NREL
NATIONAL RENEWABLE ENERGY LABORATORY

# Overview of CGI/Dynos/PHIL Platform

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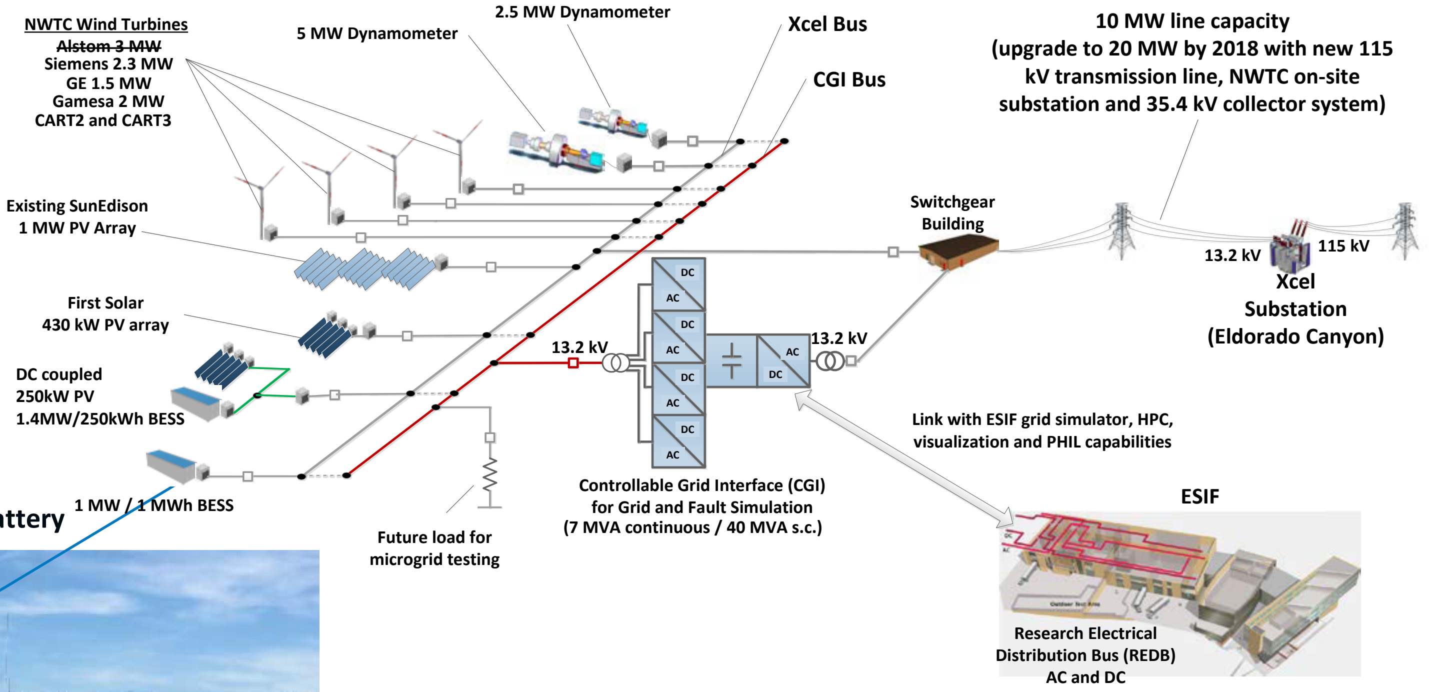
NREL/PR-5000-72923

# National Wind Technology Center

## New: 430-kW PV array

Source: NREL / Dennis Schroeder (40806)




Source: NREL

## New: 1-MW/1-MWh battery


Source: NREL

# NWTC Dynamometers

## Specifications

Source: NREL/Mark McDade (27249)

Source: NREL/Robb Wallen (17400)

Source: NREL/Dennis Schroeder (25887)

## 2.5-MW Dyno

- 2.5 MW
  (on the low-speed shaft)
- 17–31 rpm (at full power)
- 1.64 MNm (1.2 M ft-lb) max torque
- Non-torque loads, 3 degrees of freedom
- 50-t crane, 30-ft (9-m) hook height
- 12.2 x 15.2-m test bay
- 0–6-degree adjustable-drive table tilt.

## 5-MW Dyno

- 5.8 MW
  (on the low-speed shaft)
- 12–24 rpm (at full power)
- 4.6 MNm (3.4 M ft-lb) max torque
- Non-torque loads, 5 degrees of freedom
- Dual 75-t cranes, 45-ft (14-m) hook height
- 20 x 12-m test bay
- 5-degree fixed-drive table tilt.

# 2.5-MW Dynamometer Projects

- Multiple projects in 2017–2018 for validating wind turbine power train low-voltage ride-through (LVRT) response to foreign grid codes (50 Hz using controllable grid interface [CGI])
- Preinstallation verification of Gearbox Reliability Collaborative 1.5 data acquisition system. The gearbox was installed in the U.S. Department of Energy-owned (DOE-owned) GE 1.5-MW turbine and is subjected to grid events using the CGI.
- Year 2019 projects include validation of two different wave energy devices.


GE 1.5-MW high-speed shaft instrumentation checkout at 2.5-MW dynamometer.

Source: NREL/Mark McDade (49050)

*Source: NREL / Jonathan Keller (49498)*

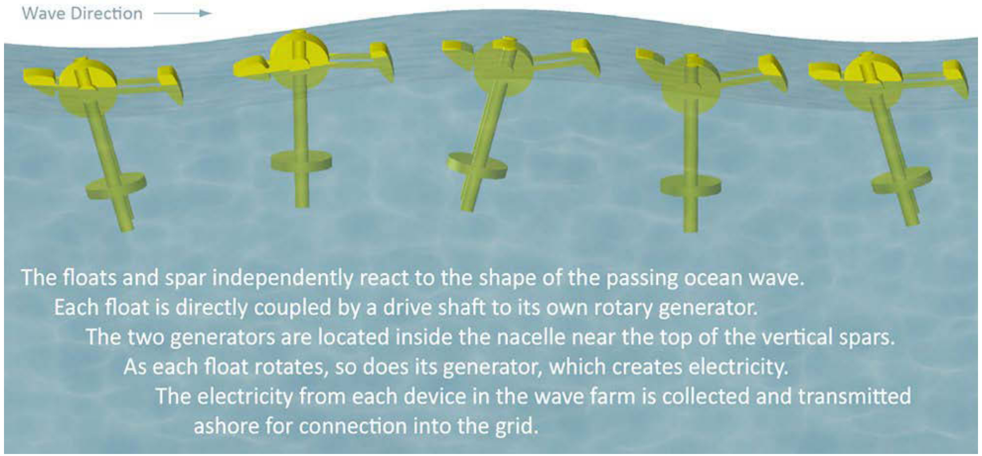
Installation of instrumented gearbox at NWTC.

# 5-MW Dynamometer Projects

- 2016–2018: Validation of the Columbia Power Technologies (C-Power) utility-scale wave energy device. The device was tested using realistic, oscillating, bidirectional speed and torque profiles. Testing was complete as of Nov. 2018.
- 2018: Validation of multimegawatt, medium-voltage, doubly-fed induction generator power train via direct coupling with 5-MW motor
- 2019: Projects include upgrading non-torque loading system to achieve 10-MNm moment capacity and potential wind turbine power train tests
- 2019: The 2.5-MW and 5-MW facilities will be upgraded with additional 13.2-kV medium-voltage feeds selectable between CGI or Xcel utility.

*Source: NREL /* Mark McDade *(44103)*

C-Power wave energy device installation at the NREL 5-MW dynamometer.

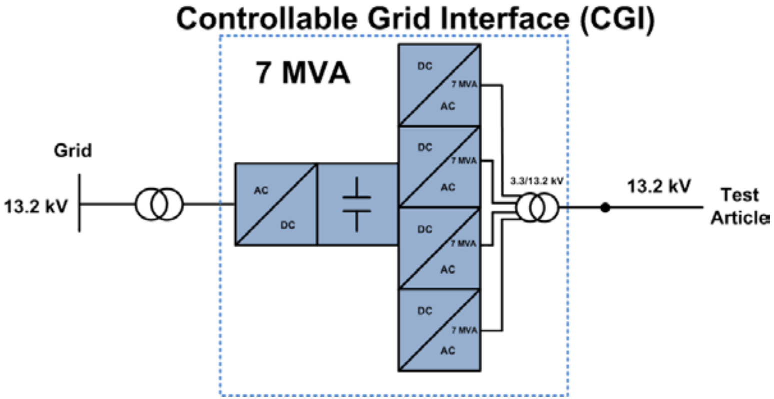



Source: C-Power website / www.columbiapwr.com/how-it-works/

C-Power wave energy device installation at the NREL 5-MW dynamometer C-Power

# NWTC 7-MVA Controllable Grid Interface

Source: NREL / Mark McDade




**Power rating**

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

**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.

**Voltage control (no load total harmonic distortion <2%)**

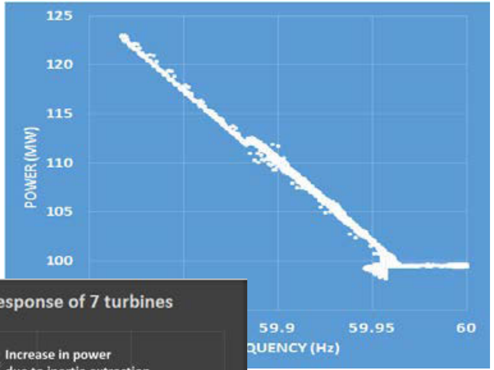
- Balanced and unbalanced voltage fault conditions (zero-voltage ride-through and 130% high-voltage ride-through [HVRT])—independent voltage control for each phase on 13.2-kV terminals
- Response time: 1 ms (from full voltage to zero, or from zero back to full voltage)
- Long-term symmetrical voltage variations (+/- 10%) and voltage magnitude modulations (0–10 Hz)—subsynchronous resonance conditions
- Programmable impedance (strong and weak grids).

**Real-time digital simulator (RTDS) – power-hardware-in-the-loop (PHIL) capability**

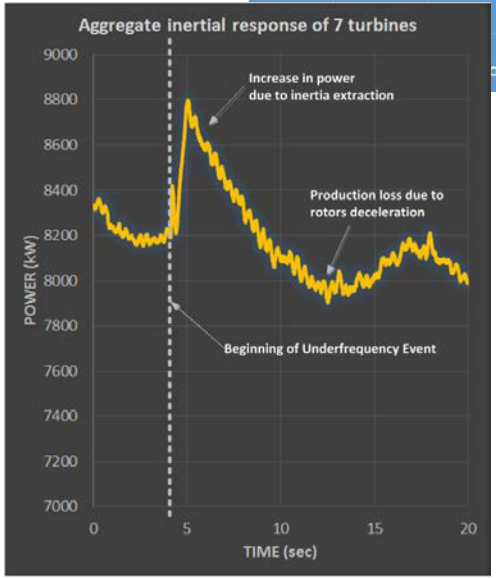
# Open-Loop Single PCC: DER Validation

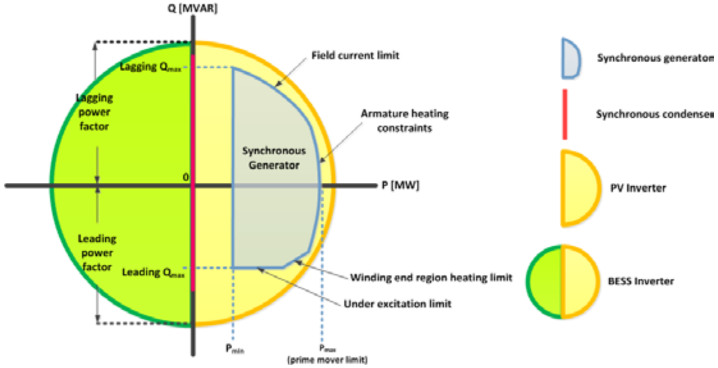
Testing of grid connected inverters and tightly coupled generation mixes

- Testing of frequency responses
- Characterization of droop characteristics
- LVRT/HVRT testing
- Full 4Q operation testing
- Models validation
- Wide spectrum analysis (impedance).




Source: NREL




Source: NREL

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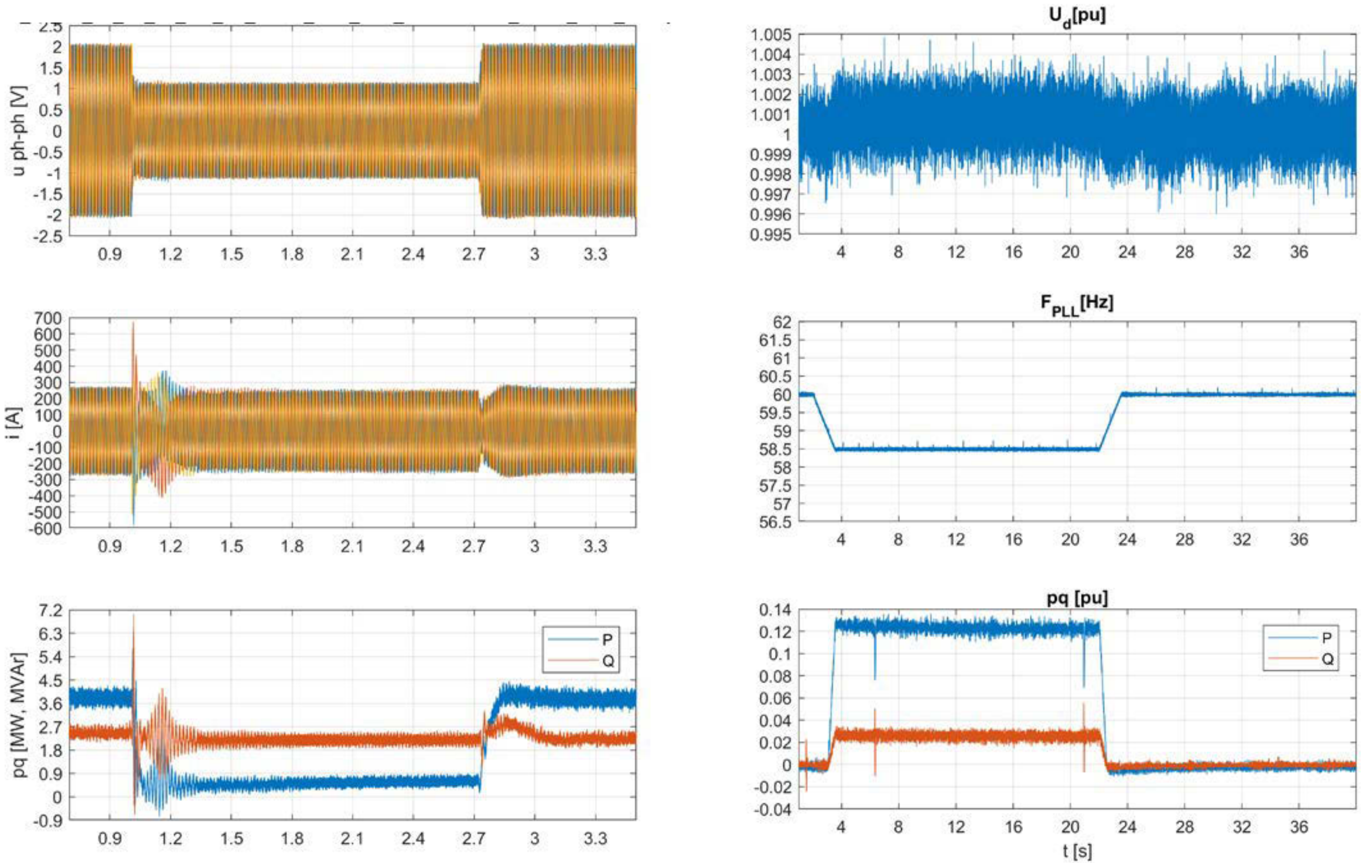
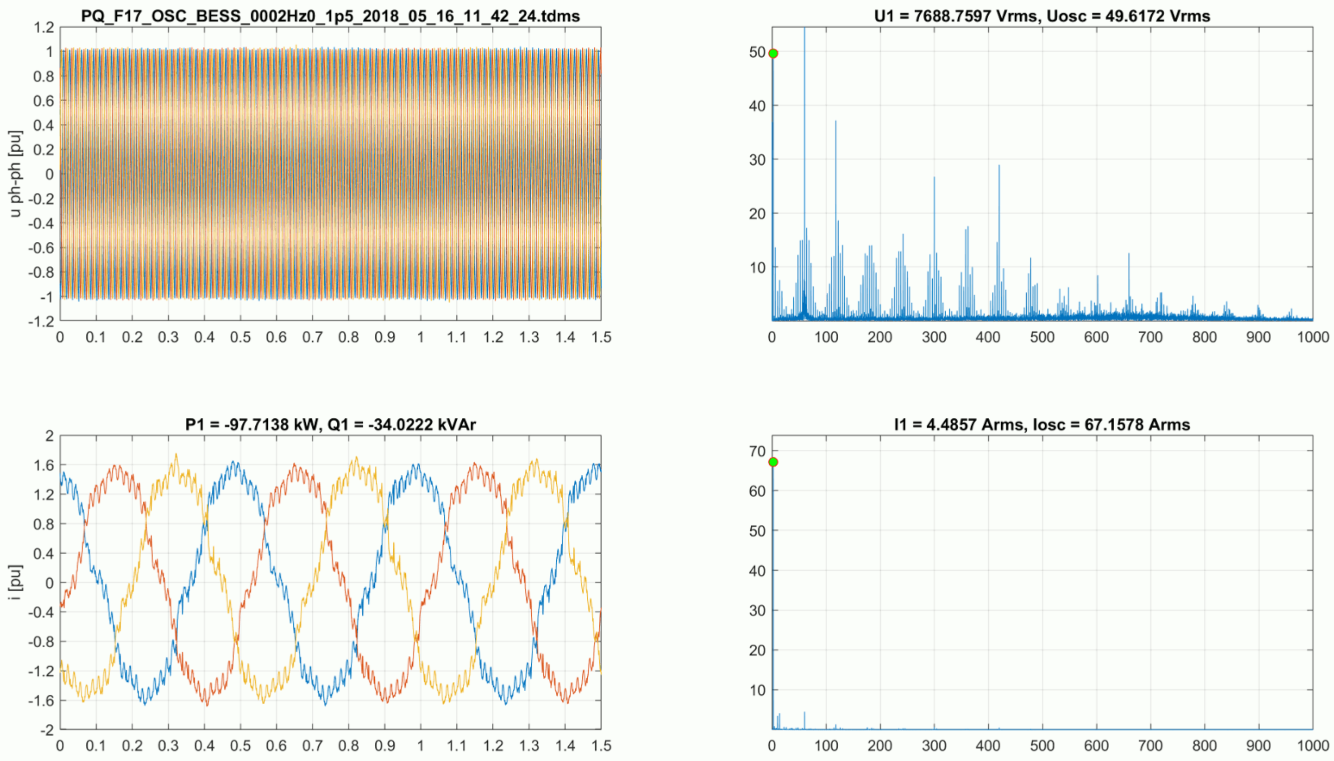
# Open-Loop Single PCC: DER Validation Examples



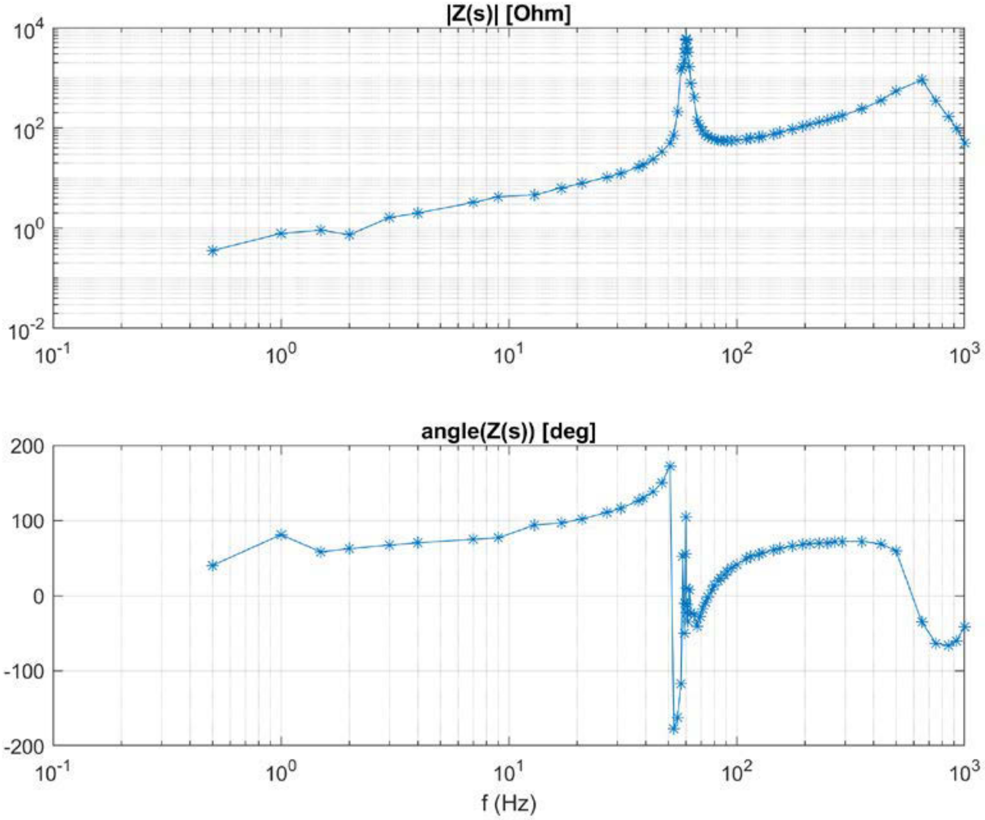

Source: NREL

# Impedance Measurements




Source: NREL

# Impedance Measurements




Source: NREL

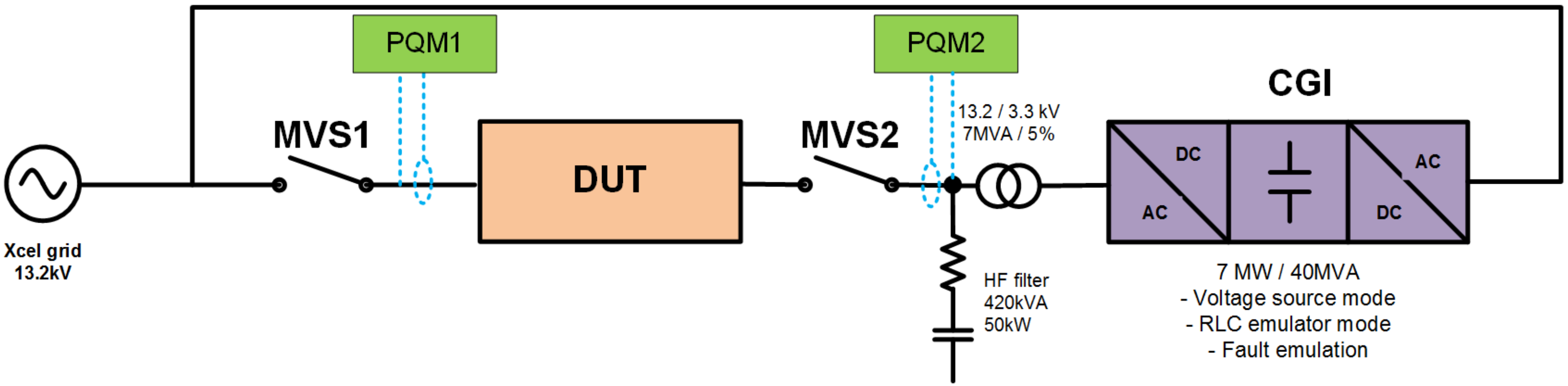
# Open-Loop Double PCC: DER Validation

Example device:

- Microgrid feeder breakers
- Power electronic tie controllers
- AC/AC converters
- Protective relays/synchronization check logic
- Transformers.

Capabilities:

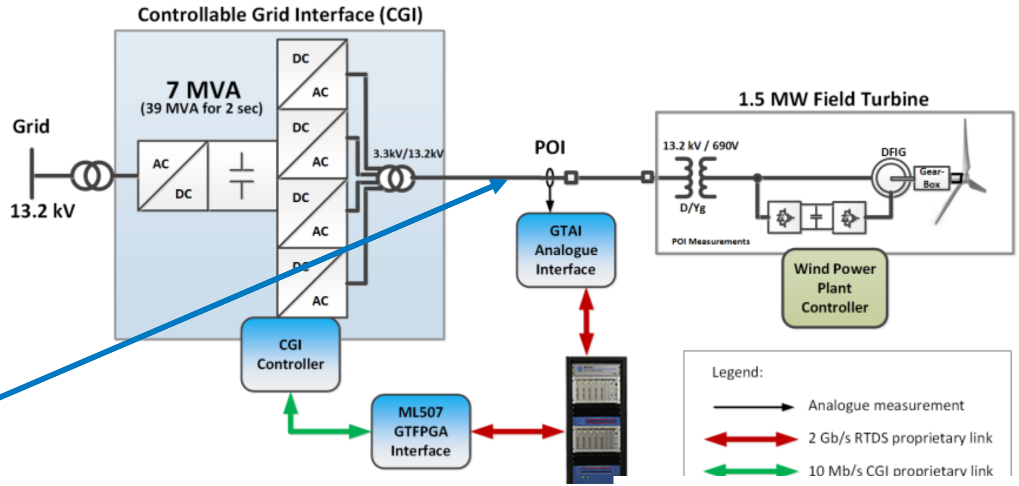
- Ability to generate any angle difference
- Ability to generate independent frequencies
- Fault testing at CGI side possible
- CGI side can run as voltage or current source inverter (VSI or CSI).

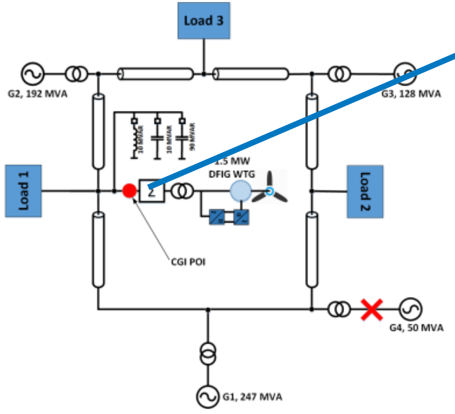


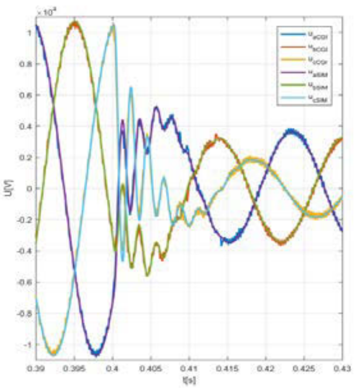

Source: NREL

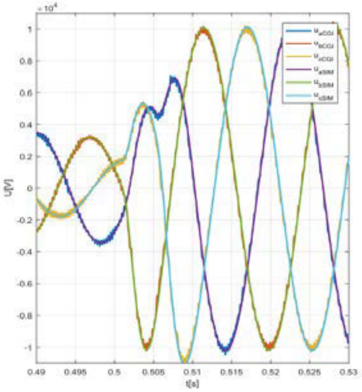
# Closed-Loop Testing: PHIL

- Voltage from simulation is tracked by CGI in real time.
- Current measured is injected back to RTDS model.
- Allows testing device under test under various grid conditions and events (e.g., microgrids)
- Distances between RTDS point of interconnection and CGI ca. 300 ft
- 2 Gb/s RTDS optical link: Glass Optical Fiber
- 10 Mb/s CGI-ABB proprietary link: Plastic Optical Fi
- Data exchange every 25 us (40 kHz).



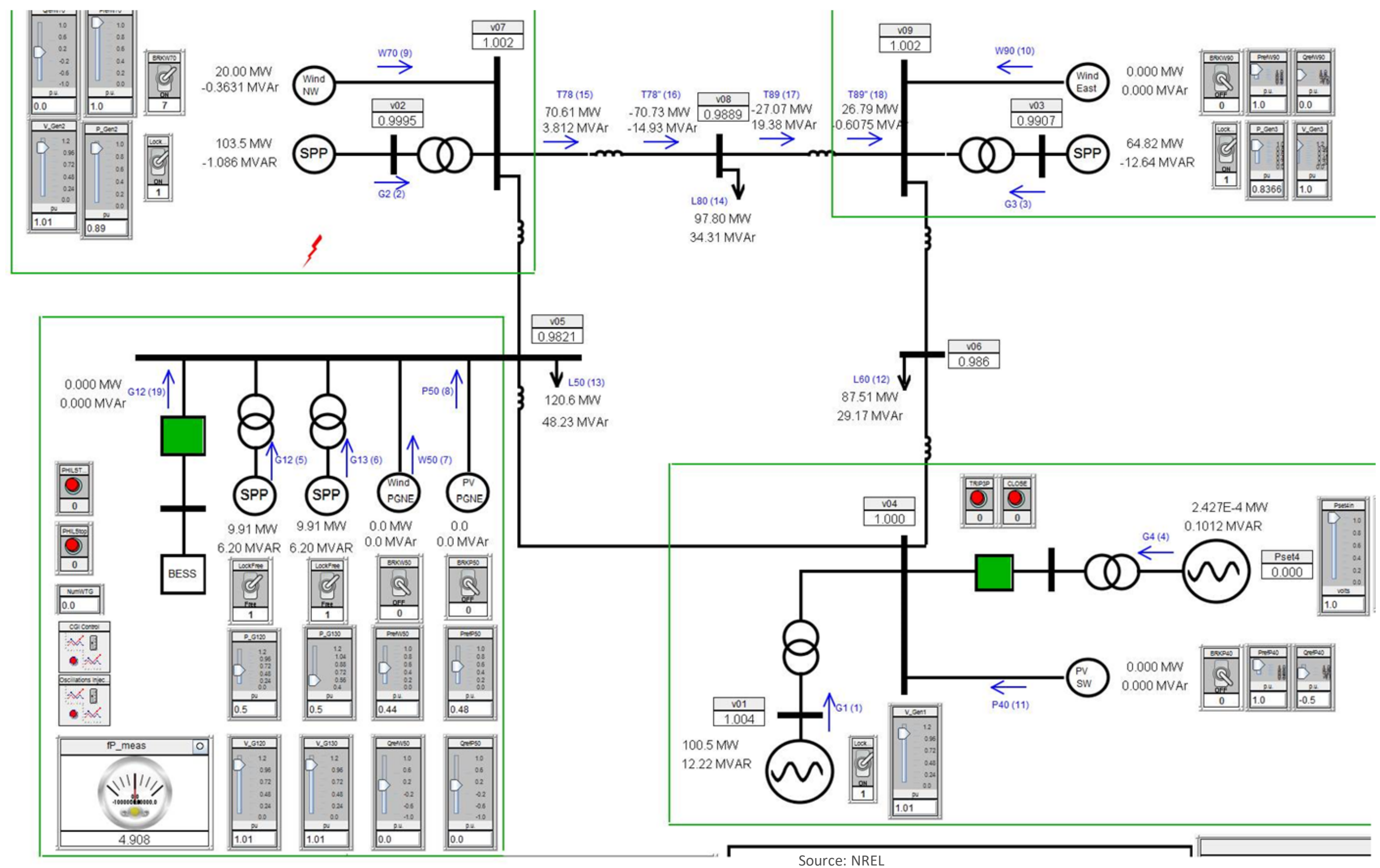




Source: NREL

# RTDS 9-Bus Transmission Model




Source: NREL

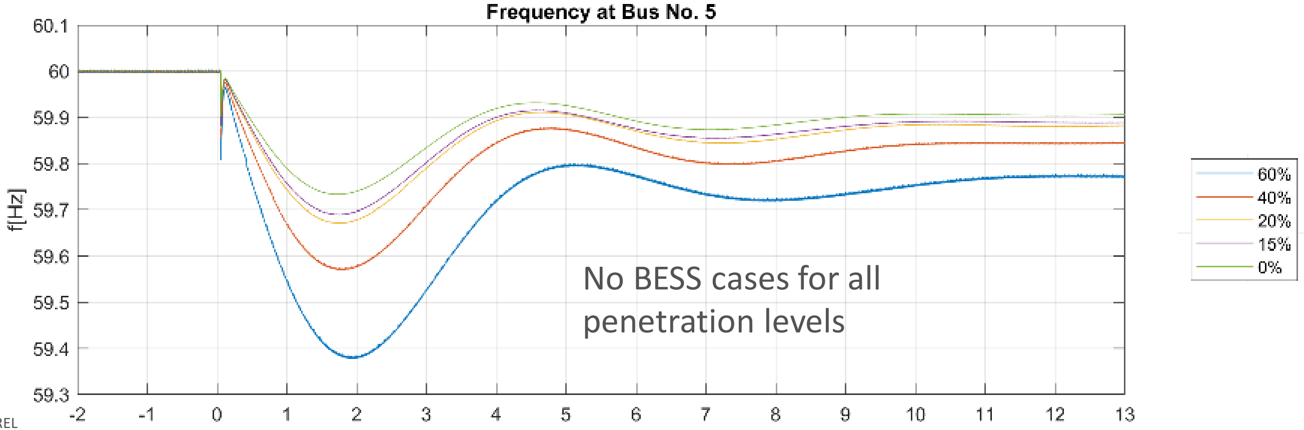
# Assumptions Used for PHIL Testing of 9-Bus System with BESS

| | Conventional Generators | | | PV & Wind | Loads | Total H |
|---|---|---|---|---|---|---|
| Renewable penetration | $P_{Gn, MW}$ | $H_{G,}$ sec | $P_{Gdispatch}$, GW | $P_{Rn,}$ GW | Loads GW | $H_{Tot}$ |
| 60% | 53.3 | 4 | 40 | 60 | 100 | 2.13 |
| 40% | 80 | 4 | 60 | 40 | 100 | 3.20 |
| 20% | 106.7 | 4 | 80 | 20 | 100 | 4.27 |
| 15% | 113.3 | 4 | 85 | 15 | 100 | 4.53 |
| 0% | 133.3 | 4 | 100 | 0 | 100 | 5.33 |

$$H_{Tot} = \frac{H_G P_{Gn} + H_B P_{Bn} + H_R P_{Rn}}{P_{Tot}}$$

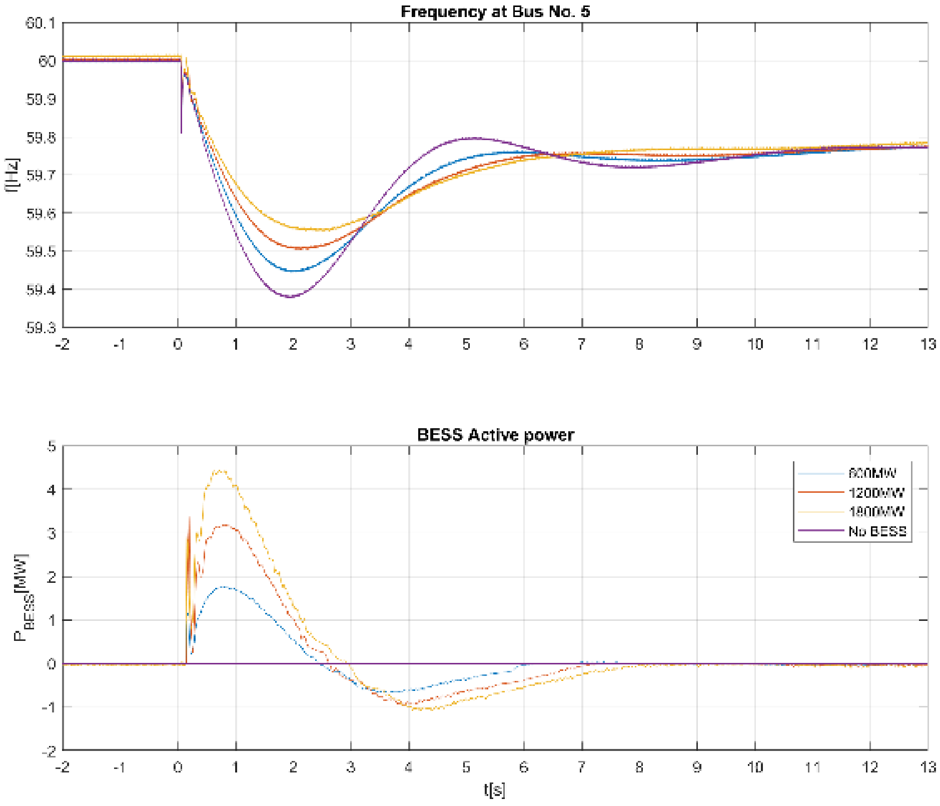
$$H_R = 0$$

Generation loss = 3.8 GW/3.8%




Source: NREL

# Renewable Penetration 60%: Inertia




Source: NREL

Battery scaling assuming 100-GW system:

- 600 MW -> 0.6%
- 1200 MW -> 1.2%
- 1800 MW -> 1.8%

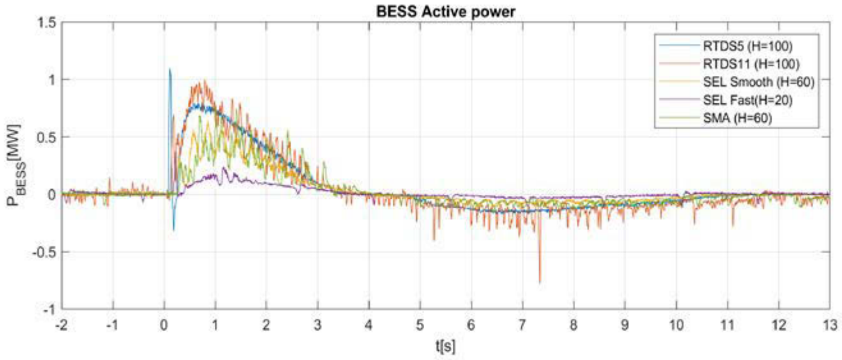
BESS controlled proportional to ROCOF using LabView controller. H=50 s

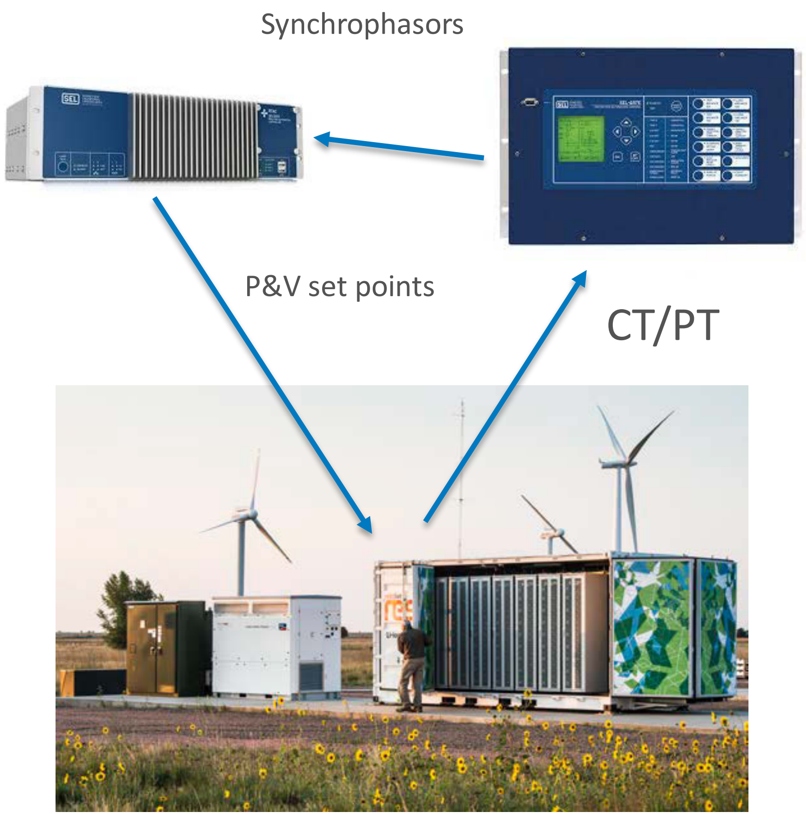
Frequency response improves with increasing BESS installed capacity at 60% renewable penetration.

| BESS [MW] | 0 | 600 | 1200 | 1800 |
|---|---|---|---|---|
| 60% | 2.13 | 2.43 | 2.73 | 3.03 |
| 40% | 3.20 | 3.50 | 3.80 | 4.10 |
| 20% | 4.27 | 4.57 | 4.87 | 5.17 |
| 15% | 4.53 | 4.83 | 5.13 | 5.43 |
| 0% | 5.33 | 5.63 | 5.93 | 6.23 |

# Renewable Penetration: RTAC Inertia Controller

- Implemented inertia controller based on commercial of-the-shelf devices
- Found limitations on maximum inertia depending on where frequency is measured
- Tested various frequency sources.

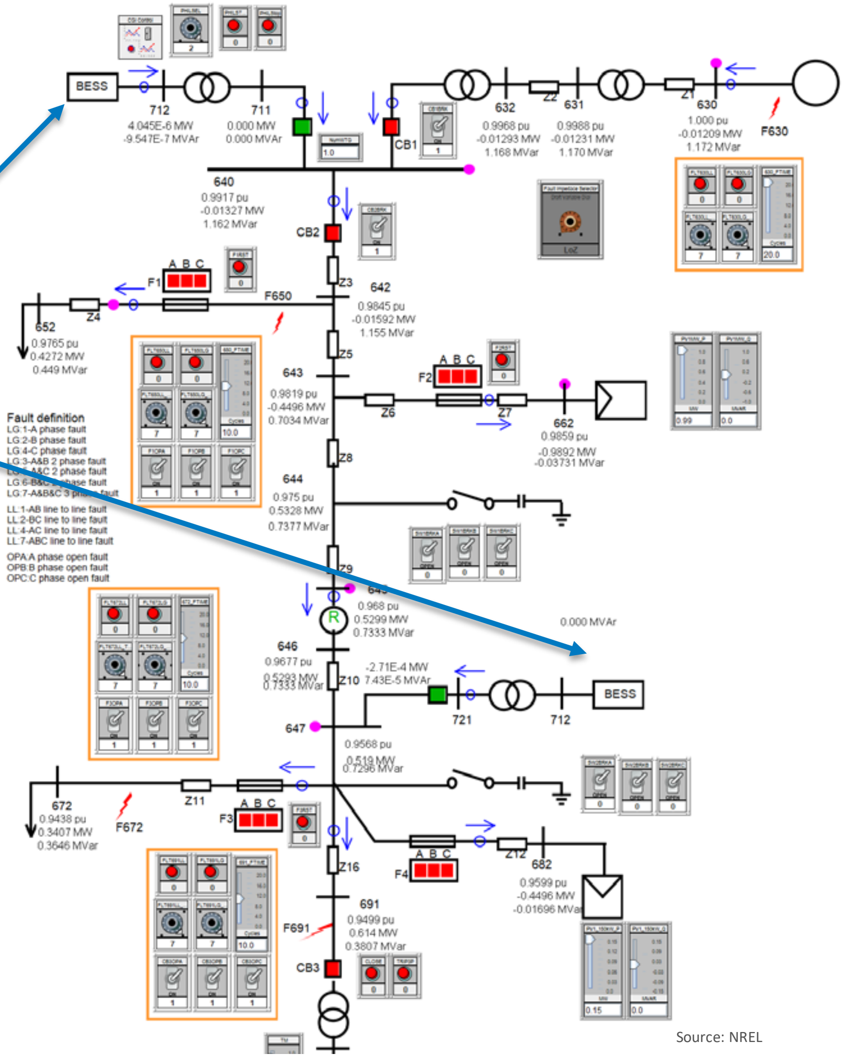



Source: NREL

# About RTDS Distribution Model

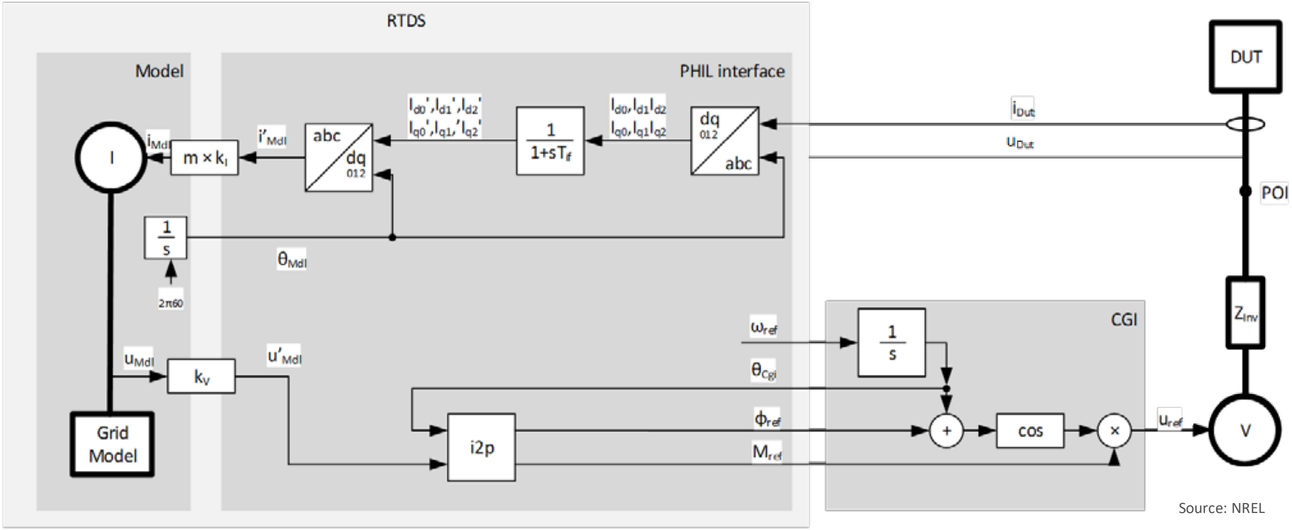
- Model based on data from PG&E
- BESS can be added using PHIL to two locations:
  - Bus 640
  - Bus 647.
- Four fault locations used for fault emulation:
  - Bus 630: Fault at transmission level
  - Bus 650: Fault at load branch—unfused
  - Bus 672: Fault at load branch—fused (F3)
  - Bus 691: Fault at motor branch—unfused
- Faults can be:
  - 1 x L-G, 2 x L-G, 3 x L-G, 1 x L-L, 2 x L-L, open phase
  - Low impedance: 0.1 Ohm
  - High impedance: 10 Ohm.




Source: NREL

# CGI-RTDS PHIL Interface

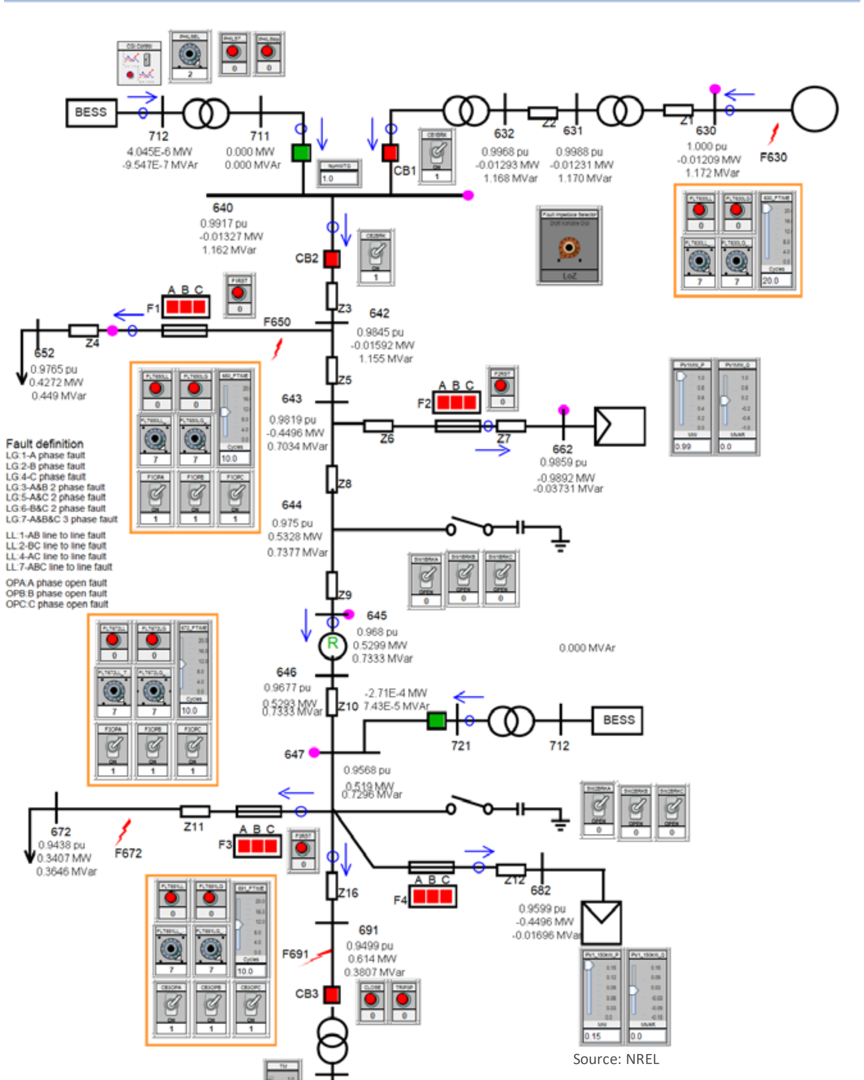
- Instantaneous voltage measured in model and commanded to CGI
  - Very fast tracking achieved thanks to instantaneous-to-phasor (I2P) algorithm
  - Compensated phase delay.
- Positive-, negative-, and zero-sequence current injection into model
  - Decoupled positive- and negative-sequence DQ current measurement
  - Filtered with 10-ms filter for high-frequency stability.




Source: NREL

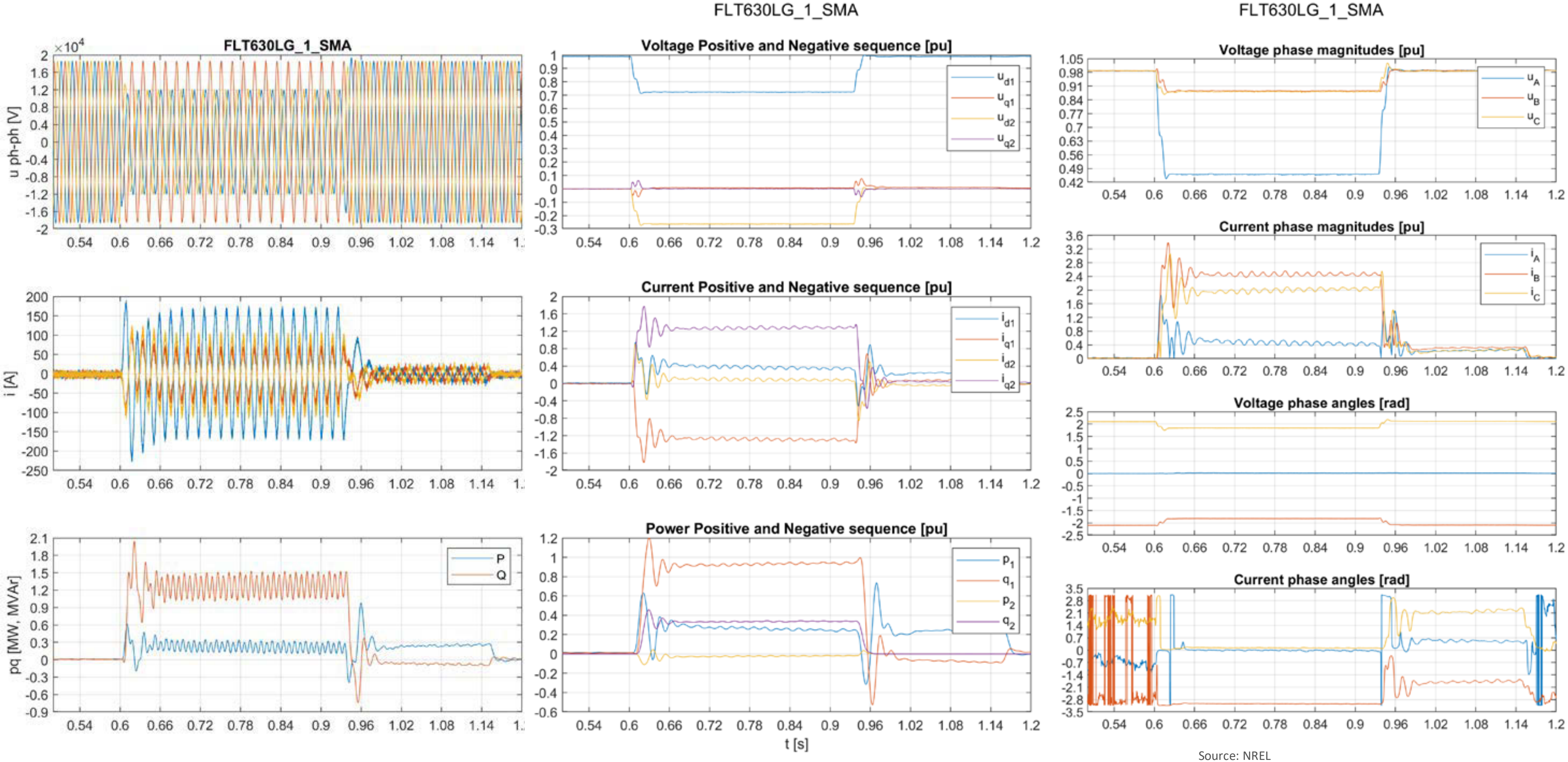
# About RTDS Distribution Model

- RTDS automated script
- Total number of fault cases executed per script run (ca. 15 min): 53x
- For each test case, data were captured using RTDS:
  - 100-us resolution
  - 7 x 3 phase voltage measurements (magenta dots)
  - 12 x 3 phase current measurements (blue arrows)
  - 3-s data buffer
  - ~ 1.5 GB of data per run.



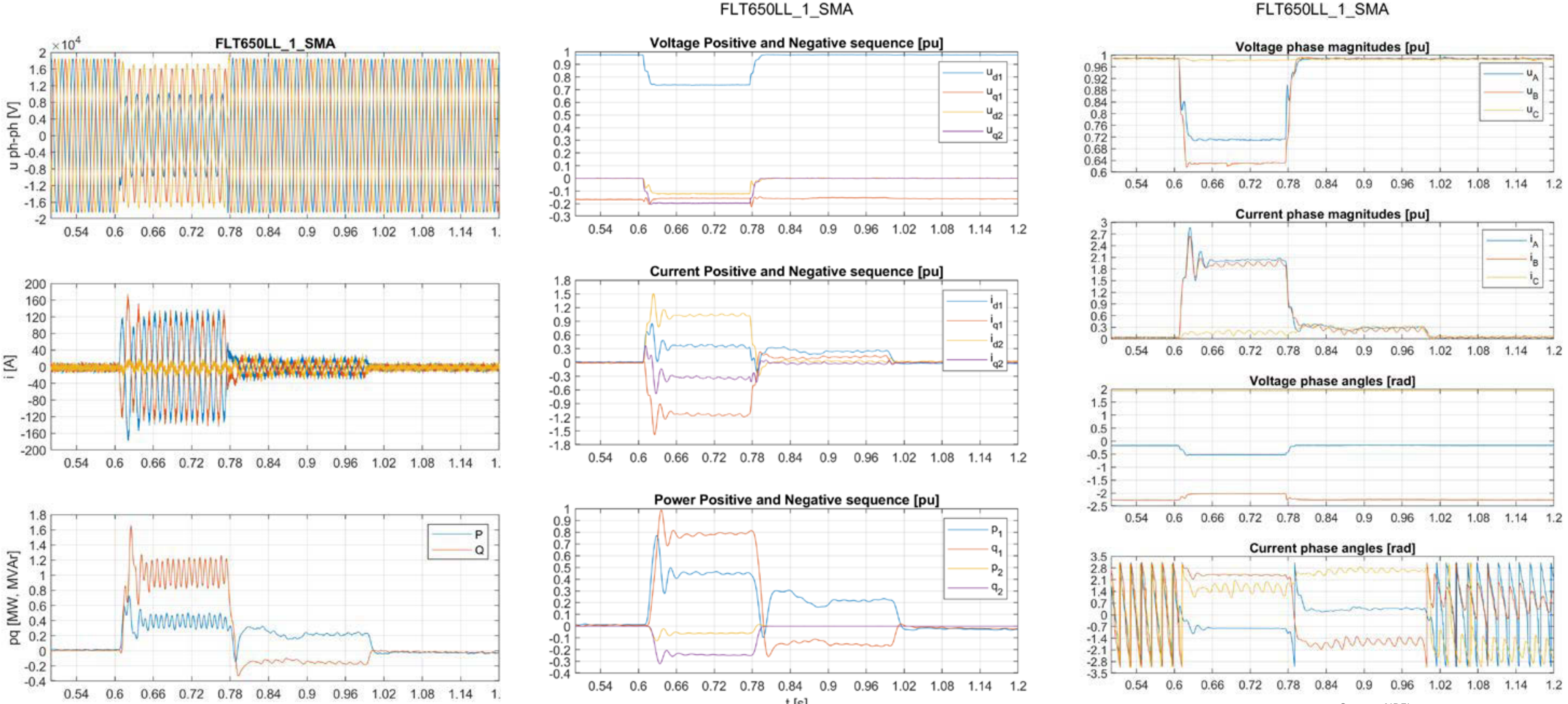
Source: NREL

# FLT630 Line A to Ground



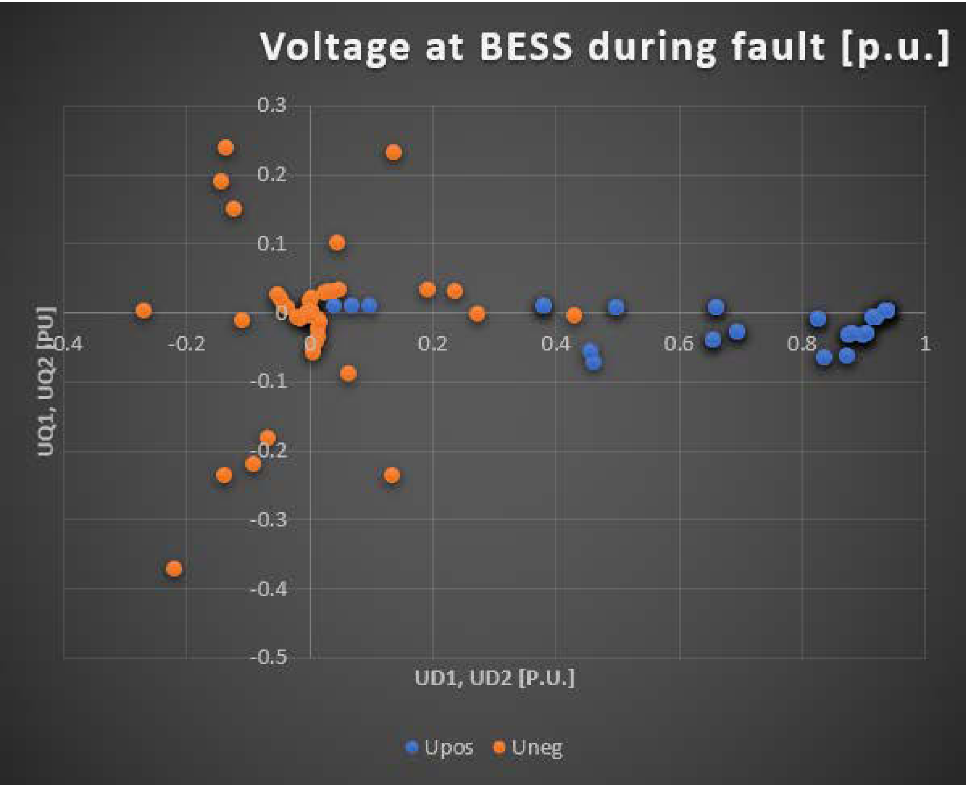

Source: NREL

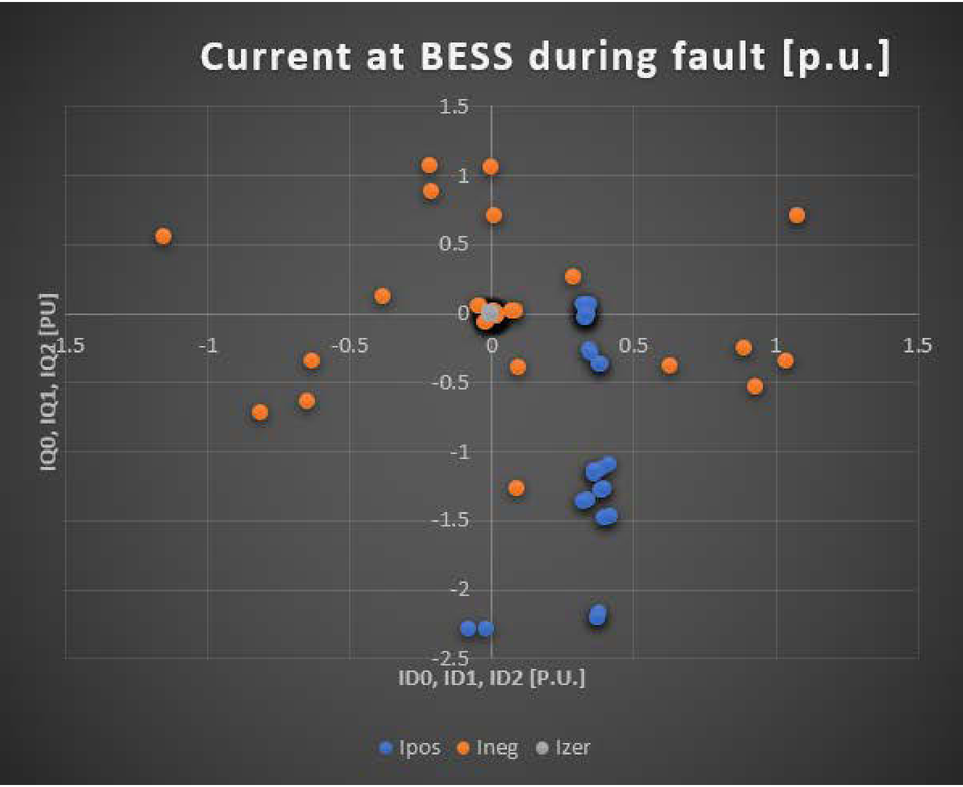
# FLT650 Line A to Line B




Source: NREL

# Spectrum of LVRT Voltage During Faults

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# Thank you

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