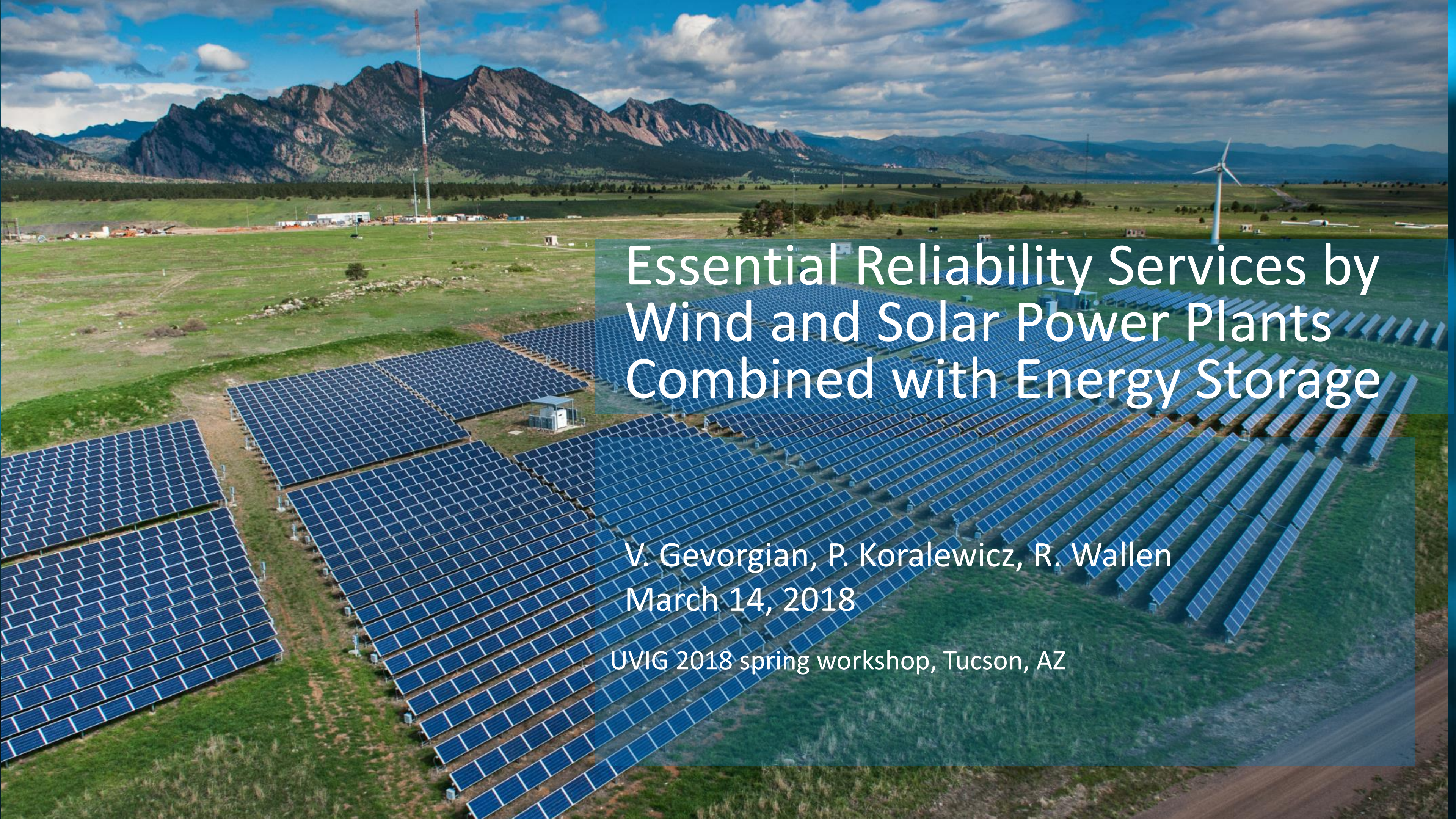


# Essential Reliability Services by Wind and Solar Power Plants Combined with Energy Storage

V. Gevorgian, P. Koralewicz, R. Wallen

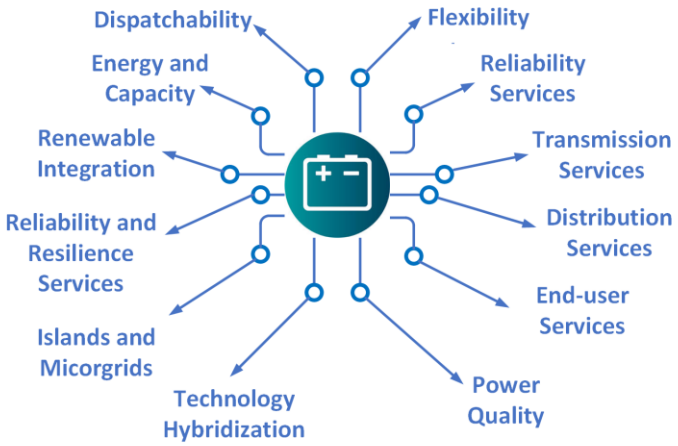
March 14, 2018

UVIG 2018 spring workshop, Tucson, AZ

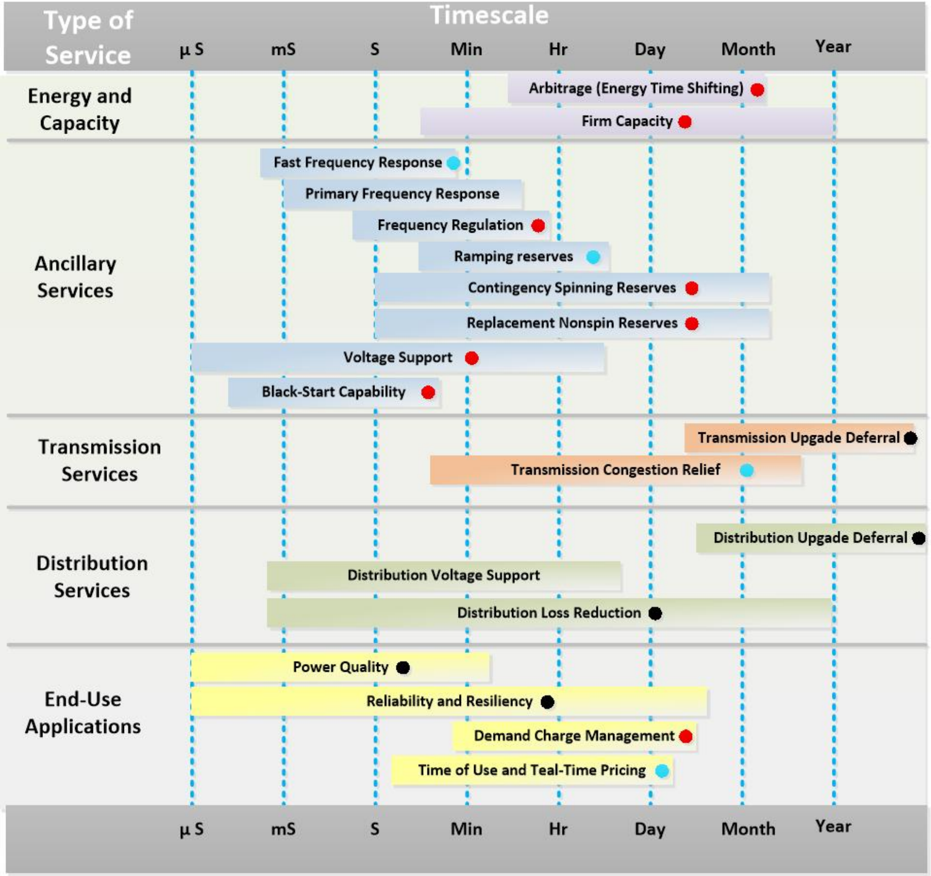
# Grid Integration Challenges for Variable Generation

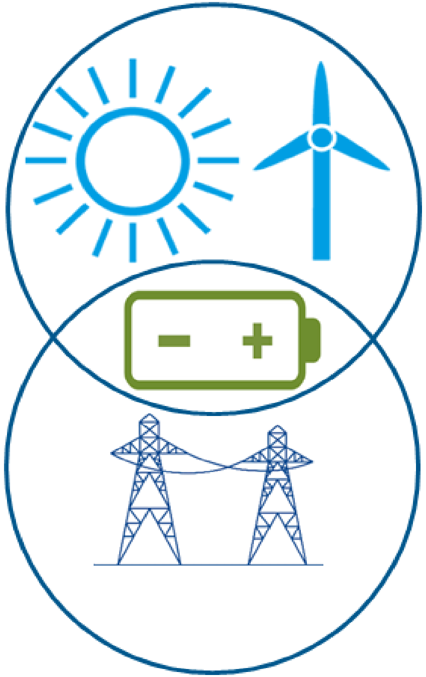
NREL Research

| SOLUTIONS | VARIABILITY | UNCERTAINTY | LOCATION-SPECIFICITY | NON-SYNCHRONOUS NATURE | LOW CAPACITY FACTOR | |
|---|---|---|---|---|---|---|
| Improved Market Design | • | • | • | | | Markets |
| Joint Market Operation | • | • | • | | | Markets |
| New Ancillary Service Markets | • | | | • | | Markets |
| Transmission Expansion | • | | • | | | Grids |
| Transmission Reinforcement | • | | • | | | Grids |
| Advanced Network Management | • | | • | | | Grids |
| Coal, CT, CCGT and Hydro Ramping | • | | | | | Flexibility |
| Balancing Areas Consolidation | • | • | • | | | Operation |
| Sub-hourly Dispatch and Scheduling | • | • | • | | | Operation |
| Improved Forecast | | • | | | | Operation |
| Grid Services by Renewables | | | | • | | Operation |
| New Grid Codes | | | | • | | Operation |
| RE Curtailment | • | | | • | | Operation |
| Demand Response | • | | | • | | Load |
| Energy Storage | • | • | • | • | • | Storage |
| Hybrid Renewable Plants | • | • | • | • | • | Storage |



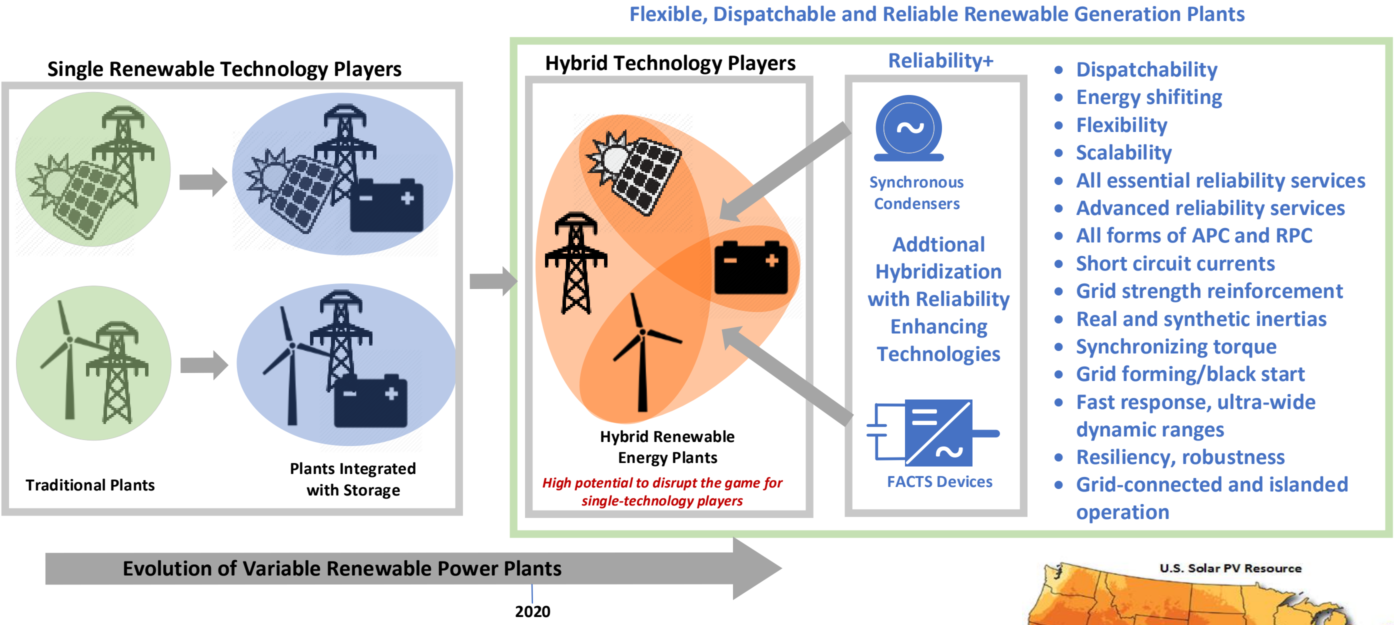

# Value Streams of Battery Energy Storage

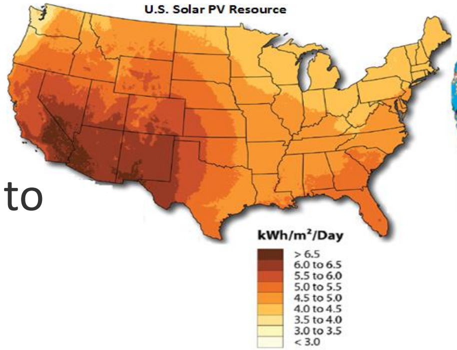


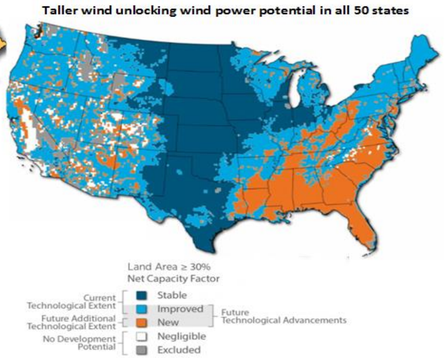



- Services currently valued in some markets
- Proposed or early adoption services
- Currently not valued services

# Thinking beyond traditional variable-generation plants



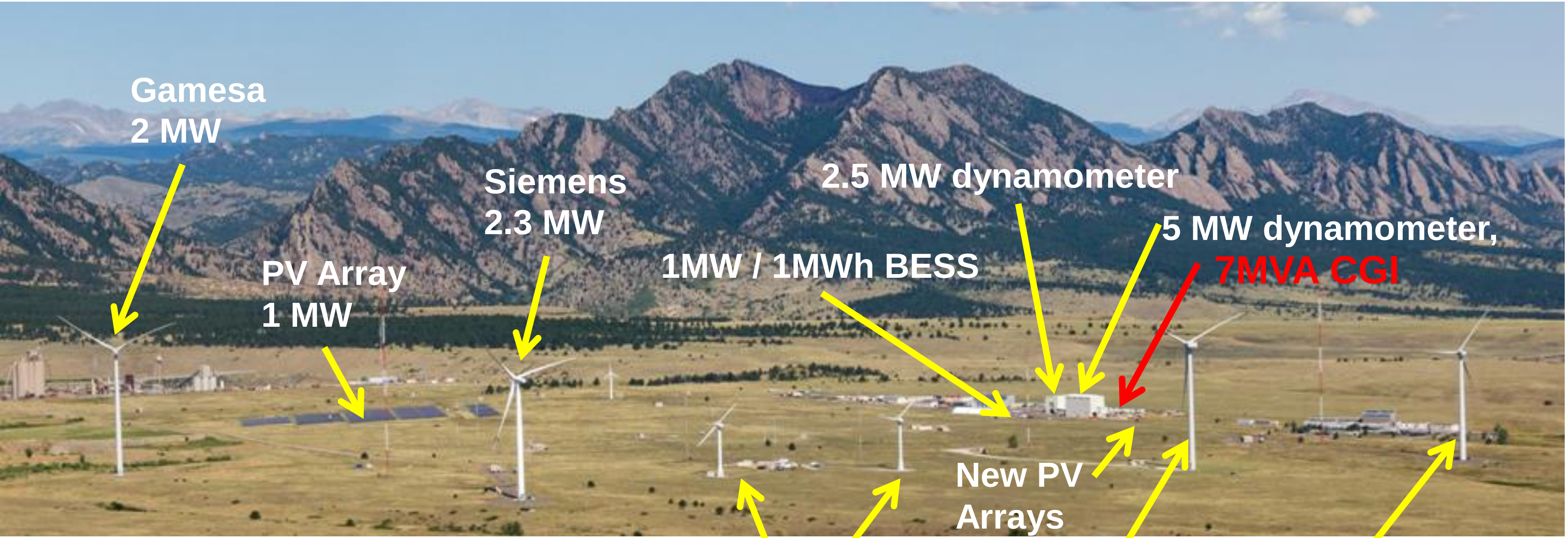



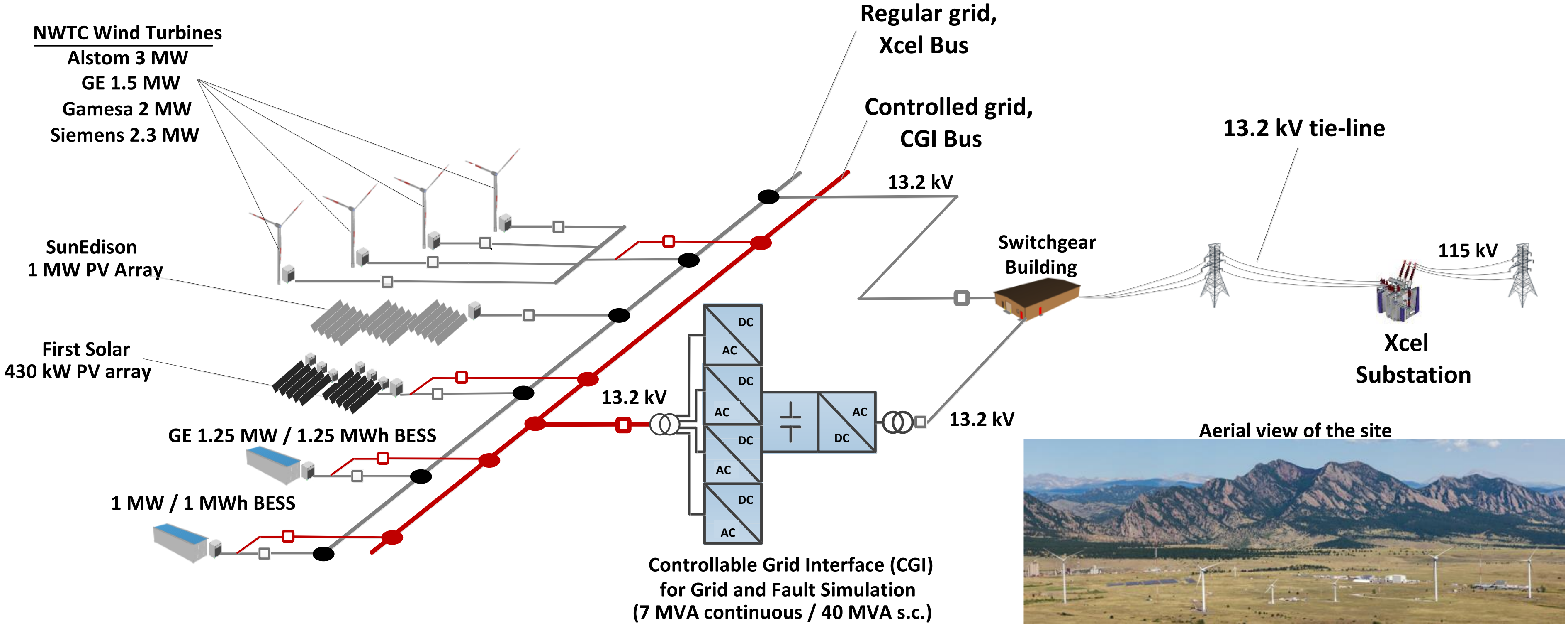

Bringing “taller” economic wind power to areas rich in solar resource

# NREL/NWTC Test Site

- *Total of 12+ MW variable renewable generation currently*
- *7 MVA Controllable Grid Interface (CGI)*
- *Multi-MW energy storage test facility*
- *2.5MW and 5 MW dynamometers (industrial motor drives)*
- *13.2 kV medium voltage grid*



# NWTC Controllable Grid Platform




Aerial view of the site

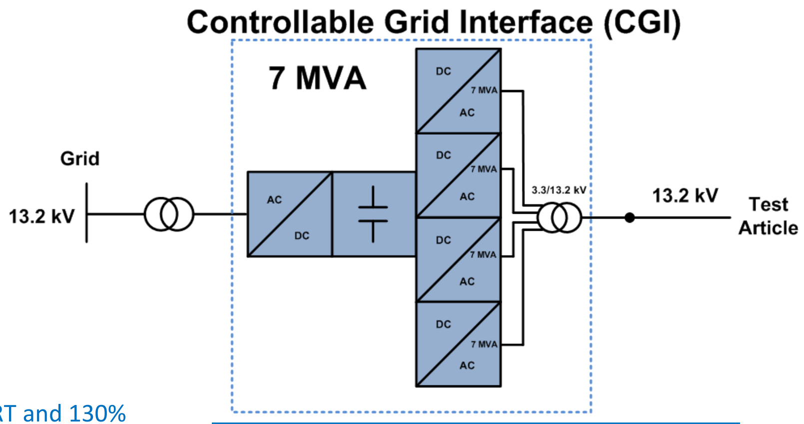
# Controllable Grid Interface (CGI)

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

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

**Voltage control (no load THD <3%)**
- Balanced and un-balanced voltage fault conditions (ZVRT and 130% 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) – SSR conditions
- Programmable impedance (strong and weak grids)
- Programmable distortions (lower harmonics 3, 5, 7)

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

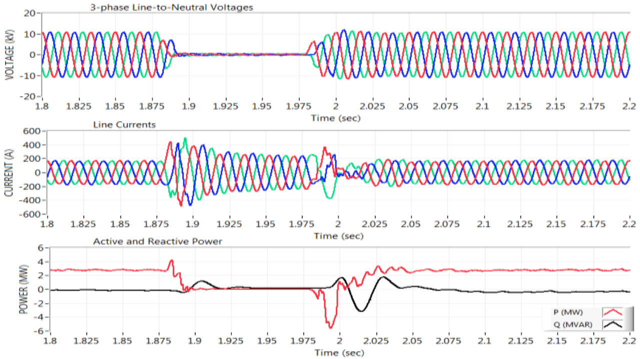


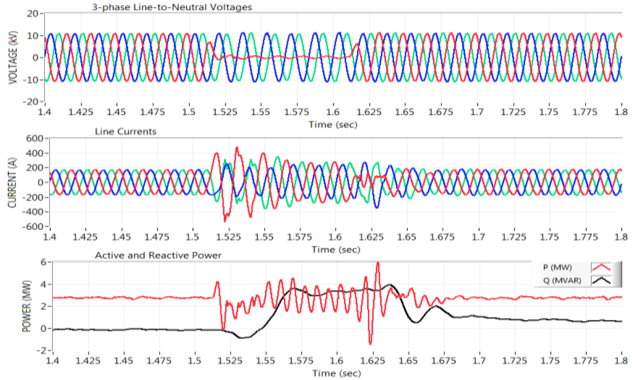

**Capabilities**
- Balanced and unbalanced over and under voltage fault ride-through tests
- Frequency response tests
- Continuous operation under unbalanced voltage conditions
- Grid condition simulation (strong and weak)
- Reactive power, power factor, voltage control testing
- Protection system testing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

# What can be tested with CGI?

All controls that response directly to grid conditions on plant terminals:

- “Nasty” and ”Clean Room” grid conditions
- Inertial Response (synthetic synchronous inertia)
- Fast Frequency Response (FFR)
- Primary frequency response controls (governor droop-like control)
- Direct frequency control (for islands or microgrids)
- Black-start capability
- Voltage fault ride-through (LVRT, ZVRT, HVRT – 1, 2, 3 – phase) in accordance to any existing or future grid codes or standard
- Harmonic injections
- Reactive power controls (full reactive power range tests without impacting NTWC grid)
  - Weak and strong grid conditions
- Other advanced controls testing:
  - Inter-area oscillation damping controls
  - Sub-synchronous resonance (SSR) damping controls
  - Other plant-level controls using RTDS/PHIL for larger plant simulation
  - Microgrid controls testing

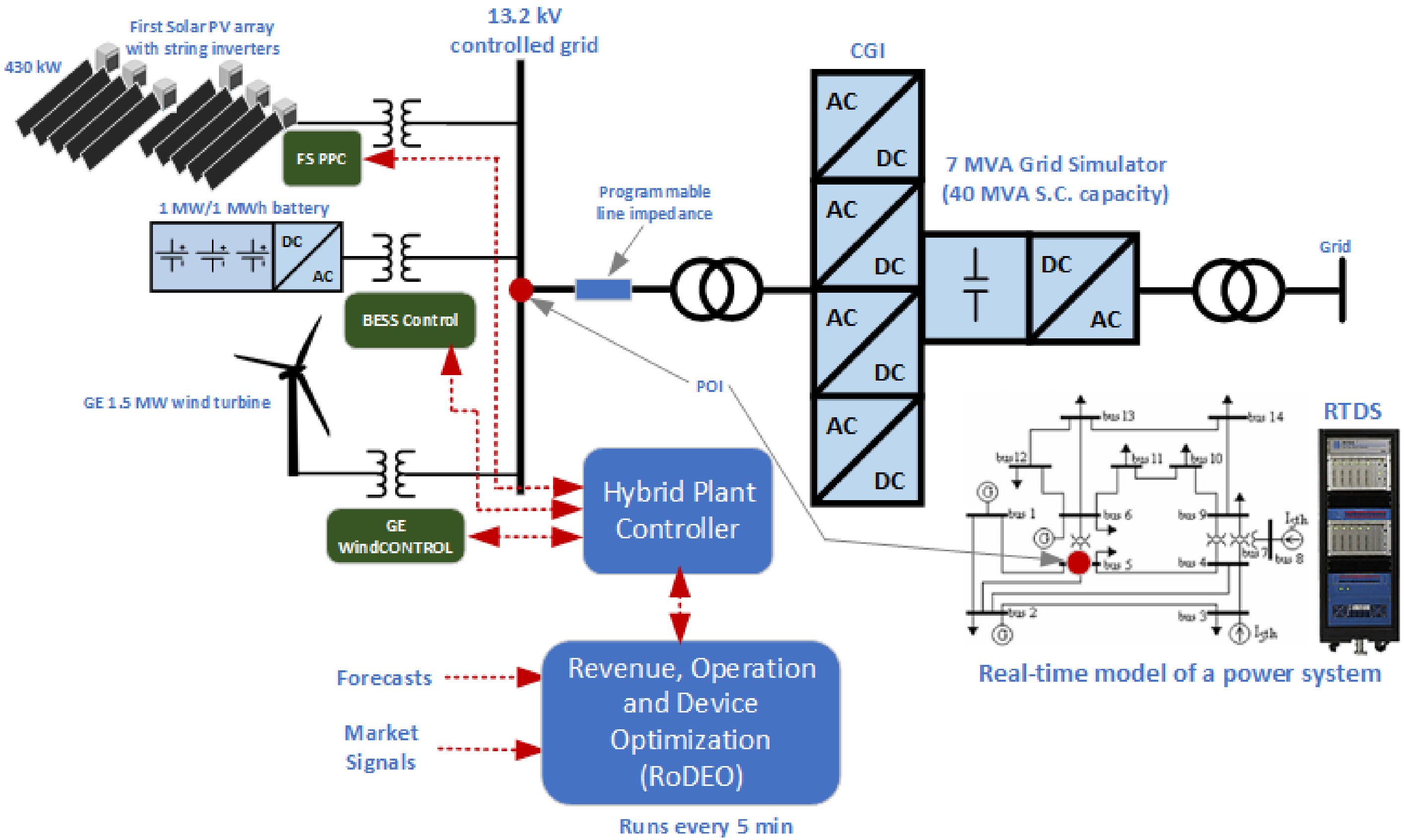


# Active Projects Involving Energy Storage

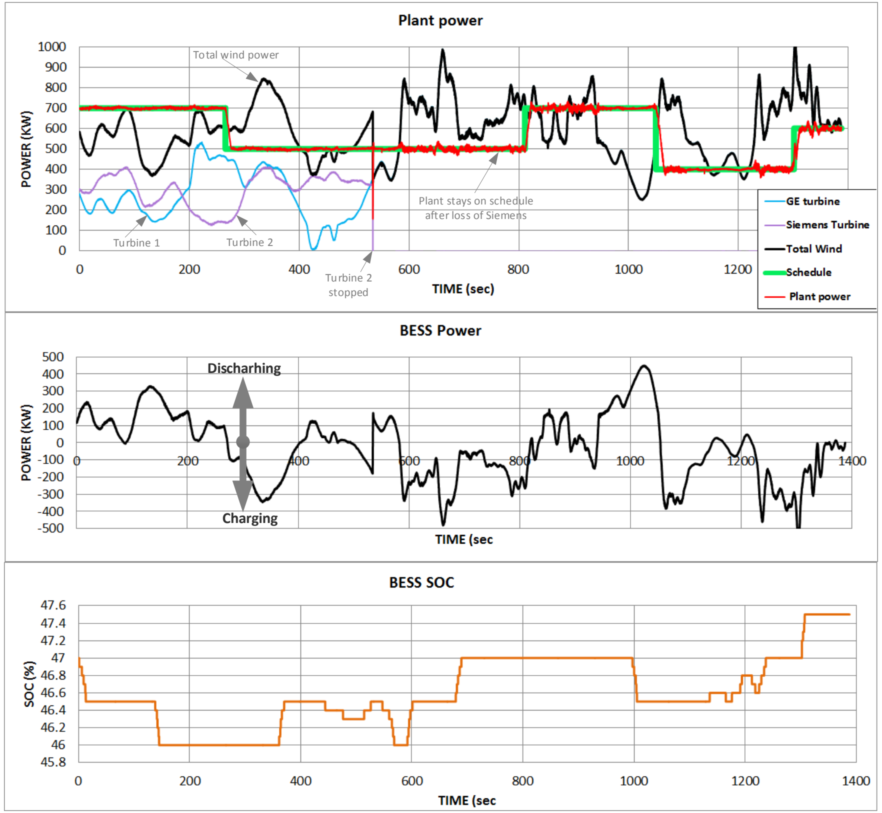
- DOE GMLC / WETO – Active power controls by wind power combined with energy storage systems
- DOE SETO – Hybrid PV/storage plants in collaboration with First Solar
- DOE WPPTO – Integrating energy storage with ROR hydro power plants
- PG&E / EPIC – Development and testing of advanced active power controls and grid gault performance for a battery energy storage system
- DOE OE (US-China CCWG) – NREL-CEPRI PV-storage work
- AES –Tightly-coupled PV/storage plants
- GE – Clusters of hybrid wind/solar PV/storage power plants
- Statoil – energy storage for offshore wind power plants

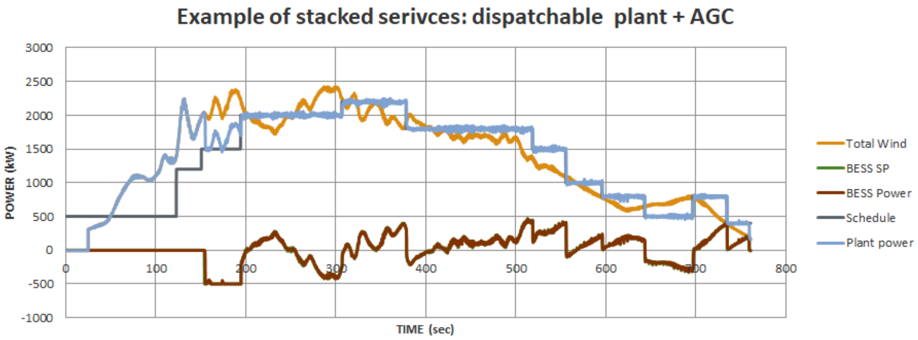
# Multi-technology Plant Controls Validation Platform

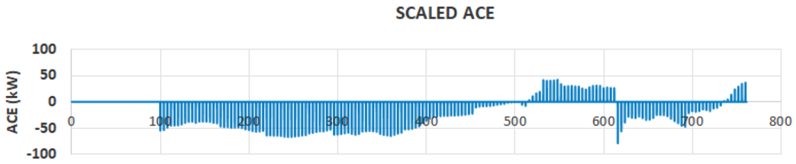


# Examples of Dispatchable Operation Demo

Dispatchable Wind Power plant

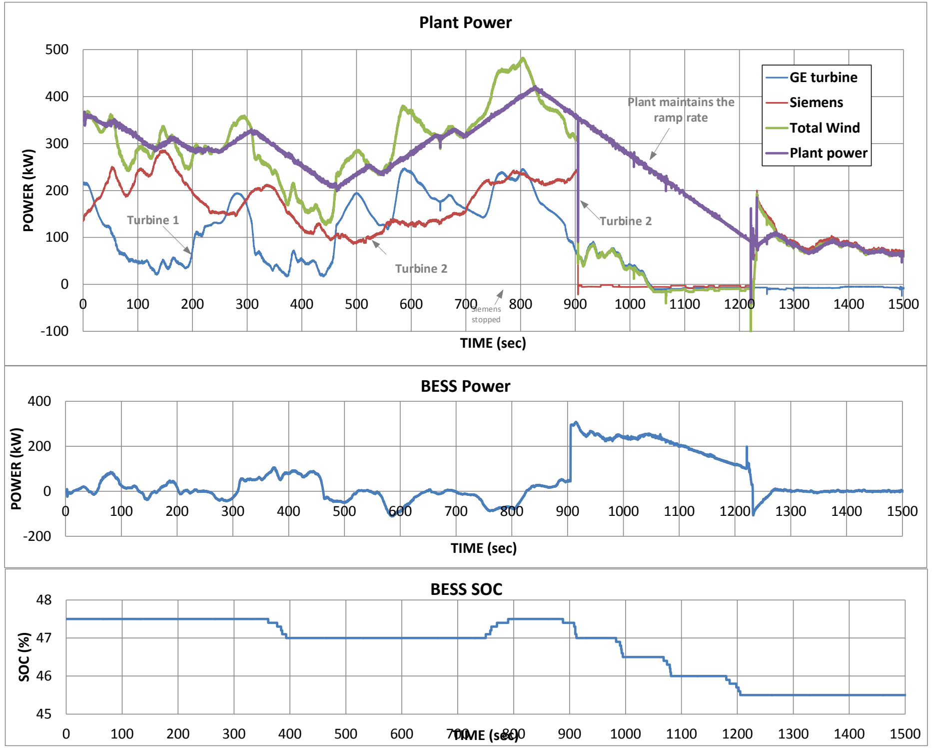


# Examples of Ramp Rate Controls

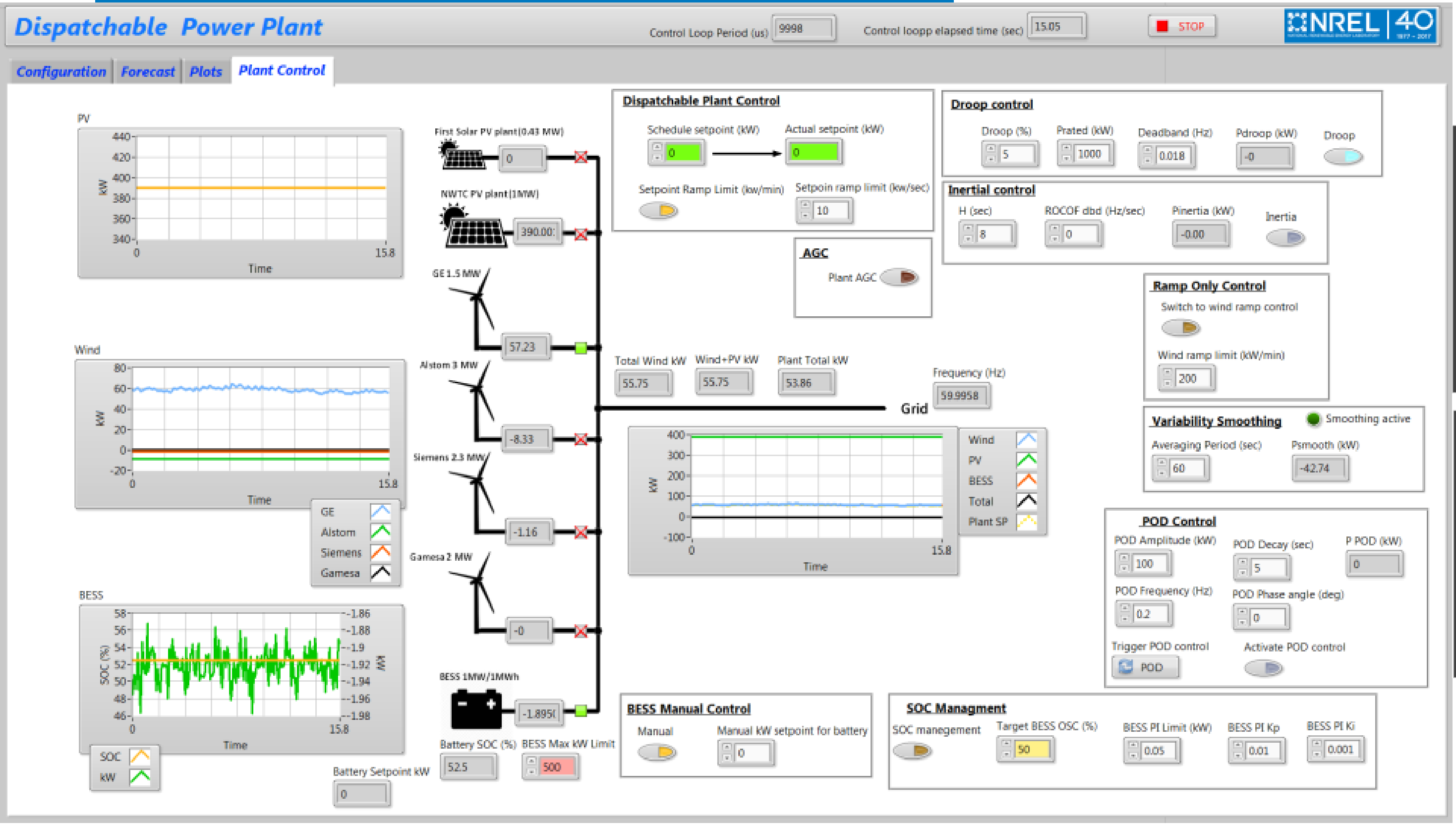
## Wind Ramp Control




## Wind Variability Smoothing

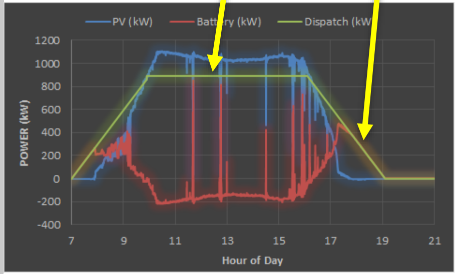
# Dispatchable Power Plant

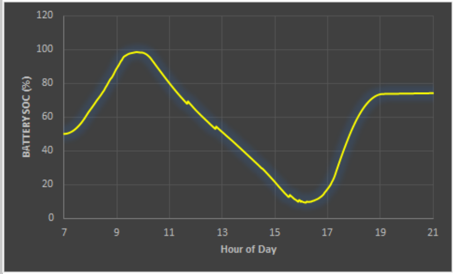
## Main control panel



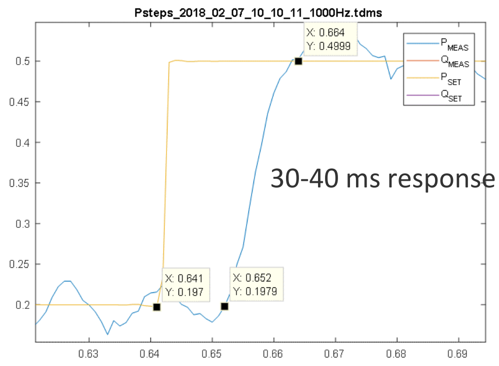

Reduced ramps

No curtailment

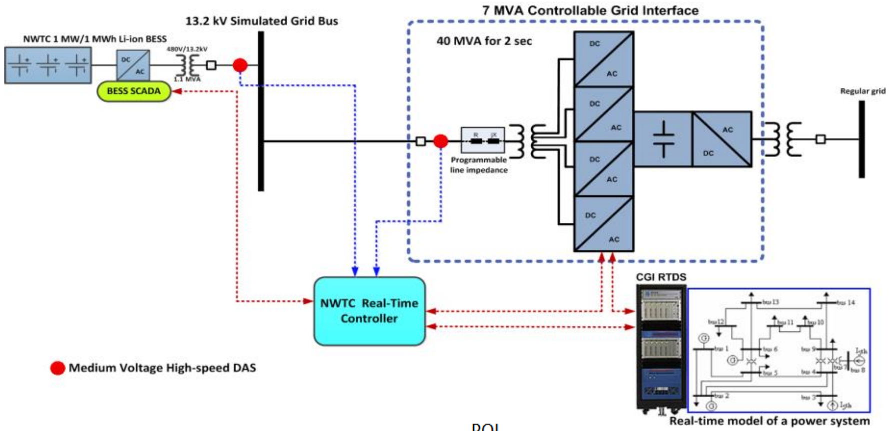


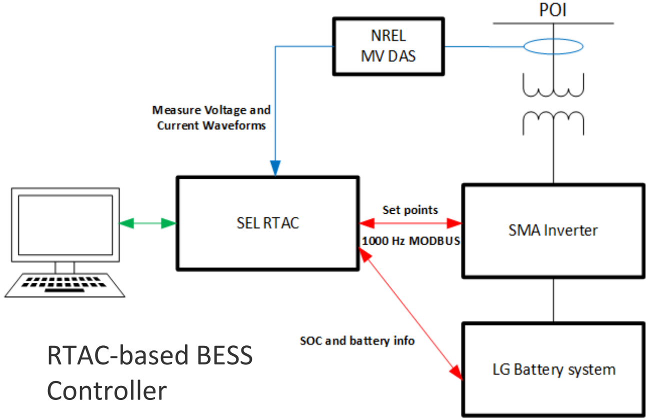



# PHIL Platform for Validating BESS Controls

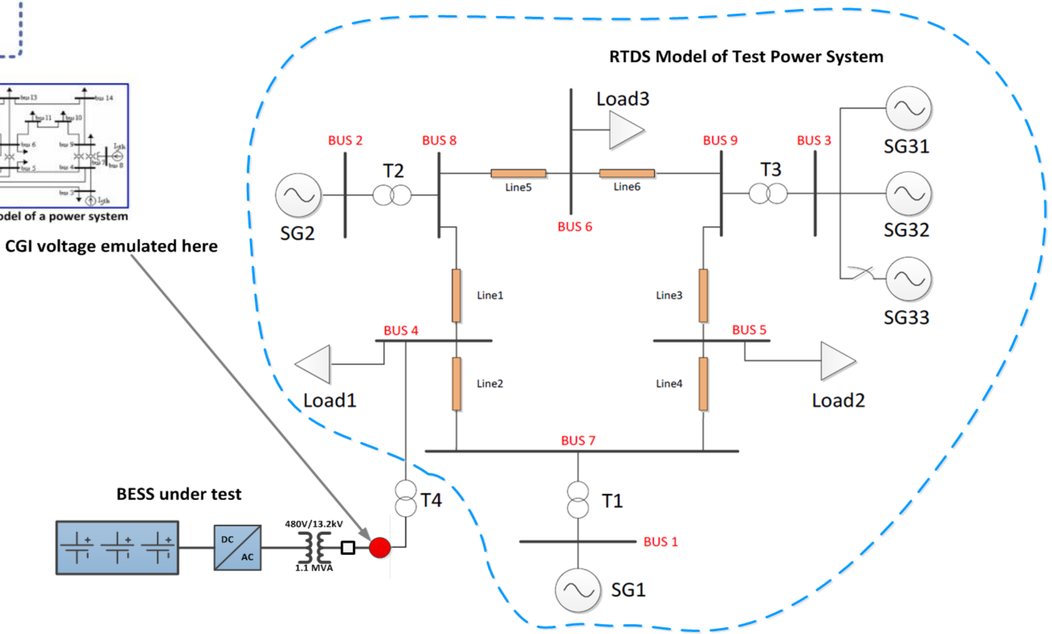



30-40 ms response time

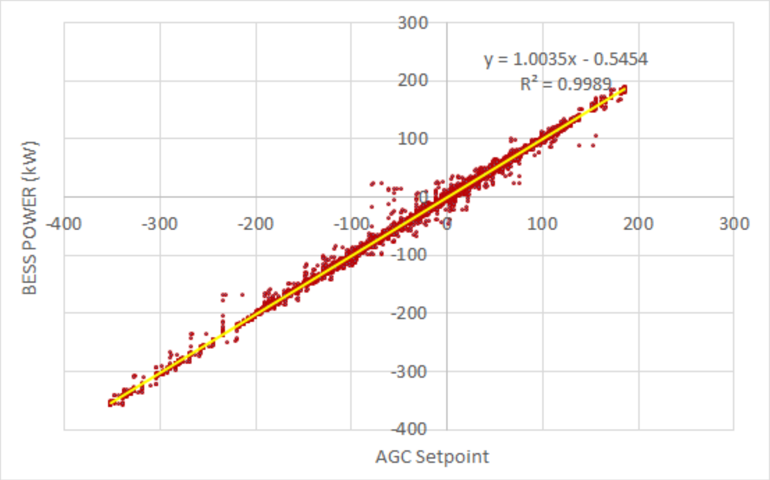


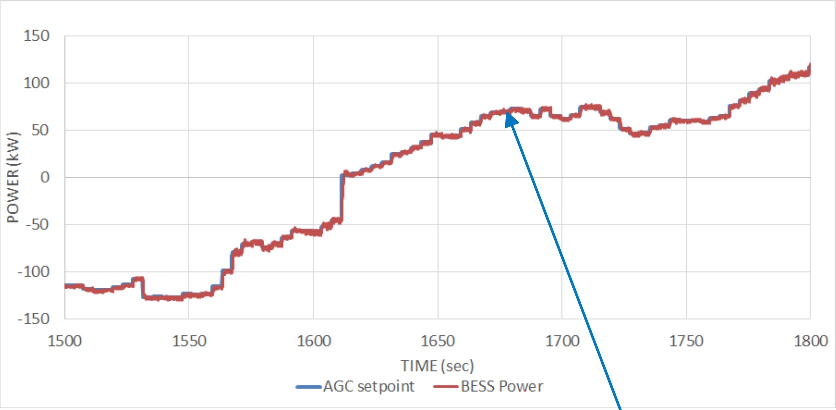



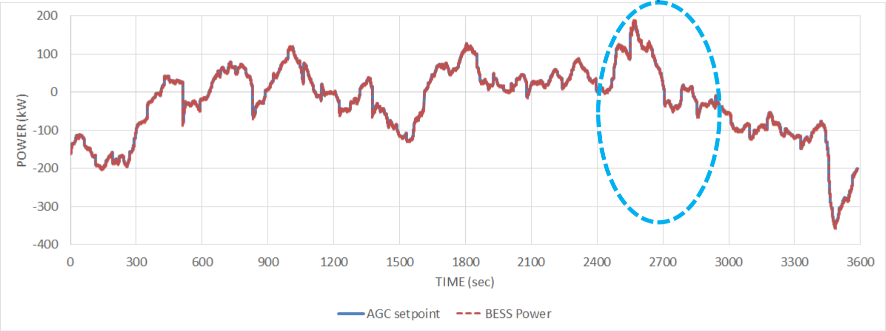

RTAC-based BESS Controller

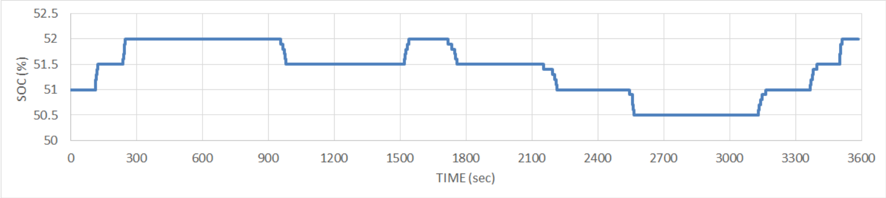


# BESS Participating in AGC



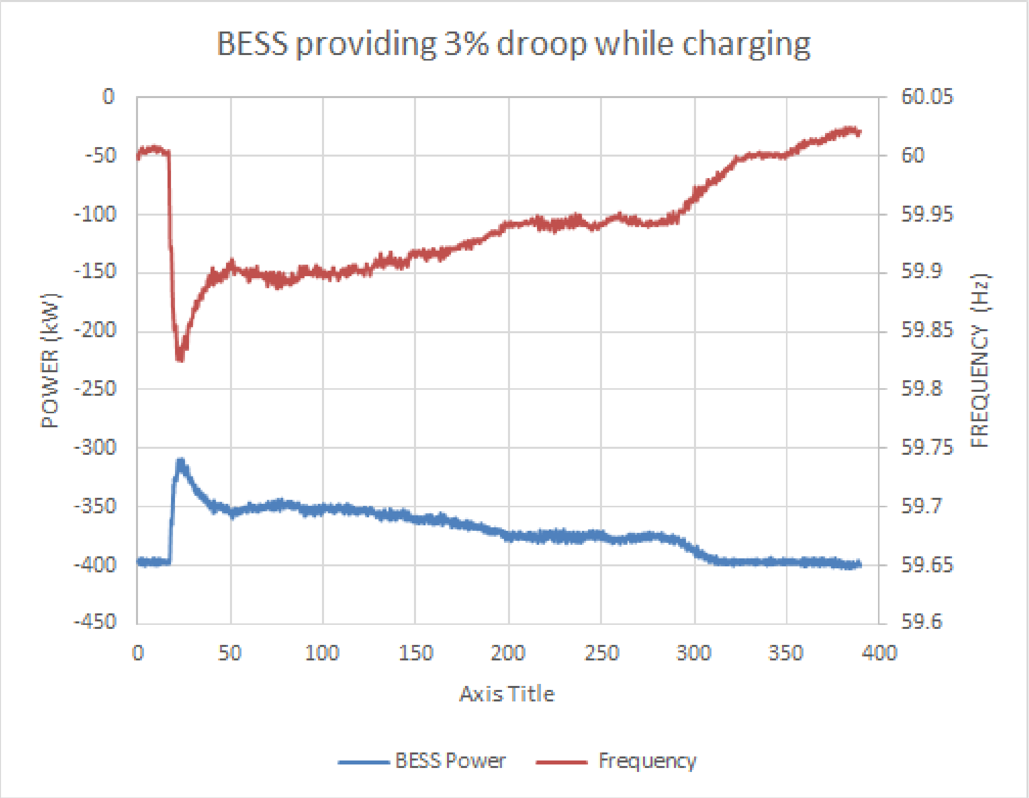



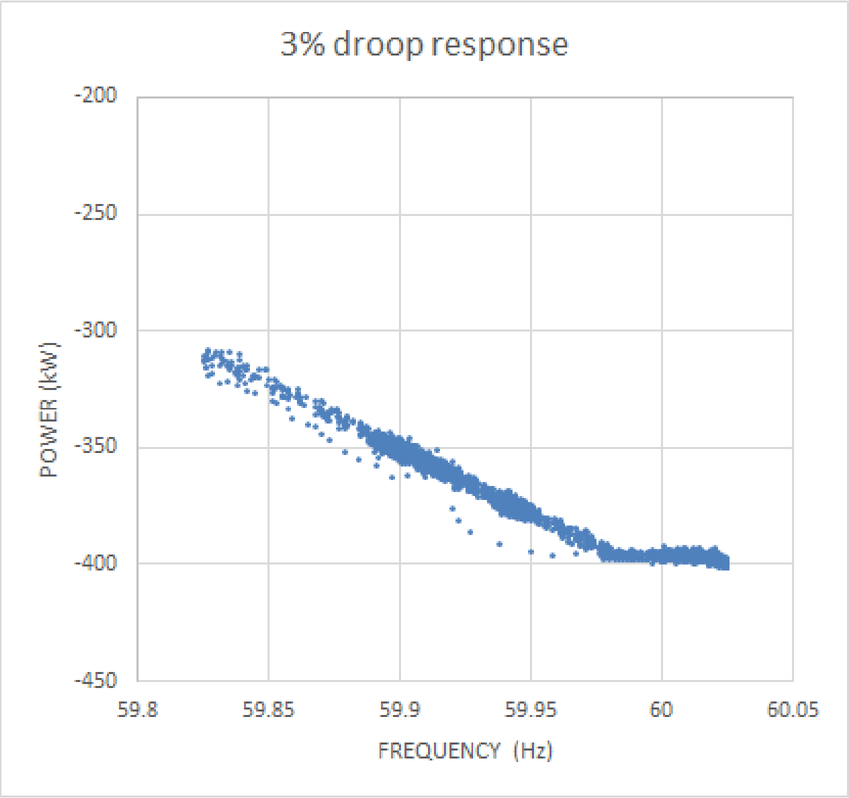



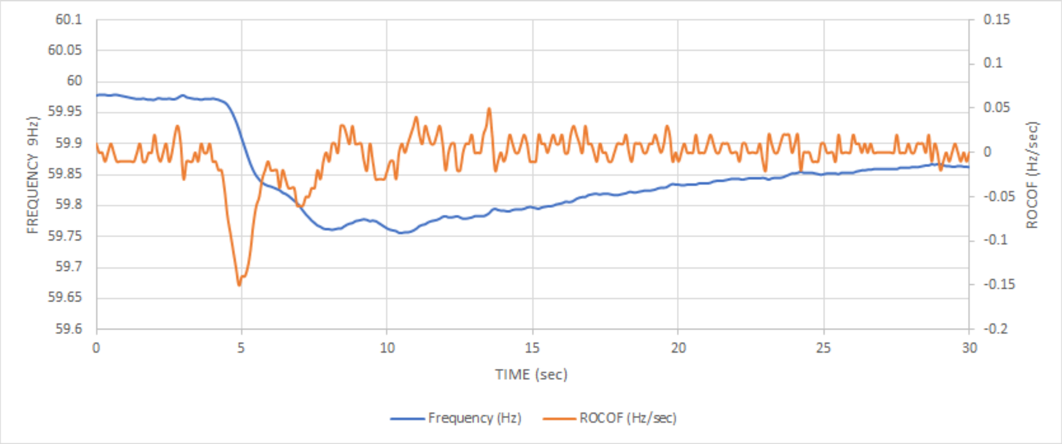

- PSCO historic ACE time series (updated every 4 sec)
- ACE is scaled down to match BESS rating

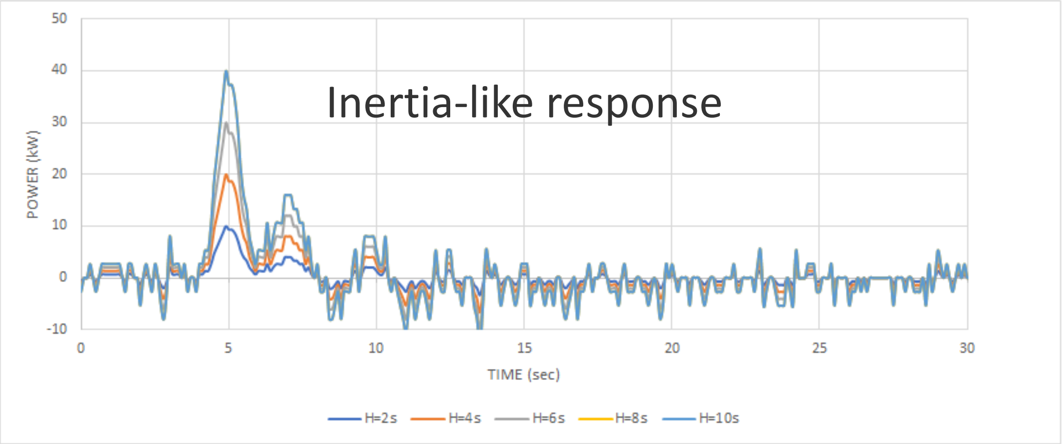
# BESS Providing PFR



# BESS Emulating Response of Rotating Generator



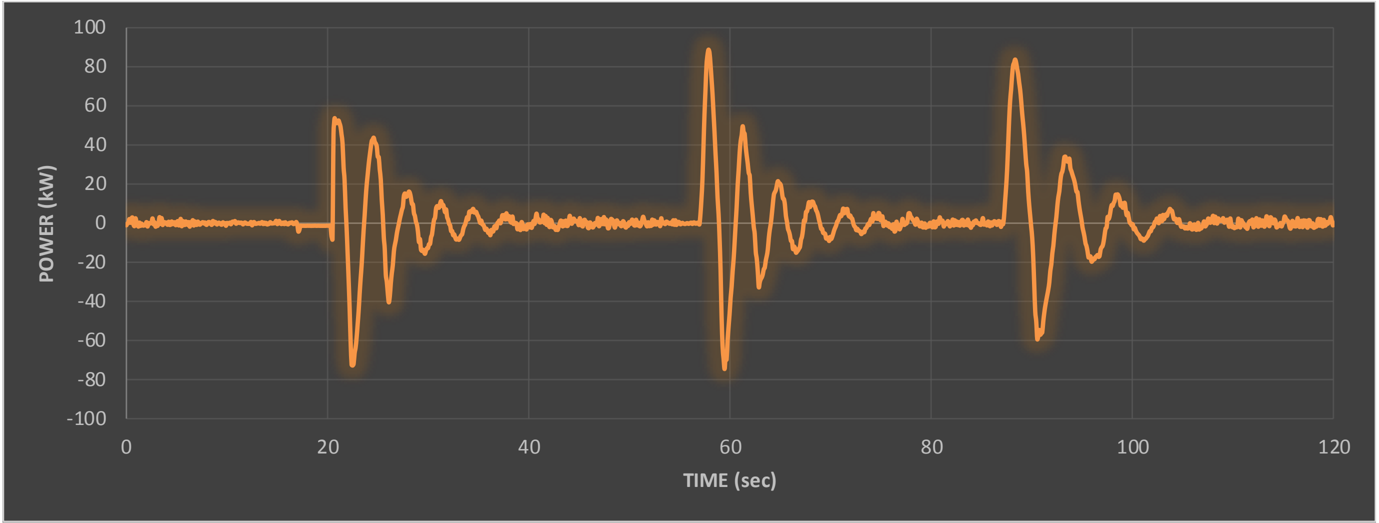




$$\Delta P = -2H \cdot f \cdot \frac{df}{dt}$$

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

# POD Controls by BESS

Demonstration of Power Oscillations Damping control by BESS



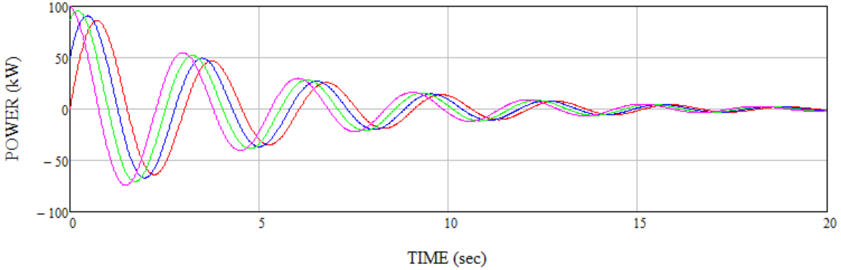

**Magnitude of POD response**

**Frequency of oscillations**

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

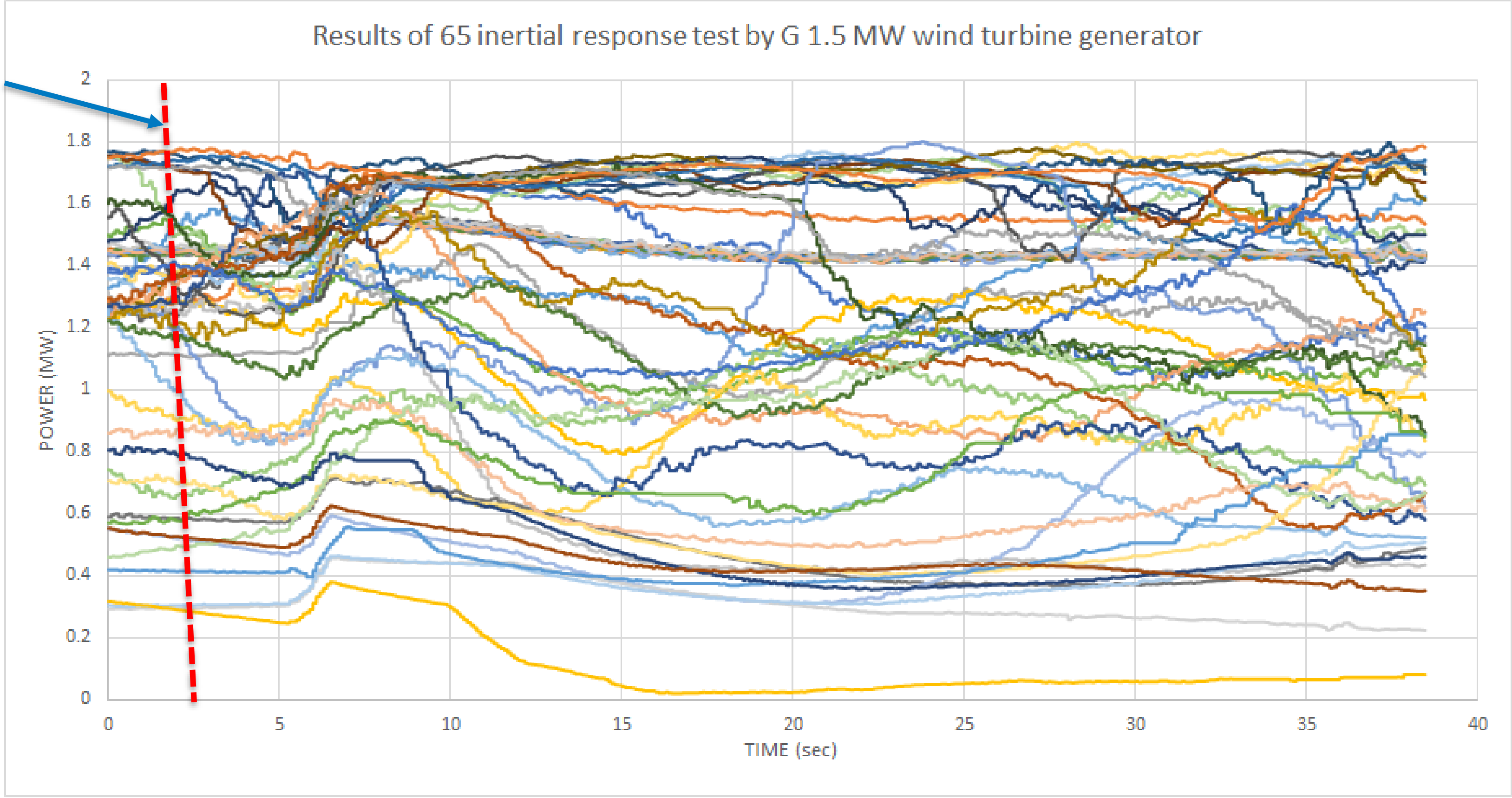
**Decay time**

**Phase angle of oscillations**

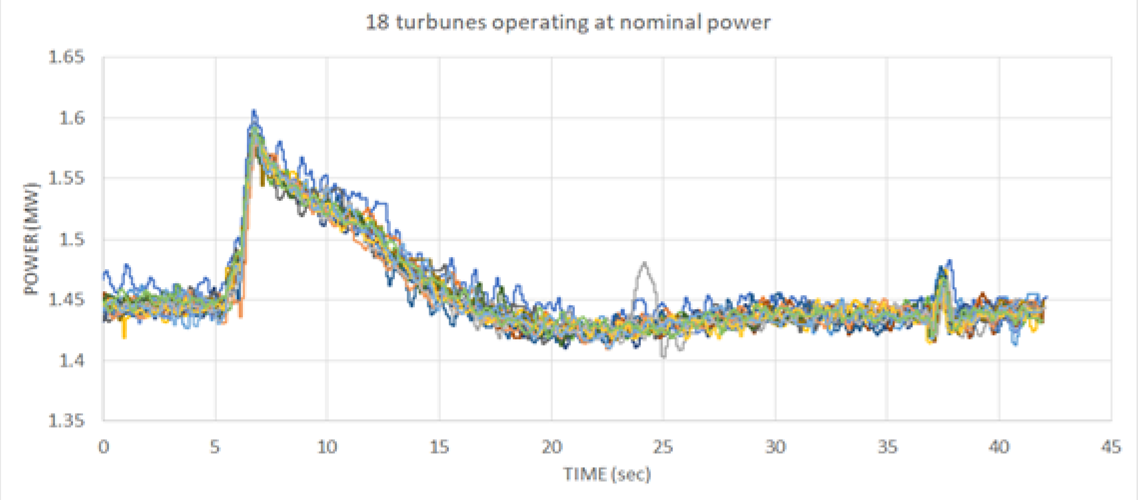


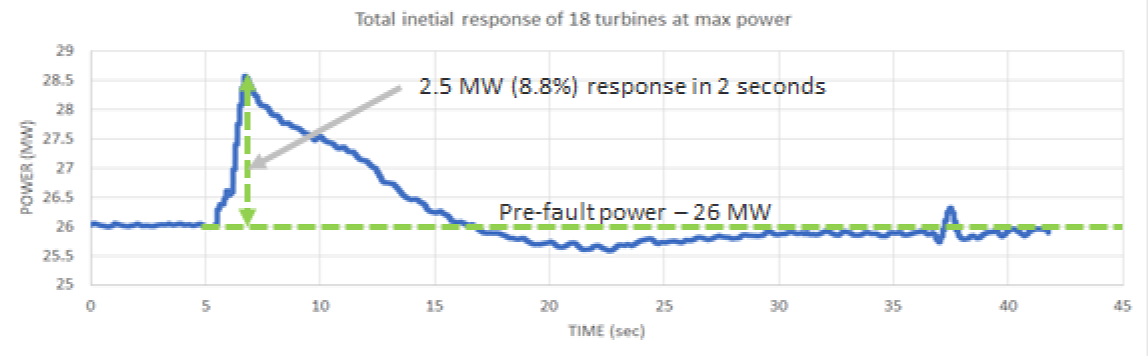
# Emulated Inertial Responses Individual Wind Turbines in a 150 MW wind power plant

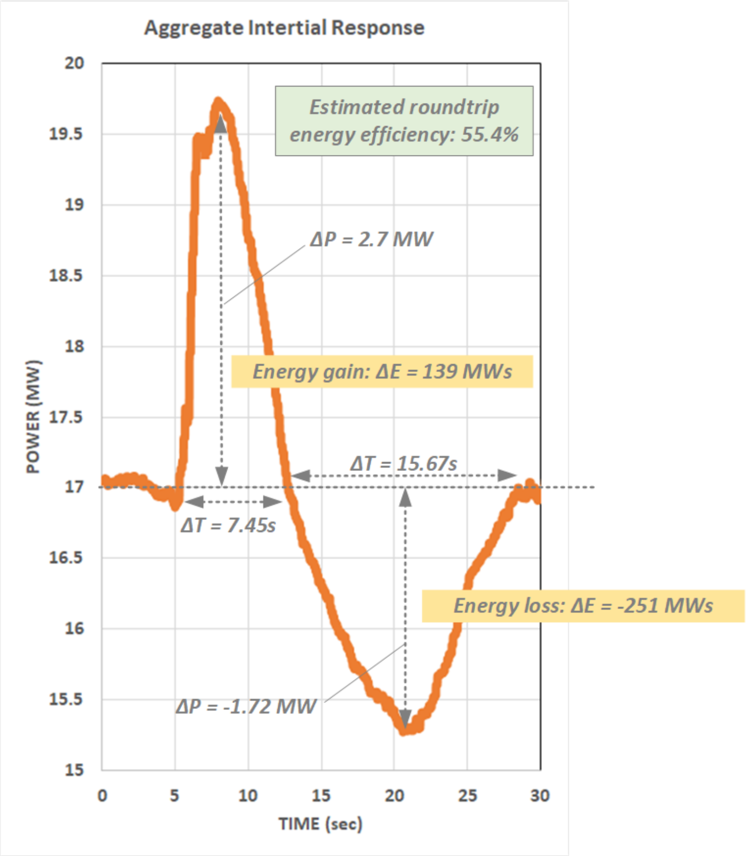
Frequency event emulated by CGY – 1Hz/sec ROCOF



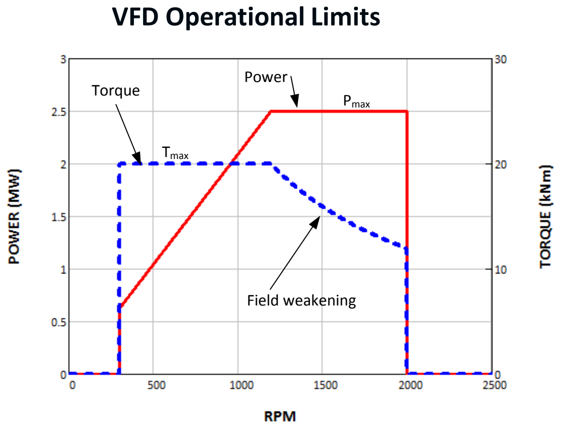
# Aggregate Inertial Response of Large Wind Power Plant

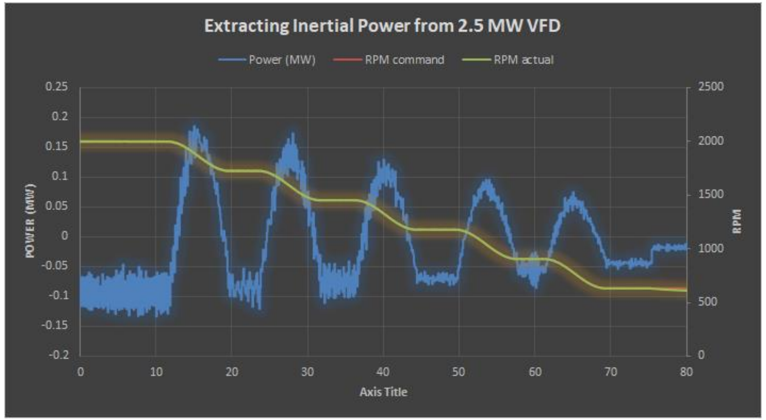


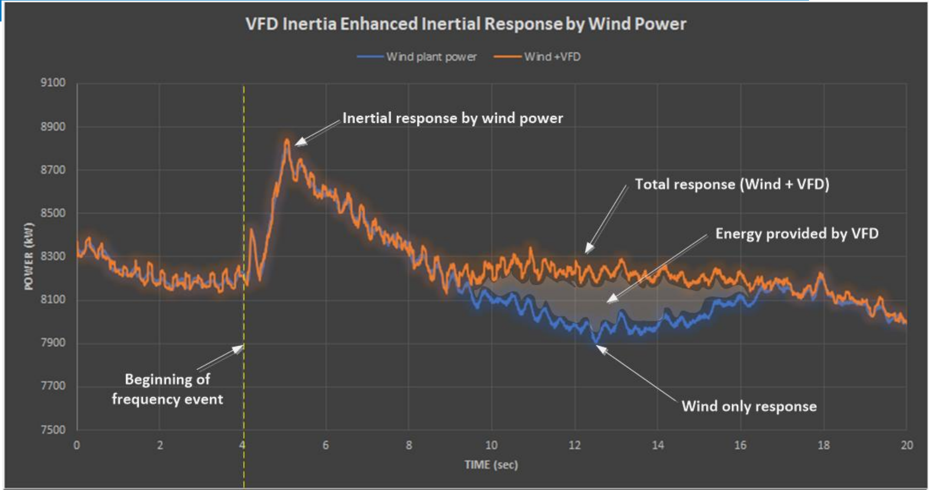



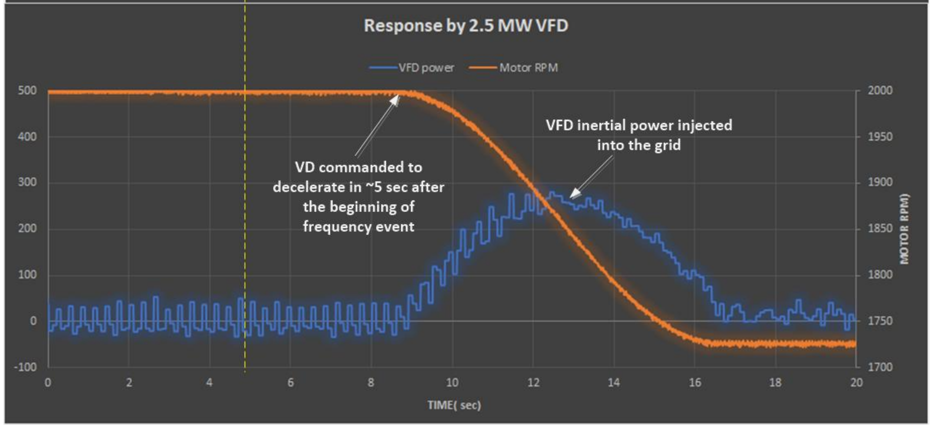



# VFD Enhancing Inertial Response by Wind Power



# 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
- 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
- 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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