Power Systems Hardware-in-the-Loop Laboratory Testbed and Open Platform (HILLTOP)

Erik Limpaecher

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MIT Lincoln Laboratory

U.S. DEPARTMENT OF ENERGY
Electricity Delivery & Energy Reliability

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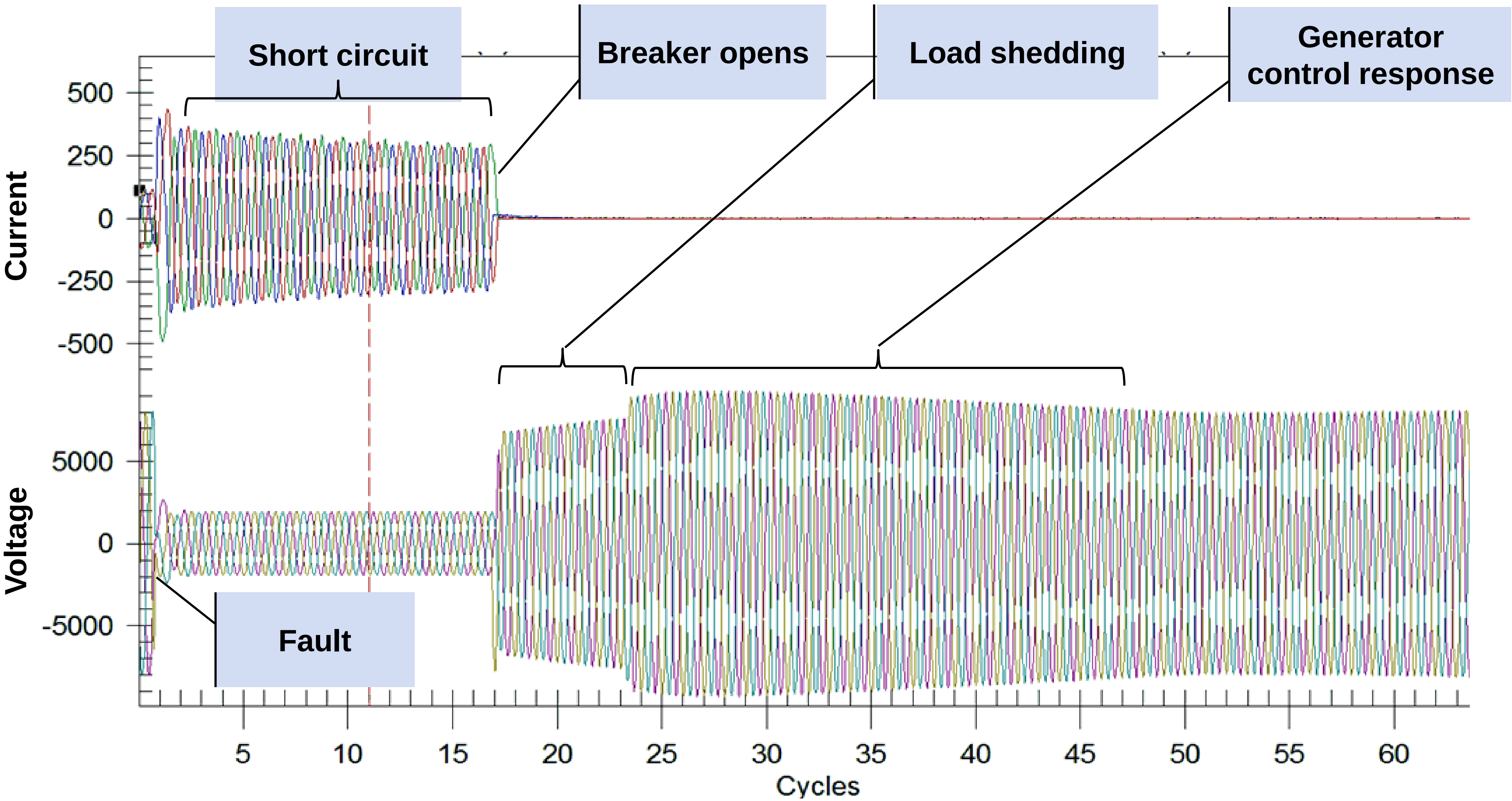
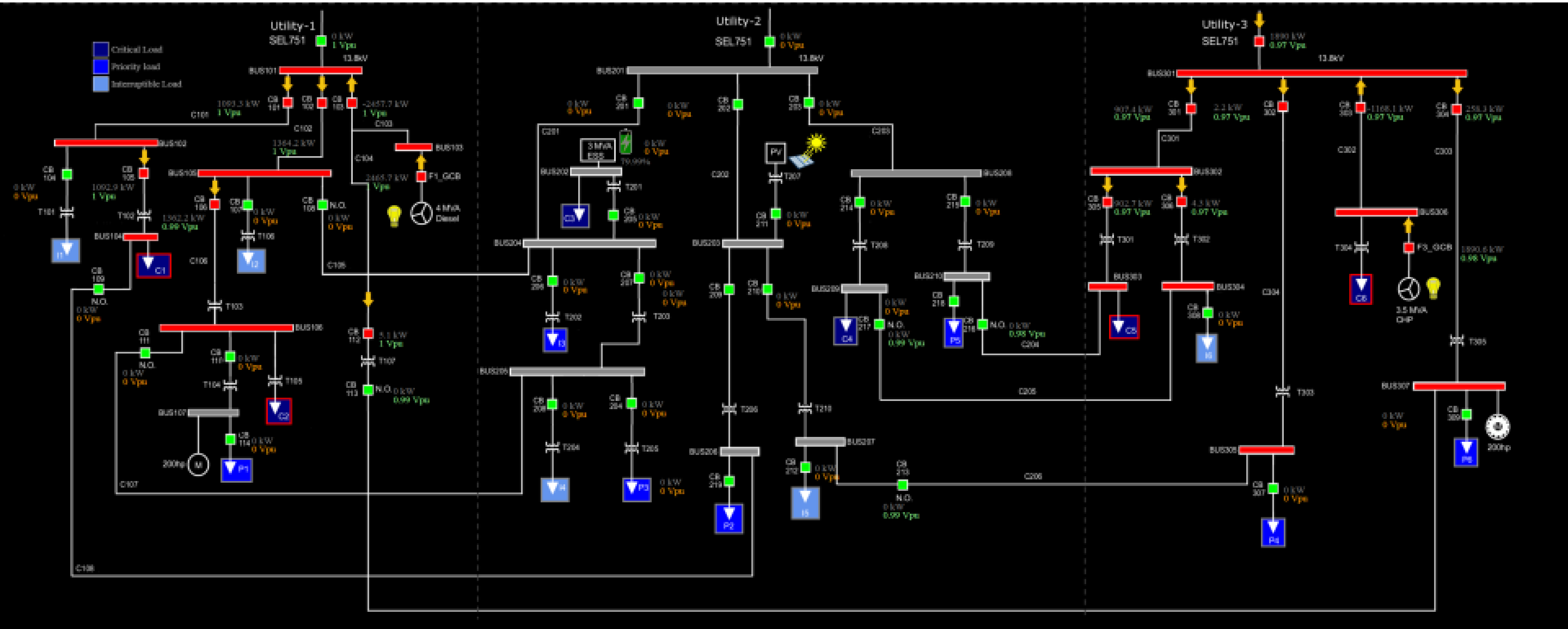
深水泵控制屏
低压厂变控制屏

Integration Test Example



Data capture: Scott Manson, SEL

Microgrid Test Feeders



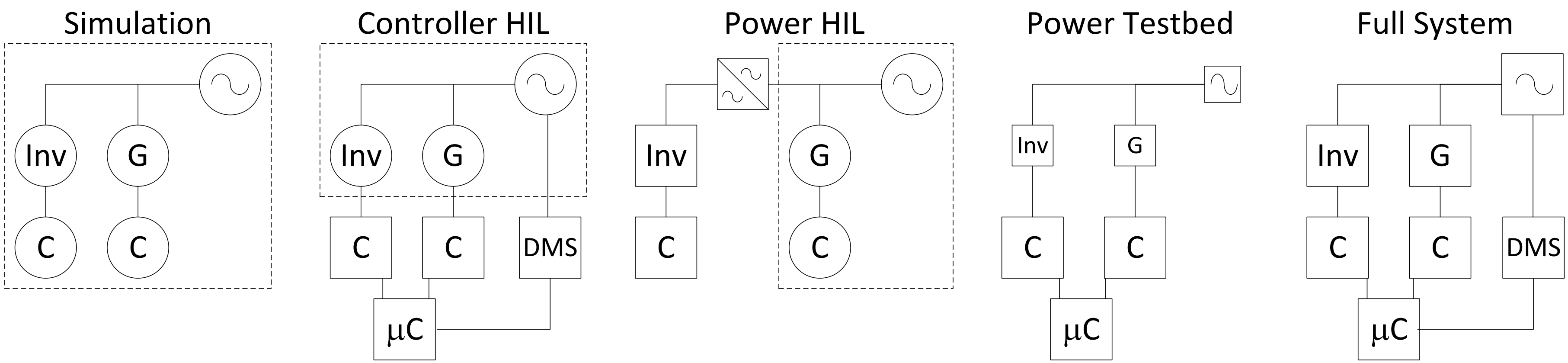
Emergent behavior **is behavior of a system that does not depend on its individual parts, but on their relationships to one another. Thus emergent behavior cannot be predicted by examination of a system's individual parts. It can only be predicted, managed, or controlled by understanding the parts and their relationships.**

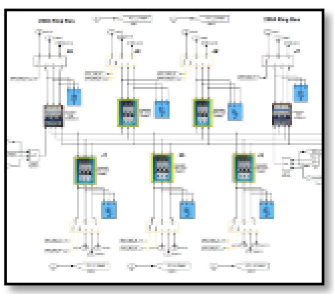
How To Accelerate Advanced Distribution System Deployment?

- 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

Need to reduce integration time, cost, & risk

Types of Power System Testbeds

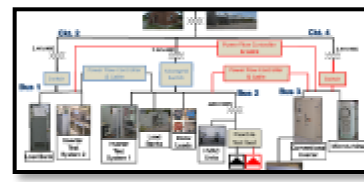




Matlab SimPowerSystems simulation (not real-time)

MIT-LL HILLTOP System

Florida State CAPS facility



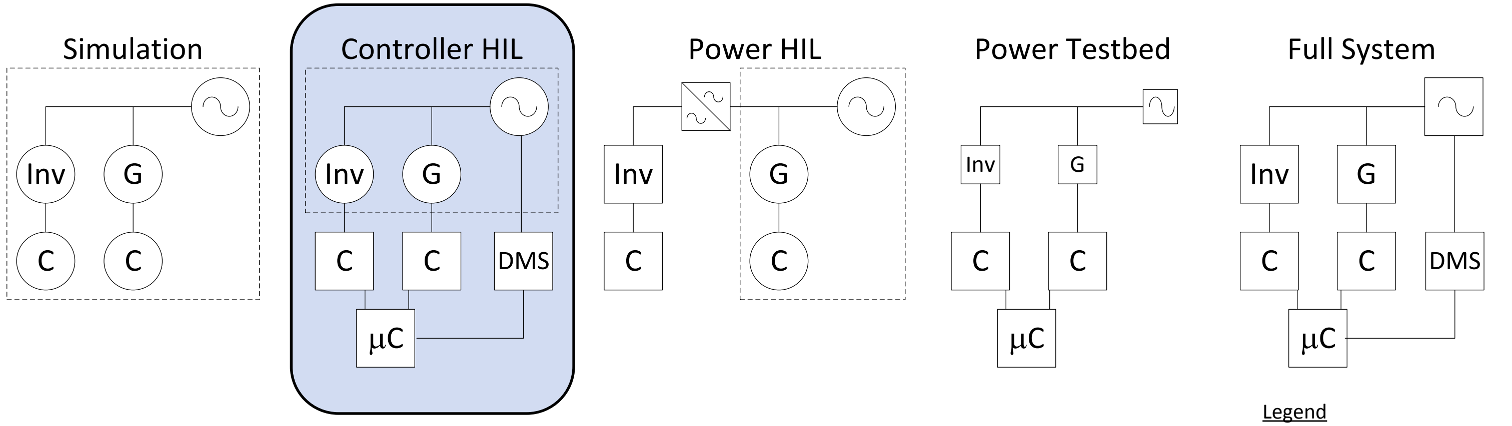
ORNL DECC Microgrid Lab

Princeton University cogeneration plant and microgrid

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)

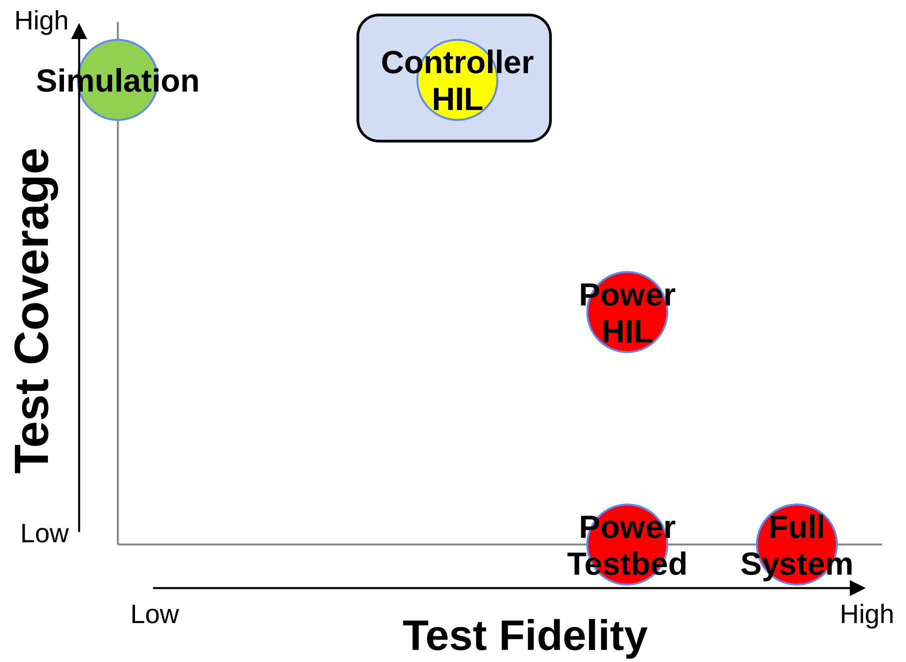
Power Distribution Integration Platforms and Testbeds



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

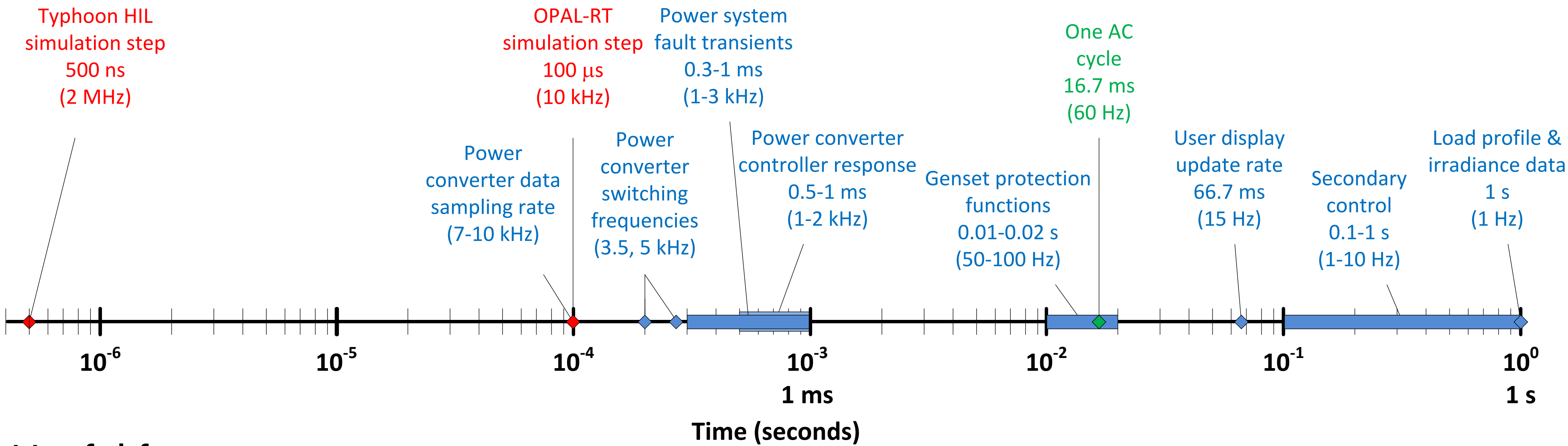
hardware
virtual (simulated or emulated)

low cost
moderate cost
high cost



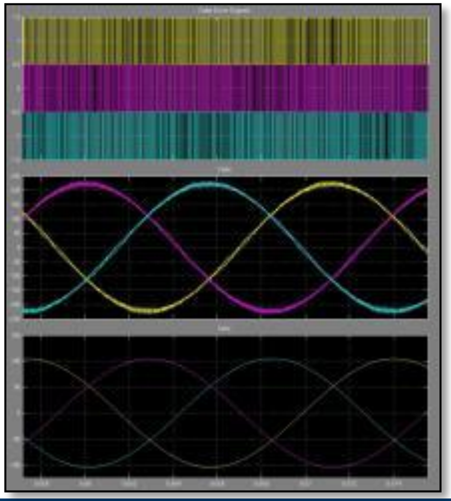
Full Test Coverage

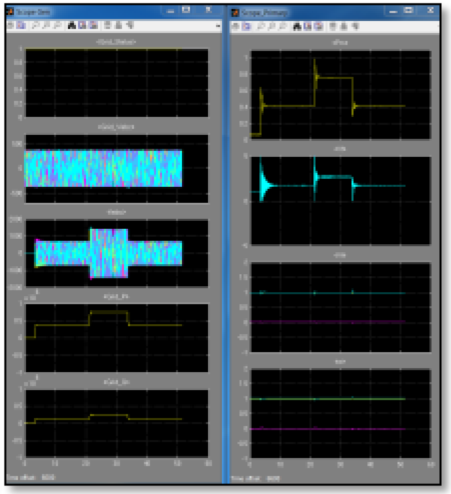
- **Microgrid controller HIL simulates in real-time at sub-cycle timescales**

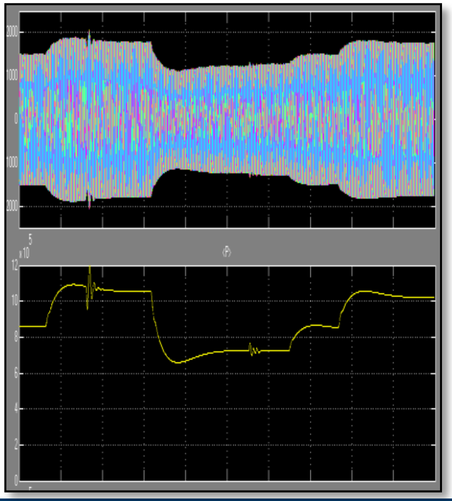


Useful for:

- Steady-state
- Dynamic analysis
- Transient analyses







RD&D Cycle for Modern Distribution System Projects

– 1 –
Engagement Platform

– 2 –
Development Platform

– 3 –
Deployment Platform

– 4 –
Standards Test Platform

- **Research & Development**
- **Standards Compliance Testing**
- **Partner / Vendor Selection**
- **Proposal, Business Development**
- **Feasibility Study, Conceptual Design**
- **Preliminary & Final Design, Development**
- **Factory Acceptance Testing**
- **Commissioning / Field Testing**
- **Root Cause Investigation**

Vision for Power Systems HILLTOP

– 1 –
Engagement Platform

- Provide a tangible proof-of-concept to new project stakeholders
- Accelerate the sales cycle by showing an operating system
- Use for rapid iteration of feasibility studies
- *Demonstrations at Microgrid and DER Controller Symposium*

– 2 –
Development Platform

- Cost-effective systems integration and testing
- Decrease risk on “brownfield” sites operating legacy equipment
- Enable performance evaluation of commercial products

– 3 –
Deployment Platform

- Pre-commission testing of advanced power system projects
- Test edge conditions and exercise the actual device controllers
- Technical risk reduction for electric power utilities

– 4 –
Standards Test Platform

- Industry-standard test platform for new power systems
- Certify to IEEE P2030.8, P1547, and utility interconnection rules

– 5 –
Electric Power HIL Controls Collaborative (EPHCC) Shared Repository

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Improvements Since Previous Symposium

Category	Improvement Since 1st Symposium
Real-time test platforms & microgrid controllers	2x
Ported simulation environments	5x
Physical device controllers	4x
Test feeders	3x
Test cases	4x

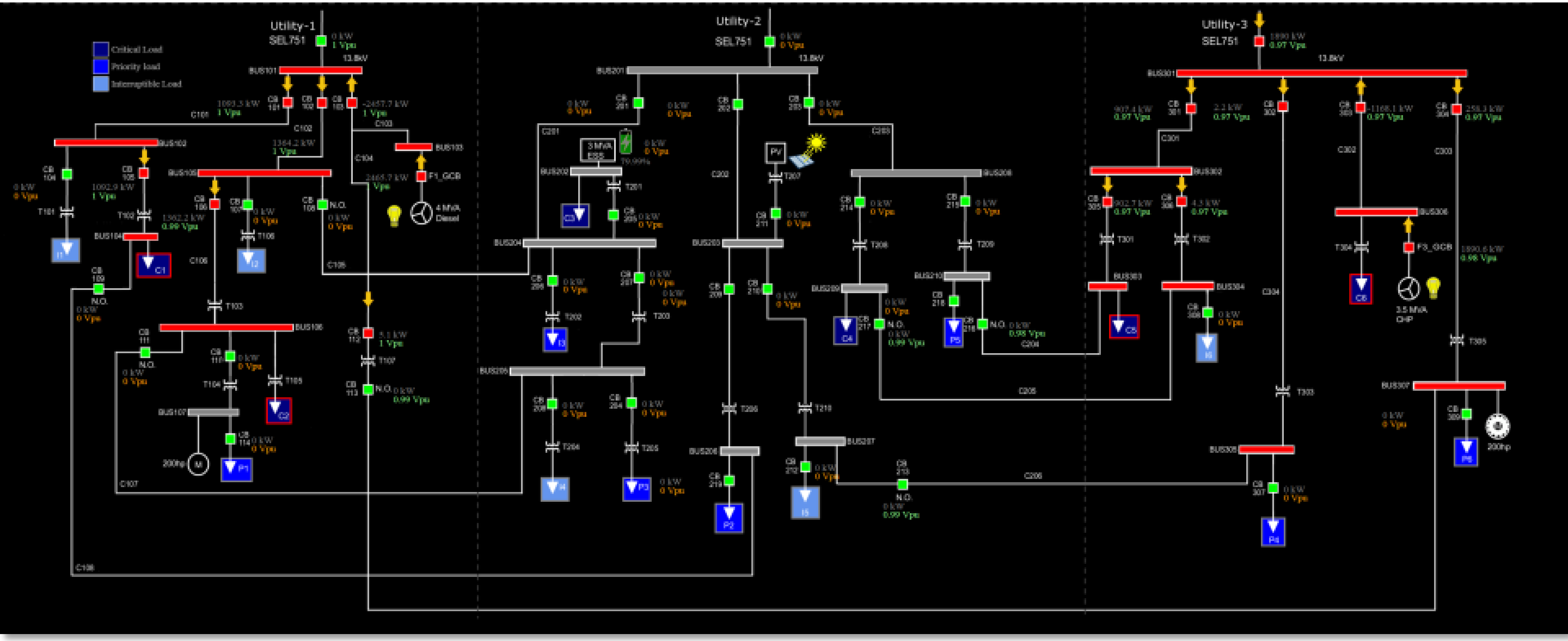
Total	1000x

In other words	+60 dB

Outline

- Motivation
- Testbed Buildup
- Integration Process
- Demonstration Orientation

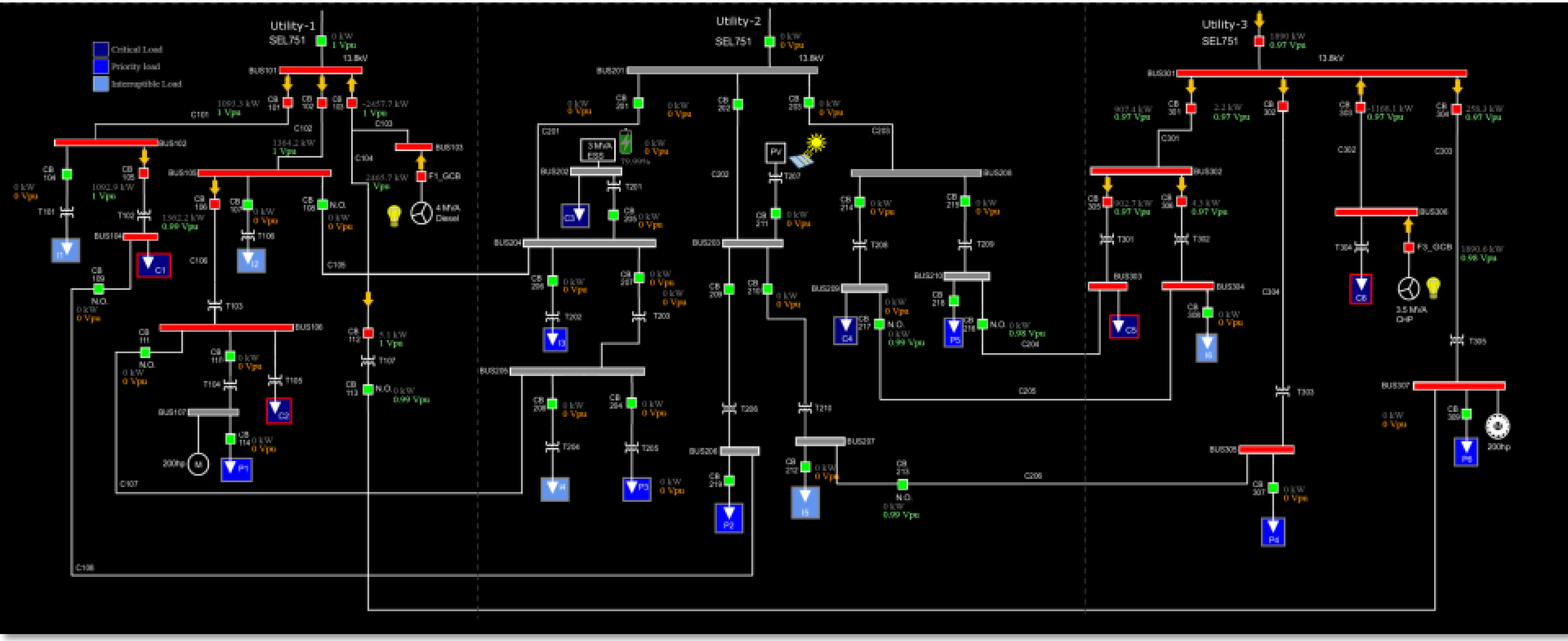
Test Feeders



- **Representative of a community microgrid**
- **Supports thorough controller evaluation**
  - **Multiple reconfigurations possible**
  - **Multiple interconnections to the utility**
  - **Insufficient generation when islanded**

Peak demand	14 MW
Available generation	10 MW
Software components	100+
DERs	5
Relays	~50

Test System Segmentation for Real-time Simulation

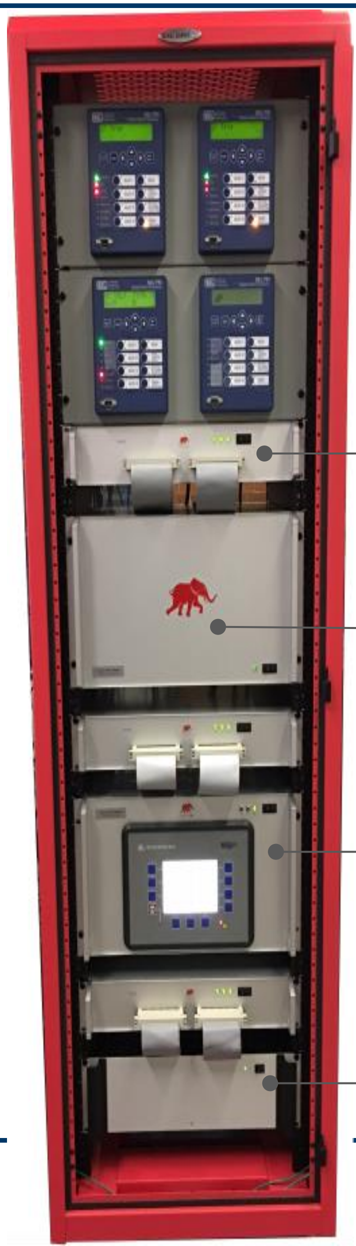


- 3 cores: One per feeder + machine models
- 3 cores: Relay models for each feeder + UDP communications
- 1 core: Storage & PV power electronics models
- 1 core: Utility substation + high-speed data collection

HILLTOP Rack #1
Using OPAL-RT Simulator

- **Real-time target with Xeon Intel® Processor**
  - **Using 8 of 12 cores**
  - **2.7 to 3.2 GHz**
- **FPGA-based I/O management with**
  - **Xilinx Spartan-3**

HILLTOP Testbed #2
Using Typhoon HIL Simulator



HIL603 real-time simulator

SEL HILConnect

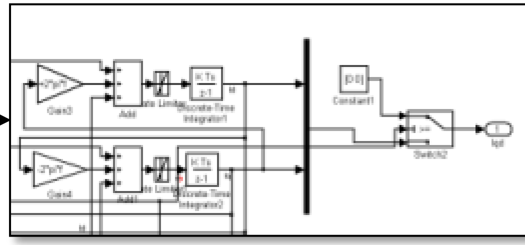
Woodward HILConnect

EPC HILConnect (PV and ESS)

- **4 HIL603 units**
  - High speed serial link interconnection 8 lane - 5GHz
- **2µs & 4µs time steps**
  - Multirate electrical simulation
- **23 cores used**
- **20ns digital sampling**
- **42 simulated relays with Modbus comms**
  - 1.2 ms execution rate

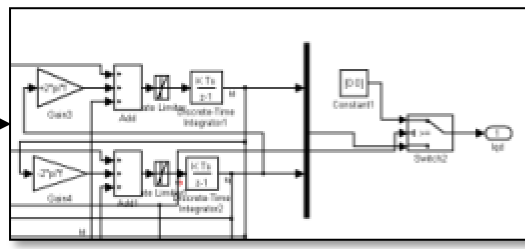
Add Machine and Power Electronics Models

Solar Inverter



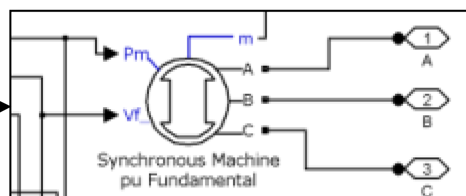
Power Electronics Model

Bidirectional Power Converter

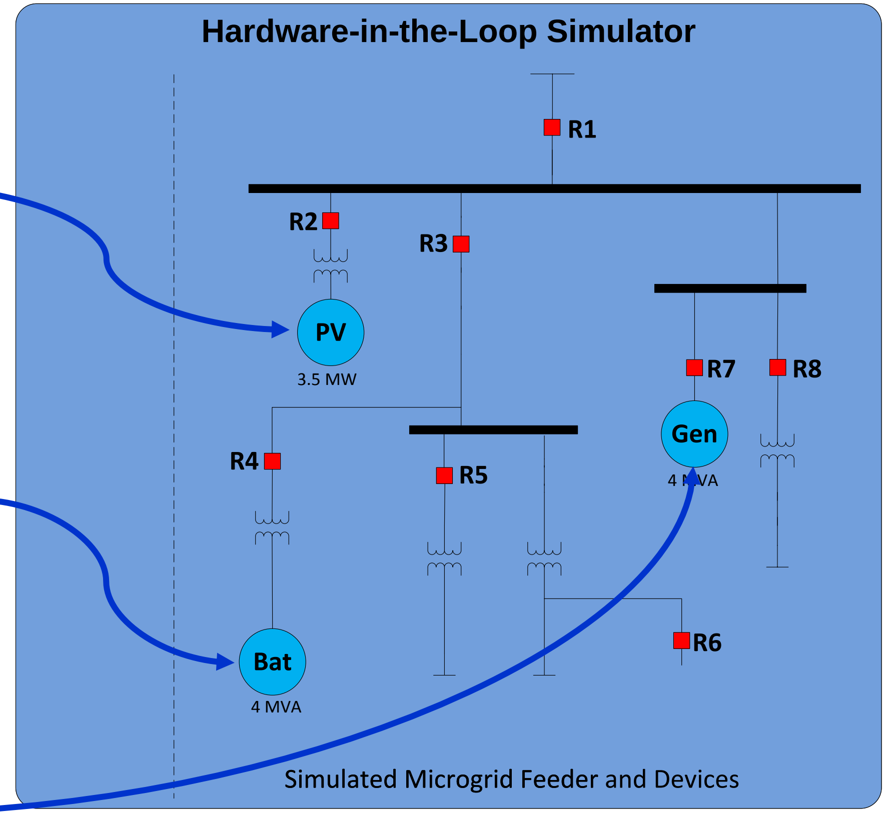


Power Electronics Model

Genset

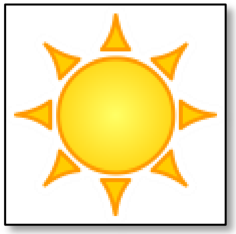


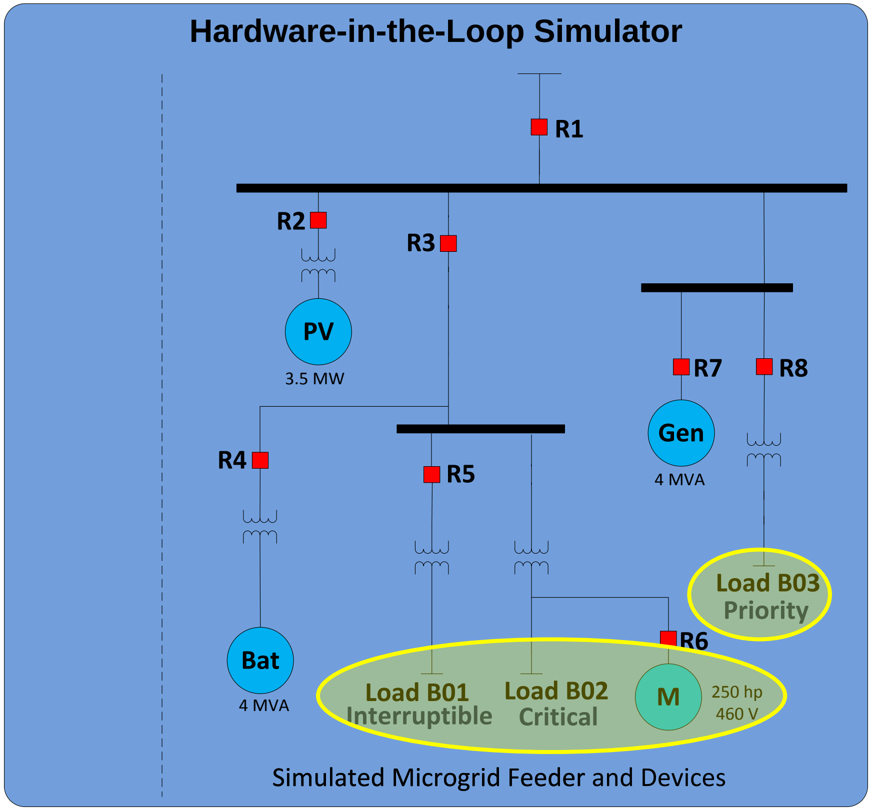
Machine Model

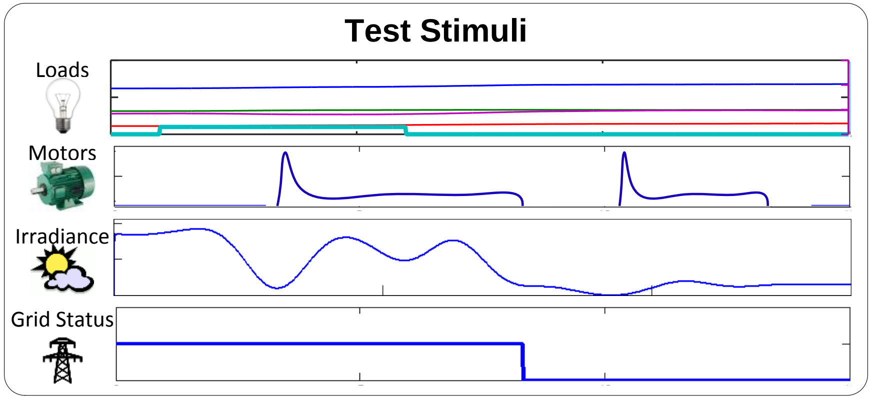


Create detailed models of the DER devices

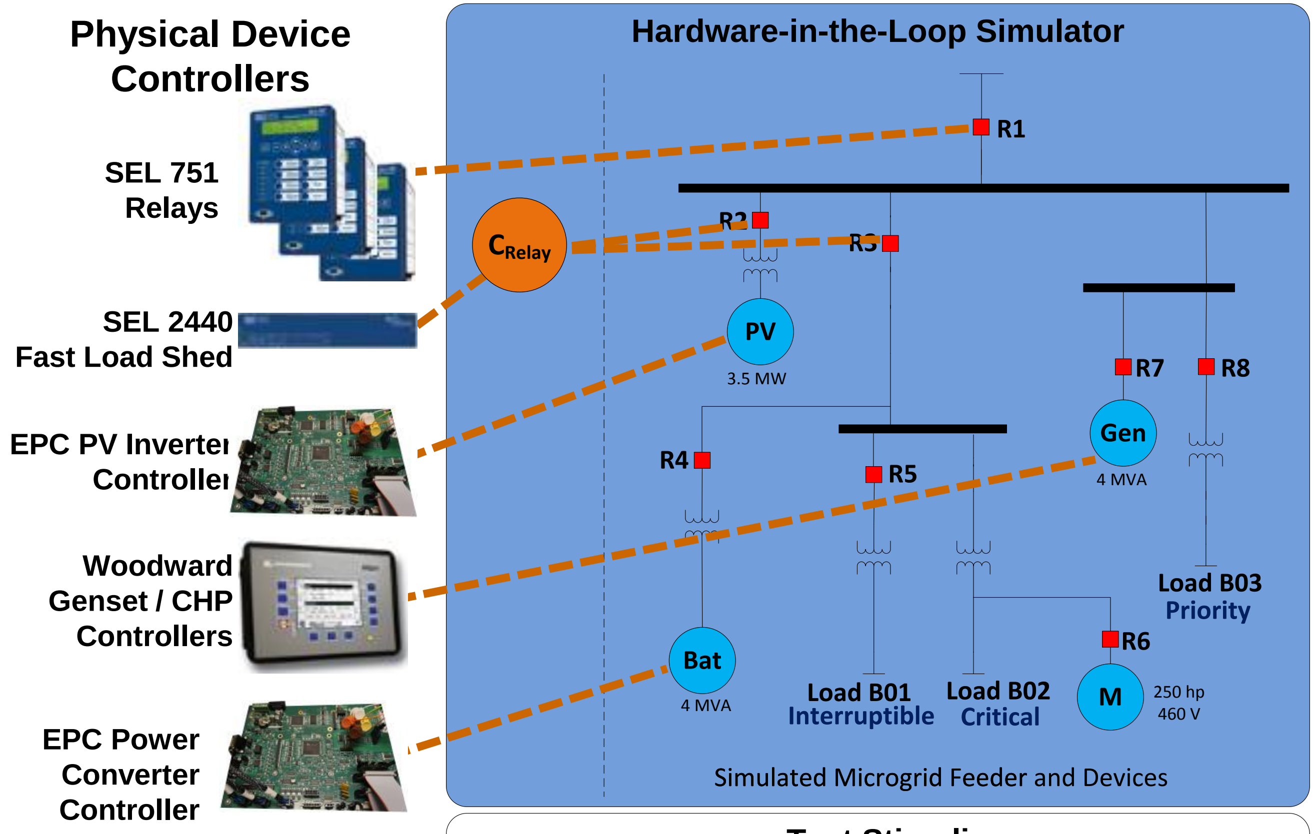
Assign Load Priorities, Add Test Stimuli

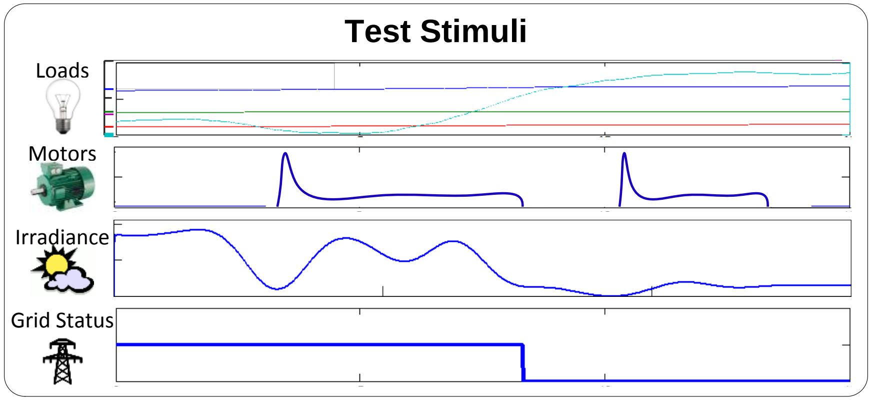




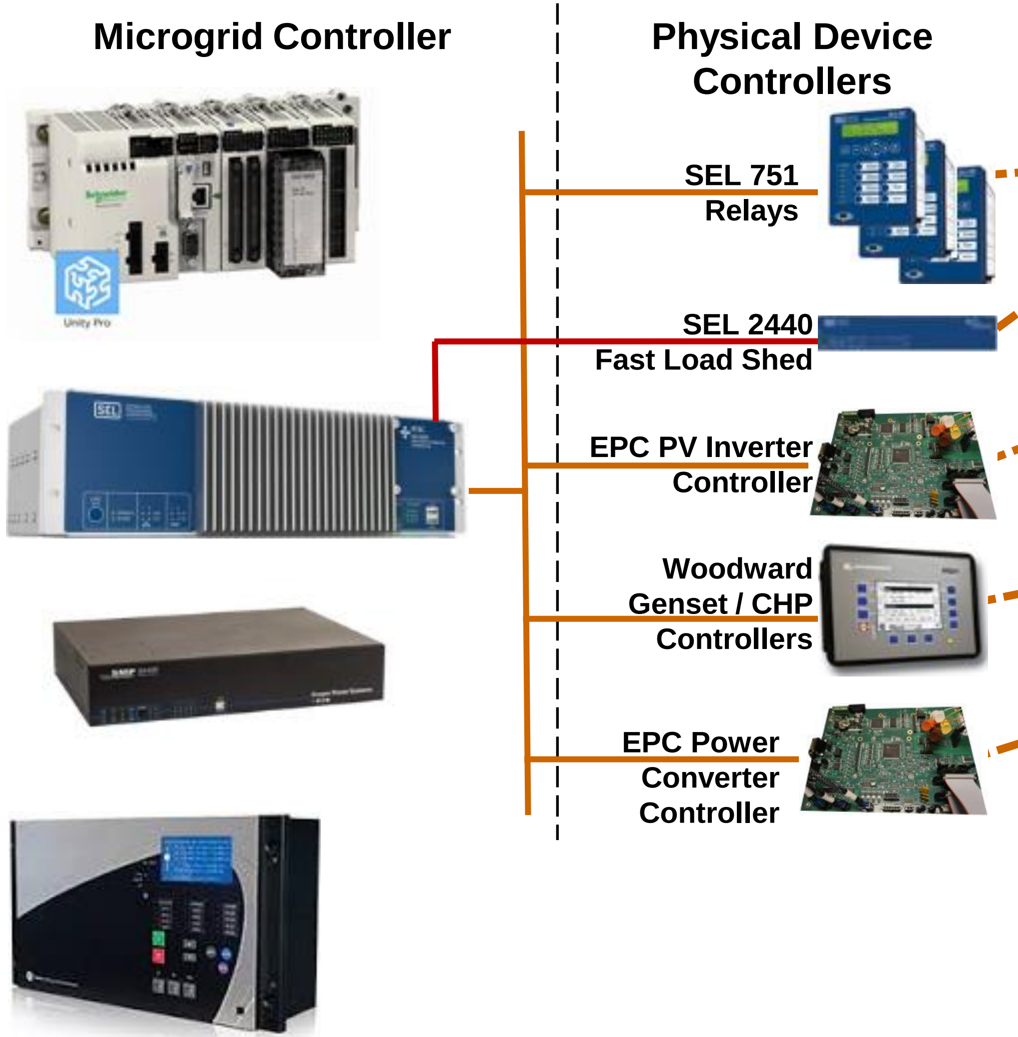


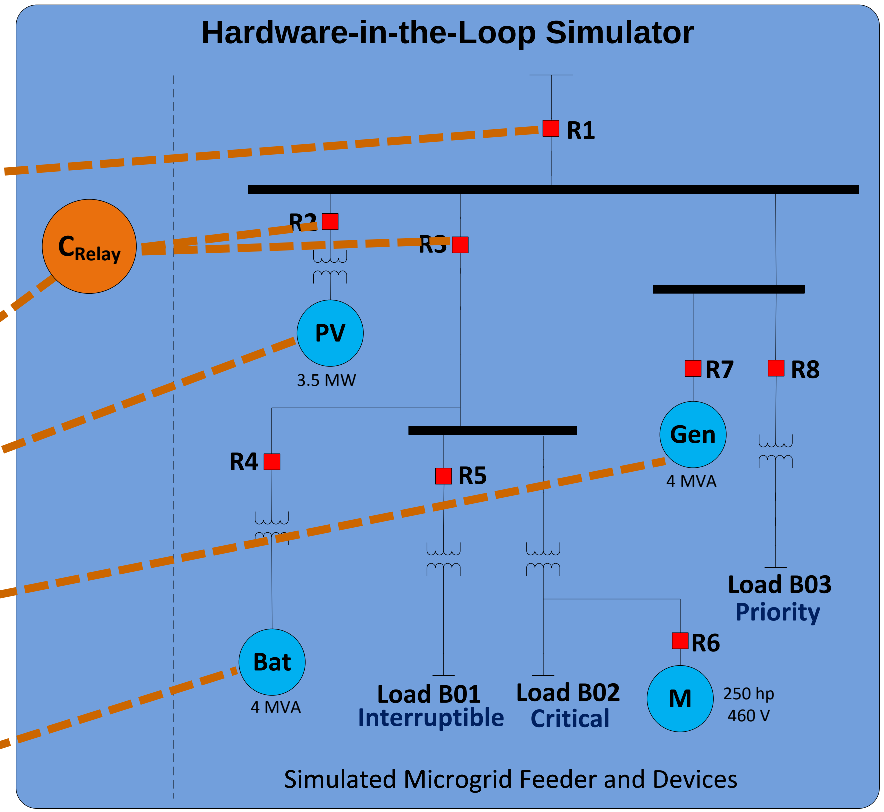
Add Commercial Controllers as Hardware-in-the-Loop

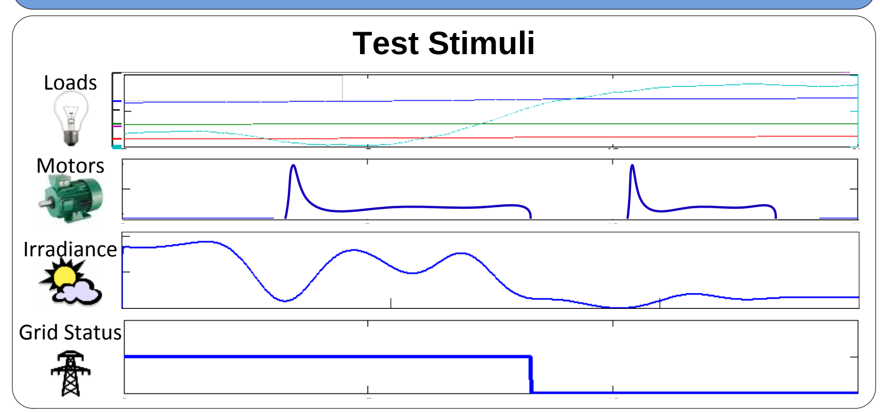




Integrate Microgrid Controllers







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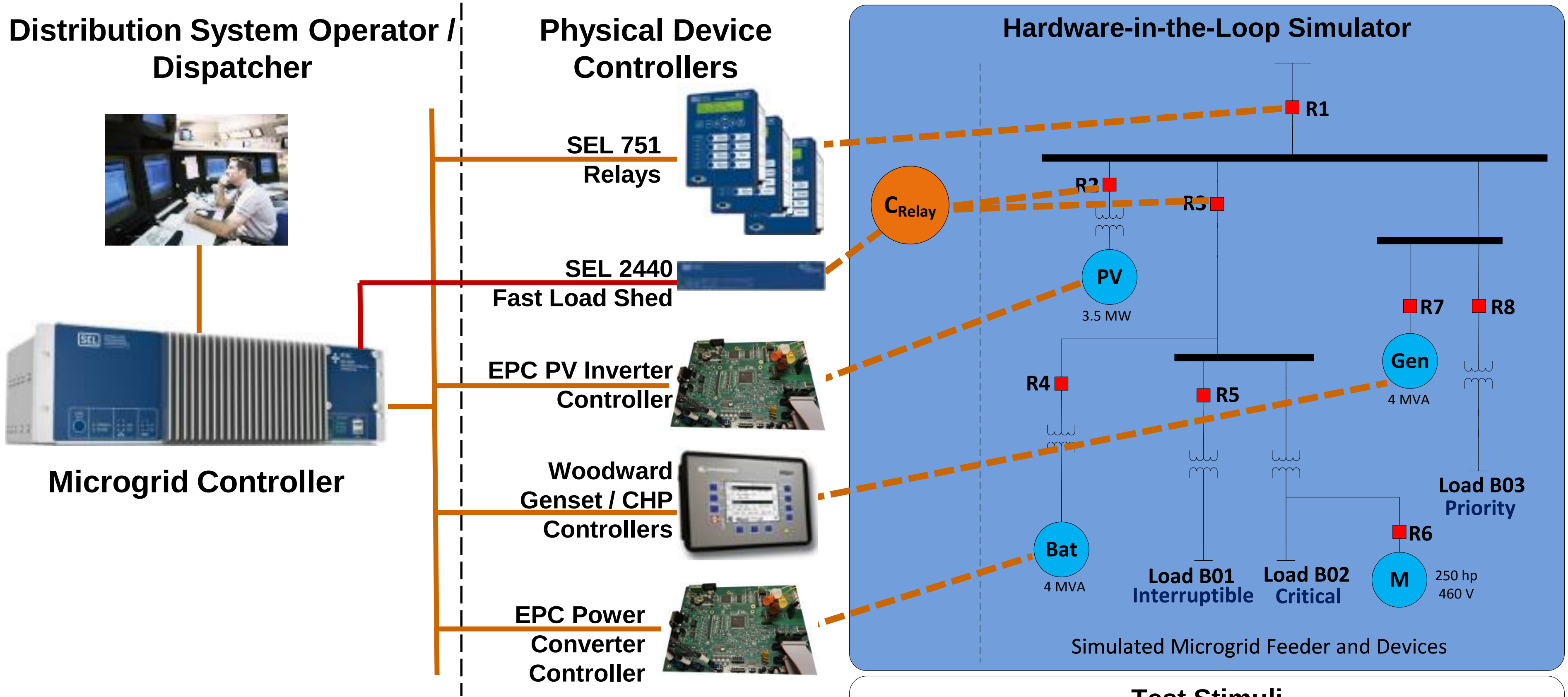
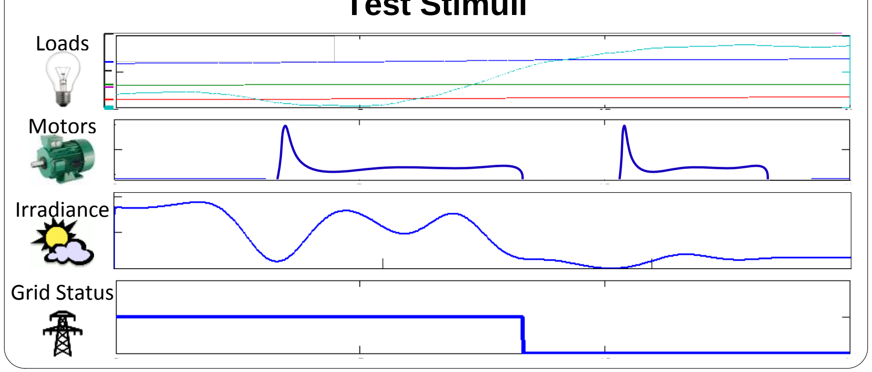


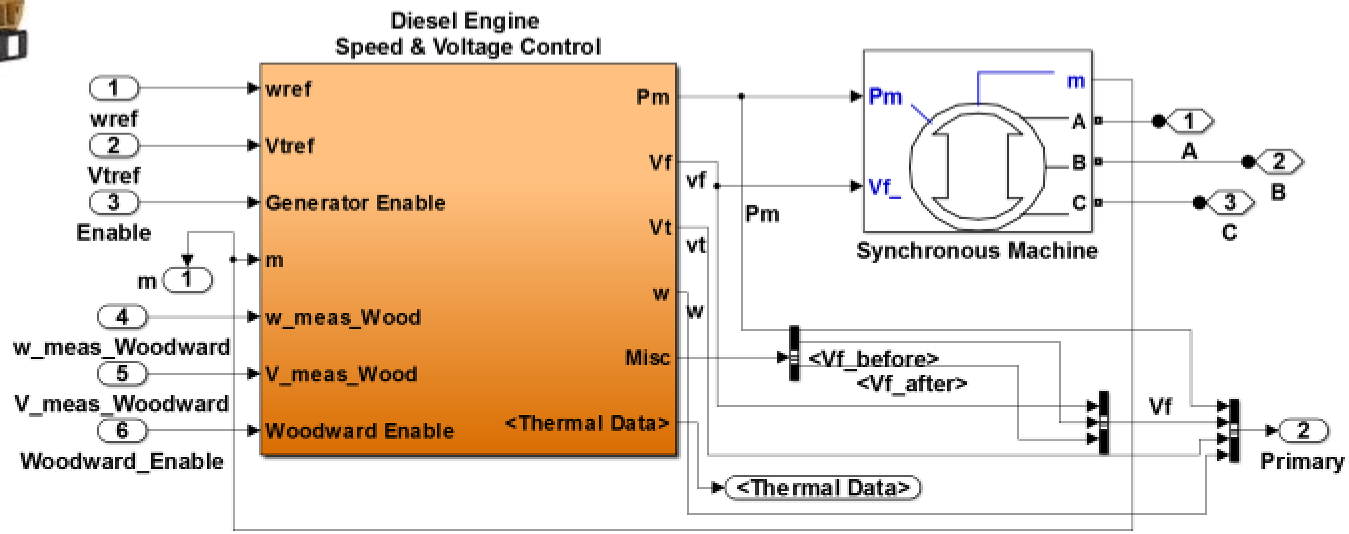


Command	Range of Values
DSO Export/Import	+10 MW (import) to –5 MW (export); 0 = any import/export permitted
DSO PF	-0.75 - +0.75
Volt/VAR support	-5 MVAr - +5 MVAr
Demand Response	0 – 5 MW

Simulated Diesel Genset Block

	1 MW Genset	4 MW Genset
Manufacturer / Model	CAT C32	CAT C175-20
Rating (kVA)	1,000	4,000
Power Factor	TBD	TBD
Voltage (V)	480	13,800
Frequency (Hz)	60	60
Speed (RPM)	1800	1800
Minimum Output Power	25kW	100kW
Startup Time	<10 sec	<15 sec

Genset ratings and characteristics

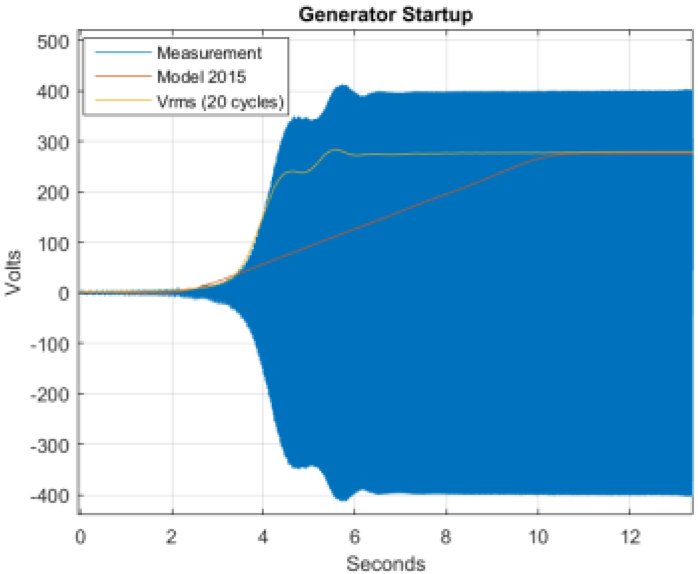


Synchronous Machine, Governor, and AVR Models

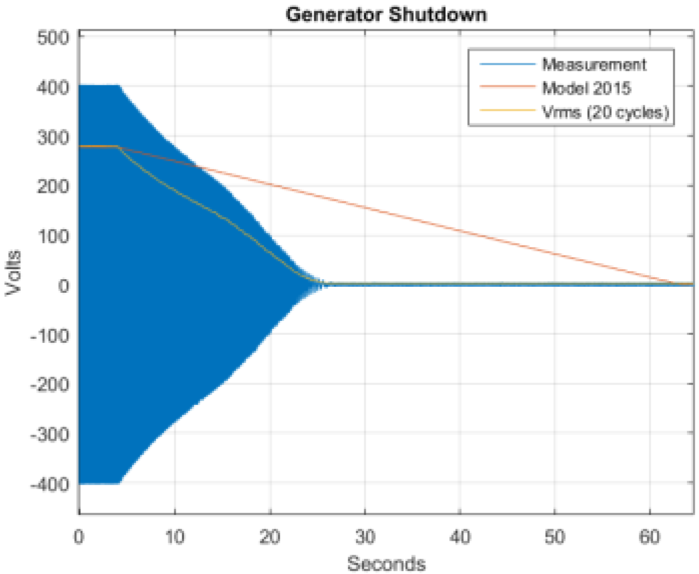
HILLTOP Integration: Model Validation

- 1 MVA
- 480Vac
- 3 phase

- **Generator statistics**
- **High speed instrumentation**
  - 8kHz sampling
  - Voltage and current
  - Bias signals



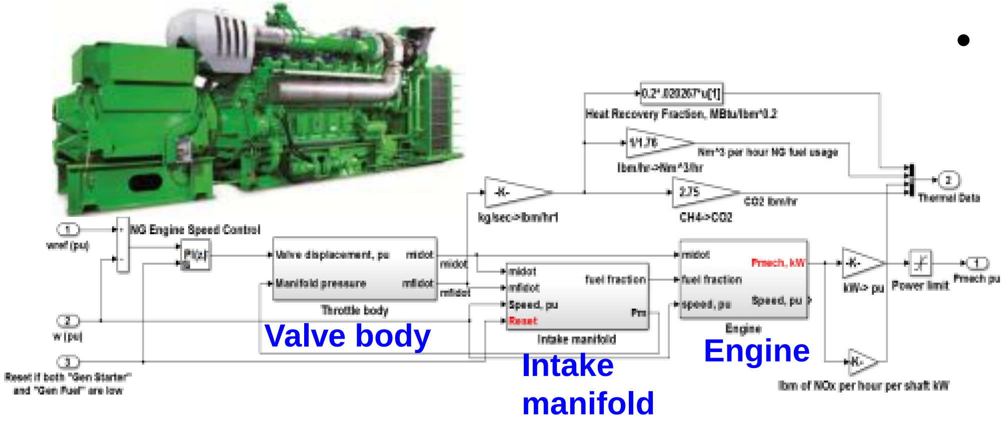
Start-up of Generator and Model



Shutdown of Generator and Model

Natural Gas Combined Heat and Power

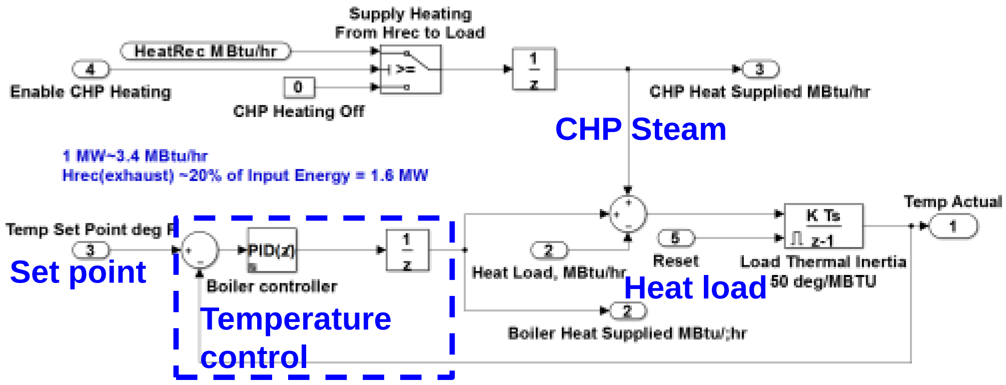
Electrical



GE/Jenbacher J620 NG Engine (1800 RPM)
3.5 MW Natural Gas Engine Model (Physics Based)

- Physics-based, scalable 3.5 MW NG genset with gas valve, intake manifold, combustion
  - Fuel usage
  - GHG emissions
  - Heat recovery
  - Woodward easYgen 3500 compatible

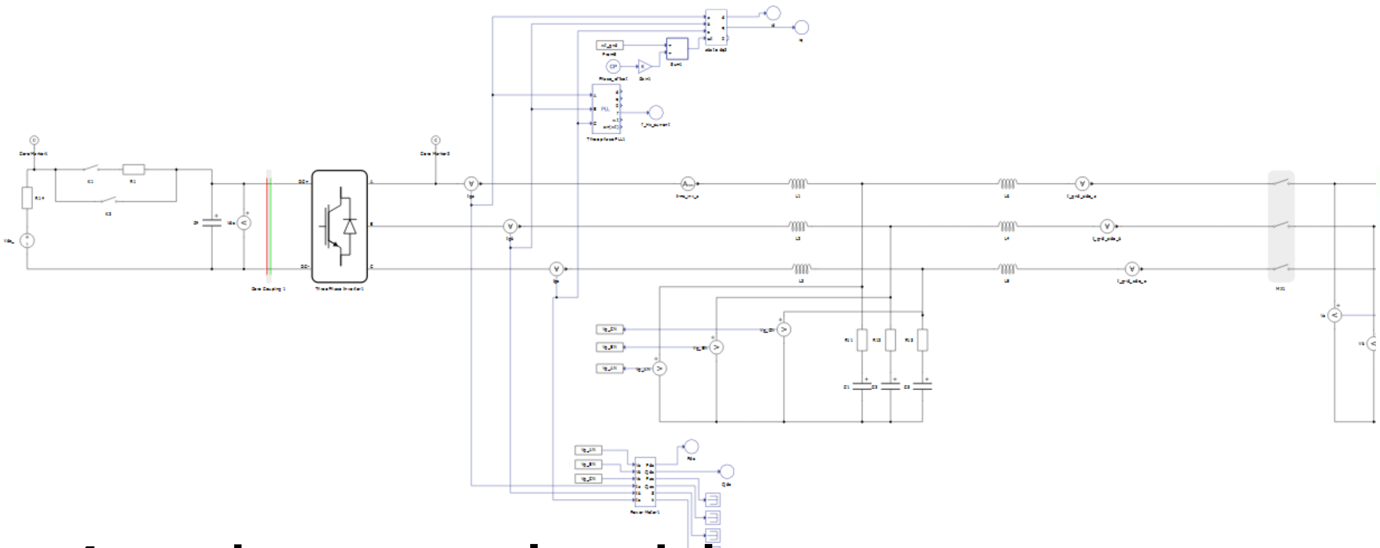
Thermal



CHP Aggregate Thermal Model

- Aggregate CHP system model
  - Modbus commanded heating or cooling mode, temperature set-point
  - Independent heat load input
  - Parametrically settable losses, cooling coefficient of performance, thermal inertia

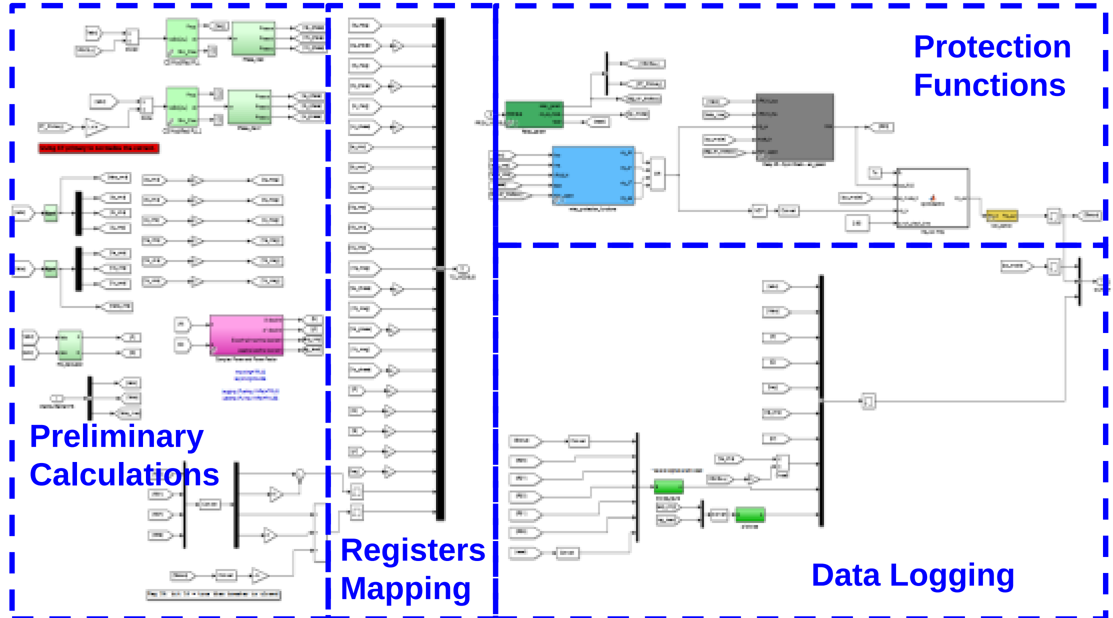
EPC Power Electronics Models: Solar PV and Energy Storage System

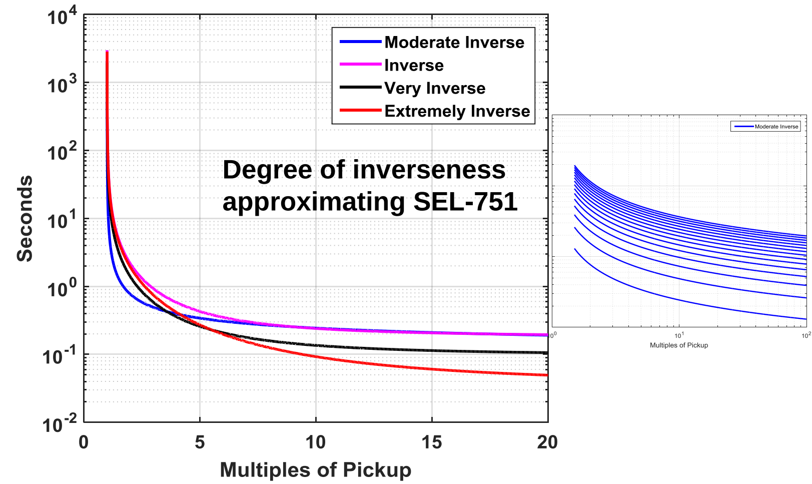


- **4-quadrant control module**
- **Control capabilities for microgrid operation**
  - **Real (P) and Reactive (Q) power dispatch**
  - **Voltage islanding mode**
  - **UPS parallel backup mode**
- **Manufacturer validated inverter model**
- **Modbus over RS485 Communication**

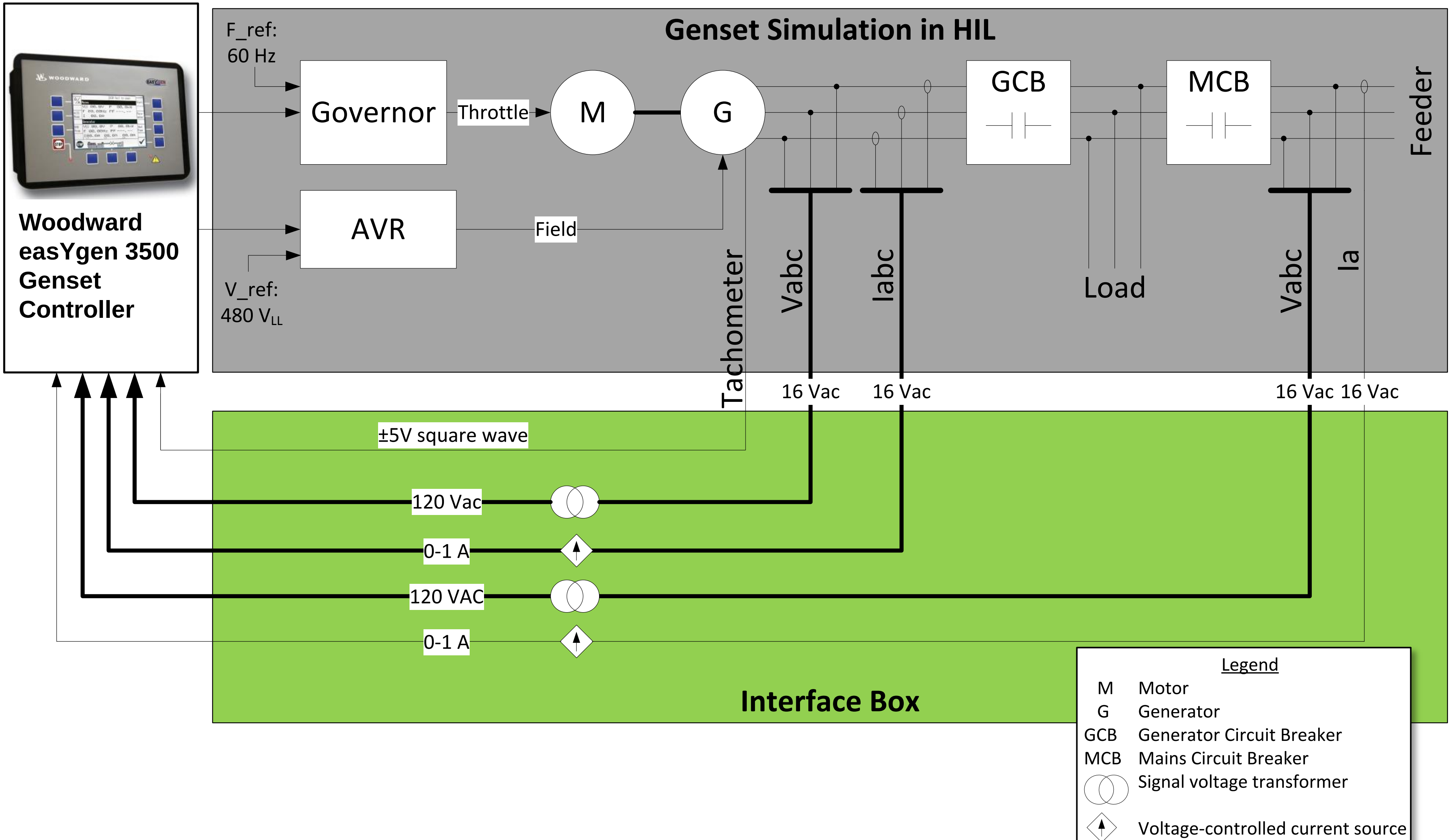
Generic Software Relay

- **Used for telemetry**
- **Various time current characteristic curves (TCC)**
- **Active protection features:**
  - **Overcurrent (50, 51)**
  - **Over/under voltage (27, 59)**
  - **Synchronism check (25)**
  - **Reclosing (79)**
- **Modbus TCP interface**
- **Multiple protection group settings accessible by the microgrid controller**
  - **Grid-tied protection**
  - **Islanded protection**

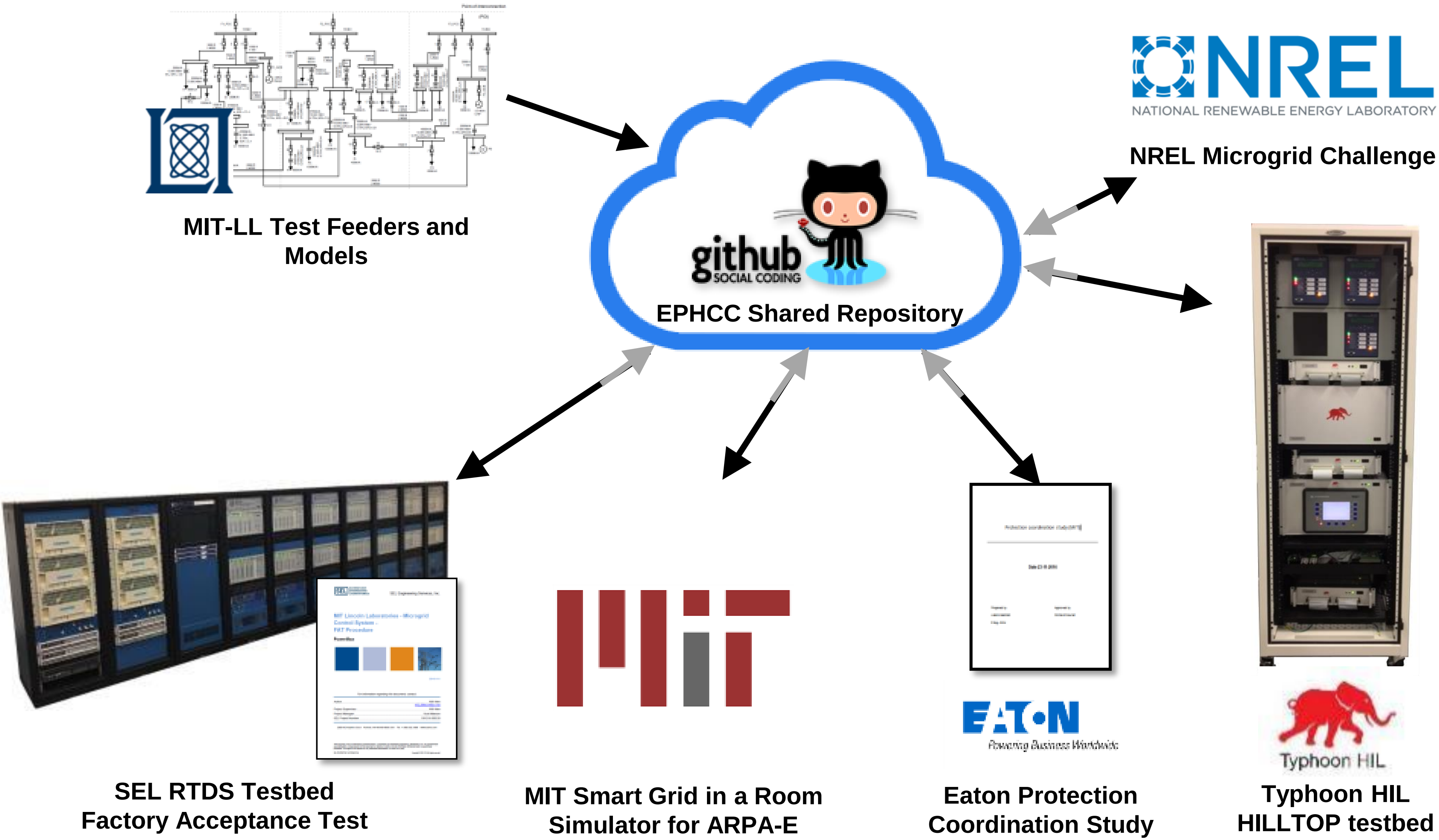




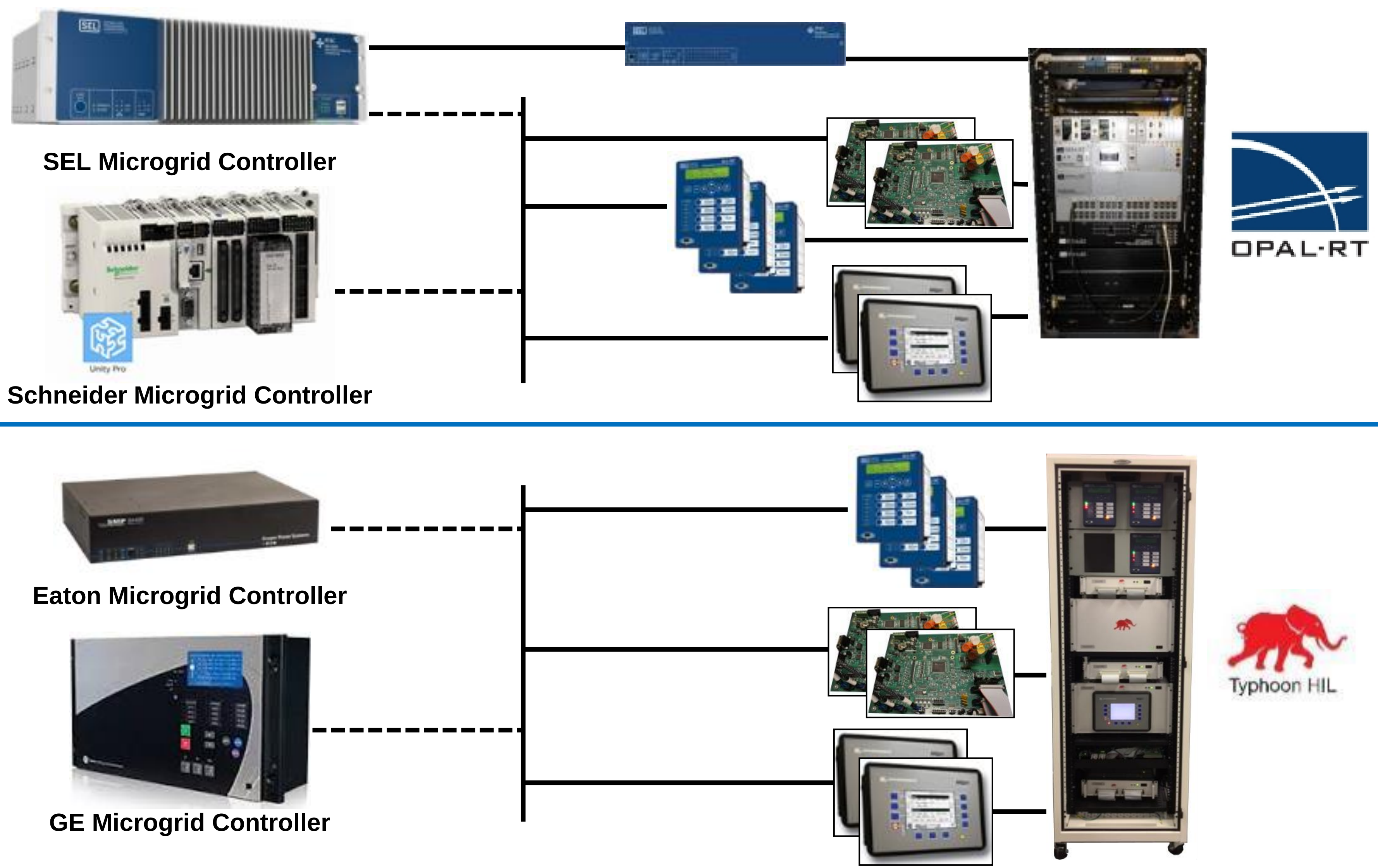
Device Controller Integration: Woodward easYgen 3500



Models Ported to Numerous Platforms



Today: HILLTOP on 2 Real-time Sims Operating 4 Microgrid Controllers



Outline

- Motivation
- Testbed Buildup
- Integration Process
- Demonstration Orientation

The Integration Process: Device Integration

- I/O point check
- Communications
  - Comm w/out errors, change setpoints, scale factors
- Device-level performance characterization
  - Load acceptance, load rejection tests
  - Large setpoint changes
  - Determine capability curves
- Customize site-specific controls / DER mode changes
- DER paralleling / generator load sharing

The Integration Process: Microgrid Controller Configuration

- **Transitions**
  - **Intentional islanding**
  - **Unplanned islanding**
  - **Synchronization and reconnection**
- **Steady-state operation**
  - **Grid-tied optimal dispatch**
  - **Islanded stability**
- **Faults**
  - **Protection**
  - **Reconfiguration for critical load service**

Outline

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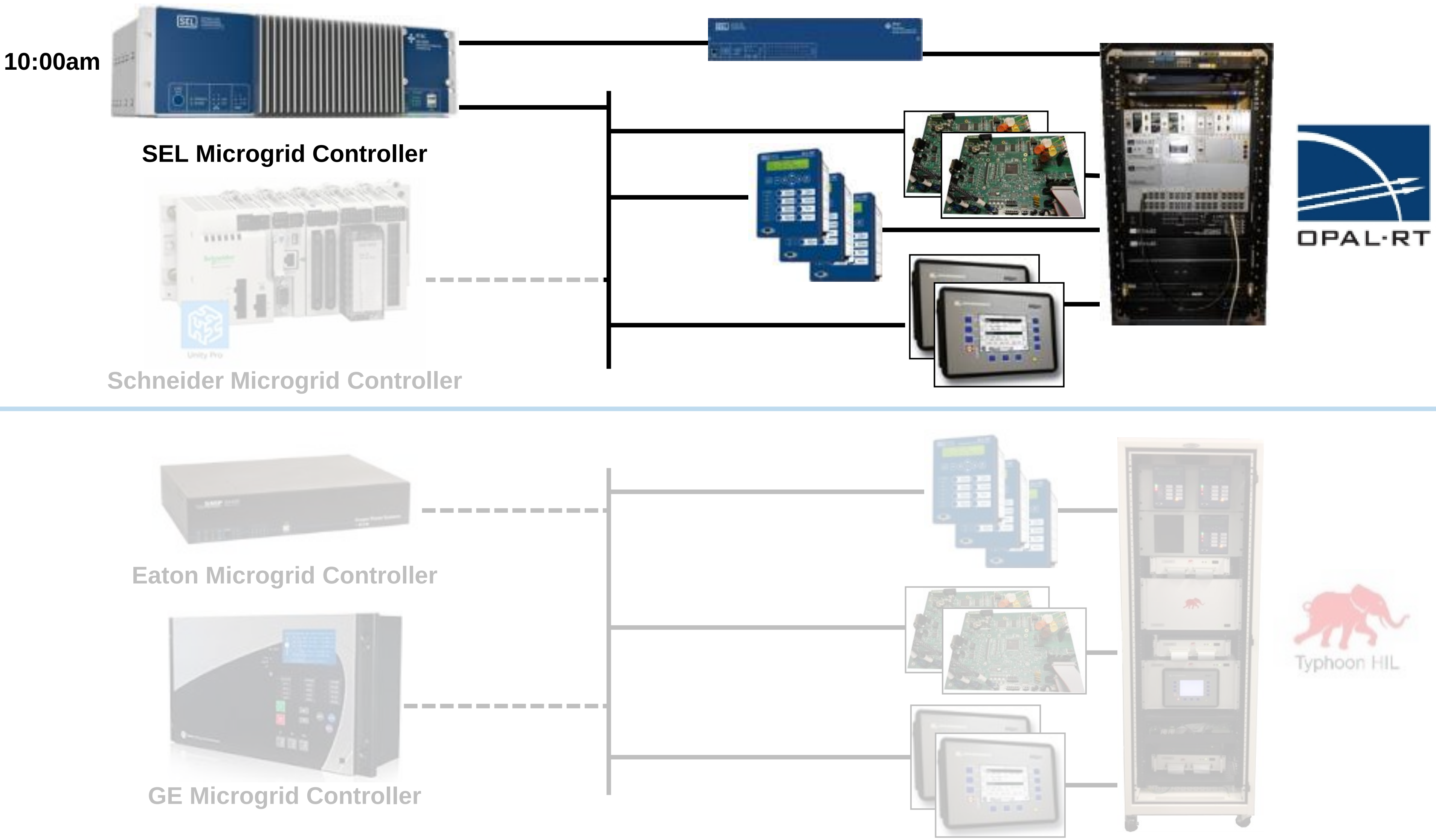
Demo #1: SEL Controller on OPAL-RT

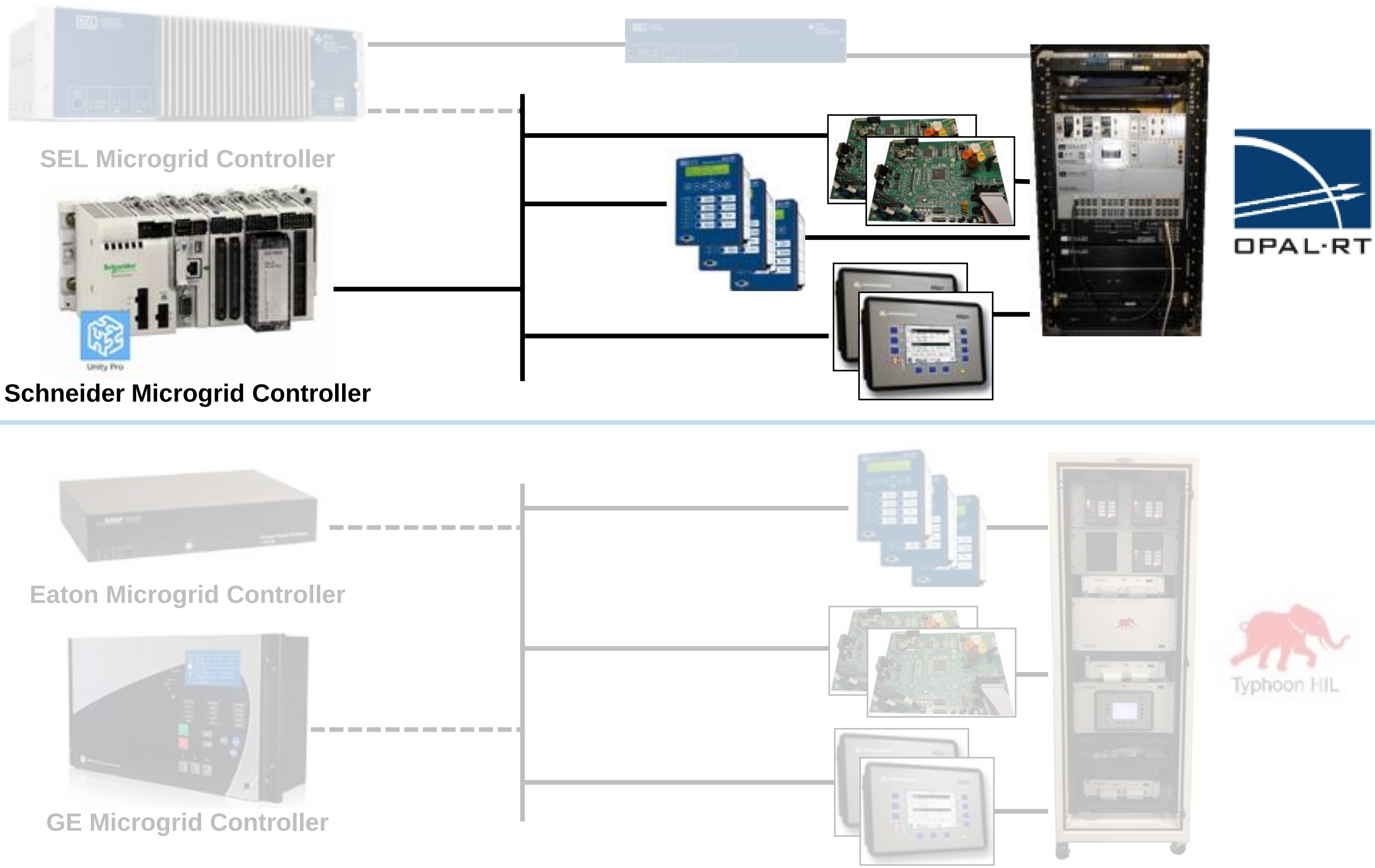
Focus: Black Start, Islanding, & Fast Load Shedding



#3: Schneider on OPAL-RT

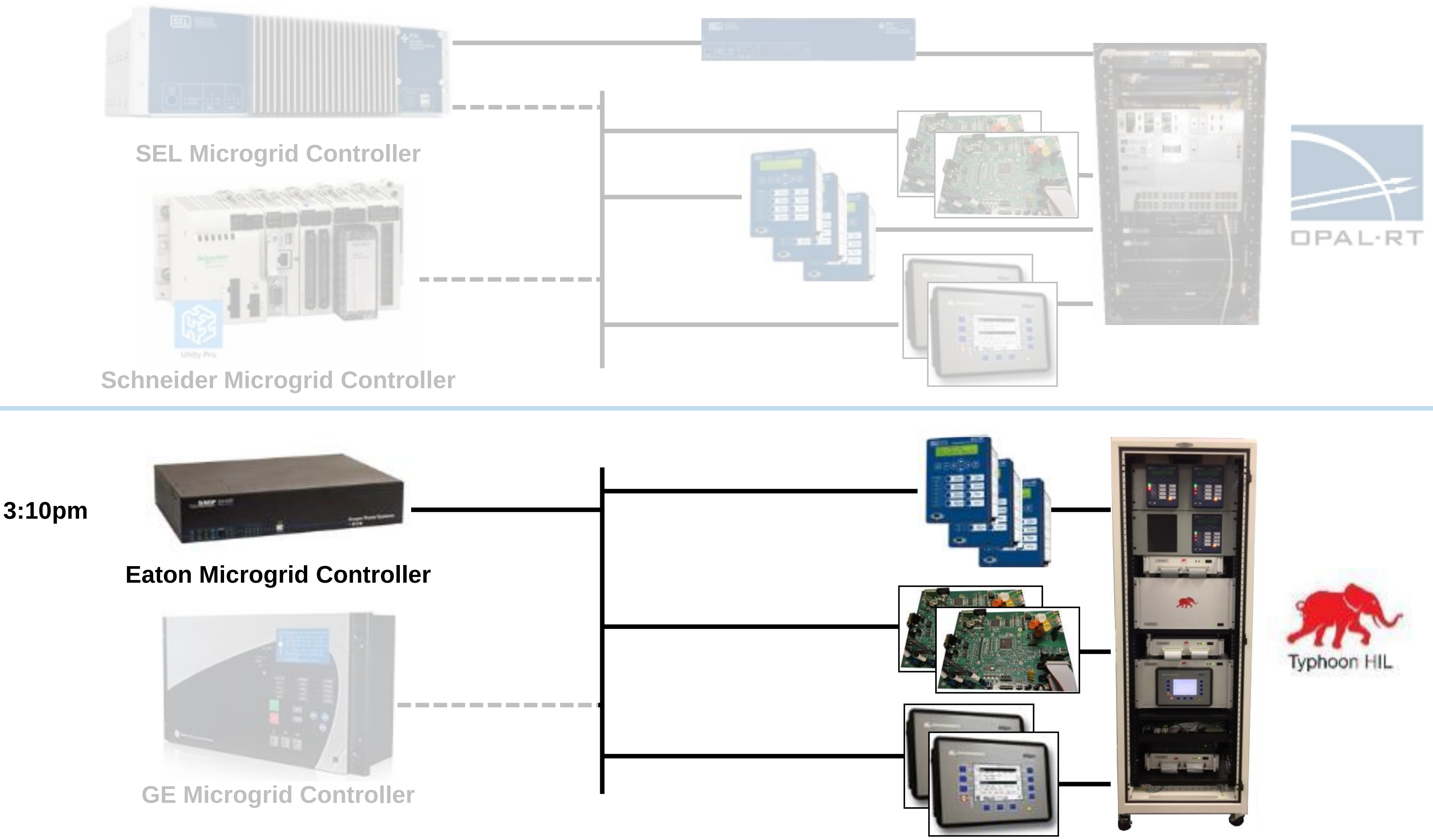
Focus: Reconfiguration & Load Prioritization

2:10pm break



#4: Eaton Controller on Typhoon HIL

Focus: Protection & DER Dispatch



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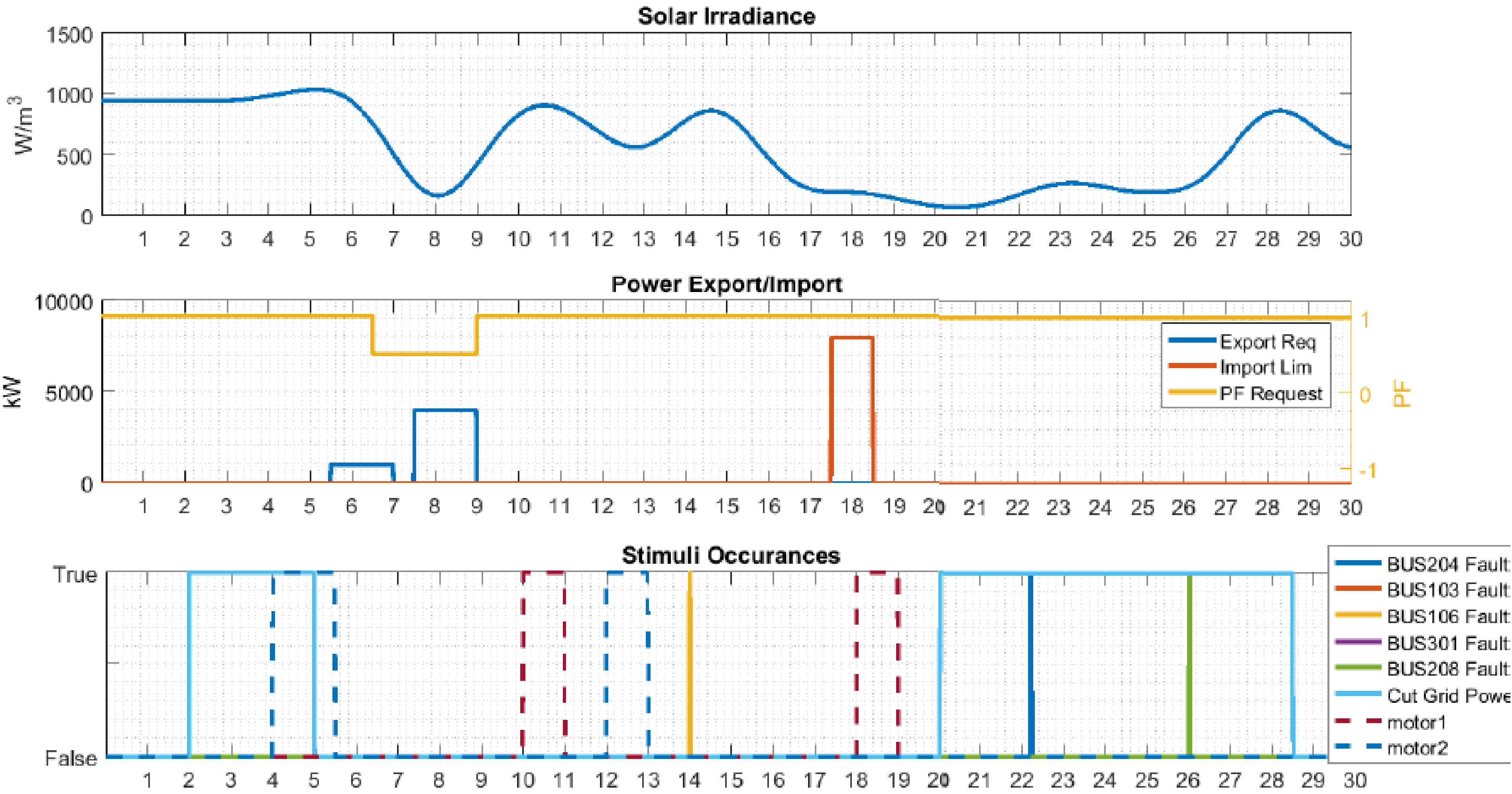
Demonstration Sequence



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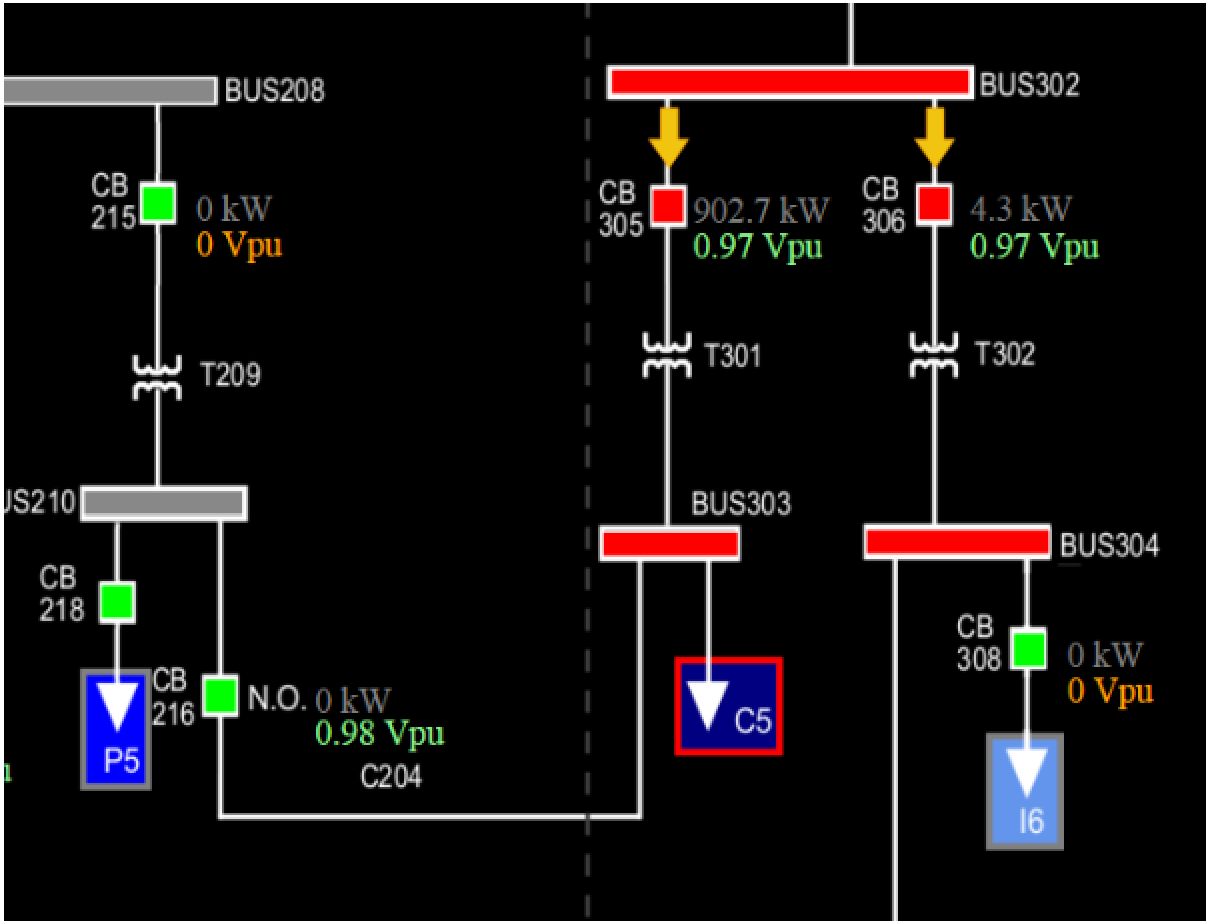
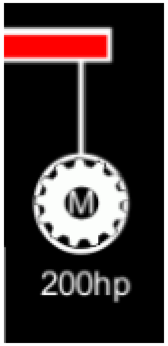
Buses, Breakers, and Loads



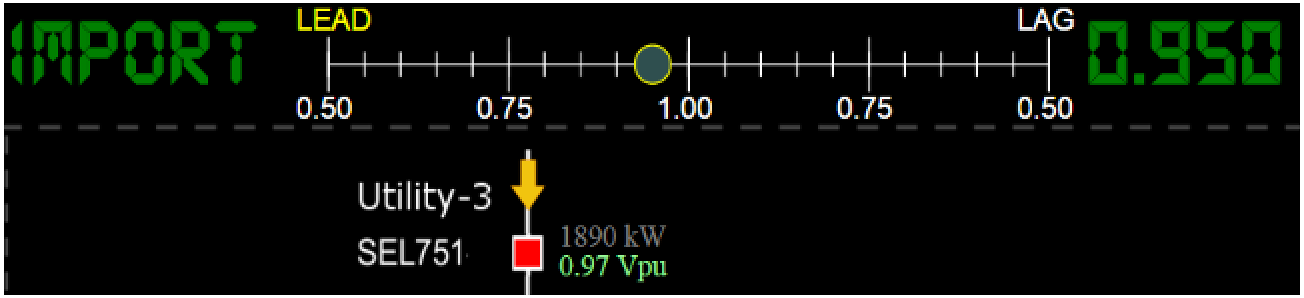
LEGEND

- Live Bus
- Dead Bus
- Closed Breaker
- Open Breaker
- Critical Load
- Priority Load
- Interruptible Load
- Energized Load
- Dropped Load

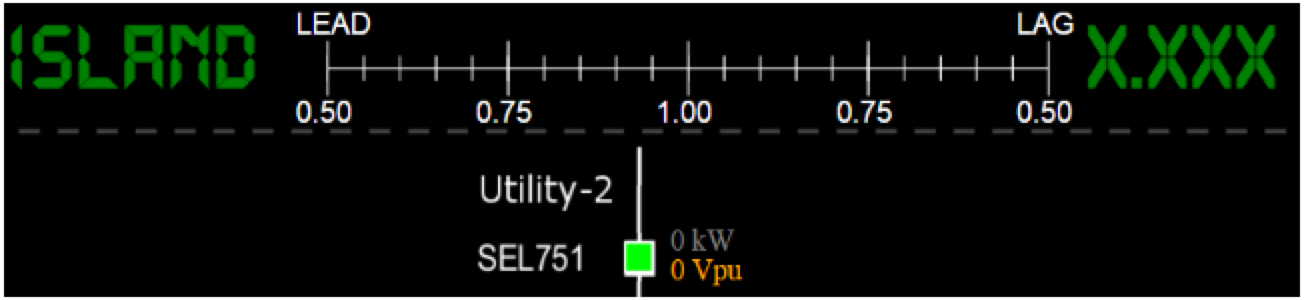


Energized Motor Load

Feeder Status and Power Factor

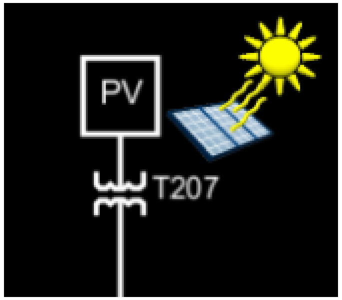


Grid-tied Feeder

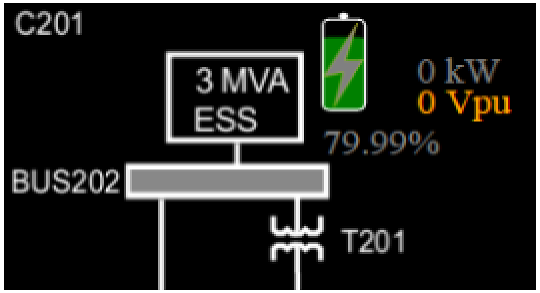


Islanded Feeder

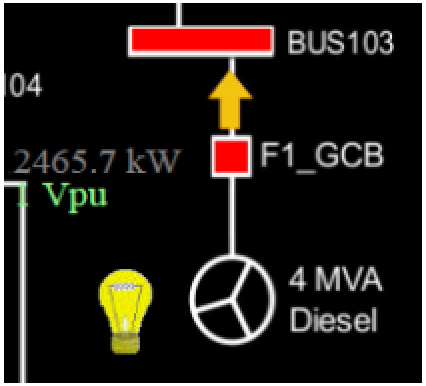
Distributed Energy Resources



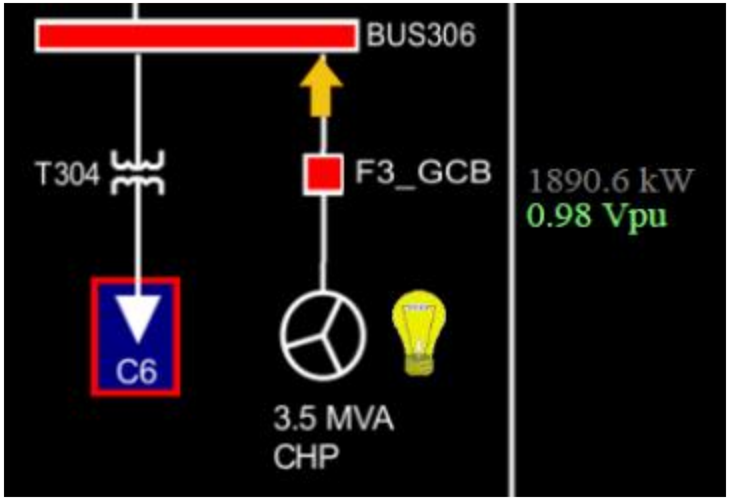
Energized Solar
PV Array



Discharging Energy Storage
System (ESS) / Battery

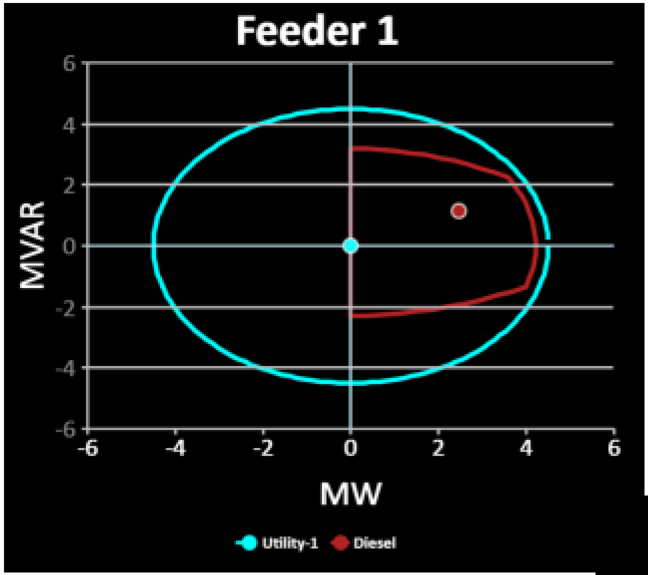


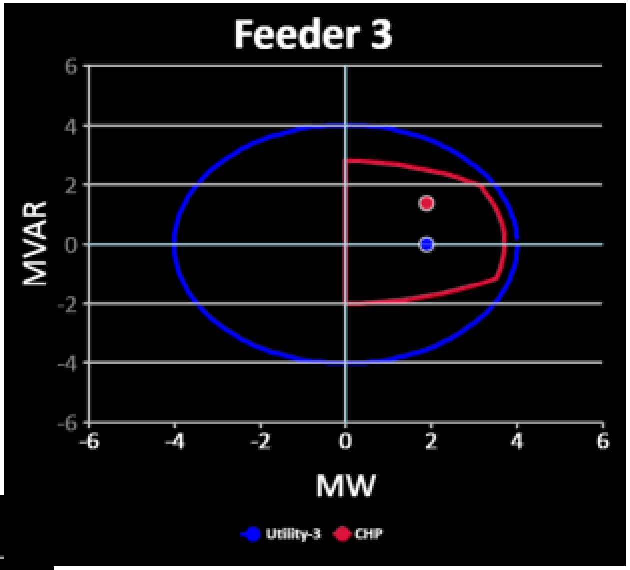
Energized Diesel Genset

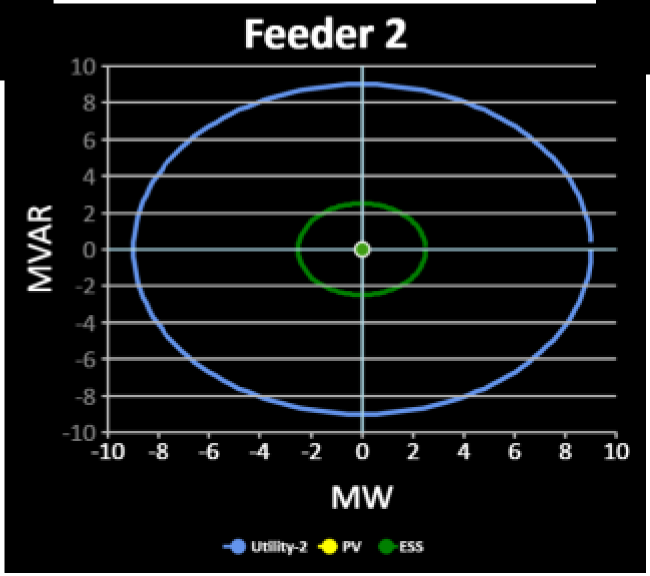


Energized Natural Gas-fired Combined
Heat and Power (CHP) Plant

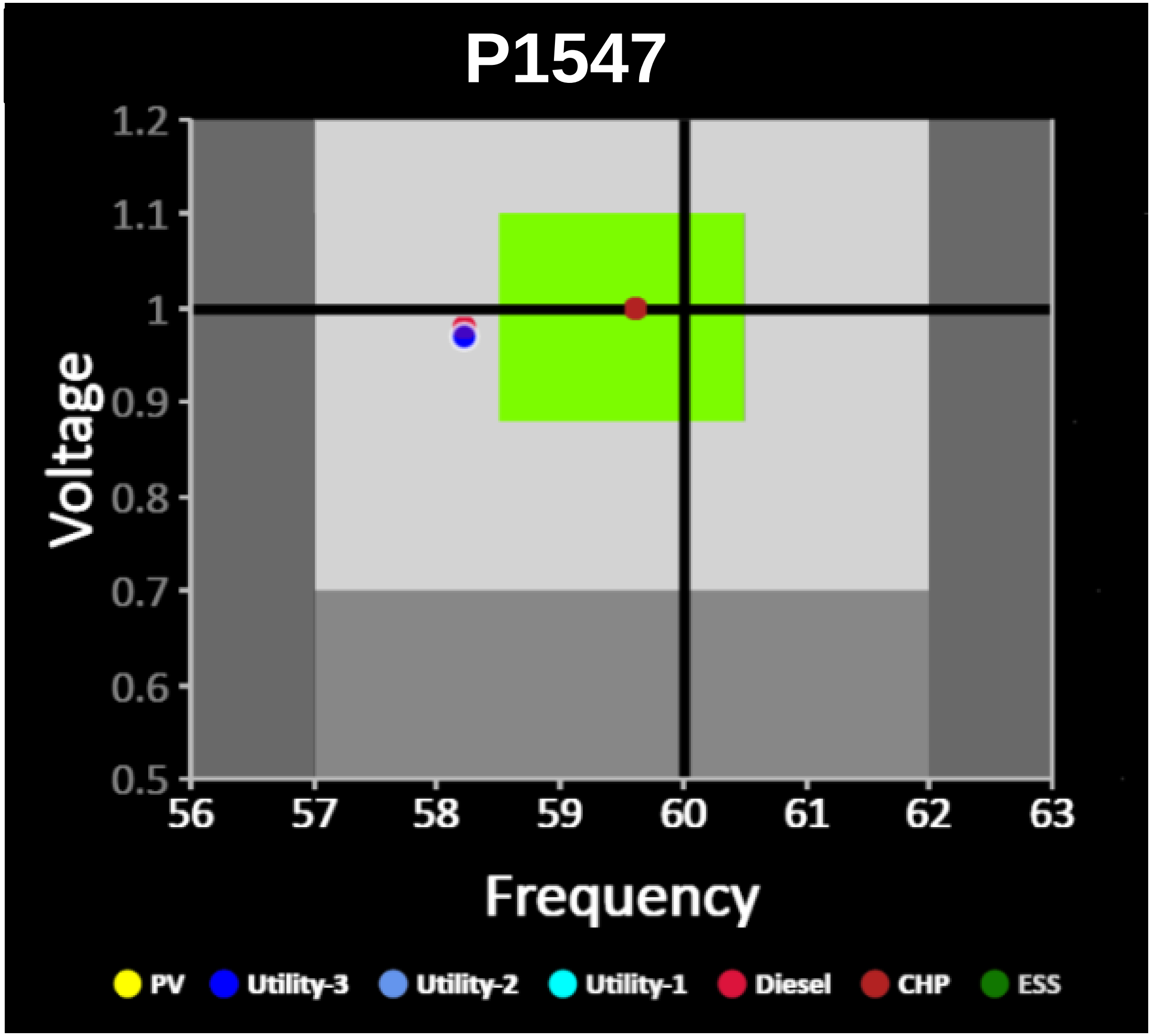
Real and Reactive Power Production and Capability Curves







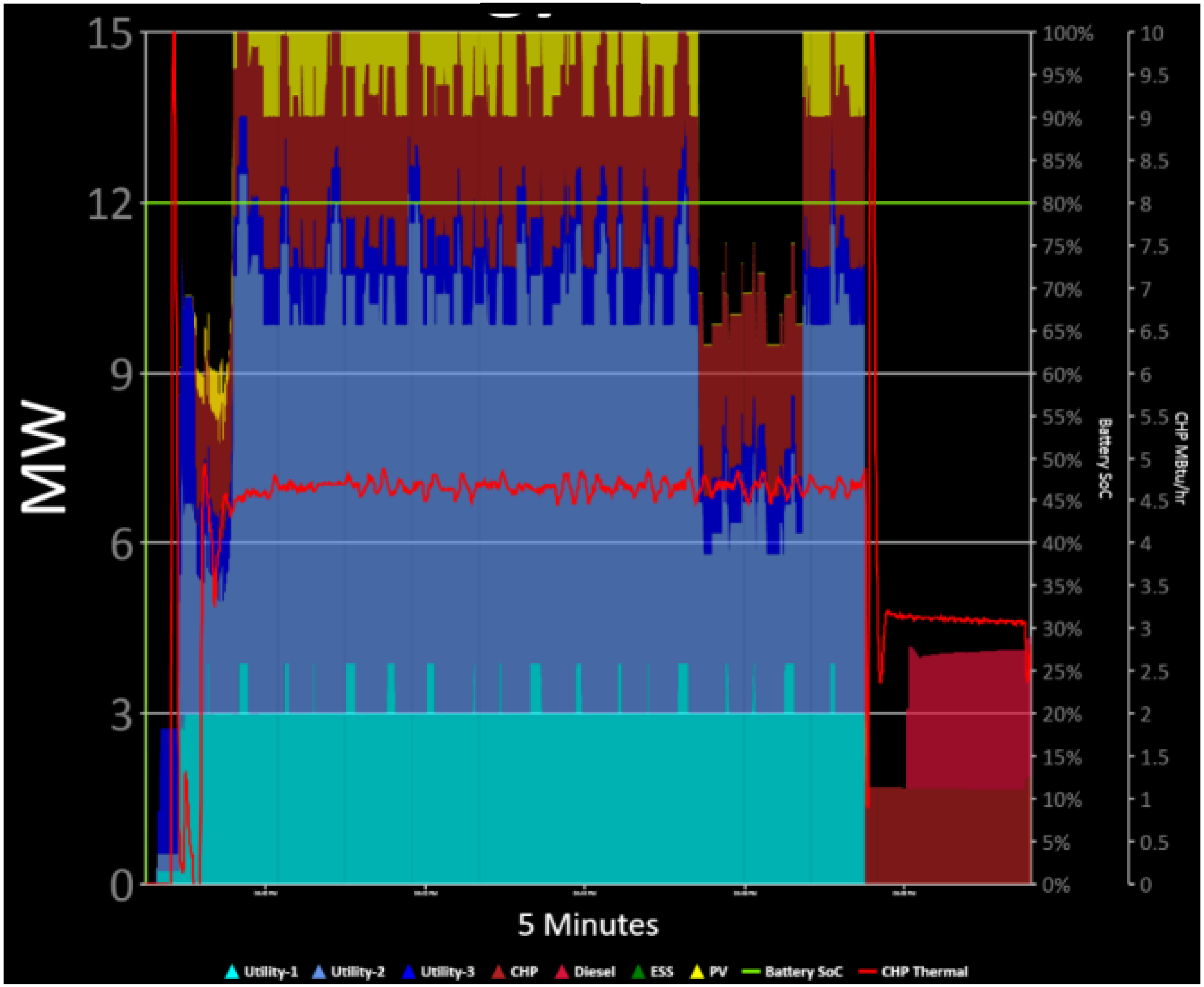
Testing of Future Advanced DER: IEEE P1547 Draft Amendment



LEGEND

- Nominal
- Normal range
- Must ride through
- May ride through
- Must trip

Energy Sources "Sand Chart"



High-fidelity Oscilloscope Waveforms

LEGEND

- Grid voltage
- CHP current
- CHP voltage
- Diesel genset voltage

Our Mission: Transitioning Technology for National Energy Resilience

– 1 –
Engagement Platform

- Proof-of-concepts
- Stakeholder engagement (utilities, regulators, host sites)

– 2 –
Development Platform

- Vendor / new equipment evaluation
- Advanced controls R&D

– 3 –
Deployment Platform

- Controller integration
- Pre-commissioning testing

– 4 –
Standards Test Platform

- IEEE P2030.8 and P1547 conformance testing

- Industry support: model repository

– 5 –
Electric Power HIL Controls Collaborative (EPHCC) Shared Repository

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Collaborators

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EPC Power
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Scott Manson, SEL
Will Allen, SEL
Tom Steber, Schneider
Vijay Bhavaraju, Eaton
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Jessica Ridlen, MassCEC
Fran Cummings, Peregrine Group
Babak Enayati, National Grid
Jim Reilly, Reilly Associates

Erik Limpaecher

Assistant Group Leader

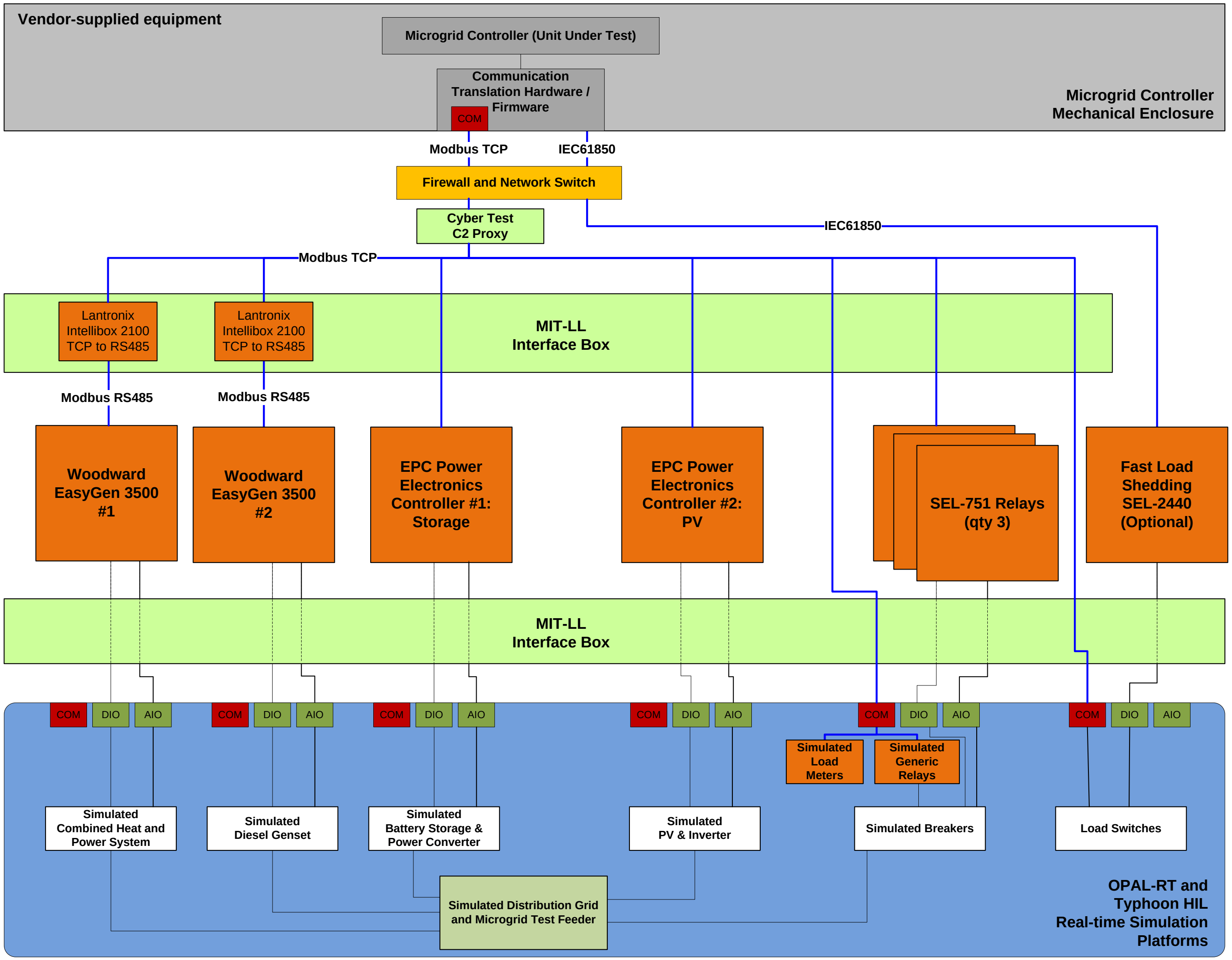
Energy Systems, Group 73

781-981-4006 (lab)

elimpaecher@ll.mit.edu

BACKUP

HIL Platform Block Diagram



Update diagram to make text larger, add