The Energy Systems Integration Facility

Electrical Testing Capabilities and PHIL Research Activities – November 2015

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ESIF Laboratories
ESIF Laboratories

1. Power Systems Integration
2. Smart Power
3. Energy Storage
4. Electrical Characterization
5. Energy Systems Integration
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Thermal Systems Laboratories
6. Thermal Storage Process and Components
7. Thermal Storage Materials
8. Optical Characterization
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**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
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**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
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

- PSIL Lateral A
- PSIL Lateral B
- PSIL Ladder Tie Switch
- Neighboring Ring Bus Switch for the UC
- UC Ring Bus Switch
- PSIL Ladder Rung
- PSIL Ladder A Switch
- PSIL Ladder B Switch
- PSIL Ring Bus Switch
- UC Lateral
- Ring-tie
REDB Routing—Conceptual

- SPL: Smart Home Loads
- PSIL: Large-Scale Inverters, PV Simulators, Microgrid Power Distribution
- ESL: Energy Storage
- ESIL: Fuel Cells, Electrolyzer
- MVOTA: Medium Voltage Distribution Equipment
- LVOTA: Diesel Gensets, Programmable Load Banks

NATIONAL RENEWABLE ENERGY LABORATORY
Lab Equipment
1.08 MVA Grid Simulator (2.16 MVA)

**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-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:**
  2-3 kHz
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 – Auction!

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

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**Basic Specifications**

- **Voltage:** 0–346 V_{l-n}/600 V_{l-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
Power Hardware-in-the-Loop (PHIL) Research at ESIF
NOTE: as per the SDW, the Smart Distribution DER involve the control of physical DER (4 of the following 5 devices identified)
Remote PHIL and Co-simulation Test Bed

Combines actual hardware testing using PHIL with co-simulation of larger electric power grid using off-the-shelf modeling tools. Very flexible architecture enables multi-site testing (e.g. NREL links to PNNL and CSIRO), and scenario flexibility.

**Very Flexible:**
- **Arbitrary Grid:** location, topology & equipment
  - Demo: IEEE 8500 and 123 with no hardware changes
- **Any scenario:** normal ops, faults, contingencies
  - Demo: Cloud transients, home thermal physics models
- **Actual hardware:** no proprietary models required
  - Demo: 2 advanced inverters at various points of common coupling
- **Multi-site:** hardware and/or simulation
  - Demo: PNNL (WA) link to NREL (CO)
  - CSIRO (Australia)
Multiple-PCC PHIL

System to be tested:

One possible PHIL test setup:
Multi-inverter, Multi-PCC Volt-VAr Test

Reactive power cycling between two inverters with high $Q(V)$ slope

Instability caused by slower volt-VAr response time

- Simulated impedance in loop with actual inverters – two different inverters from leading manufacturers
- Experimental validation with transient PHIL – no problems found in limited testing to date
PHIL Testing of DER Grid Support Functions

- Hardware testing of advanced inverter/DER features with grid voltage and frequency dynamics simulated using PHIL
- Can simulate multiple PCCs simultaneously

PHIL test emulating major grid frequency event, with commercial advanced inverter performing frequency ride-through:

**Diagram Description**:
- Grid dynamic model
  - Turbine
  - Governor
  - Power set point
- Inverter model
  - 1/ (2Hs+D)
  - Δf
- Thévenin voltage model
- Voltage commands to AC source
  - Va, Vb, Vc
- Measured currents
  - Ia, Ib, Ic
- Load profile
- PHIL real-time computer simulation
- Control AC voltage source
- Hardware-simulated grid
- Load
- PV array / DC source
- Inverter under test

**Graphs**:
- Frequency, Hz vs. time, seconds
- Power, p.u. vs. time, seconds
- p.u. vs. time, seconds
Distributed PV with Energy Storage

- Simulation of high penetration of rooftop PV with battery storage on
  - IEEE123 feeder in GridLAB-D
  - Historical residential commercial load profiles
  - Added control strategies to inverter model:
    - Local Volt-VAR, Inverter smoothing, Transformer smoothing, PV firming, PV curtailment

- PHIL testing at ~10kW scale
  - Replaced one inverter / PV / battery system in the simulation with hardware
Use of PHIL techniques to evaluate novel energy system devices and control systems connected to specific network configurations involves:

1. Validation of PHIL simulation configuration for a known condition (e.g., field data or hardware) to ensure reliability of technique with particular hardware
2. PHIL simulation with updated devices, models, or control systems to prove new developments before field implementation