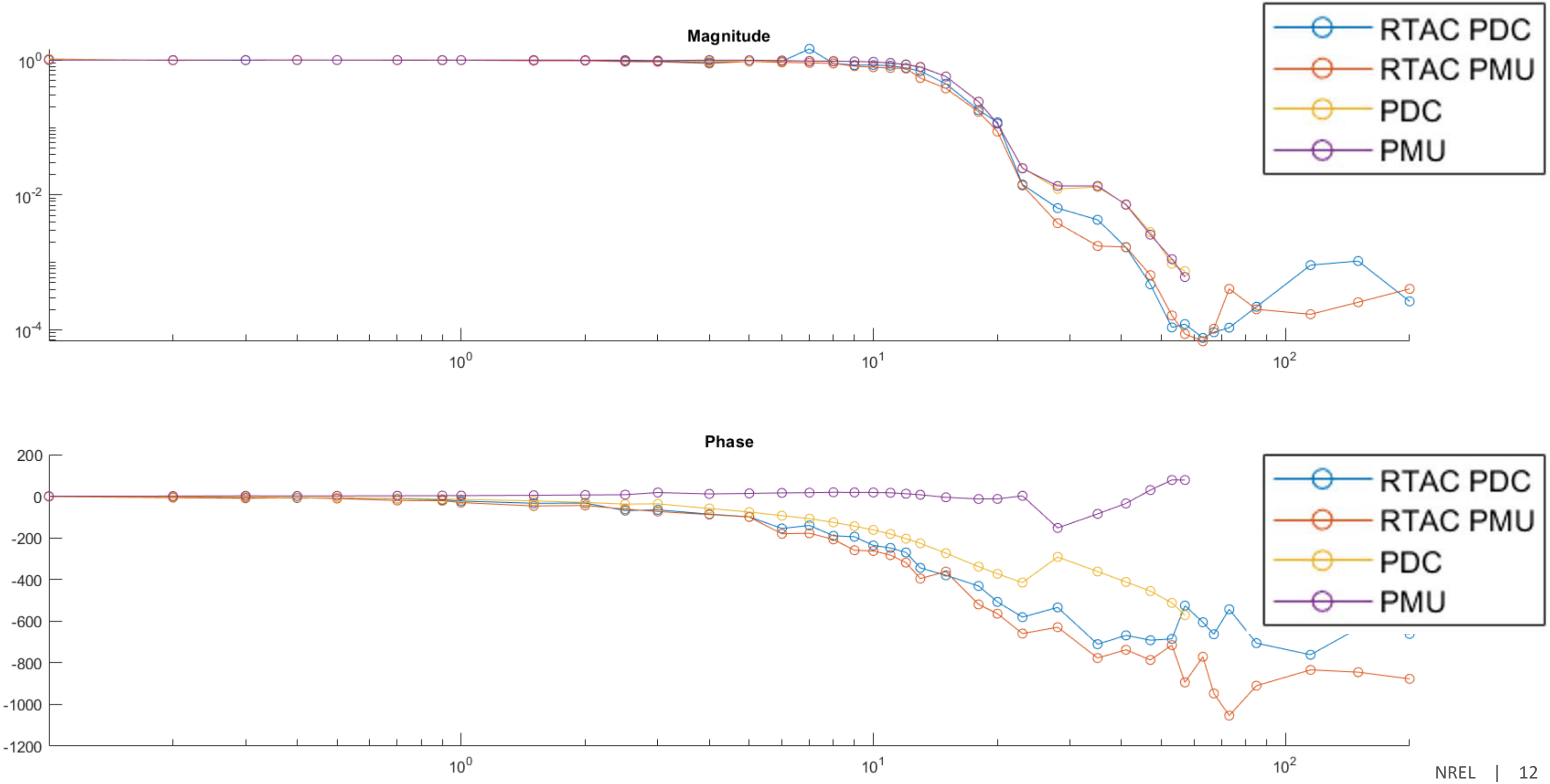
- GPS clock synchronization across all devices
- CGI voltage, angle, frequency perturbation injection through RTDS
- Perturbation captured on MVDAS and phasor measurement unit (PMU)
- Synchrophasor data paths
  - PMU to RTAC
  - PMU to PDC
  - PDC to RTAC.
- Time-align all synchrophasors to MVDAS capture.



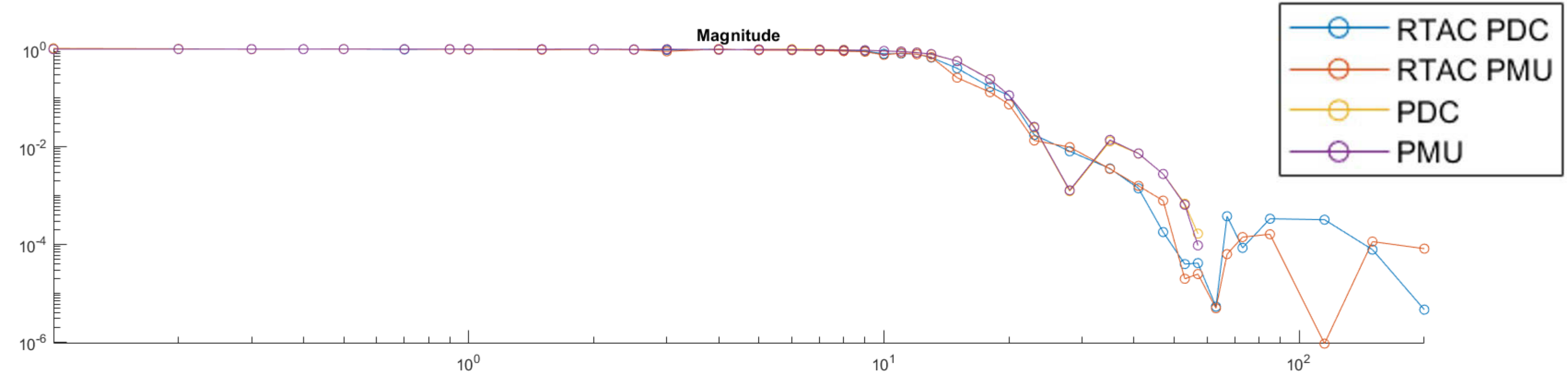
Transfer Function: 5% Magnitude Injection

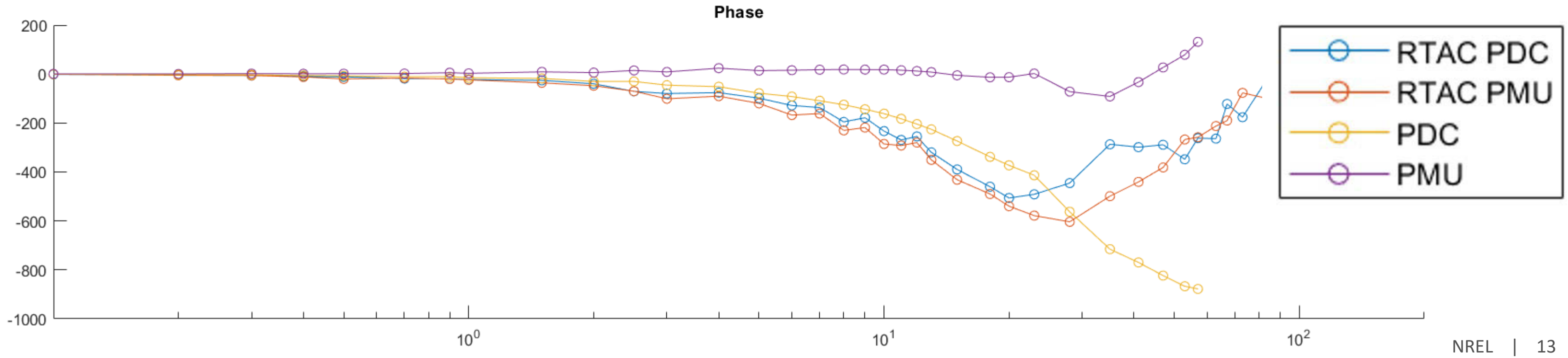


Transfer Function: 0.5-Hz Frequency Injection



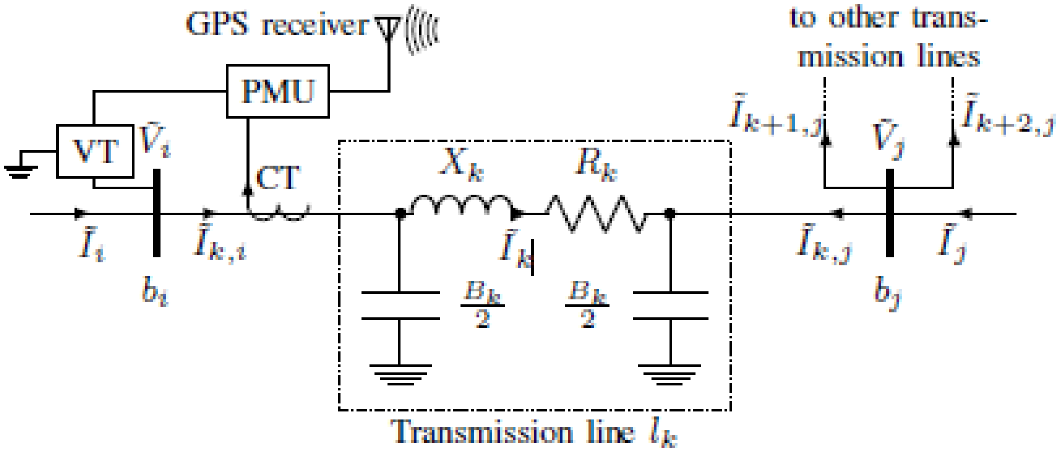
Transfer Function: 0.1 Rad Angle Injection





Power System Observability for Fast Frequency Response

Bulk transmission system and PMU placement problem

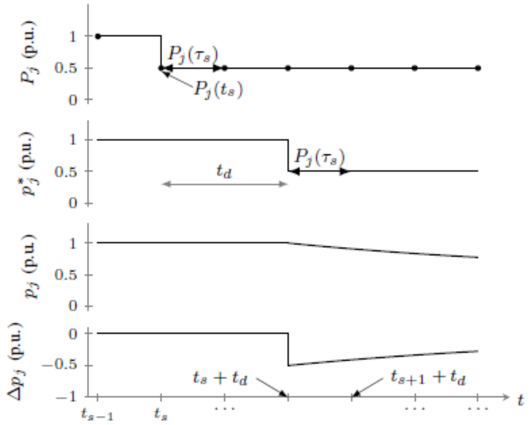


$$\begin{aligned} \underset{x_1,\ldots,x_k,\ldots,x_M}{\text{minimize}} \quad & \sum_{k=1}^{M} x_k \\ \text{subject to} \quad & Ax \geq 1 \\ & x_k \in \{0,1\},\ k = 1,\ldots,M \end{aligned}$$

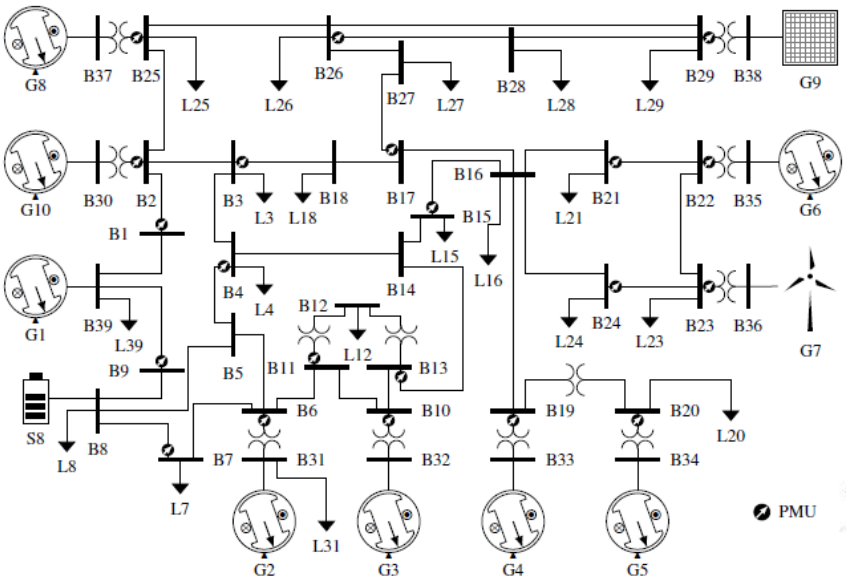
Constraint Ax ≥ 1 ensures that every bus voltage becomes observable via measurement or estimation when placing the PMUs.

Solution ensures that all positive-sequence bus voltages, and the currents leaving a bus, become available at a phasor data concentrator facility by direct measurement and/or estimation.

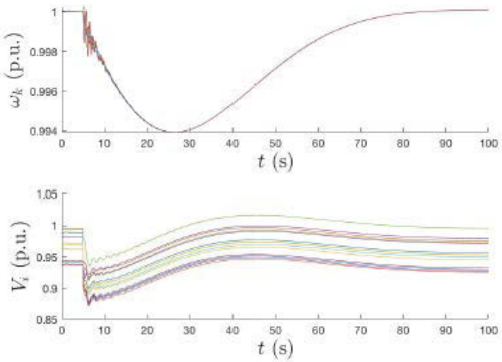
Load-generation disturbance detection dynamics



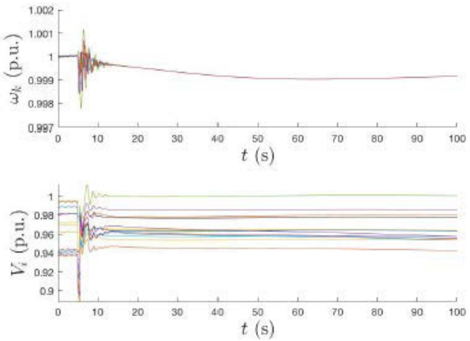
IEEE 39-bus test system



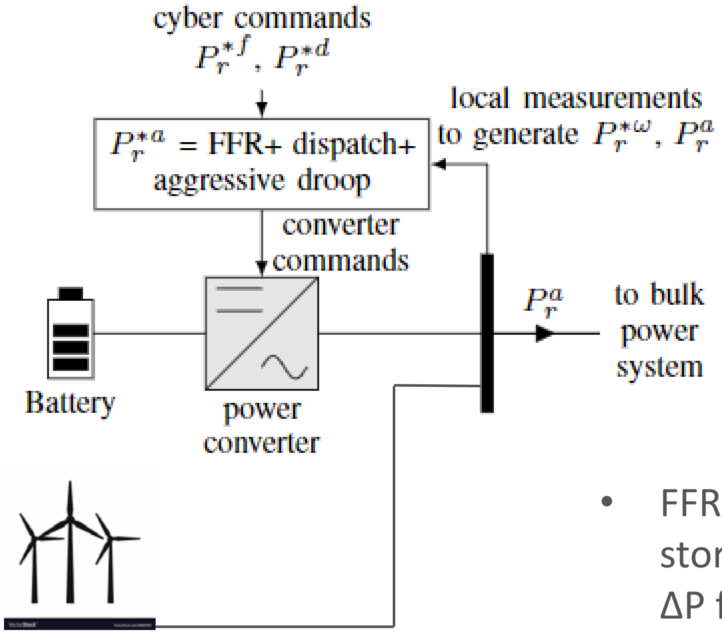
No PMU-based FFR controls

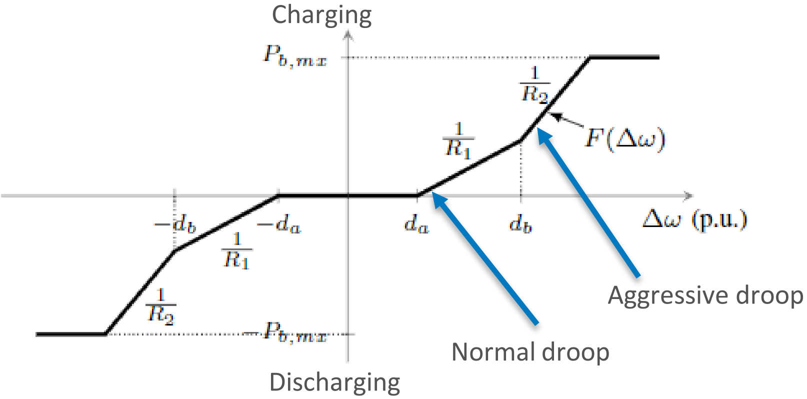


With PMU-based FFR controls



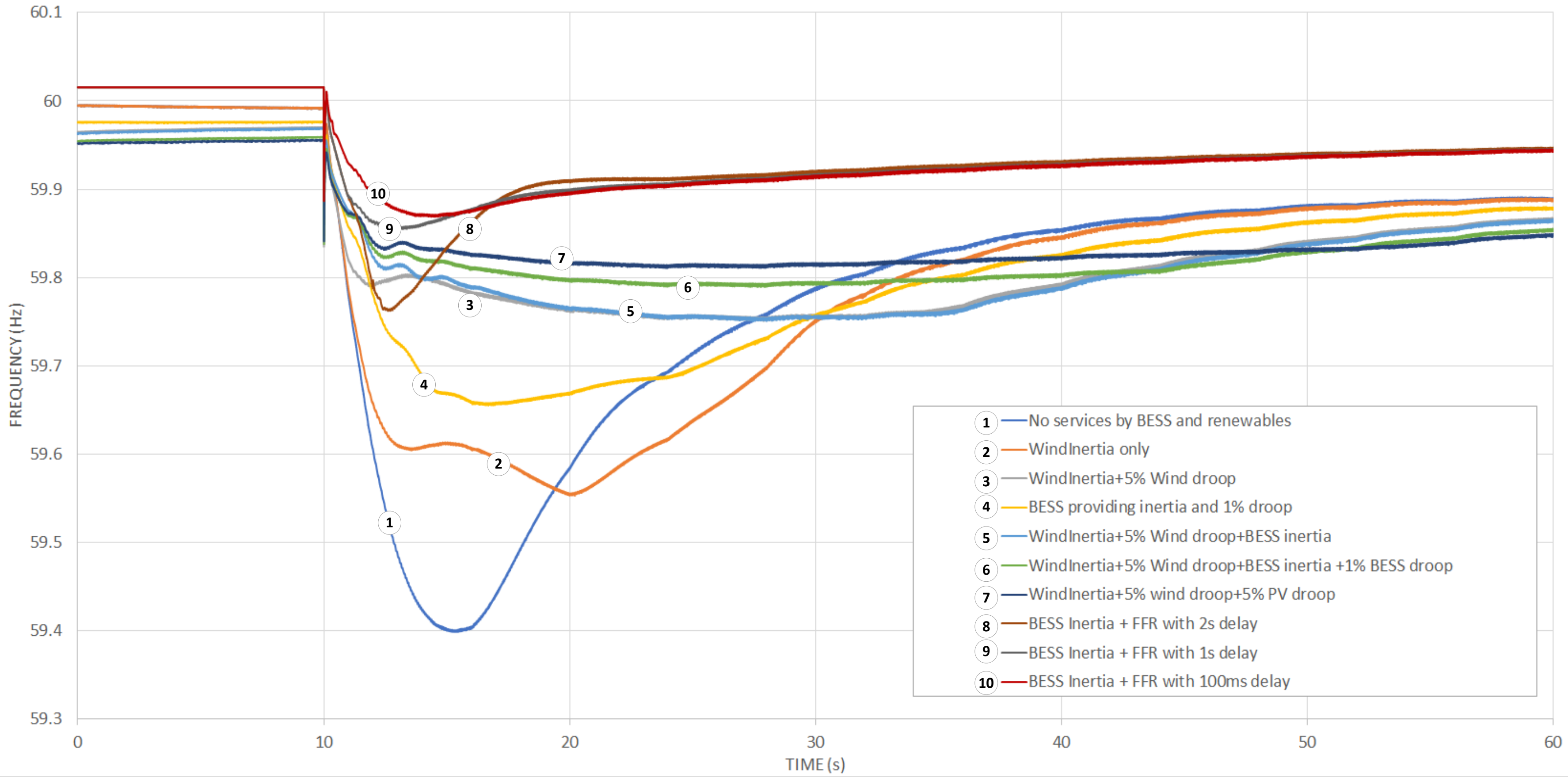
Fast Frequency Response and Backup Option



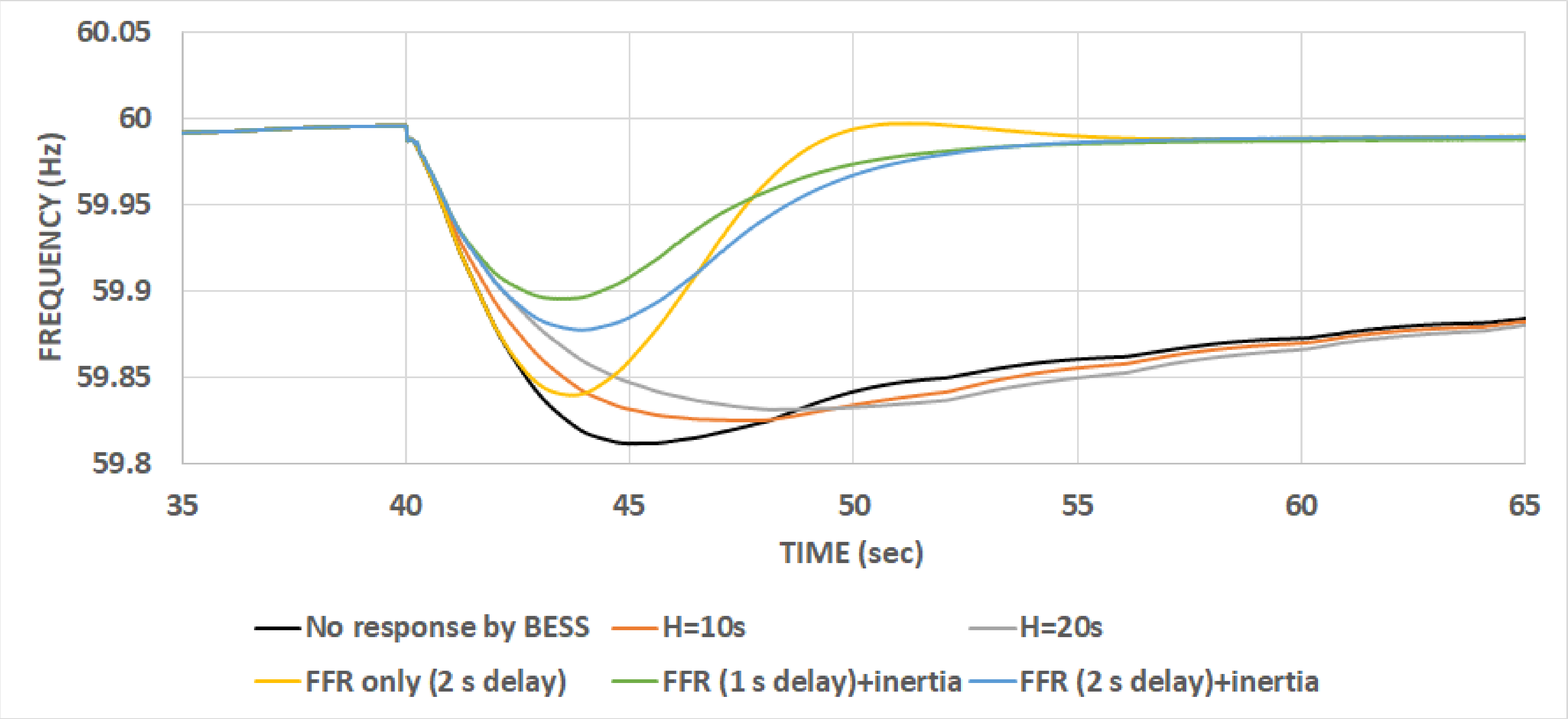


- FFR response is dispatched to participating wind and storage plants based on estimated generation or load loss ΔP from PMU-based algorithm.
- If accuracy of PMU-based measurements is compromised (communications loss or cyberattack), then local aggressive droop control will kick in as a backup response.

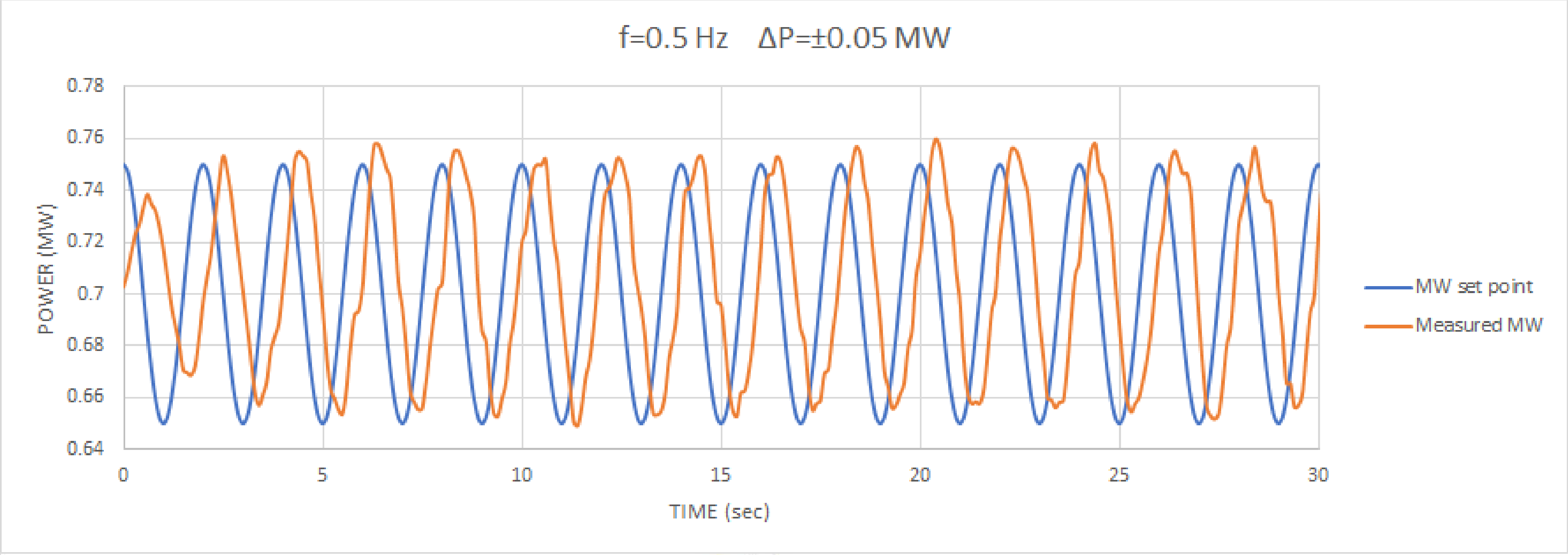
Frequency Response of an Island System



Results of PHIL Experiment Using Fast Frequency Response by Battery Energy Storage System

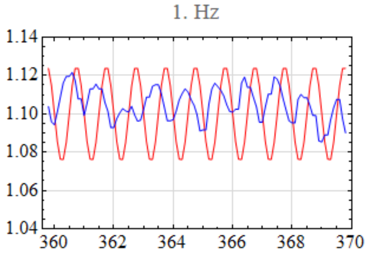


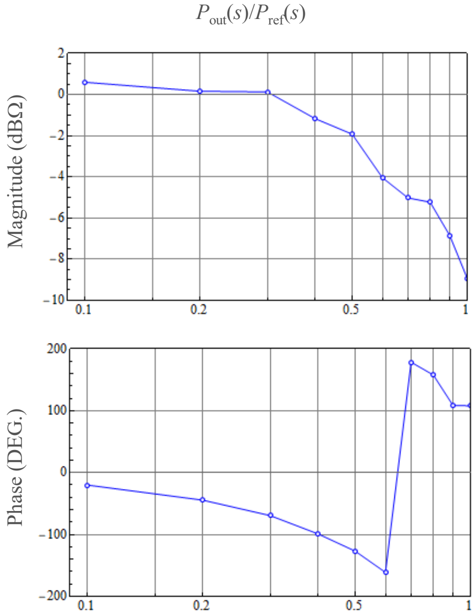
1.5-MW Wind Turbine Generator Active Power Modulation (25 kW pk-to-pk)



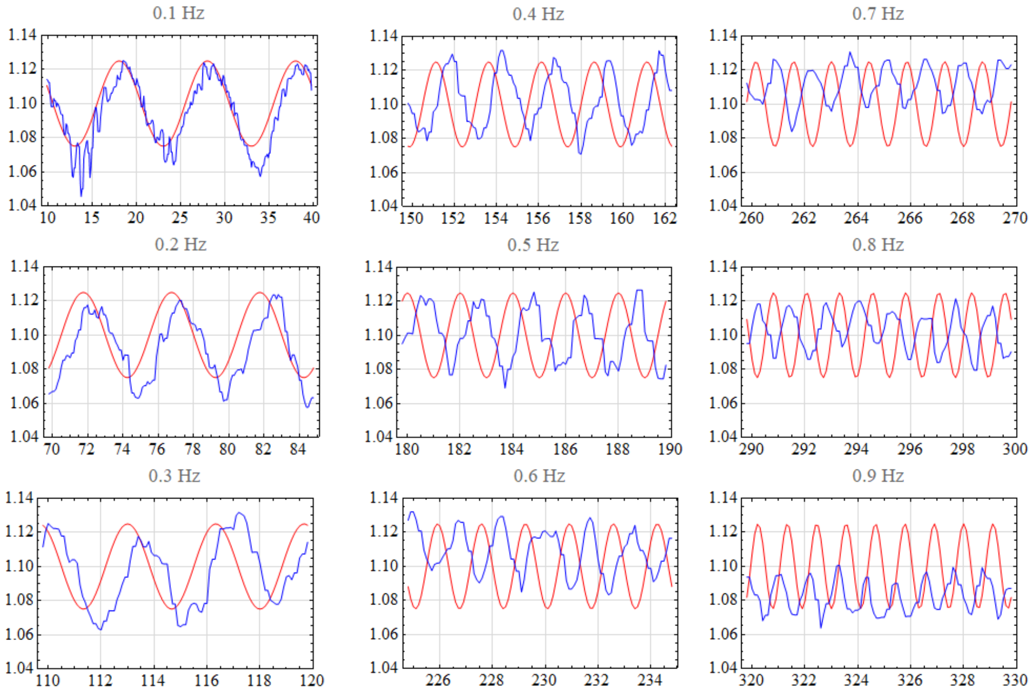
Transfer Function Analysis

- Transfer function for active power has been identified
- Stable amplitude response up to 0.3 Hz
- Phase delay is declining with oscillation frequency
- For higher oscillation frequencies, compensation technique can be applied.

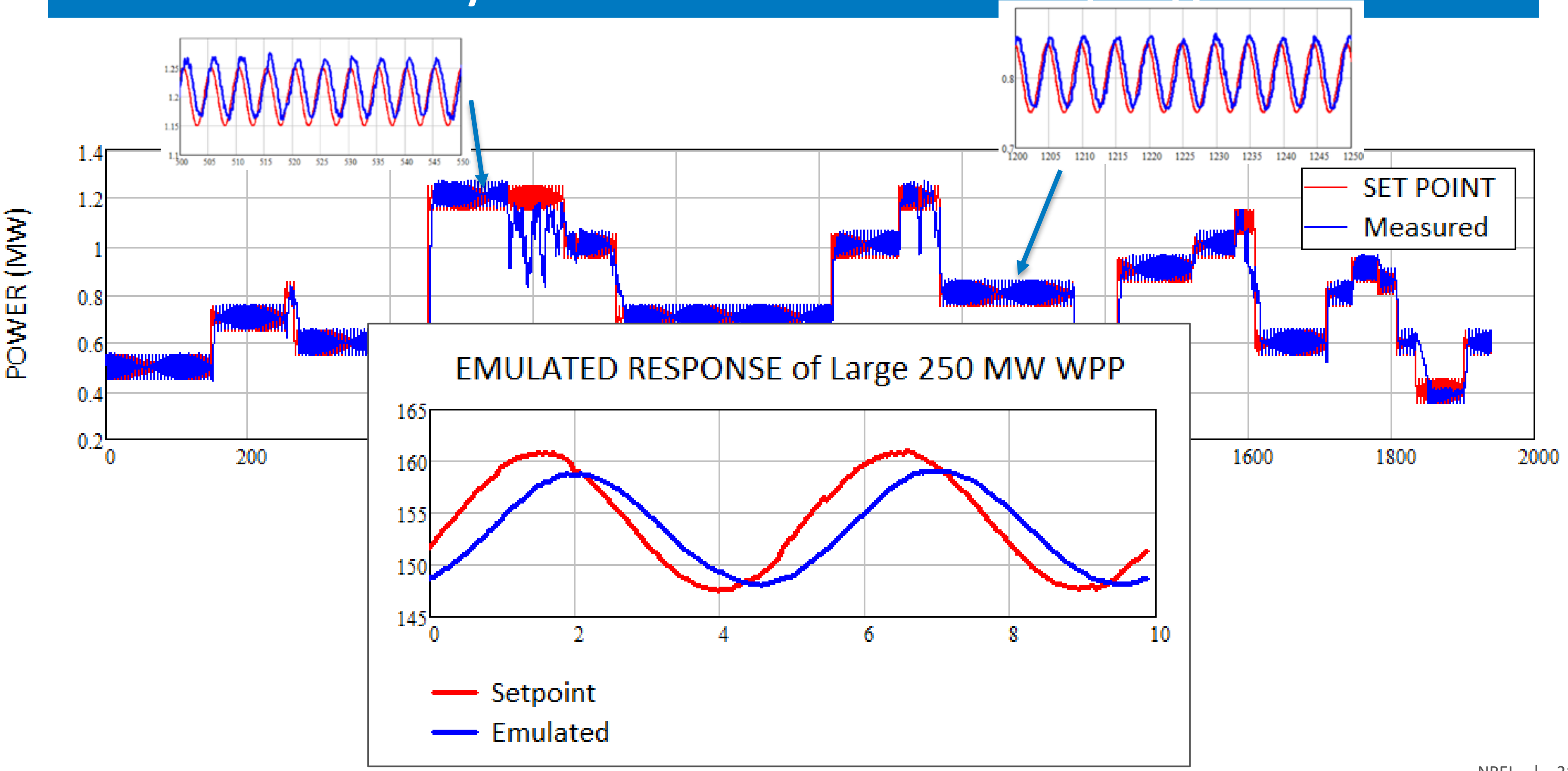




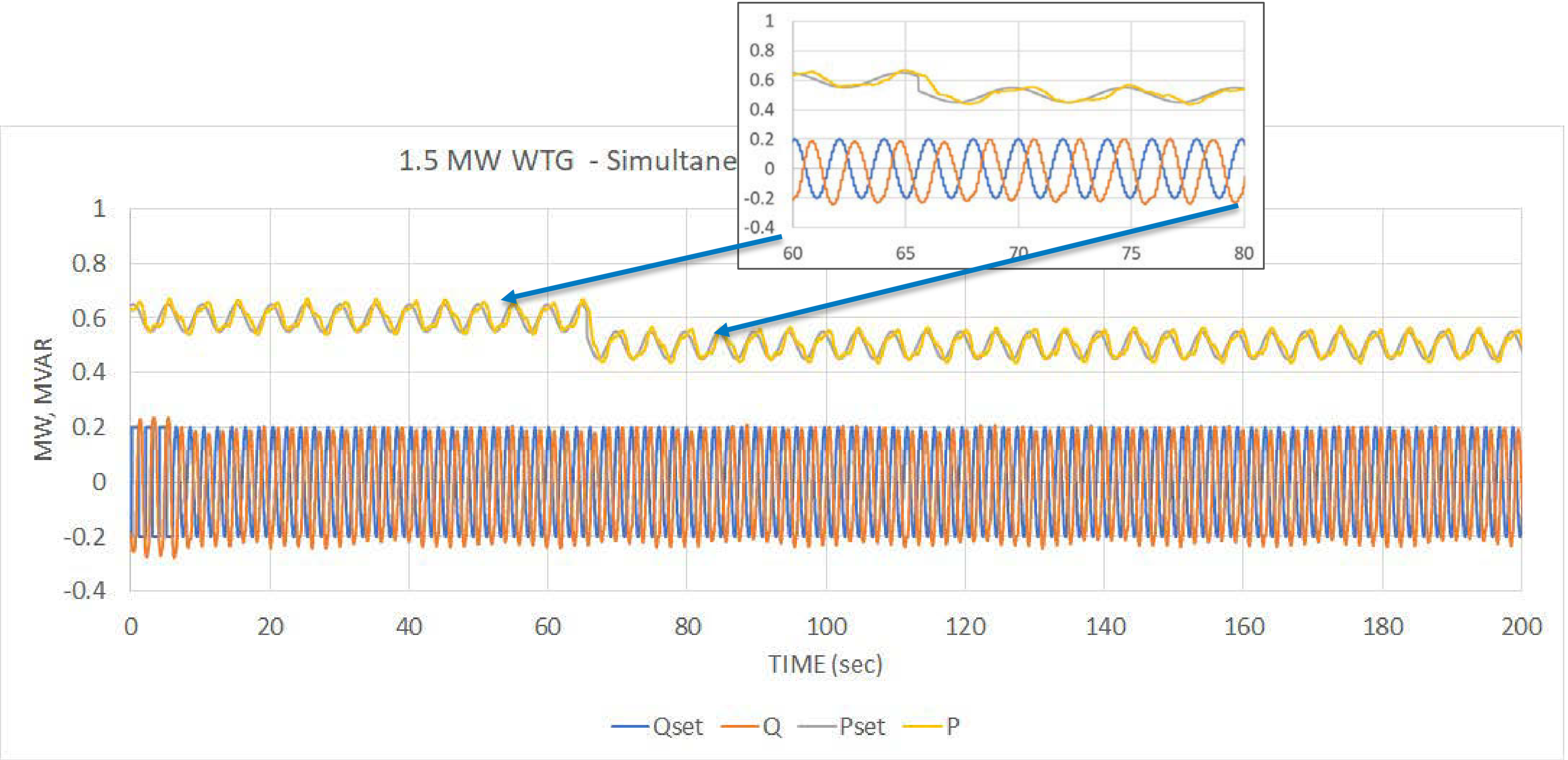
Time-domain captures for FFT analysis



Testing of 1.5-MW Type 3 Wind Turbine Generator for Power System Oscillation Damping Services



Ability of DFIG Wind Turbine Generator to Provide Simultaneous Modulation of P and Q



Conclusions and Future Plans

- Inverter-coupled resources are capable of providing FFR.
- PMU-based estimation of needed system-level FFR response is possible, but:
  - How can it be done in an optimal way?
  - How can it address the curtailment issue?
  - What is the optimal ratio between FFR and conventional droop resources?
  - FFR by grid-forming resources—still needs to be studied.
- Curtailed inverter-coupled resources have the potential for the provision of wide-area stability services using PMU-based controls as well.

Thank you!

Go raibh maith agat!

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