# Validation and Testing of Advanced Grid Services by Inverter-Coupled Resources

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November 12, 2019

# Outline

- Introduction
- Description of advanced testing capabilities
- Results from various research projects
- Conclusions

# NREL Mission, Long-Term Strategy, and Vision

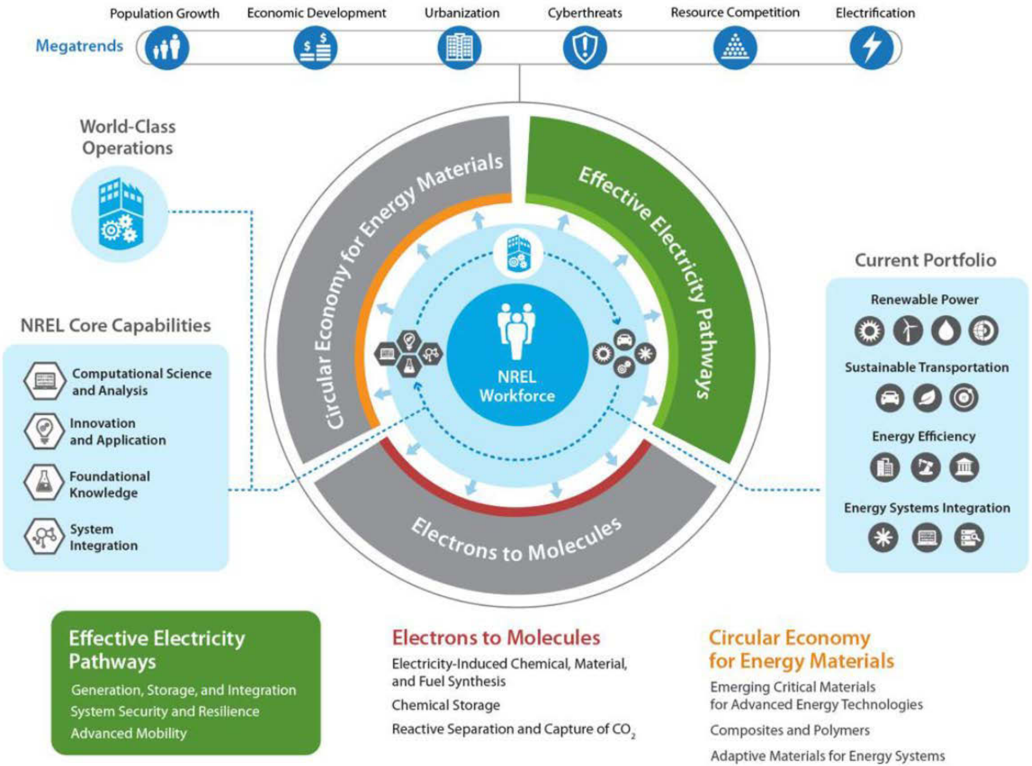
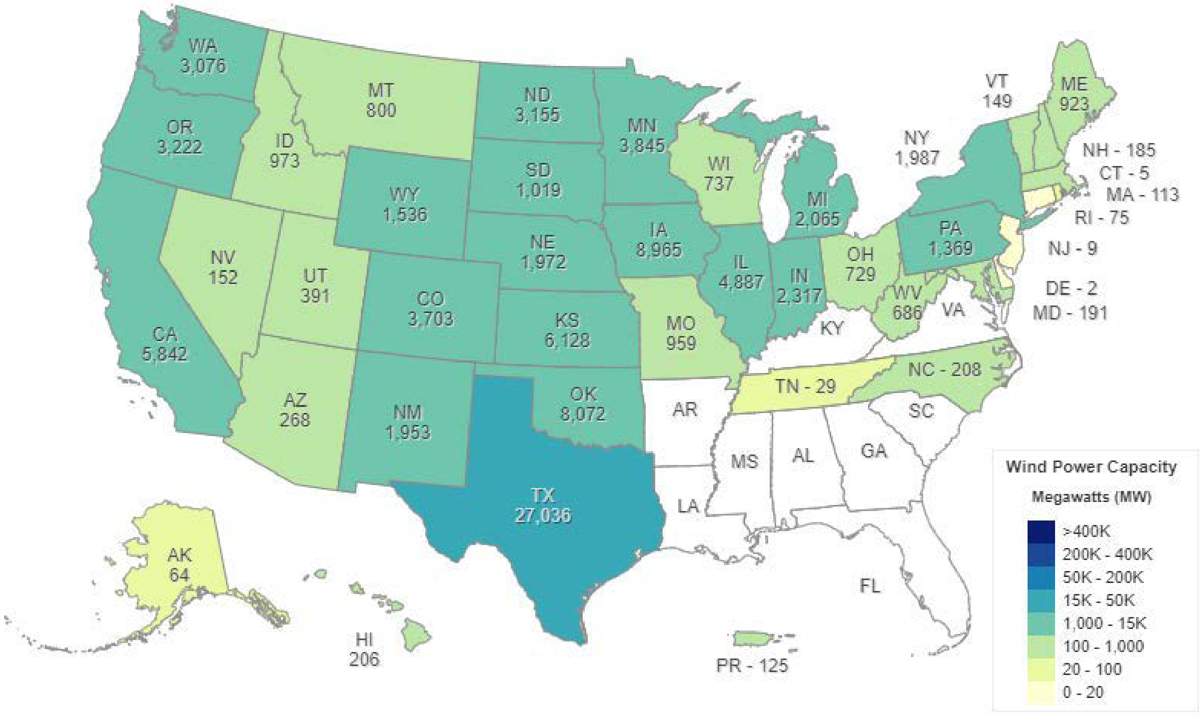



*Photo by NREL*

NREL advances the science and engineering of energy-efficiency, sustainable transportation, and renewable power technologies and provides the knowledge to integrate and optimize energy systems.

*Photo by NREL*

# U.S. Wind Power Installed Capacity by State




Total Installed Wind Capacity: 100,128 MW

Source: https://windexchange.energy.gov/maps-data/321

# Vision

## Wind energy could supply **20%** of the U.S. electrical demand by **2030.**

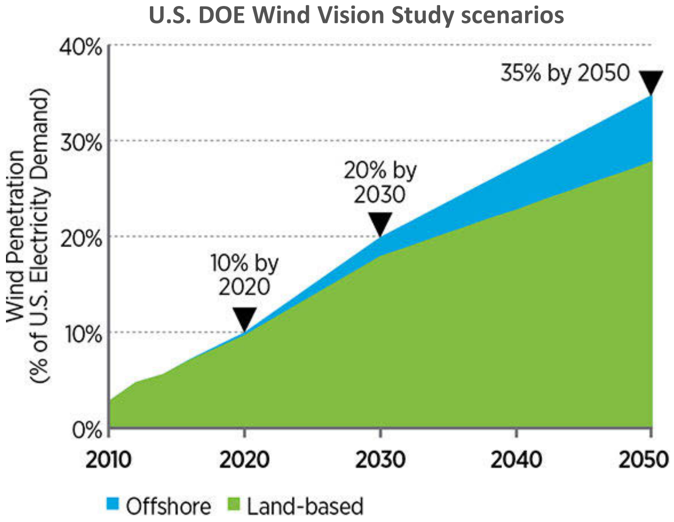
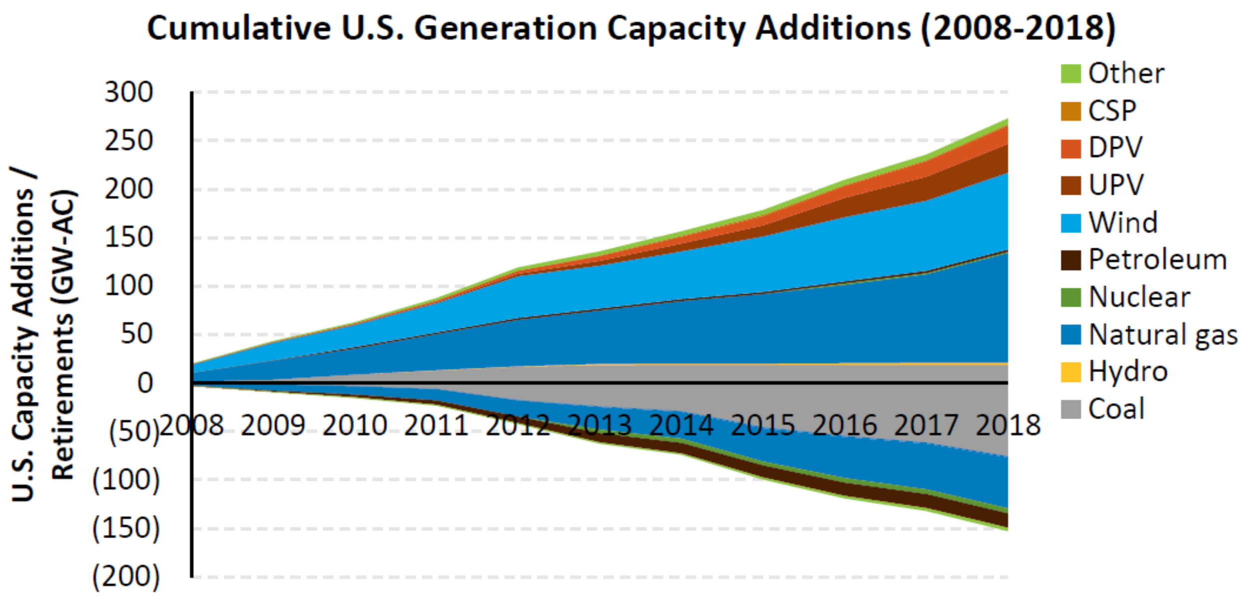
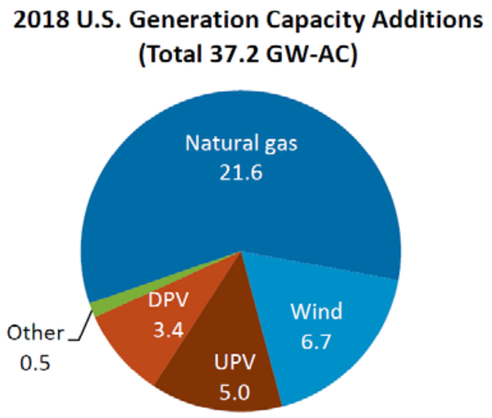



*Photo by Dennis Schroeder, NREL*

*Photo by Dennis Schroeder, NREL*

# New U.S. Electricity Capacity Additions



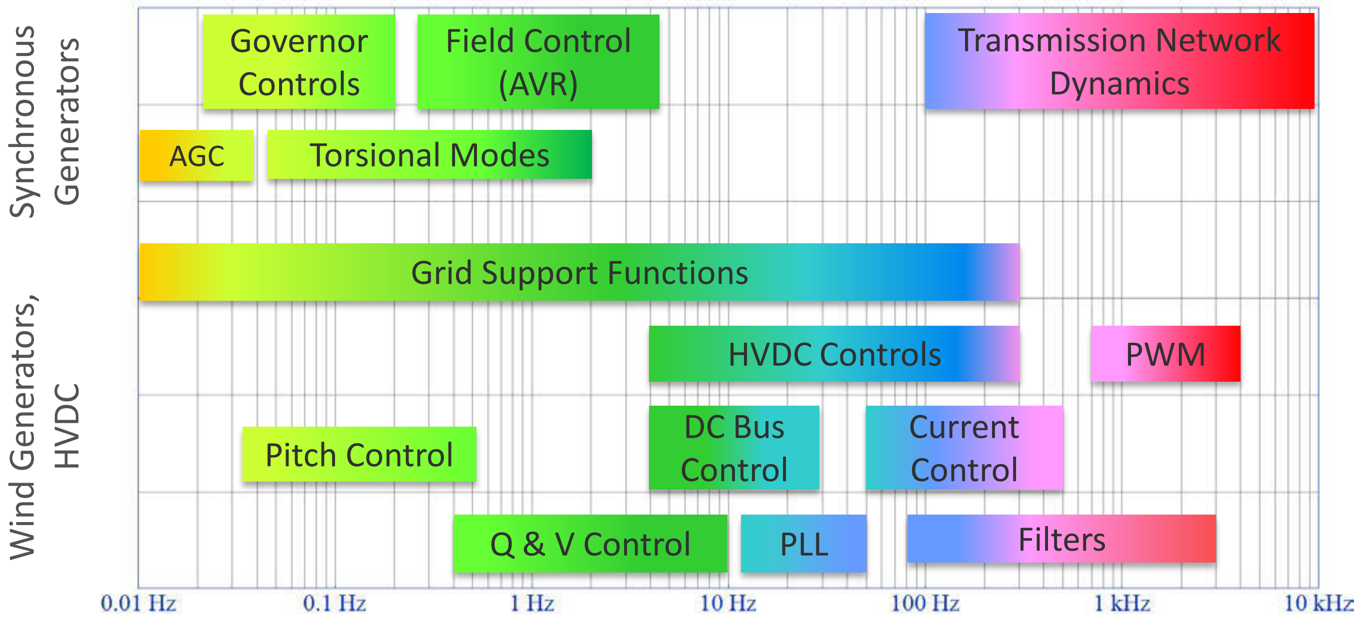




Source: Feldman, D., and R. Margolis. 2019. “Q4 2018?Q1 2019 Solar Industry Update” (NREL/PR-6A20-73992).

# Main Engineering Challenges for High Variable Renewable Energy Systems

- Reducing system inertia, degrading frequency stability with increasing penetration
- Issue of degrading voltage stability in weaker grids
- New protection at any level in the grid (lack of short-circuit current)
- Who will provide grid forming and how? Why can’t we operate all inverters as grid forming? Do we still need grid following?
- New stability issues in inverter-dominated grids—control interactions and resonances
- How we control new transmission technologies—high-voltage direct current (HVDC) lines and multiterminal HVDC connections, FACTS, etc.?
- Role of frequency in inverter-dominated grids and in 100% grids:
  - Option 1: Everything is inverter-coupled (even hydro and all loads), no synchronizing torque, so frequency stability becomes totally irrelevant.
  - Option 2: We still have some synch generation at 100% (hydro, concentrating solar power, etc.), so classic frequency stability still matters.
- Reliability and resilience of decentralized and autonomous grids, medium-voltage/low-voltage direct current grids
- Issue of cybersecurity in inverter-dominated grids.

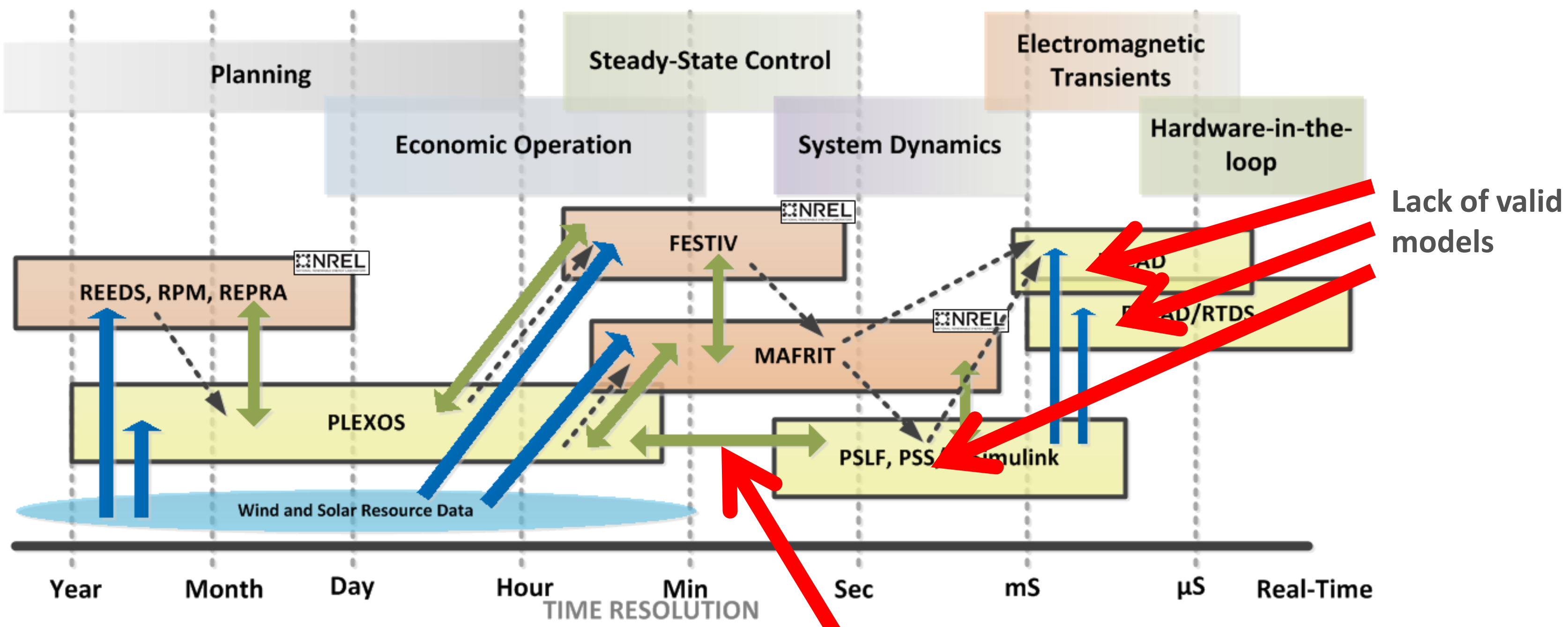
# New Stability Problems: Control Interactions




- Impedance-based analysis has proven effective for the evaluation of resonance problems and control interactions in wind power plants

Inspired by publication by Dr. Jian Sun, "Power Quality in Renewable Energy Systems: Challenges and Opportunities," presented at the International Conference on Power Quality (ICREPQ), Spain, March 2012.

# NREL Software Tools for Grid Integration Studies




NREL in-house modeling tools:

- REEDS: Regional Energy Deployment System model
- RPM: Resource Planning Model tool
- REPRA: Renewable Energy Probabilistic Resource Assessment tool
- FESTIV: Flexible Energy Scheduling Tool for Integrating Variable Generation
- MAFRIT: Multi-Area Frequency Response Integration Tool

**Gap with the existing commercial software tools**

# 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 of total photovoltaic (PV) capacity.

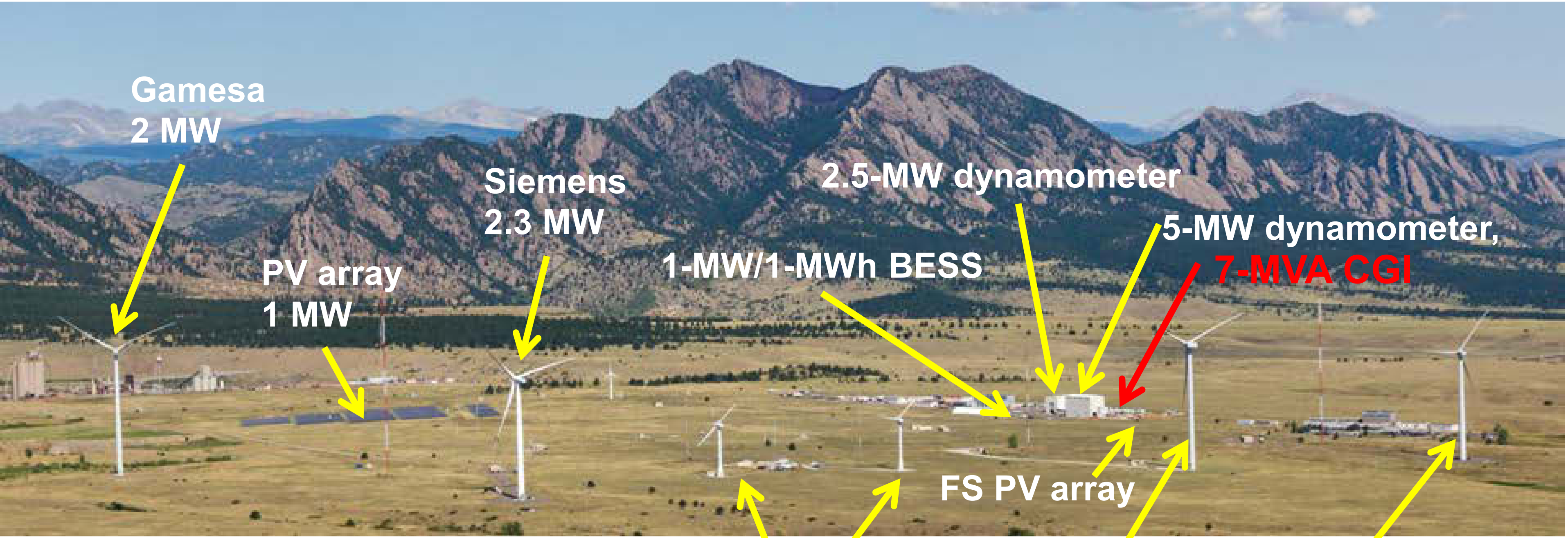
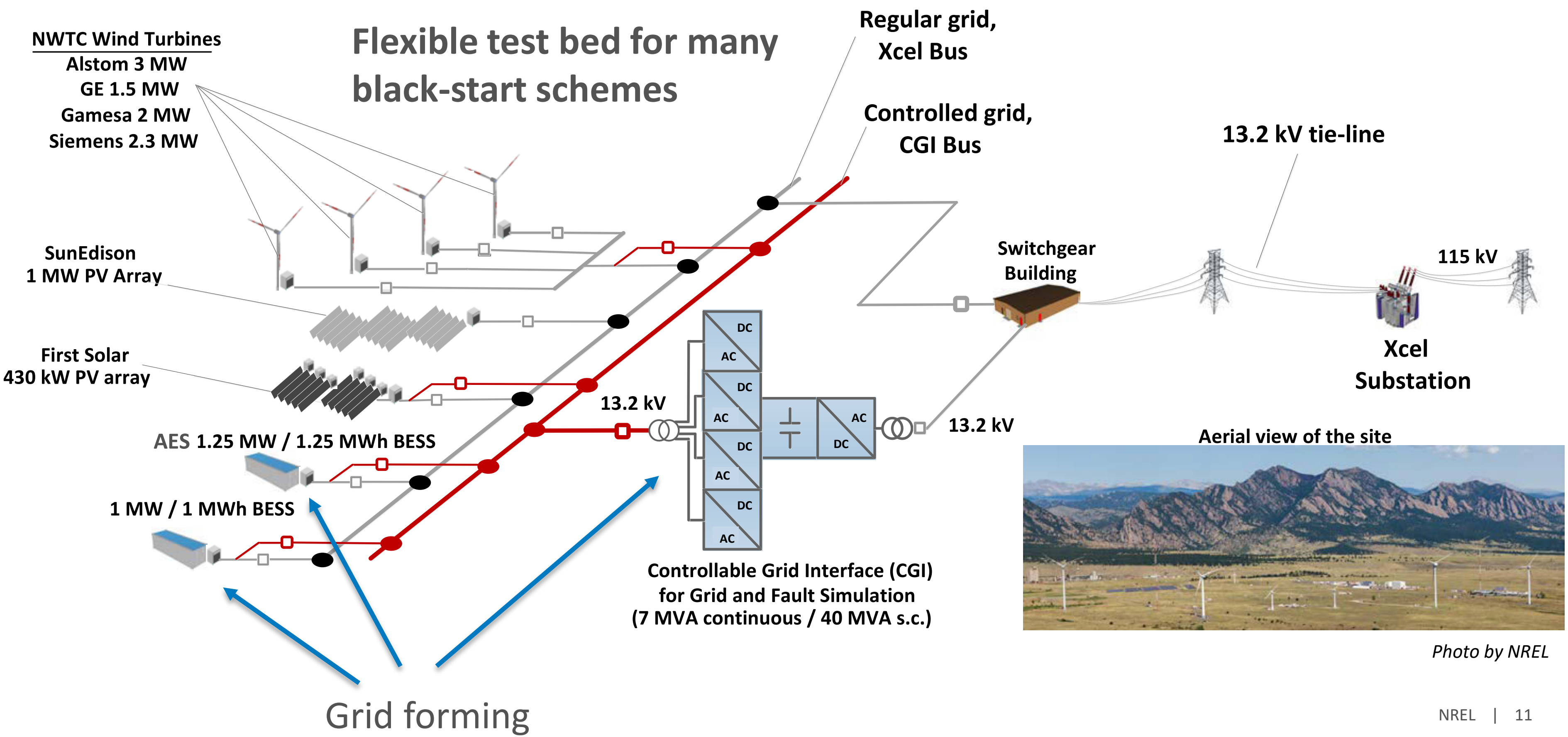



*Photo by NREL*

# National Wind Technology Center Controllable Grid Platform




Aerial view of the site

*Photo by NREL*

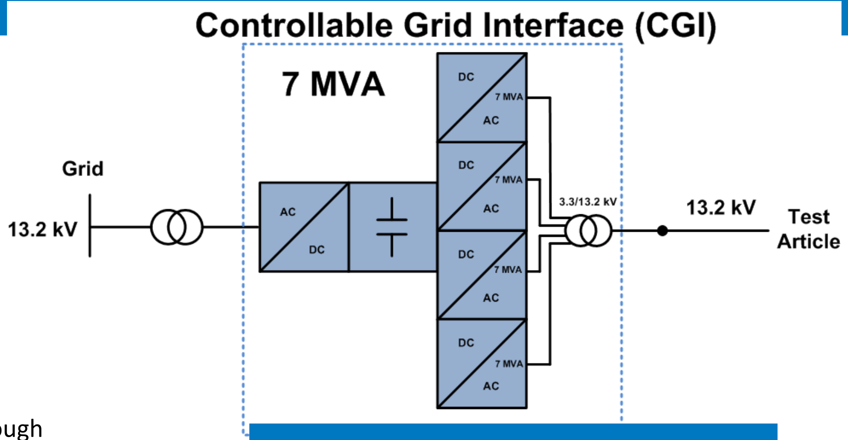
# Controllable Grid Interface #1

**Power rating:**
- 7 MVA continuous
- 39-MVA short-circuit capacity (for 2 s)
- 4-wire, 13.2 kV.

**Possible test articles:**
- Types 1, 2, 3 and 4 wind turbines
- PV inverters, energy storage systems
- Conventional generators
- Combinations of technologies.

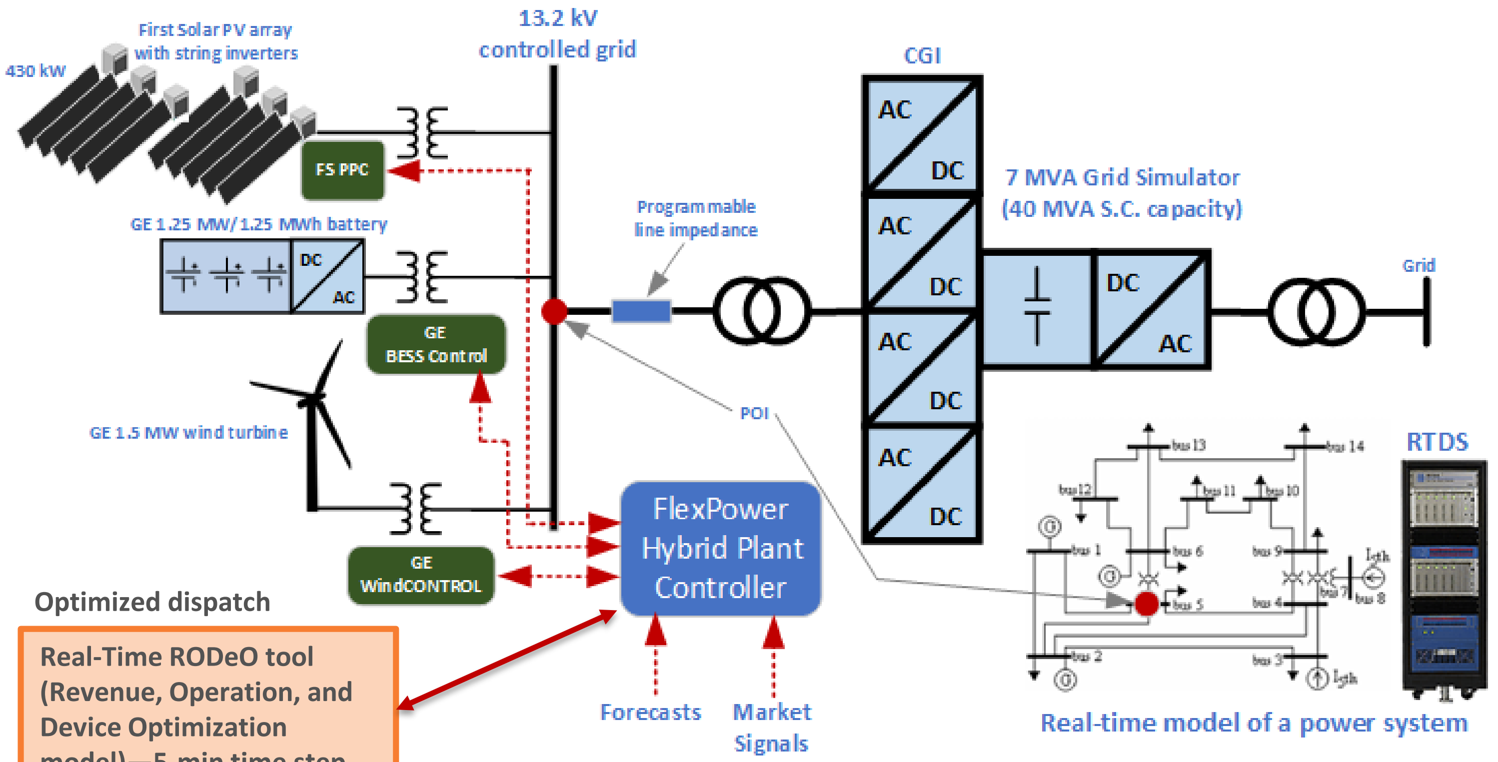
**Voltage control (no load total harmonic distortion <1%):**
- Balanced and unbalanced voltage fault conditions (zero-voltage ride-through (ZVRT) and 140% high-voltage ride-through (HVRT)—independent voltage control for each phase on 13.2-kV terminals
- Response time—1 millisecond (from full voltage to zero, or from zero back to full voltage)
- Long-term symmetrical voltage variations (+/- 10%) and voltage magnitude modulations (0–10 Hz)—subsynchronous resonance conditions
- Programmable impedance (strong and weak grids)
- Programmable distortions (lower harmonics 3, 5, 7)
- Impedance characterization of inverter-coupled generation.

**Frequency control:**
- Fast output frequency control (3 Hz/s)  within 45–65-Hz range
- 50/60-Hz operation
- Can simulate frequency conditions for any type of power system
- Power-hardware-in-the-loop (PHIL) capable (coupled with RTDS, Opal-RT, etc.)
- Test bed for phasor measurement unit- (PMU) based wide-area stability controls.




**Capabilities**
- Balanced and unbalanced over and under voltage fault ride-through tests
- Frequency response tests
- Continuous operation under unbalanced voltage conditions
- Grid condition simulation (strong and weak)
- Reactive power, power factor, voltage control testing
- Protection system testing (over and under voltage and frequency limits)
- Islanding operation
- Sub-synchronous resonance conditions
- 50 Hz tests

# Hybrid Systems Test and Control Validation Platform

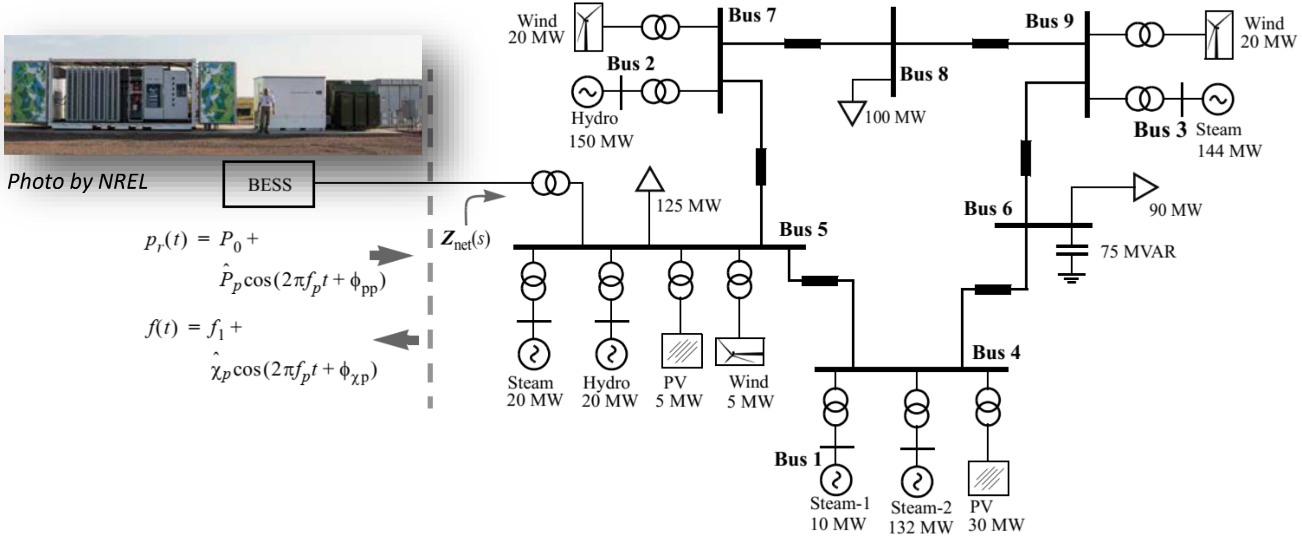



Optimized dispatch

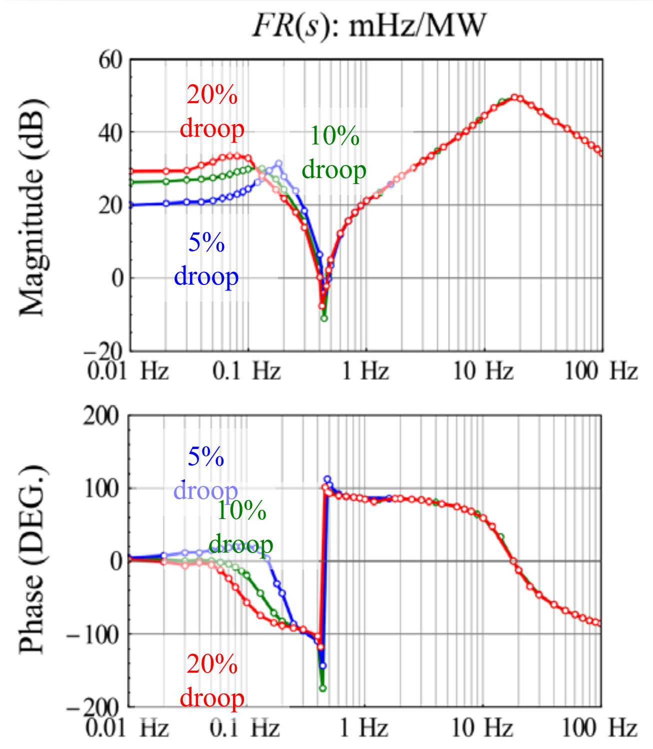
Real-Time RODeO tool (Revenue, Operation, and Device Optimization model)—5-min time step

# Power-Domain Impedance

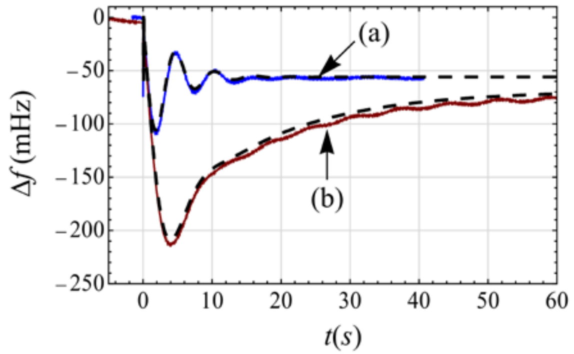
- Transfer function from active power to frequency at point of interconnection



# Power System Frequency Response Characterization in Real Time




## Loss of generation




## Applications:

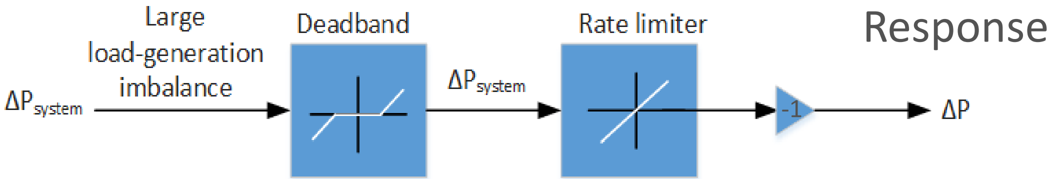
– Real-time estimation of inertia, primary frequency response, nadir, etc.
– Frequency support design by renewable generation.

# What Is Fast Frequency Response?

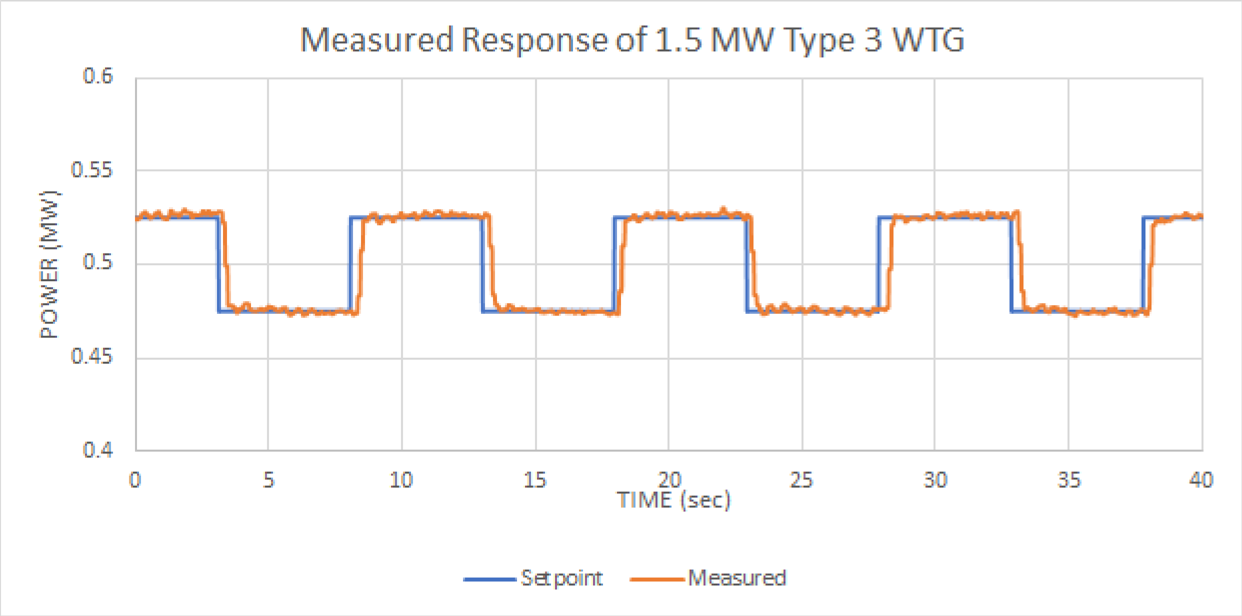
- An alternative method to achieving faster compensation to load-generation imbalances that resorts to detecting the amount of a disturbance that triggers a frequency transient
- We propose q control strategy to deploy ultrafast frequency response converter-based assets. The objective is to prevent relatively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

**Inertia** **FFR** **Droop** **AGC**

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



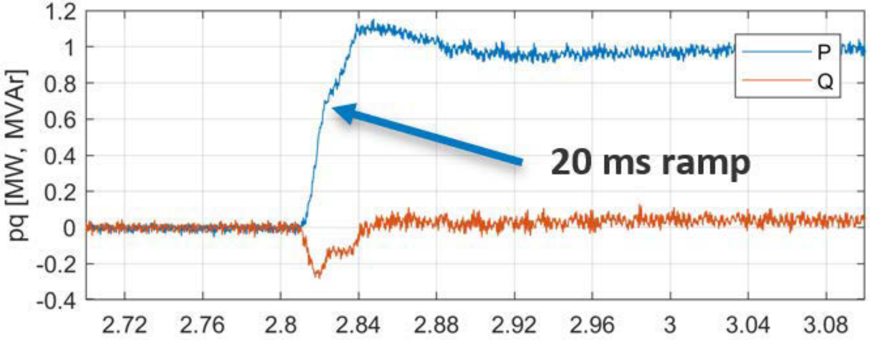
# Active Power Response of Type 3 Wind Turbine Generator



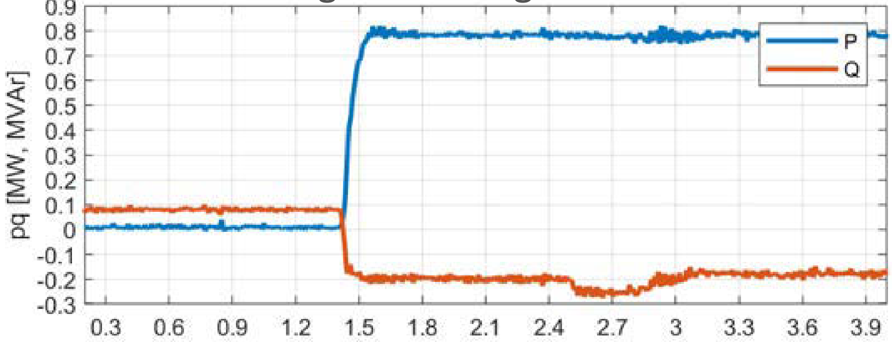

- This test was conducted with commercial wind power plant controller.
- All plant-level and turbine-level control delays are real.

# Ability of Battery Energy Storage System to Provide Fast Frequency Response

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



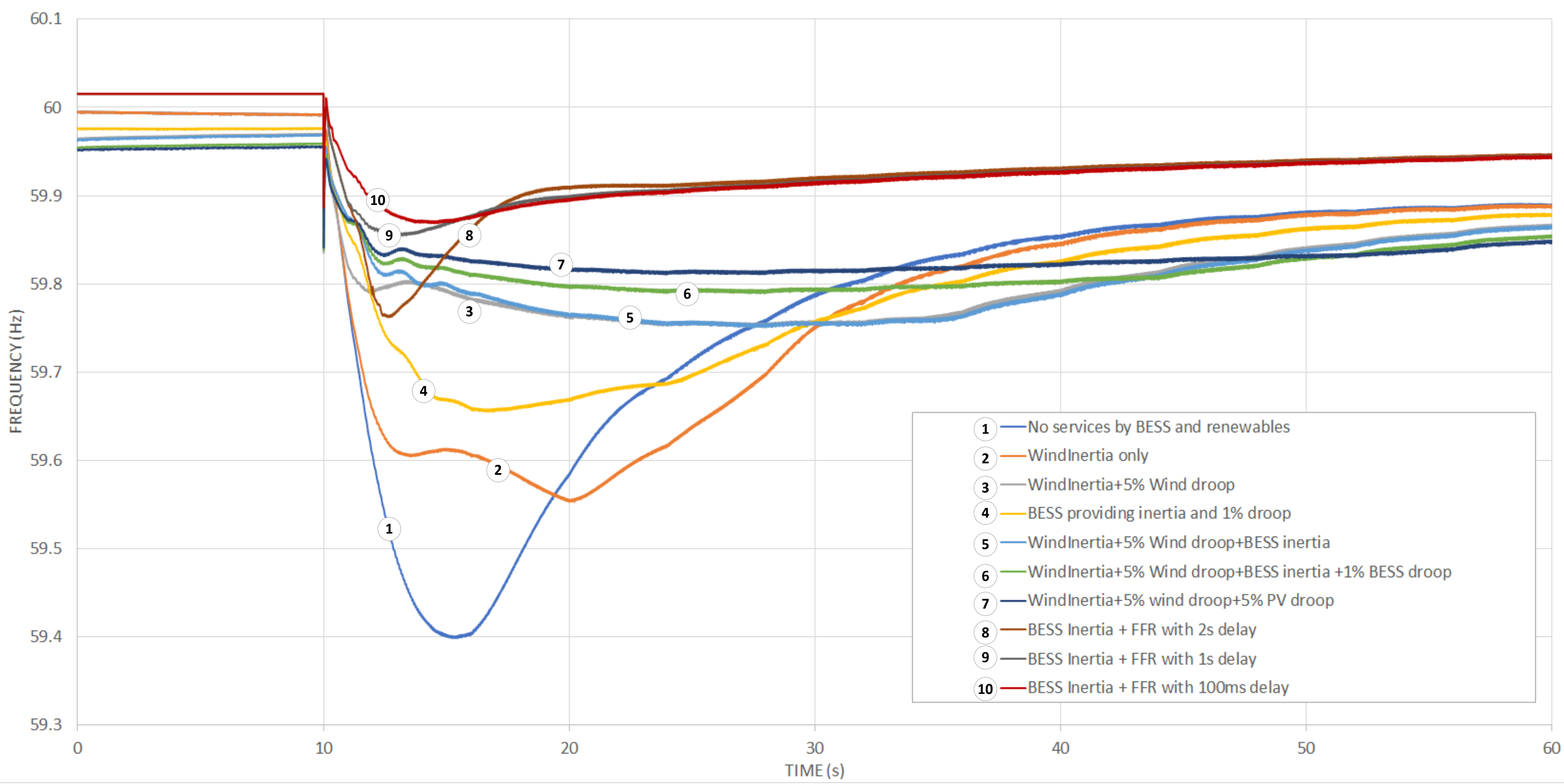

BESS active and reactive power in grid-forming mode



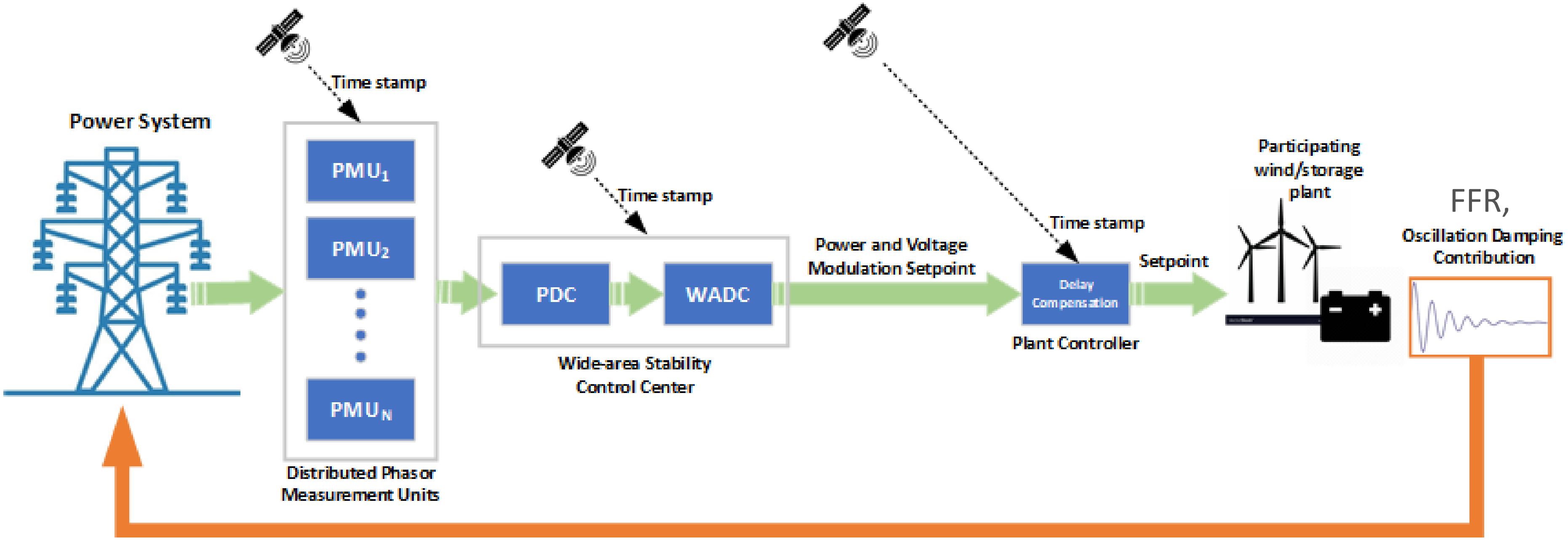

1-MW/1-MWh BESS at NREL test site

*Photo by NREL*

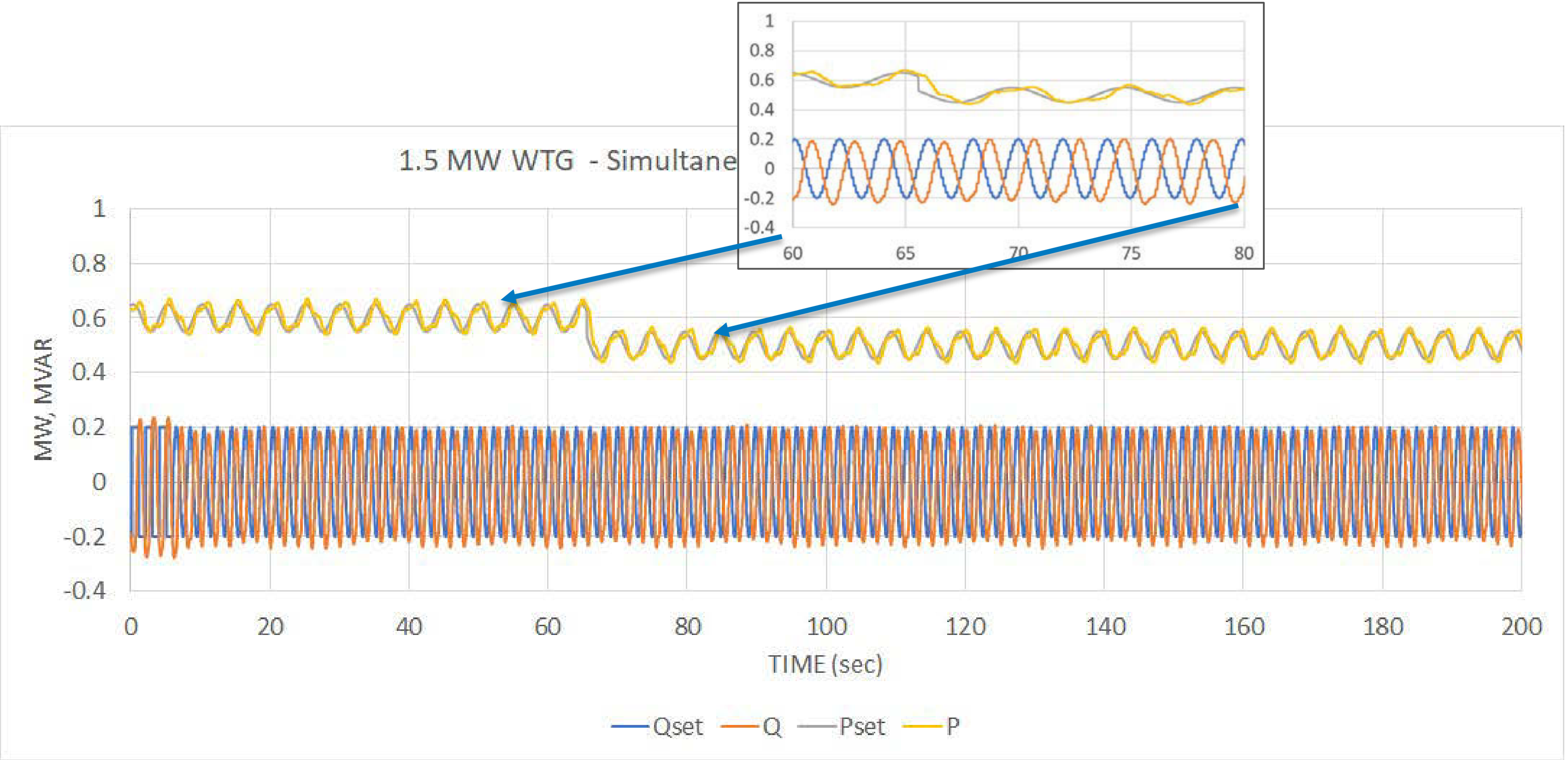
# Frequency Response of an Island System



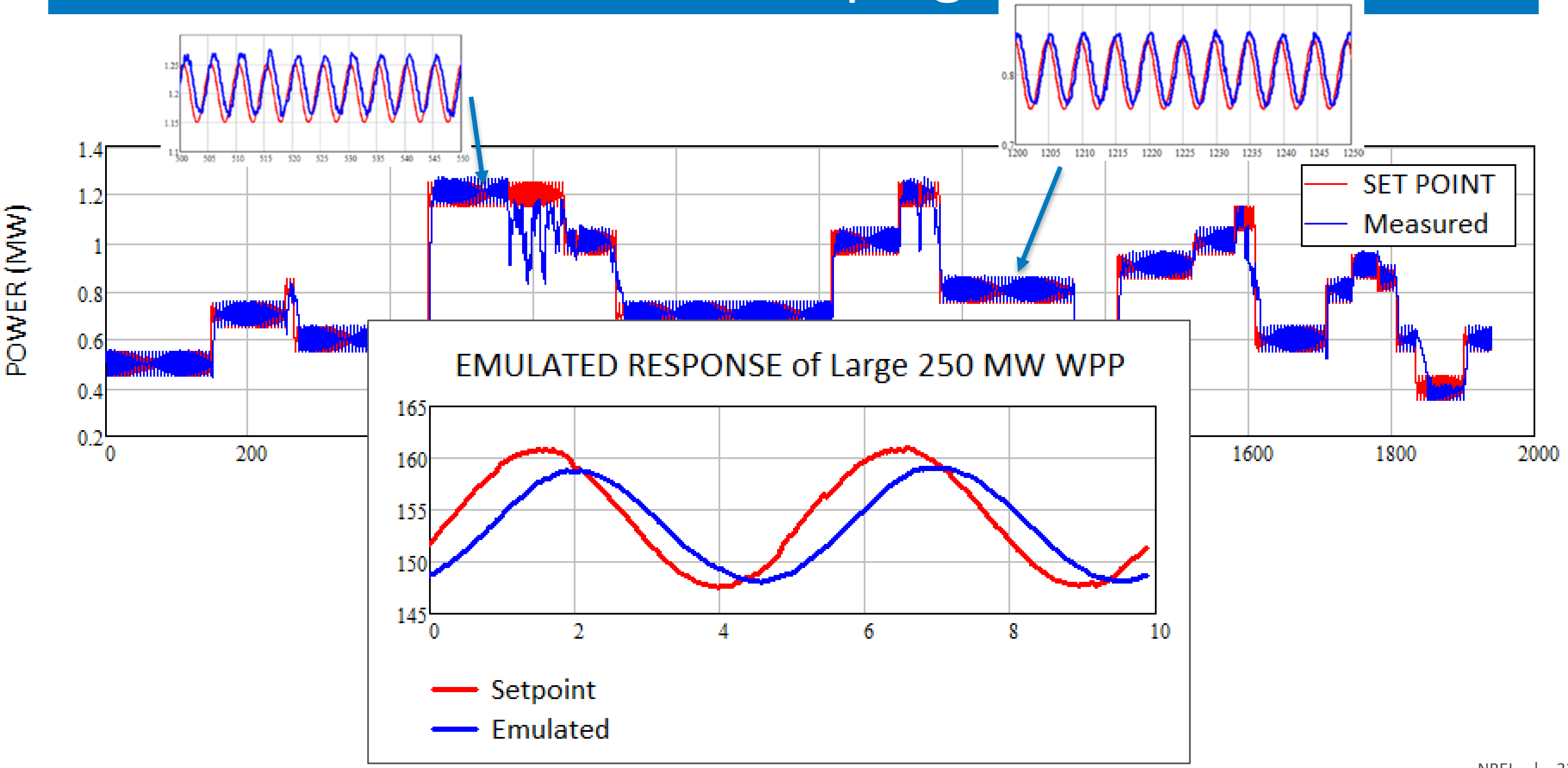
# Phasor Measurement Unit-Based Wide-Area Stability Control Concept



# Ability of DFIG WTG to Provide Simultaneous Modulation of P and Q

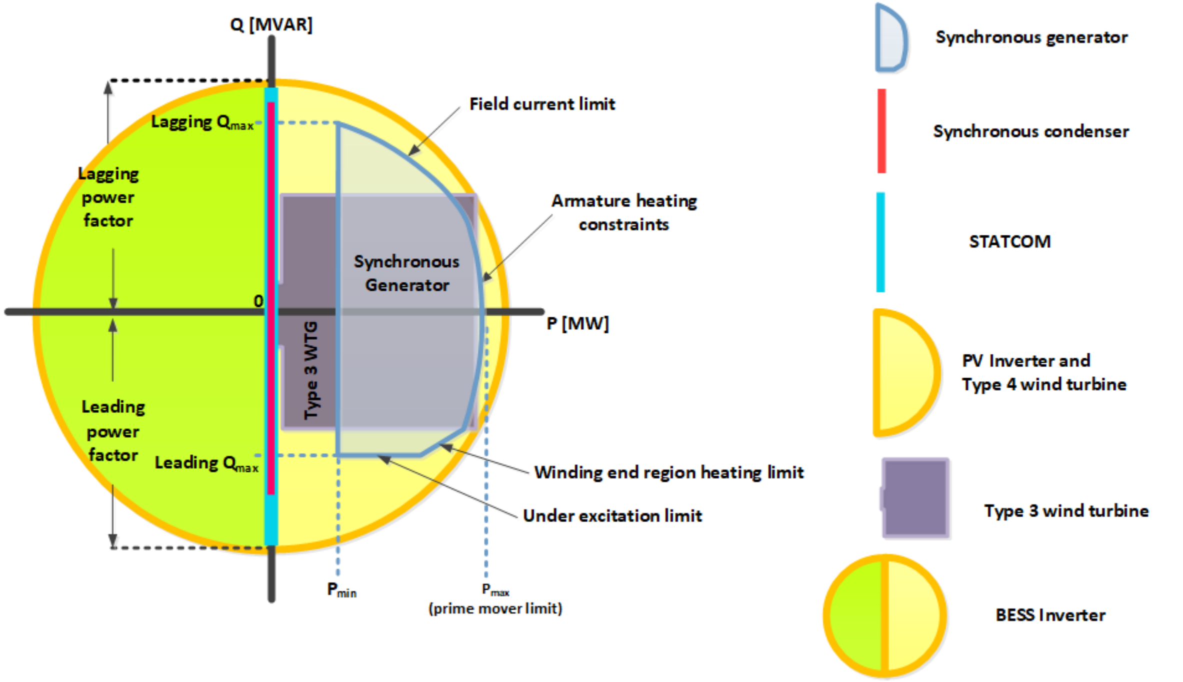


# Testing of 1.5-MW Type 3 WTG for Power System Oscillations Damping Services

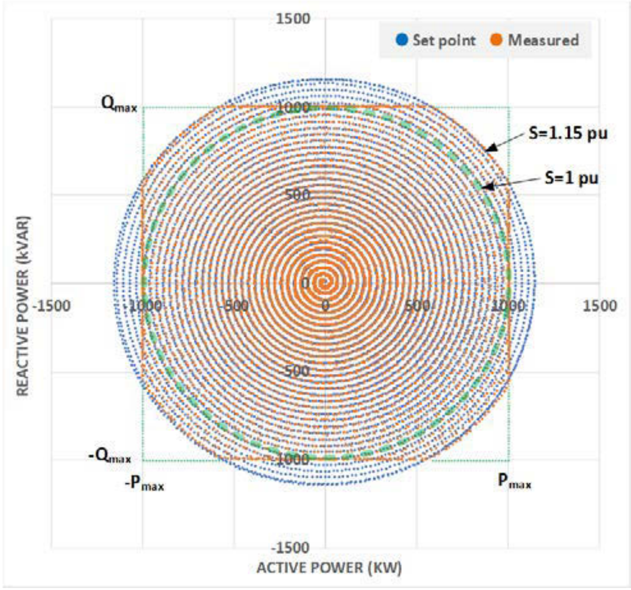


# Reactive Power Capabilities of Inverter-Coupled Resources

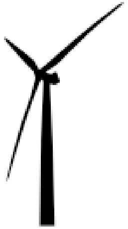
## Comparison of reactive power capabilities

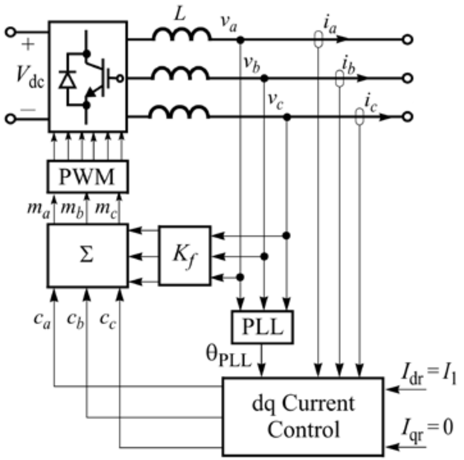



## Measured P-Q capability of 1-MW/1-MWh Li-ion BESS



# Impedance-Based Stability Analysis






$Z_p(s)$
$Z_n(s)$

$Z_g(s)$

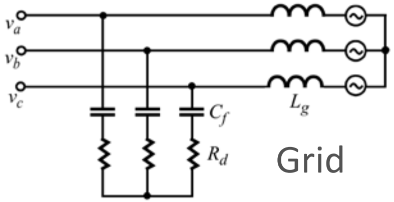



*Photo by NREL*

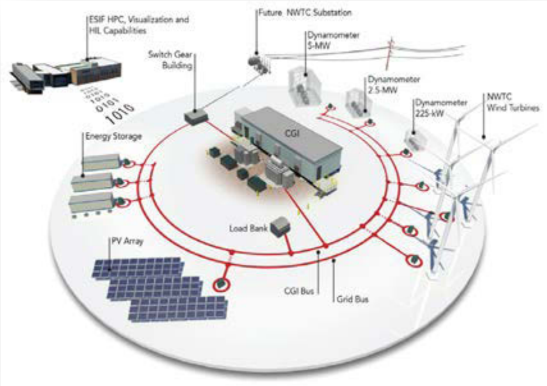
Loop gain:

$Z_g(s)/Z_p(s)$, $Z_g(s)/Z_n(s)$

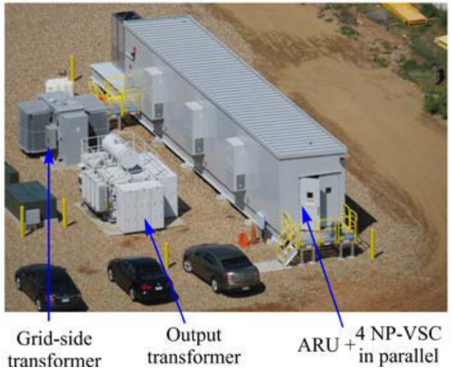
- Transmission system operators have started demanding impedance response of wind turbines for the evaluation of resonance and control interaction problems.
- Impedance-based specifications are being developed for wind turbines to reduce the risks of resonance problems.

# Impedance Measurement Test Bed at NREL

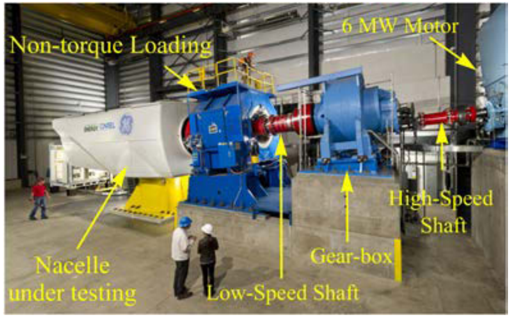
- 7-MVA grid simulator for injection of voltage perturbations
- Turbine nacelle coupled to a dynamometer
- GPS-synchronized medium-voltage measurements.




7-MVA grid simulator




5-MW dynamometer

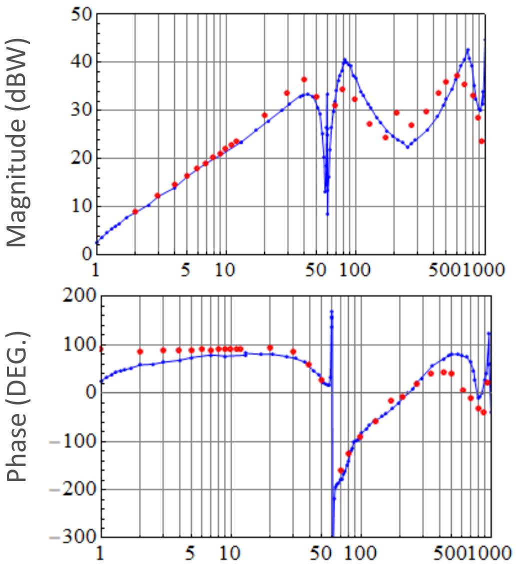



Medium-voltage measurements

*Photos by NREL*

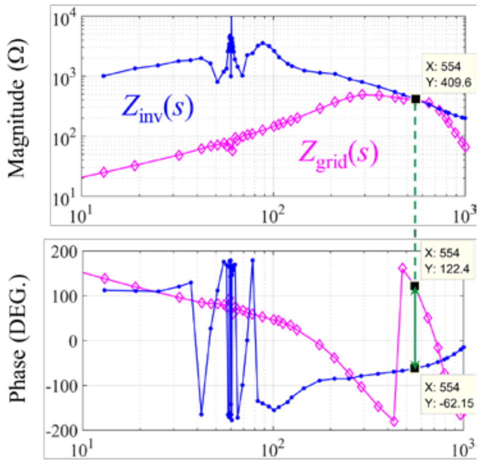
# Applications of Impedance Measurement

- Model validation

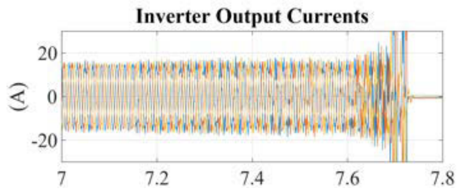



Blue: Measurements of 4-MW DFIG
Red: PSCAD model from OEM

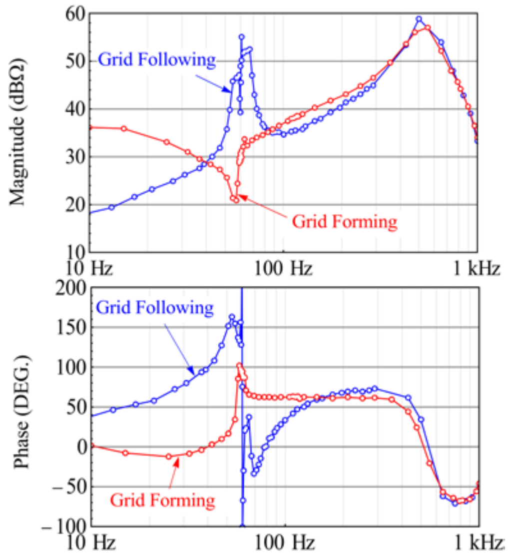
- Resonance analysis




Res. Freq.: 554 Hz Phase Margin: –4.5°




- Grid-forming inverters



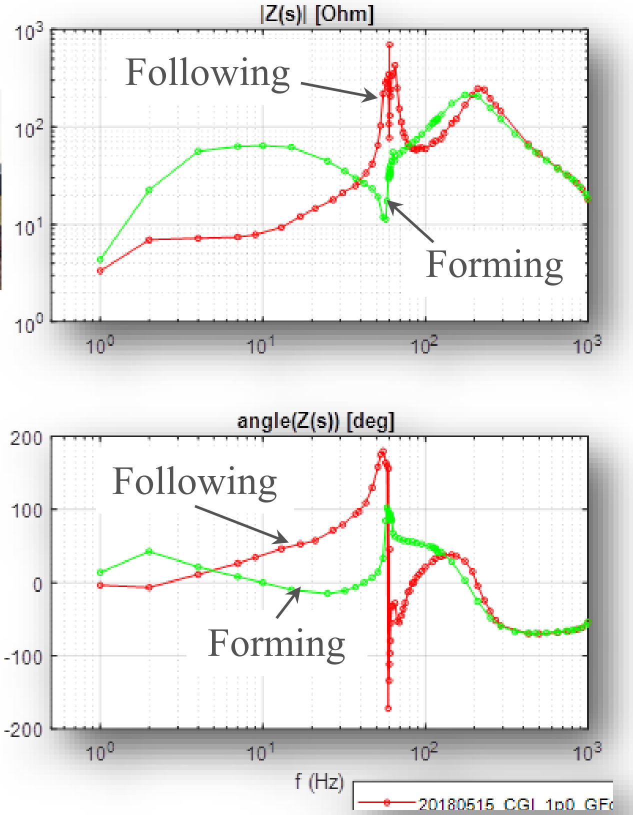

Solve resonance problems, control design, grid codes

# Grid-Forming Inverter from *Outside*

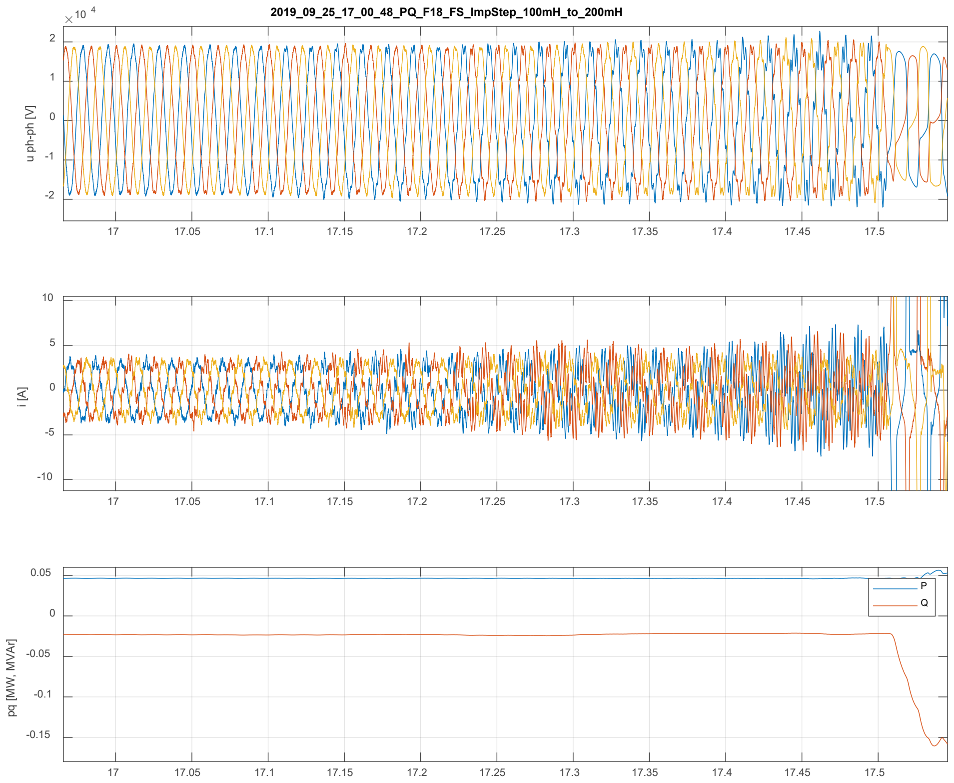
- BESS inverter

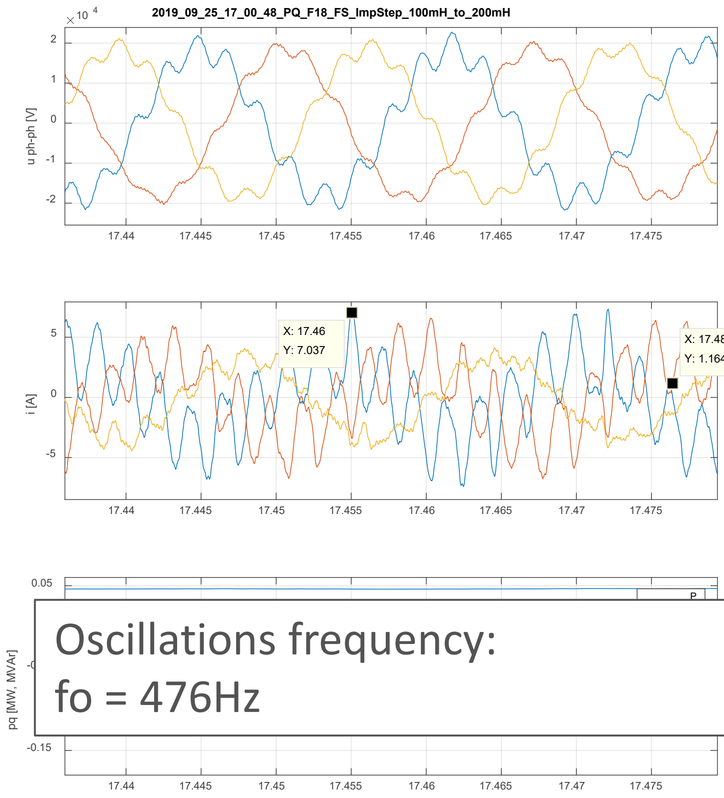
*Photo by NREL*

- Impedance measurements can **<u>quantify</u>** different aspects of grid-forming ability.



# Resonance Measured in Photovoltaic Plant




Oscillations frequency:
fo = 476Hz

# New Black-Start Paradigm

**The black-start process can be divided into three stages:**

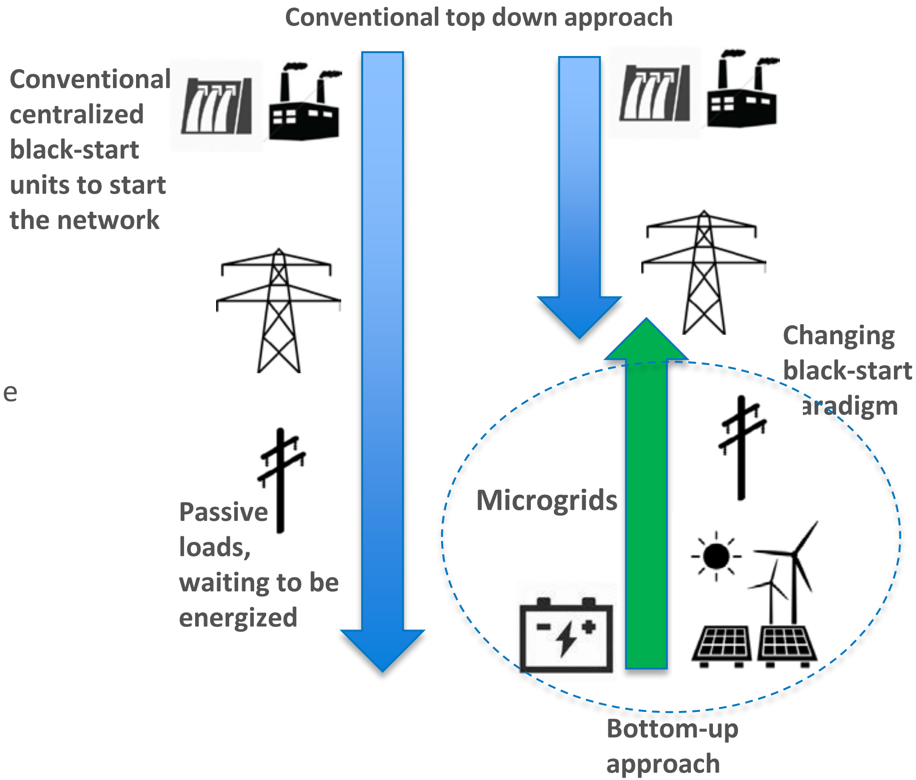
- **Preparation stage**
- **Network reconfiguring**
- **Load restoration.**

A typical restoration plan for the bulk power system includes the following essential steps:

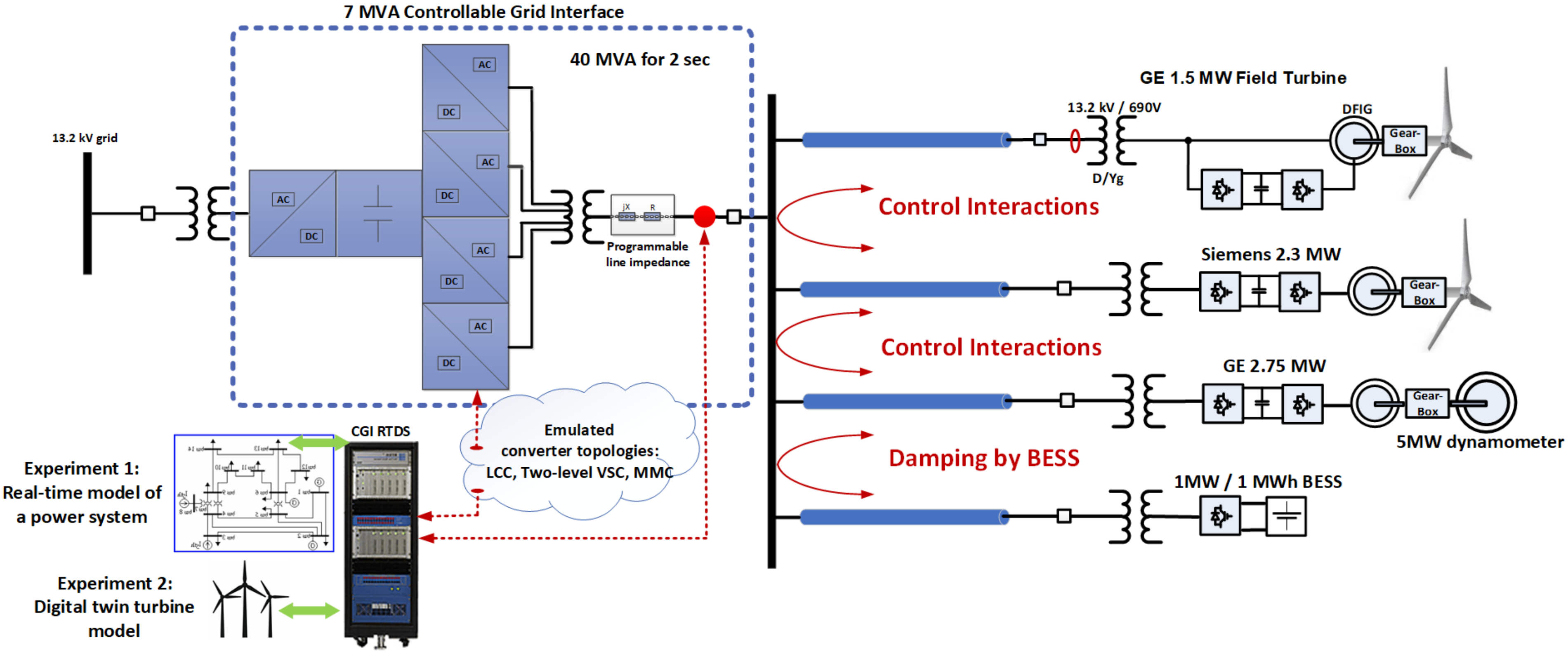
- System status identification: blackout boundaries and location in respect to critical loads, status of circuit breakers, capacity of available black-start units, etc.
- Starting at least one black-start unit to supply critical loads, such as nuclear or large thermal power plants
- Progressive restoration: step-by-step supply of other loads, avoiding over- and undervoltage conditions.

The restoration strategies:

- Serial: simpler strategy, slower but more stable
- Parallel: quicker but more complex.



# Stability Controls Demonstration Platform at NREL's Flatirons Campus



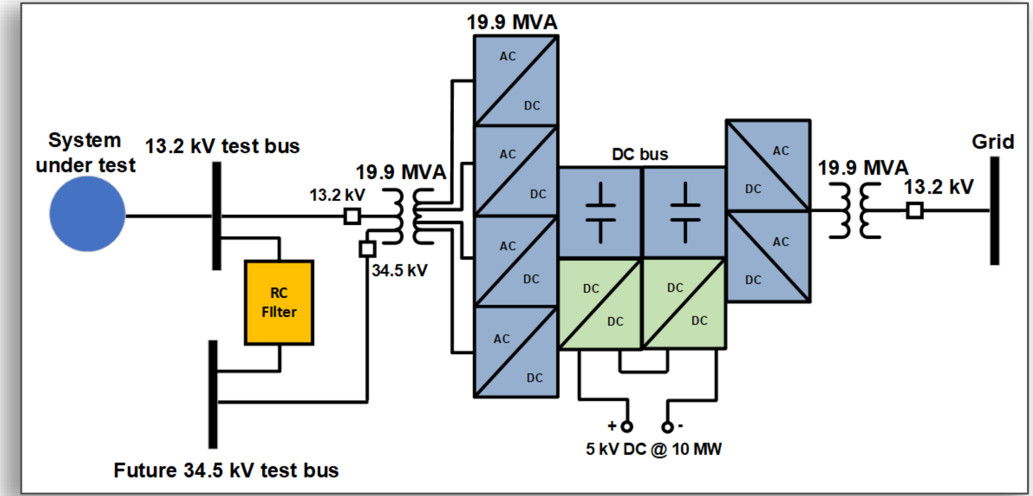
# Summary of CGI#2 Specifications

**Power rating:**
- Continuous AC rating: 19.9 MVA at 13.2kV and 34.5 KV
- Overcurrent capability (x5.7 for 3 s, x7.3 for 0.5 s)
- 4-wire 13.2-kV or 35.4-kV taps
- Continuous operational AC voltage range: 0–40 kVAC
- Continuous DC rating: 10 MW at 5 kVDC.

**Possible test articles:**
- Types 1, 2, 3 and 4 wind turbines
- PV inverters, energy storage systems
- Conventional generators
- Combinations of technologies/hybrid systems
- Responsive loads.

**Voltage control (no load total harmonic distortion <1%):**
- Balanced and unbalanced voltage fault conditions (ZVRT, LVRT, and 140% HVRT)—independent voltage control for each phase on 13.2-kV and 34.5-kV terminals
- Response time: less than 1 millisecond (from full voltage to zero, or from zero back to full voltage)
- Programmable injection of positive, negative, and zero-sequence components
- Long-term symmetrical voltage variations (+/- 10%) and voltage magnitude modulations (0–10 Hz)—subsynchronous resonance conditions
- Programmable impedance (strong and weak grids, wide SCR range corresponding to a point of interconnection with up to 250 MVA of short-circuit apparent power)
- Injection of controlled voltage distortions
- Wide-spectrum (0–2-kHz) impedance characterization of inverter-coupled generation and loads
- All-quadrant reactive power capability characterization of any system.

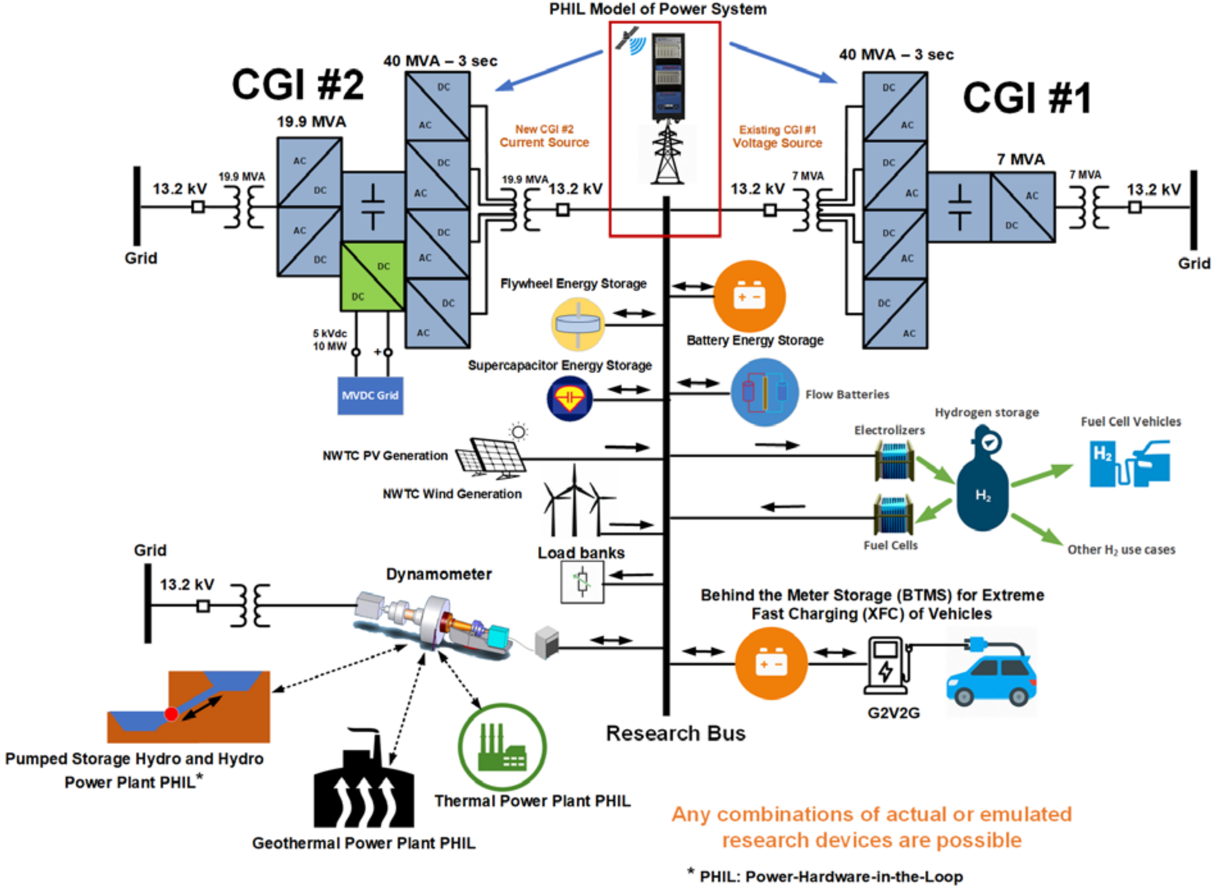
**Frequency control:**
- Fast output frequency control (3 Hz/s) within 45–65-Hz range
- 50/60-Hz operation
- Can simulate frequency conditions for any type of power system
- PHIL capable (can be coupled with RTDS, Opal-RT, Typhoon, etc.)
- Coupled with PMU-based wide-area stability controls validation platform.




**New features:**
- 5-kV MVDC grid simulator (PHIL capable)
- Voltage or current source operation
- Seamless transition between voltage and current source modes
- Emulation of full set of resiliency services:
    - Black start
    - Power system restoration schemes
    - Microgrids.
- Flexible configurations are possible when combined with CGI#1:
    - Two independent experiments
    - Parallel operation
    - Back-to-back operation
    - Emulation of isolated, partially, or fully grid-connected microgrids.

# Optimized Hybrid Energy Storage Systems

- Validation of design optimization tools and operational strategies for hybrid energy storage systems for provision of grid services at various timescales (ms-s-min-hr-day)
- Development and validation of optimized control theory for hybrid energy storage to provide essential reliability and resilience services to the grid:
    - Optimal ratios between device-level, plant-level, and system-level controls.
- Design and operation of hybrid renewable-storage plants for improved dispatchability, increased capacity factors, and enhanced grid services
- Optimized storage technology mixes for microgrids and islanded systems.



# Summary of NREL Research Portfolio

- Many research projects funded by the U.S. Department of Energy Wind Energy Technologies Office, Water Power Technologies Office, Solar Energy Technologies Office, and Office of Electricity
- Many collaborative projects with industry (inverter-based technologies vendors, utilities, system operators, academia)
- Research at the scale that matters
- Solving integration challenges at any timescale
- Development, demonstration, and validation of new controls and new testing methods and protocols
- Development of validated models at any timescale
- Providing information to standardization groups and regulatory bodies
- Stakeholder engagement
- Education of future workforce.

# Thank you!

# 谢谢！

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