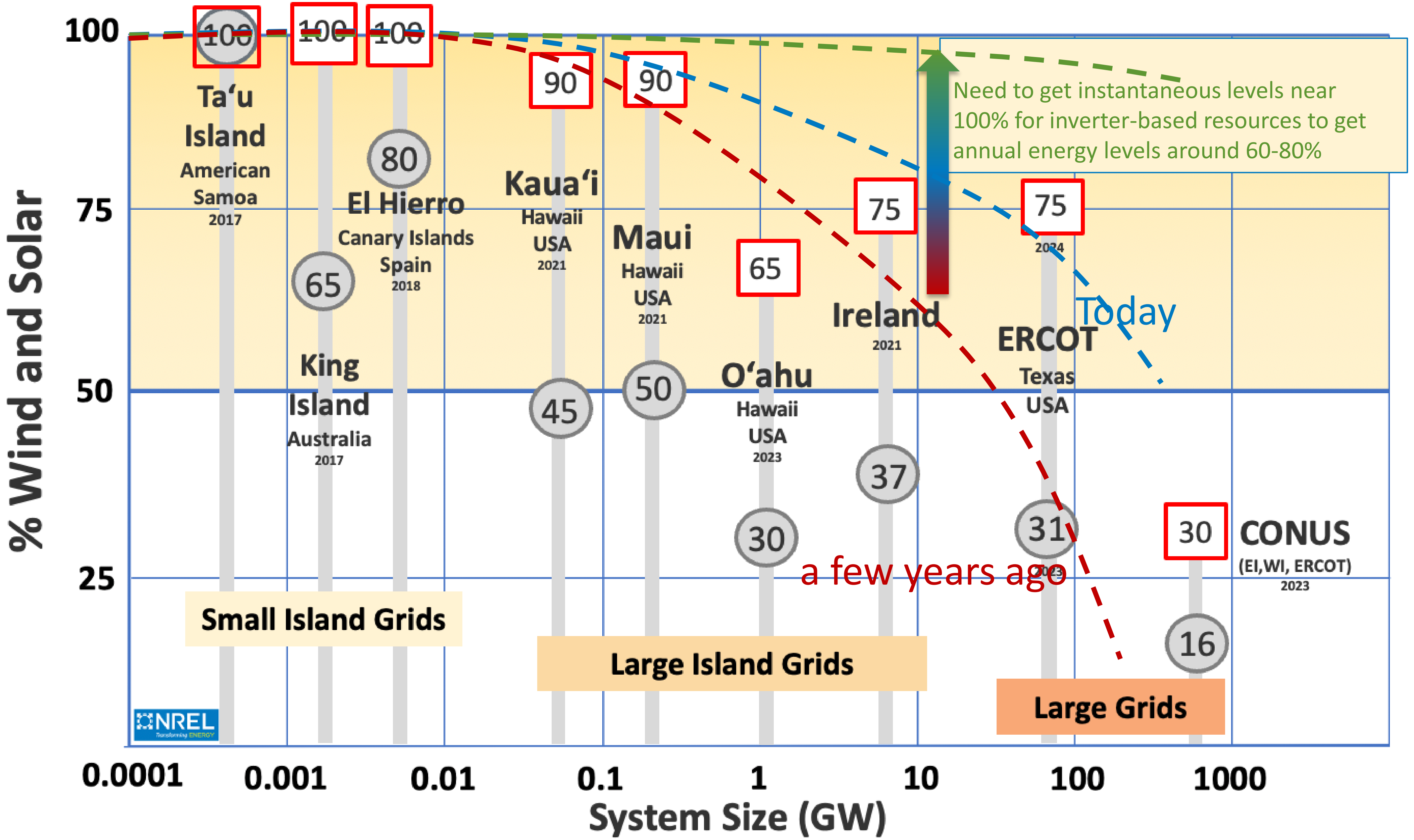
Leveraging PHIL for Inverter Functionality Requirement Evaluation to Ensure a Reliable Grid

Vikram Roy Chowdhury and Barry Mather – Oct. 23rd,2024

To get closer to 100% IBR, you need interoperable inverters



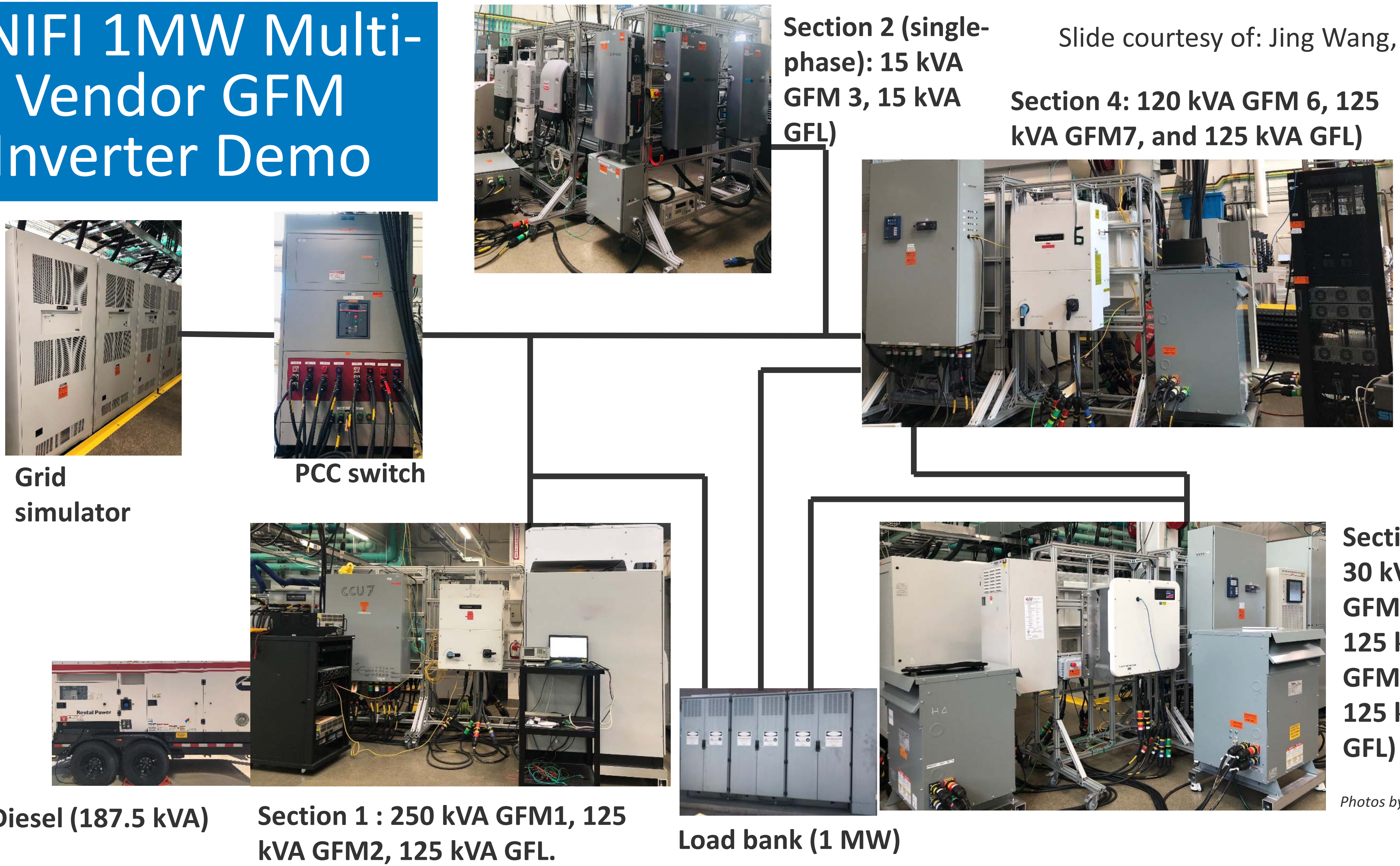
Presentation Overview

- Multi-point PHIL to demonstrate in-system interoperability and stability
- High-power PHIL to evaluate wide-area stability
- PHIL Interfaces for GFL/GFM mode switching
- Multi-domain PHIL/CHIL enabling evaluation of technology mixes

Multi-point PHIL to demonstrate in-system interoperability and stability

UNIFI 1MW Multi-Vendor GFM Inverter Demo

Slide courtesy of: Jing Wang, NREL

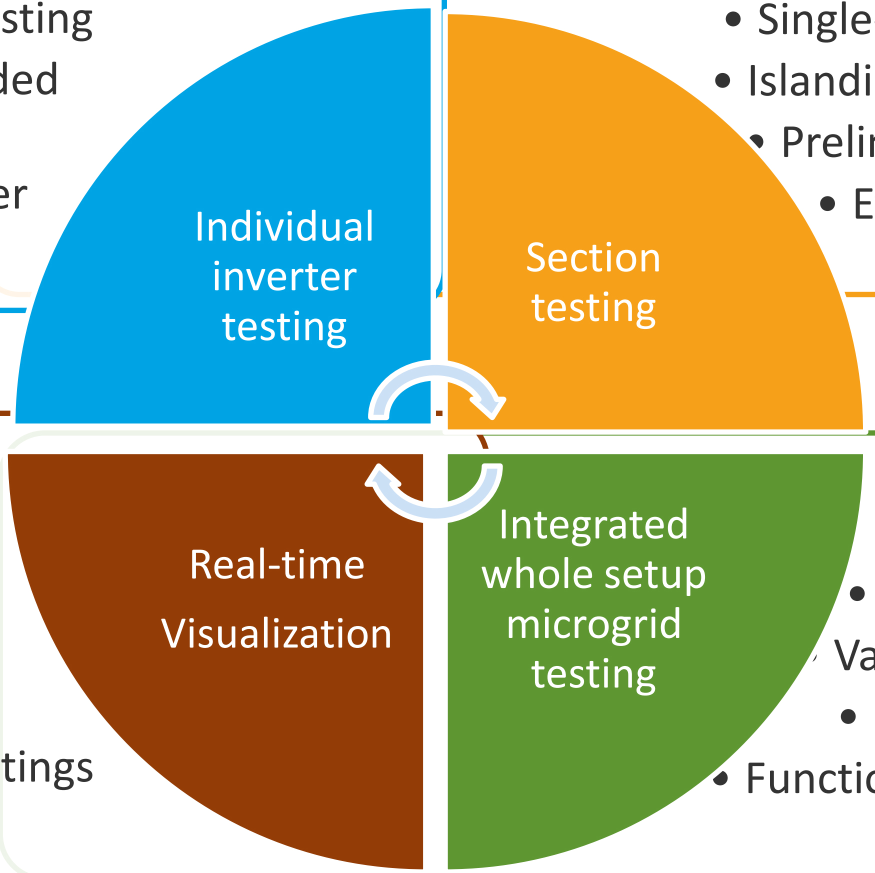


Photos by NREL

UNIFI Testing Activities - Overall

- Black-box testing
- Programmable inverter testing
- Grid-connected and islanded mode
- Evaluate individual inverter stability and performance

- Mix of GFM, GFL and SG
- Single-phase residential homes
- Islanding and resynchronization
- Preliminary interactions study
- Evaluate nano-grid system



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- RMS values (V, I, P, Q, f)
- Sinusoidal waveforms
- Coordination signals
- Operation modes and settings

- Multi-vendor GFM inverters
- Various GFM penetration level
- Emulate a realistic microgrid
- Functionalities and interoperability

Work closely with inverter vendors to troubleshooting to adjust their controller and make products work!

PHIL – Based Evaluation – Specific Scenarios

Testing Configuration

Configuration	Test Type	Scenario
Islanded Operation	Steady State	Balanced Load
		Unbalanced Load
		Nonlinear load
	Transient	Black start and motor start
		Overload/Overcurrent
		GFL variations
		Load Step
		Secondary Control
		Loss of Generation
		Dispatch GFM inverters
Grid Connected Operation	Steady State	Sourcing active and reactive power, sinking active power
	Transient	Dynamic event (voltage jump and ROCOF)
		Varying grid impedance and SCR
		Phase jump
Transition operation	Transient	Synchronization and islanding

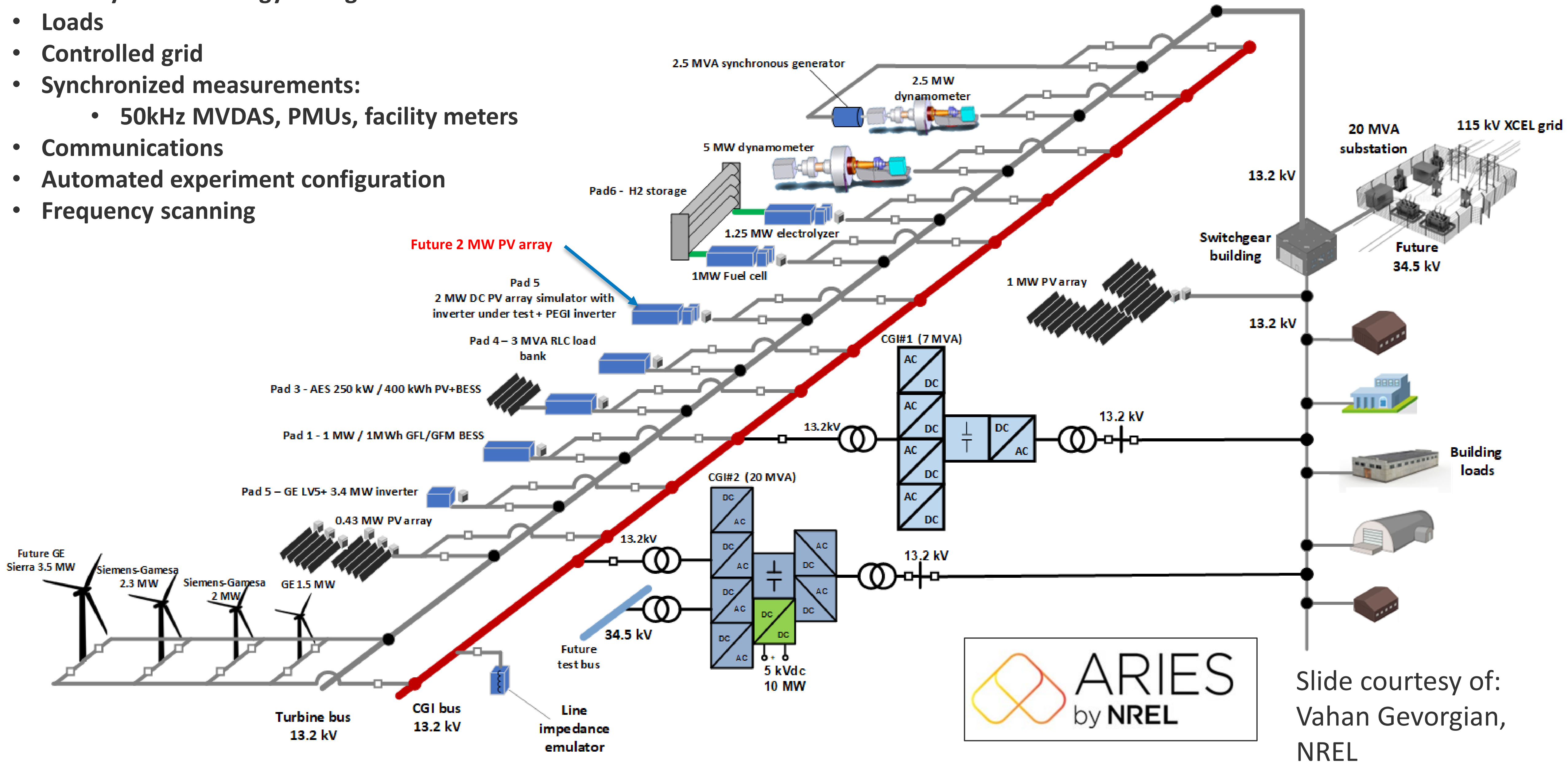
Denotes PHIL-Based Evaluation Scenario:

Slide courtesy of: Jing Wang, NREL

High-power PHIL to evaluate wide-area stability

NREL Flatirons Campus Test and Validation Platform

- Utility-scale wind
- Utility-scale PV
- Battery and H2 energy storage
- Loads
- Controlled grid
- Synchronized measurements:
  - 50kHz MVDAS, PMUs, facility meters
- Communications
- Automated experiment configuration
- Frequency scanning



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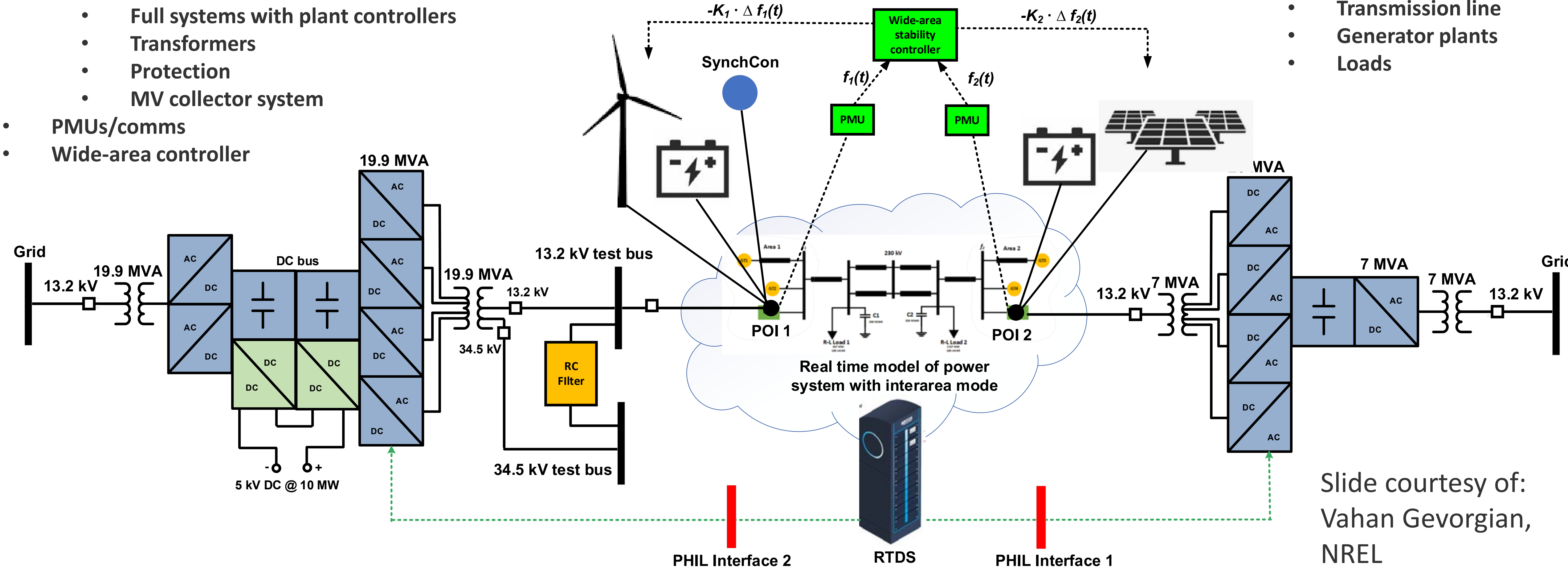
Wide-Area Stability Controls Validation Platform

Real components:

- Wind turbine, PV plant, BESS, condenser
  - Full systems with plant controllers
  - Transformers
  - Protection
  - MV collector system
- PMUs/comms
- Wide-area controller

Virtual components:

- Transmission line
- Generator plants
- Loads



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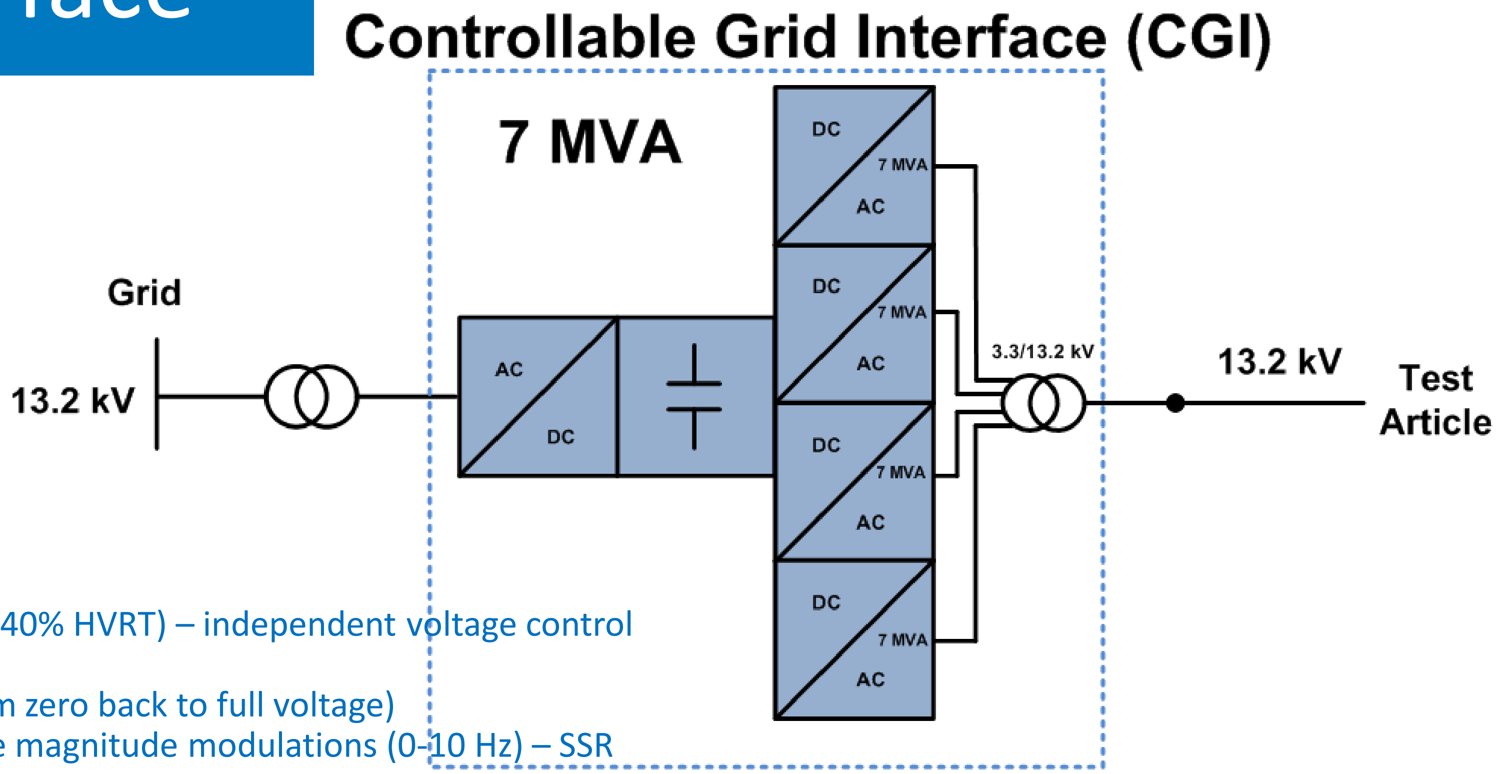
- Two-POI PHIL platform using real-time model of a power system
- Multi-MW real IBRs (wind, PV, BESS), synchronous machine and loads coupled with real controllers, measurement units and communications

Controllable grid Interface



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
- PV inverters, energy storage systems
- Conventional generators
- Combinations of technologies

Voltage control (no load THD <1%)
- Balanced and un-balanced voltage fault conditions (ZVRT and 140% 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)
- Impedance characterization of inverter-coupled generation
- Full STATCOM functionality

Frequency control
- Fast output frequency control (5 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)
- Test-bed for PMU-based wide-area stability controls
- **Test article impedance scan**

Less than 1 ms response time

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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 sec, x7.3 for 0.5 sec)
- 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

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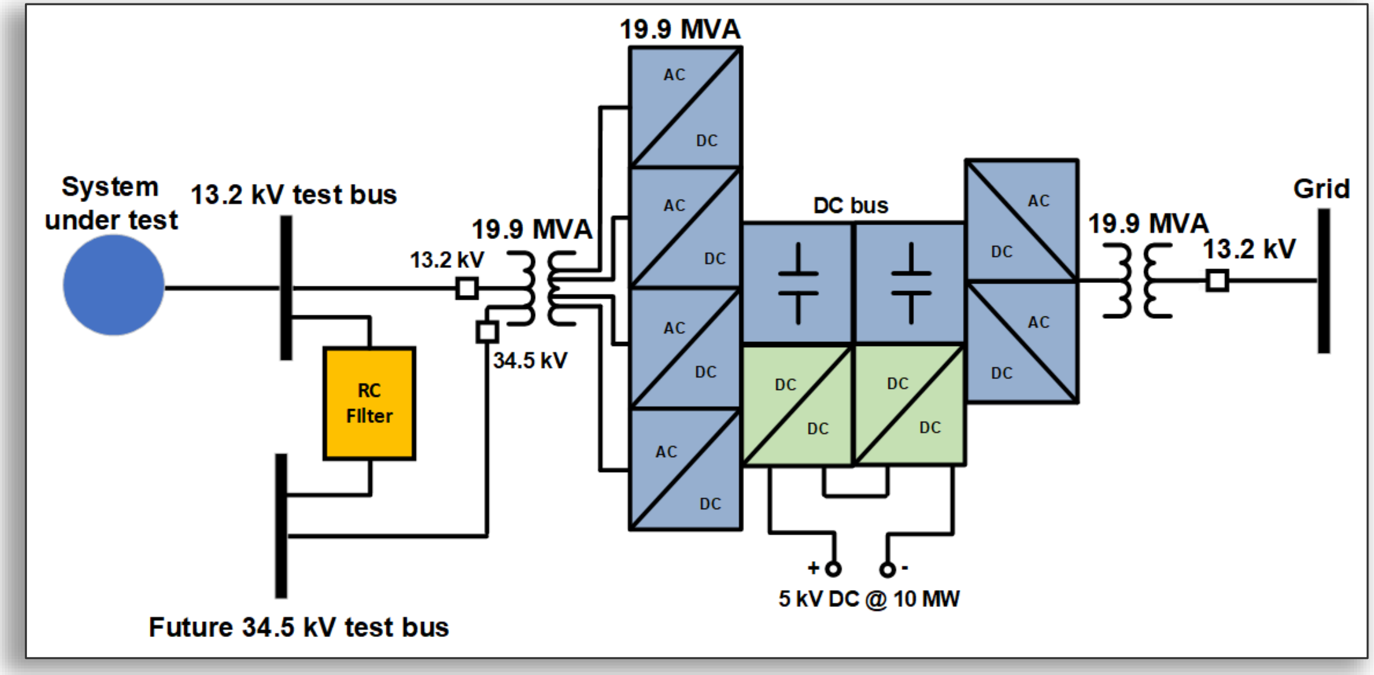
Voltage control (no load THD <1%)

- 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) – SSR conditions
- Programmable impedance (strong and weak grids, wide SCR range corresponding to a POI with up to 250 MVA of short circuit apparent power)
- Injection of controlled voltage distortions
- Wide-spectrum (0-2kHz) 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/sec) 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)
- Coupled with PMU-based wide-area stability controls validation platform



100 µS response time

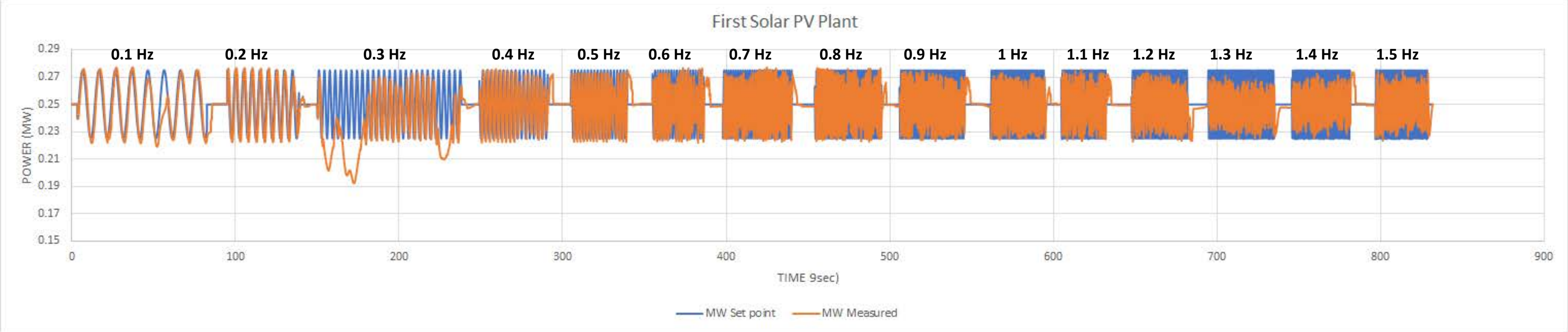
New features

- 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

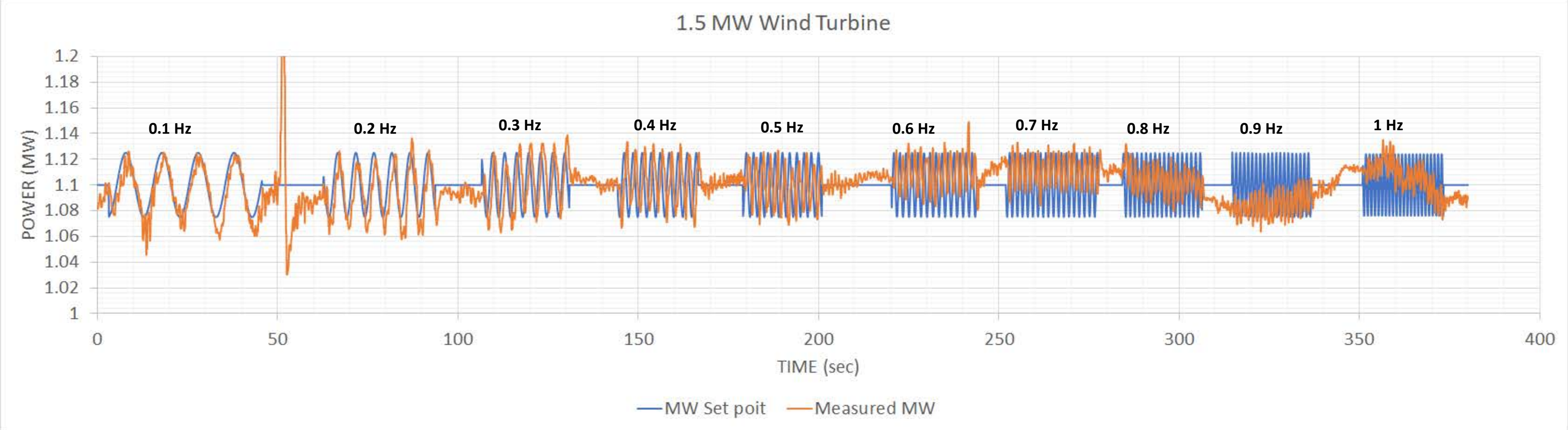
IBR Resources to provide damping: Examples of tests at NREL

1MW BESS

450 kW PV



1.5 MW Wind



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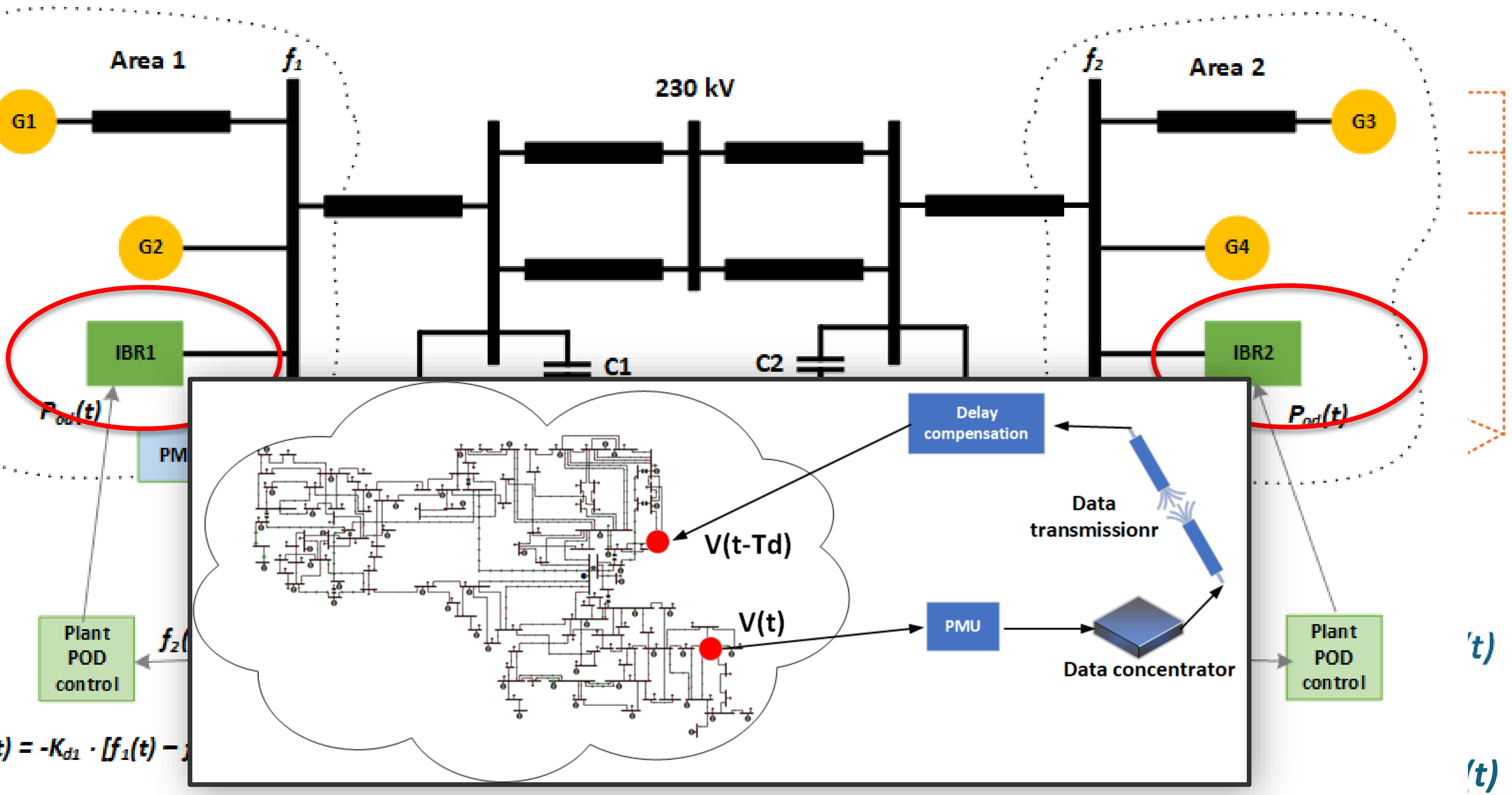
POD controls

V_{ref} –



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$P_{od}(t) = -K_{d2} \cdot [f_2(t) - f_1 \cdot (t\text{-}T_d)]$

K_{d1} – damping gain (MW/mHz) for area 1

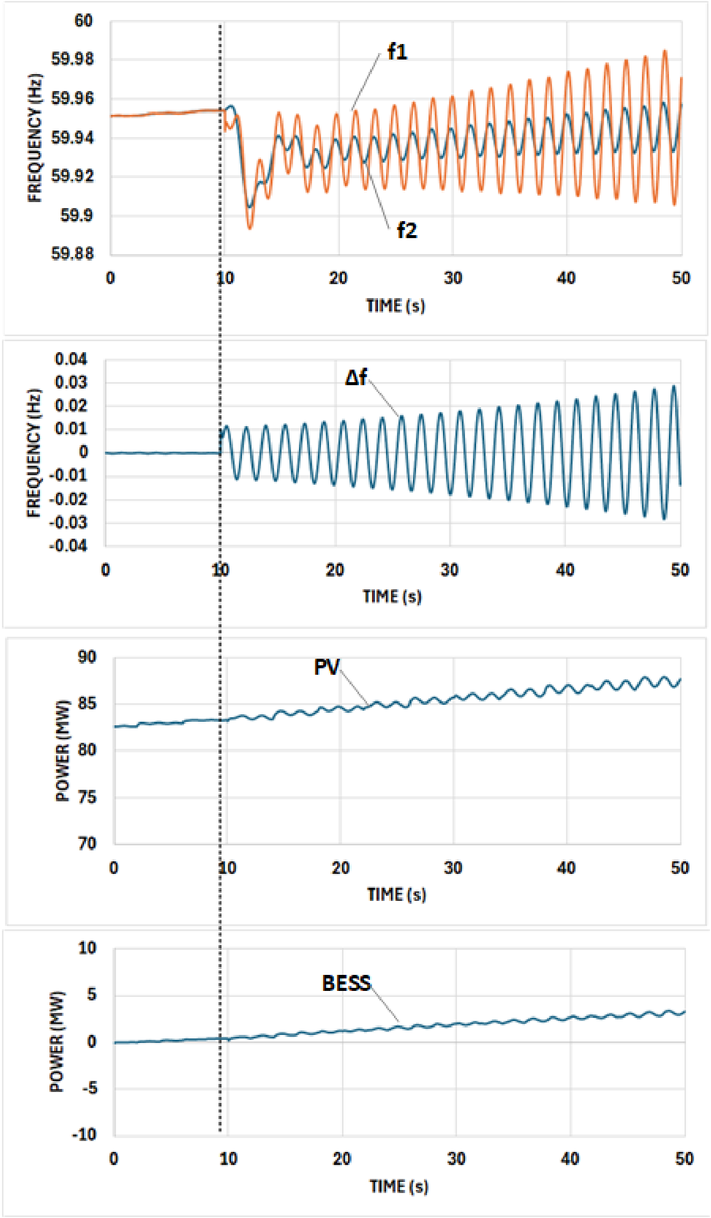
$T_d = T_{d1} + T_{d2}$ – communication delay (ms)

K_{d2} – damping gain (MW/mHz) for area 2

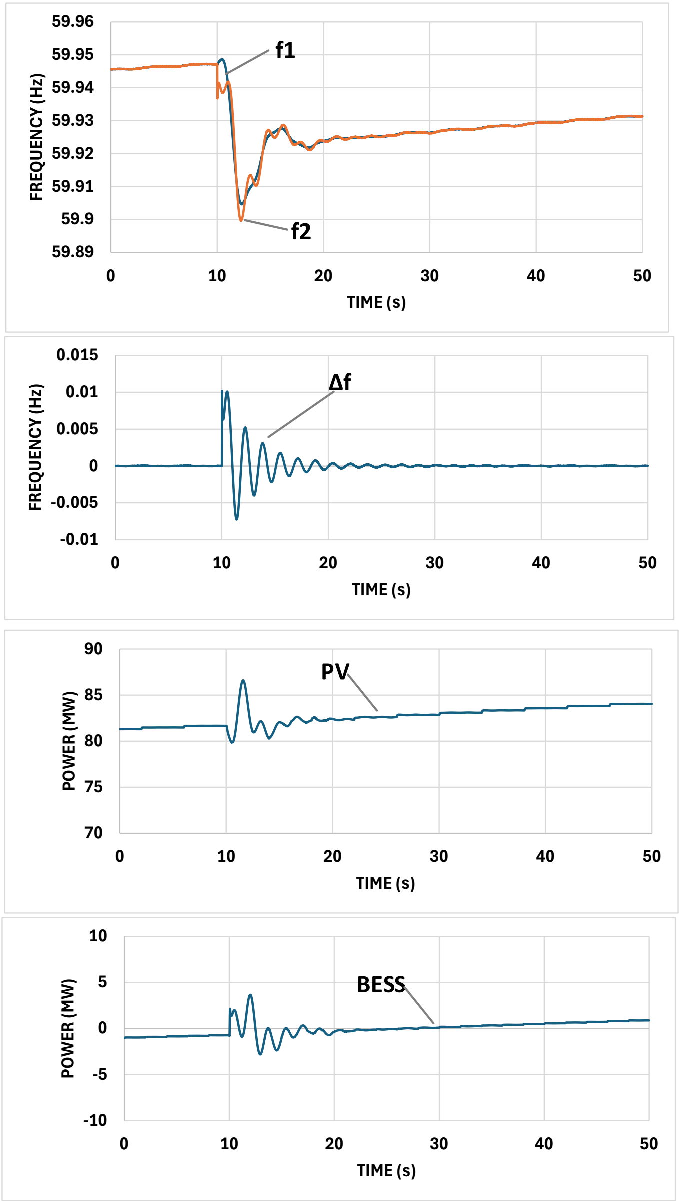
Method presented in: J. Neely, et. al. “Damping of Inter-area Oscillations using Energy Storage”, IEEE PES GM, July 2013

PV and BESS provide damping

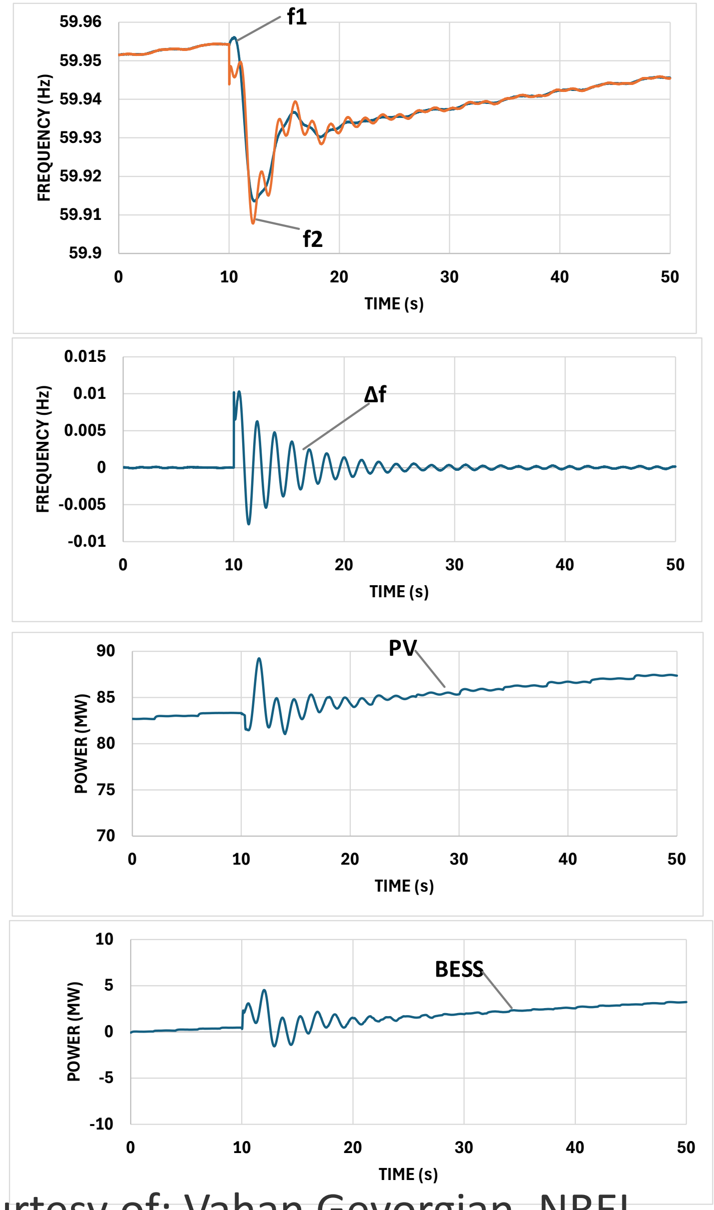
1. No damping – system unstable



2. Damping – 300 ms delay



3. Damping – 900 ms delay



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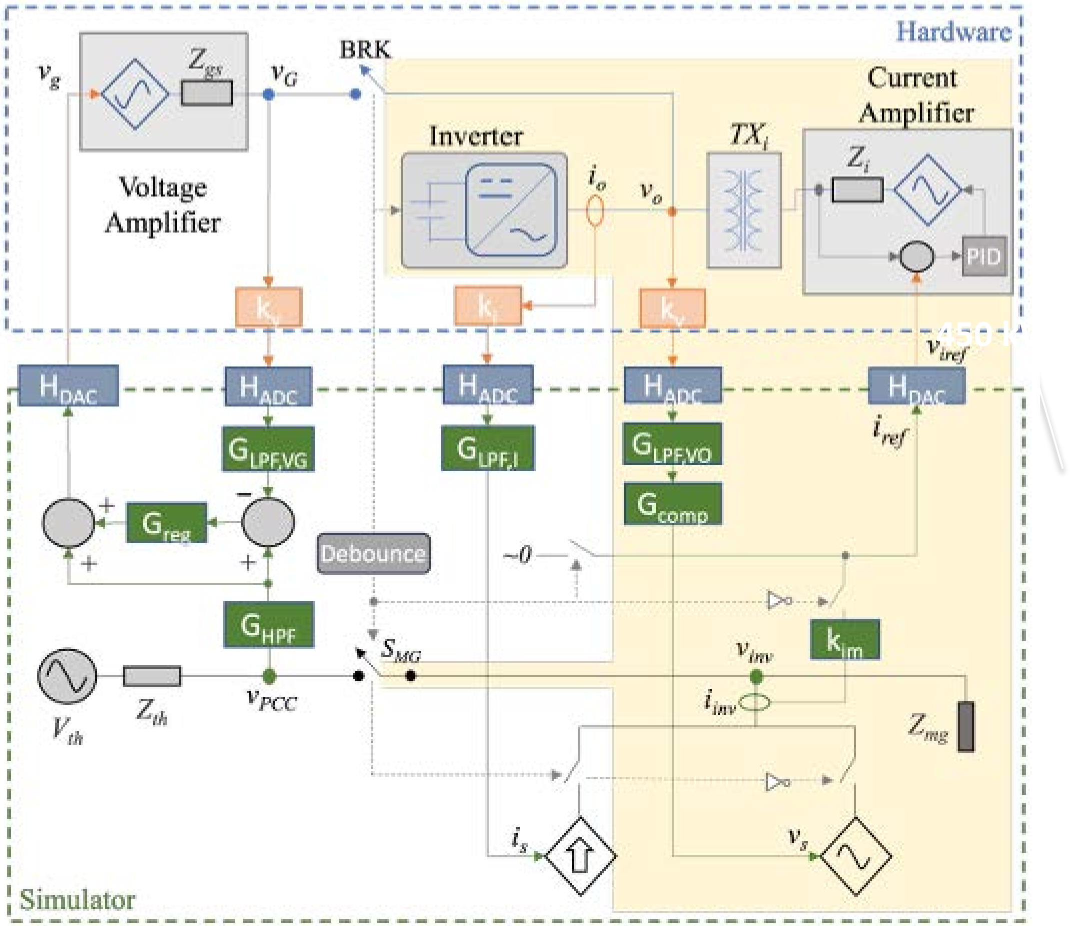
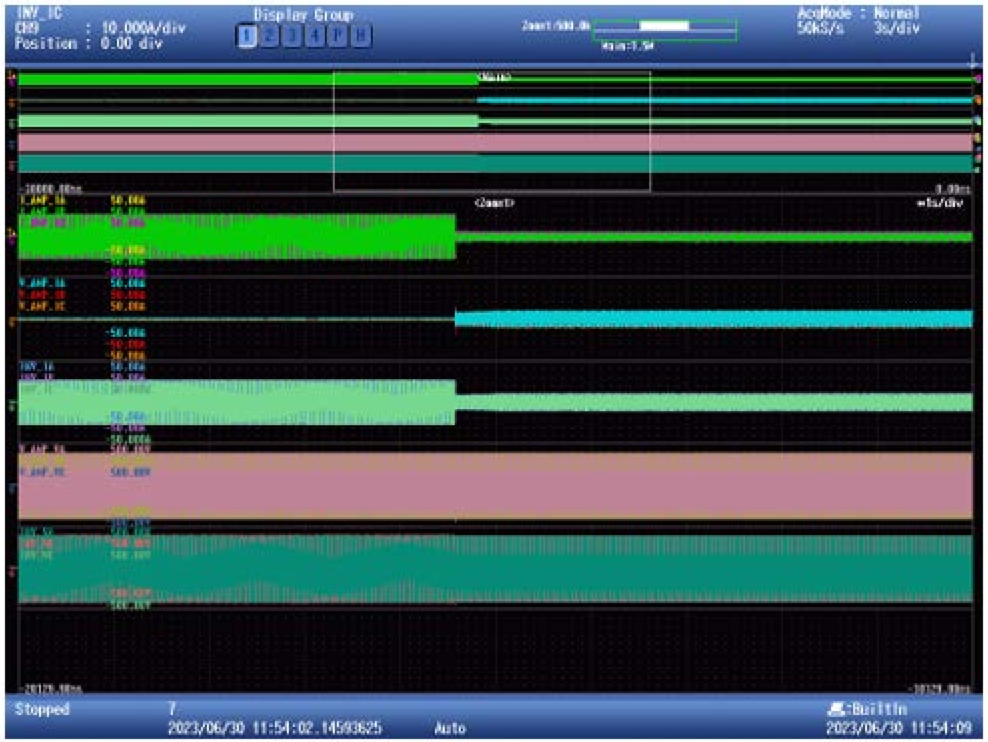
PHIL Interfaces for GFL/GFM mode switching

Experimental Setup with Voltage and Current Amplifiers



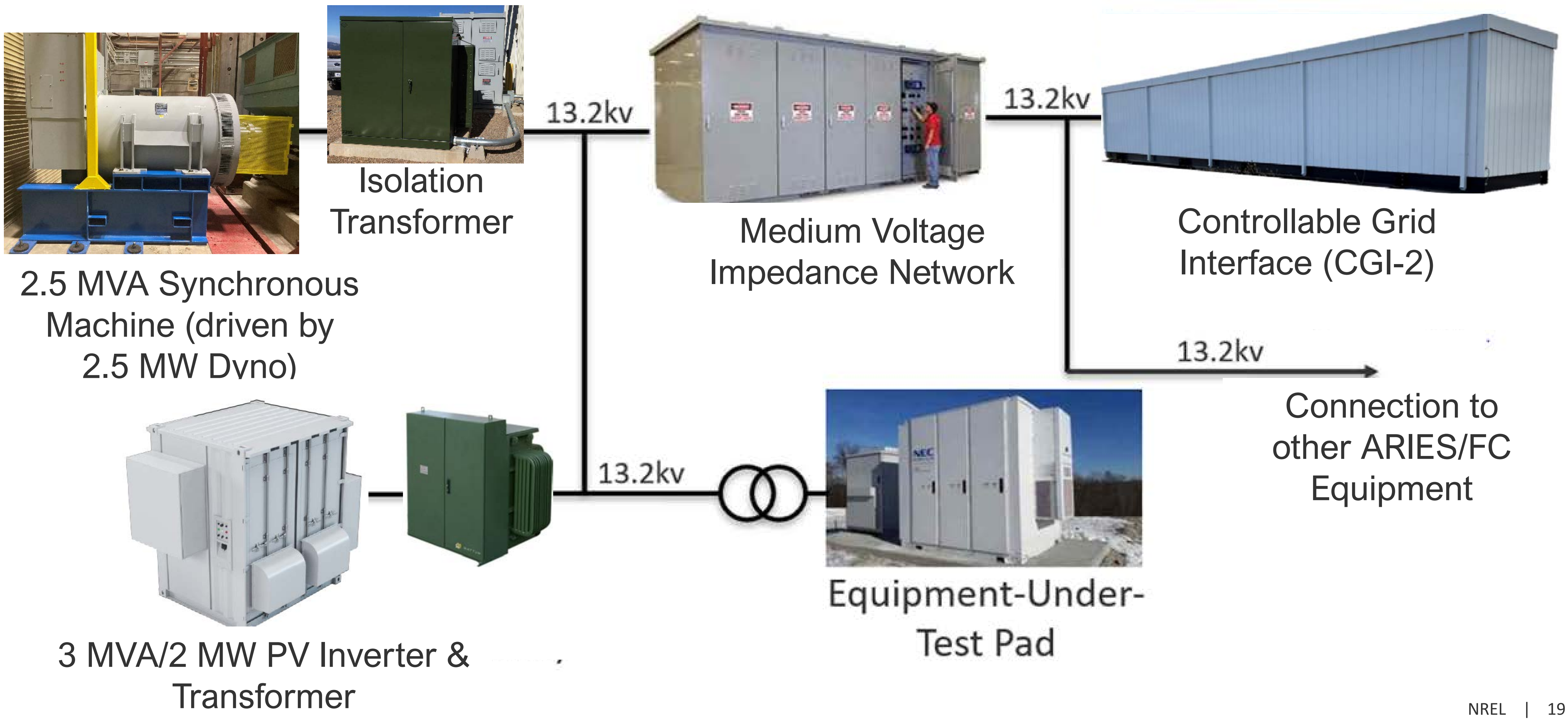


Showing transition from islanded operation to grid-connected. PHIL is running the Banshee microgrid model (with grid connection if appropriate)

See: Pratt, A., Prabakar, K., Ganguly, S. and Tiwari, S. “Power Hardware-in-the-Loop Interfaces for Inverter-Based Microgrid Experiments Including Transitions,” IEEE ECCE, Oct. 29-Nov.2, 2023, Nashville, TN.

Multi-domain PHIL/CHIL enabling evaluation of technology mixes

Equipment Comprising the Foundational Elements of the Power Electronics Grid Interface Platform



Synchronous Machine

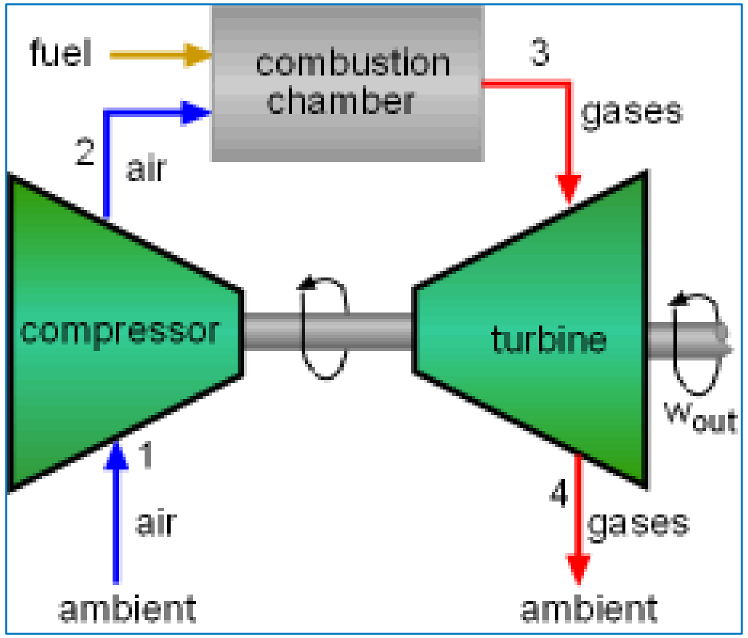
Marathon Generator model 1020FDH1248 is a 13.2 kV three-phase wye-configured 2 MW generator that operates at 1800 rpm and 60 Hz. This generator features a wide reactive capability curve to output power factors from 0.4 lagging to 0.8 leading.

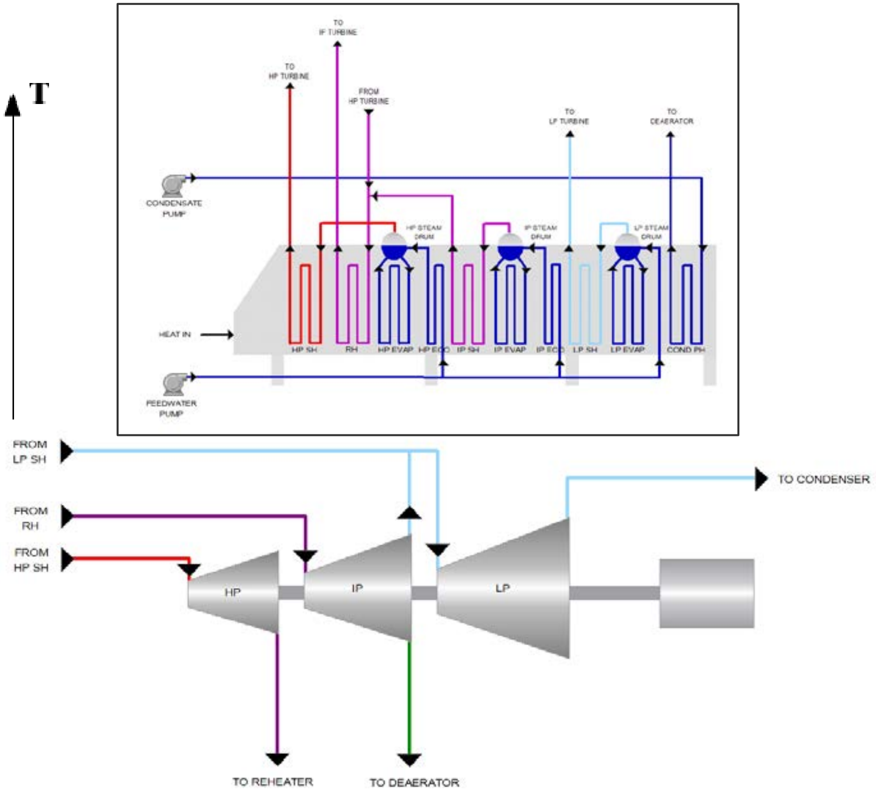
Role with the PEGI Platform:

- Serves as a representative of conventional generation technology
  - Allows the adjustment of PEGI grid operating conditions from 0<SNSP<100%
  - Realizes fast-time-scale operation of conventional generation (i.e., response to voltage/frequency disturbances, faults, etc.)
  - Provides inertia for interoperability evaluation of power electronic-interfaced equipment controls
  - Enables control oscillation research between generation of different technologies
- Operates as a synchronous condenser enabling grid evaluations (e.g., weak grids) with conventional mitigation solutions

$$SNSP = 100 \times \frac{MVA_{Synchronous}}{MVA_{Non-synchronous}}$$

Sync. Machine Capability – Emulating a Conventional Combustion Turbine Plant



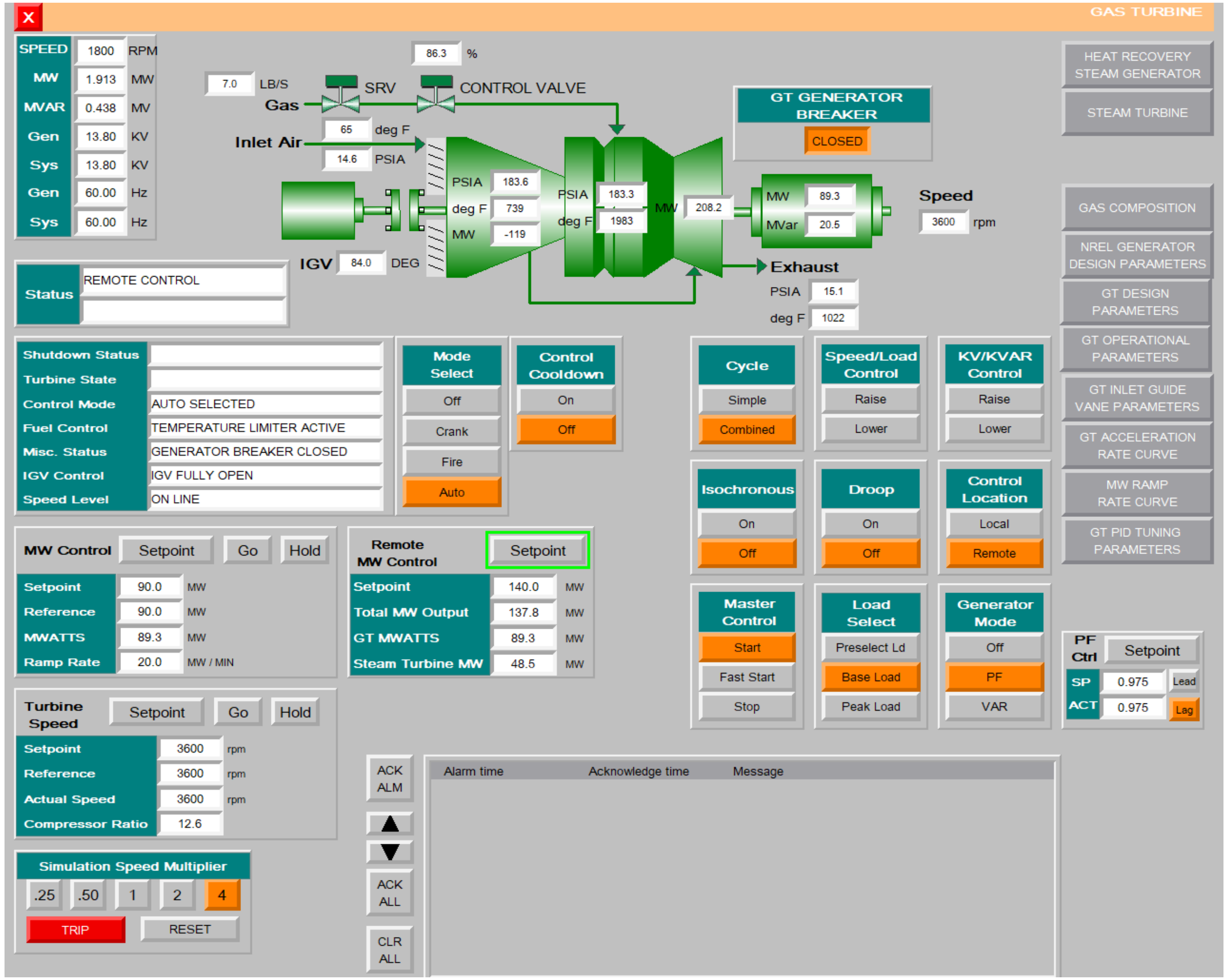


- Emulates a natural gas turbine (GE 7EA – 90MW) including a real, industry relevant governor controller
- Prime-mover dynamics are emulated and realized via the dyno driving the sync. machine
- Enables experiments were changes in conventional generation controls is considered (e.g., value of IBR-based FFR vs. “fast-valving” options for conventional gen.

Emulating all the Controls

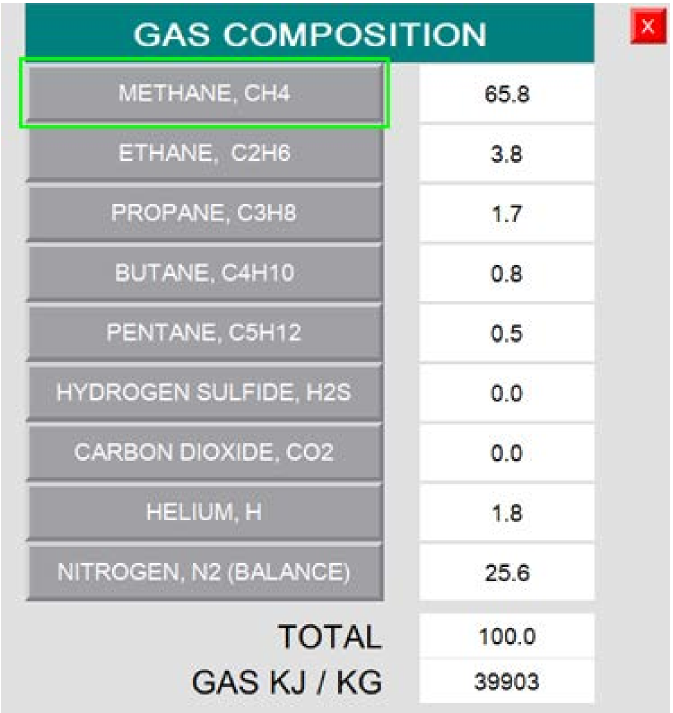
Control emulation included:

- Gas value dynamics
- Inlet guide vane (IGV) operations
- Start-up/Shutdown sequences:
  - Purge speed/duration
  - Lightoff speed
  - Ramp up rate
  - Grid synchronization/disconnection
  - Ramp down rate
  - Cooldown speed
- Fuel composition
- PID control gains
- HRSG:
  - Superheat pressure drop curves
  - Frist stage steam pressure curves
  - Condenser back pressure
  - …

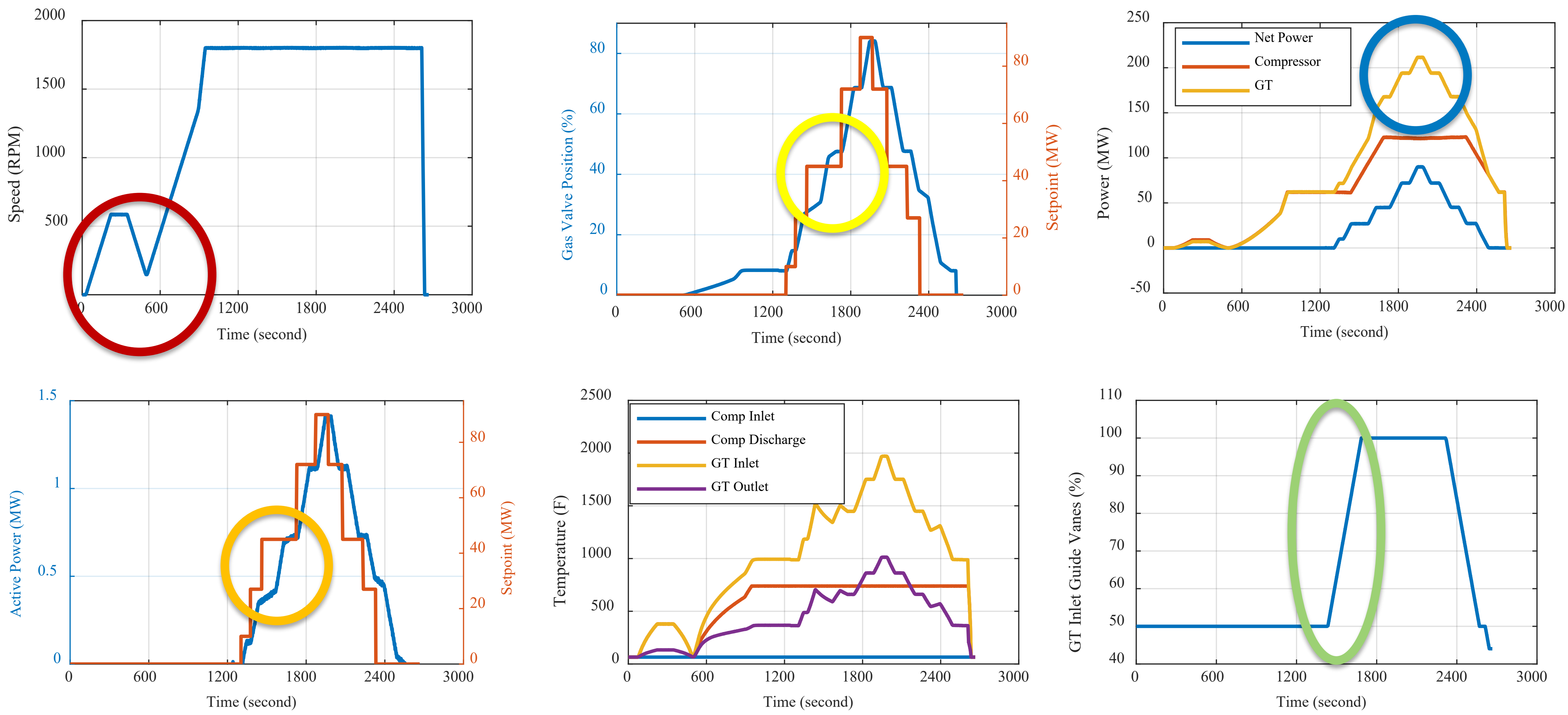


Example of Flexibility – Fuel Composition

Gas	Canada	Kansas	Texas	HHV (btu/ft³)	HHV (btu/lb)	HHV (kJ / kg
Methane	77.1	73.0	65.8	1011	23811	55384
Ethane	6.6	6.3	3.8	1783	22198	51633
Propane	3.1	3.7	1.7	2572	21564	50158
Butane	2.0	1.4	0.8	3225	21640	50335
Pentane	3.0	0.6	0.5	3981	20908	48632
H2S	3.3	0.0	0.0	672	7479	17396
CO2	1.7	0.0	0.0	0	0	0
N2	3.2	14.5	25.6	0	0	0
He	0.0	0.5	1.8	0	0	0
Total Gas	100.0	100.0	100.0			
Average HHV (btu/scf)	1,183.0	1,014.6	822.4			
Average HHV (btu/lb)	21,798	20,006	17,155			
Average HHV (kJ / kg)	50,703	46,535	**39,903**			



Grid-Connected Natural Gas Combustion Turbine



Thank You

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Please contact Vikram Roy Chowdhury (Vikram.RoyChowdhury@nrel.gov) or Barry Mather (barry.mather@nrel.gov) with any feedback, comments or questions.

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