NREL Controllable Grid Interface (CGI): Overview of Progress and Projects

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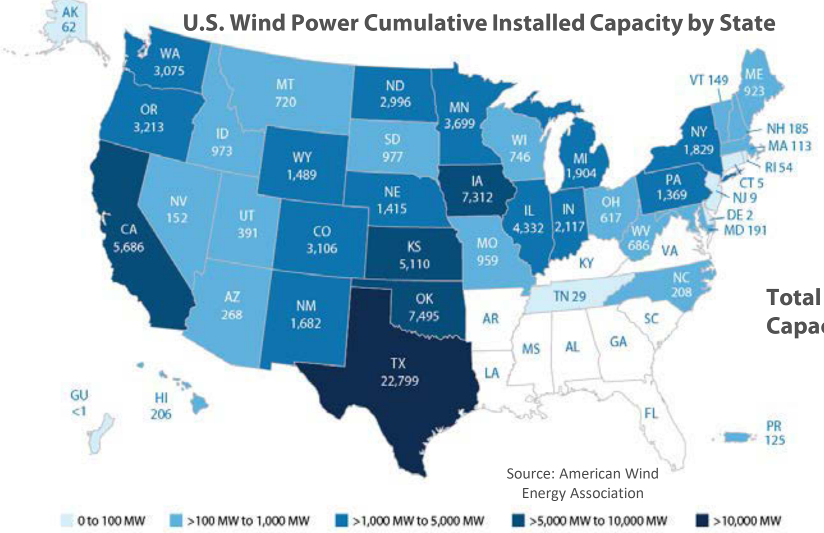
Status of Wind and Solar PV Capacity in U.S.

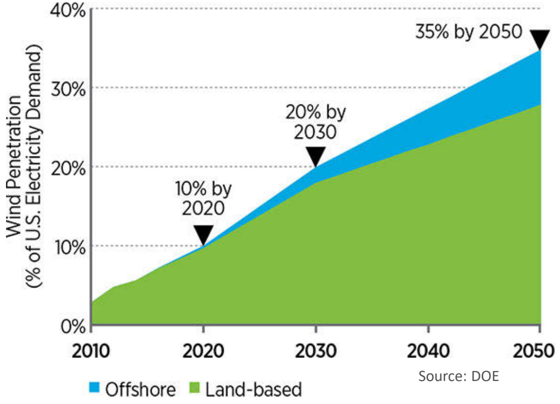
U.S. Wind Power Cumulative Installed Capacity by State



Source: American Wind Energy Association

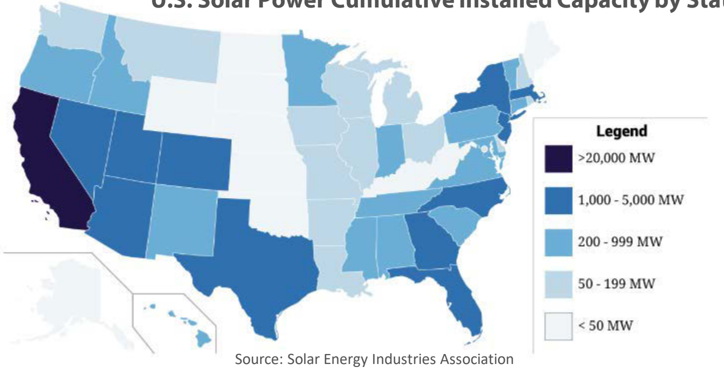
Total U.S. Wind Capacity: 90 GW

U.S. DOE Wind Vision Study Scenarios



Source: DOE

U.S. Solar Power Cumulative Installed Capacity by State



Source: Solar Energy Industries Association

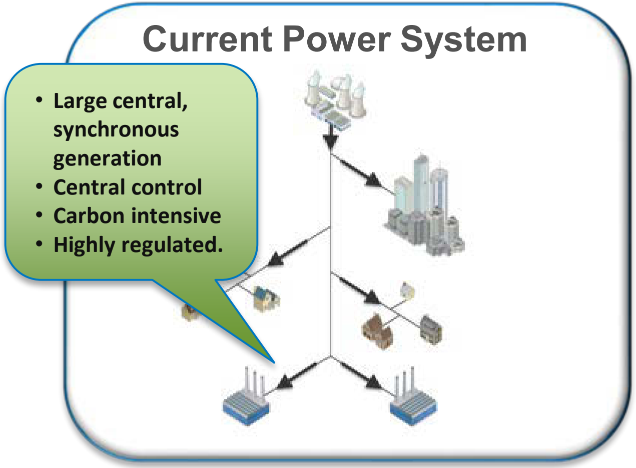
Top 10 Solar States

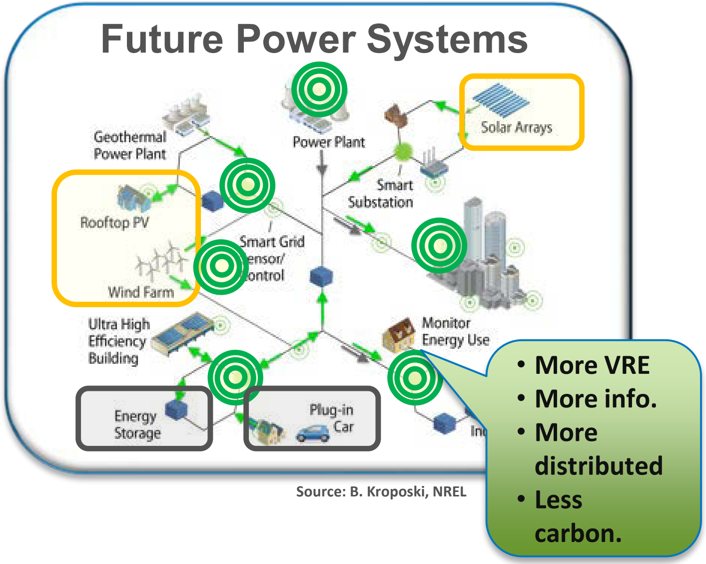
1. **California – 22,777 MW**
2. **North Carolina – 4,491 MW**
3. **Arizona – 3,613 MW**
4. **Nevada – 2,658 MW**
5. **Texas – 2,624 MW**
6. **New Jersey – 2,526 MW**
7. **Massachusetts – 2,226 MW**
8. **Florida – 1,943 MW**
9. **Utah – 1,627 MW**
10. **Georgia – 1,556 MW**

Source: Solar Energy Industries Association

Total U.S. Solar Capacity: 58.3 GW

Evolution of the Power System





Source: B. Kroposki, NREL

New challenges in a modern grid:

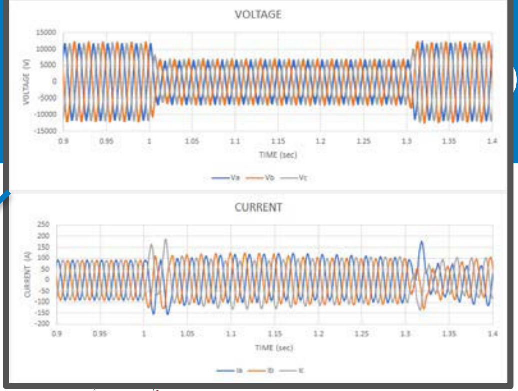
- Increasing levels of power electronics-based variable renewable energy (VRE)—wind and solar
- More use of communications, controls, data, and information (e.g., smart grids)
- Other new technologies: electric vehicles, distributed storage, flexible loads
- Becoming highly distributed—more complex to manage.

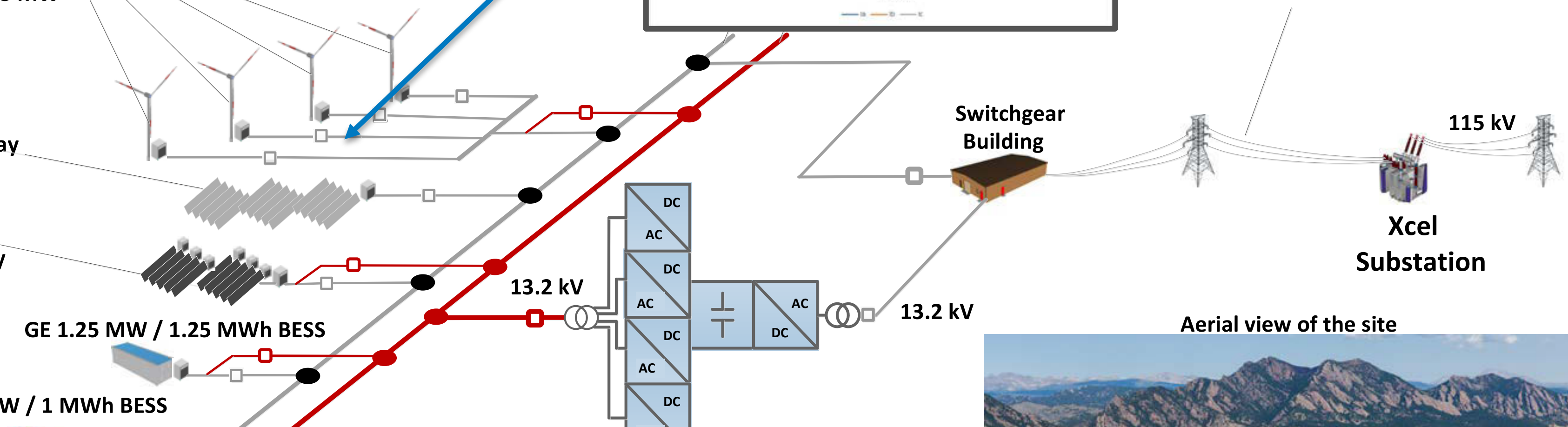
DOE Grid Modernization Initiative

Technology Innovation

Institutional Support	• Provide tools and data that enable more informed decisions and reduce risks on key issues that influence the future of the electric grid/power sector.
Design and Planning Tools	• Create grid planning tools that integrate transmission and distribution and system dynamics over a variety of time and spatial scales.
System Operations, Power Flow, and Control	• Design and implement a new grid architecture that coordinates and controls millions of devices and integrates with energy management systems.
Sensing and Measurements	• Advance low-cost sensors, analytics, and visualizations that enable 100% observability.
Devices and Integrated System Testing	• Develop new devices to increase grid services and utilization and validate high levels of variable generation integrated systems at multiple scales.
Security and Resilience	• Develop advanced security (cyber and physical) solutions and real-time incident response capabilities for emerging technologies and systems.

NWTC Control … rm





Aerial view of the site

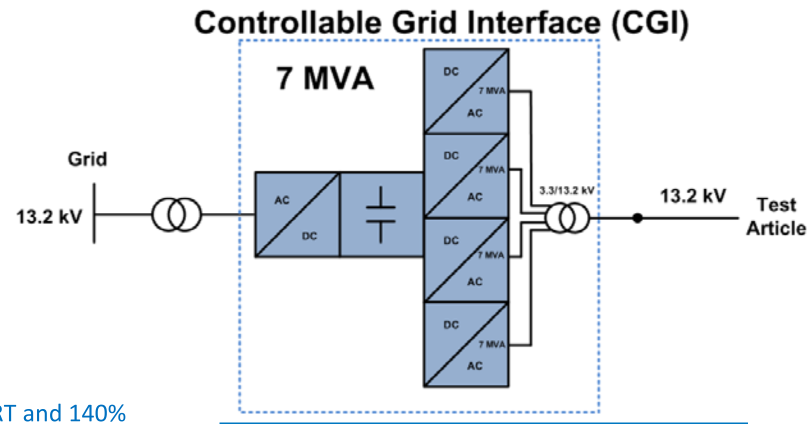
Controllable Grid Interface

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
- Capable of fault testing largest Type 3 wind turbines
- PV inverters, energy storage systems
- Conventional generators
- Combinations of technologies.

Voltage control (no load THD <3%)
- Balanced and unbalanced voltage fault conditions (ZVRT and 140% HVRT ride-through)—independent voltage control for each phase on 13.2-kV terminals
- Response time: 1 ms (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)—SSR conditions
- Programmable impedance (strong and weak grids)
- Programmable distortions (lower harmonics 3, 5, 7).

Frequency control
- Fast output frequency control (3 Hz/s) within a range of 45–65 Hz
- 50/60-Hz operation
- Can simulate frequency conditions for any type of power system
- PHIL capable (coupled with RTDS, Opal-RT, etc.).

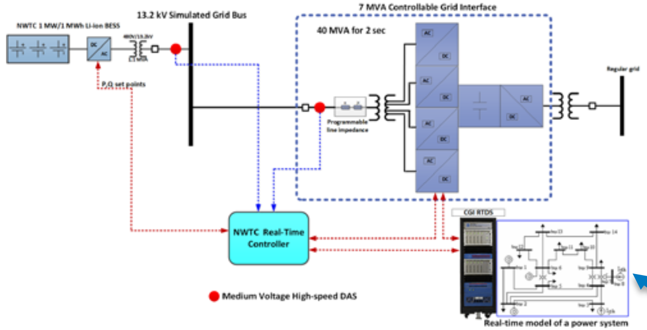


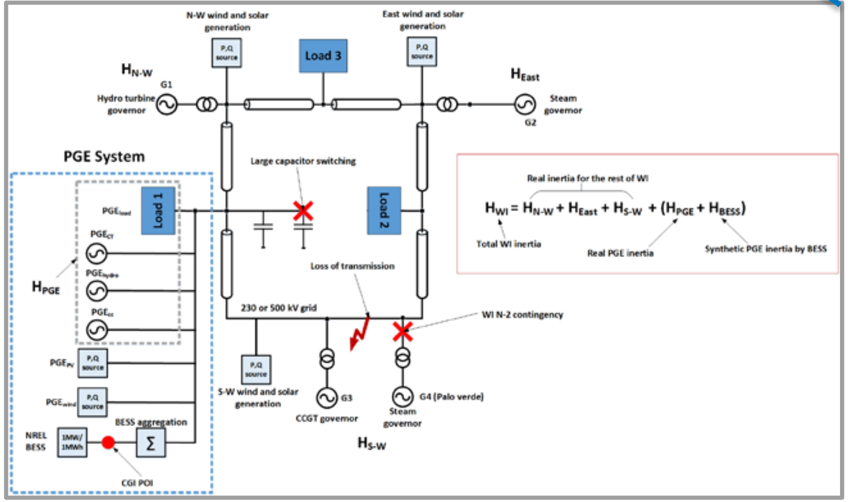
Capabilities
- Balanced and unbalanced over and under voltage fault ride-through tests
- Frequency response tests
- Continuous operation under unbalanced voltage conditions
- Grid condition simulation (strong and weak)
- Reactive power, power factor, voltage control testing
- Protection system testing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

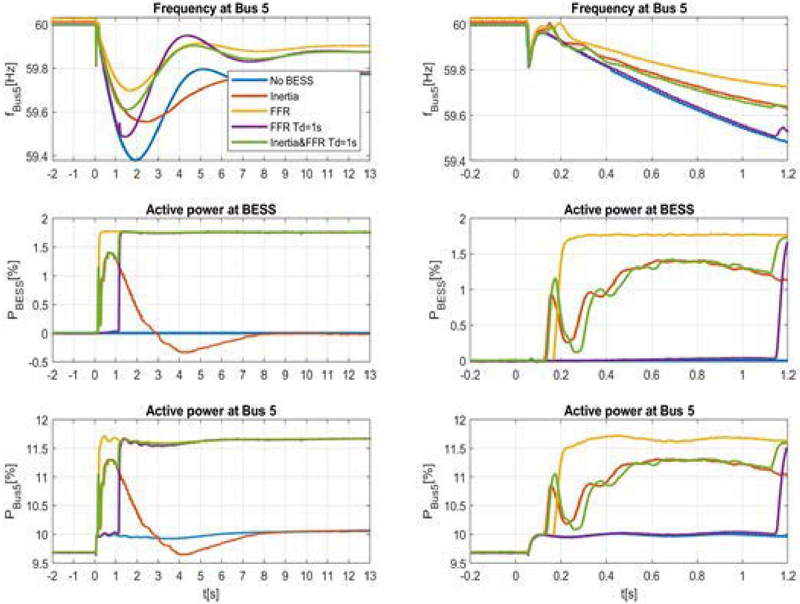
Active Projects Involving Energy Storage

- U.S. Department of Energy (DOE) GMLC/WETO: Active power controls by wind power combined with energy storage systems
- DOE SETO Hybrid PV/storage plants in collaboration with First Solar
- DOE WPTO: Integrating energy storage with run-of-river hydropower plants
- PG&E/EPIC: Development and testing of advanced active power controls and grid gault performance for a battery energy storage system (BESS)
- DOE OE (U.S.-China CCWG): NREL-China EPRI project
- AES: Tightly coupled PV/storage plants
- GE: Clusters of hybrid wind/solar PV/storage power plants
- Statoil: Energy storage for offshore wind power plants.

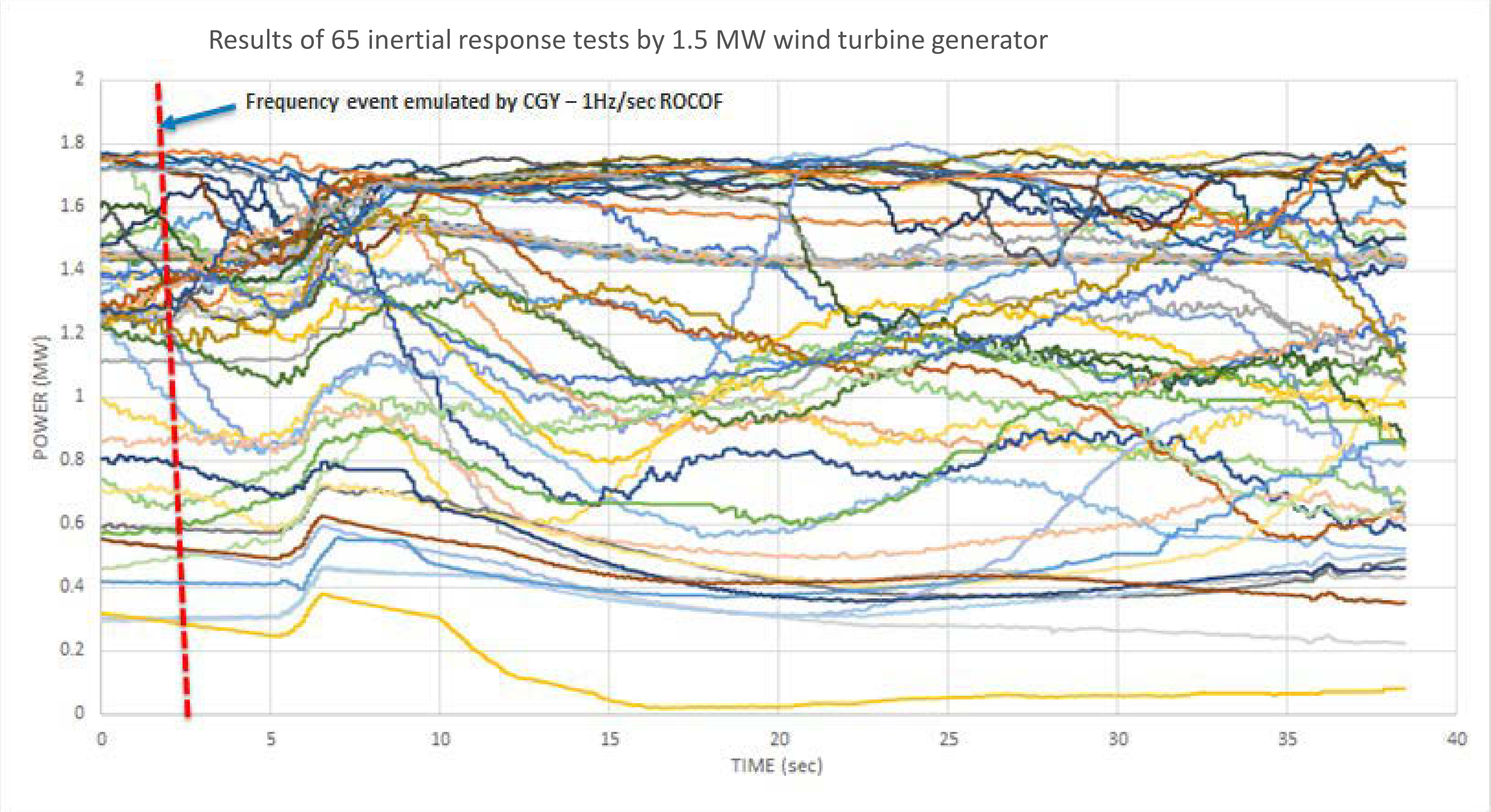
NREL-PG&E Project on BESS Inertial Controls



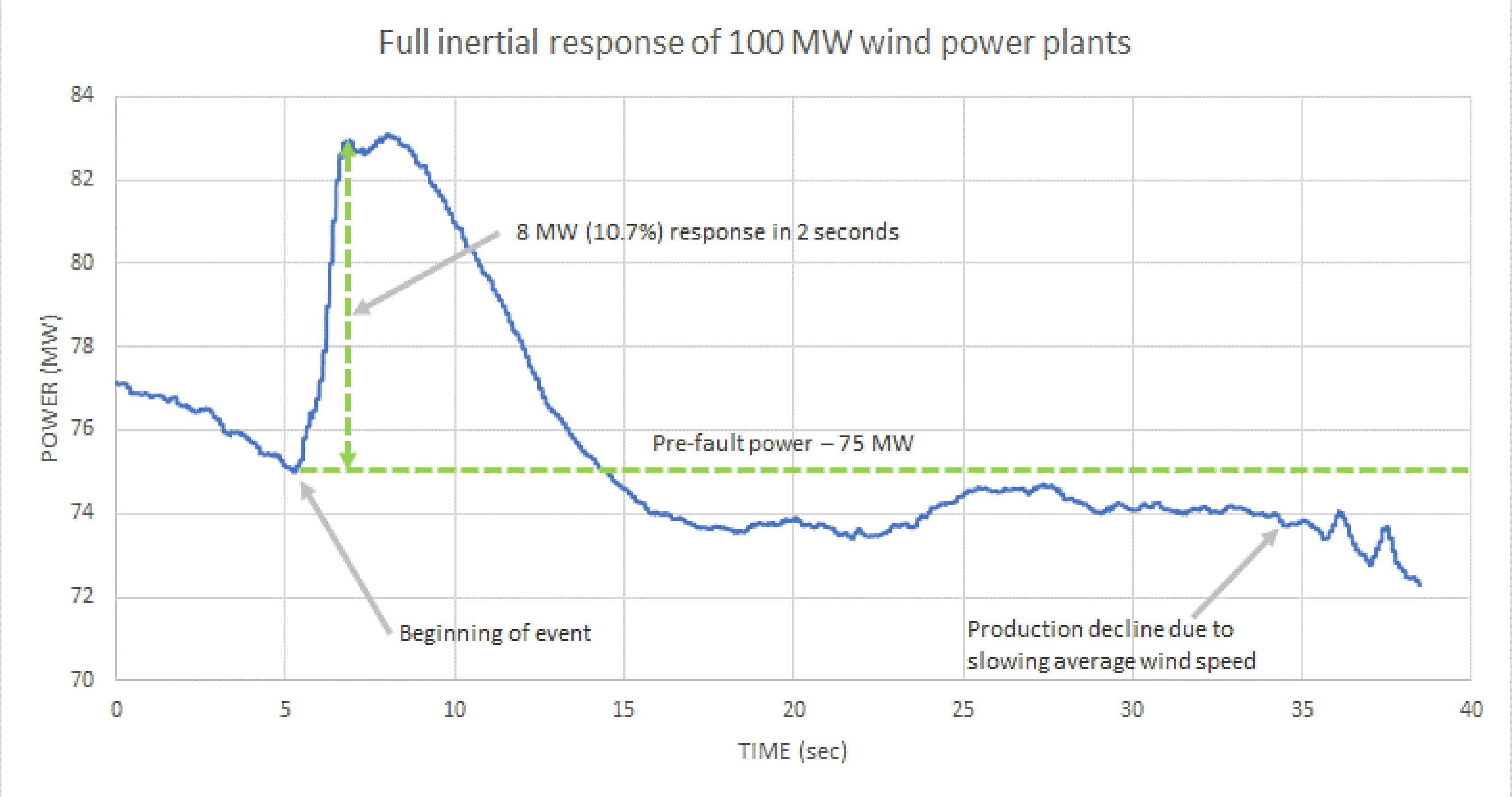




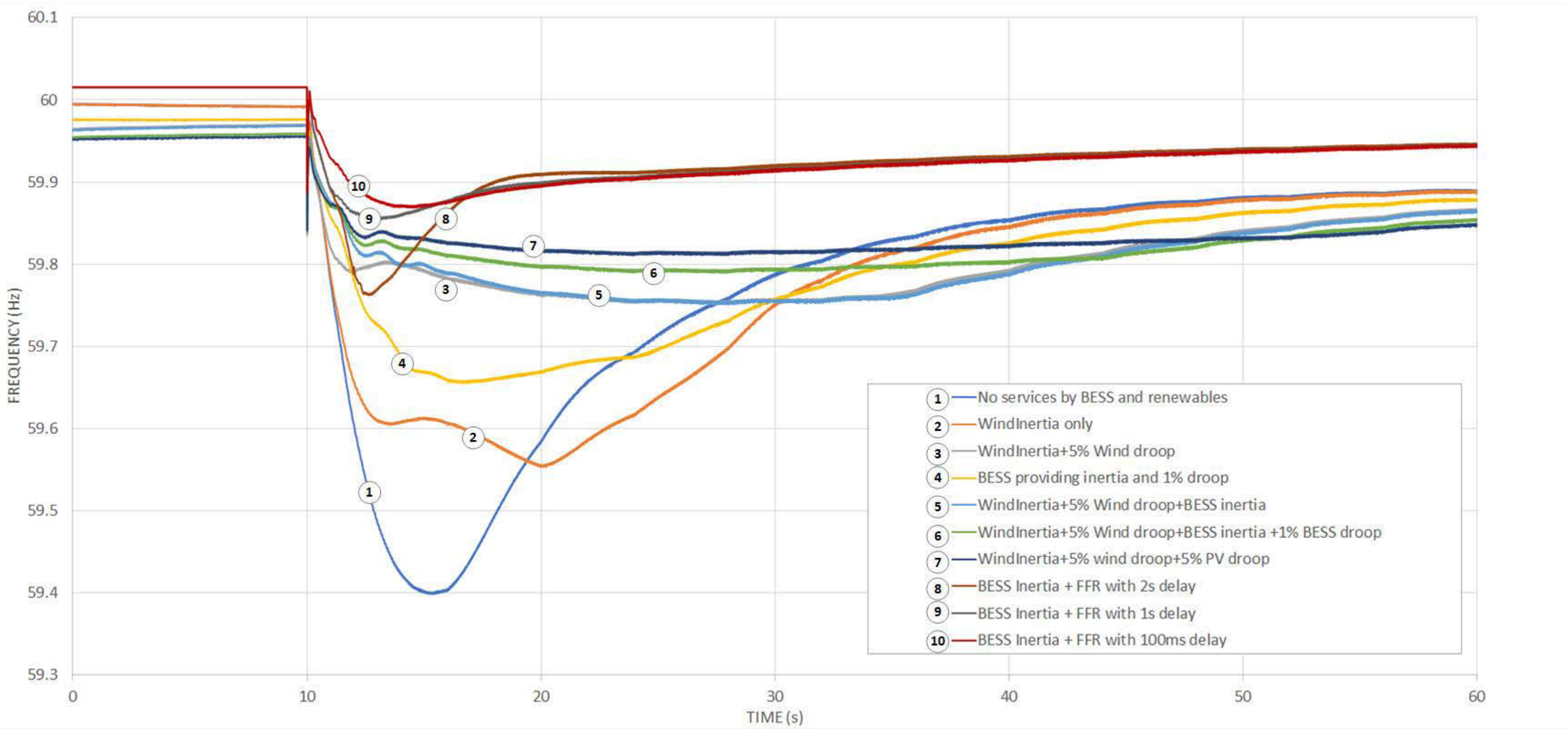
Inertial Response by Large Wind Power Plant



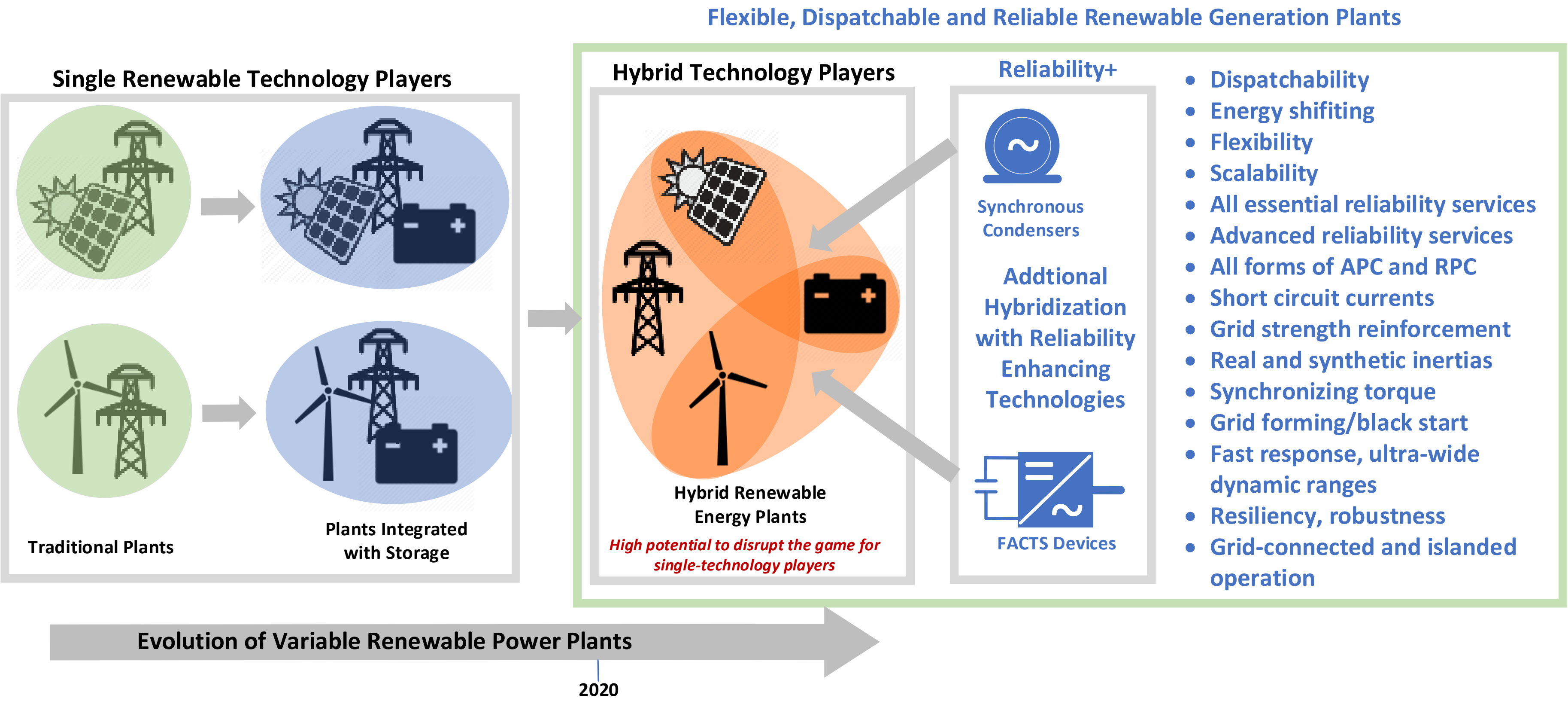
Aggregate Inertial Response



Impacts of Wind and Energy Storage Controls on Frequency Response



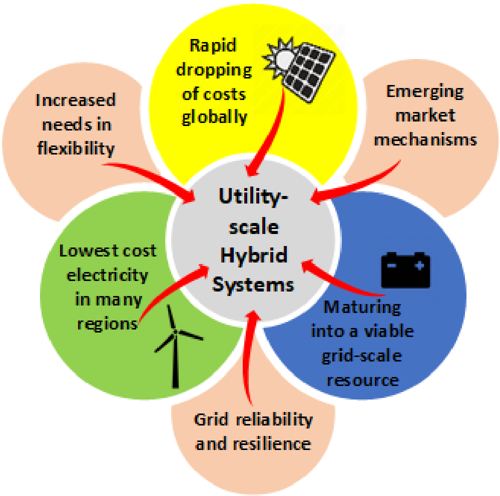
Thinking Beyond Traditional Variable Generation Plants



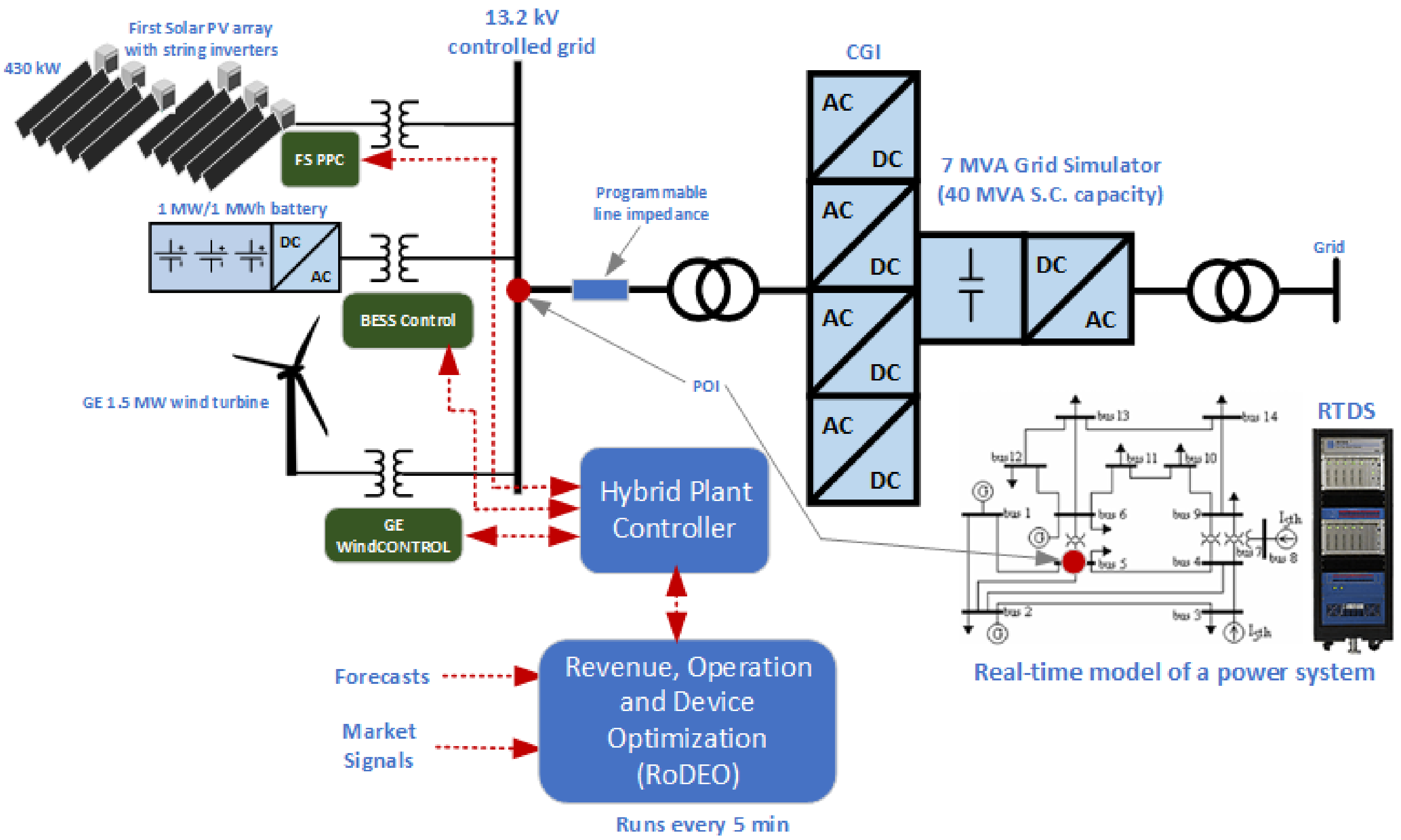
Services by Multi-Technology (Hybrid) Plants

- Dispatchable renewable plant operation
  - Long-term and short-term production forecasts
  - Capability to bid into day-ahead and real-time energy markets like conventional generation
  - Flexibility services.
- Ramp limiting, variability smoothing, cloud-impact mitigation
- Provision of spinning and nonspinning reserves
- AGC functionality
- Primary frequency response (programmable droop control)
- Fast frequency response
- Inertial response:
  - Programmable synthetic inertia for a wide range of H constants emulated by wind generation
  - Selective inertial response strategies by wind turbines.
- Reactive power/voltage control
- Black start, resiliency services
- Advanced controls: power system oscillations damping, phasor measurement unit measurement-based controls, wide-area stability services
- Stacked services
- Plant electric loss reduction, annual energy production increase
- Battery state-of-charge management
- Optimization model-predictive control strategies
- Revenue optimization for transmission- and distribution-level applications.

Hybridization Recipe

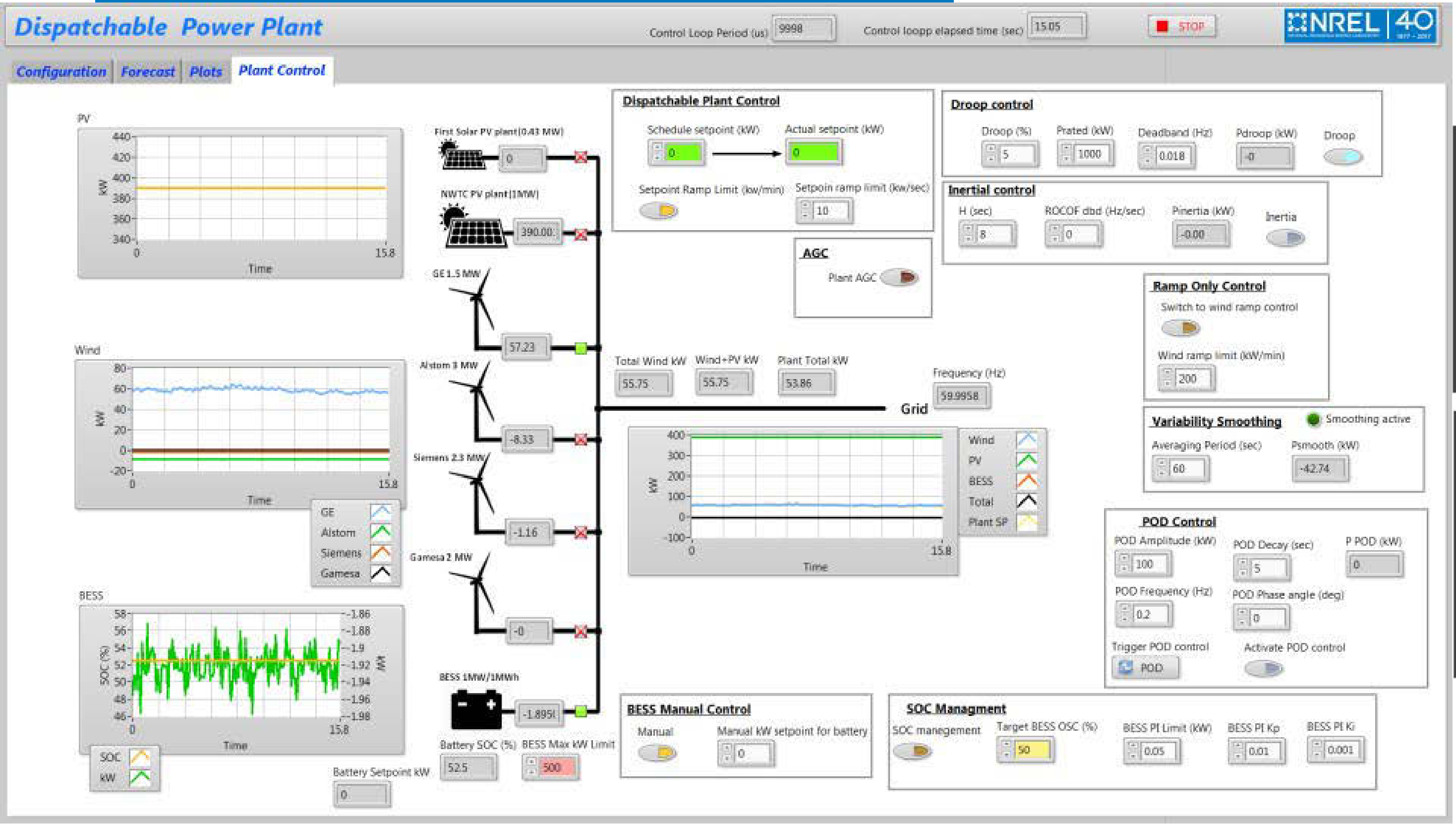


Multi-Technology Plant Controls Validation Platform



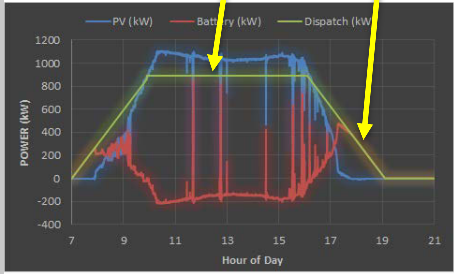
Dispatchable Power Plant

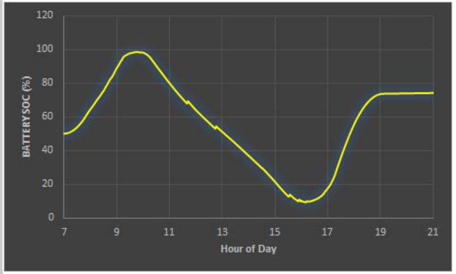
Main control panel



Reduced ramps

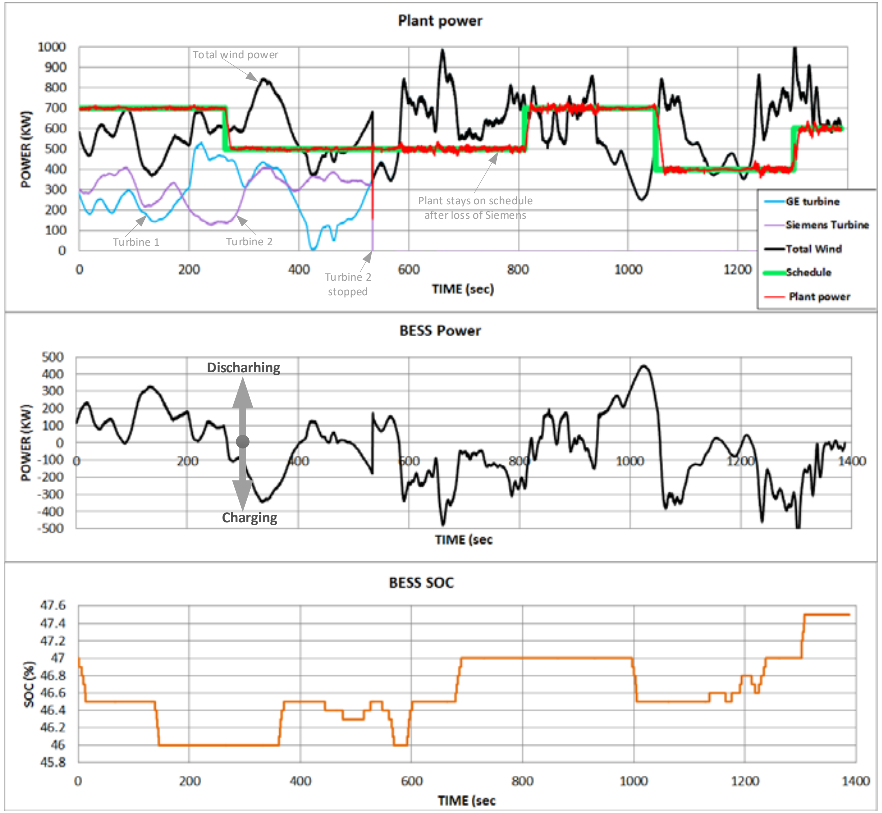
No curtailment

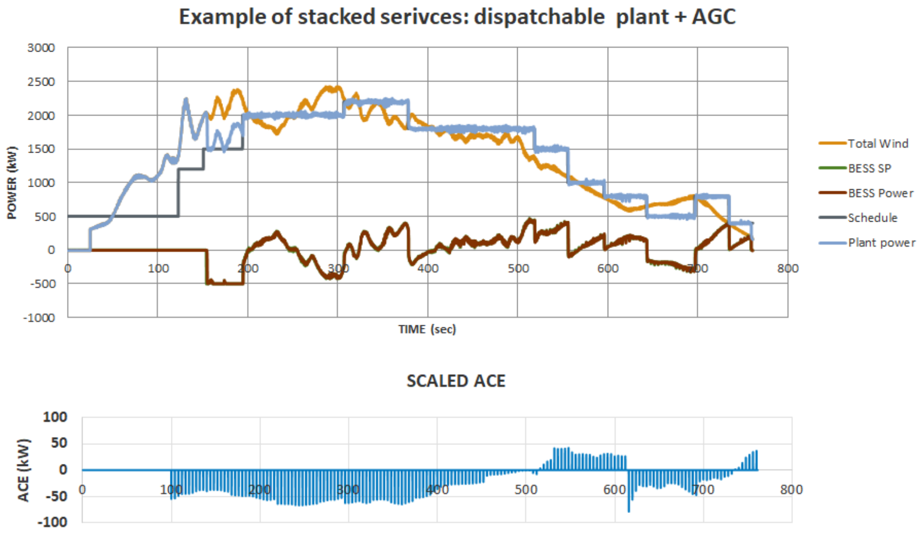




Examples of Dispatchable Operation Demo

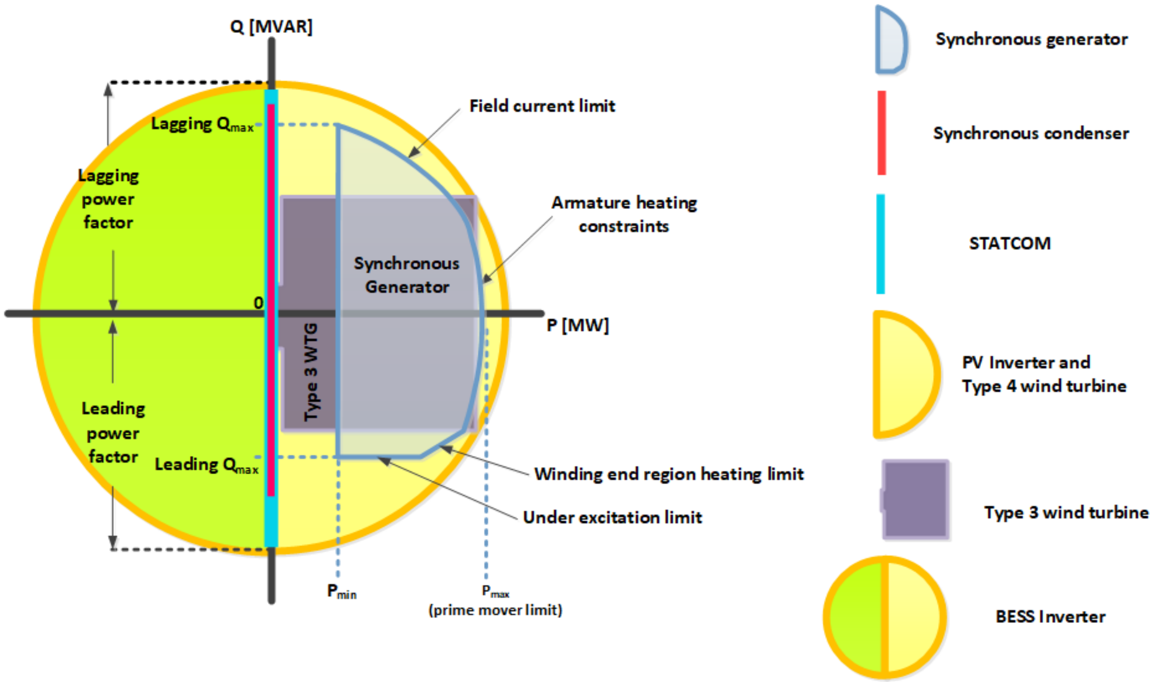
Dispatchable wind power plant



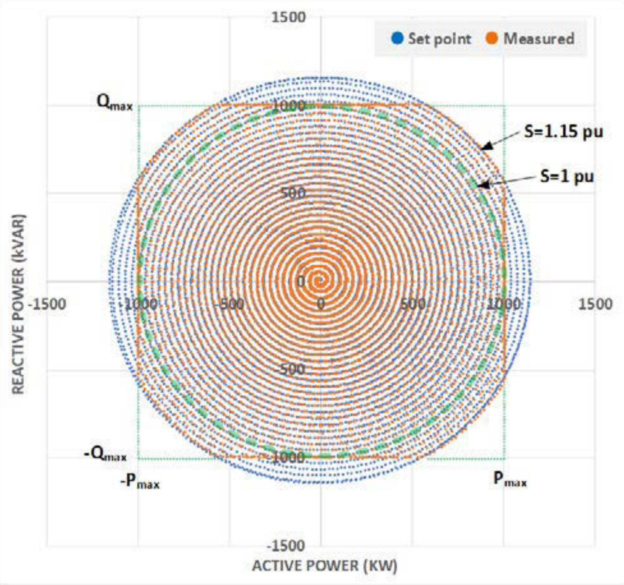


Reactive Power Capability Testing

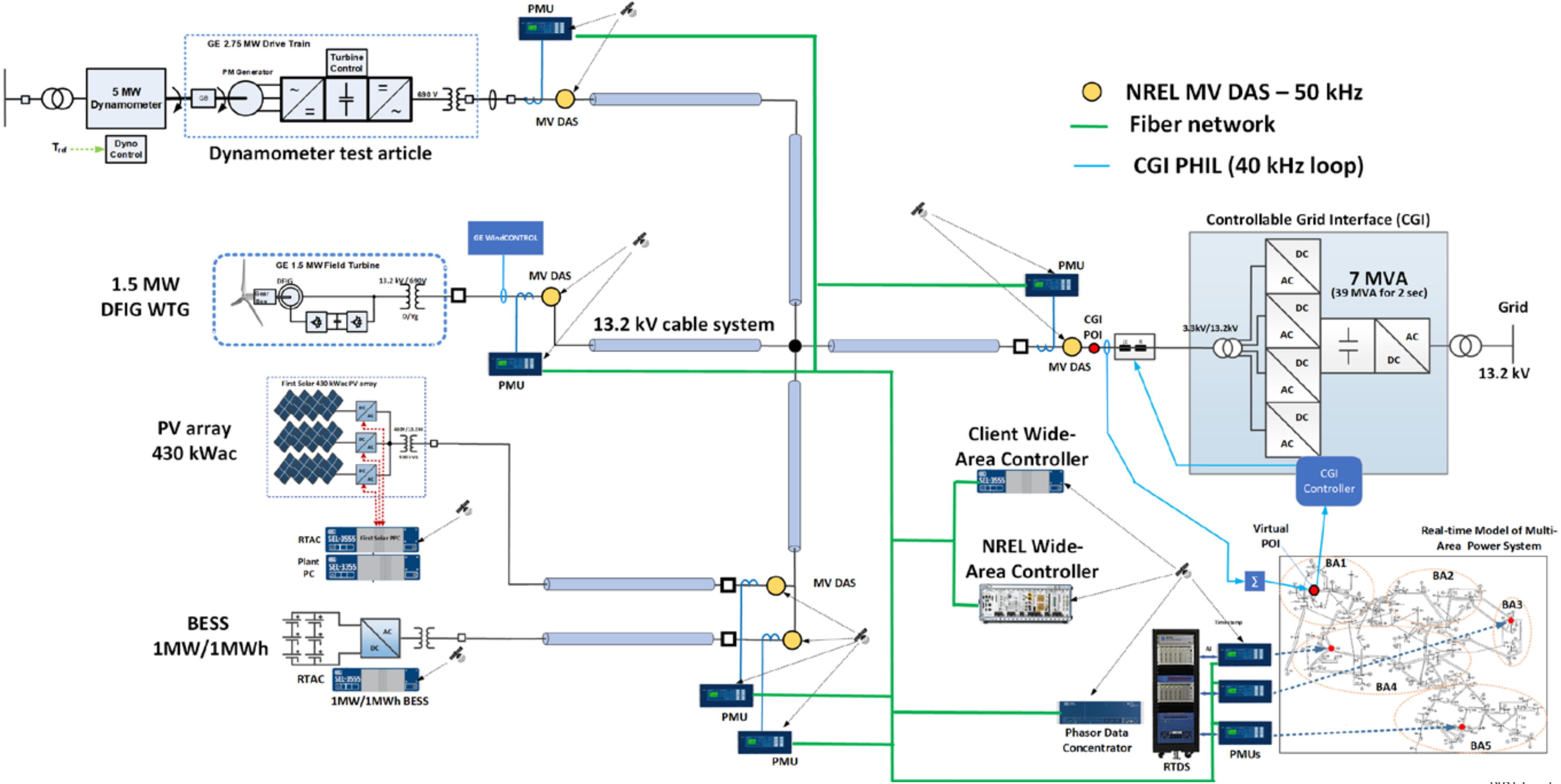
Comparison of Reactive Power Capabilities



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



New NWTC Wide-Area Control Test Bed



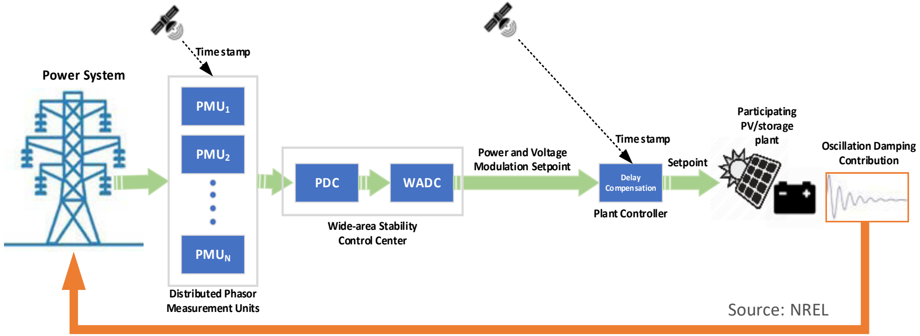
Source: NREL

Components of WAC Test Bed

- Seven GPS-synchronized SEL PMUs installed:
  - MV sides of 1.5-MW wind turbine, 1-MW BESS, 430-kW PV plant, dynamometer test article
  - Coupled with RTDS, so they can be virtually placed at any bus in real-time power system model.
- SEL phasor data concentrator (PDC)
- SEL RTAC
- PMU fiber network
- Integrated with NWTC site controller
- All in parallel with the existing 50-kHz medium-voltage DAS.

Research Opportunities Enabled by WAC Test Bed

- New groundbreaking capability—does not exist elsewhere in the world!
- Develop continuous feedback control systems for real-time power modulation by inverter-coupled generation and energy storage that can be used for enhancing local and wide-area system stability.
- Validate various optimization problems to determine maximum system benefit options for the provision of various power modulation schemes for system stability.
- Develop and test control methods that will use wind, PV, and battery inverters to provide damping for local and inter-area modes in the system. Such systems must be developed unique to each resource type to ensure maximum benefit without damaging the resource (e.g., wind turbines).
- Develop wind, PV, and battery storage transient and dynamic models with power modulation controls for conventional grid integration simulation software tools (PSCAD, PSLF, PSS/E) and validate these models for various grid conditions using the WAC test bed.
- Test NREL-developed or client-provided PMU-based WAC systems
- Use small-signal (linear) and large-signal (nonlinear) impedance-based stability theory for adaptive control development using real-time impedance measurements at both the terminals of the device and remote system feedback using PMUs for wide-area oscillations.



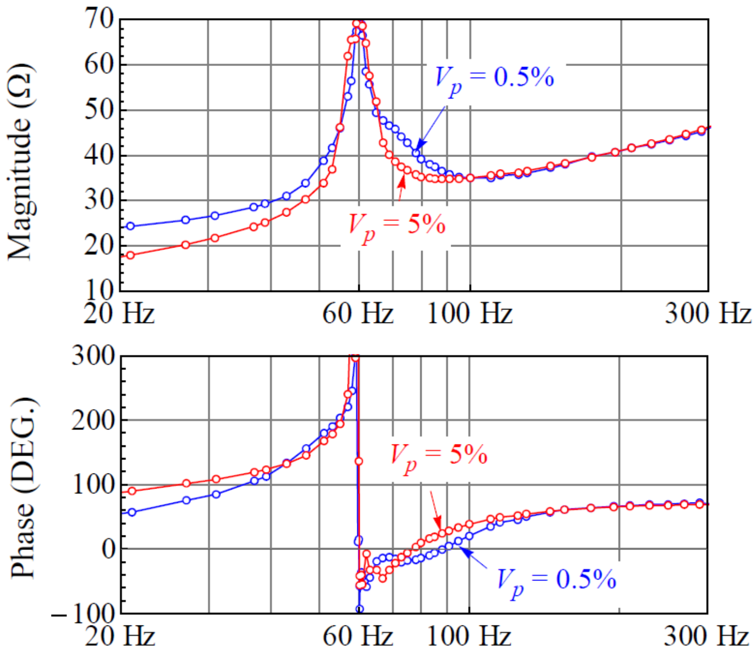
Source: NREL

Example of PV storage system participating in WAC services

Impedance Characterization of Converter-Coupled Generation using CGI

- New automated CGI control was developed for measuring small- and large-signal impedance response of multi-MW-scale inverters
- Injections of voltage perturbations on 13.2-kV bus using CGI
- Measurement system was developed to capture impedance response at different perturbation levels.

Example of measured positive-sequence impedance response of 1-MW BESS inverters for small-signal (0.5%) and large-signal (5%) voltage perturbations using CGI



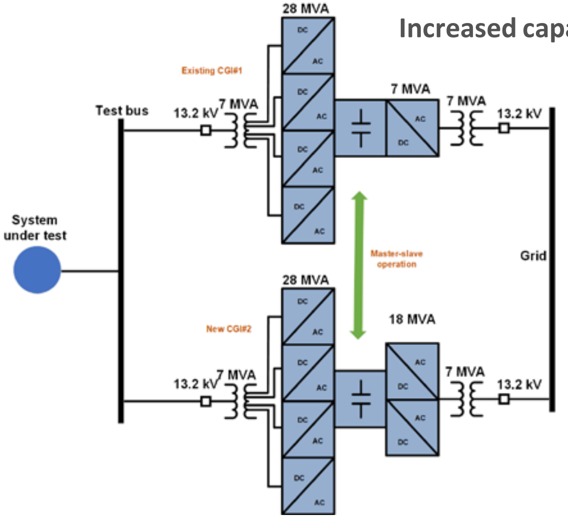
Source: NREL

New Research Opportunities

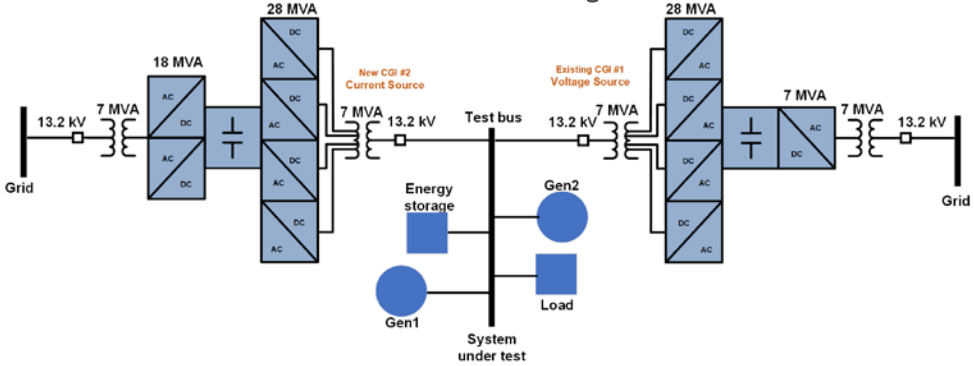
- New unique capability: Small- and large-signal impedance-based characterization of full inverter-coupled resource (wind turbines, PV plants, storage systems, etc.), including MV transformers (This cannot be done anywhere else in the world.)
- Identification of true voltage and current-control bandwidths of inverters
- New field of research: Develop and validate methods for shaping inverter-coupled resource impedances to reduce the resonance severities and mitigate oscillatory behavior in power systems.

CGI#2 Configurations

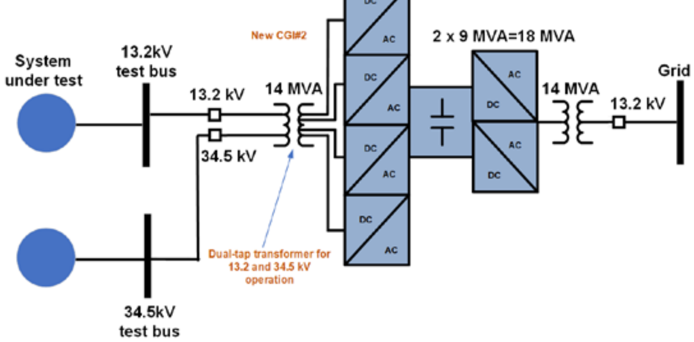
Increased capacity



Back-to-back configuration



Dual voltage

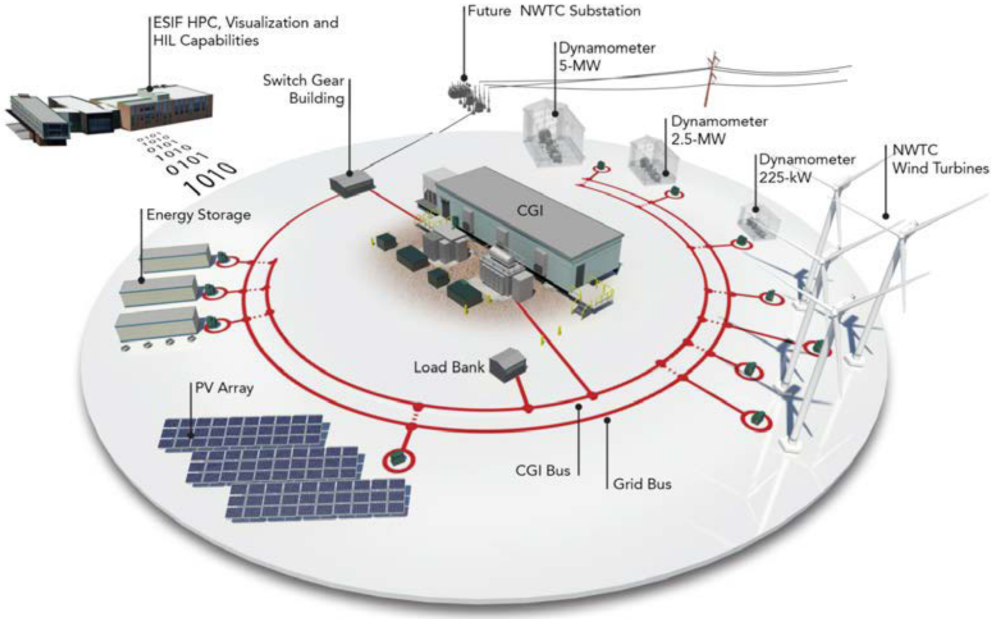


CGI#2 use cases:

- Larger MW capacity
- Conducting more independent experiments
- Voltage/current source operation
- Full microgrid testing configuration
- PHIL with two independent POIs
- Dual medium-voltage levels.

Value Proposition of Grid Simulators

- Cross-technology grid compliance and ancillary services testing at the multi-MW level under controlled grid conditions
- Tool to test for compliance with national and international electrical standards, grid codes, and interconnection requirements
- Tool for advanced controls testing and validation
- Real hardware testing combined with simulation (PHIL)
- Helps increase reliability and reduce integration cost of renewable generation and energy storage.



Thank you

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