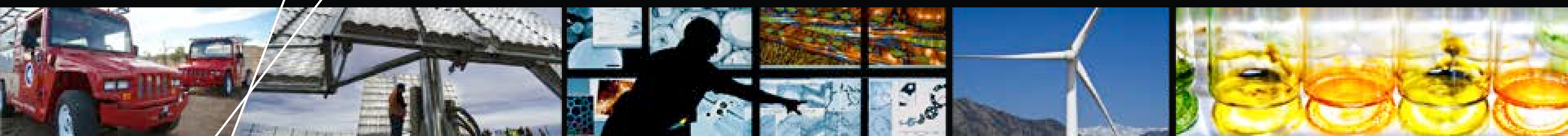
The Energy Systems Integration Facility



Electrical Testing Capabilities and Research Activities – September 2014

Mariko Shirazi and Blake Lundstrom

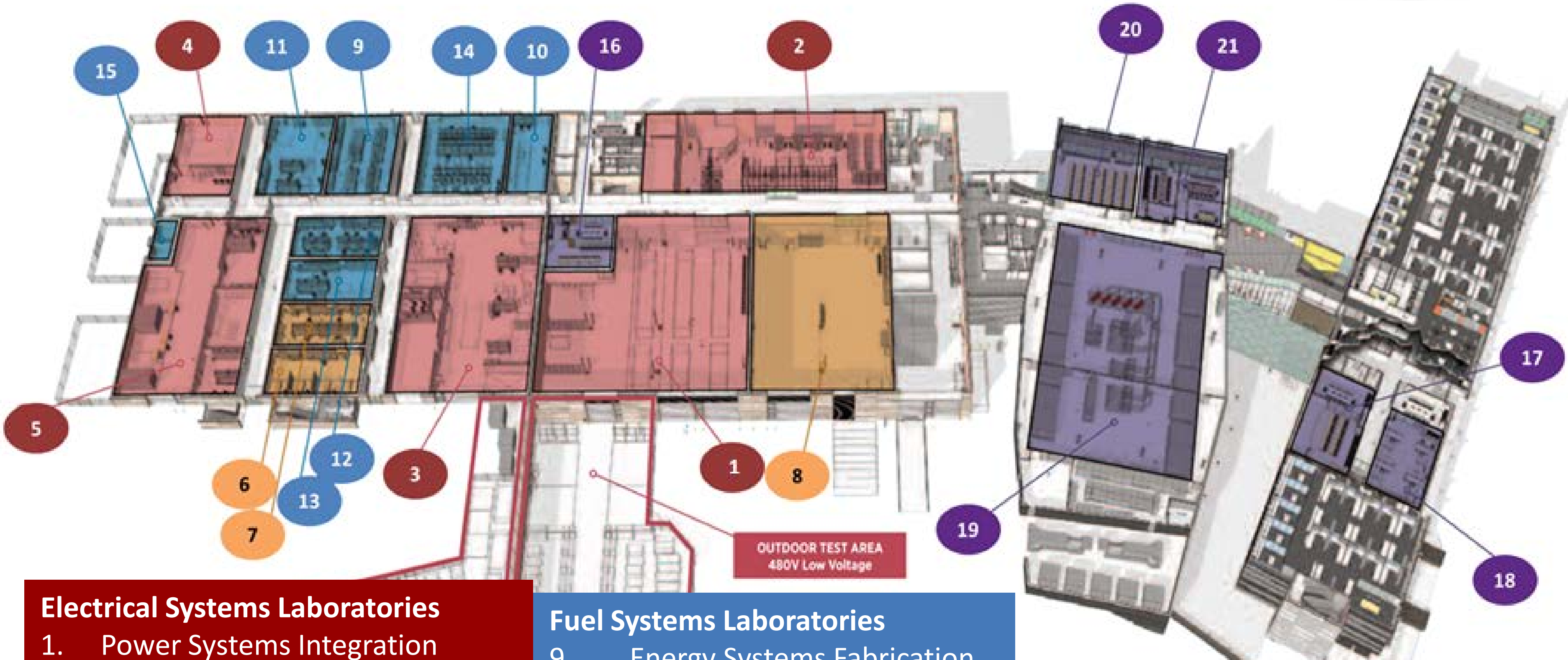
Grid Simulator Testing of Energy Systems and Wind Turbine Powertrains 2014 Workshop, Clemson University Restoration Institute

September 17, 2014

Energy Systems Integration Facility (ESIF)

NREL's first user facility
15 laboratories, 2 outdoor test areas, 183k sq ft

ESIF Laboratories



Electrical Systems Laboratories

1. Power Systems Integration
2. Smart Power
3. Energy Storage
4. Electrical Characterization
5. Energy Systems Integration

Thermal Systems Laboratories

6. Thermal Storage Process and Components
7. Thermal Storage Materials
8. Optical Characterization

Fuel Systems Laboratories

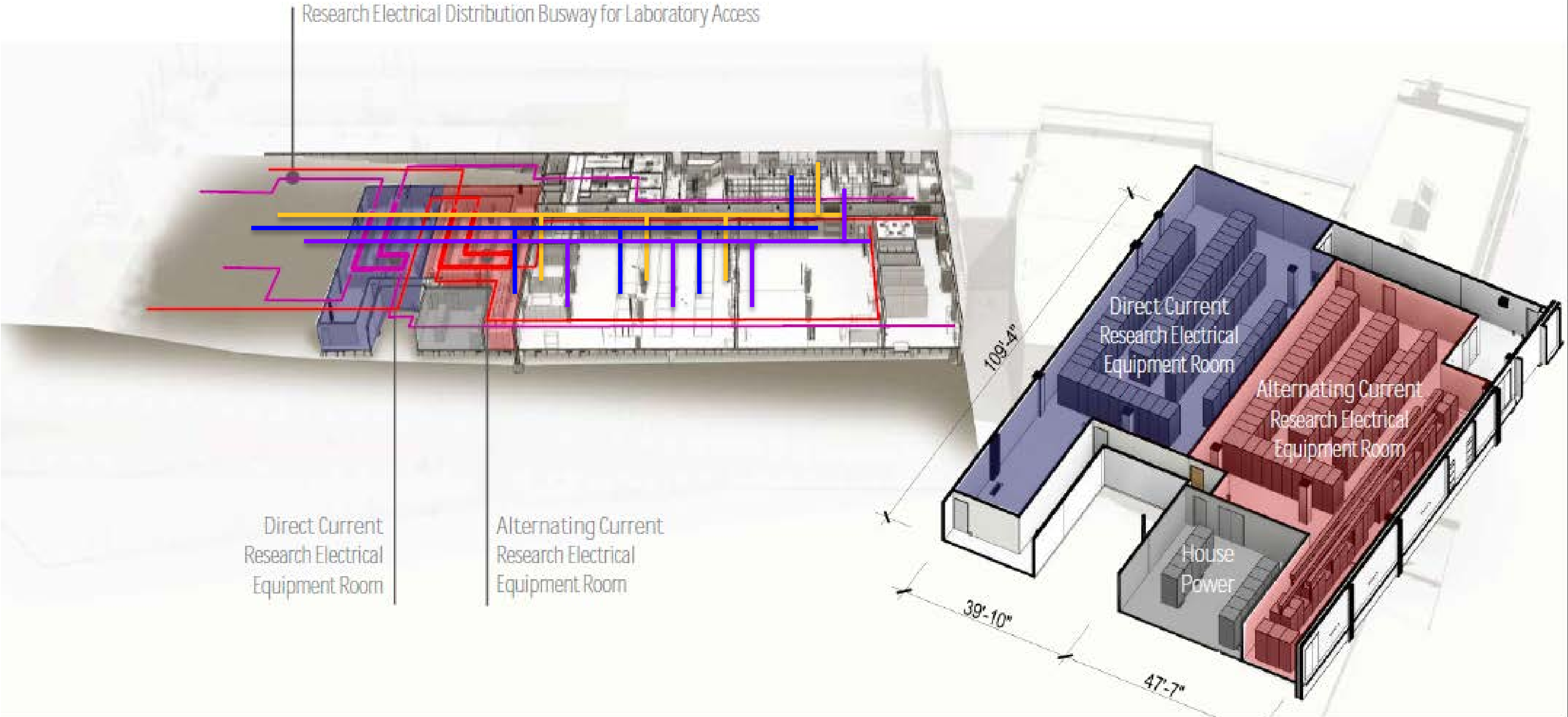
9. Energy Systems Fabrication
10. Manufacturing
11. Materials Characterization
12. Electrochemical Characterization
13. Energy Systems Sensor
14. Fuel Cell Development & Test
15. Energy Systems High Pressure Test

High Performance Computing, Data Analysis, and Visualization

16. ESIF Control Room
17. Energy Integration Visualization
18. Secure Data Center
19. High Performance Computing Data Center
20. Insight Center Visualization
21. Insight Center Collaboration

ESIF Research Infrastructure

- Research Electrical Distribution Bus—REDB (AC 3ph, 600V, 1600A and DC +/-500V, 1600A)
- Thermal Distribution Bus
- Fuel Distribution Bus
- Supervisory Control and Data Acquisition (SCADA)



Research Electrical Distribution Bus (REDB)

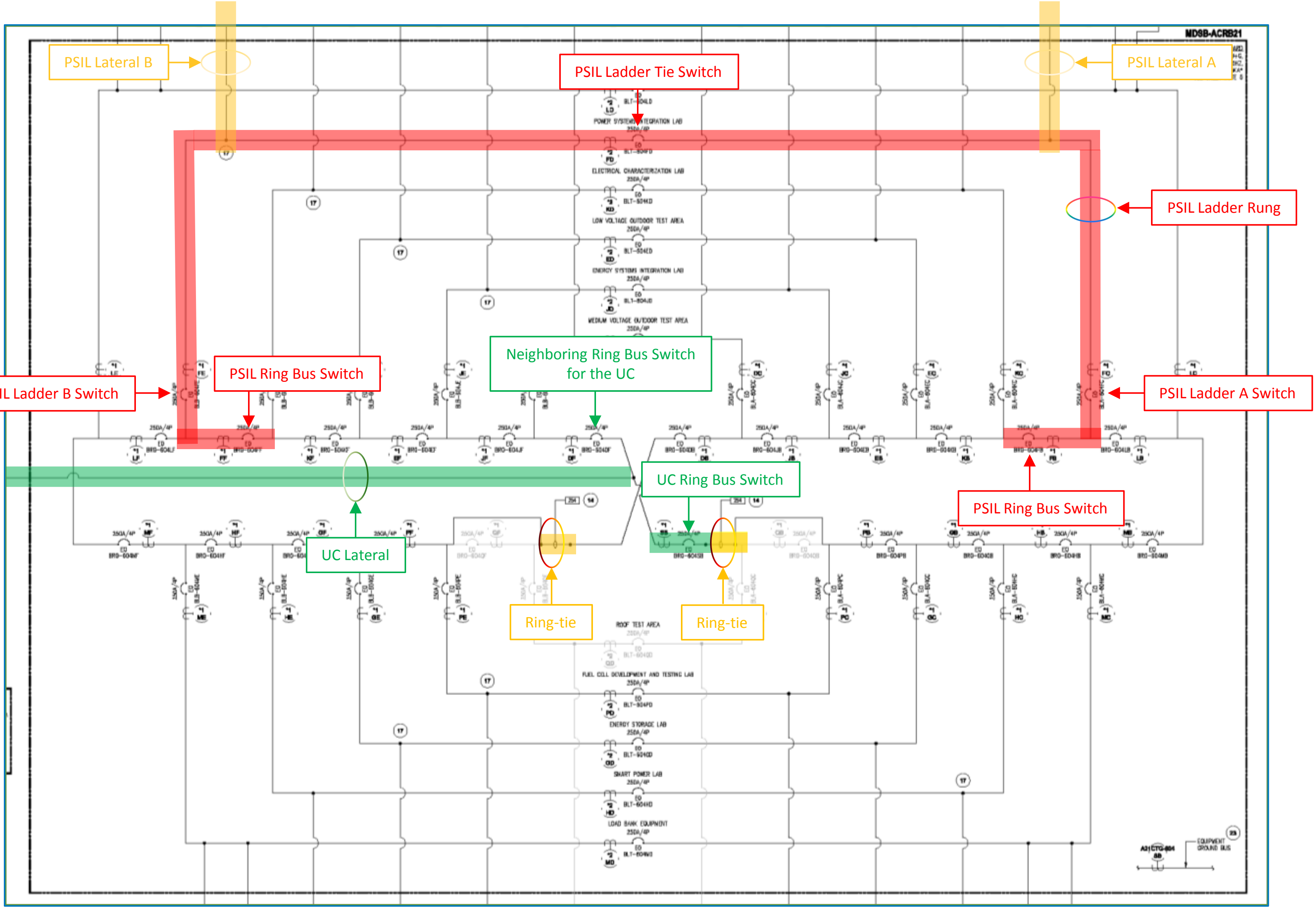
AC

- 4-wire plus ground
- Floating or grounded neutral
- 600 Vac
- 16 Hz to 400 Hz
- 250A and 1600A installed
- 250A and 2500A planned (future)
- 4-pole switches
- Connects PSIL, SPL, ESL, GSE, LBE, LVOTA, MVOTA, ESIL

DC

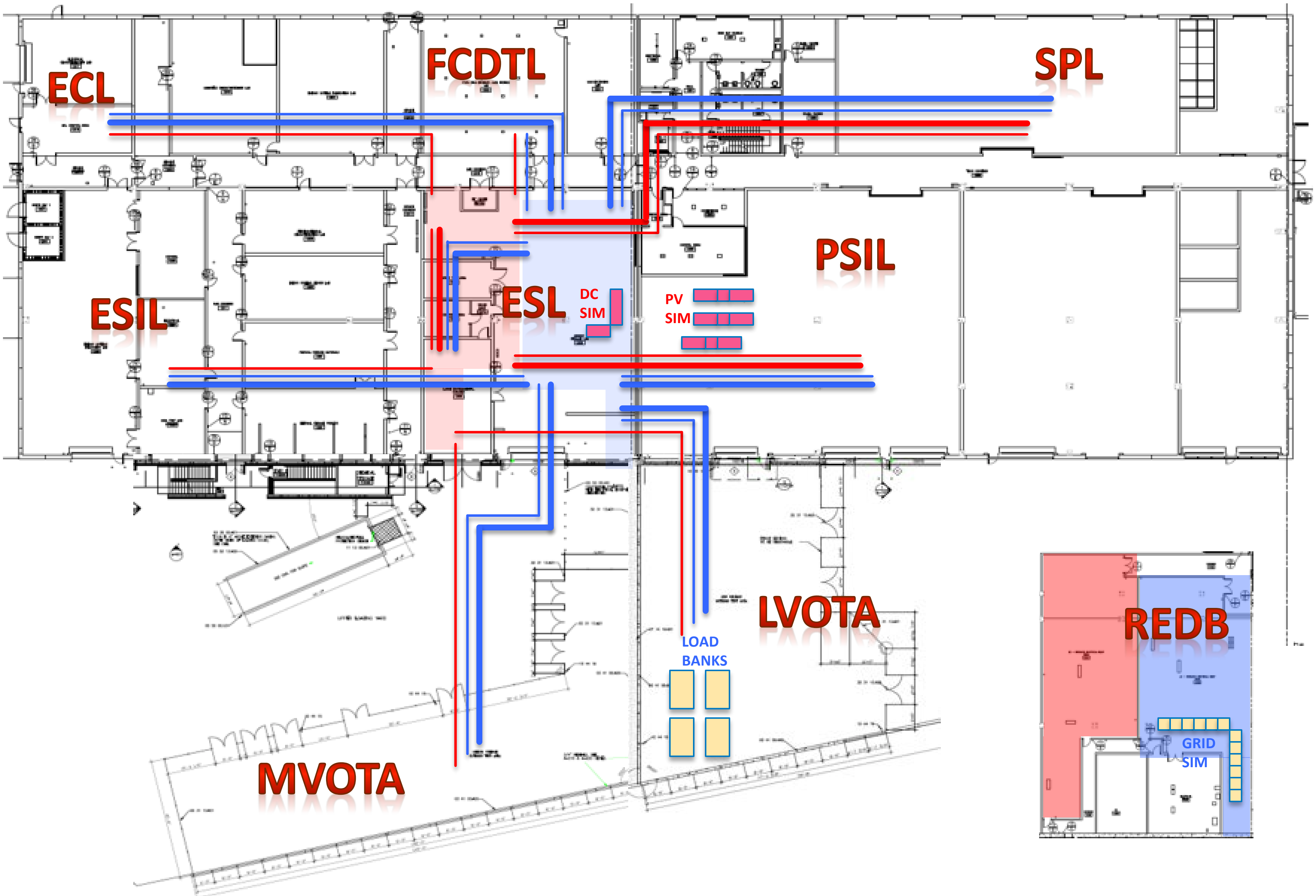
- 3-wire plus ground
- Any pole may be grounded
- ±500Vdc or 1000Vdc
- 250A and 1600A installed
- 250A and 2500A planned (future)
- Experiment connection via cart contactor/fuse or direct (main lug only)
- Connects PSIL, SPL, ESL, PVE, LVOTA, MVOTA, ESIL

Example Racetrack and Lab Section

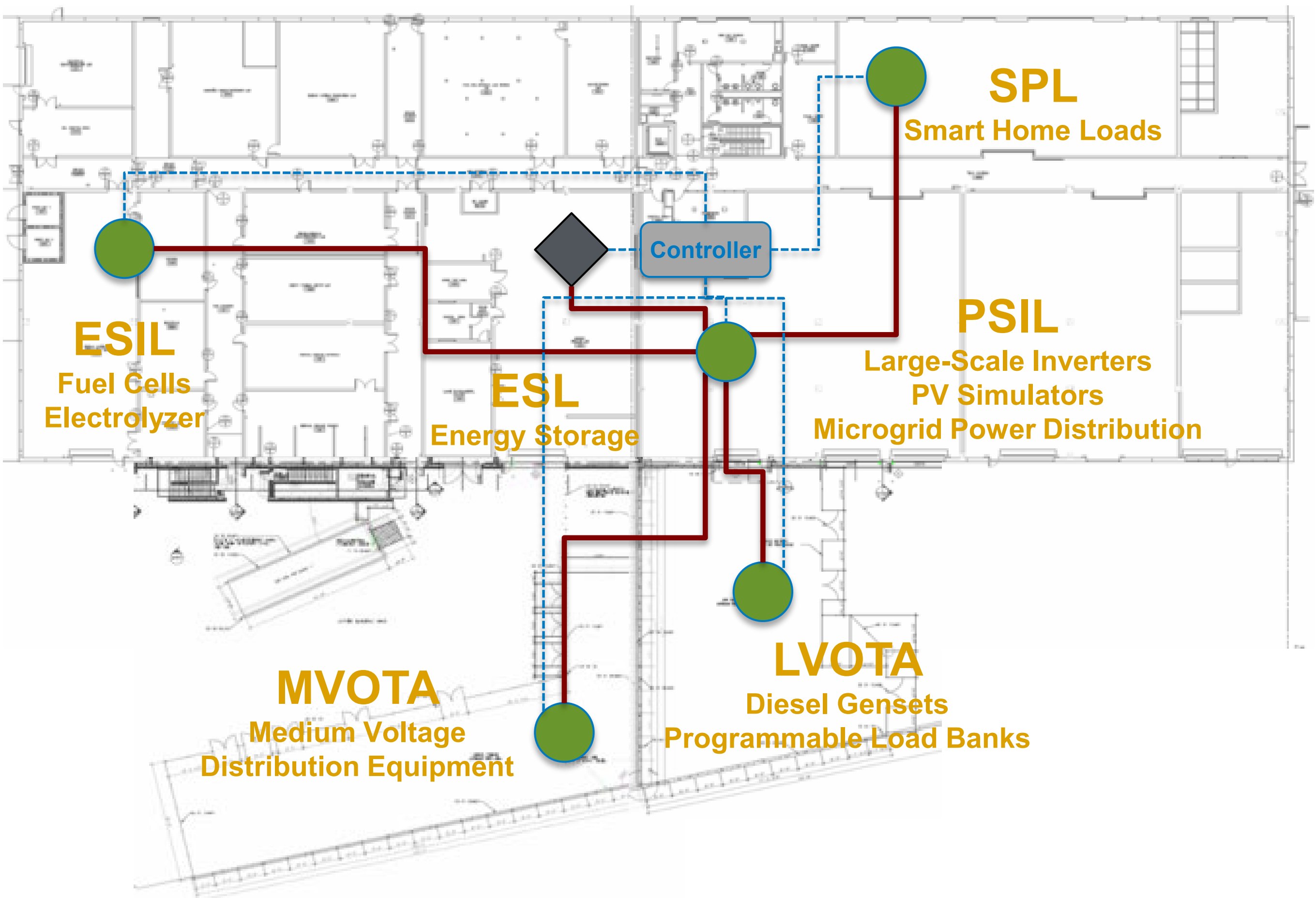


REDB Switchgear Room (AC)

REDB Installed Laterals



REDB Routing—Conceptual



ESIF Laboratory Connections

Fuels Distribution Network

- Hydrogen
- Natural Gas
- Diesel

Thermal Distribution Bus

- Hot Water
- Chilled Water
- Process Cooling Water

Research Electrical Distribution Bus

AC (600 V, 4-wire)

- 250 A
- 1600 A

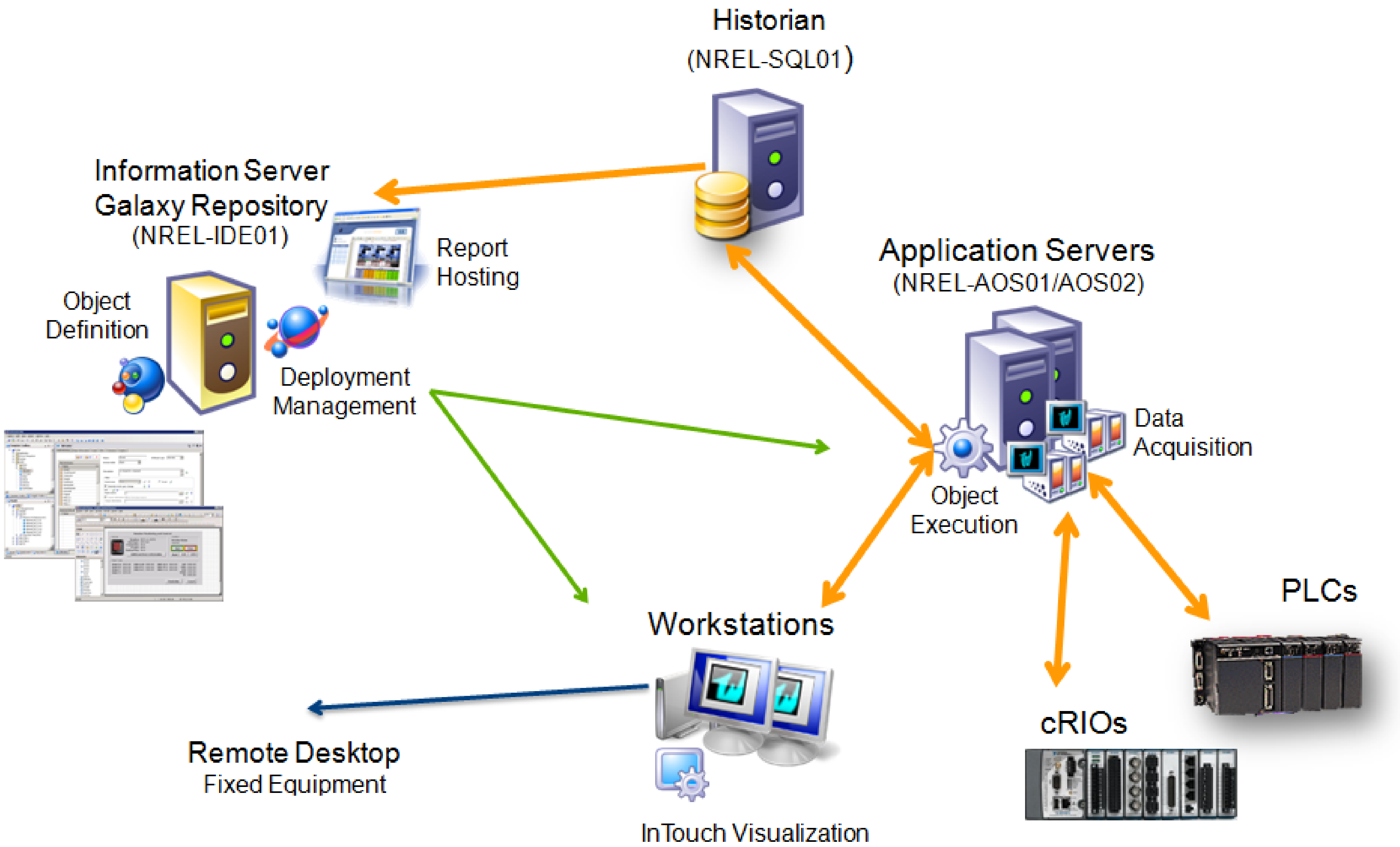
DC (±500 V, 3-wire)

- 250 A
- 1600 A

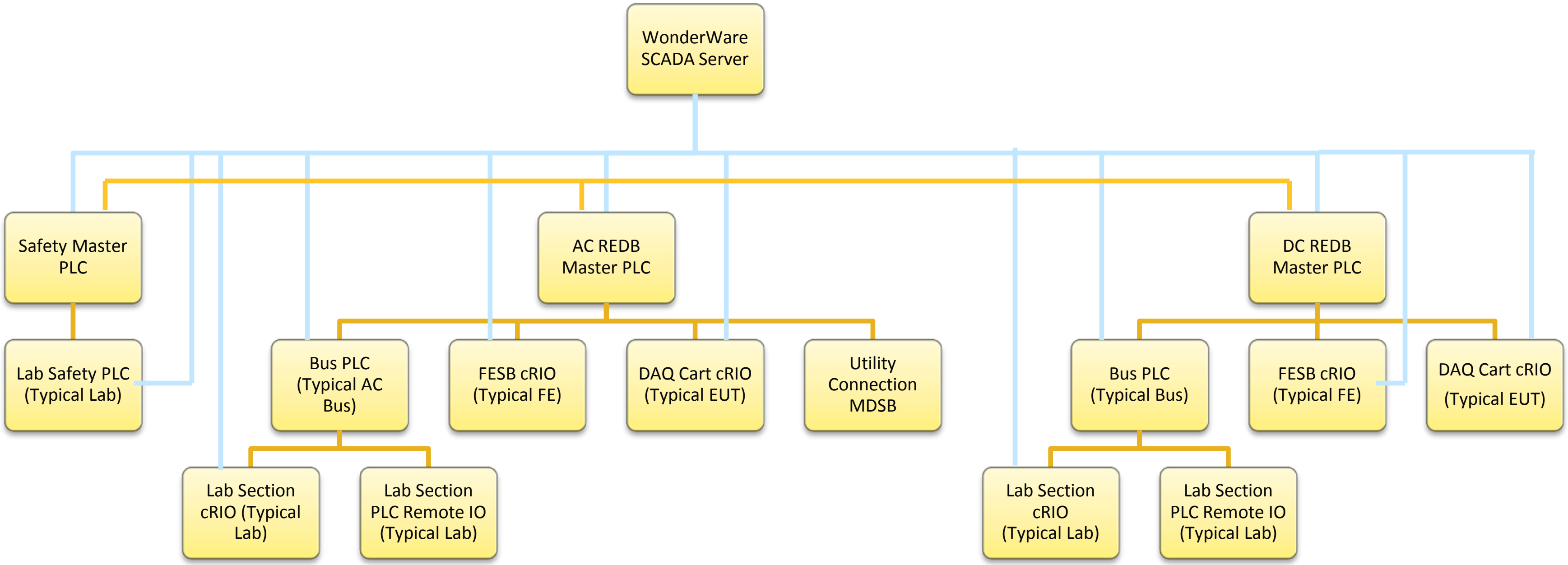
Power Systems Integration Facility

Busway Connections in PSIL

Core SCADA System



REDB Control Architecture



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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)**





Select Research Activities and Testing

Large PV Inverter Testing—Advanced Energy

- **Solar Energy Grid Integration Systems—Advanced Concepts**
- **500TX (500 kW): First test article at ESIF**
- **1000NX (1 MW)**

- **Advanced Functionality**
  - LVRT/HVRT (3ϕ and 1ϕ, HV up to 1.25 X)
  - LFRT/HFRT
  - Volt/VAR
  - Freq/Watt
- **PHIL**

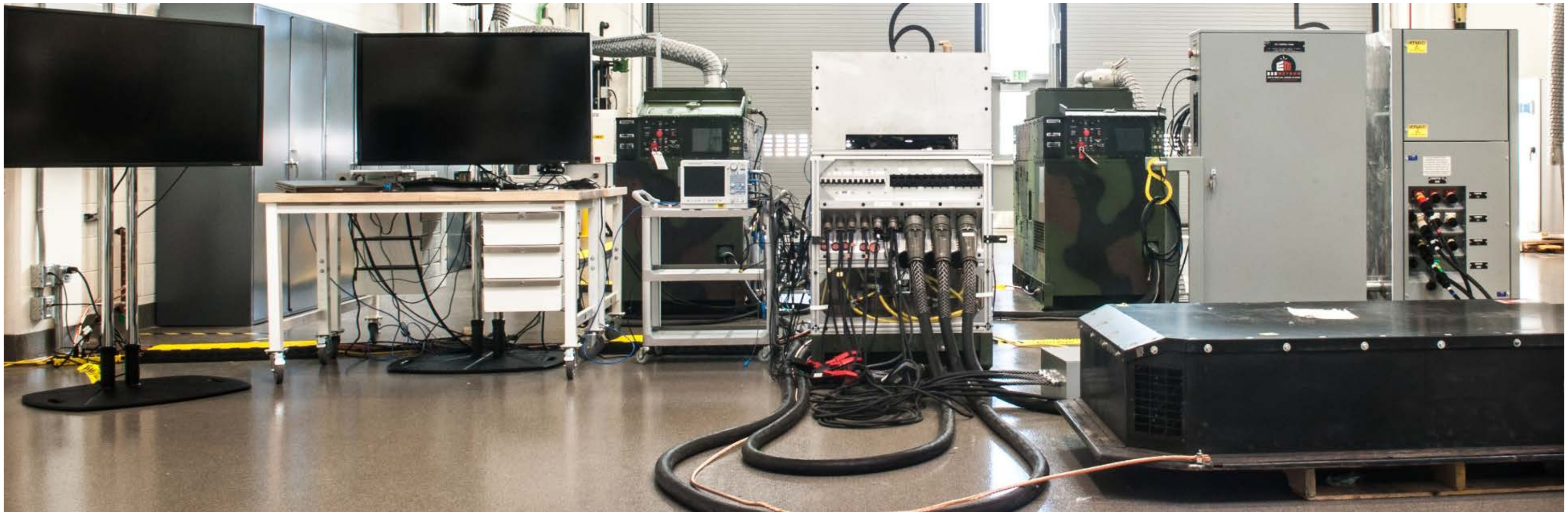
Large PV Inverter Testing—Solectria

- **500 SGI (500 kW)**
- **750 XTM (750 kW)**

- **Advanced Functionality**
  - LVRT/HVRT (3ϕ and 1ϕ, HV up to 1.25 X)
  - LFRT/HFRT
  - Volt/VAR
  - Freq/Watt

Other Current Testing Activities

- **Microgrid Controls Testing (Commonwealth Scientific and Industrial Research Organisation—CSIRO)**
- **Mobile Hybrid Electric Power System for FOBs (DoD)**
- **Redox Flow Battery Testing (American Vanadium)**
- **Electric Vehicle Integration Testing (Toyota)**
- **Performance Testing of Large Active Area PEM Electrolyzer Stacks (Giner)**
- **Upcoming Microgrid Tests**



Challenges

Challenges

- **Design**
  - Safety—LOTO
- **Operational**
  - Safety—Arc Flash Analysis
  - House Power Limitations
  - Scheduling

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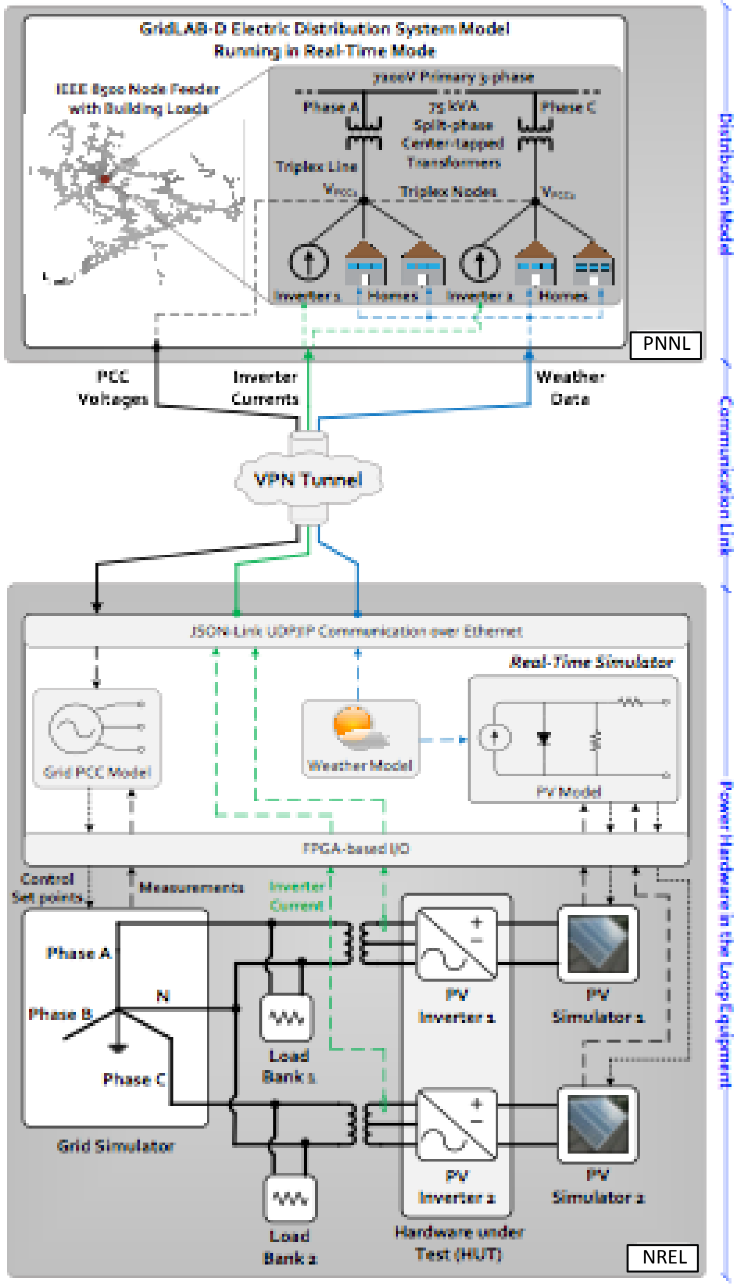
Power Hardware-in-the-Loop (PHIL) Research at ESIF

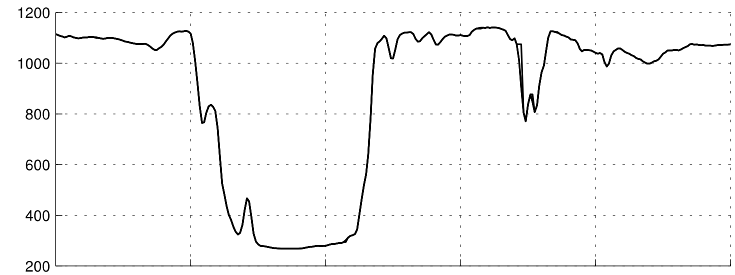
Brief Overview of Recent PHIL Work at ESIF

- **PHIL Co-Simulation**
- **Unintentional Islanding PHIL**

PHIL Co-Simulation: Motivation

- **Leverage benefits of PHIL:**
  - Examine system-level and multi-device impacts
  - Repeatability of complex scenarios
  - Flexible, modular
- **But add:**
  - Simplify model conversion
  - Allow use of more complex, multi-discipline system models without simplification or abstraction
  - Connection/link of multiple sites into a single PHIL simulation
- **Within limitations**



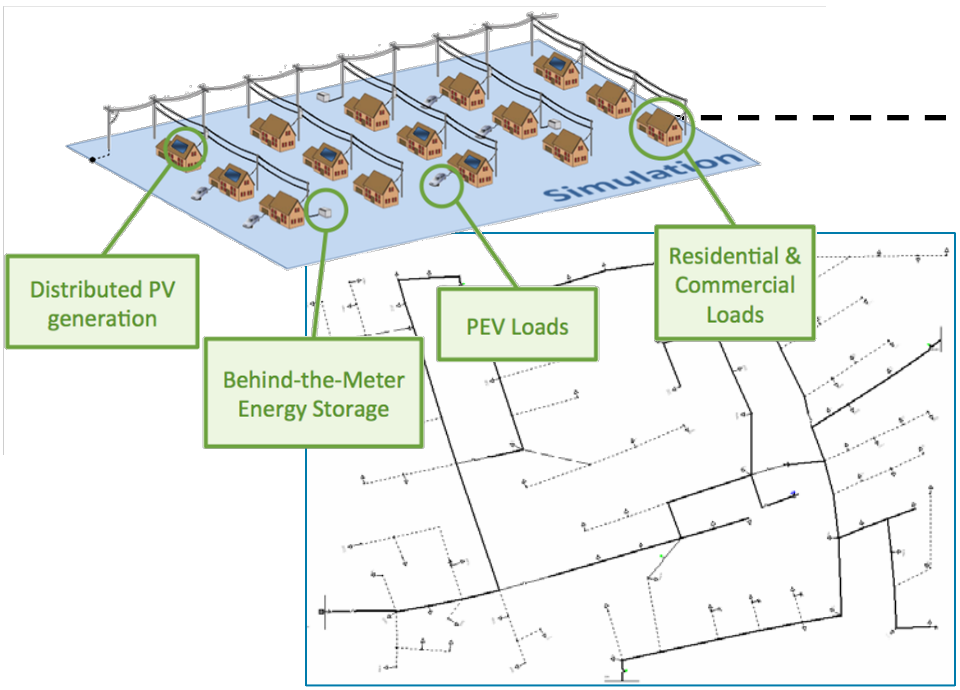


1. B. Palmintier, B. Lundstrom, S. Chakraborty, T. Williams, J. Fuller, K. Schneider, D. Chassin, "A Power-Hardware-in-the-Loop Platform with Remote Distribution Circuit Co-simulation," *IEEE Transactions on Industrial Electronics, to appear.*
2. T. Williams, J. Fuller, K. Schneider, B. Palmintier, B. Lundstrom, S. Chakraborty, "Examining System-Wide Impacts of Solar PV Control Systems with a Power Hardware-in-the-Loop Platform," in *IEEE PVSC*, 2014.

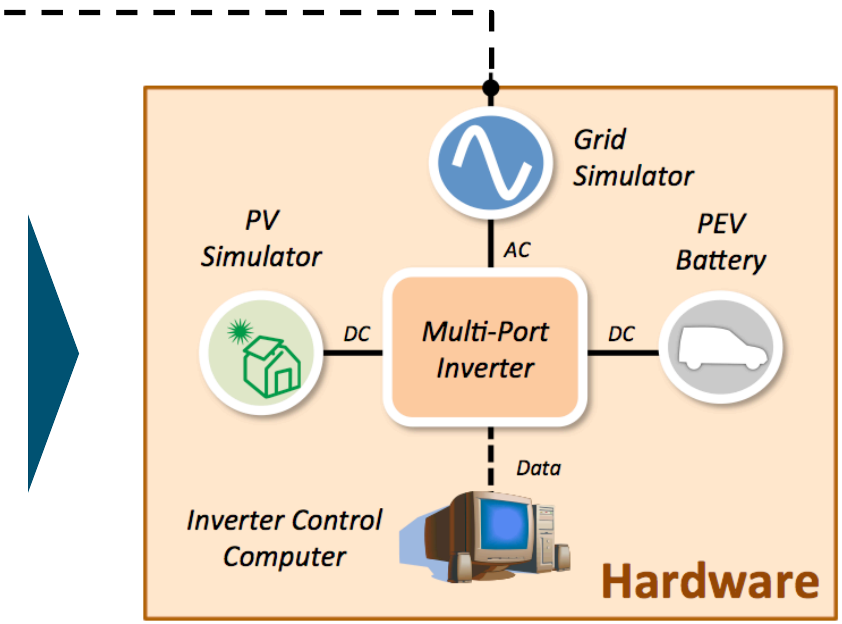
PHIL Co-Simulation Testbed

Distributed Control of Energy Storage

- NREL integrated PHIL simulation of energy storage + PV with residential inverter
- ±10kW battery + 10kW PV
- 123 node grid simulation



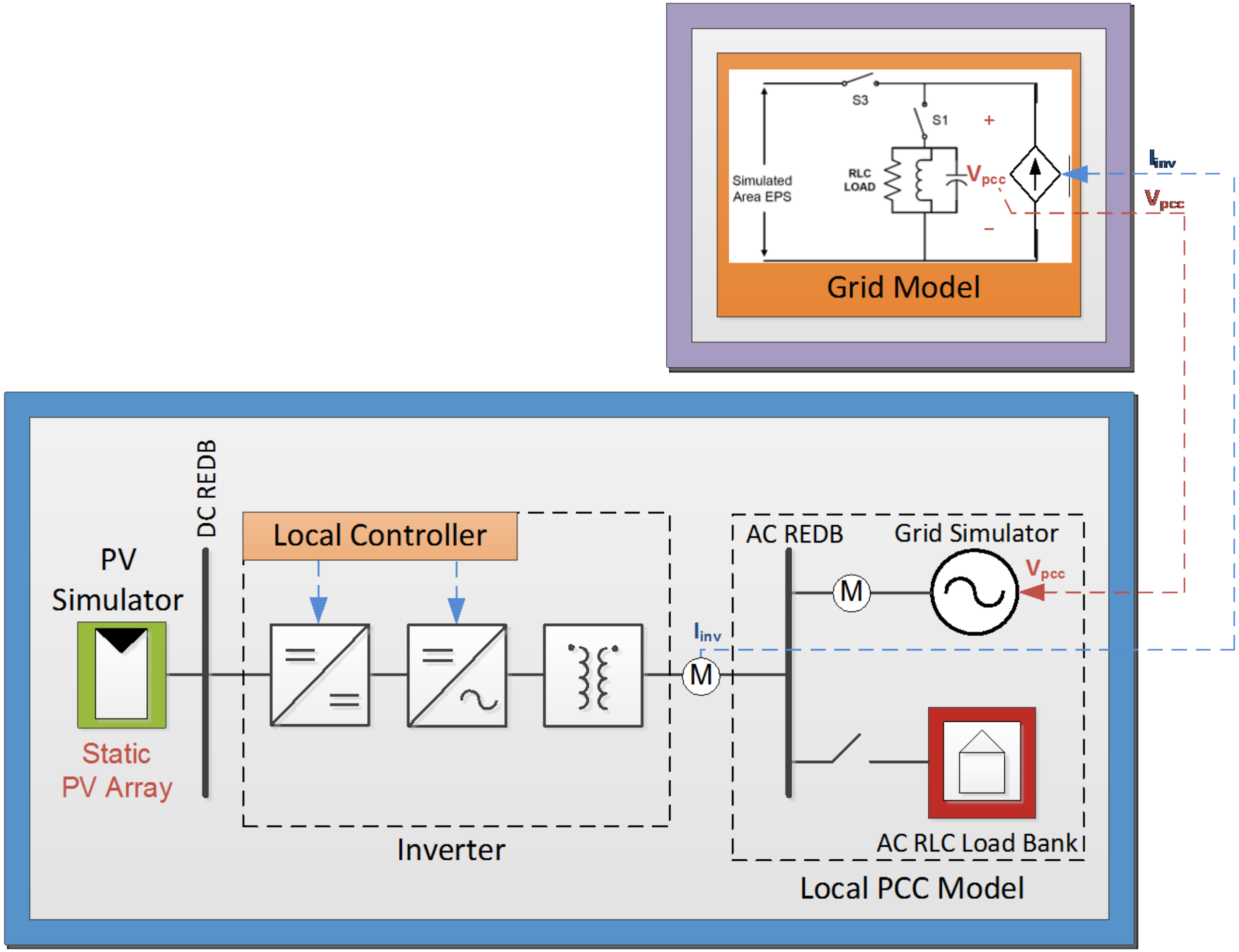
IEEE 123 Node Feeder Model



Unintentional Islanding PHIL: Motivation

- **Complex Test—**efficiency, realism, precision, repeatability
- **At MW-scale, RLC load bank very rare**
- **Validation step before more complex grid PHIL simulation**

Unintentional Islanding PHIL: Test Setup



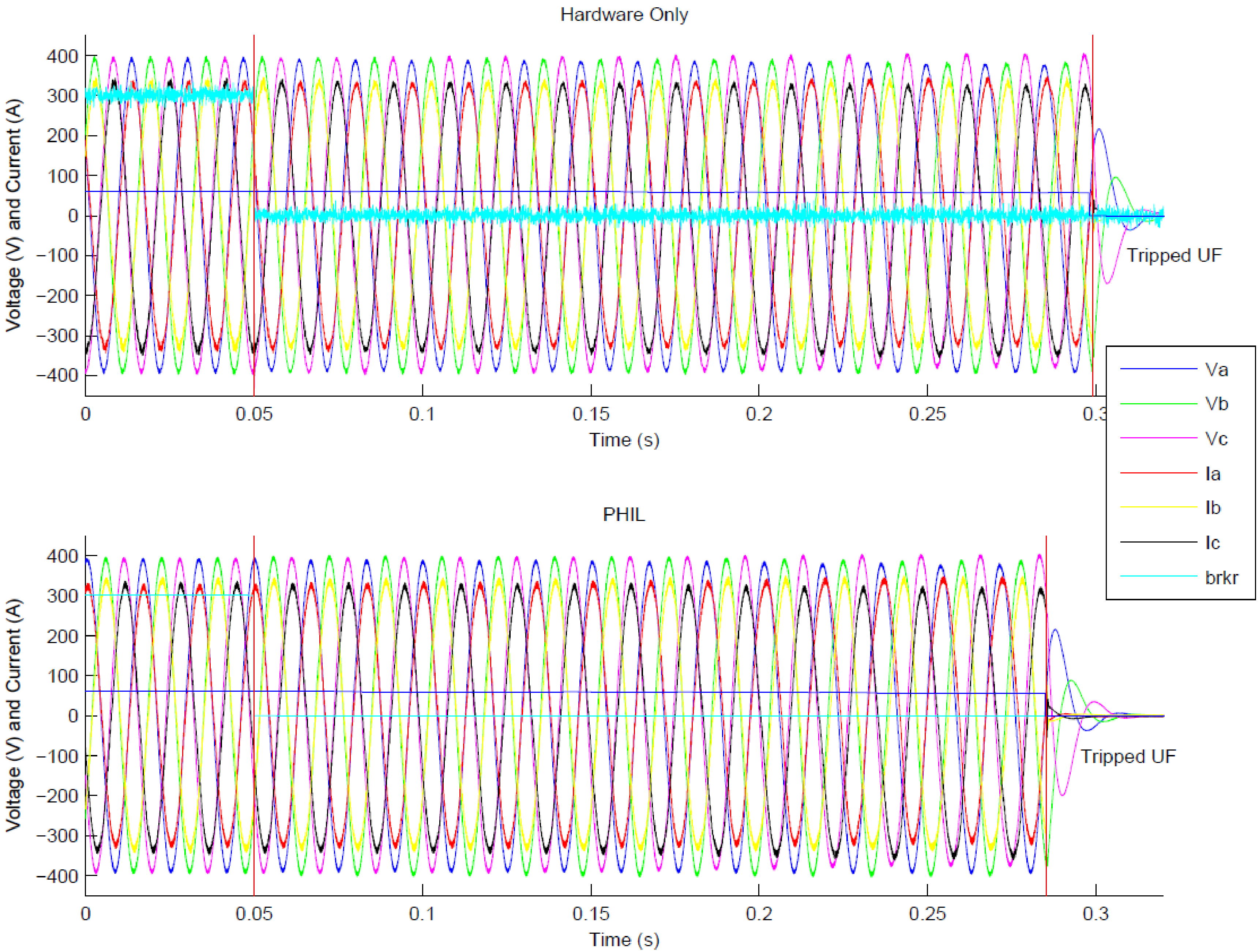
Hardware:

- (EUT) Advanced Energy 500TX 500 kW PV inverter
- 810 kVA grid simulator with analog control
- 1.5 MW PV simulator
- 1 MVA (50 VA) RLC load bank
- LEM current and voltage transducers

Real-Time Modeling:

- Opal-RT eMegaSim RTS
- Real-time model developed in SimPowerSystems (no co-simulation)
  - ITM interface
  - Phase compensation
  - HW feedback filtering
  - 33 μs < Ts < 66 μs

Unintentional Islanding PHIL: Test Setup



1. B. Lundstrom, B. Mather, M. Shirazi, and M. Coddington, "Methods and Implementation of Advanced Unintentional Islanding Testing using Power Hardware-in-the-Loop (PHIL)," in *IEEE PVSC*, 2013.
2. B. Lundstrom, M. Shirazi, M. Coddington, and B. Kroposki, "An Advanced Platform for Development and Evaluation of Grid Interconnection Systems using Hardware-in-the-Loop: Part III–Grid Interconnection System Evaluator," in *IEEE Green Technologies Conference*, Denver, CO, April 2013.