NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Hybrid Utility-Scale PV-Wind Storage Plants for Dispatchability and Reliability Services

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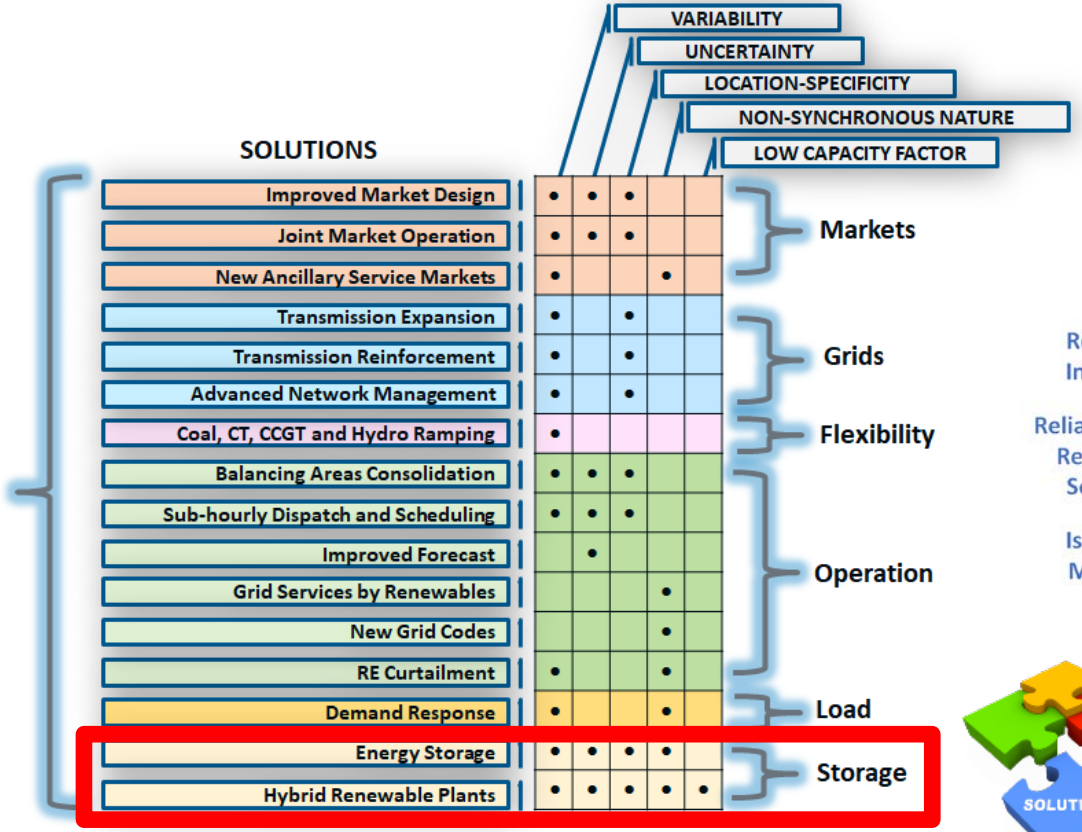
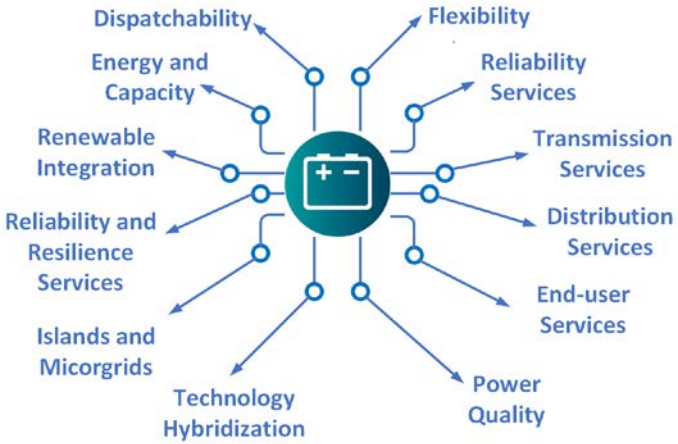
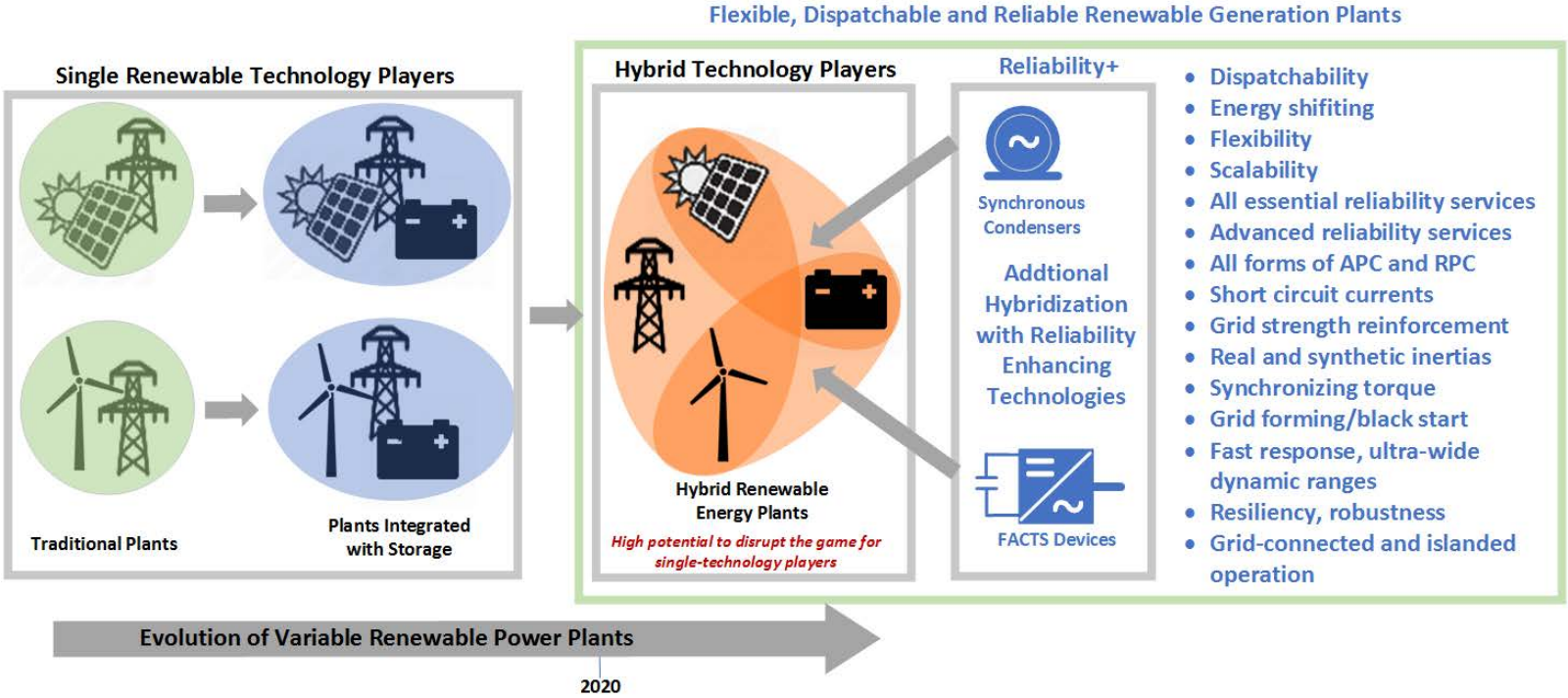
Grid Integration Challenges for Variable Generation



NREL Research

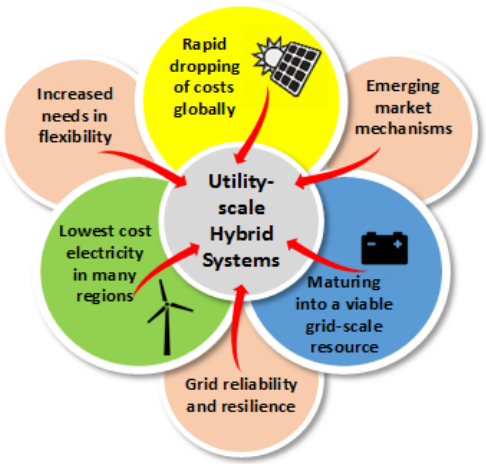


Thinking Beyond Conventional Variable Generation Plants

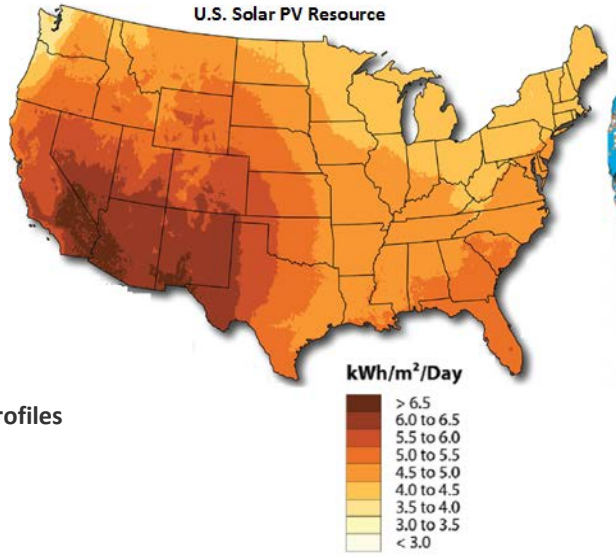


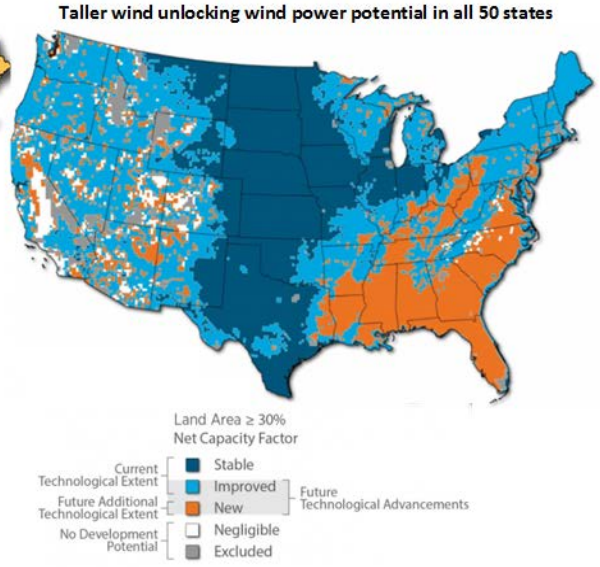
- New source of **dispatchability, flexibility, and reliability**
- Potential to disrupt the market for traditional single-technology players
- Potential transformational impacts on global renewable energy markets.

Ingredients of the Hybridization Recipe

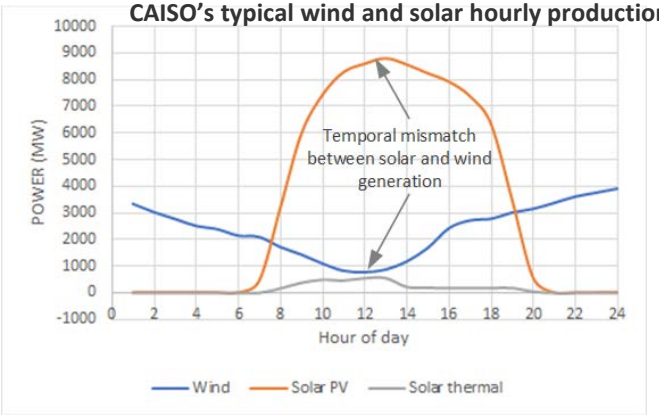


Bringing "taller" economic wind power to areas rich in solar resource



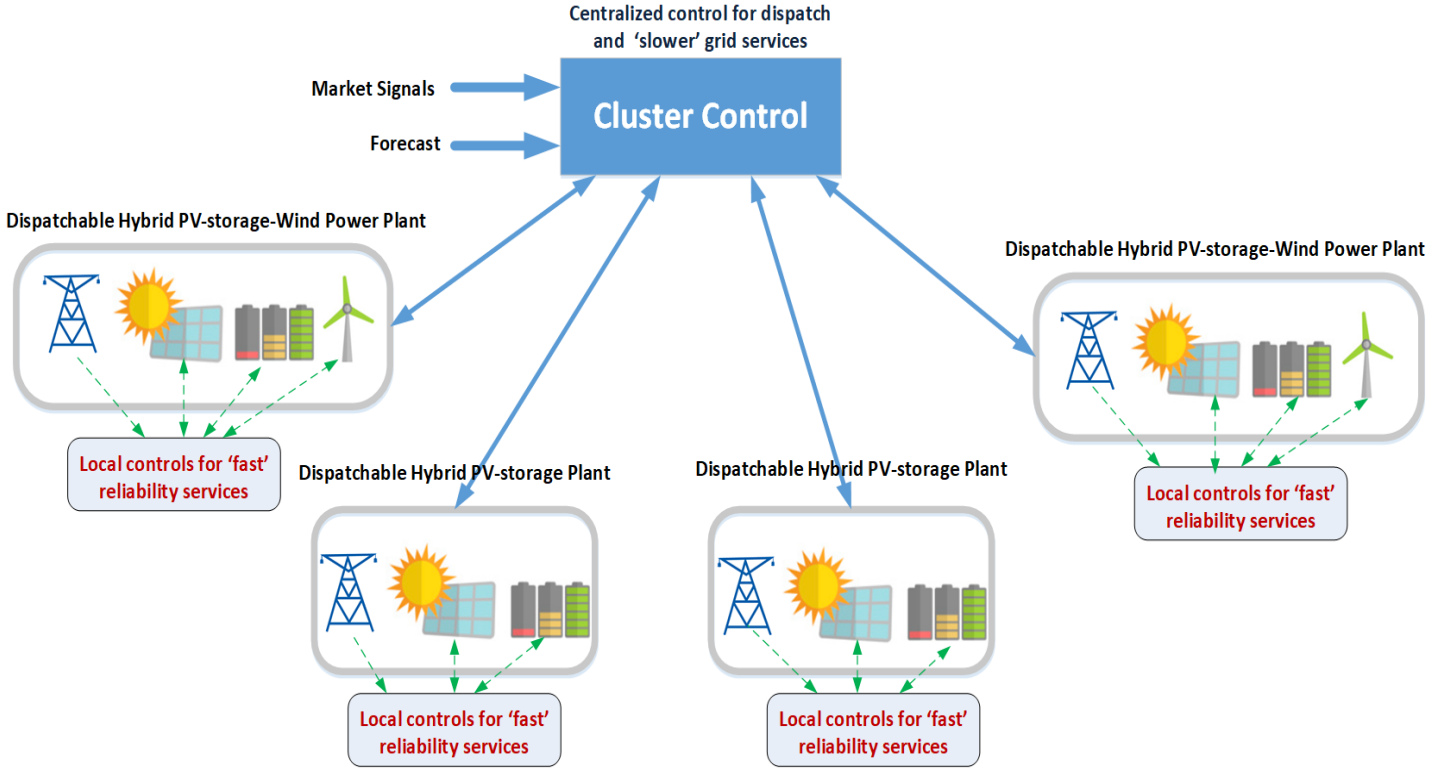


CAISO's typical wind and solar hourly production profiles



- **Unlocking wind energy's potential across an additional 700,000 miles²**
- **Potential for vast expansion of the geographic areas where the complementary nature between economic solar and wind resources can exist**
- **Geographical overlap between solar resource-rich areas and new land areas that can achieve a minimum 30% net capacity factor for wind generation at 140-m hub height.**

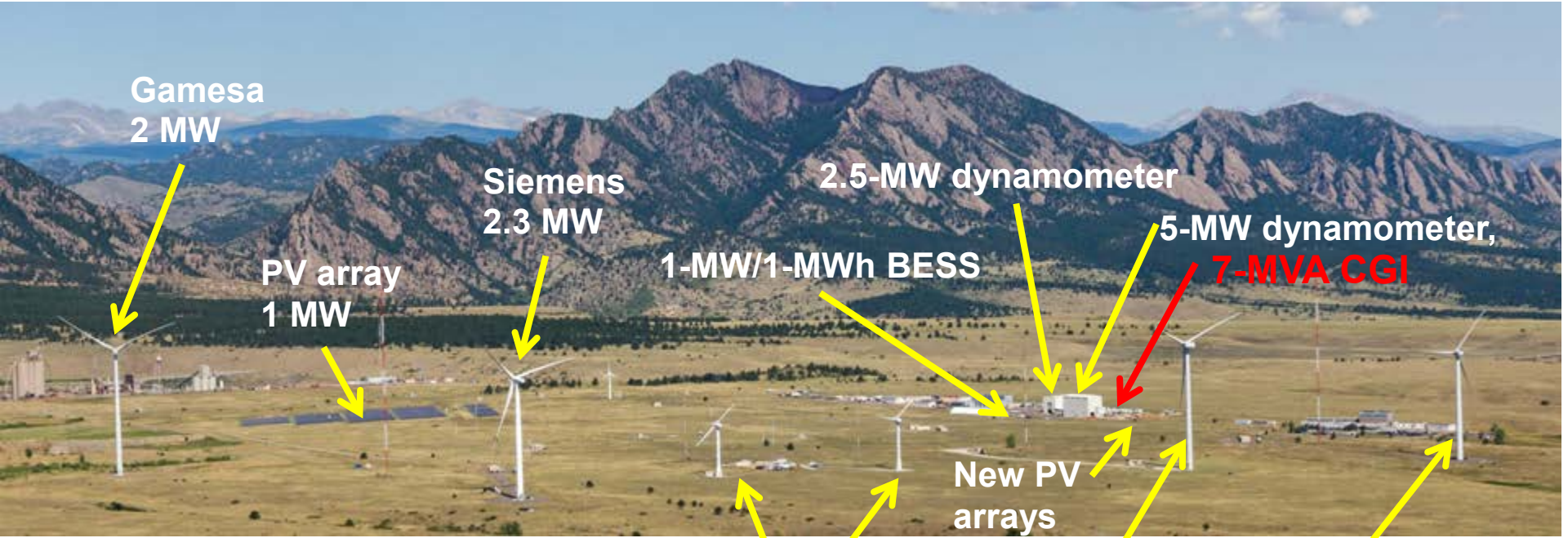
GE–NREL Concept



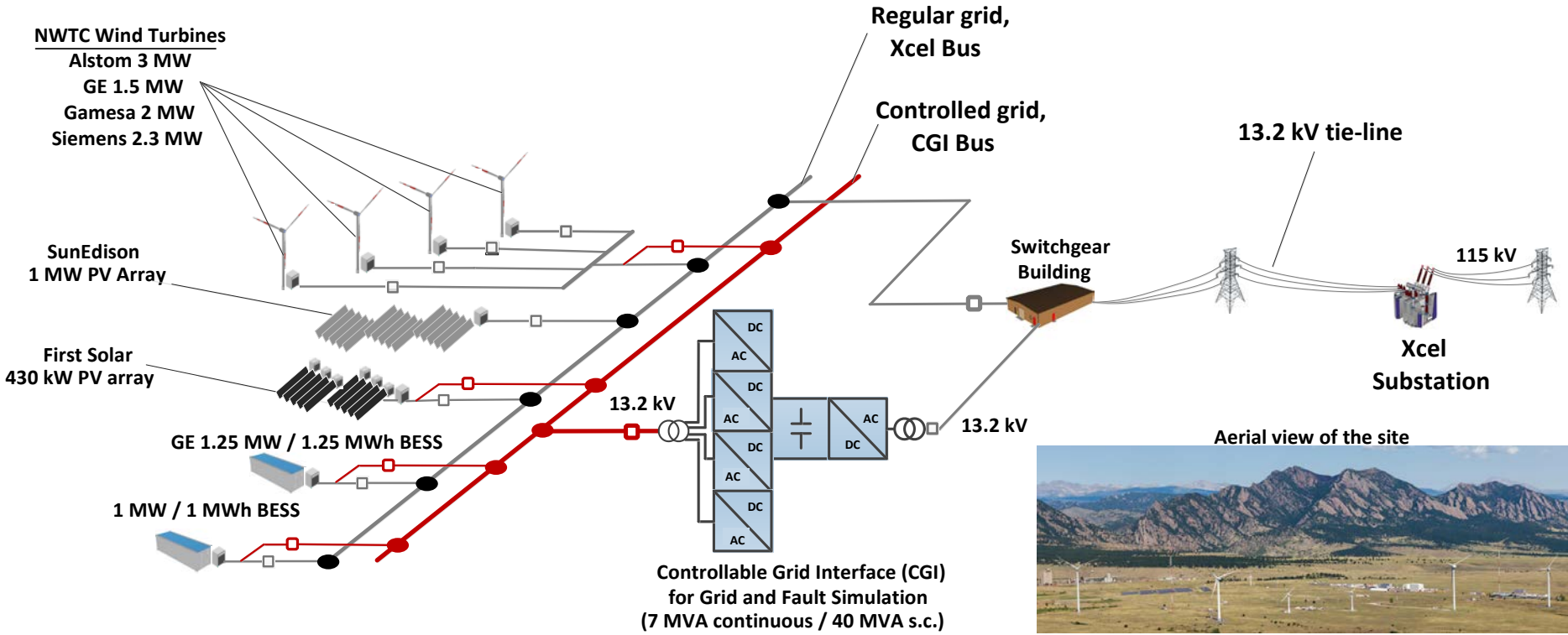
- **Benefits?**
- **Use cases?**
- **How to size?**
- **How to control?**

NREL NWTC Test Site

- *Current total of more than 12 MW variable renewable generation*
- *7-MVA controllable grid interface (CGI)*
- *Multi-MW energy storage test facility*
- *2.5-MW and 5-MW dynamometers (industrial motor drives)*
- *13.2-kV medium-voltage grid.*



NWTC Controllable Grid Platform



Aerial view of the site

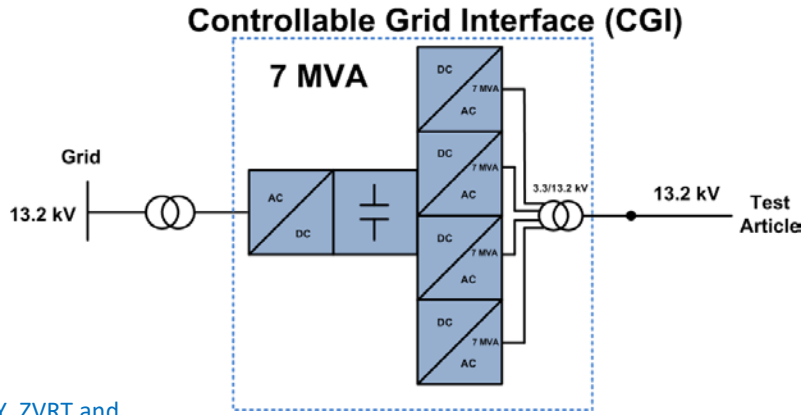
Controllable Grid Interface

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

Possible test articles
- Wind turbine types 1, 2, 3, and 4
- Capable of fault testing largest Type 3 wind turbines
- PV inverters, energy storage systems
- Conventional generators
- Combinations of technologies.

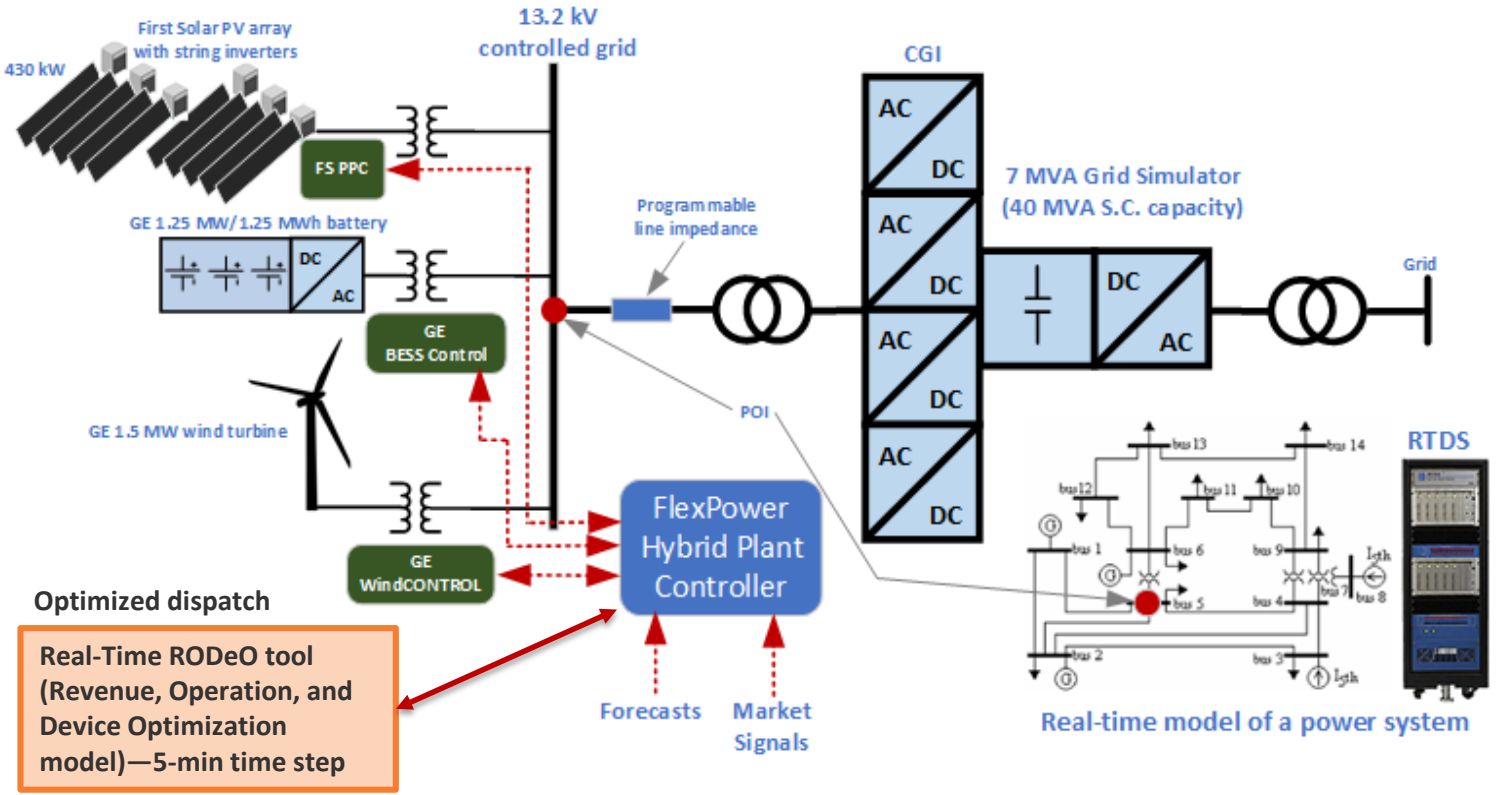
Voltage control (no load THD <3%)
- Balanced and unbalanced voltage fault conditions (LVTY, ZVRT and 130% HVRT)—independent voltage control for each phase on 13.2-kV terminals
- Response time: 1 ms (from full voltage to zero—or from zero back to full voltage)
- Long-term symmetrical voltage variations (+/- 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 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.)

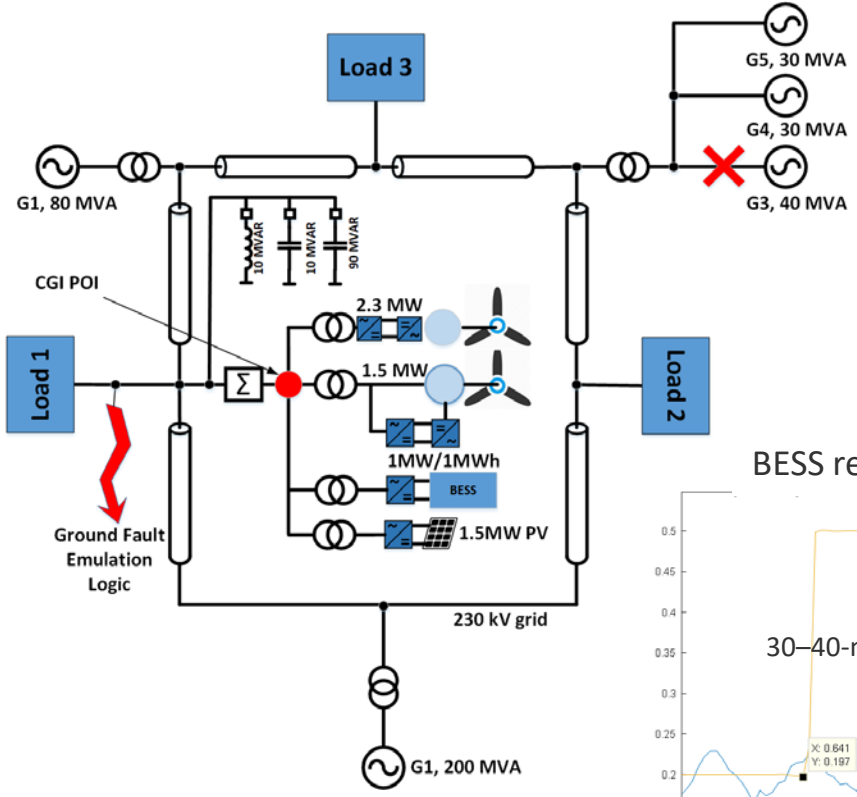


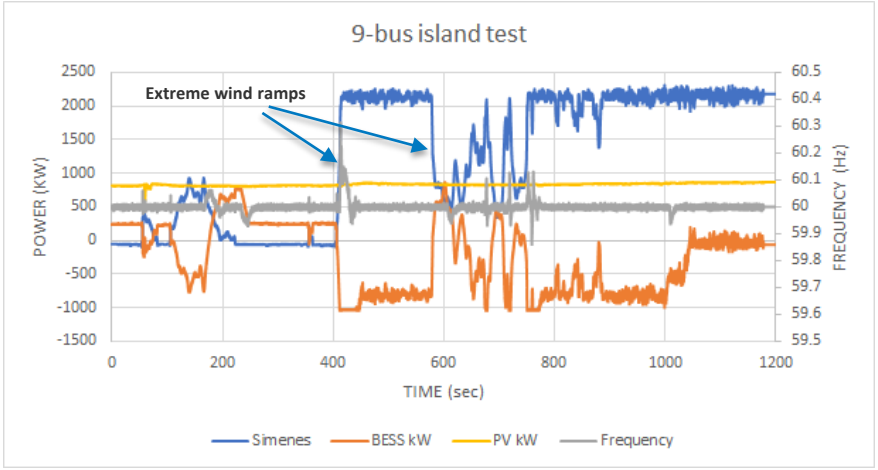
Capabilities
- Balanced and unbalanced over and under voltage fault ride-through tests
- Frequency response tests
- Continuous operation under unbalanced voltage conditions
- Grid condition simulation (strong and weak)
- Reactive power, power factor, voltage control testing
- Protection system testing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

Hybrid Systems Test and Control Validation Platform

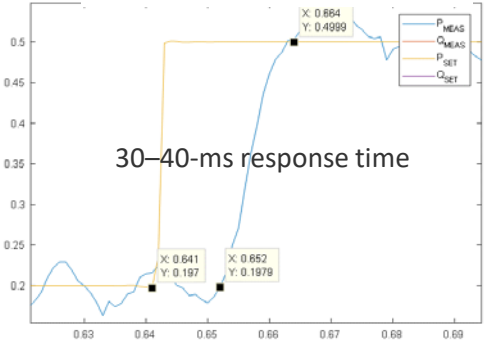


Island Power System Model in RTDS (IEEE 9 Busses)

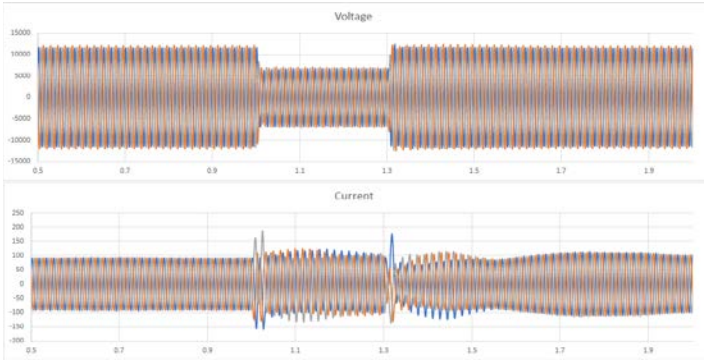




BESS response times

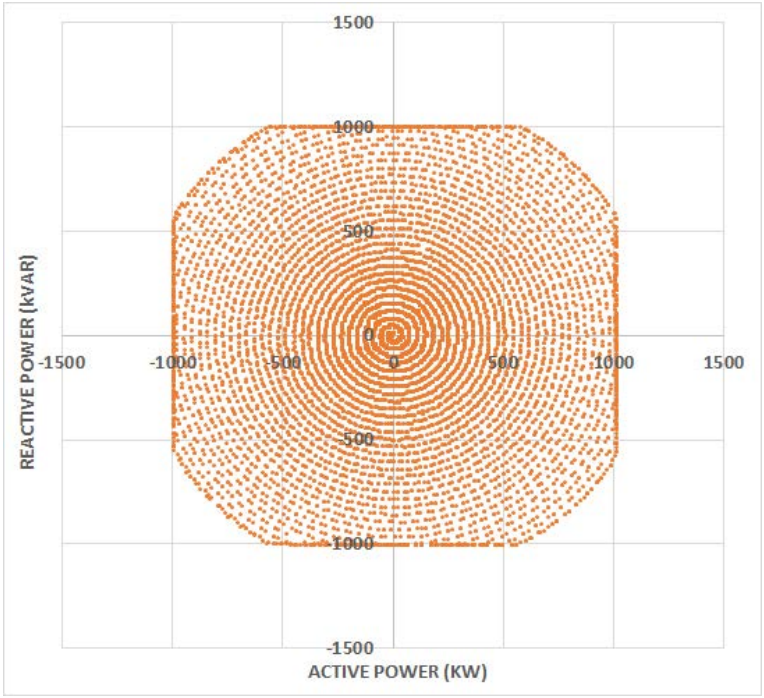


Hybrid plant voltage FRT test

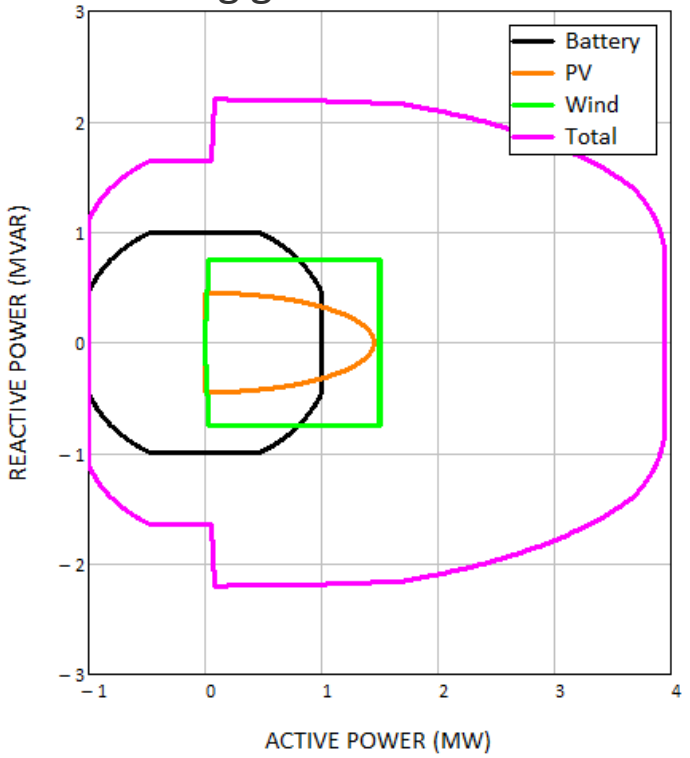


Hybrid Plant P-Q Capability

BESS only—strong grid

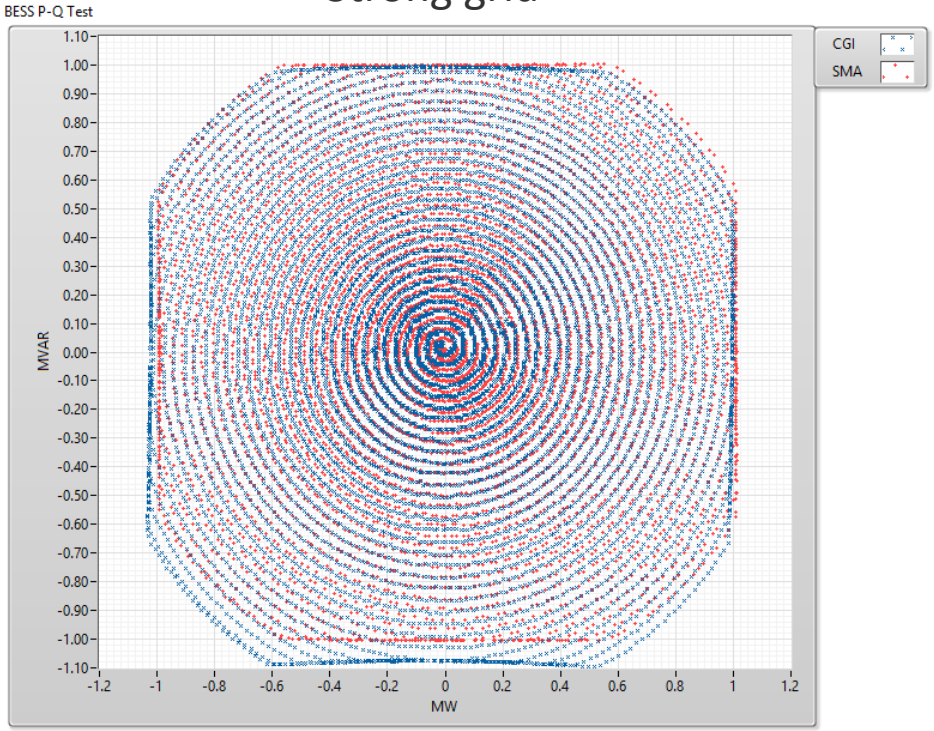


Hybrid plant: 1.5-MW PV, 1.5-MW wind, 1-MW BESS—strong grid

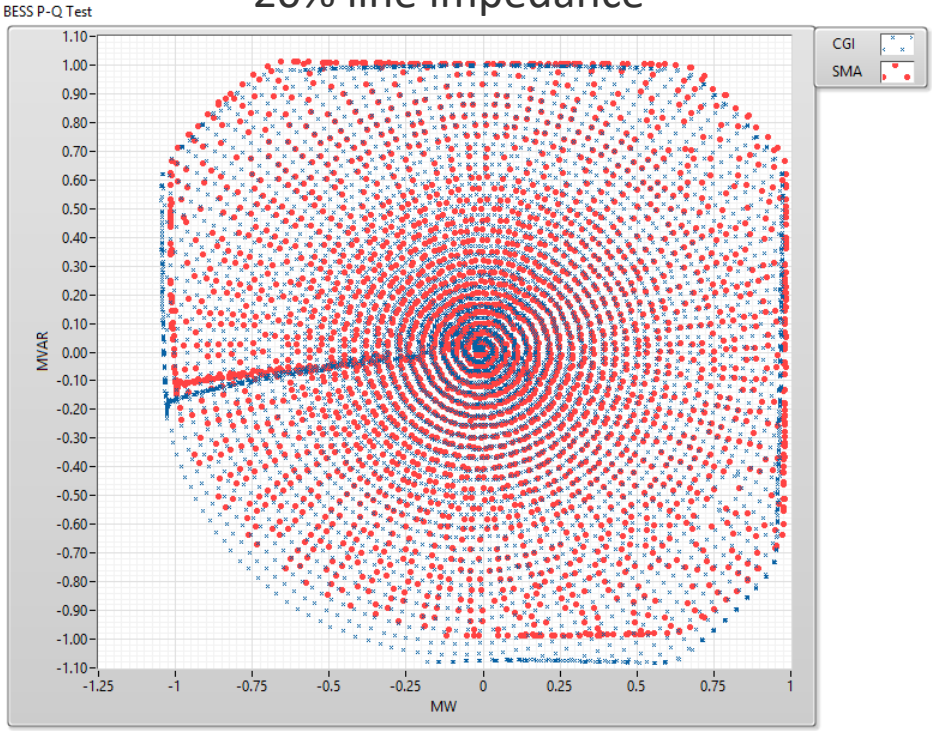


BESS P-Q Capability

Strong grid

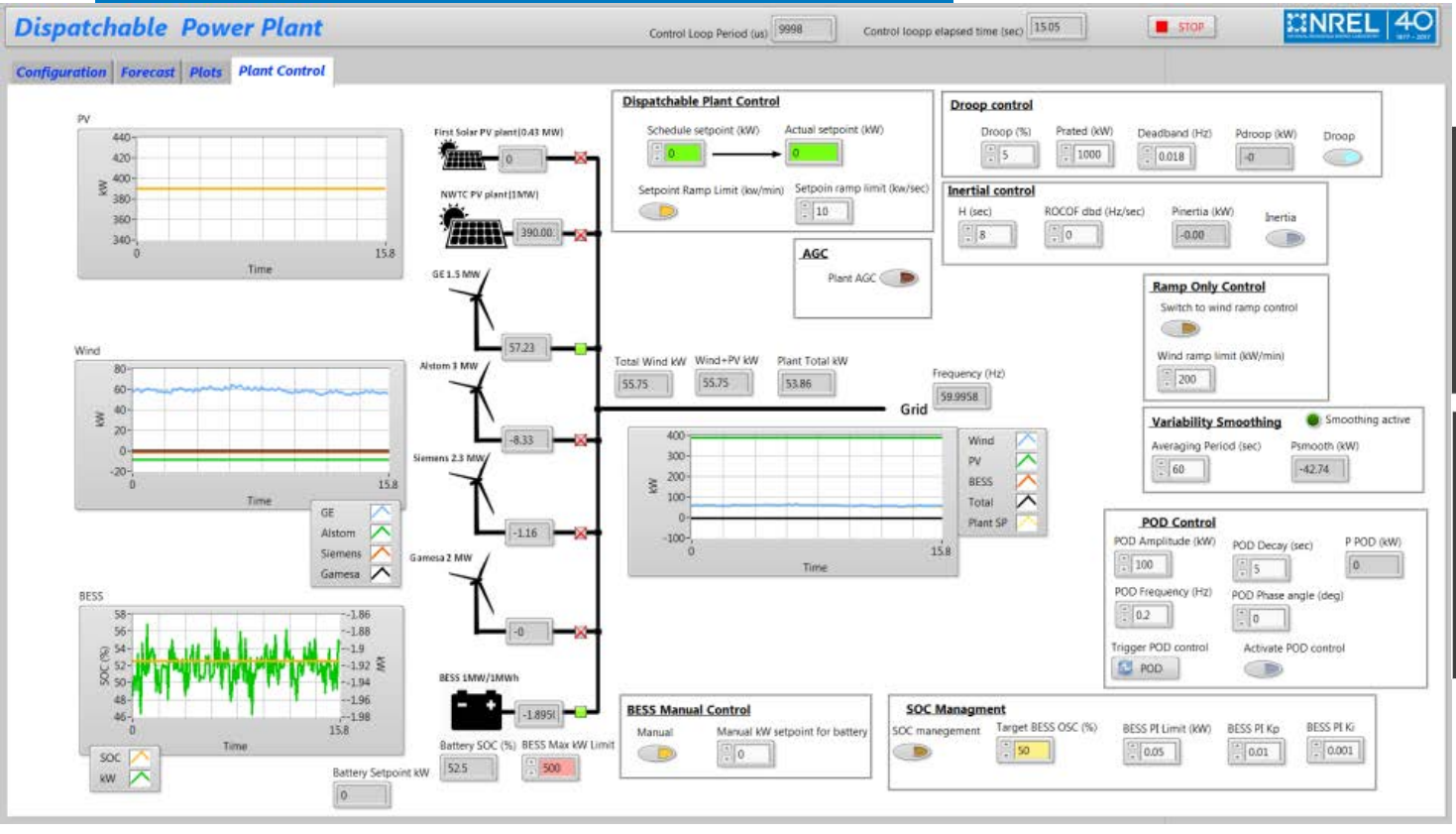


20% line impedance



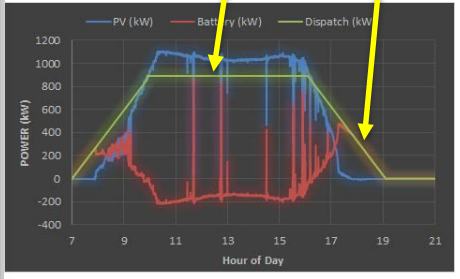
Dispatchable Hybrid Power Plant

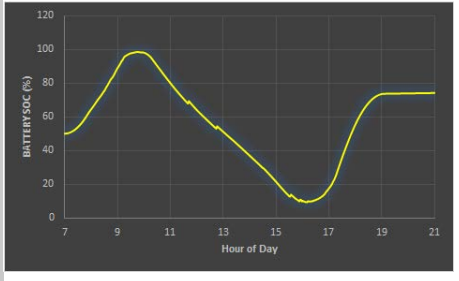
Main control panel



Reduced ramps

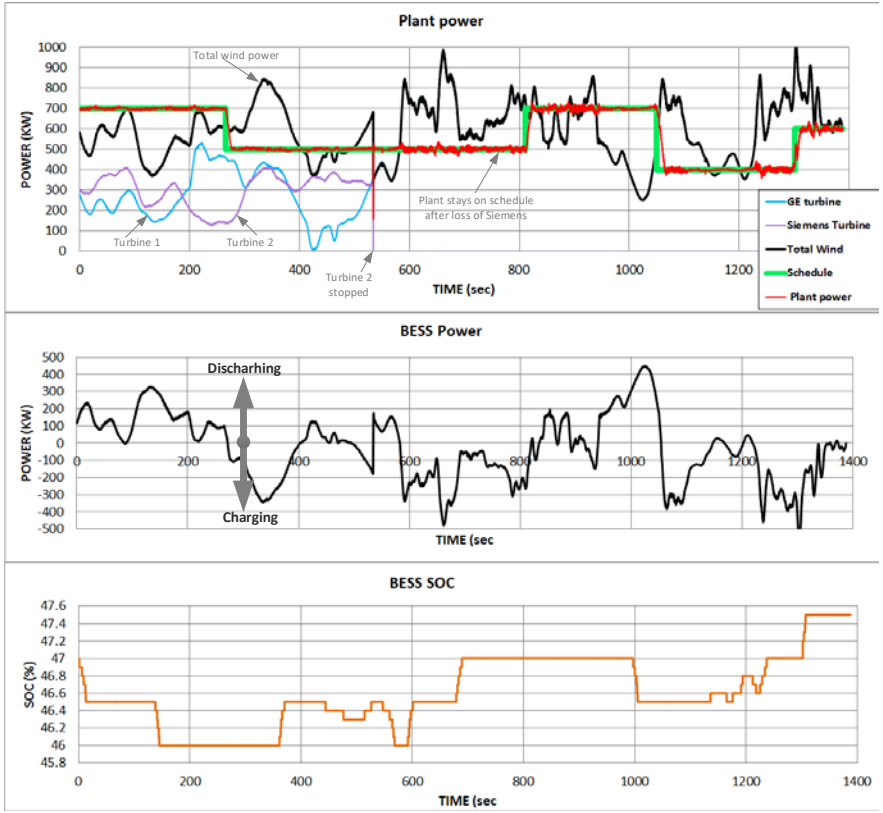
No curtailment

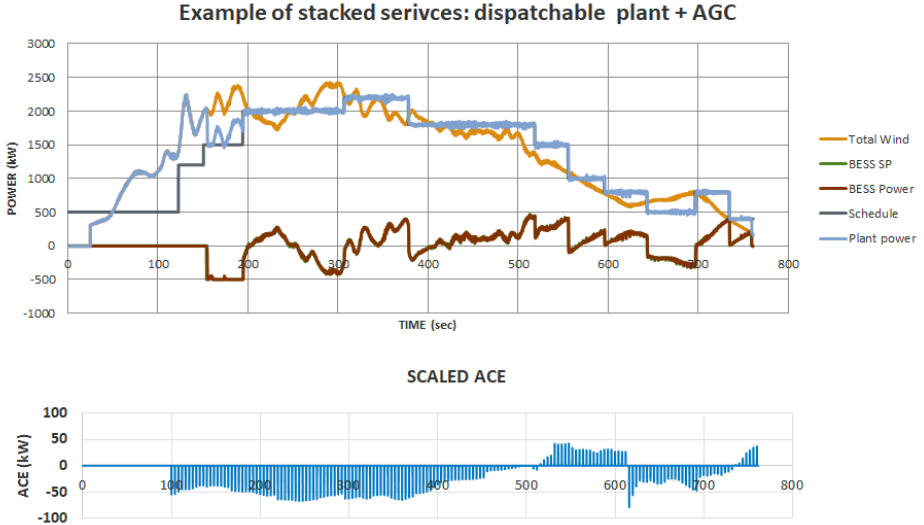




Examples of Dispatchable Operation Demo

Dispatchable wind power plant

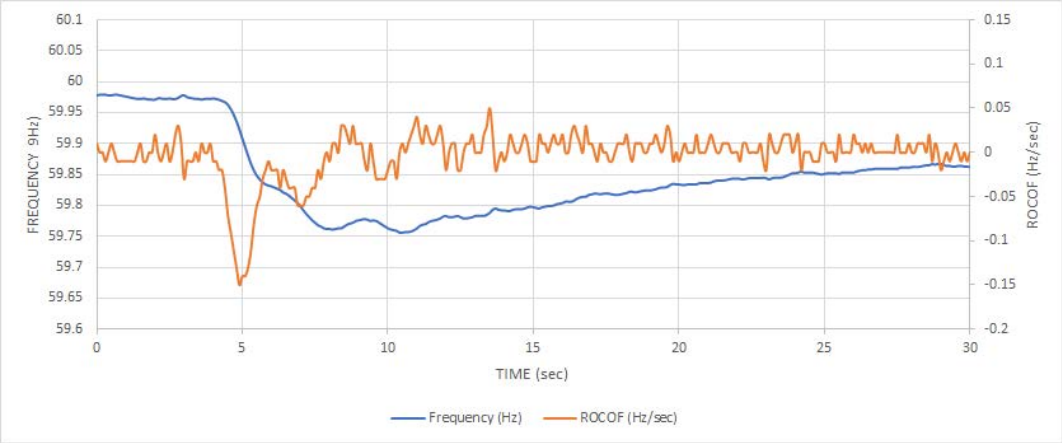


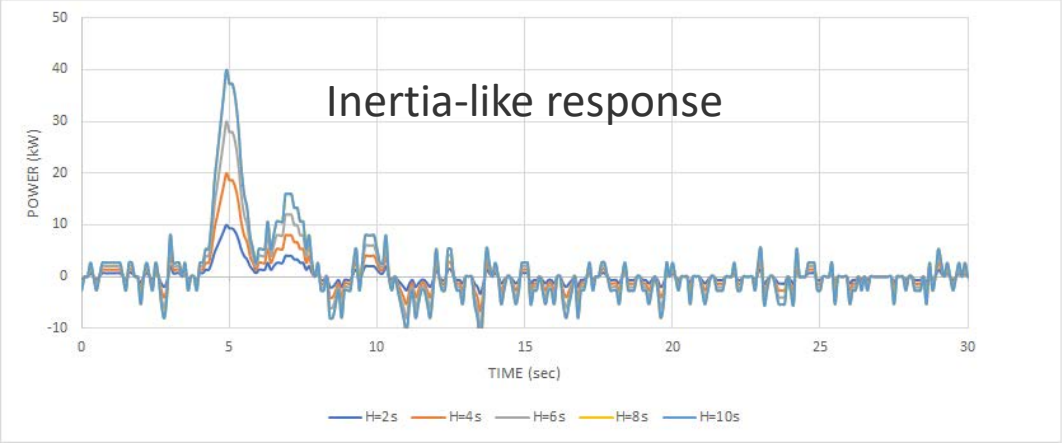


Dispatch set point | **Synthetic inertia** | **Primary frequency response** | **AGC participation**

$$P_{bess}(t) = P_0 - 2H\frac{df}{dt} - \frac{\Delta f}{droop} + K_P \cdot \text{ACE}$$

BESS Emulating Response of Rotating Generator

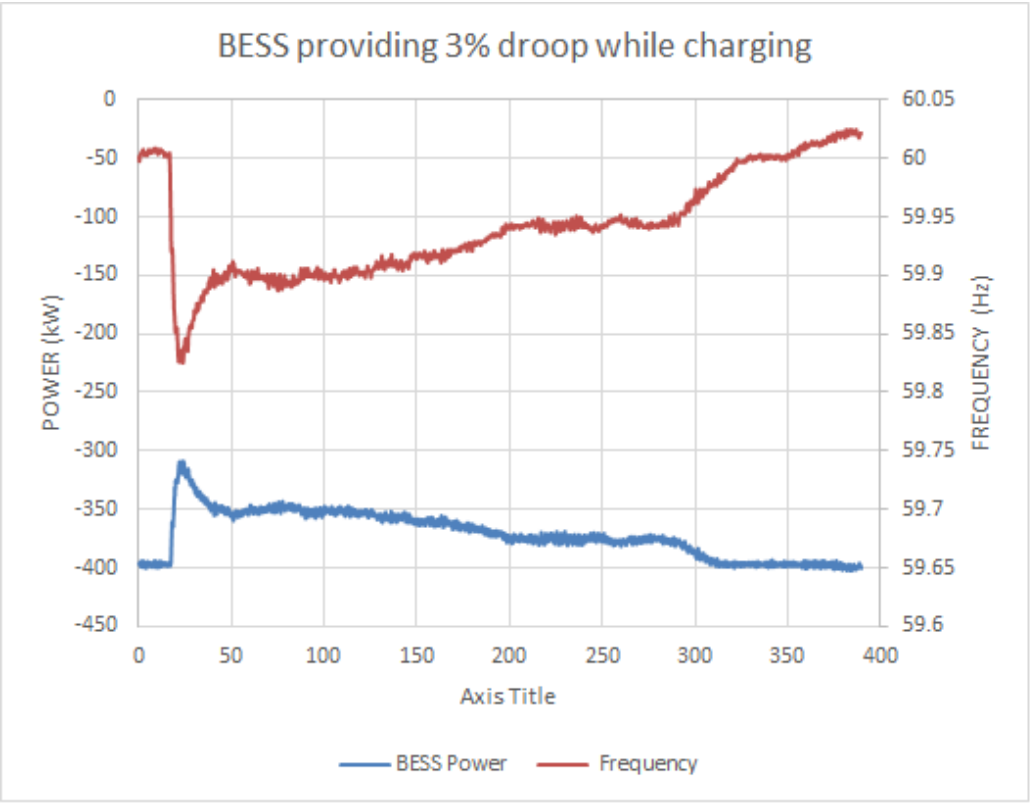


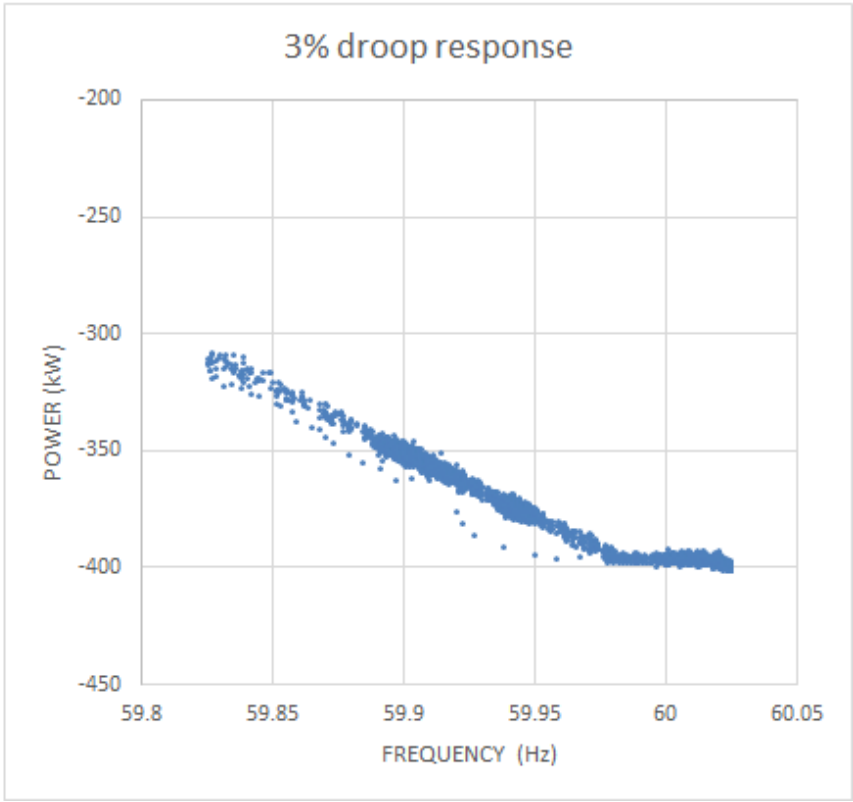


$$\Delta P = -2H \cdot f \cdot \frac{df}{dt}$$

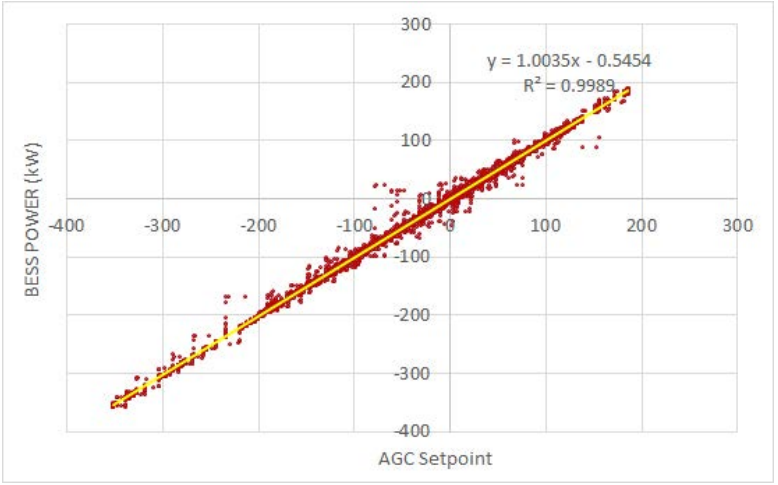
- BESS can operate with programmable H.
- Different shapes of inertial response can be implemented.
- ROCOF deadbands are implemented to reduce impacts on battery life.

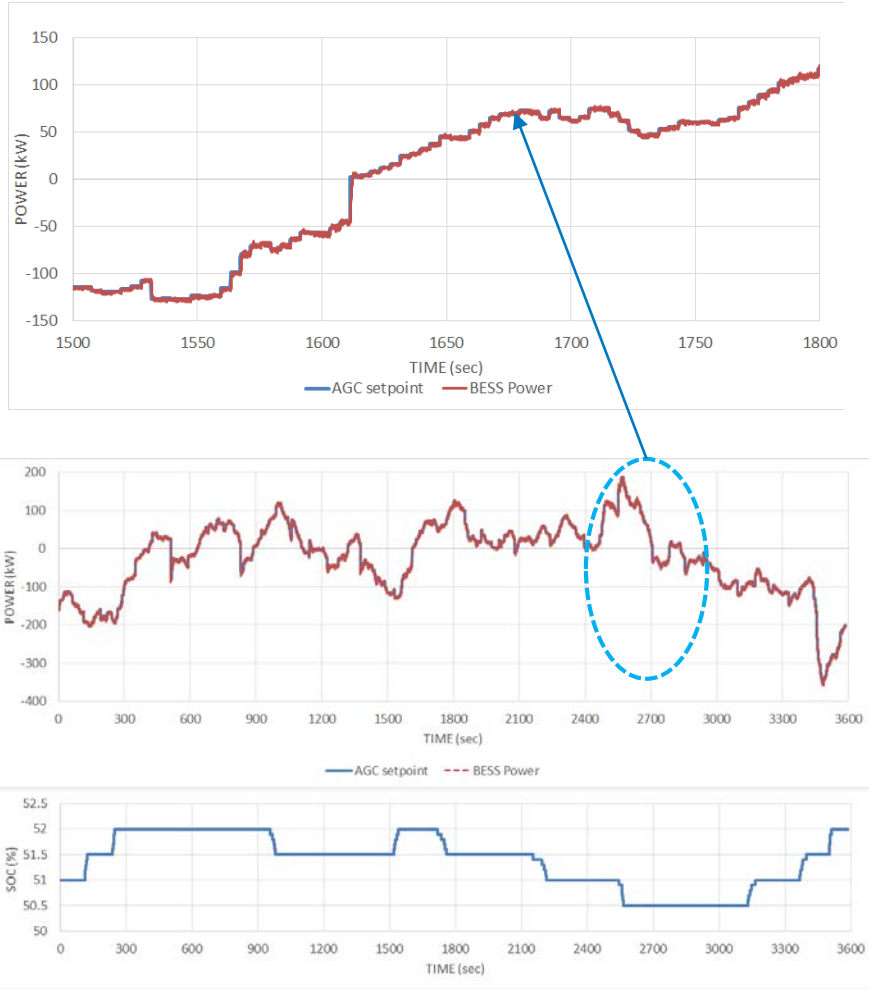
BESS Providing PFR





BESS Participating in AGC

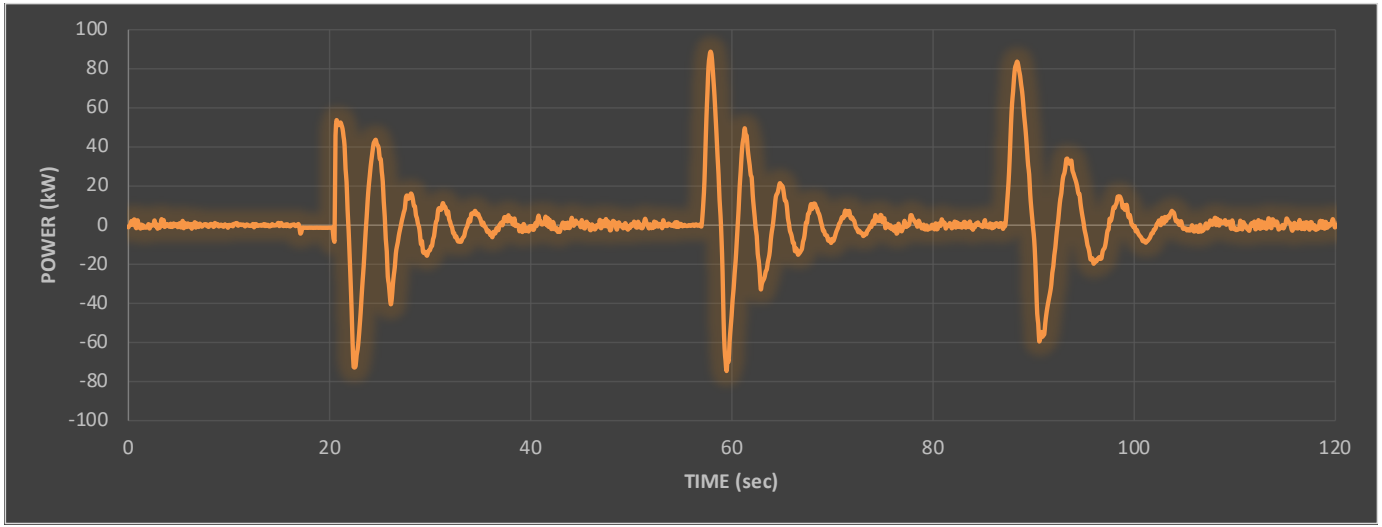




- PSCO historic area control error (ACE) time series (updated every 4 s)
- ACE is scaled down to match BESS rating.

POD Controls by BESS

Demonstration of power oscillations damping control by BESS



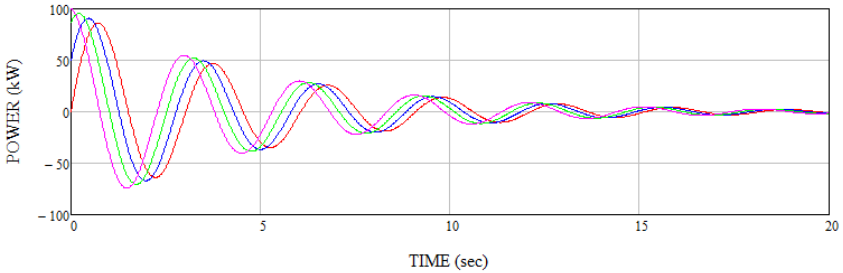
Magnitude of POD response

Frequency of oscillations

$$P(t) = P_m e^{-\frac{t}{T}} \sin(2\pi f t + \varphi)$$

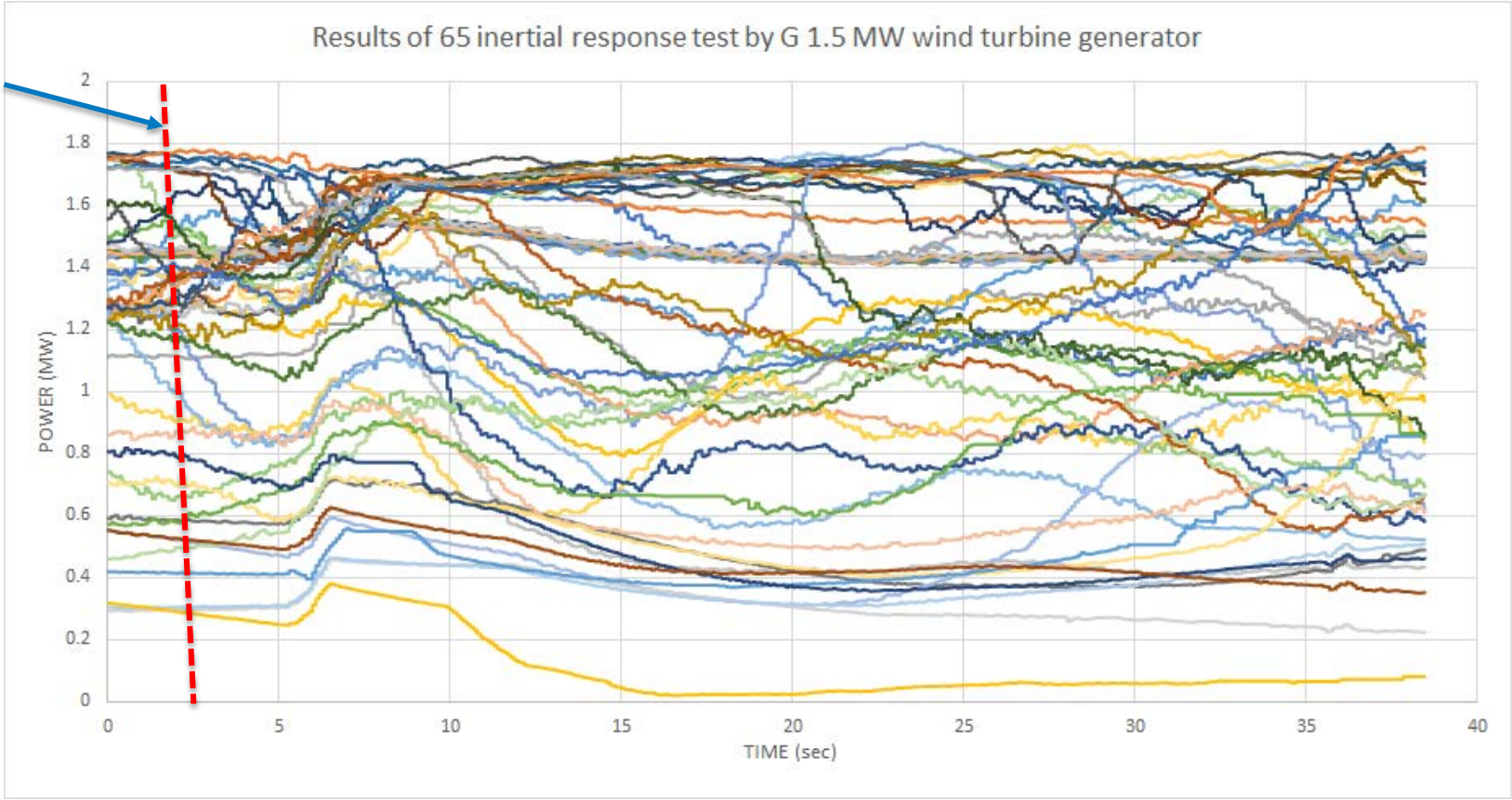
Decay time

Phase angle of oscillations

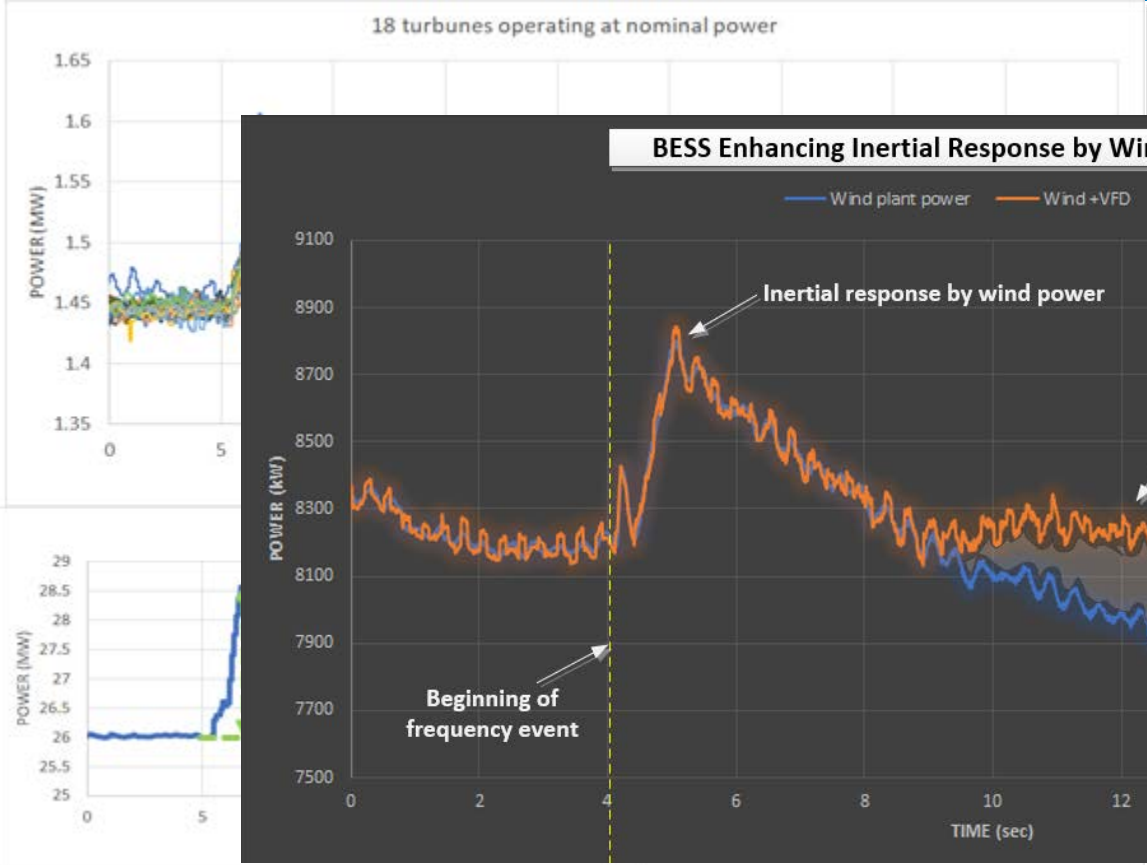


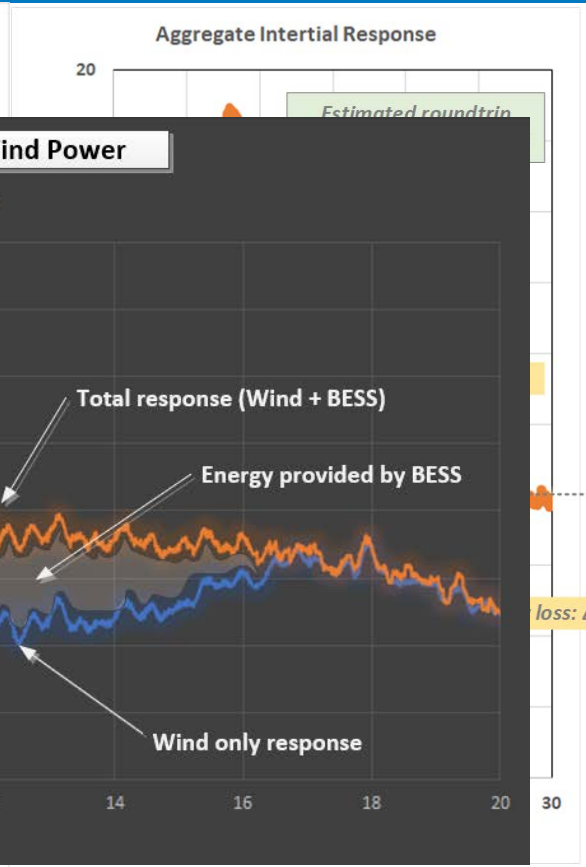
Emulated Inertial Responses of Individual Wind Turbines in a 150-MW Wind Power Plant

Frequency event emulated by CGI—1 Hz/s ROCOF



Aggregate Inertial Response of Large Wind Power Plant





loss: ΔE = -251 MWs

Services by Multi-Technology (Hybrid) Power 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
- Ramp limiting, variability smoothing, cloud-impact mitigation
- Provision of spinning reserve
- AGC functionality
- Primary frequency response (programmable droop control)
- Fast frequency response (FFR)
- Inertial response:
  - programmable synthetic inertia for a wide range of H constants emulated by BESS
  - Selective inertial response strategies by wind turbines
- Reactive power/voltage control
- Black start by BESS
- Advanced controls: power system oscillations damping
- Stacked services
- Plant electric loss reduction, AEP increase
- Selective plant configuration for BESS: ability to serve a whole wind power plant, or selected rows/turbines
- Battery SOC management
- Optimization model-predictive control strategies – work in progress
- Revenue optimization – work in progress

Thank you

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