Microgrid Controller Hardware-in-the-Loop Demonstration Platform

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Test Coverage & Fidelity of New Power Distribution + Control Projects?

- Example: NYU-Poly study
- Validated 3φ time-domain model of Flushing network
- Analyzed performance of smart grid concepts
  - Automatic reconfiguration and self-healing capabilities
  - Auto-loop operations; required switching speed
  - Overcurrent, equipment malfunctioning, switch failures
  - Effect of backfeeding

<table>
<thead>
<tr>
<th>Overall Power Demand</th>
<th>400 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feeder breakers</td>
<td>30</td>
</tr>
<tr>
<td>Feeder/Tie/Subnetwork switches</td>
<td>73</td>
</tr>
<tr>
<td>Auto-loops</td>
<td>2</td>
</tr>
<tr>
<td>Transformers</td>
<td>980</td>
</tr>
<tr>
<td>Network protectors</td>
<td>871</td>
</tr>
<tr>
<td>Primary feeder and secondary grid sections</td>
<td>6,796 + 17,458</td>
</tr>
<tr>
<td>Aggregated loads</td>
<td>7,780</td>
</tr>
</tbody>
</table>

Computational burden:
- Intel Core i7 CPU 975 Processor at 3.33 GHz with 24 GB RAM
- Simulations with EMTP-type software
- Integration step of 50 µs to solve a 650 ms scenario

Manual preprogrammed scenarios based on expected switching sequences
- Good test coverage or fidelity? –

16-hour wait per 650 ms scenario
– Good coverage possible? –

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How Do We Accelerate Microgrid Deployment?
Reduce Integration Time, Cost, & Risk

• High NRE for each project
  – One vendor’s microgrid controller quote: $1M starting price

• “Vaporware”
  – No standard list of functions or performance criteria
  – Difficult to validate marketing claims

• Risk of damage to expensive equipment
  – One utility-deployed microgrid: 1 year of controls testing, damaged a 750 kW transformer, required significant engineering staff support

• Interconnection behavior unknowable to utility engineers
  – Controls are implemented in proprietary software
  – Microgrids are a system of systems: Exhibit emergent behavior

• No standards verification
  – IEEE P2030.7 and P2030.8 standards are on the horizon
Microgrid Controller Hardware-in-the-Loop (HIL) Testbed

Types of Controller Testbeds

Legend:
- G: generator
- Inv: battery or solar inverter
- C: device controller
- μC: microgrid controller
- DMS: distribution management system controller
- Power grid
- High-bandwidth AC-AC converter
- Simulation or emulation boundary
- Hardware
- Virtual (simulated or emulated)

Image: Florida State Univ. CAPS
Power Simulation: Flight Simulator Analogy

Legend
- G: generator
- Inv: battery or solar inverter
- C: device controller
- μC: microgrid controller
- DMS: distribution management system controller
- Power grid
- High-bandwidth AC-AC converter
- Simulation or emulation boundary
- Hardware
- Virtual (simulated or emulated)

Matlab SimPowerSystems simulation (not real-time)
Actual device and microgrid controller with real-time simulation
Real-time simulation coupled with power electronics testbed
Low-power microgrid testbed
Actual microgrid

Simulation
Controller HIL
Power HIL
Power Testbed
Full System

Legend
- G: generator
- Inv: battery or solar inverter
- C: device controller
- μC: microgrid controller
- DMS: distribution management system controller
- Power grid
- High-bandwidth AC-AC converter
- Simulation or emulation boundary
- Hardware
- Virtual (simulated or emulated)

- Slow PC simulation, small screen, keyboard/mouse inputs
- Actual plane cockpit, advanced simulation, wide field-of-view
- Moving cockpit, field-of-view visualization
- Trainer aircraft
- Passenger-carrying aircraft

Matlab SimPowerSystems simulation (not real-time)
High-fidelity Real-time Simulation

- Microgrid controller HIL simulates in real-time at sub-cycle timescales
  - Useful for steady-state, dynamic, and transient analyses

- HIL simulation rate: 80 μS (12.5 kHz)
- One AC cycle: 16.7 ms (60 Hz)
- User display update rate: 66.7 ms (15 Hz)
- Load profile & irradiance data: 1 s (1 Hz)
- Power converter controller response: 0.5-1 ms (1-2 kHz)
- Power system fault transients: 0.3-1 ms (1-3 kHz)
- Genset protection functions: 0.1-0.2 s (50-100 Hz)
- Secondary control: 0.1-1 s (1-10 Hz)
- Genset protection functions: 0.1-0.2 s (50-100 Hz)

Time (seconds)

10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0}
Construction of Detailed Microgrid Test Feeder Model

1. One-line diagram
2. Netlist
3. MATLAB data connectivity diagram
4. Simulink model
Elements of the Microgrid Controller HIL Platform

Hardware-in-the-Loop Simulator

Simulated Microgrid Feeder

Load the feeder model into the HIL simulator “target”
Elements of the Microgrid Controller HIL Platform

Hardware-in-the-Loop Simulator

Simulated Microgrid Feeder and Devices

Create detailed models of the DER devices
Elements of the Microgrid Controller HIL Platform

Add load profiles & other test stimuli; assign load priorities

Test Stimuli

Hardware-in-the-Loop Simulator

Simulated Microgrid Feeder and Devices

Loads
Motors
Irradiance
Grid Status

Real Power
Reactive Power

Time (seconds)

Kw / kVAr
Elements of the Microgrid Controller HIL Platform

Simulated Device Controllers

- Relay Protection Functions
- Inverter Control
- Genset Primary & Secondary Control
- Bidirectional Power Converter Control

Hardware-in-the-Loop Simulator

- Simulated Microgrid Feeder and Devices
- Load B03 Priority
- Gen 4 MVA
- Bat 4 MVA
- M 250 hp 460 V

Test Stimuli

- Loads
- Motors
- Irradiance
- Grid Status

Implement DER control algorithms
Elements of the Microgrid Controller HIL Platform

...or add commercial controllers as hardware-in-the-loop

Test Stimuli
Integrate a microgrid controller.
Elements of the Microgrid Controller HIL Platform

Integrate additional microgrid controllers
- Vendor capability demonstration
- Performance comparison

Hardware-in-the-Loop Simulator

Physical Device Controllers
- SEL 787 Relay

Simulated Device Controllers

Acme Energy PV Inverter Controller

Woodward easYgen 3000 Genset Controller

Eaton Microgrid Controller

PV
3.5 MW

Gen
4 MVA

Load B01 Interruptible

Load B02 Critical

Bat
4 MVA

Bat

M
250 hp
460 V

R1
R2
R3
R4
R5
R6
R7
R8

Test Stimuli

Loads

Motors

Irradiance

Grid Status
Elements of the Microgrid Controller HIL Platform

Add data visualization, collection, and post-processing
- Real-time operation
- Performance analysis
Microgrid Controller HIL Platform

Physical Device Controllers

Schneider Microgrid Controller

Woodward easYgen 3000 Genset Controller

Simulated Device Controllers

Hardware-in-the-Loop Simulator

Load B03 Priority

R1

R2

R3

R7

R8

PV 3.5 MW

Gen 4 MVA

Bat 4 MVA

M 250 hp 460 V

Bat

Real-time Data Visualization

Data Collection & Post-processing

Test Stimuli

Loads

Motors

Irradiance

Grid Status
Vision for the Microgrid Controller HIL Platform

- **Development Platform**
  - Application of real-time sim. technology to power engineering
  - Cost-effective engineering and project development
  - Enables performance evaluation of commercial products
  - *Demonstrations at Mass. Microgrid Controls Symposium*

- **Deployment Platform**
  - Perform controller and systems integration
  - Pre-commission testing of advanced power system projects
  - Test edge conditions and exercise the actual device controllers
  - Technical risk reduction and confidence building for the utility
  - *Project enabler: South Boston microgrid*

- **Standards Test Platform**
  - Industry-standard test platform for new power systems
  - *Test against IEEE P2030.8 standard and utility requirements*

- **Electric Power Controls Consortium (EPCC) Shared Repository**
Demo-centric Tech. Evaluation
U.S. Marine Corps’ ExFOB Example

In-kind integration manhours and $

Anonymized test results, Maturity status of commercial equipment

Independent Laboratory

Vendors

Realistic testbed; 3rd party validation

Procurement specs

High-level visibility

ExFOB 2013 – Twentynine Palms

Government Program Offices

Procurement specs

Independent Laboratory

In-kind integration manhours and $

Anonymized test results, Maturity status of commercial equipment

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ExFOB 2013 – Twentynine Palms
Anonymized Results of Demonstration Runs

Load-not-Served (kWh) while Islanded*

Voltage Profile (sec exceeding ±5%)

* Vendor #2 islanded one minute earlier than Vendor #1, resulting in the higher demand during islanded operation.
Anonymized Results of Demonstration Runs (cont.)

### Energy Consumption

<table>
<thead>
<tr>
<th>Vendor</th>
<th>Fuel Used (gal.)</th>
<th>Energy Imported (kWh)</th>
<th>Energy Exported (kWh)</th>
<th>Fuel Used (gal.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vendor #1</td>
<td>5.7</td>
<td>317</td>
<td>14</td>
<td>5.0</td>
</tr>
<tr>
<td>Vendor #2</td>
<td>6.3</td>
<td>272</td>
<td>38</td>
<td>5.9*</td>
</tr>
<tr>
<td>Difference</td>
<td>+11%</td>
<td>-14%</td>
<td>+170%</td>
<td>+18%</td>
</tr>
</tbody>
</table>

*Vendor #2 islanded one minute earlier than Vendor #1, resulting in the higher demand during islanded operation.*
Outline

- Introduction to Controller Hardware-in-the-Loop
- Orientation to the HIL Platform Demonstration
- Way Ahead
Example Load (B011)

- Peak kW: 879
- Min kW: 319
- Peak kVAR: 832
- Min kVAR: 382
- Nominal Voltage: 460 V

1 work week compressed into 2 hours
Microgrid Controller
Hardware-in-the-Loop Platform

- Firewall and Network Switch
- Console
- Woodward easYGens
- Interface Box
- Monitoring I/O
  - Analog & Digital
- Opal-RT HIL Target
- MIT Lincoln Lab Windows Server
- Power Supply

Two integrated Woodward easYgen 3000 genset controllers
HIL Platform Block Diagram

Vendor-supplied equipment

Microgrid Controller – Unit Under Test

Connection to HIL Demonstration Platform

Modbus TCP

Firewall and Network Switch

Prime Mover Device Controller Woodward EasyGen 3500 #1

Prime Mover Device Controller Woodward EasyGen 3500 #2

Lantronix Intellibox 2100 TCP to RS485

Modbus TCP

Lantronix Intellibox 2100 TCP to RS485

Interface Box

Simulated 1 MVA Genset

Simulated 4 MVA Genset

Simulated Battery Storage & Power Converter

Simulated Battery Power Converter Controller

OPAL-RT HIL 5607

Simulated PV Inverter

Simulated PV & Inverter

Simulated Protection Controller

Simulated PV Inverter Controller

Simulated Relays, Breakers, and Telemetry

Simulated Grid and One Line Diagram of the Test Feeder (~18 Buses and 17 lines)
# Device Address List

<table>
<thead>
<tr>
<th>Device</th>
<th>IP Address</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 MVA Genset Controller</td>
<td>192.168.10.35</td>
<td>-</td>
</tr>
<tr>
<td>4 MVA Genset Controller</td>
<td>192.168.10.36</td>
<td>-</td>
</tr>
<tr>
<td>Storage Controller</td>
<td>192.168.10.40</td>
<td>-</td>
</tr>
<tr>
<td>PV Controller</td>
<td>-</td>
<td>No interface</td>
</tr>
<tr>
<td>Relay 1</td>
<td>10.10.45.101</td>
<td>Point of Common Coupling</td>
</tr>
<tr>
<td>Relay 2</td>
<td>10.10.45.102</td>
<td>Serves &amp; senses sub-panel B021</td>
</tr>
<tr>
<td>Relay 3</td>
<td>10.10.45.103</td>
<td>Serves &amp; senses sub-panel B012</td>
</tr>
<tr>
<td>Relay 4</td>
<td>10.10.45.104</td>
<td>Serves &amp; senses load B001 + genset1</td>
</tr>
<tr>
<td>Relay 5</td>
<td>10.10.45.105</td>
<td>Serves &amp; senses B022</td>
</tr>
<tr>
<td>Relay 6</td>
<td>10.10.45.106</td>
<td>Serves &amp; senses loads B009-B011</td>
</tr>
<tr>
<td>Relay 7</td>
<td>10.10.45.107</td>
<td>Serves &amp; senses genset 1</td>
</tr>
<tr>
<td>Relay 8</td>
<td>10.10.45.108</td>
<td>Serves &amp; senses genset 2</td>
</tr>
<tr>
<td>Relay 9</td>
<td>10.10.45.109</td>
<td>Serves &amp; senses load B009</td>
</tr>
<tr>
<td>Relay 10</td>
<td>10.10.45.110</td>
<td>Serves &amp; senses load B010</td>
</tr>
<tr>
<td>Relay 11</td>
<td>10.10.45.111</td>
<td>Serves &amp; senses load B004</td>
</tr>
<tr>
<td>Relay 12</td>
<td>10.10.45.112</td>
<td>-</td>
</tr>
<tr>
<td>Relay 13</td>
<td>10.10.45.113</td>
<td>Serves &amp; senses battery</td>
</tr>
<tr>
<td>Relay 14</td>
<td>10.10.45.114</td>
<td>Serves &amp; senses load B015 + battery</td>
</tr>
<tr>
<td>Relay 15</td>
<td>10.10.45.115</td>
<td>Serves &amp; senses load B013</td>
</tr>
<tr>
<td>Relay 16</td>
<td>10.10.45.116</td>
<td>Serves &amp; senses load B014</td>
</tr>
<tr>
<td>Relay 17</td>
<td>10.10.45.117</td>
<td>Serves &amp; sense PV</td>
</tr>
<tr>
<td>Motor Relays</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Simulated Battery and PV Systems

- Four quadrant power source with sub-cycle transient accuracy, modeled in real time
  - Boost rectifier average model
  - Three phase PLL
  - D and Q axis current PIDs respond to power commands
- PV MPP tracker
- Inverter physical limits monitored by fault controller

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real Power Command</td>
<td>kW</td>
<td>(-) discharge; (+) charge</td>
</tr>
<tr>
<td>Reactive Power Command</td>
<td>kVAR</td>
<td>(+) capacitive; (-) inductive</td>
</tr>
<tr>
<td>Modbus Enable</td>
<td>0/1</td>
<td>1 to indicate active Modbus connection.</td>
</tr>
<tr>
<td>Fault Status</td>
<td></td>
<td>Phase A Over Current</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Phase B Over Current</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Phase C Over Current</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DC Link Overvoltage</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PLL Loss of Sync</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vrms out of spec</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Battery Empty</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Battery Full</td>
</tr>
<tr>
<td>Battery SoC</td>
<td>%</td>
<td>Battery start at 50%</td>
</tr>
<tr>
<td>Enable</td>
<td>0/1</td>
<td>Cycle to clear any faults.</td>
</tr>
</tbody>
</table>

Register list for battery system device controller
# Simulated Genset Block

<table>
<thead>
<tr>
<th></th>
<th>1 MW Genset</th>
<th>4 MW Genset</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Manufacturer / Model</strong></td>
<td>CAT C32</td>
<td>CAT C175-20</td>
</tr>
<tr>
<td><strong>Rating (kVA)</strong></td>
<td>1,000</td>
<td>4,000</td>
</tr>
<tr>
<td><strong>Power Factor</strong></td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td><strong>Voltage (V)</strong></td>
<td>480</td>
<td>13,800</td>
</tr>
<tr>
<td><strong>Frequency (Hz)</strong></td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td><strong>Speed (RPM)</strong></td>
<td>1800</td>
<td>1800</td>
</tr>
<tr>
<td><strong>Minimum Output Power</strong></td>
<td>25kW</td>
<td>100kW</td>
</tr>
<tr>
<td><strong>Startup Time</strong></td>
<td>&lt;10 sec</td>
<td>&lt;15 sec</td>
</tr>
</tbody>
</table>

**Genset ratings and characteristics**

**Synchronous Machine, Governor, and AVR Models**
Device Controller Integration: Woodward easYGen 3000

Legend
- M Motor
- G Generator
- GCB Generator Circuit Breaker
- MCB Mains Circuit Breaker
- Signal voltage transformer
- Voltage-controlled current source

Genset Simulation in HIL

Interface Box
Simulated Relay:
SEL-787 Transformer Protection Relay

Protection Function

<table>
<thead>
<tr>
<th>ANSI 50</th>
<th>Inst. overcurrent</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANSI 51</td>
<td>Avg. overcurrent</td>
</tr>
<tr>
<td>ANSI 27</td>
<td>Undervoltage</td>
</tr>
<tr>
<td>ANSI 59</td>
<td>Overvoltage</td>
</tr>
<tr>
<td>ANSI 25</td>
<td>Synchronism-check</td>
</tr>
<tr>
<td>1547 Tables 1&amp;2</td>
<td>Abnormal V &amp; f</td>
</tr>
<tr>
<td>Gen. Synch</td>
<td>Generator synch</td>
</tr>
<tr>
<td>ANSI 52</td>
<td>AC Circuit Breaker</td>
</tr>
</tbody>
</table>
## Demonstration against ORNL/EPRI Microgrid Functional Use Cases

<table>
<thead>
<tr>
<th>Functional Use Case</th>
<th>Description</th>
<th>Demonstration</th>
</tr>
</thead>
<tbody>
<tr>
<td>F-1 Frequency Control</td>
<td>Selection of grid-forming, -feeding, and -supporting energy sources to maintain stability; sub-second control to maintain stable frequency while islanded</td>
<td>The microgrid controller selects from among the two gensets and battery DERs.</td>
</tr>
<tr>
<td>F-2 Voltage Control</td>
<td>Regulate voltage at the microgrid point of common coupling</td>
<td>No demo</td>
</tr>
<tr>
<td>F-3 Intentional Islanding</td>
<td>Planned disconnect from area electric power system (AEPS)</td>
<td>Islanding will be initiated by the microgrid controller</td>
</tr>
<tr>
<td>F-4 Unintentional Islanding</td>
<td>Fast disconnect from AEPS upon large disturbance to provide continuous supply to loads</td>
<td>No demo due to battery and PV inverter controller PLL instability</td>
</tr>
<tr>
<td>F-5 Transition from Islanded to Grid-tied</td>
<td>Resynchronize and reconnect to AEPS</td>
<td>Initiated by microgrid controller once generators and grid synchronize</td>
</tr>
<tr>
<td>Functional Use Case</td>
<td>Description</td>
<td>Demonstration</td>
</tr>
<tr>
<td>-------------------------------------</td>
<td>------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>F-6(a) Energy Management: grid-tied</td>
<td>Coordinate generation, load, &amp; storage dispatch, to participate in utility operation and energy market activities</td>
<td>The microgrid controllers target a power export value for a defined period, and should also shave peak demand.</td>
</tr>
<tr>
<td>F-6(b) Energy Management: islanded</td>
<td>Coordinate generation, load, &amp; storage dispatch, to optimize islanded operation (fuel consumption, islanding duration)</td>
<td>Fuel consumption and service of critical and priority loads are measured during islanded operation.</td>
</tr>
<tr>
<td>F-7 Microgrid Protection</td>
<td>Configure protection devices for different operating conditions</td>
<td>DER and relay protection are implemented, but are not configurable.</td>
</tr>
<tr>
<td>F-8 Ancillary Services: regulation</td>
<td>Provide frequency regulation, generation reserves, reactive power support, and demand response to AEPS</td>
<td>Demand response to hit a target power export value; Reactive power support to maintain unity power factor at PCC</td>
</tr>
<tr>
<td>F-9 Microgrid Blackstart</td>
<td>Restore islanded operation after a complete shutdown</td>
<td>Likely limited by present genset control capabilities</td>
</tr>
<tr>
<td>F-10 User Interface, Data Collection</td>
<td>Organize, archive, and visualize real-time and non-real-time data</td>
<td>Data collection and visualization performed by MIT-LL, not μC</td>
</tr>
</tbody>
</table>
15-minute Demonstration Sequence

Load Profile

- Total Real Power (kW)
- Total Reactive Power (kVAR)
- Interruptible Loads (kW)
- Power Export (kW)
- Power Factor (p.u.)

PV Array Output

Power (kW)

Power Factor

Grid Status

0=Off
1=On

Time (minutes)
Heads-up Display (screen 1)
Heads-up Display (screen 2)
Outline

• Introduction to Controller Hardware-in-the-Loop
• Orientation to Today’s Demonstration
• Way Ahead
Vision for Eventual HIL Capabilities

Host Utility’s Distribution Management System (DMS)

Actual Controllers for DER Deployed in the Microgrid

Multiple Real-time Digital Sim. Platforms

Validated Controller Models

Vendor-validated Device Models

RTDS

Opal-RT

Typhoon HIL

National Instruments

Multiple Standard Test Feeders

Test Stimuli per IEEE P2030.8 and Host Utilities

Industry-standard Test Platform

Microgrid Controller Under Test
Vision for Power Systems HIL & Shared Repository

- **1 - Development Platform**
  - Application of real-time sim. technology to power engineering
  - Cost-effective engineering and project development
  - Enables performance evaluation of commercial products
  - *Demonstrations at Mass. Microgrid Controls Symposium*

- **2 - Deployment Platform**
  - Perform controller and systems integration
  - Pre-commission testing of advanced power system projects
  - Test edge conditions and exercise the actual device controllers
  - Technical risk reduction and confidence building for the utility
  - *Project enabler: South Boston microgrid*

- **3 - Standards Test Platform**
  - Industry-standard test platform for new power systems
  - *Test against IEEE P2030.8 standard and utility requirements*

- **4 - Electric Power Controls Consortium (EPCC) Shared Repository**
# Elements of the EPCC Shared Repository

## Microgrid Test Repository
- **Microgrid Test Feeders**
  - Netlists

## Controller-in-the-Loop Repository
- **Interface Circuitry for Device Controllers**
  - Circuit schematics, bills of materiel
- **Interface Code for Device Controllers**
- **Communications Interface Translation Code**
  - Modbus TCP
  - IEC 61850
  - GOOSE
  - MMS

## HIL Platform Repository
- **HIL Target Platform Conversion Scripts**
  - Targets: OPAL-RT, Typhoon HIL, RTDS, NI, and others
- **Validated Device Models**
  - Motor-generators, power converters / inverters, and relays
- **Validated Device Controller Software**
  - Genset controllers, power converter controllers, relay protection functions
Potential Applications

• Integration of control systems
  – Microgrid controller testing; integrate with DER & IED sub-systems
  – Distribution management system testing and integration
  – Transmission operator dispatch integration and ancillary services testing
  – Volt VAR control systems testing

• Protection system testing, including
  – Evaluation of automation sequences
  – Development of automated self-healing systems
  – Feeder sectionalization studies

• Prime mover DG controller testing
  – Evaluating stability issues due to DG dynamics

• Anti-islanding and blackstart testing
Potential Applications (cont.)

• DER controls behavior testing
  – DG penetration studies
  – Anti-islanding / intentional islanding controls studies

• Detailed power systems analysis
  – Evaluating electromagnetic transients due to switching or faults
  – Assessment of symmetrical and non-symmetrical events
  – Evaluation of transient overvoltage and resonance

• Micro-PMU (phasor measurement units) studies

• Implementation and evaluation of smart grid concepts

• Communications testing and integration

• Other distribution-level studies
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Mark Buckner, ORNL  
Fran Cummings, Peregrine Group  
Babak Enayati, National Grid  
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