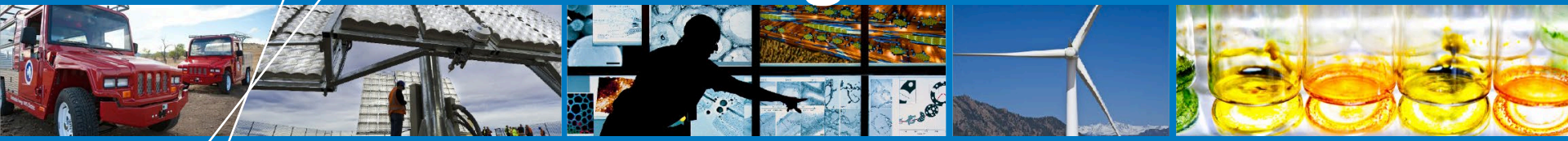
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

NREL Controllable Grid Interface for Testing of Renewable Energy Technologies



3rd International Workshop on Grid Simulator Testing of Energy Systems and Wind Turbine Powertrains

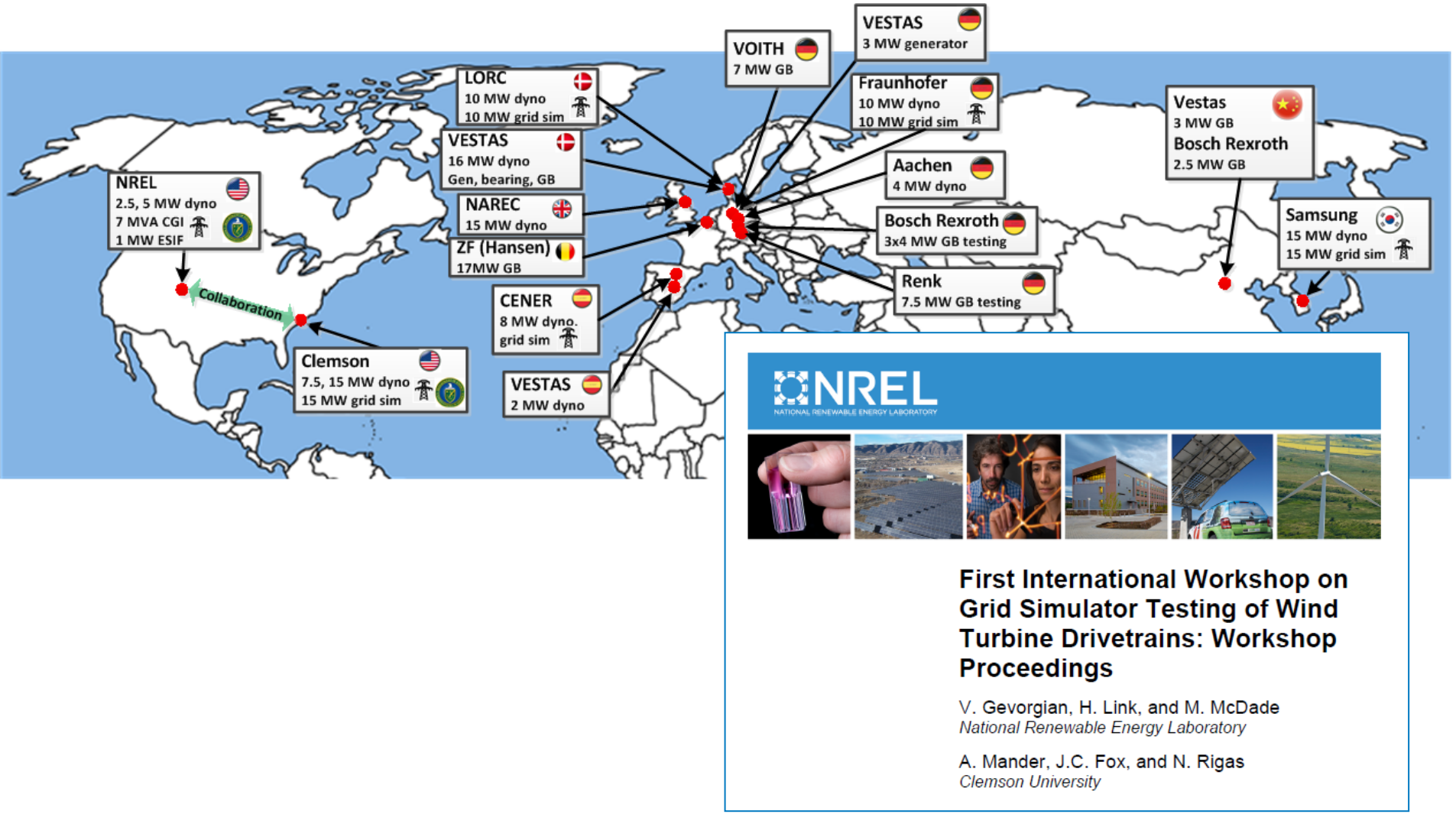
V. Gevorgian, R. Wallen, M. McDade,
M. Shirazi, and B. Lundstrom: NREL

November 5-6, 2015

FSU CAPS, Tallahassee, FL

NREL/PR-5D00-65557

1st Workshop at NREL – June 2013



Workshop report: http://www.nrel.gov/docs/fy14osti/60246.pdf

Workshop website: http://www.nrel.gov/electricity/transmission/grid_simulator_workshop.html

2nd Workshop at Clemson – September 2014

eGRID Introduction and Status

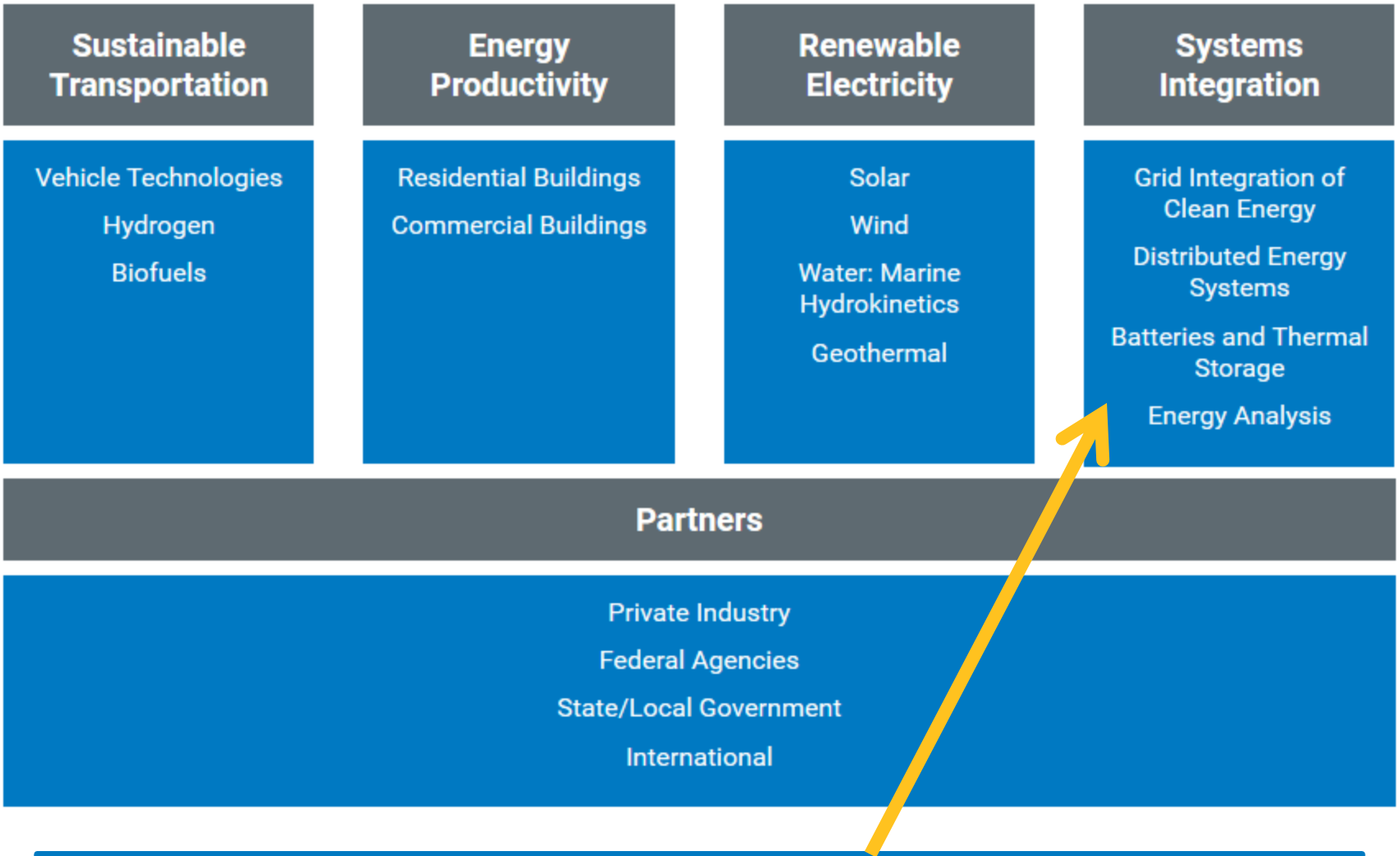
2nd International Workshop
September 17th, 2014

CLEMSON UNIVERSITY RESTORATION INSTITUTE

Driving economic growth, innovation, and workfo
development for South Carolina

http://www.nrel.gov/electricity/transmission/grid-simulator-workshop-2.html

NREL Mission Focus



Electric infrastructure systems research and development at NREL is focused on renewable energy integration, distributed energy testing and certification, energy management, interconnection standards and codes, Smart Grid research, and much more.

U.S. Multi-MW Testing Facilities for Grid Integration Testing of Renewable Technologies

Energy Systems Integration Facility (ESIF)

1+ MW

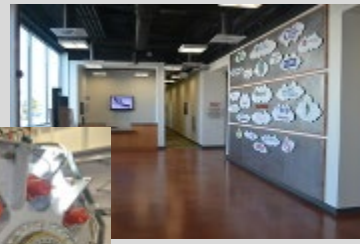
NREL

National Wind Technology Center (NWTC)

7 MVA

- DOE Wind Program investments in world class testing facilities
- Component, wind turbine, plant level testing
- Key enabler for wind technology validation and commercialization
- Goals of DOE's Grid Modernization, A2E and turbine reliability programs
- Specific focus on testing ancillary service controls

Clemson SCE&G Energy Innovation Center, eGRID Facility

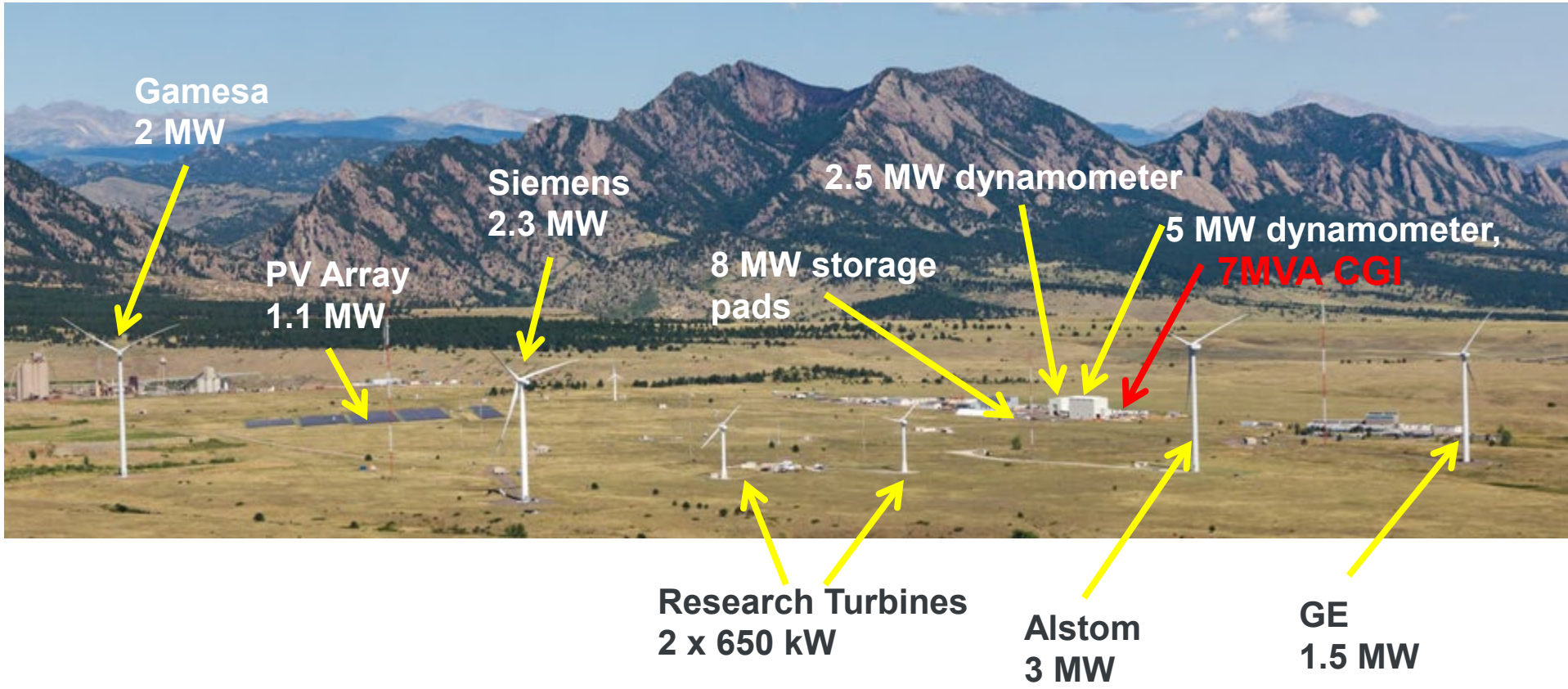


15 MW

NREL Golden Campus

NWTC Test Site

- Total of 11 MW variable renewable generation currently at NWTC test site
- There are many small wind turbines (under 100 kW) installed as well
- 2.5MW and 5 MW dynamometers
- 7 MVA Controllable Grid Interface (CGI) for grid compliance testing
- Multi-MW energy storage test pads



NWTC 5 MW Dynamometer

NWTC 7-MVA Controllable Grid Interface

Storage Test Pads

- Two pads each rated for 4 MW
- Each pad can be connected to the real grid or NWTC Grid Simulator
- Best for containerized storage solutions – up to 110ft ISO containers (up to 500,000 lbs)
- Pre-wired, automated MV switchgear / protection installed
- Fiber-optic / Ethernet

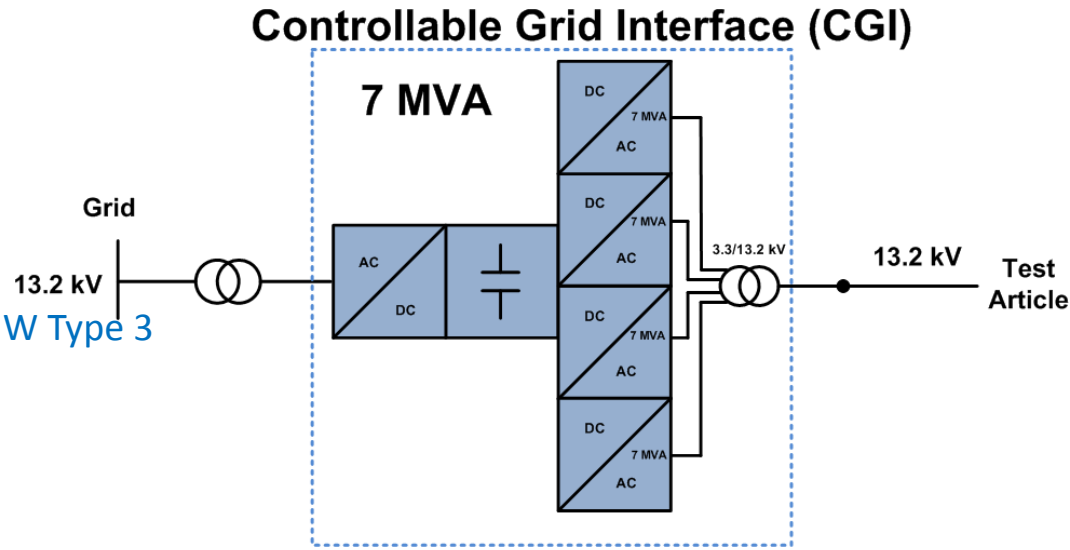
CGI Main Technical Characteristics

Power rating
- 7 MVA continuous
- 39 MVA short circuit capacity (for 2 sec)

Possible test articles
- Types 1, 2, 3 and 4 wind turbines
- Capable of fault testing of world's largest 6.15 MW Type 3 wind turbine
- PV inverters, energy storage systems
- Conventional generators
- Combinations of technologies

Voltage control (no load THD <5%)
- Balanced and un-balanced voltage fault conditions (ZVRT and 130% HVRT) – independent voltage control in each phase
- Long-term symmetrical voltage variations (+/- 10%) and voltage magnitude modulations (0-10 Hz) - SSR
- Programmable impedance (strong and weak grids)
- Programmable distortions (lower harmonics 3, 5, 7)

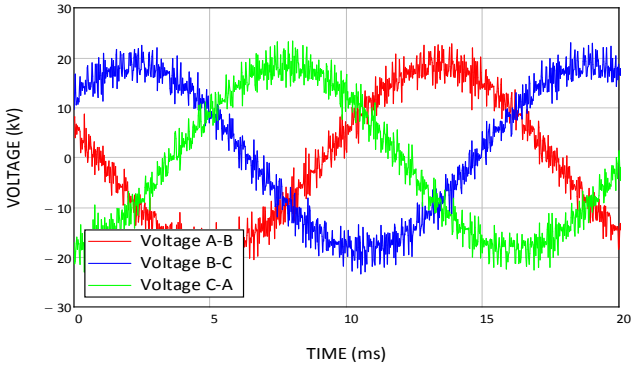
Frequency control
- Fast output frequency control (+/- 3 Hz)
- 50/60 Hz operation
- Simulate frequency response of various power systems
- RTDS / HIL capable



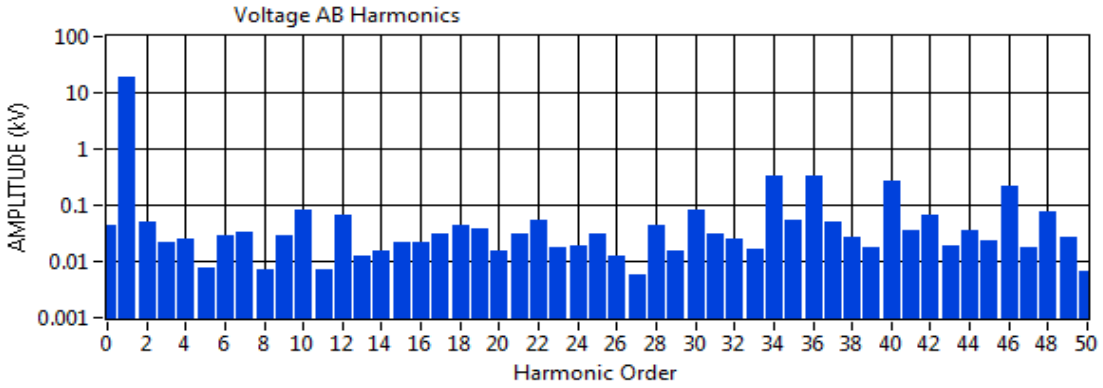
Capabilities
- Balanced and unbalanced over and under voltage fault ride-through tests
- Frequency response tests
- Continuous operation under unbalanced voltage conditions
- Grid condition simulation (strong and weak)
- Reactive power, power factor, voltage control testing
- Protection system testing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

CGI Voltage Waveform

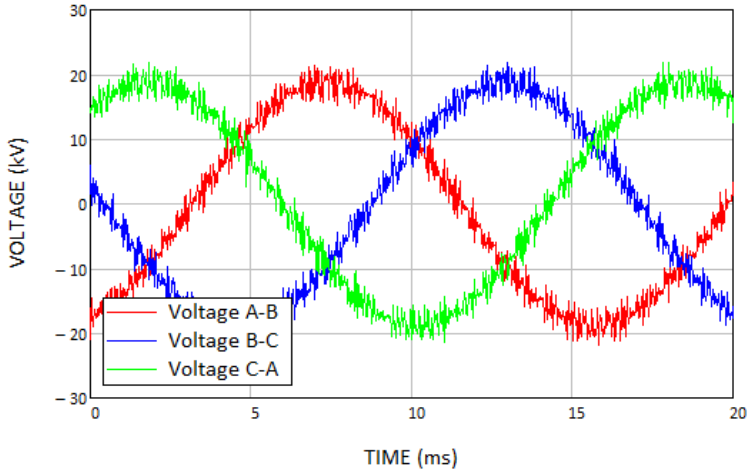
No-load L-to-L voltage



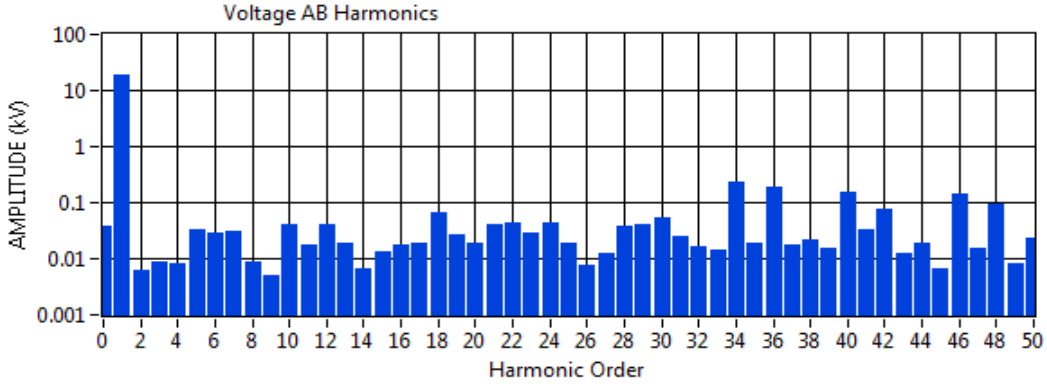
No-load voltage harmonics (THD=3.4%)



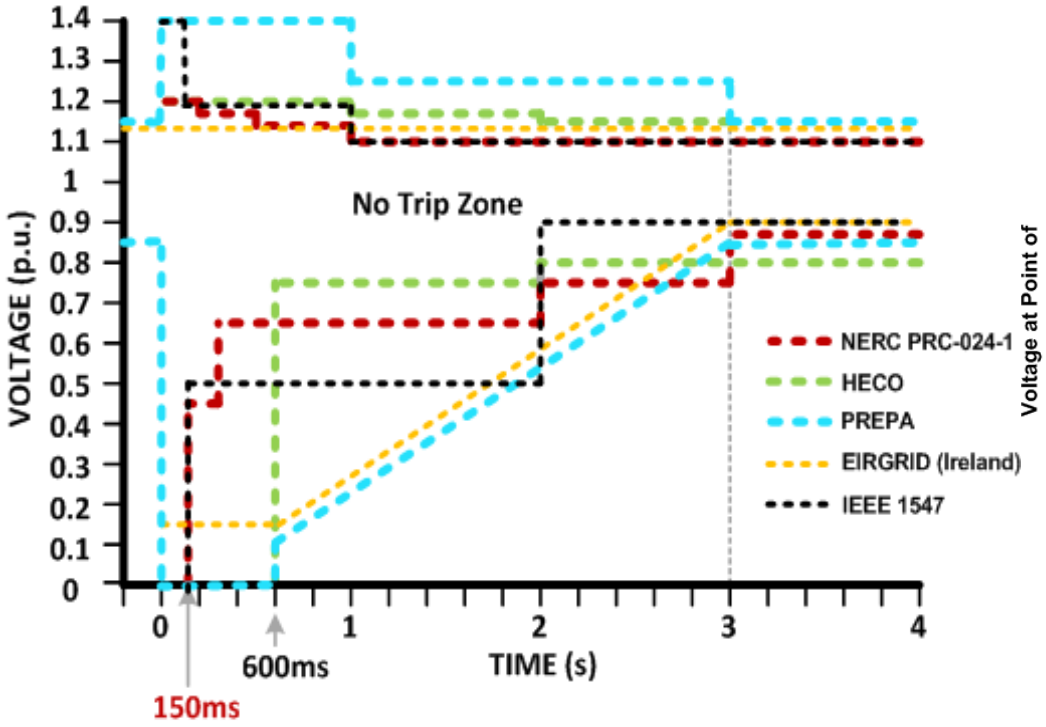
L-to-L voltage under 2.75 MW load



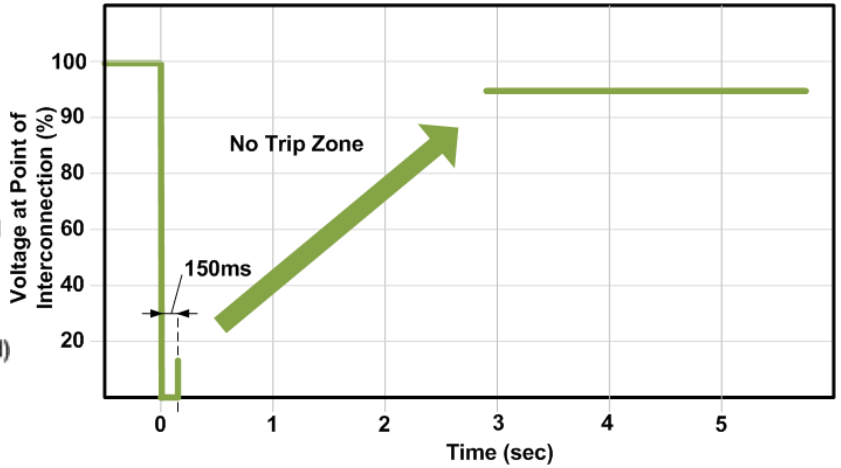
Voltage harmonics under 2.75 MW load (THD=2.5%)



Testing to All Interconnection Requirements and Grid Codes



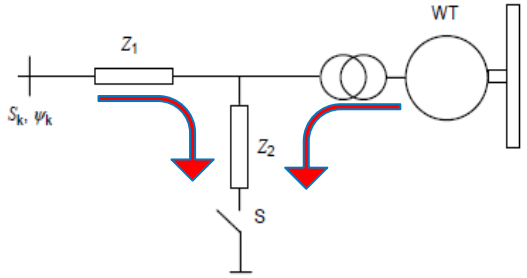
FERC LVRT requirements (order 661-A)



IEC 61400-21 LVRT Testing Matrix

Fault Type	Voltage drop (fraction of nominal L-to-L voltage)	Fault Duration (ms)
Three-phase, balanced	0.9	500
Three-phase, balanced	0.5	500
Three-phase, balanced	0.2	200
Two Line-to-Line (L-L), unbalanced	0.9	500
Two Line-to-Line, unbalanced	0.5	500
Two Line-to-Line, unbalanced	0.2	200

IEC recommended fault emulator



What can be tested using CGI?

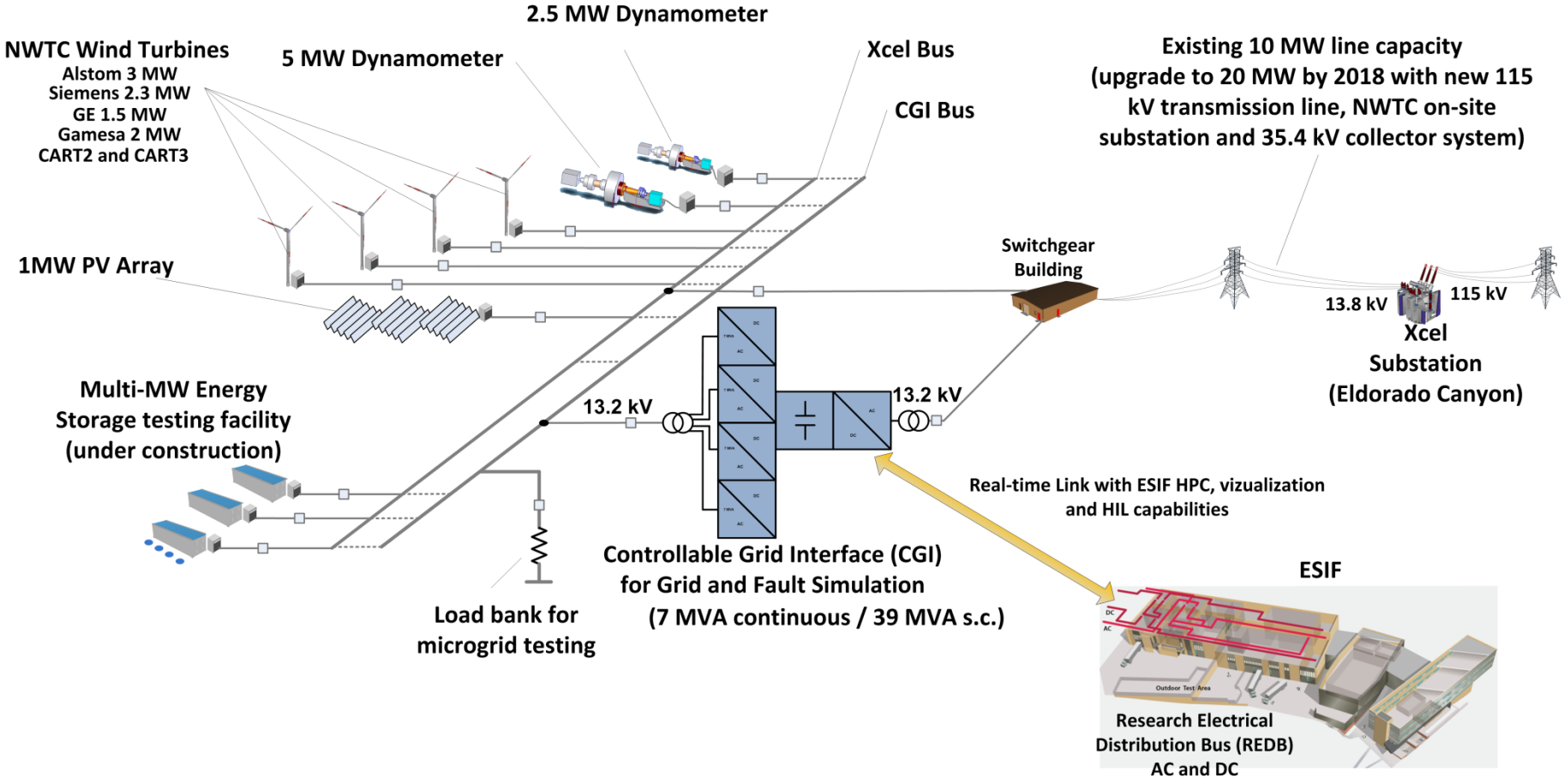
All controls that response directly to grid conditions on plant terminals*

- 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/HIL for larger plant simulation
  - Microgrid controls testing

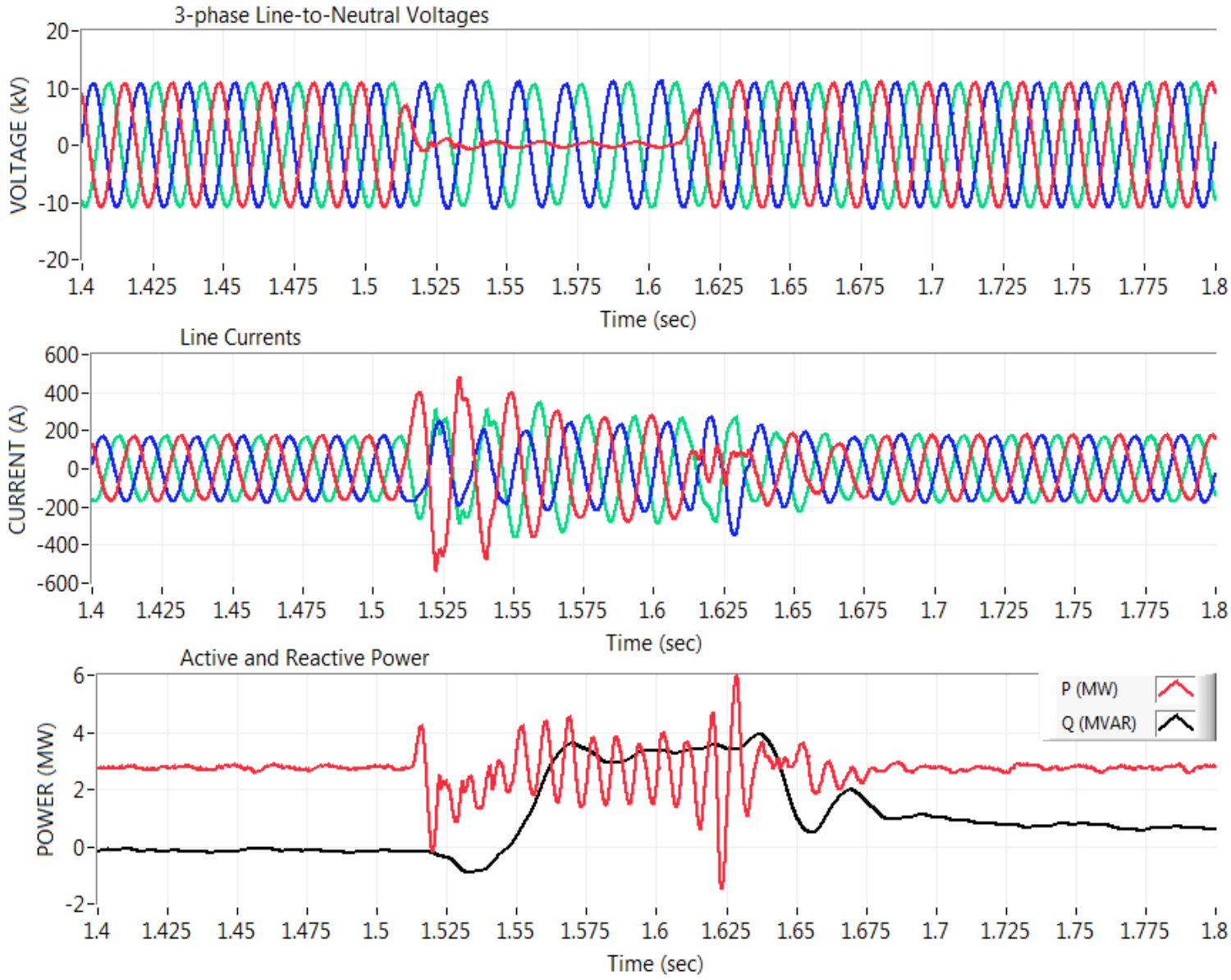
***All above tests for a single technology (energy storage, wind, PV), or for combination of technologies**

NWTC Dual-Bus Test Setup

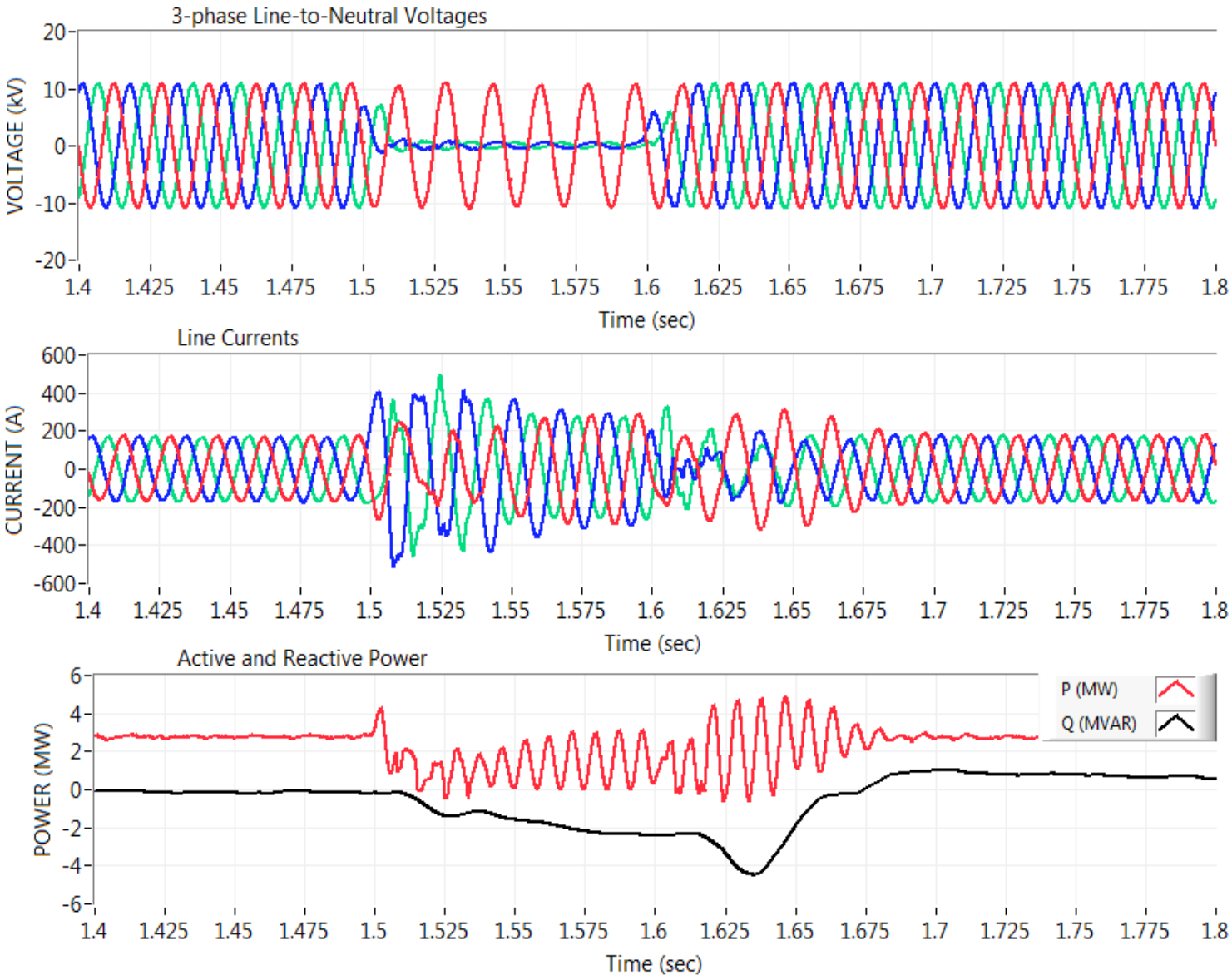
- Highly flexible and configurable system level multi-MW testing/demonstration platform
- Most components are in place and operational
- Looking for energy storage partners



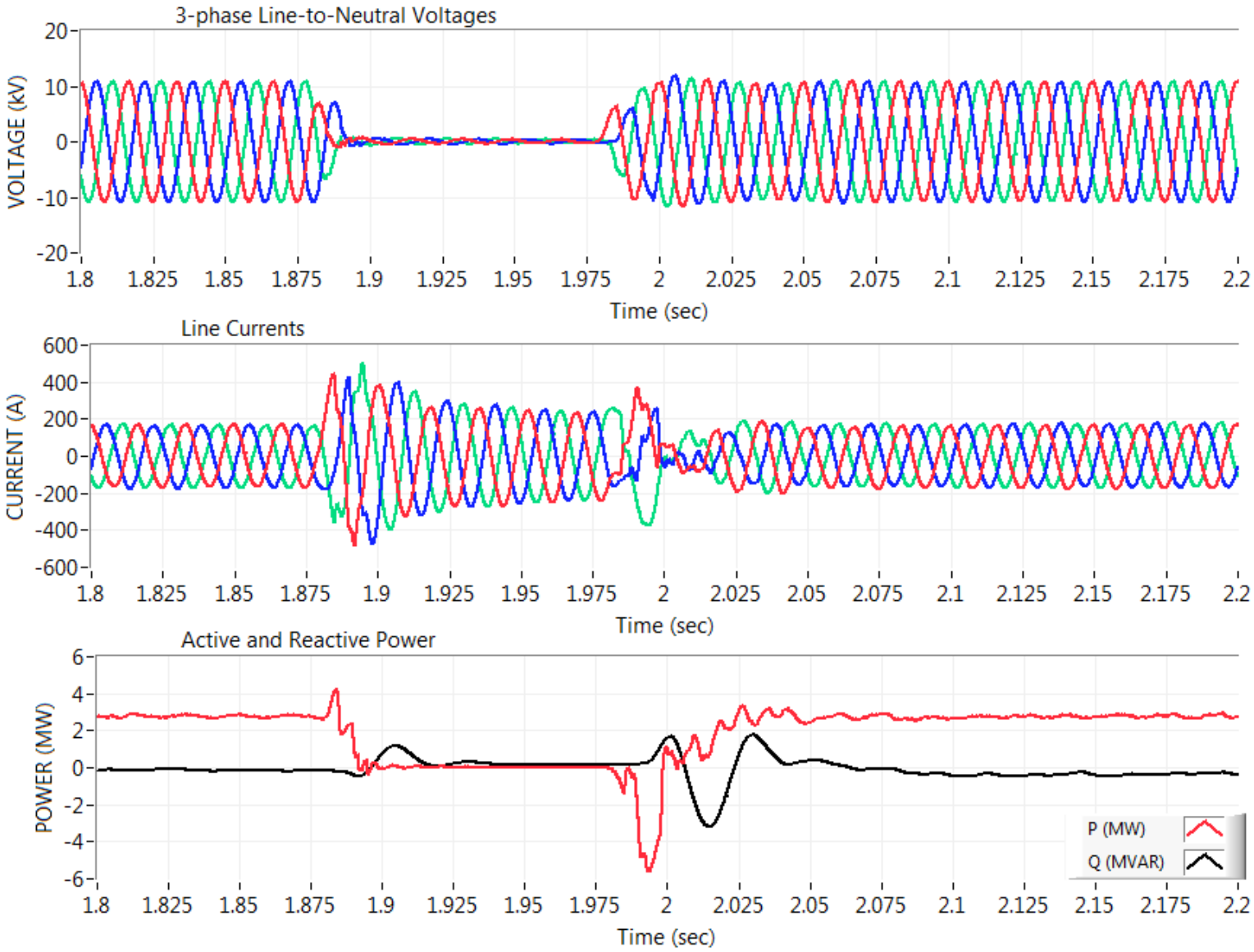
Example test result: Single-phase fault emulated on MV terminals of 2.75 MW wind turbine



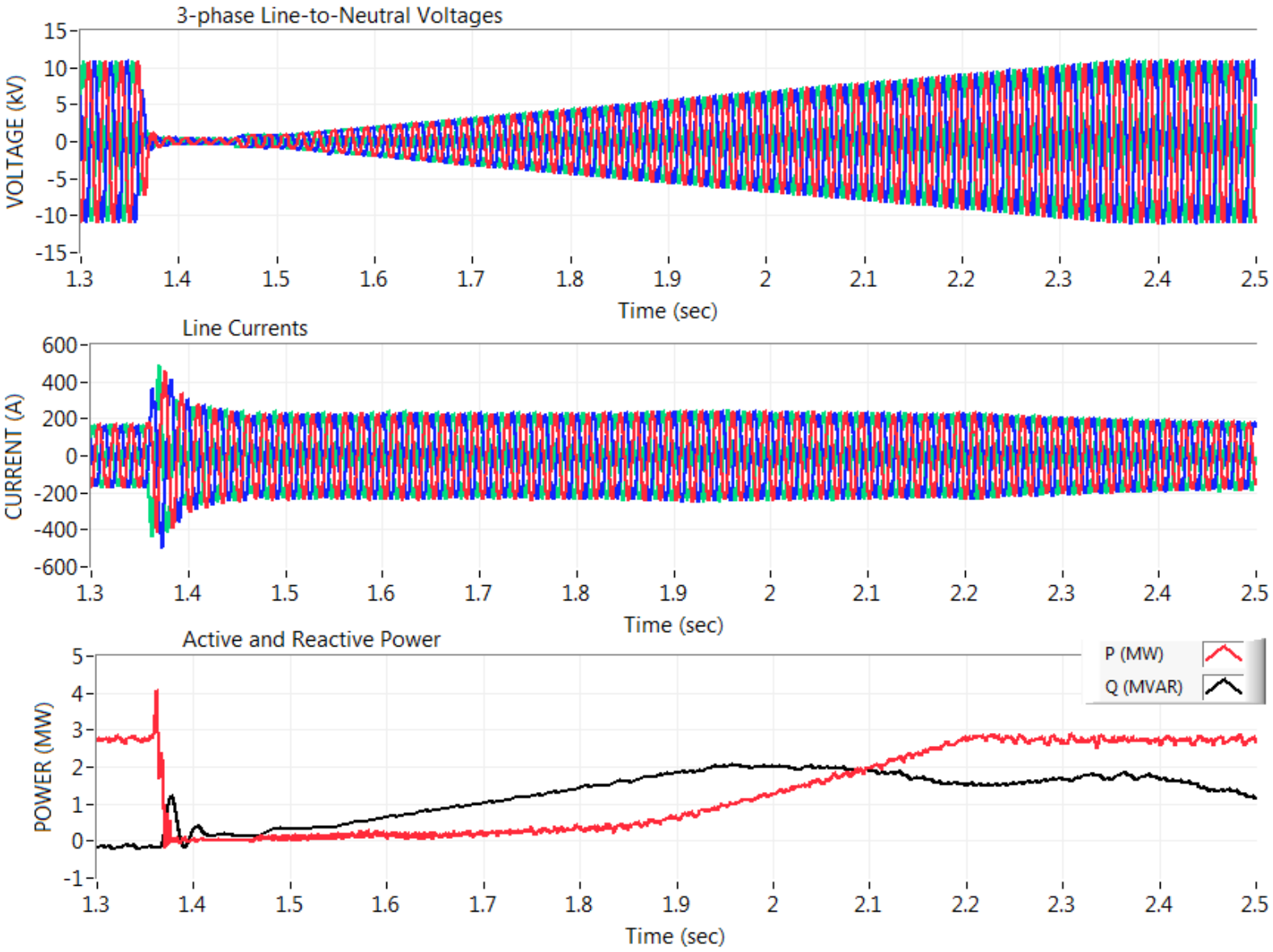
Two-Phase Fault



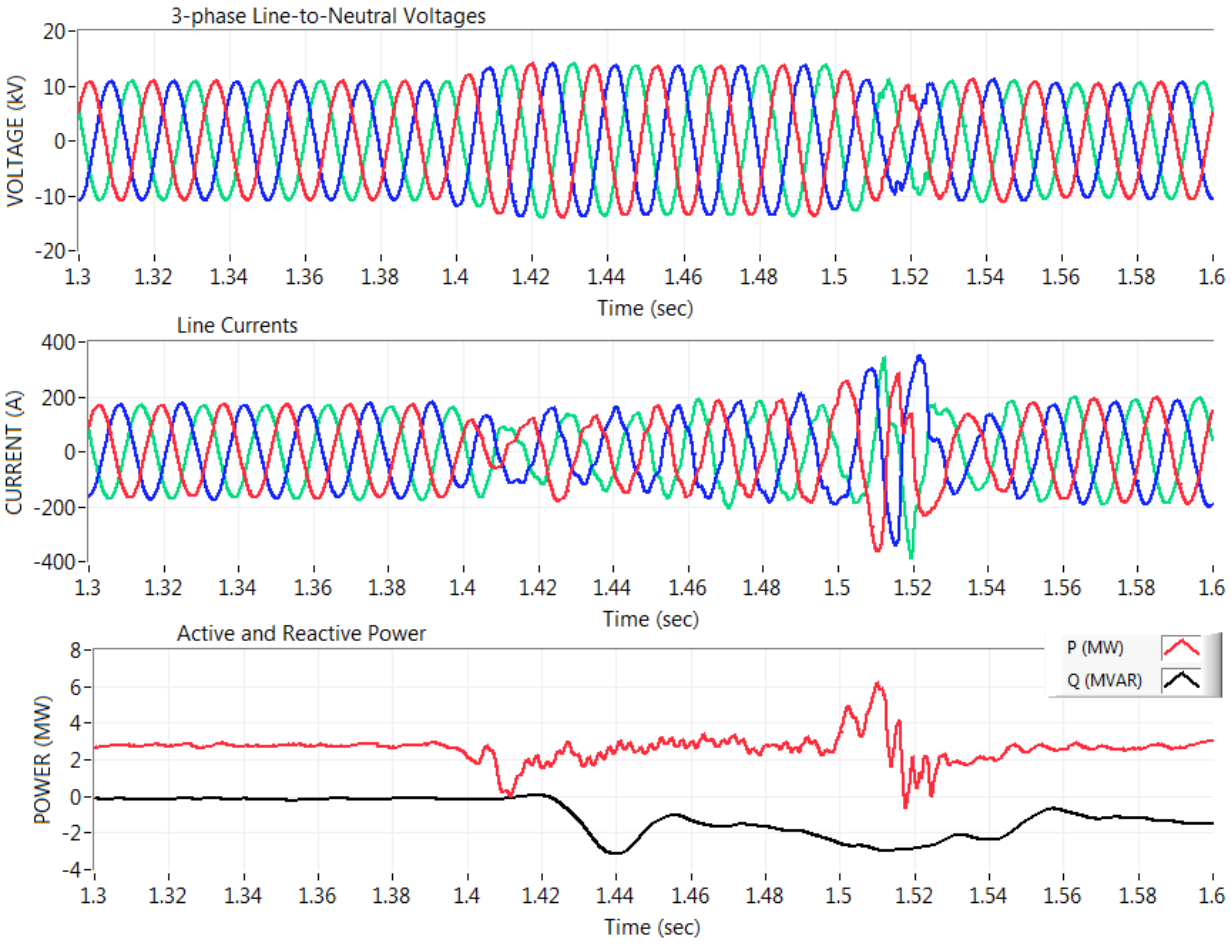
Three-Phase Fault



Three-Phase Fault - Slow Recovery

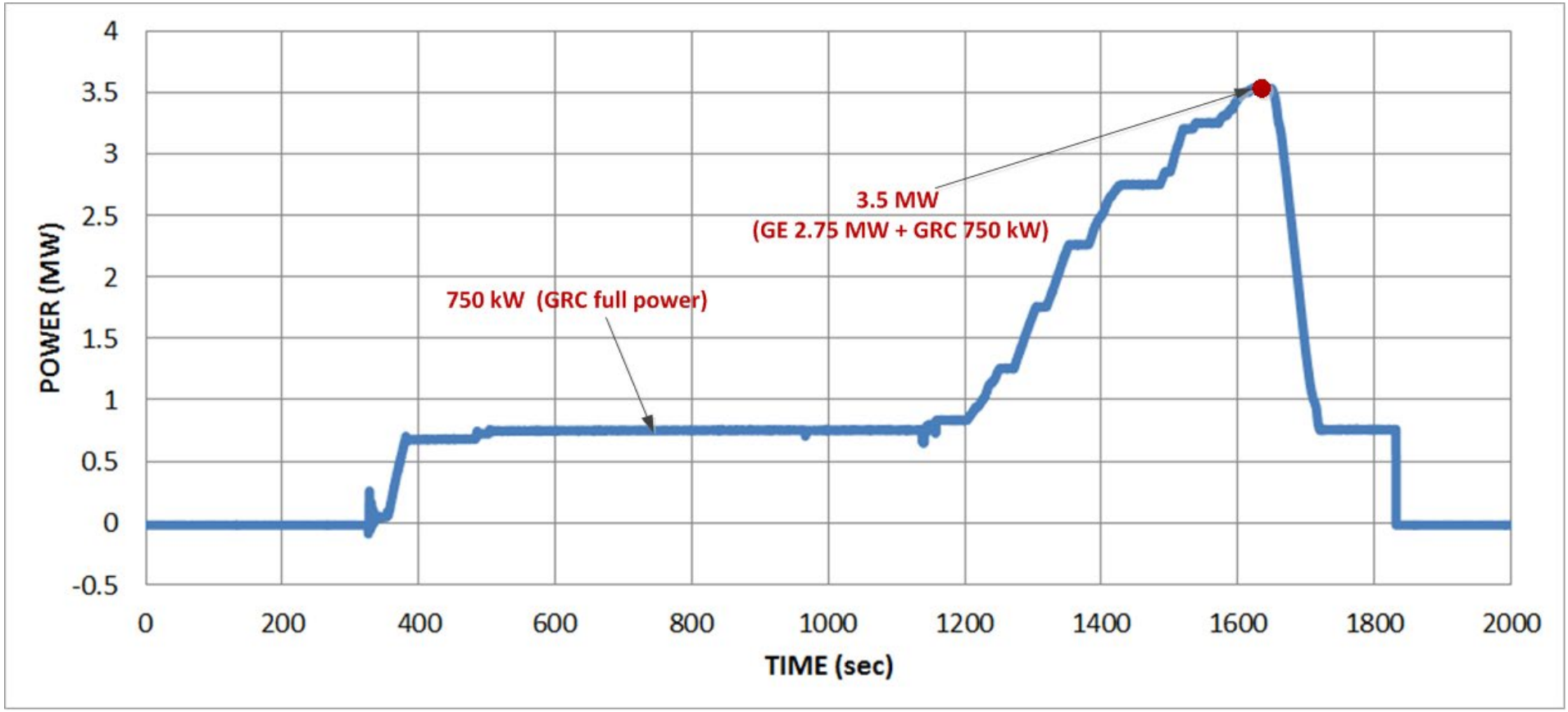


Three-Phase 130% Overvoltage

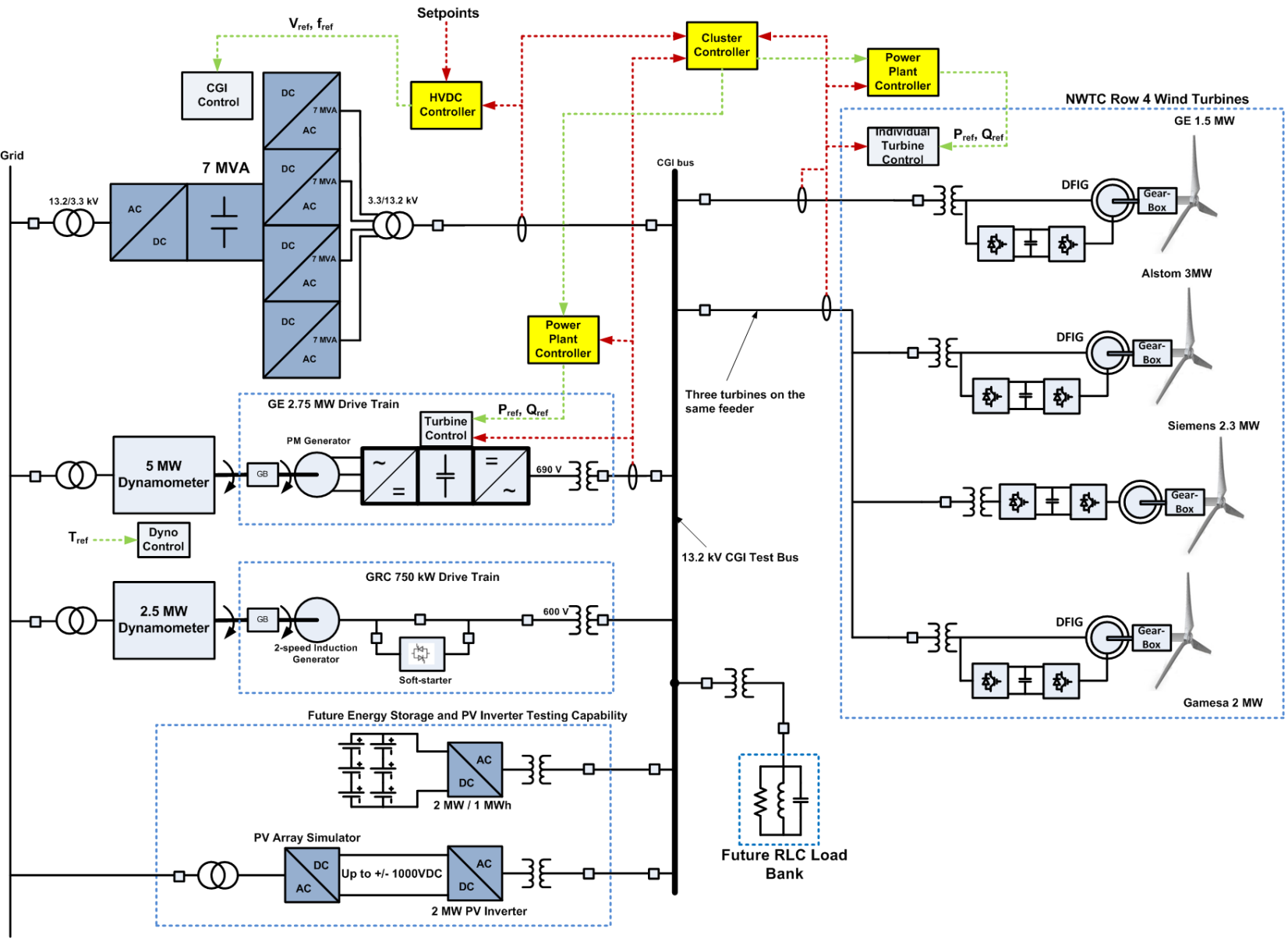


CGI - Two Dynamometers Test

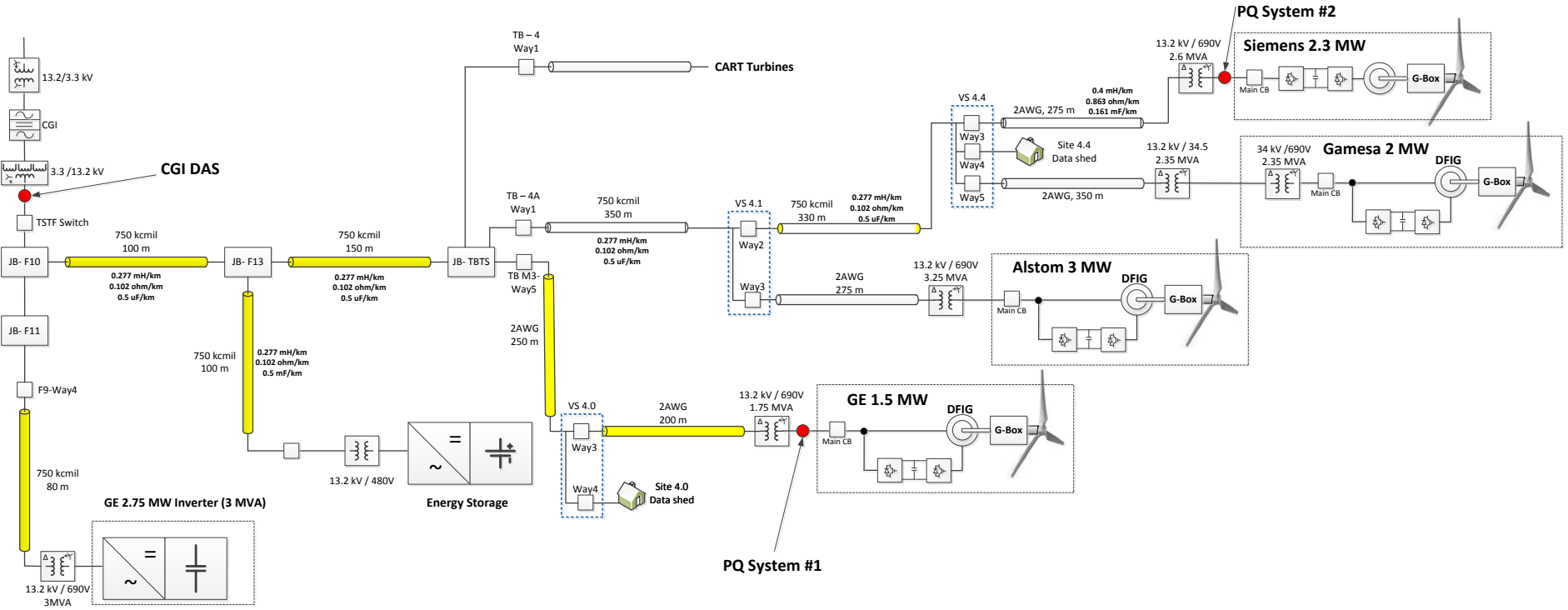
- 3.5 MW – highest CGI loading up-to-date
- Parallel operation of GE 2.75MW (Type 3) and GRC's NEG Micon 750 kW (Type 1)



Simulated Grid Multi-Technology Testing Capability

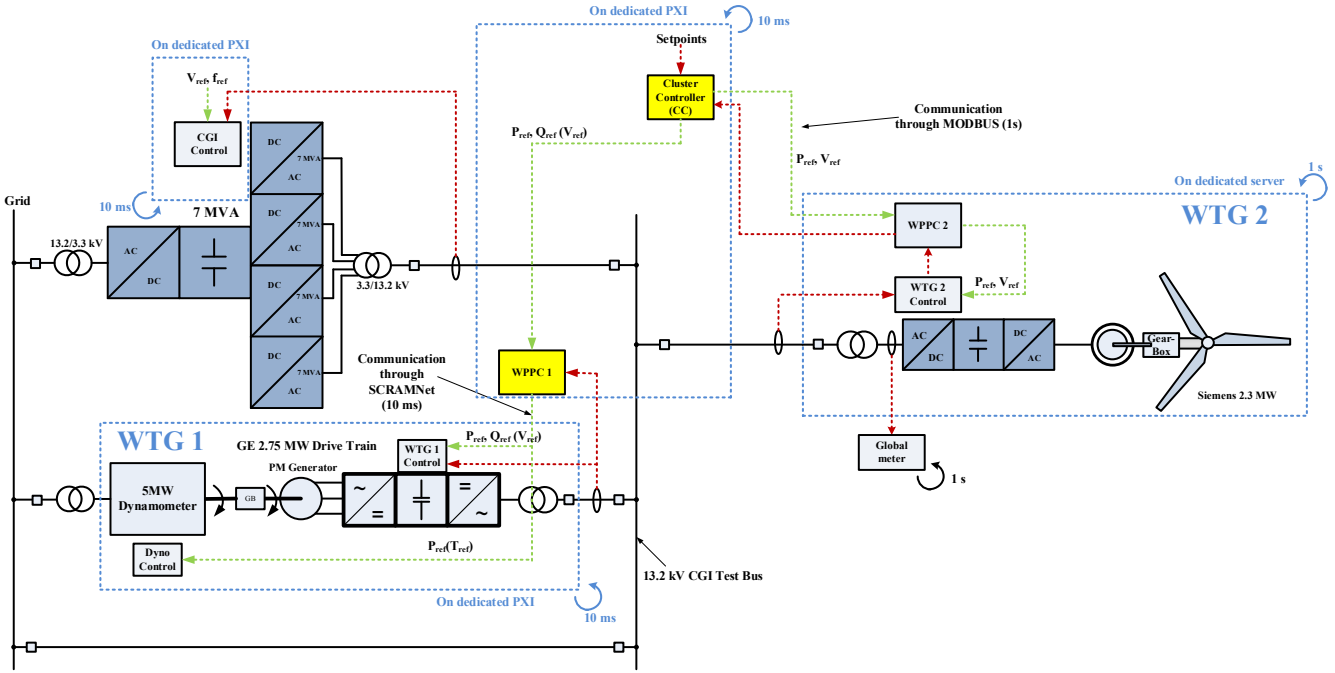


CGI 13.2 kV Test Bus – Collector System

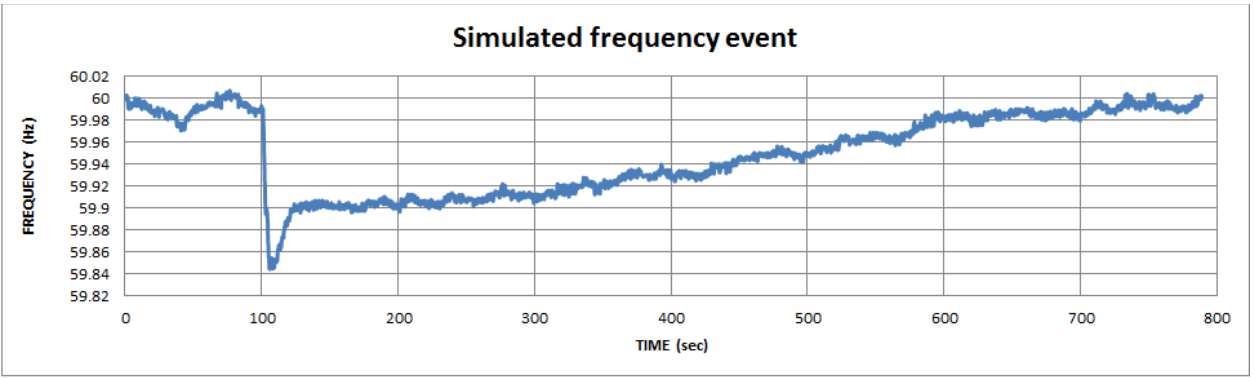


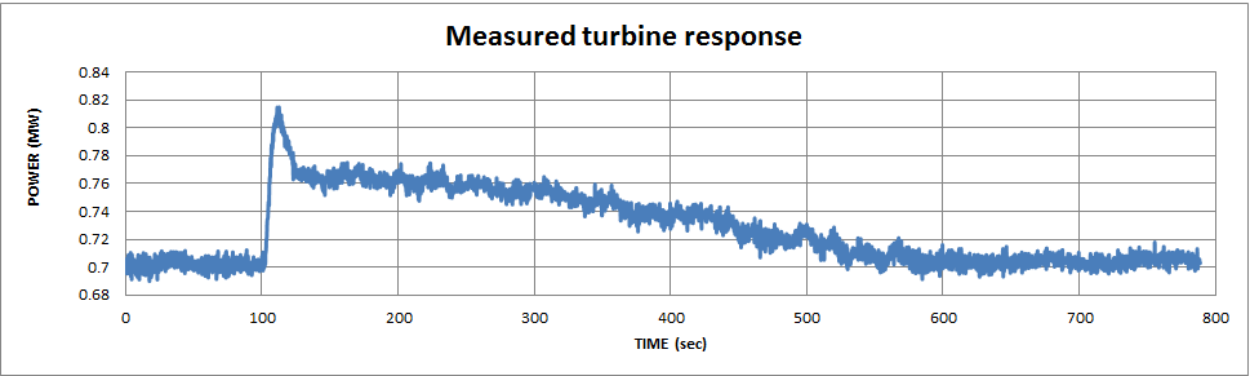
NREL-DONG Energy CRADA

- **Phase 1 – Validate models for harmonic interactions analysis in HVDC interconnected offshore wind power plants**
- **Phase 2 – Development and testing of coordinated control of clusters of wind power plants to provide ancillary services**
  - Frequency control
  - Power oscillation damping (POD) control

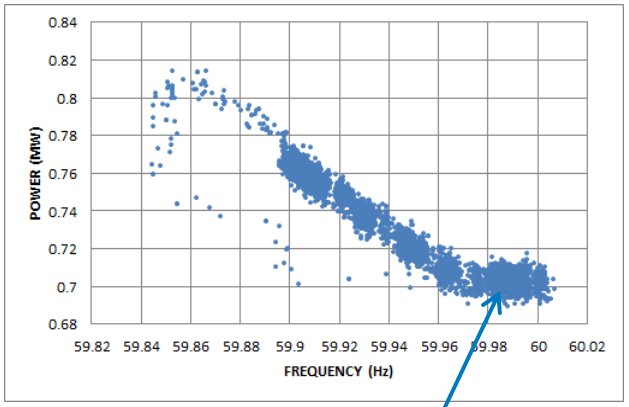


GE 2.75 MW - 5% Frequency Droop Test



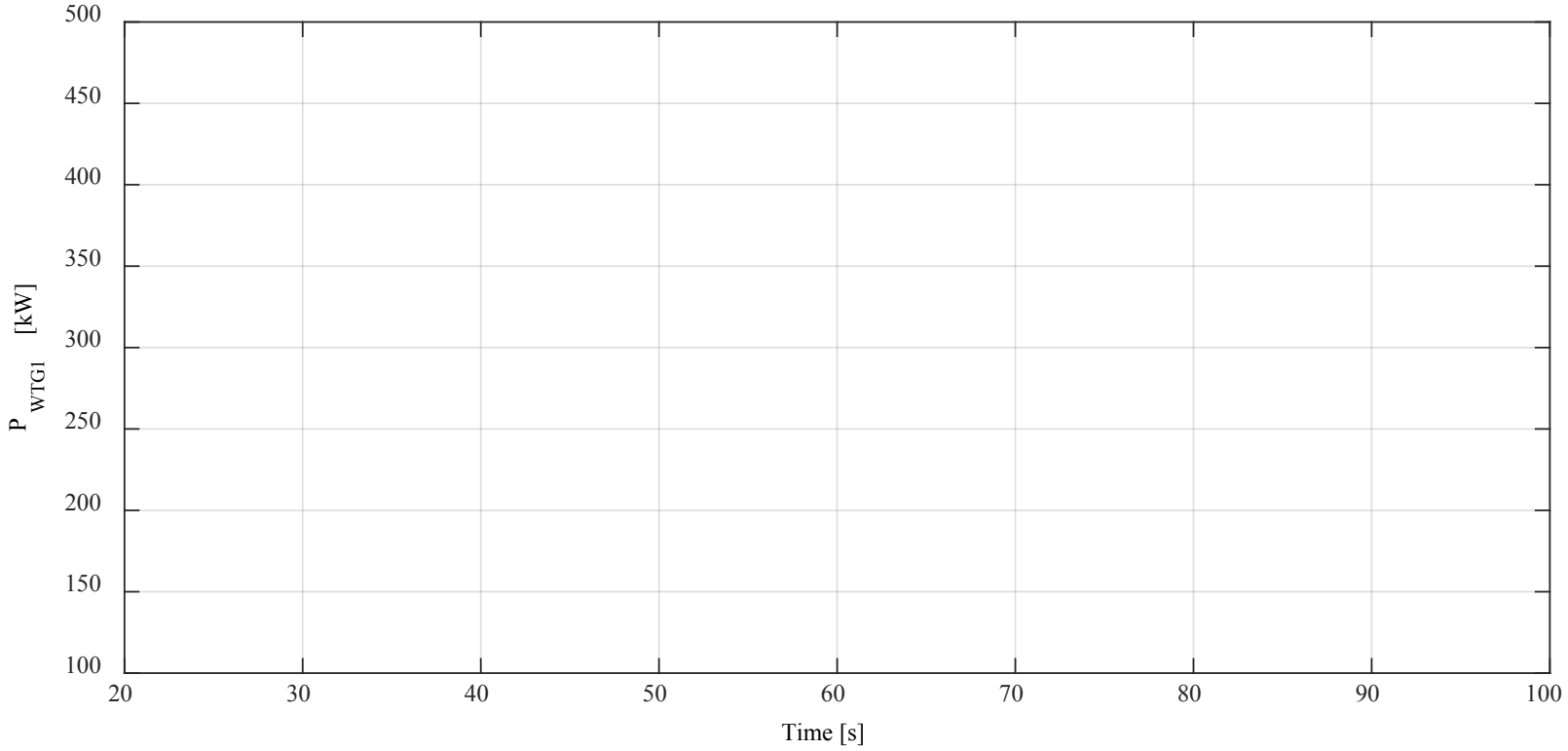


Measured droop characteristic

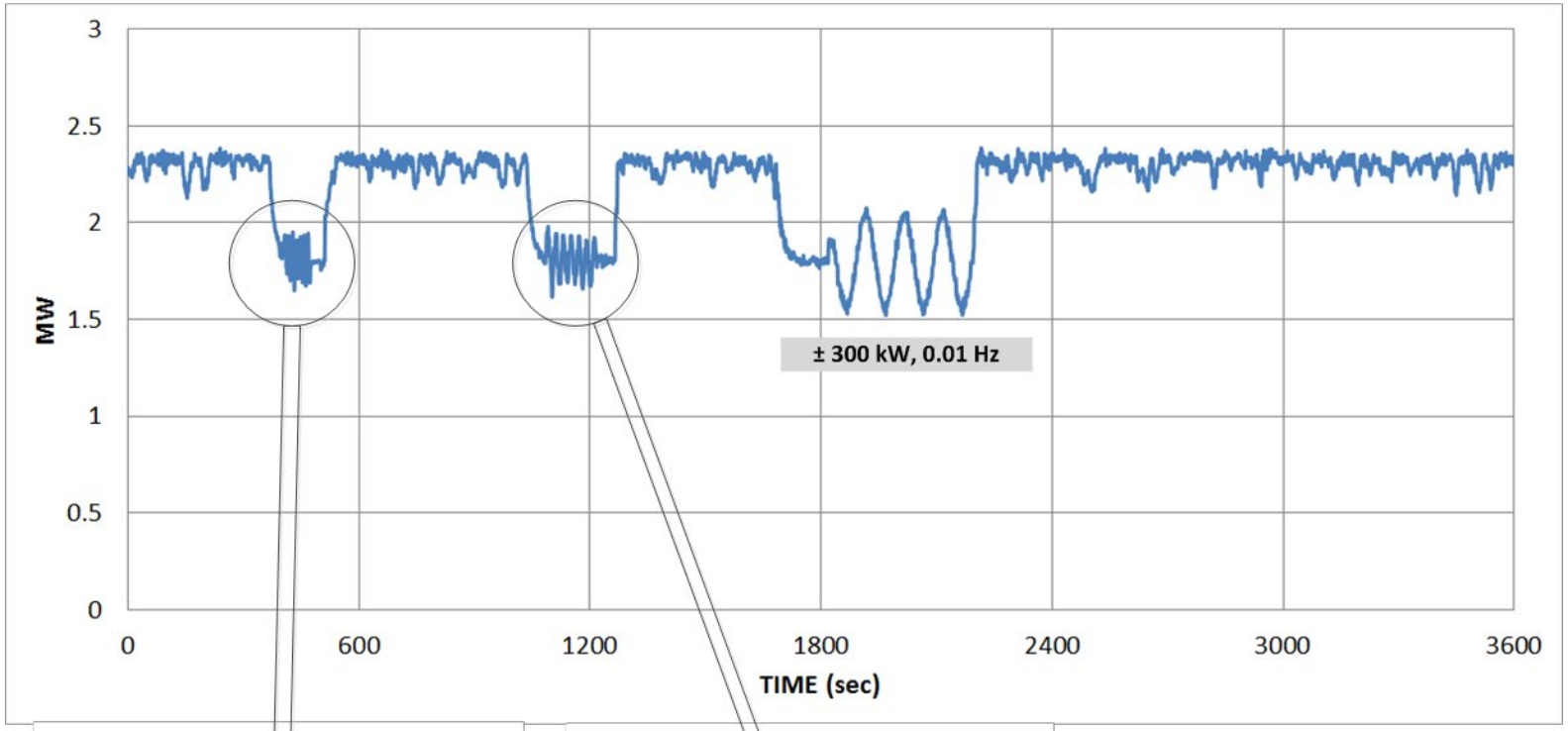


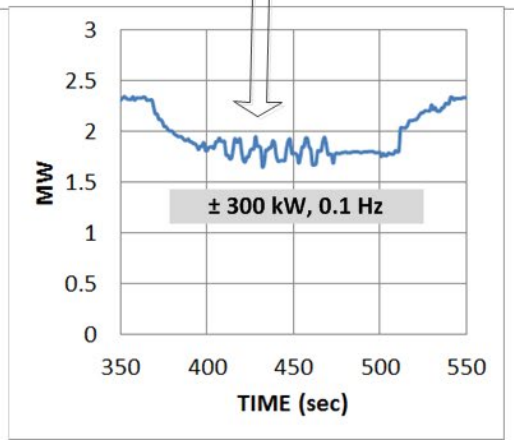
Frequency deadband

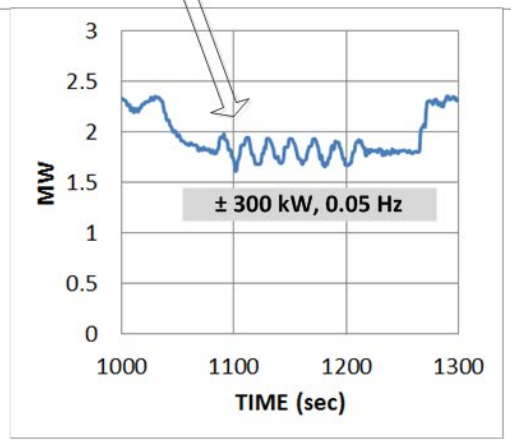
POD Control of 2.75 MW WTG



2.3 MW Turbine Test Results

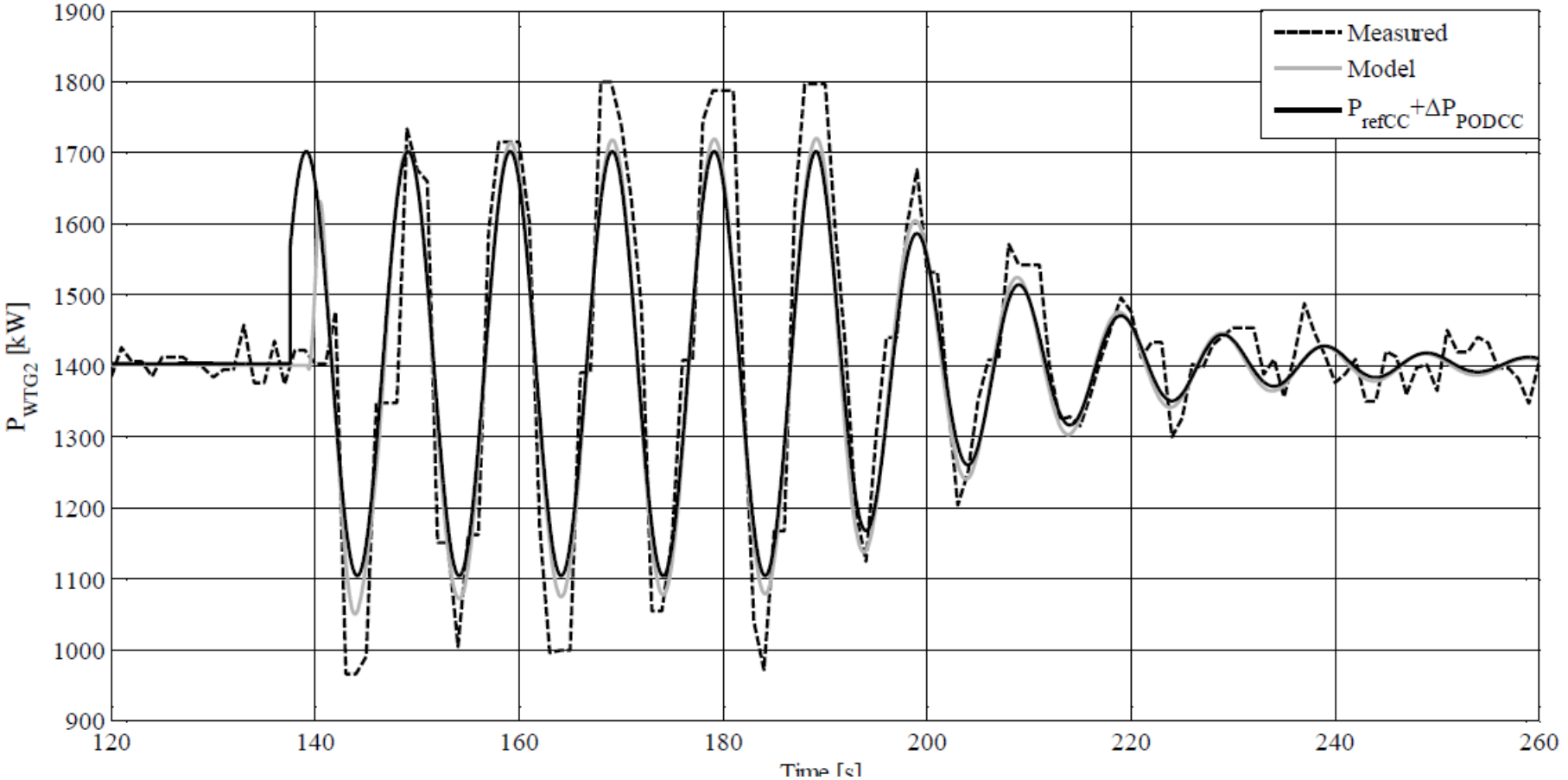




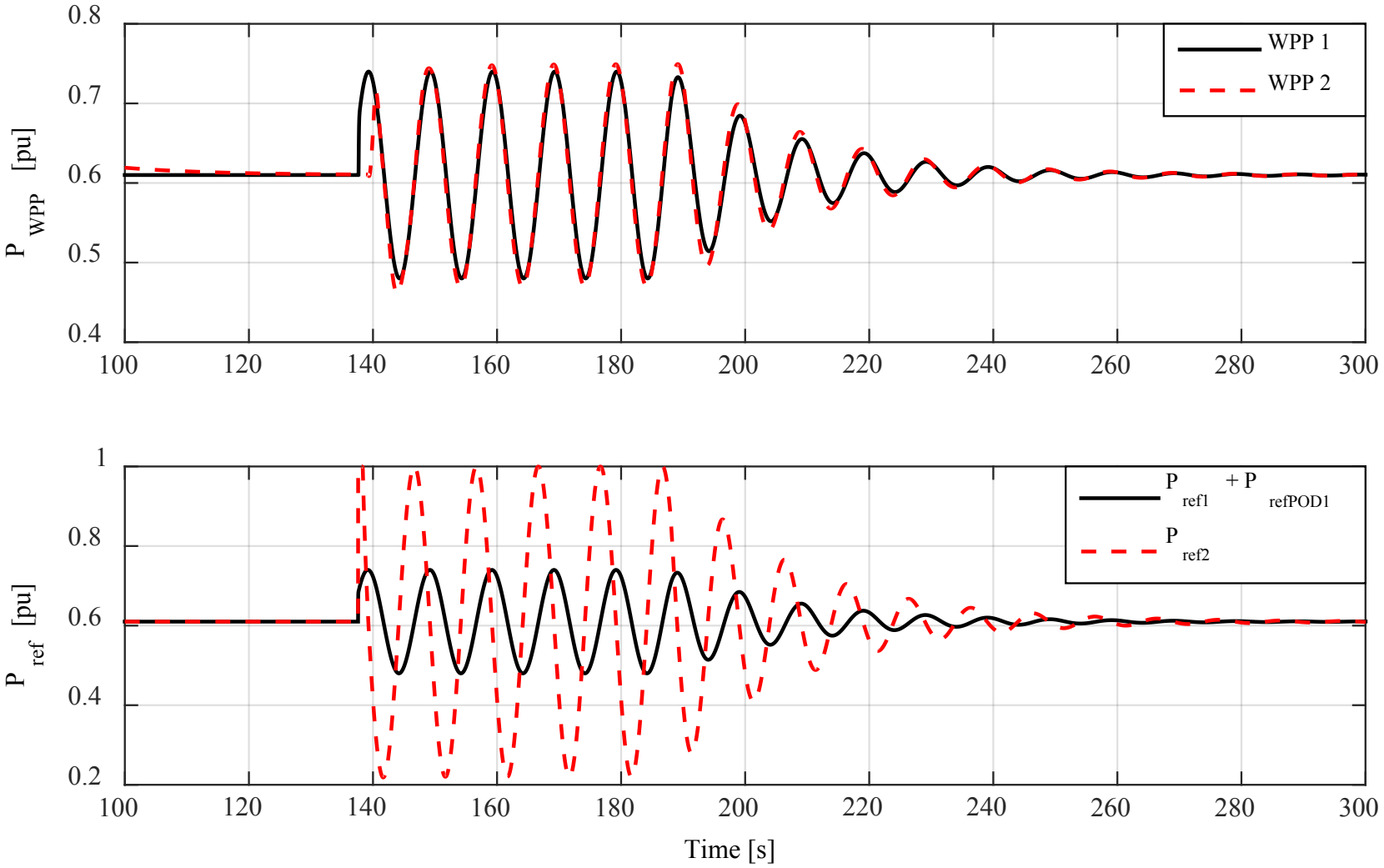


- Three tests conducted for three set point frequencies (0.1, 0.05 and 0.01 Hz)
- Same ±300 kW amplitude command used in all three tests

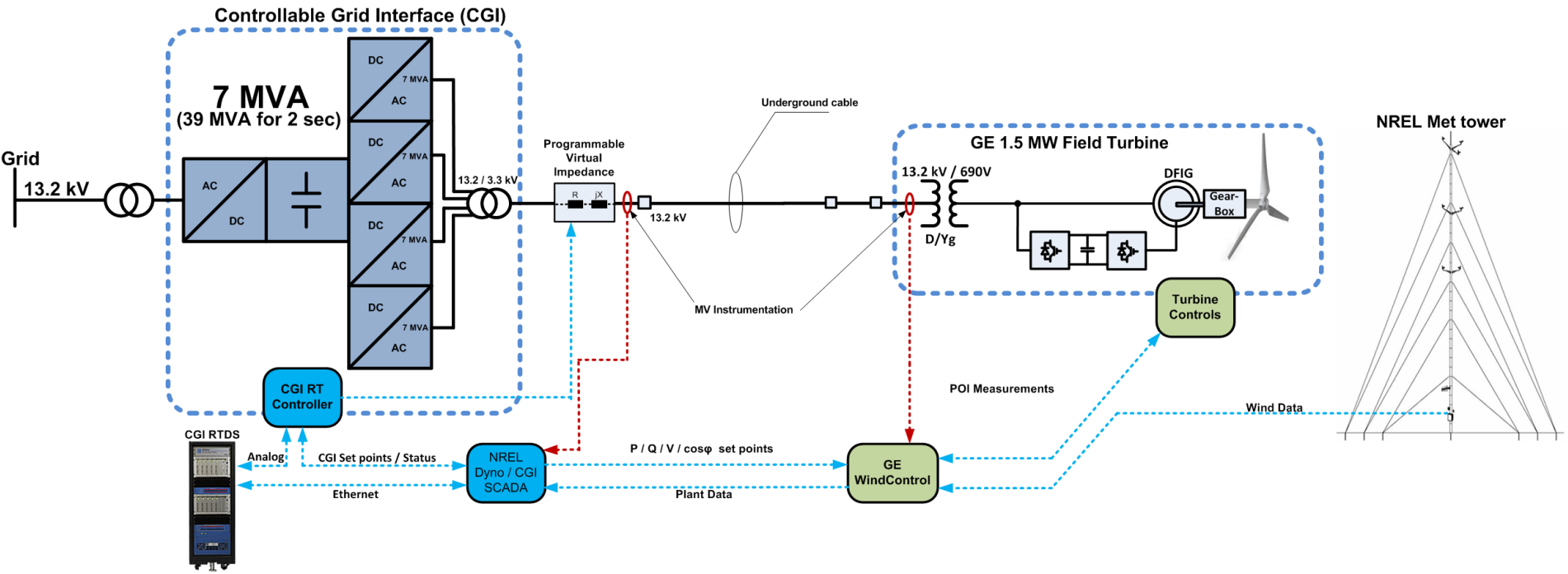
Model validation for WTG2



Results – Simulation of POD from cluster

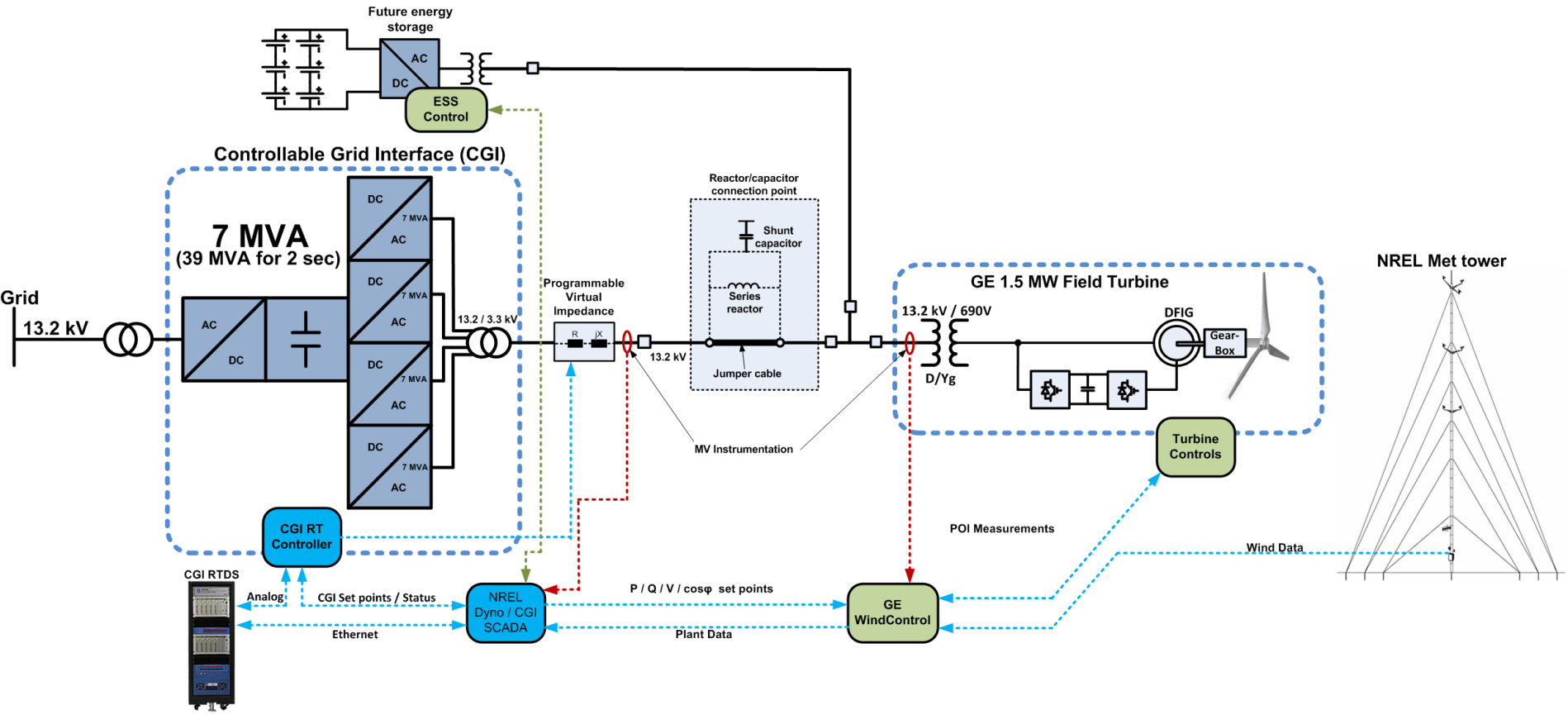


CGI – GE 1.5MW Turbine Interconnection



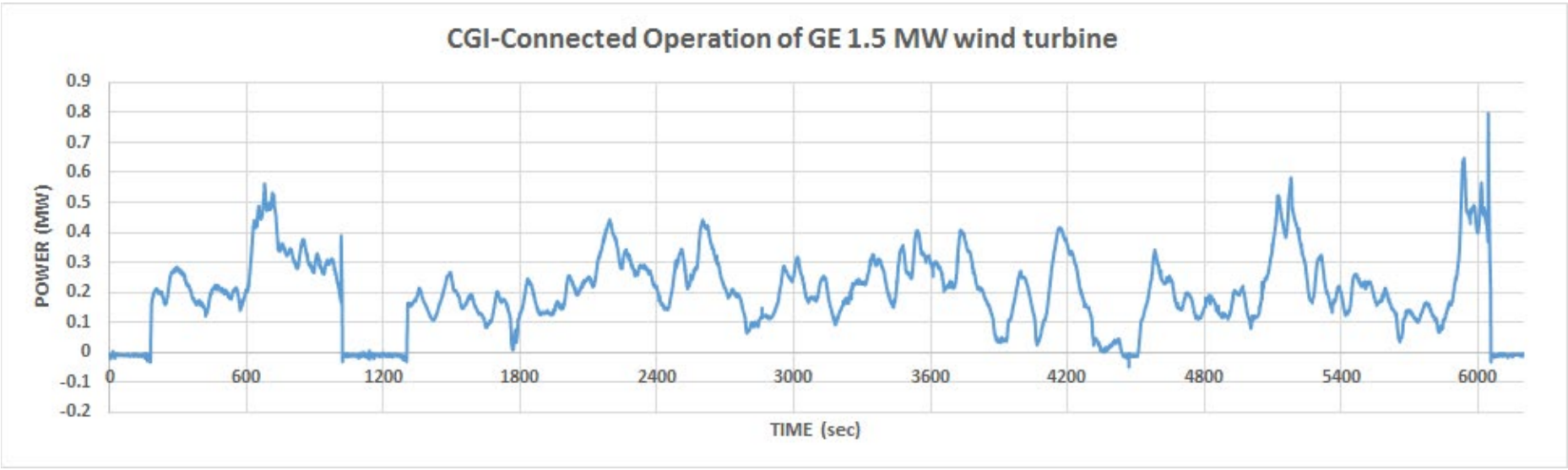
- GE WindCONTROL is being deployed including all available plant and turbine level controls

CGI – GE 1.5MW Turbine Interconnection

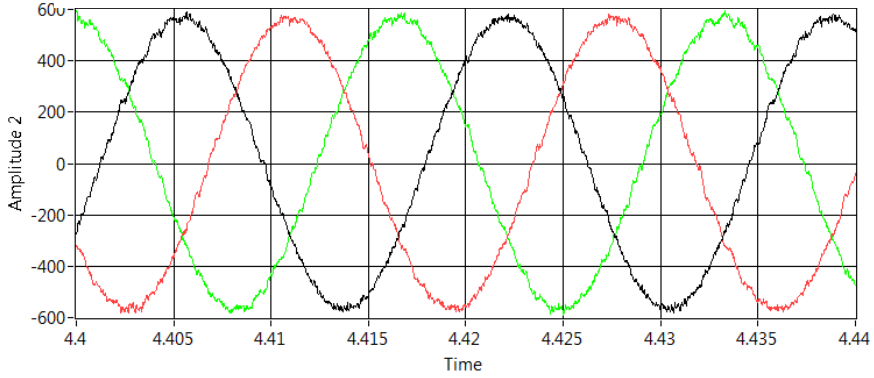


- Potential of adding a short-term energy storage
- Possible series inductor/shunt capacitor addition

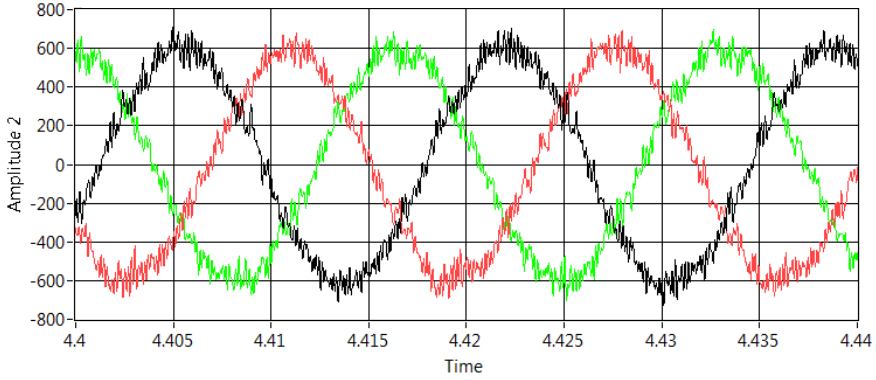
GE 1.5 MW field turbine operating with CGI



Voltage waveforms (690V terminals)



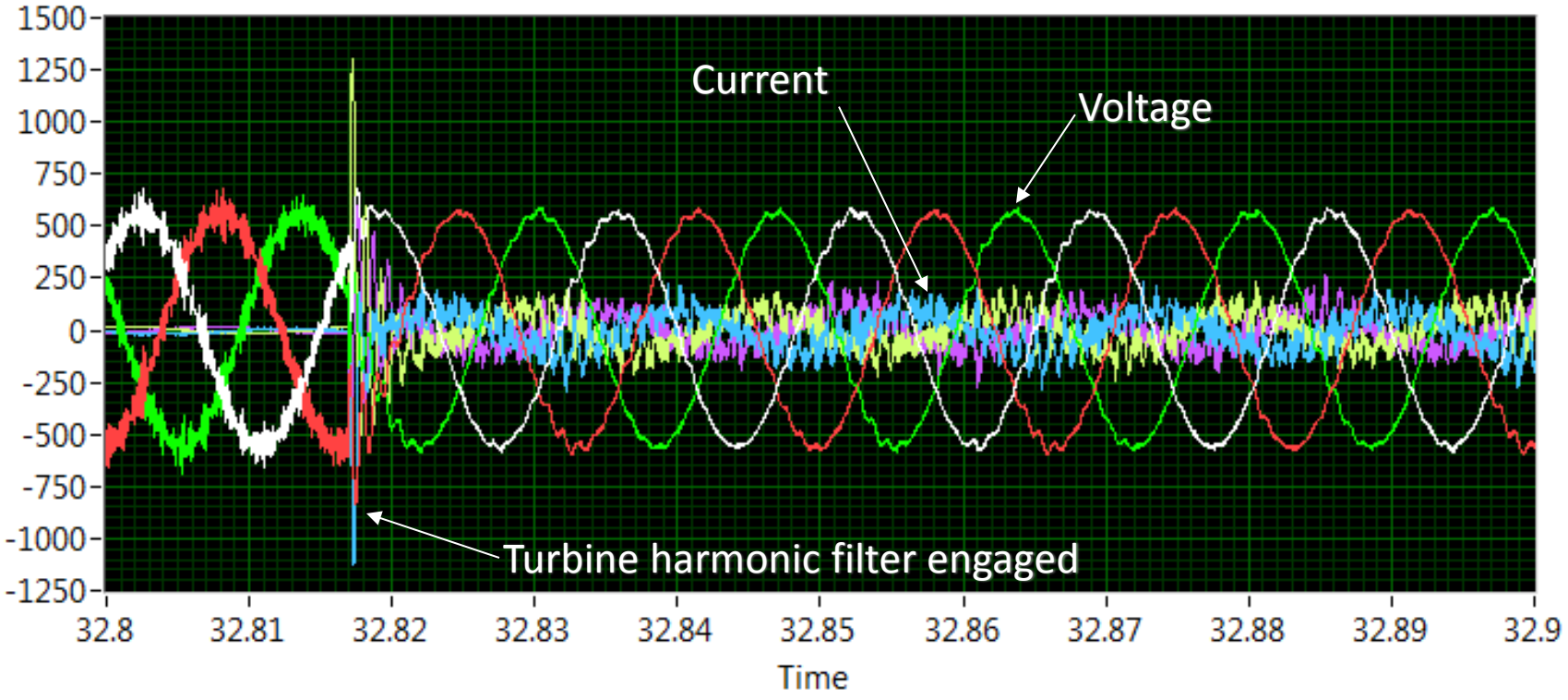
Current waveforms (690V terminals)

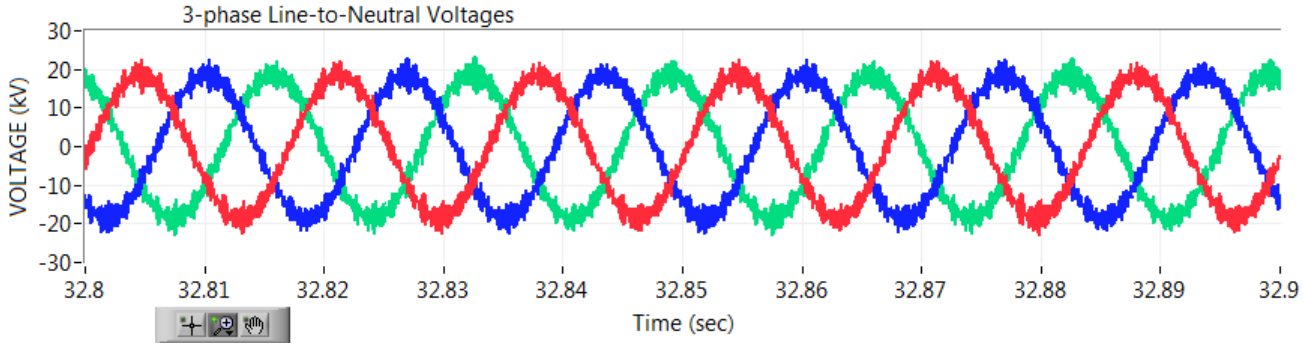


Voltage THD = 1.2%

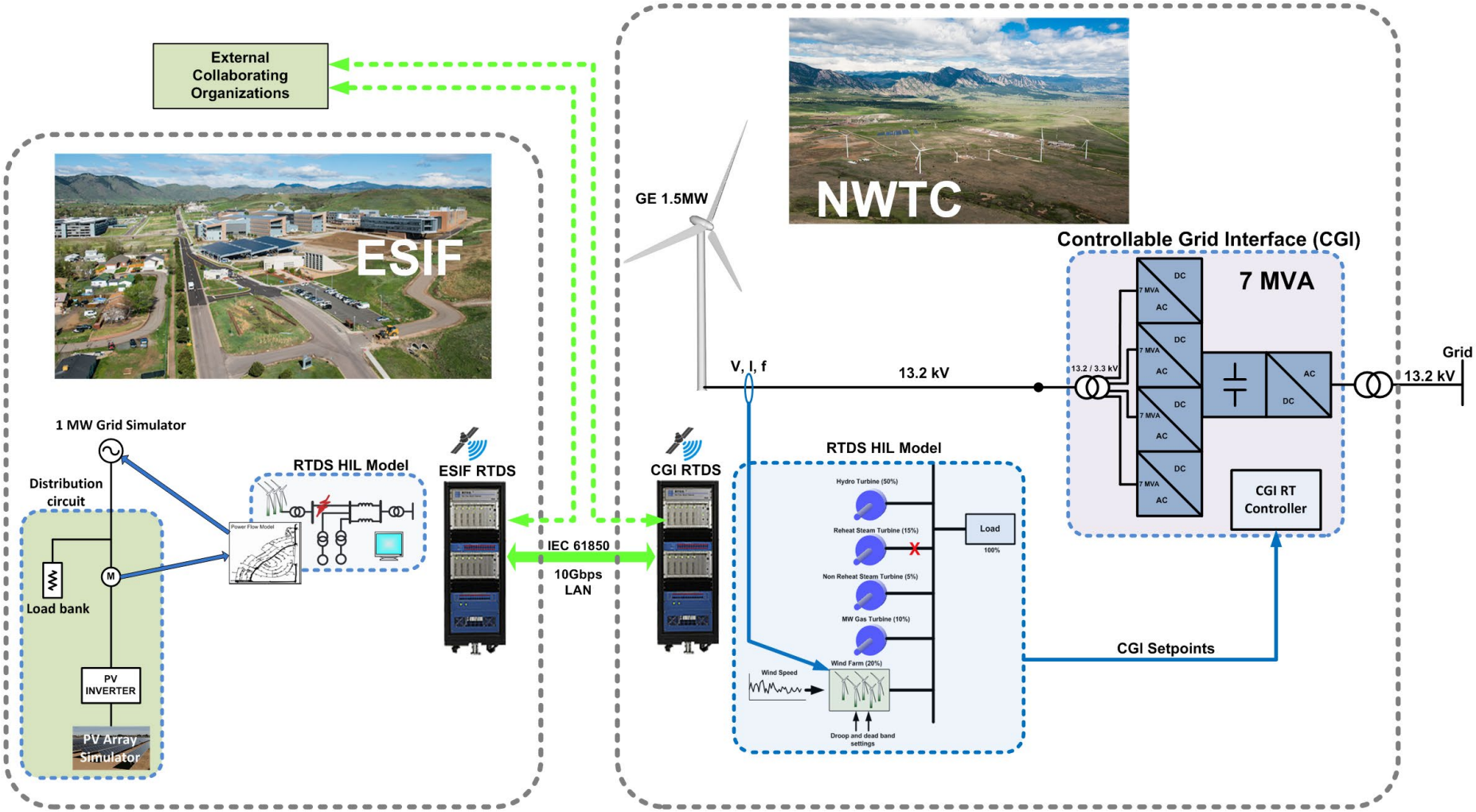
GE 1.5 MW field turbine operating with CGI

Voltage and current waveforms (690V terminals)



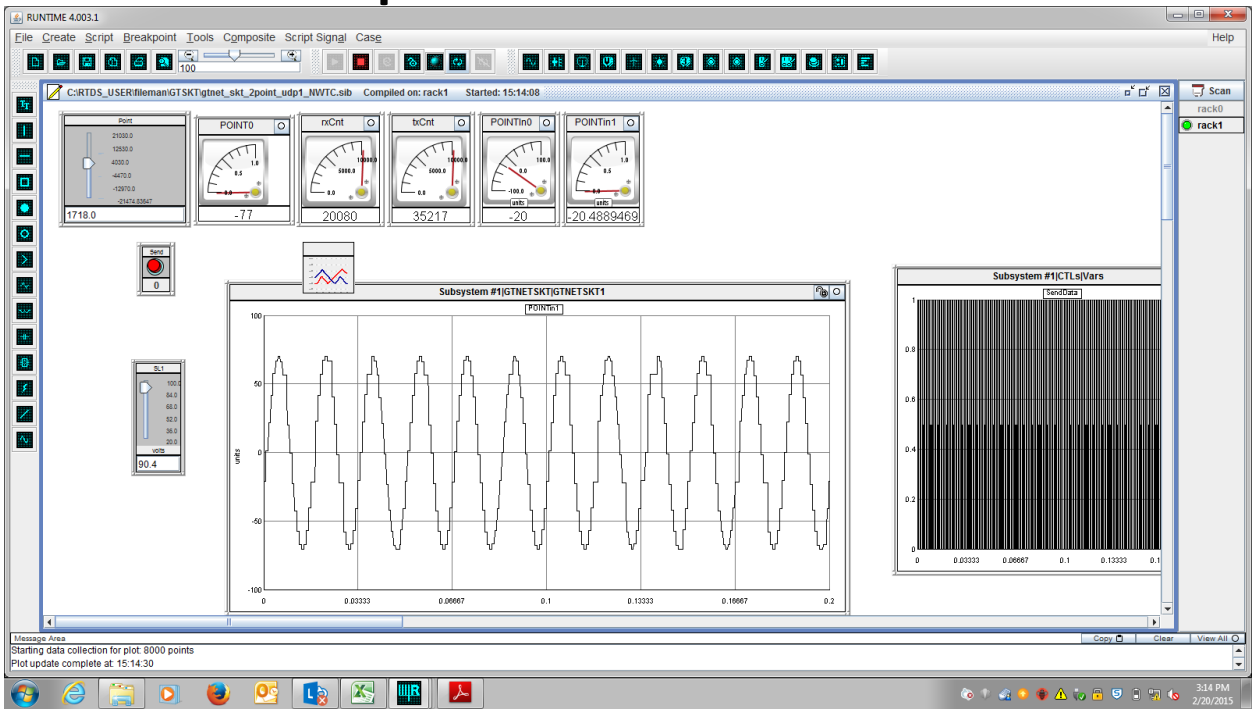


NWTC/ESIF Real-time Interconnection



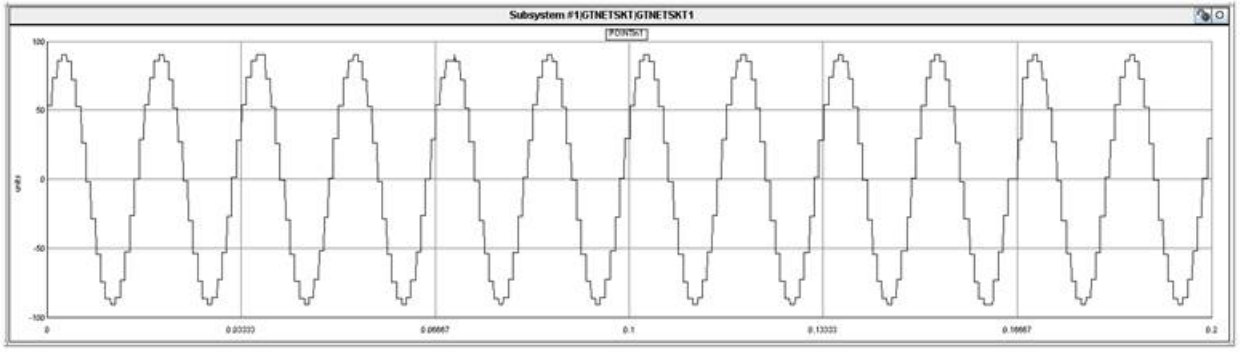
RTDS-to-RTDS Data Exchange Tests

1200 Hz sample rate received at ESIF end

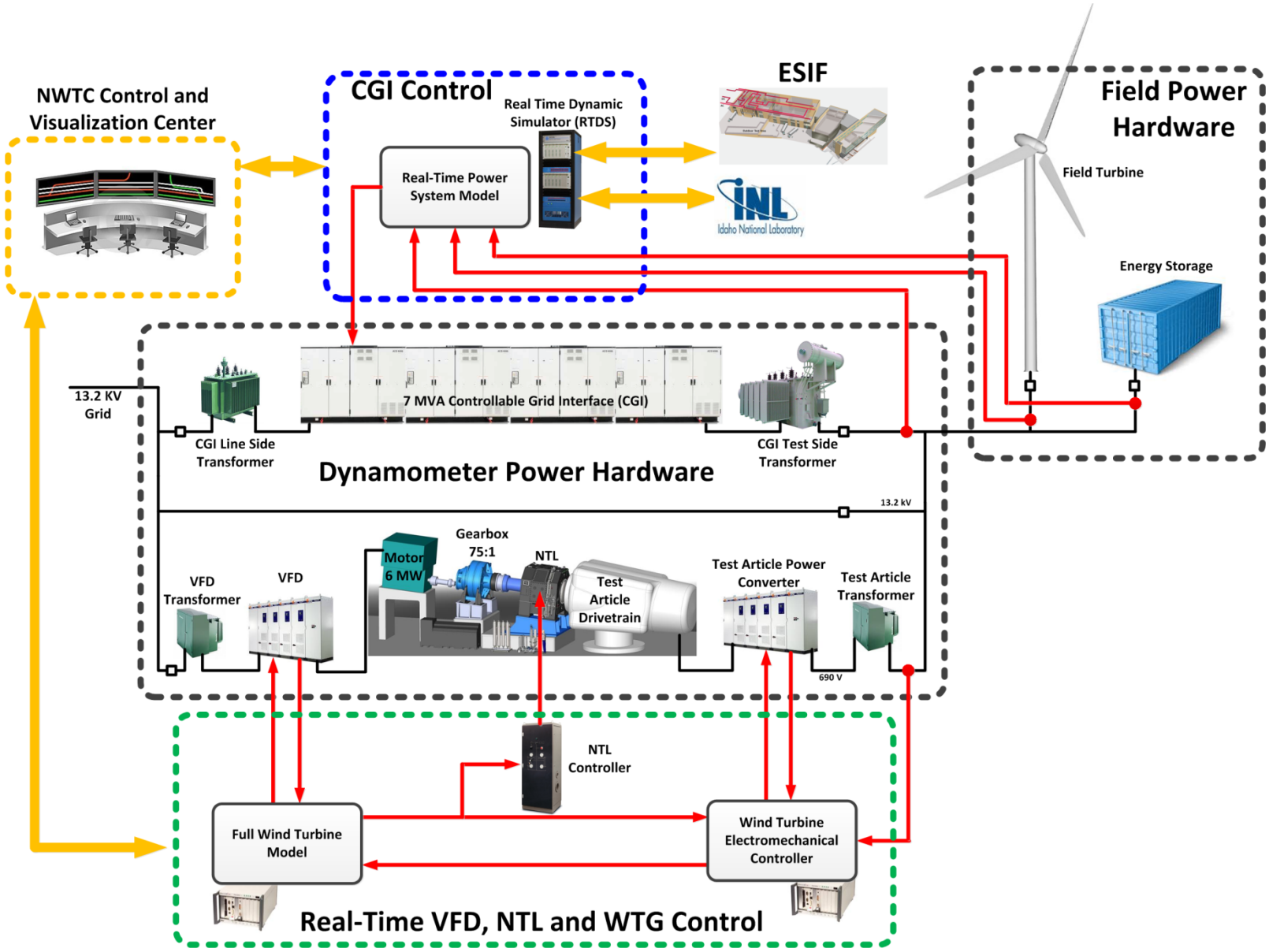


- 1200 Hz deterministic data exchange achieved
- 2000+ Hz is expected with new GTNET cards and new 10GBPS link

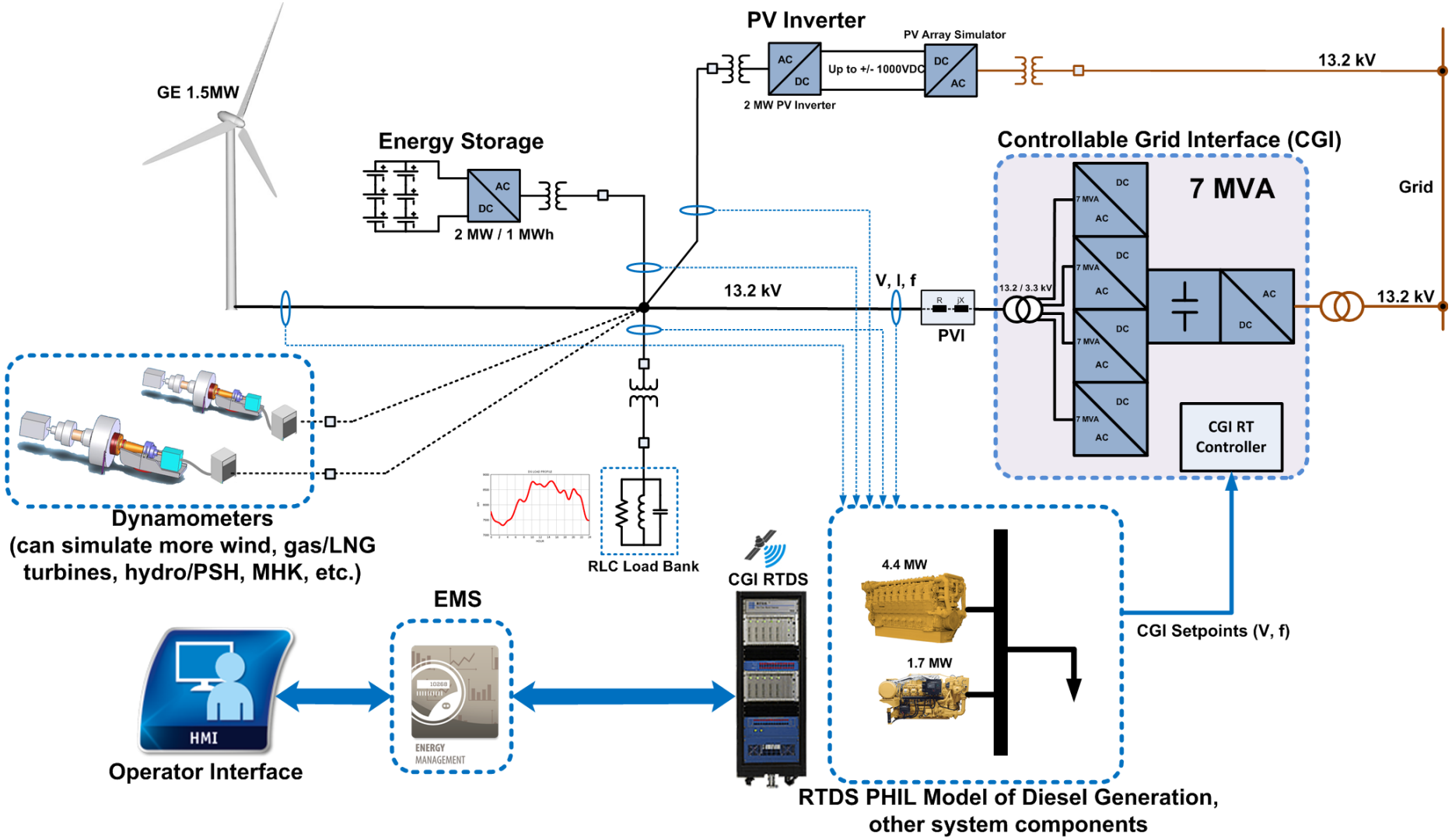
1200 Hz sample rate received at CGI end



NWTC PHIL Testing Concept

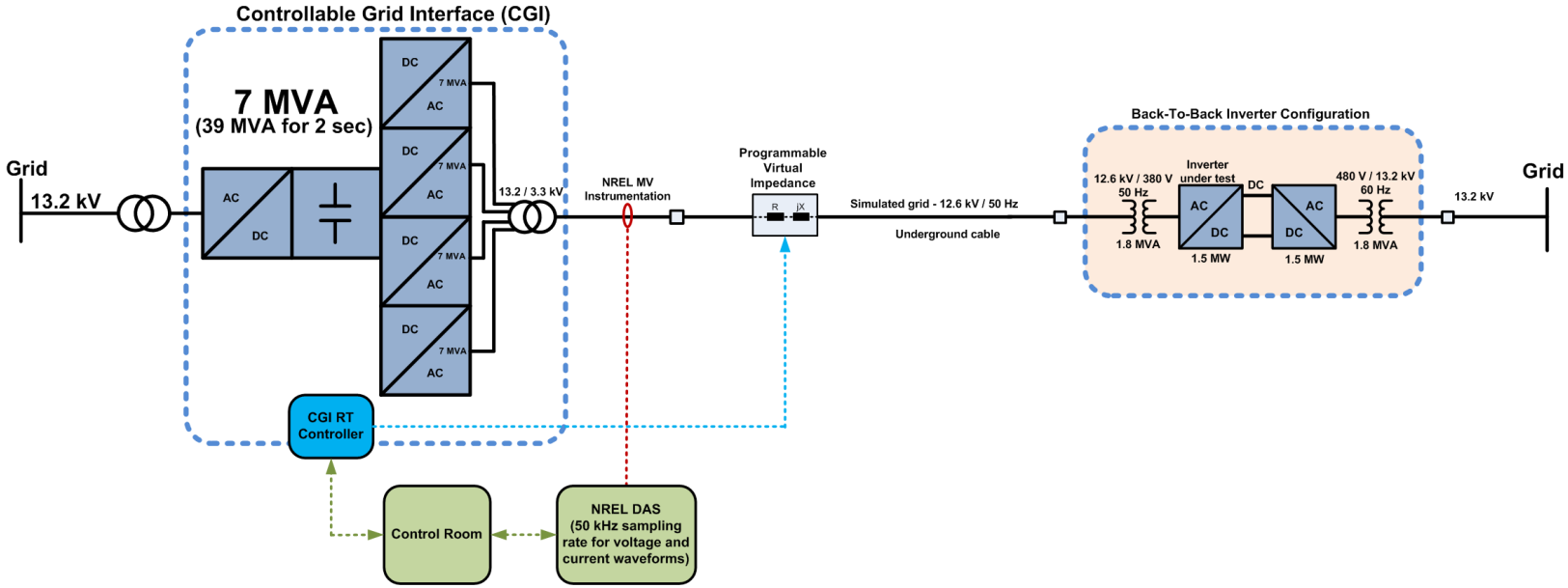


NWTC CGI for Microgrid Testing



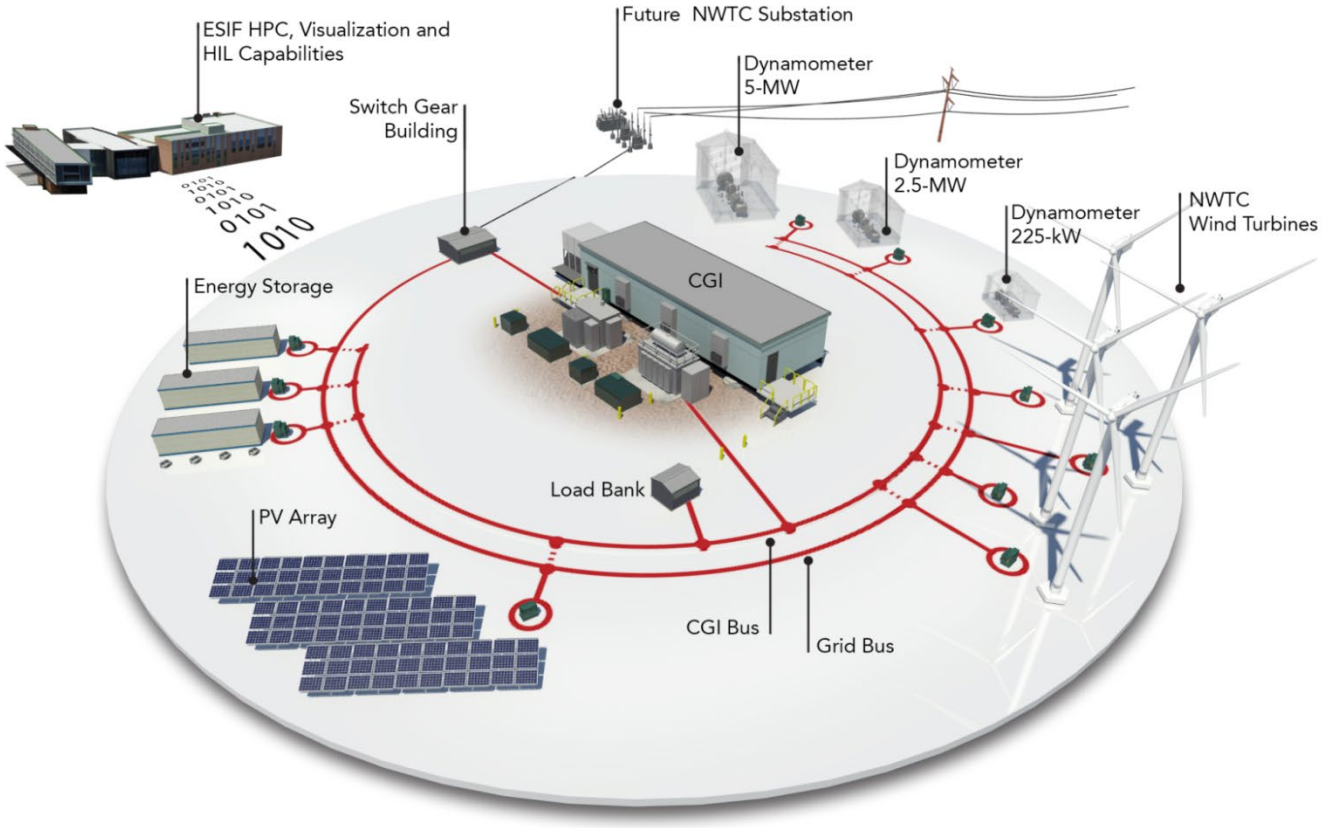
Other On-going CGI Activities

- Funding received for multi-MW load bank and DC power supply purchase (anti-islanding testing will be possible)
- Project under way to test SSR damping controls on Type 3 wind turbine using CGI
- Project to test LVRT characteristics of 1.5 MW fuel cell inverter in accordance to German grid codes at 50 Hz
- CGI controls upgrade (1ms response time, <1% no load voltage THD, scheduled Feb 2016)



Value Proposition of Grid Simulator

- Cross-technology grid compliance and ancillary services testing at multi-MW level under controlled MV grid conditions
- Tool for RE industry to test for compliance with national and international electrical standards, grid codes and interconnection requirements
- Tool for advanced controls testing and validation
- Helps increasing reliability and reducing integration cost of renewables generation



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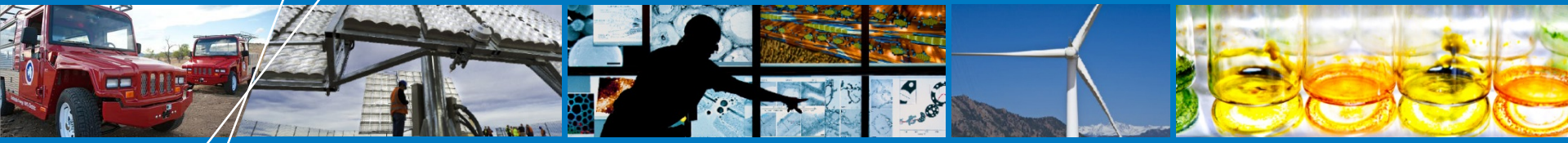

Lab Equipment

1.08 MVA Grid Simulator

Manufacturer and Base Model

Ametek RS90 (90 kVA)

Modularity

Four RS270 “quads” capable of independent or parallel operation

Basic Specifications (RS270)

- **Voltage:** 0–400 $V_{l\text{-}n}$ or 400 V_{dc}
- **Frequency:**
  - DC or 16–819 Hz (sourcing)
  - DC or 16–500 Hz (sinking)
- **Current:** 375 A (1500 A total)
- **Power Flow:** Bi-directional
- **Phase Control:** Independent phase control
- **PHIL Interface:** Analog input corresponding to instantaneous voltage waveform command
- **Input Current THD:**
  - Source mode: ~ 3%
  - Sink mode: ~ 5%
- **Software Interface:**
  - Transient list editor
  - Arbitrary waveform generation
- **Cooling:** Air-cooled

1.0 MVA Grid Simulator—More Specs

Architecture

- **Topology:** Three single-phase full-bridges
- **Device Type:** PFC = IGBT, Inverter = MOSFET
- **Inverter Switching Frequency:** 60 kHz, interleaved to 240 kHz effective

Output Specifications

- **Voltage Accuracy:** ±0.3 V AC, ±1 V DC
- **Frequency Accuracy:** ±0.01%
- **Phase Angle Accuracy:** < 1.5° @ 16–100 Hz; < 2° @100–500 Hz
- **THD at Full Load:**
  - Sourcing: < 0.5% @ 16–66 Hz; < 1% @ 66–500 Hz; < 1.25% up to 819 Hz
  - Sinking: < 1% @45–66 Hz; < 2% @ 66–500 Hz
- **Load Regulation:** 0.25% FS @ DC–100 Hz; 0.5% FS @ > 100 Hz
- **DC Offset Voltage:** < 20 mV
- **Slew Rate:** 200 µs for 20%–90% output change into resistive load, > 0.5 V/µs
- **Settling Time:** < 0.5 µs
- **-3dB Bandwidth:**

  4 kHz (but fundamental component limited to 1 kHz due to output snubber power limitations)

1.5 MW PV Simulator

Manufacturer and Base Model

Magna-Power MTD1000-250 (250 kW)

Modularity

Six modules capable of independent, parallel, or series operation (up to 4000 V)

Basic Specifications

- **Voltage:** 25–1000 V (up to 4000 V)
- **Current:** 250 A (up to 1500 A)
- **Power Flow:** Supply only
- **PHIL Interface:** Analog input corresponding to instantaneous voltage/current waveform command
- **Bandwidth:**
  - Voltage: 60 Hz
  - Current: 45 Hz
- **Slew Rate:**
  - Voltage: 4 ms for 0–63% step
  - Current: 8 ms for 0–63% step
- **Load Transient Response:** 10 ms to recover to within ± 1% of regulated output with a 50–100% or 100–50% load step
- **Load Regulation:**
  - Voltage: ±0.01% of full scale
  - Current: ±0.04% of full scale
- **Software Interface:**
  - PV IV curve emulation
  - Profile generation
- **Cooling:** Air-cooled

660 kW Battery/PV Simulator

Manufacturer and Base Model

Anderson Electric Controls AC2660P (660 kW)

Modularity

Currently one module; future two modules capable of independent, parallel, or series operation

Basic Specifications

- **Voltage:** 264–1000 V (up to 2000 V)
- **Current:** 2500 A (up to 5000 A)
- **Power Flow:** Bi-directional
- **PHIL Interface:** Digital voltage, current, irradiance, and/or temperature commands
- **Load Regulation:**
  - Steady-state: ±0.5%
  - Transient: ±3%
- **Load Transient Response:**
  < 10 ms for 10–90% or 90–10% load step
- **Bandwidth:**
  - Voltage control: 180 Hz (Next Gen = 500 Hz)
  - Current control: 2.0 kHz (Next Gen = 2.5 kHz)
- **Software Interface:**
  - PV IV curve emulation
  - Battery emulation
  - Profile generation
- **Cooling:** Liquid-cooled

1.5 MVA Load Bank

Manufacturer and Base Model

LoadTec OSW4c 390 kW/kVAR$_L$/kVAR$_C$ RLC Load Banks

Modularity

Four modules can be operated independently or in parallel

Basic Specifications

- **Voltage:** 0–346 $V_{l\text{-}n}$/600 $V_{l\text{-}l}$
- **Frequency:**
  - L and C: 45–65 Hz
  - R: DC–400 Hz
- **Power:**
  - 390 kW/kVAR @ 346/600 V 3ϕ
  - 250 kW/kVAR @ 277/480 V 3ϕ
  - 47 kW/kVAR @ 120/208 V 3ϕ
  - 47 kW/kVAR @ 120 V 1ϕ
- **Resolution**
  - 234 W/VAR @ 346/600 V 3ϕ
  - 150 W/VAR @ 277/480 V 3ϕ
  - 28 W/VAR @ 120/208 V 3ϕ
  - 10 W/VAR @ 120 V 1ϕ
- **Phase Configuration:**
  - Balanced or unbalanced 3ϕ
  - Single-phase
  - Split-phase
- **PHIL Interface:** Digital kW/kVAR cmds
- **Software Interface:**
  - Load profile entry
- **Cooling:** Air-cooled

Additional Equipment

- **PV Simulators**
  - 100 kW Ametek TerraSAS
- **DC Supplies**
  - 250 kW AeroVironment AV-900
- **Load Banks**
  - 100 kW R-L (portable)
  - 100 kW R (portable)
- **Small Grid Simulators**
  - 45 kW Ametek MX45
  - 15 kW Elgar
- **Diesel Generators**
  - 125kVA and 80 kVA Onan/Cummins
  - 300kVA Caterpillar
- **Hydrogen Systems**
  - Electrolyzers: 50kW, 10kW
  - Storage tanks
  - Fuel cells
- **Real-Time Digital Simulators**
  - Opal-RT (4 racks)
  - RTDS (2 racks)
- **LV Line Length Simulator (soon)**

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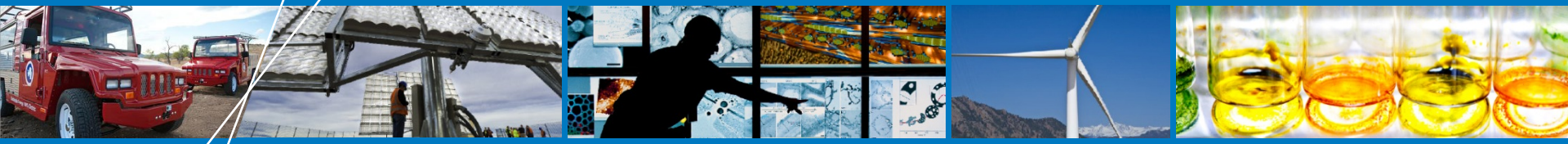
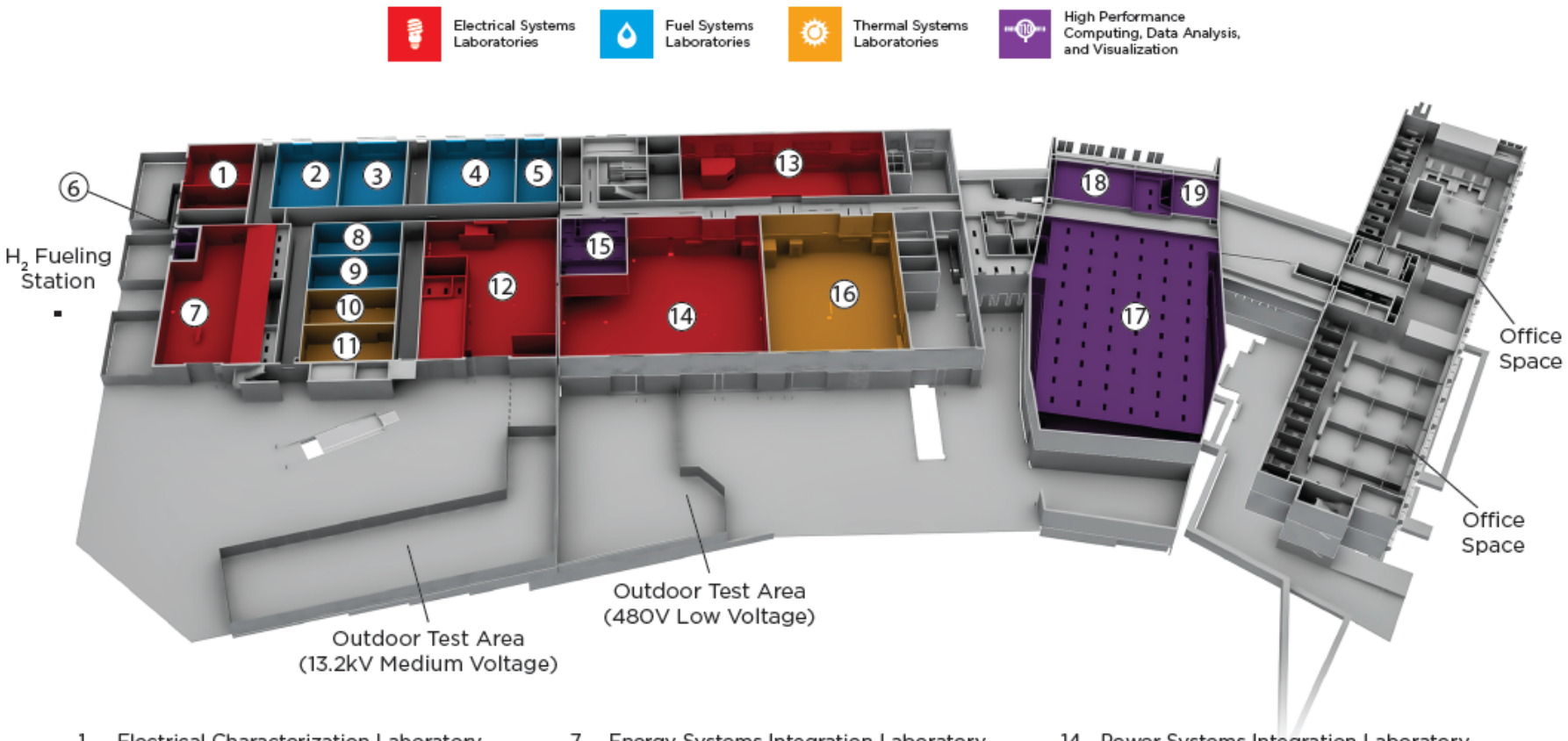
Thank you !



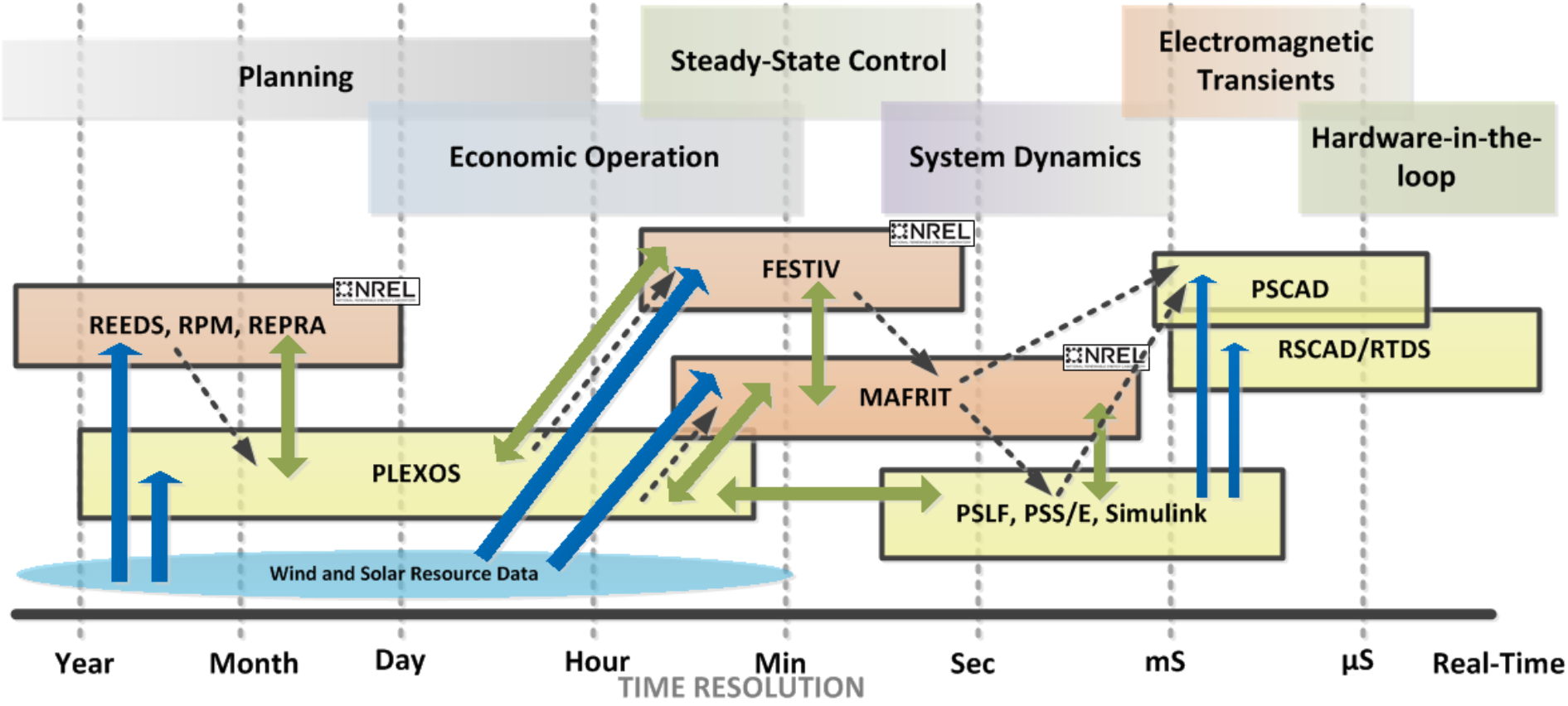
Questions?

Energy Systems Integration Facility (ESIF)



1. Electrical Characterization Laboratory
2. Materials Characterization Laboratory
3. Energy Systems Fabrication Laboratory
4. Fuel Cell Development and Test Laboratory
5. Manufacturing Laboratory
6. Energy Systems High Pressure Test
7. Energy Systems Integration Laboratory
8. Electrochemical Characterization
9. Energy Systems Sensor Laboratory
10. Thermal Storage Materials Laboratory
11. Thermal Systems Process and Component
12. Energy Storage Laboratory
13. Smart Power Laboratory
14. Power Systems Integration Laboratory
15. Control Room
16. Optical Characterization Laboratory
17. High Performance Computing Data Center
18. Insight Center Collaboration Room
19. Insight Center Visualization Room

NREL Software Tools for Grid Integration



NREL In-house Modelling Tools

REEDS – Regional Energy Deployment System model

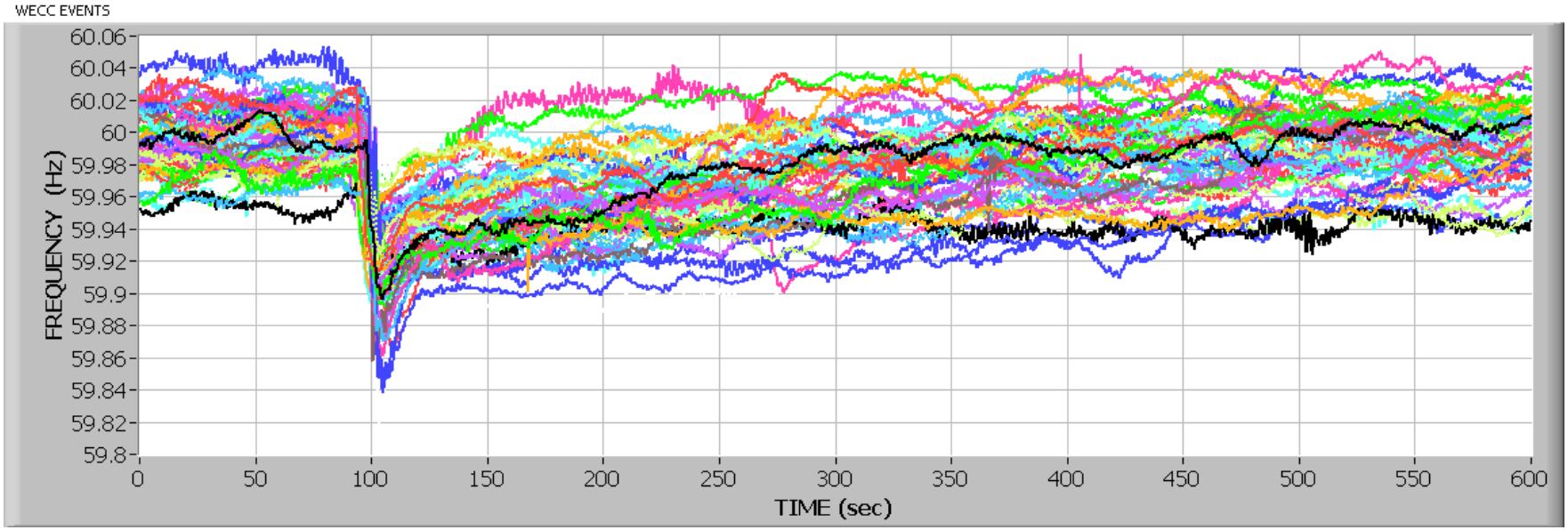
RPM – Resource Planning Model Tool

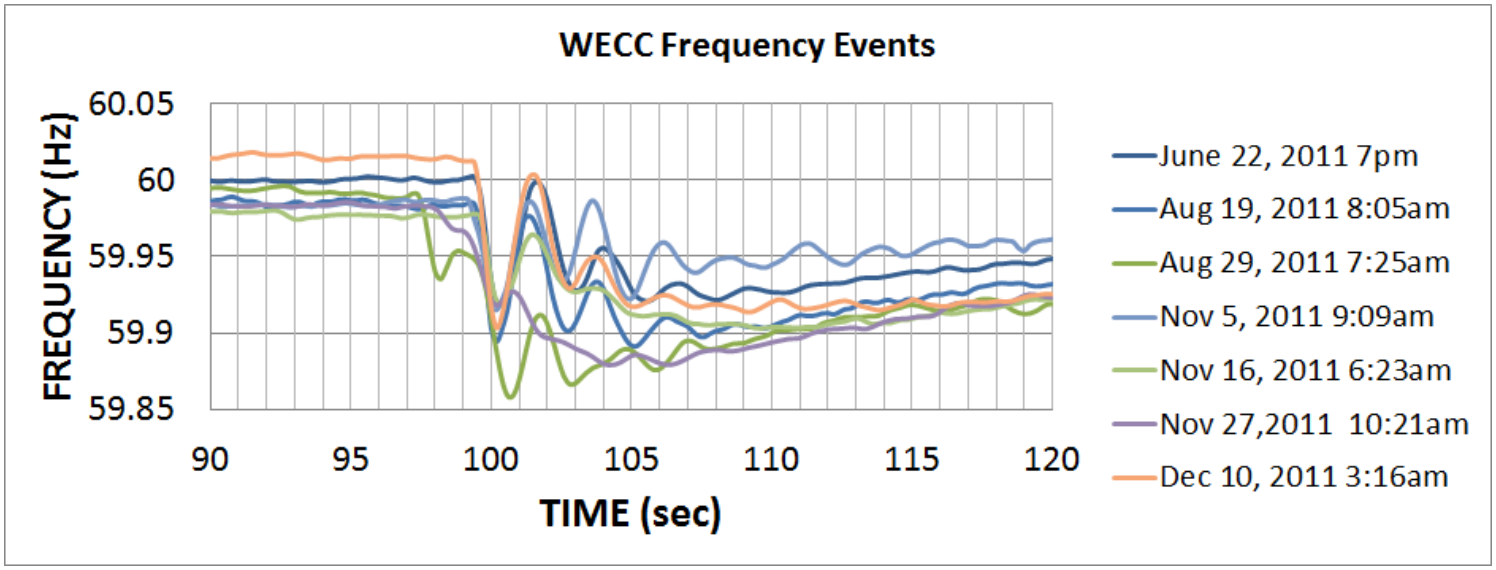
REPRA - Renewable Energy Probabilistic Resource Assessment tool

FESTIV – Flexible Energy Scheduling Tool for Integrating Renewables

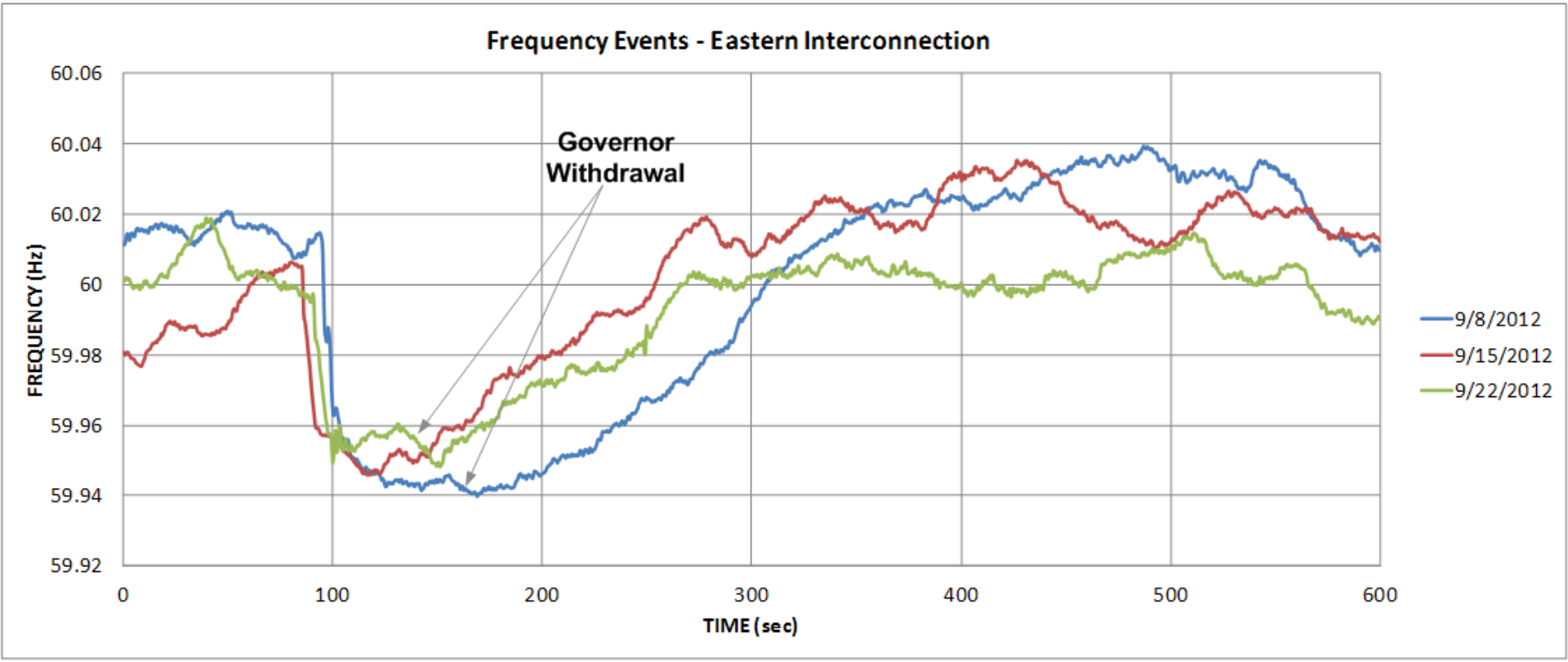
MAFRIT – Multi-area Frequency Response Integration Tool

Frequency Events in Western Interconnection

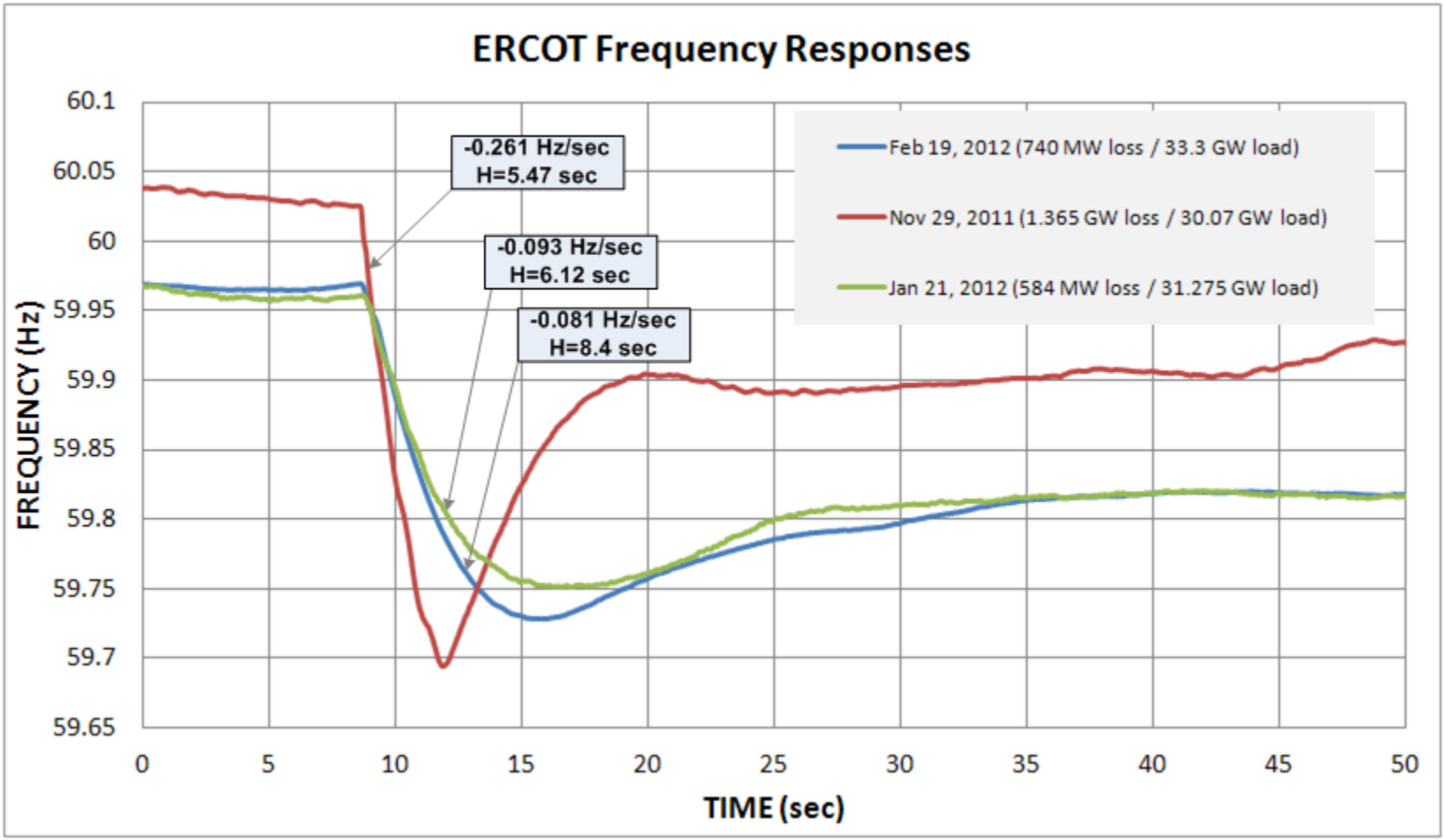




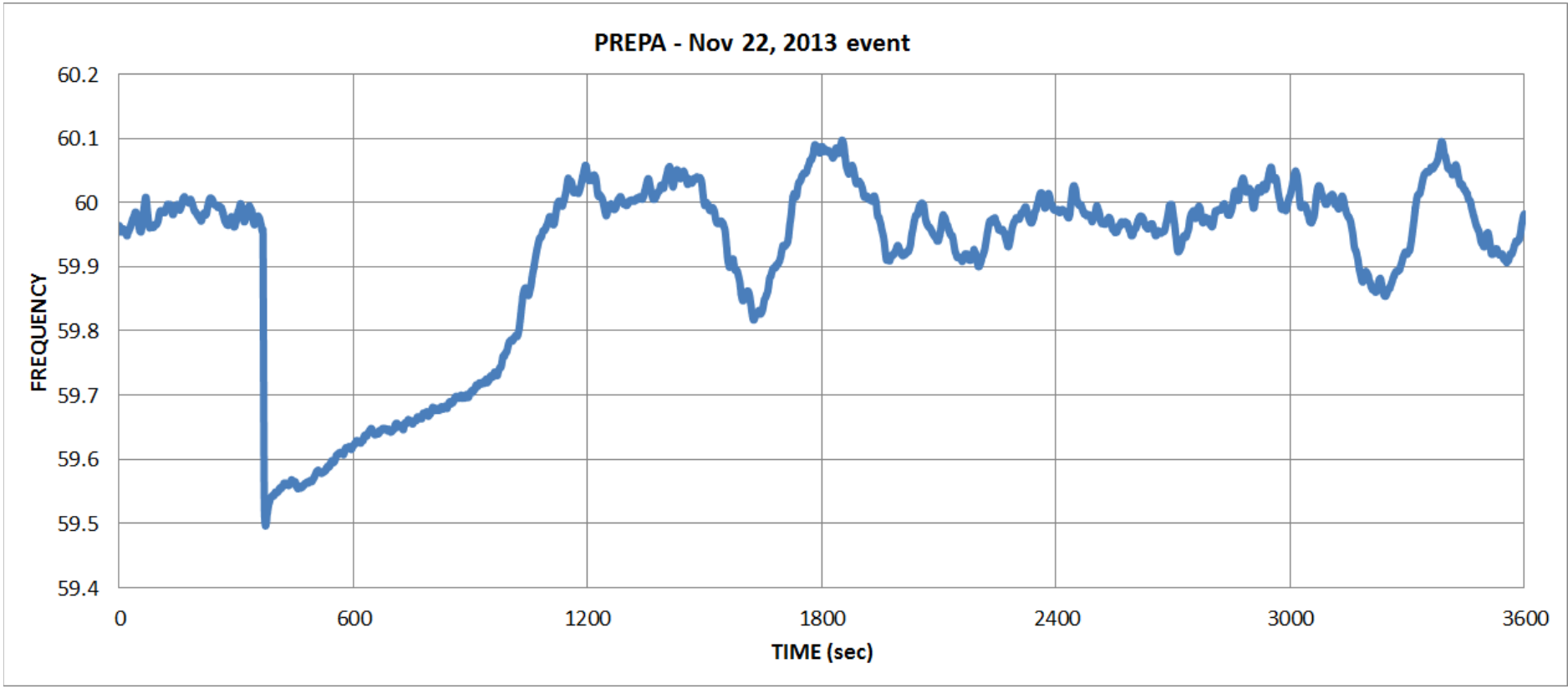
Frequency Events in Eastern Interconnection



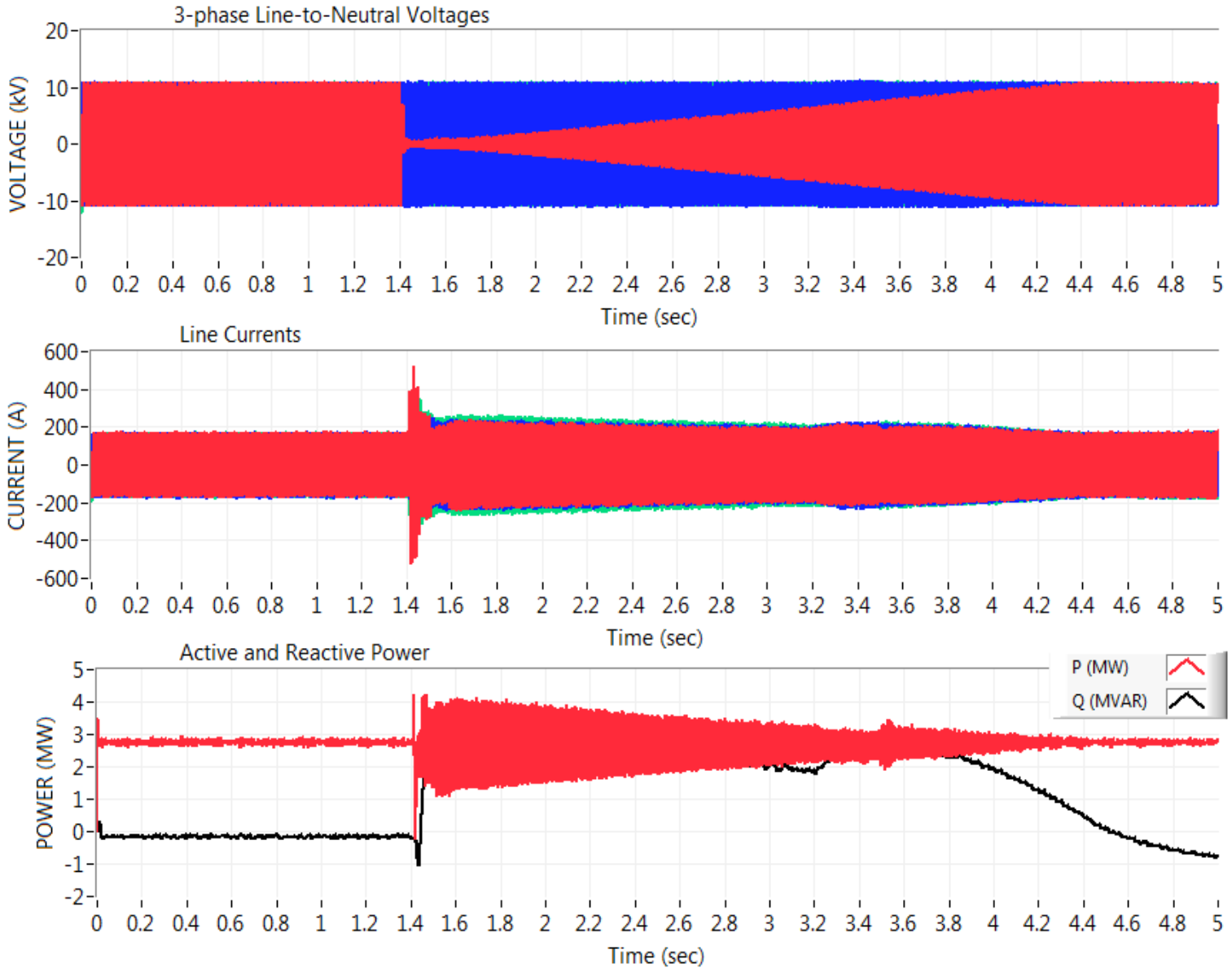
ERCOT Frequency Events



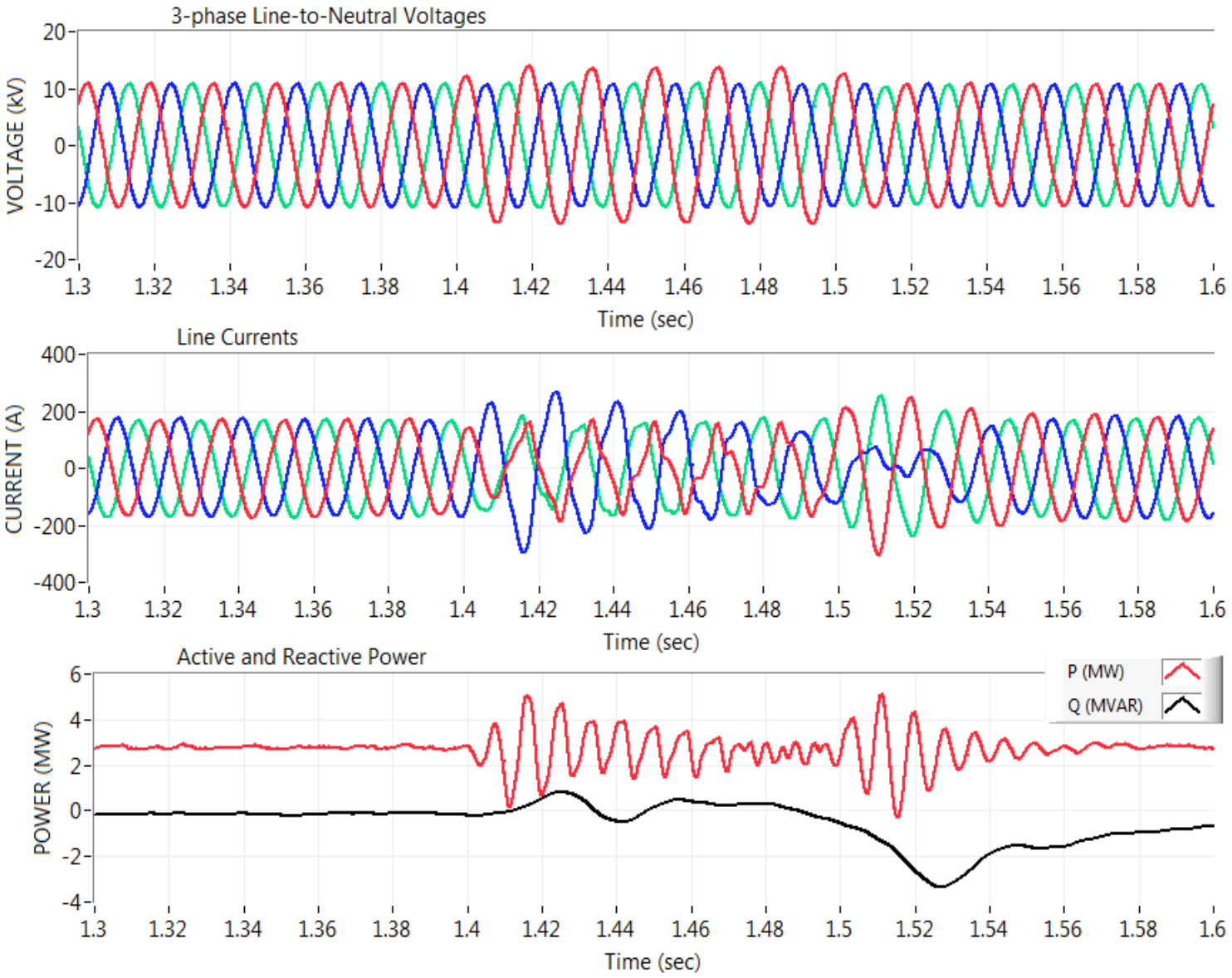
Frequency Response of an Island Power System



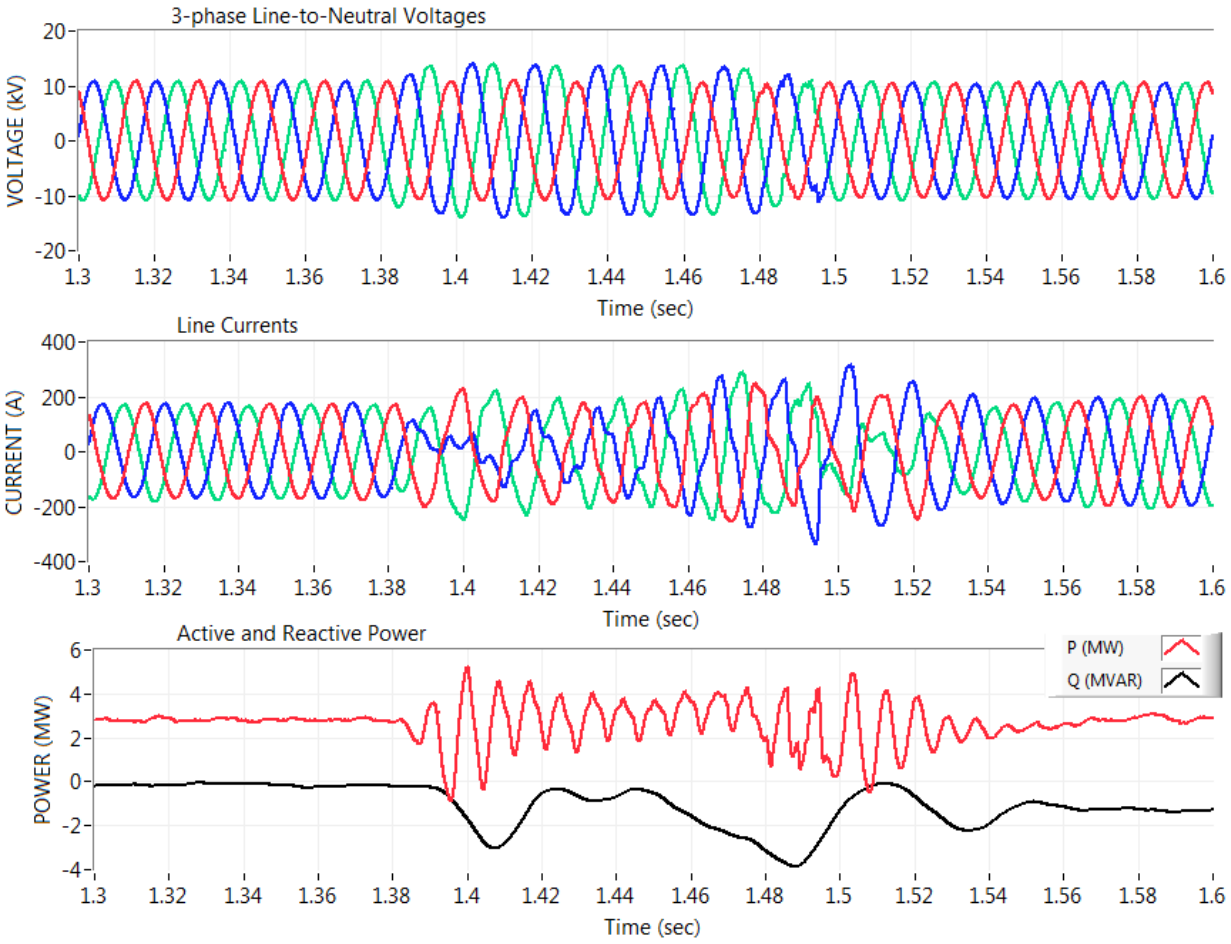
Single-Phase Fault - Slow Recovery



Single-Phase 130% Overvoltage



Two-Phase 130% Overvoltage



Three-Phase Overvoltage – Slow Recovery