Microgrid Controller Hardware-in-the-Loop Demonstration Platform

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Science and Technology

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

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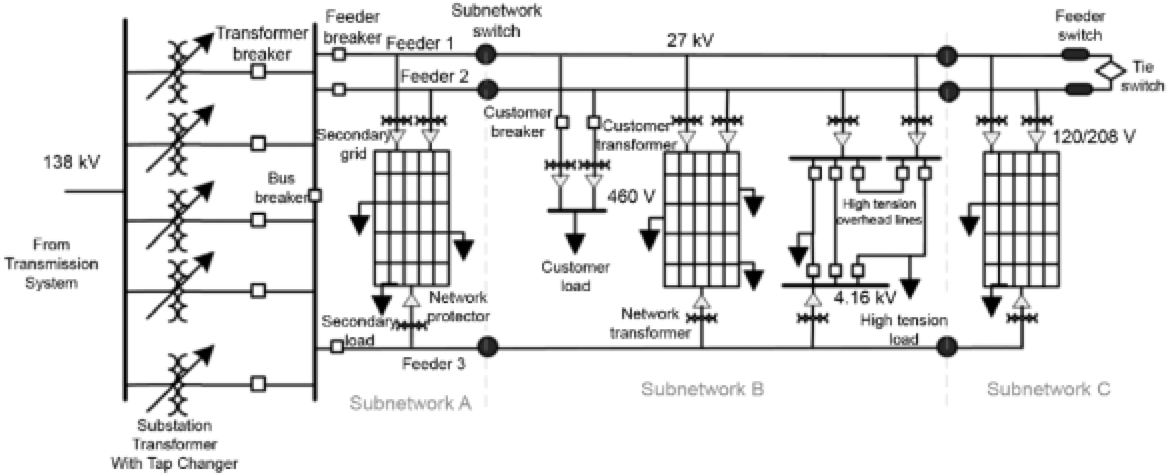
Test Coverage & Fidelity of New Power Distribution + Control Projects?

- **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**



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

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? –

[1] V. Spitsa, X. Ran, R. Salcedo, J. Martinez, R. Uosef, F. d. León, D. Czarkowski, and Z. Zabar, "On the transient behavior of large-scale distribution networks during automatic feeder reconfiguration," IEEE Trans. Smart Grid, vol. 3, no. 2, pp. 887–896, Jun. 2012
[2] V. Spitsa, R. Salcedo, X. Ran, J. Martinez, R. E. Uosef, F. De León, D. Czarkowski, and Z. Zabar, "Three-phase time-domain simulation of very large distribution network," IEEE Trans. Power Del., vol. 27, no.2, pp. 677–687, Apr. 2012.

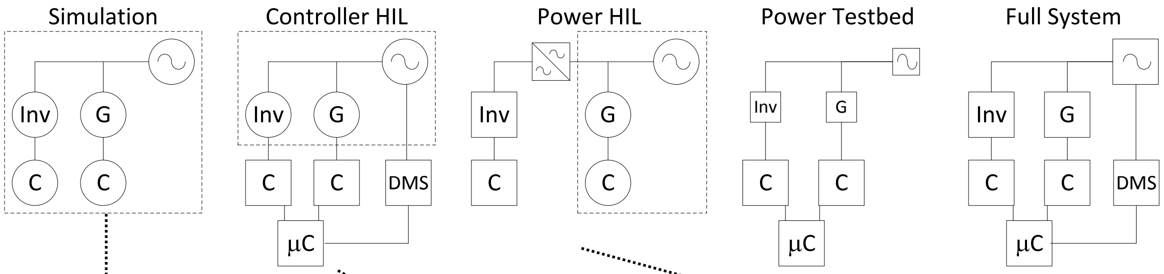
How Do We Accelerate Microgrid Deployment?

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)

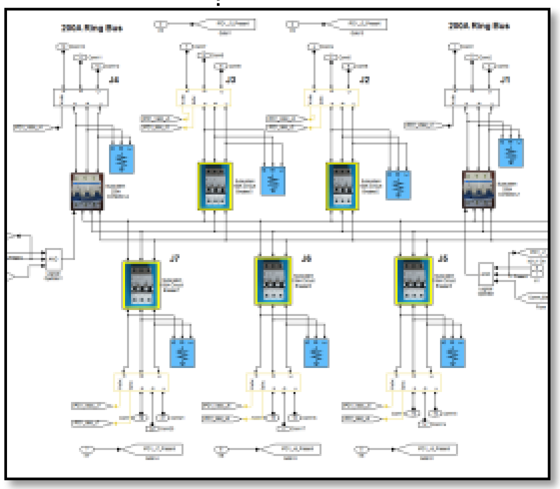
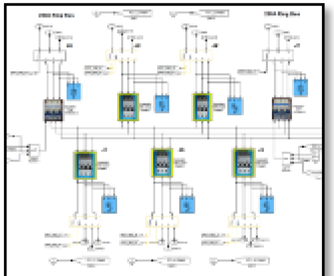


Image: Florida State Univ. CAPS

Power Simulation: Flight Simulator Analogy

Matlab SimPowerSystems simulation (not real-time)



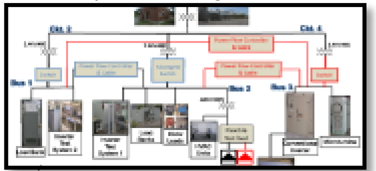
Actual device and microgrid controller with real-time simulation

(Microgrid controller HIL)

Real-time simulation coupled with power electronics testbed

(Florida State CAPS facility)

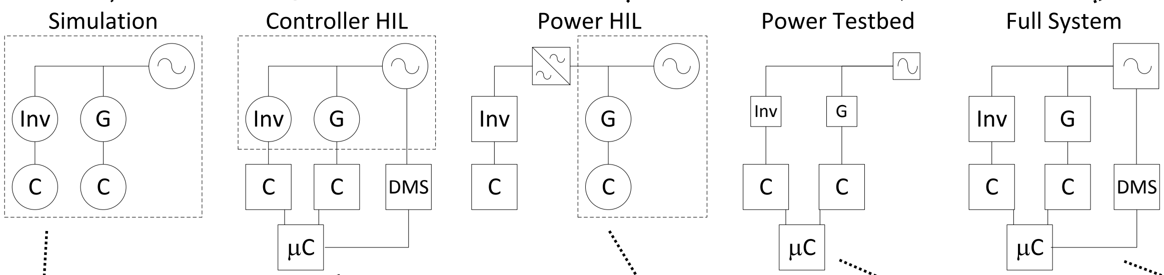
Low-power microgrid testbed



(DECC Microgrid Lab)

Actual microgrid

(Princeton U. cogen plant)



Legend

- G generator
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- C device controller
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- ∿ power grid
- high-bandwidth AC-AC converter
- simulation or emulation boundary
- □ hardware
- ○ virtual (simulated or emulated)

Slow PC simulation, small screen, keyboard/mouse inputs

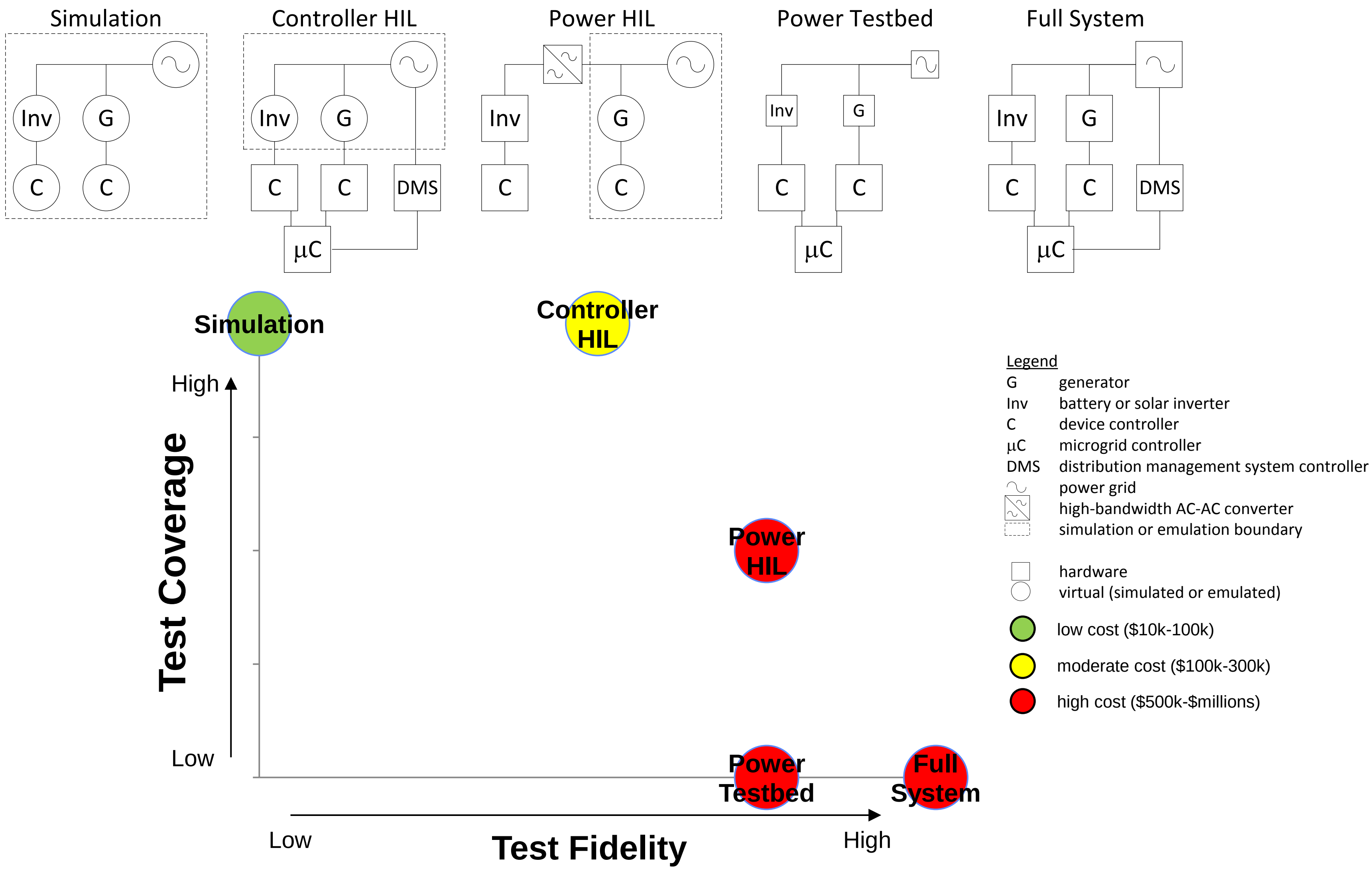
Actual plane cockpit, advanced simulation, wide field-of-view

Moving cockpit, field-of-view visualization

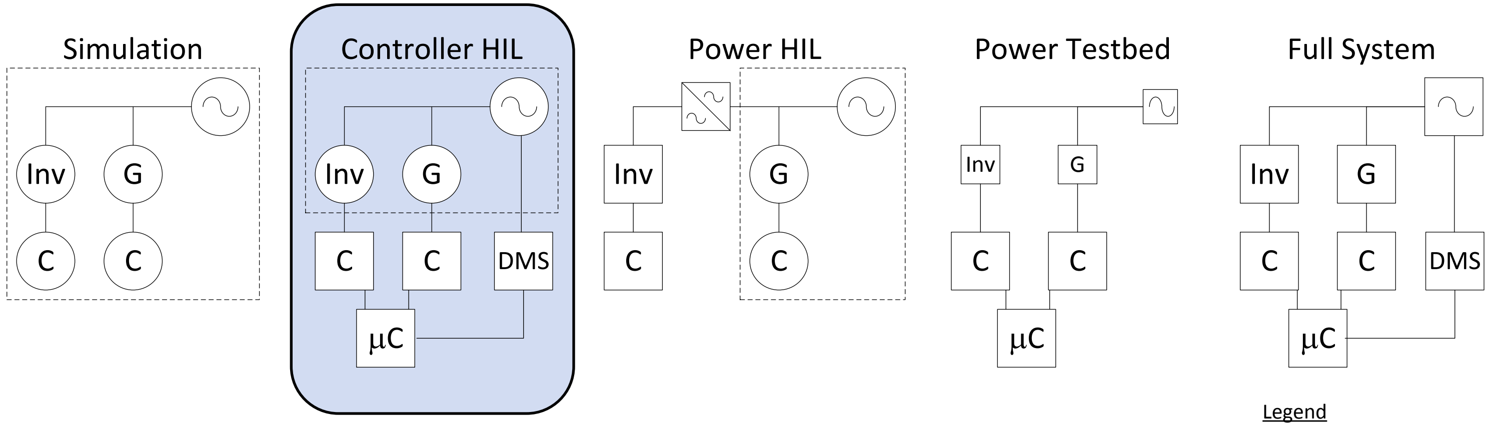
Trainer aircraft

Passenger-carrying aircraft

Power Distribution Integration Platforms and Testbeds

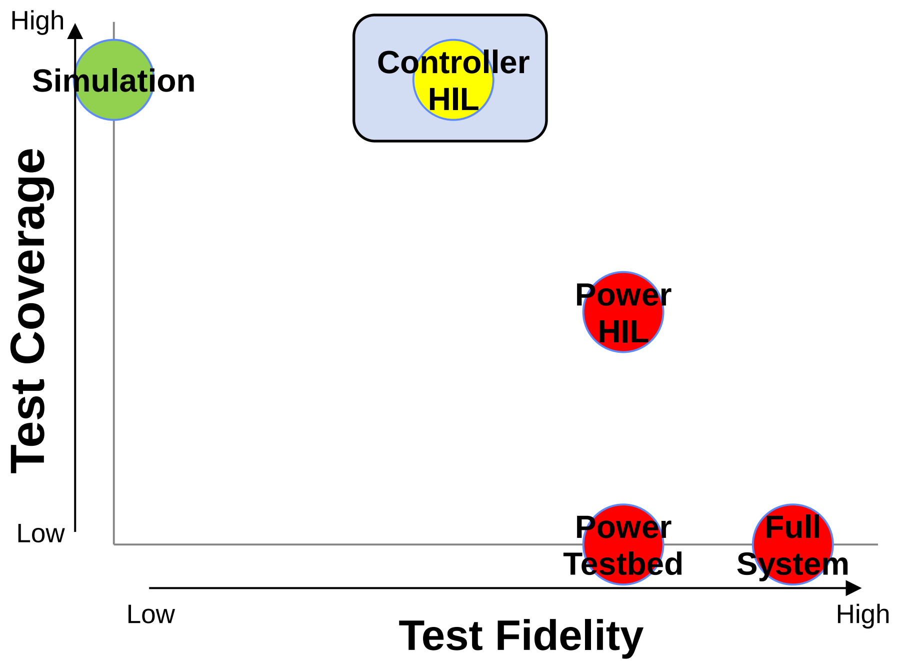


Power Distribution Integration Platforms and Testbeds



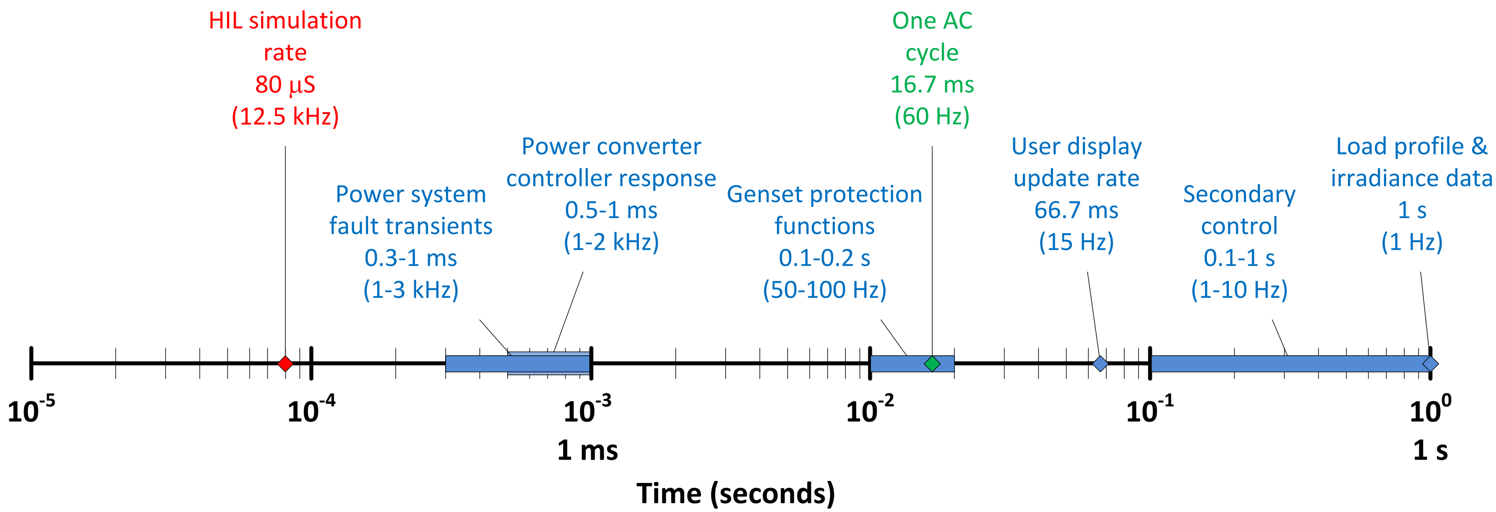
Legend

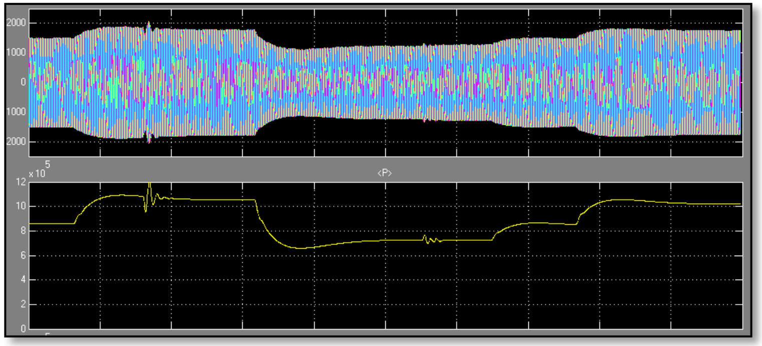
G	generator
Inv	battery or solar inverter
C	device controller
μC	microgrid controller
DMS	distribution management system controller
∿	power grid
	high-bandwidth AC-AC converter
	simulation or emulation boundary
□	hardware
○	virtual (simulated or emulated)
	low cost
	moderate cost
	high cost



High-fidelity Real-time Simulation

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

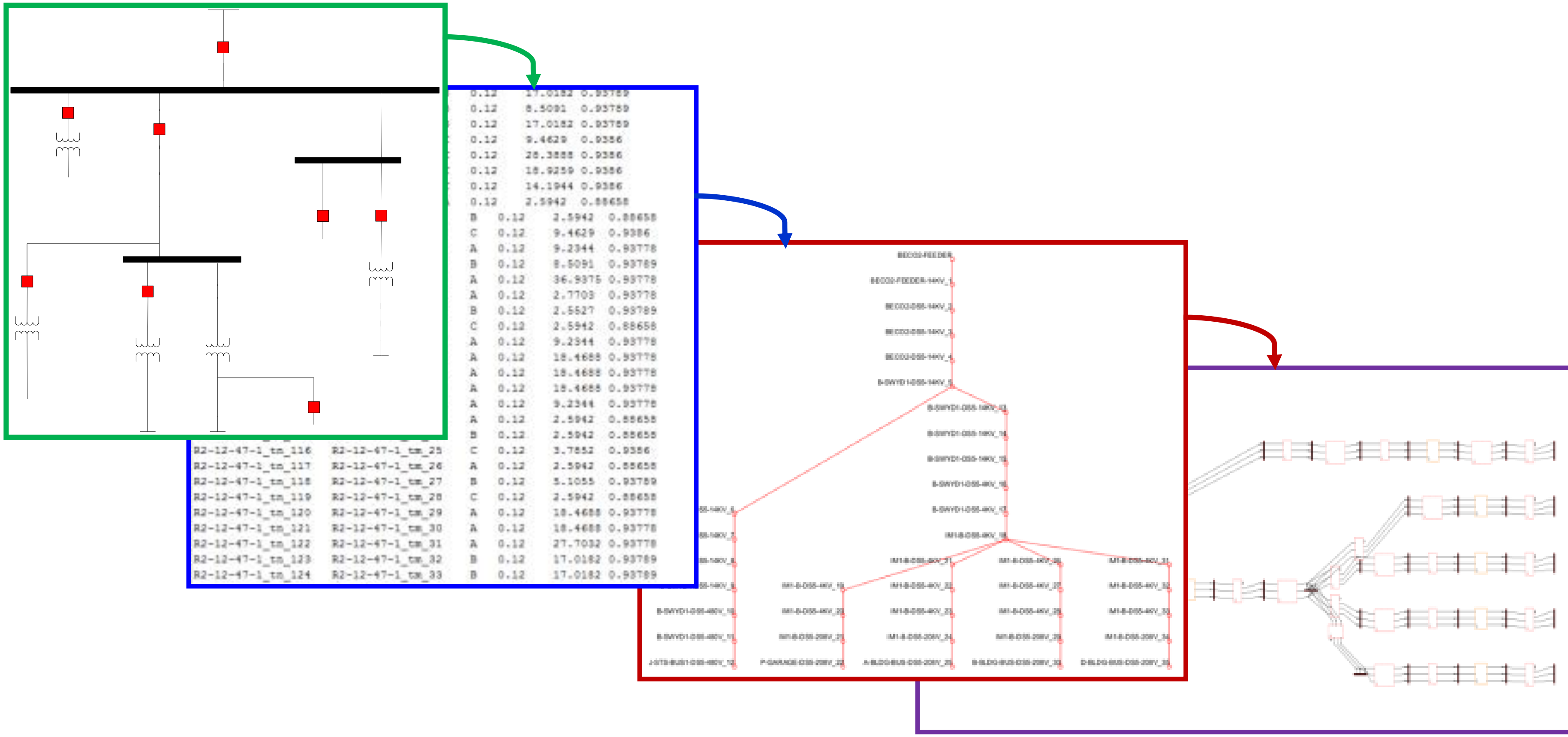




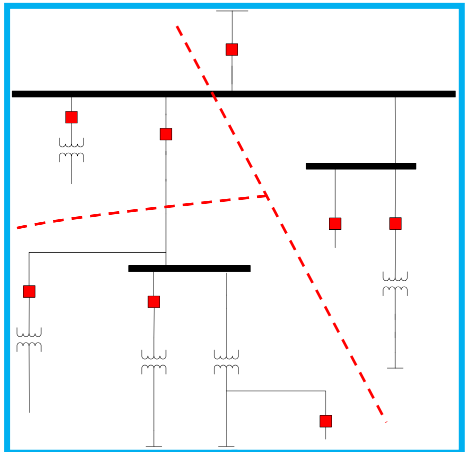
Construction of Detailed Microgrid Test Feeder Model

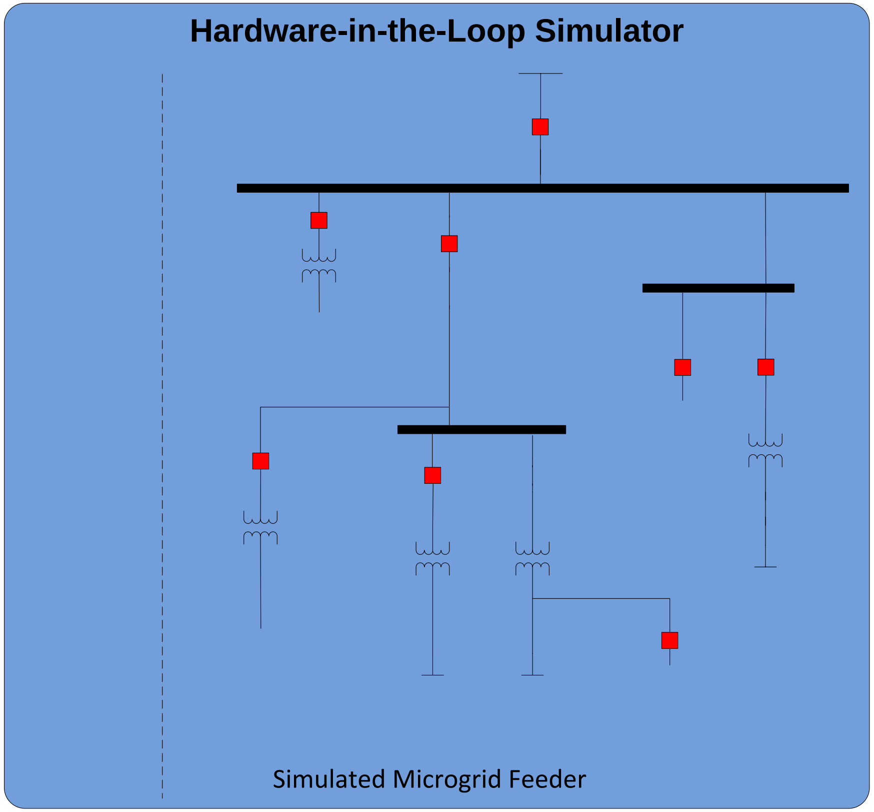
Automated with scripting

1. One-line diagram
2. Netlist
3. MATLAB data connectivity diagram
4. Simulink model



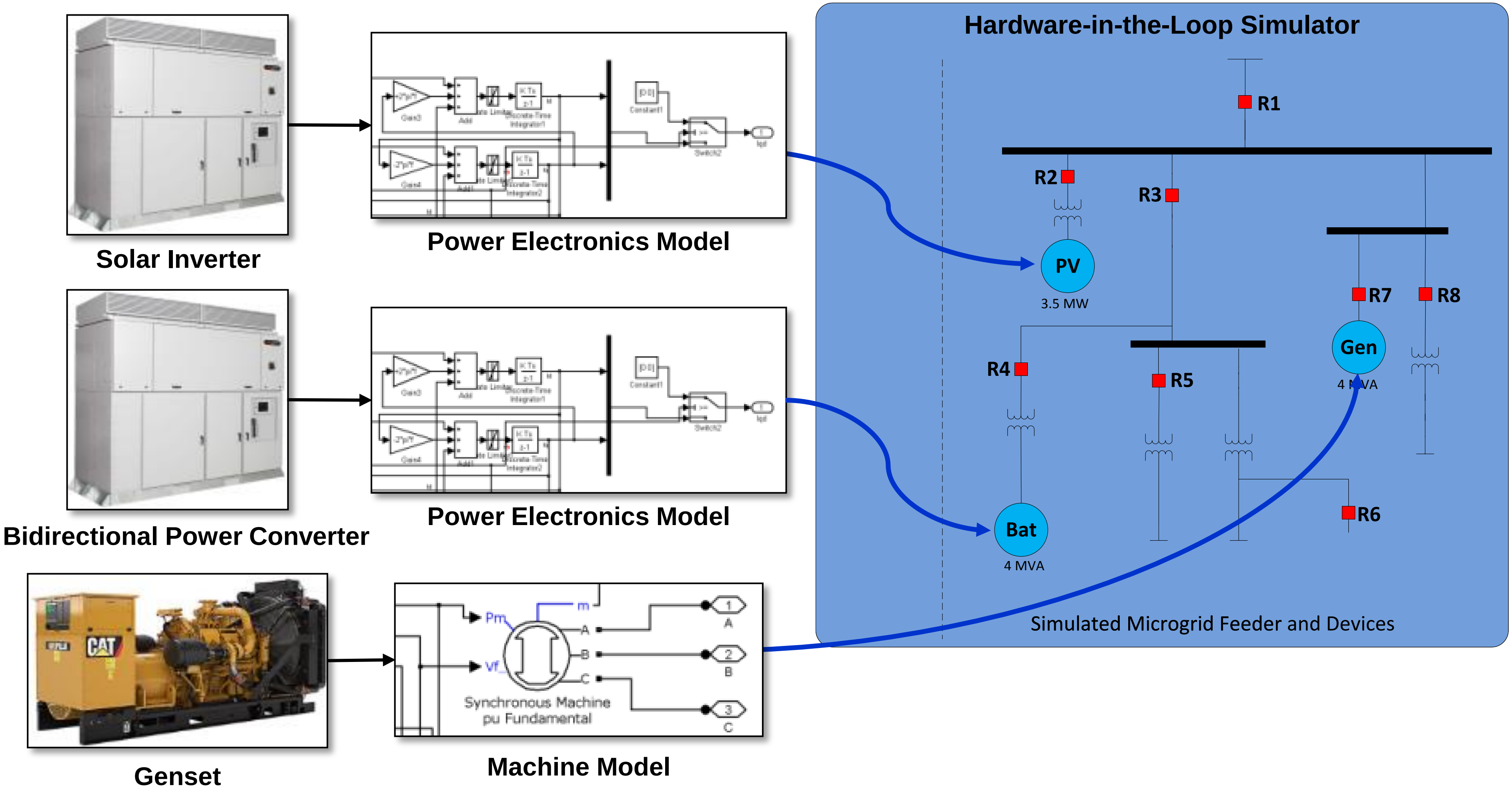
Elements of the Microgrid Controller HIL Platform





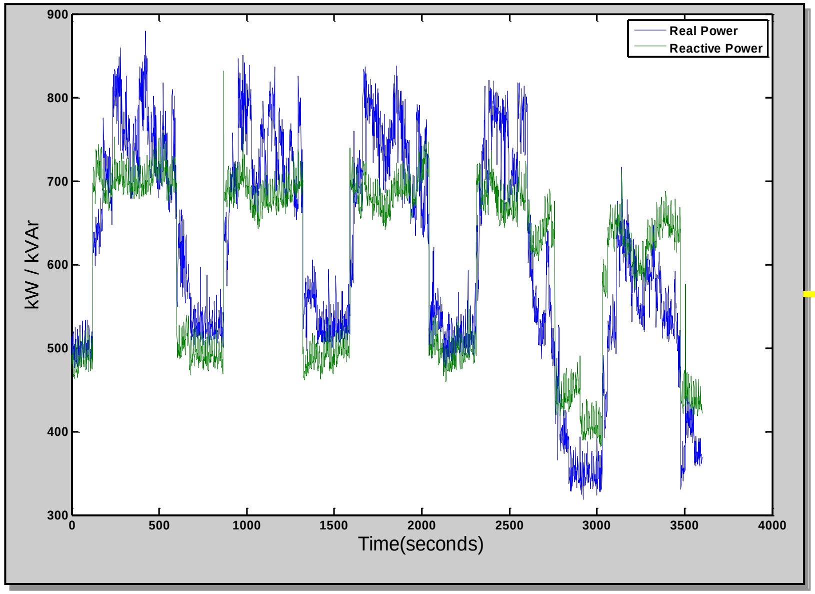
Load the feeder model into the HIL simulator "target"

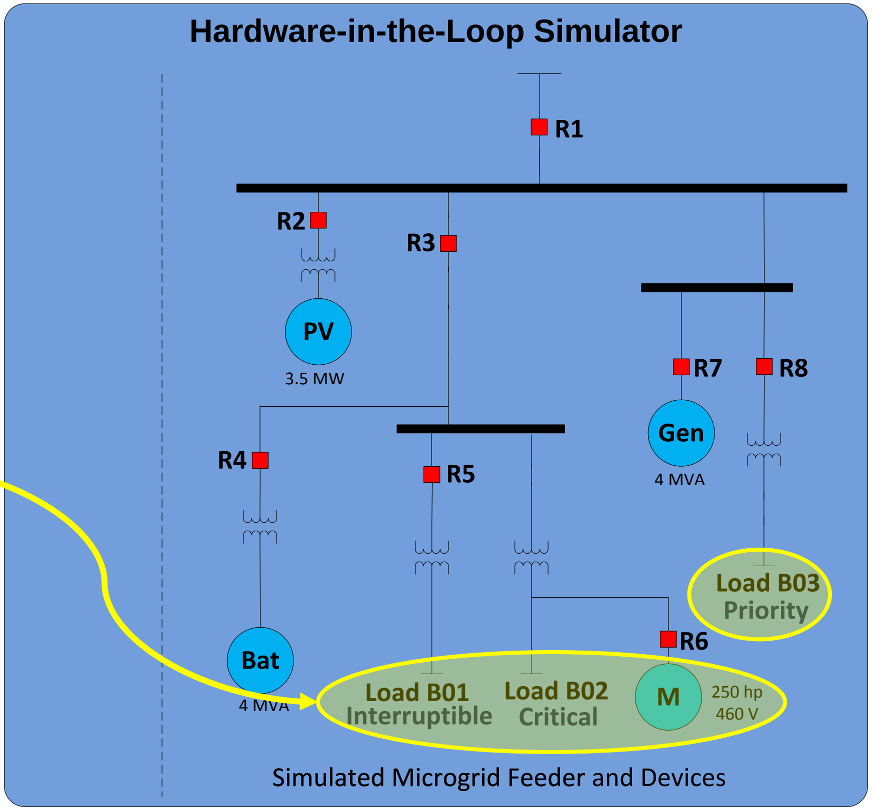
Elements of the Microgrid Controller HIL Platform



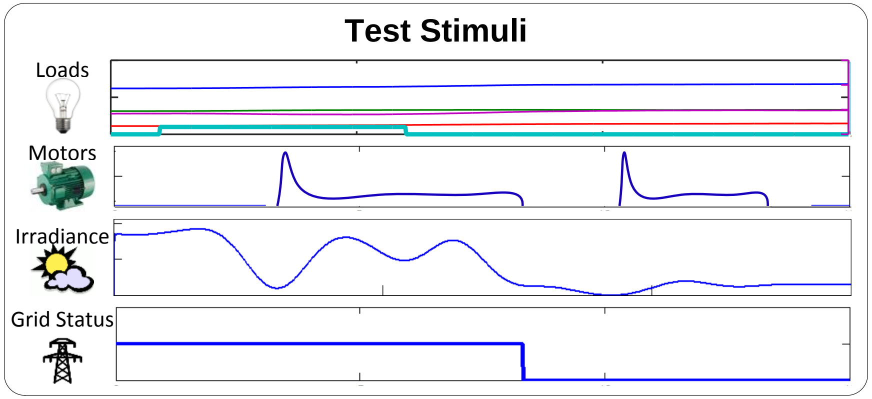
Create detailed models of the DER devices

Elements of the Microgrid Controller HIL Platform





Add load profiles & other test stimuli; assign load priorities



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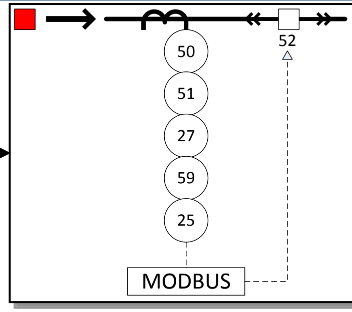
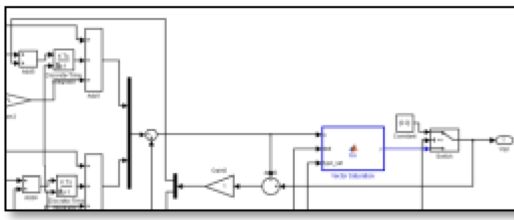
Elements of the Microgrid Controller HIL Platform

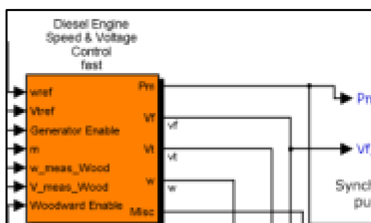
Relay



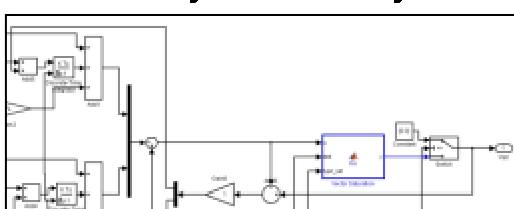
Relay Protection Functions



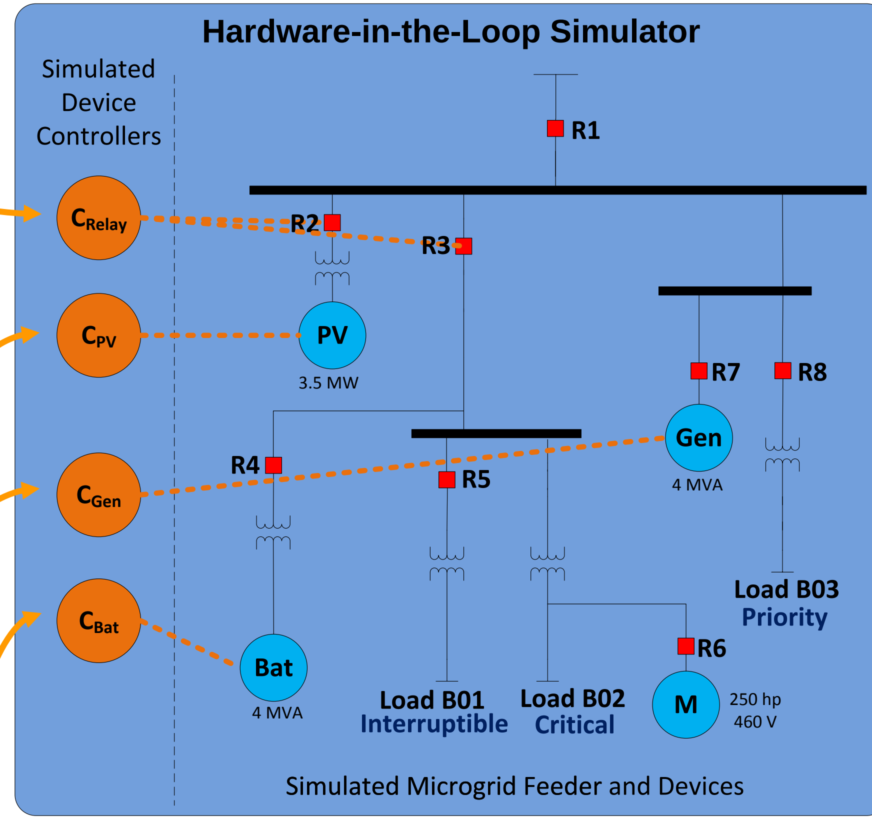
Inverter Control

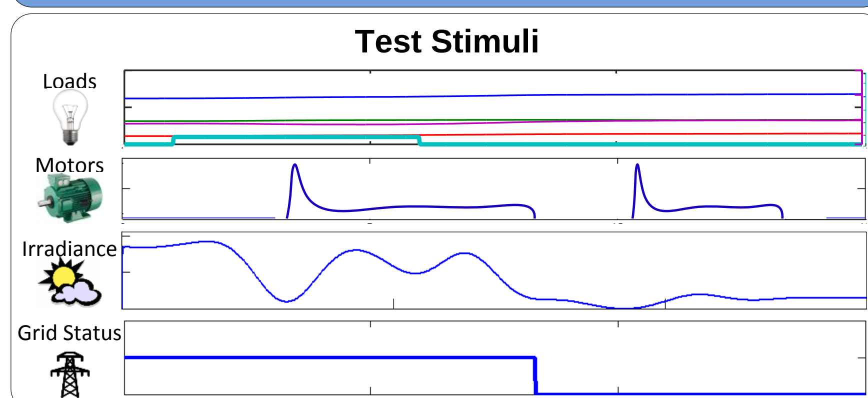


Genset Primary & Secondary Control



Bidirectional Power Converter Control





Implement DER control algorithms

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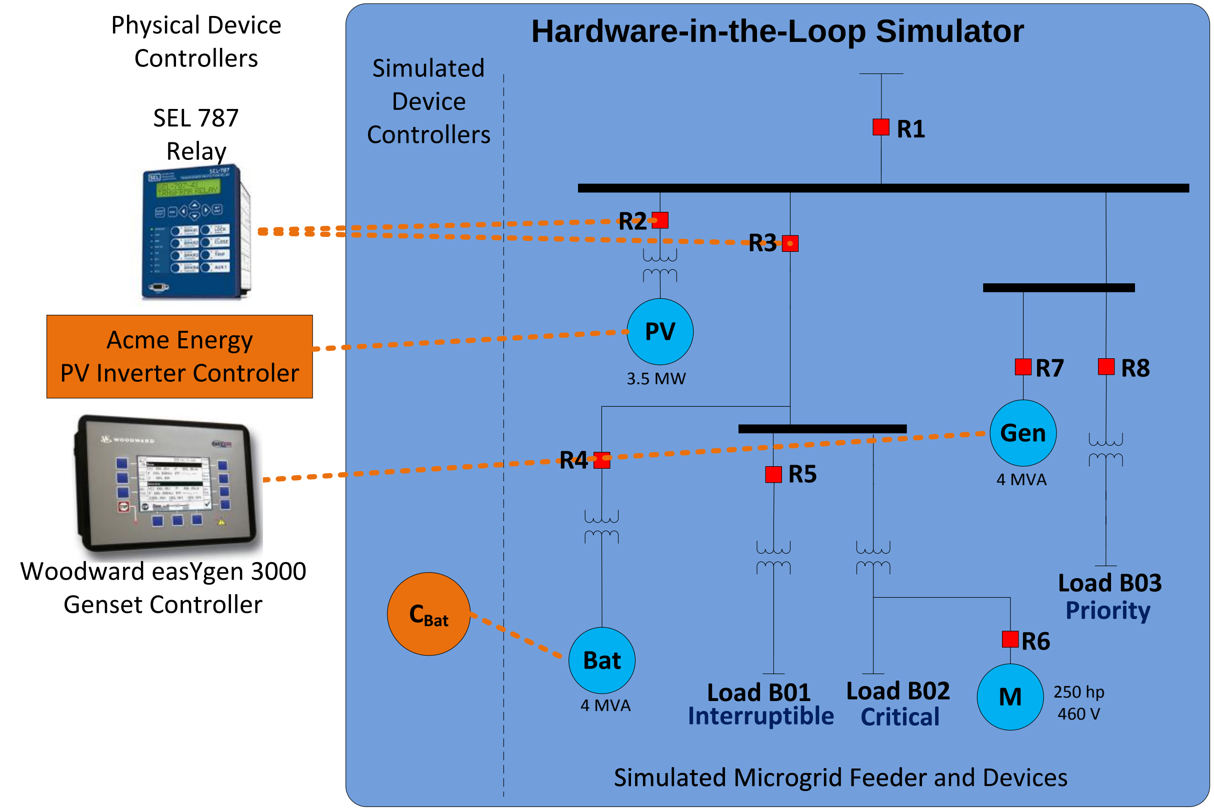
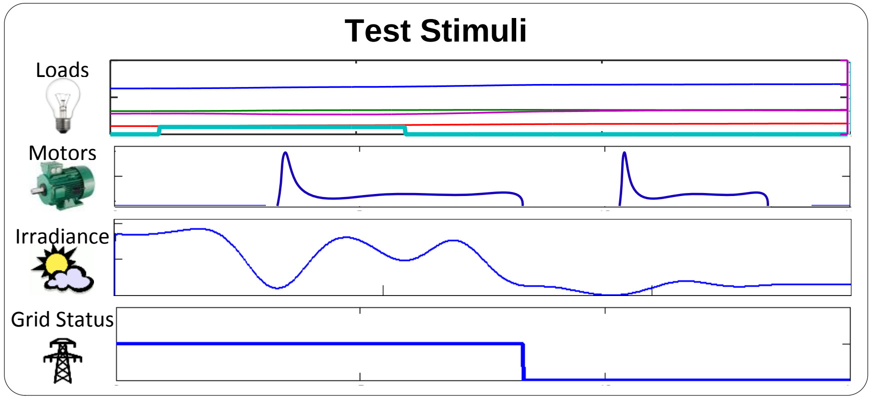
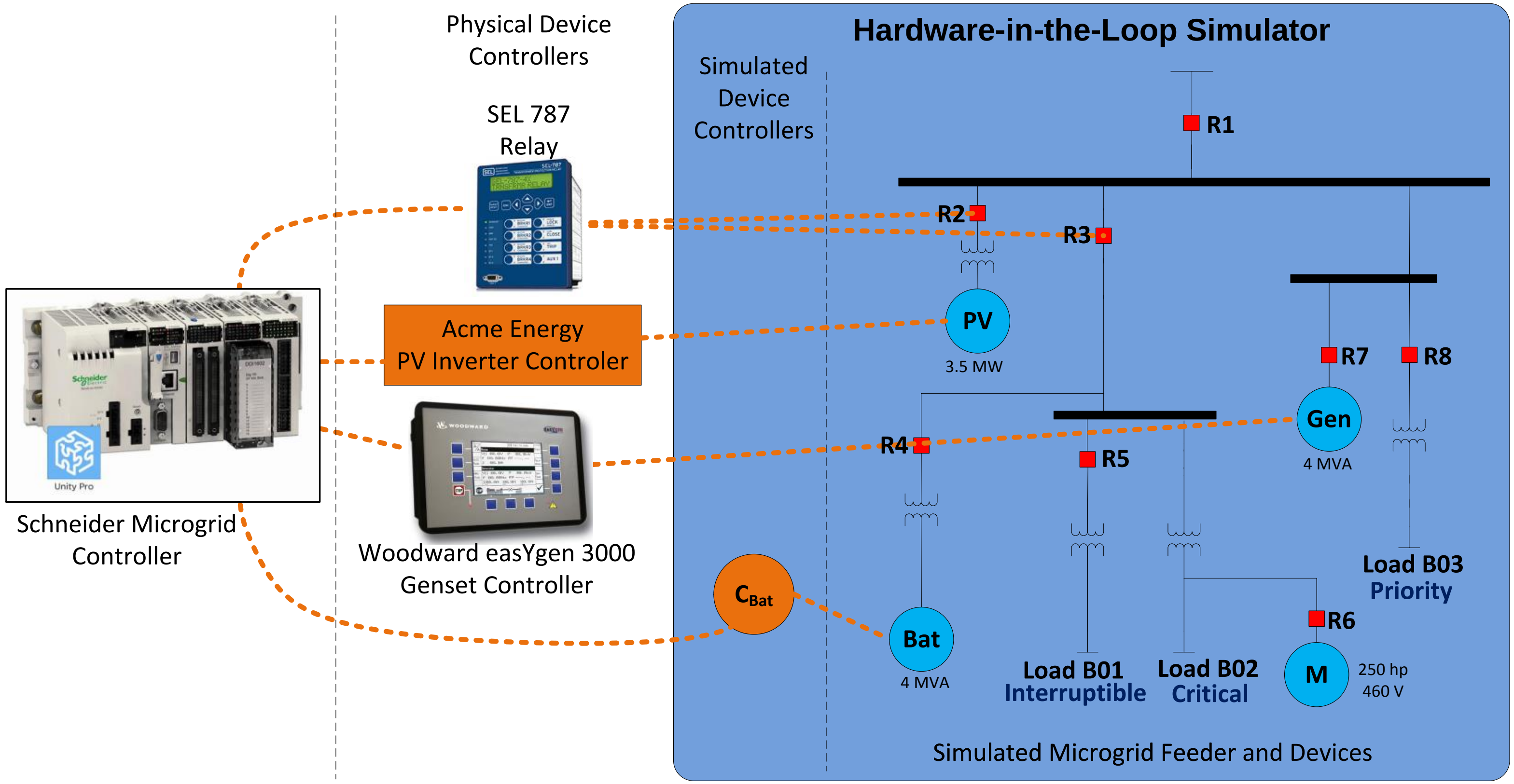
Elements of the Microgrid Controller HIL Platform

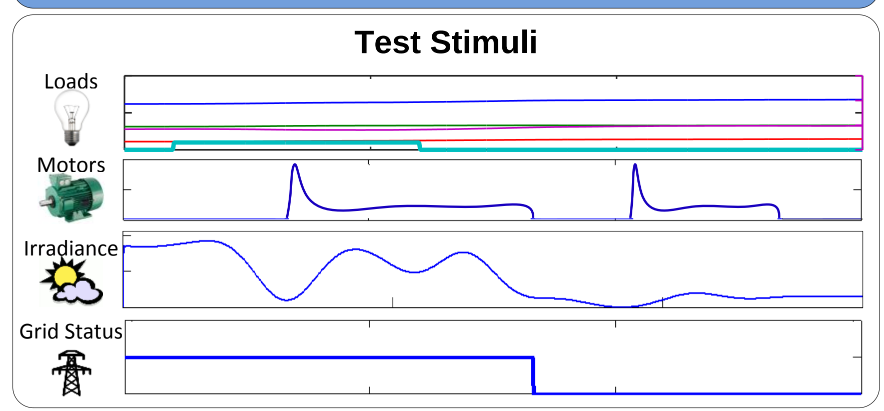




…or add commercial controllers as hardware-in-the-loop

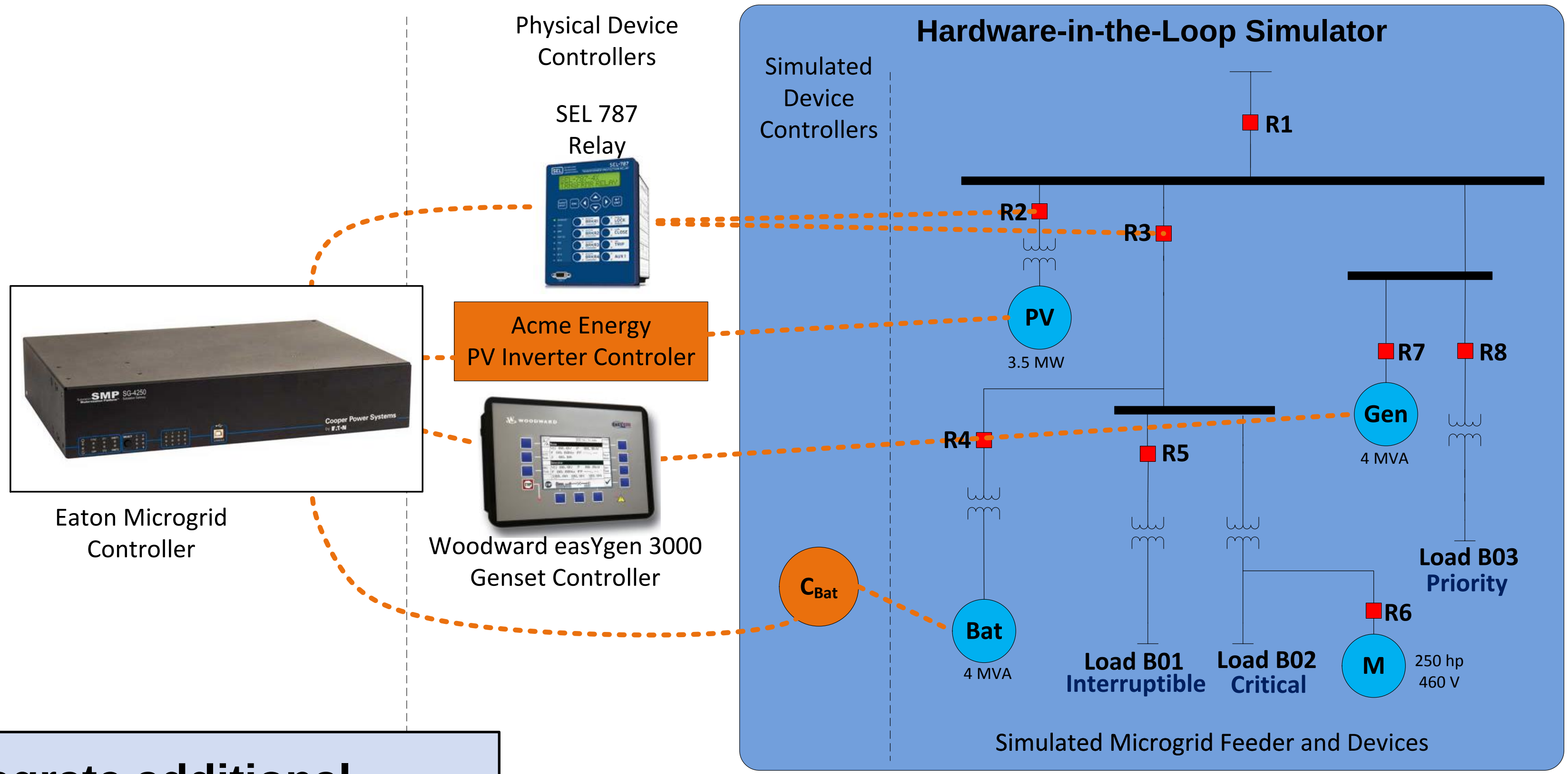
Elements of the Microgrid Controller HIL Platform

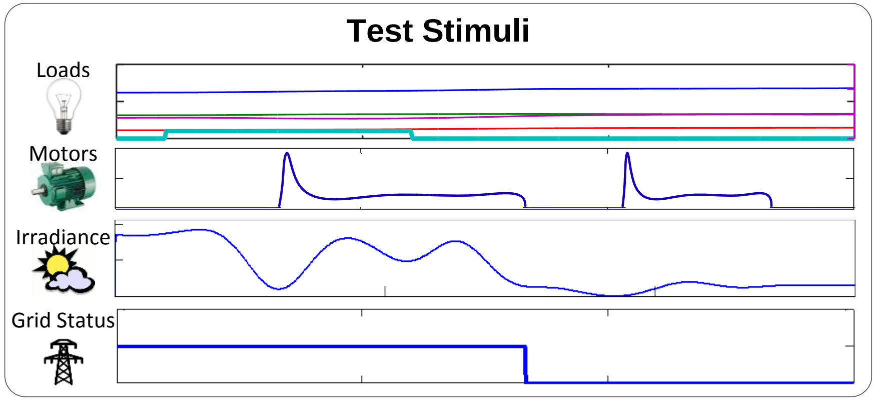




Integrate a microgrid controller

Elements of the Microgrid Controller HIL Platform





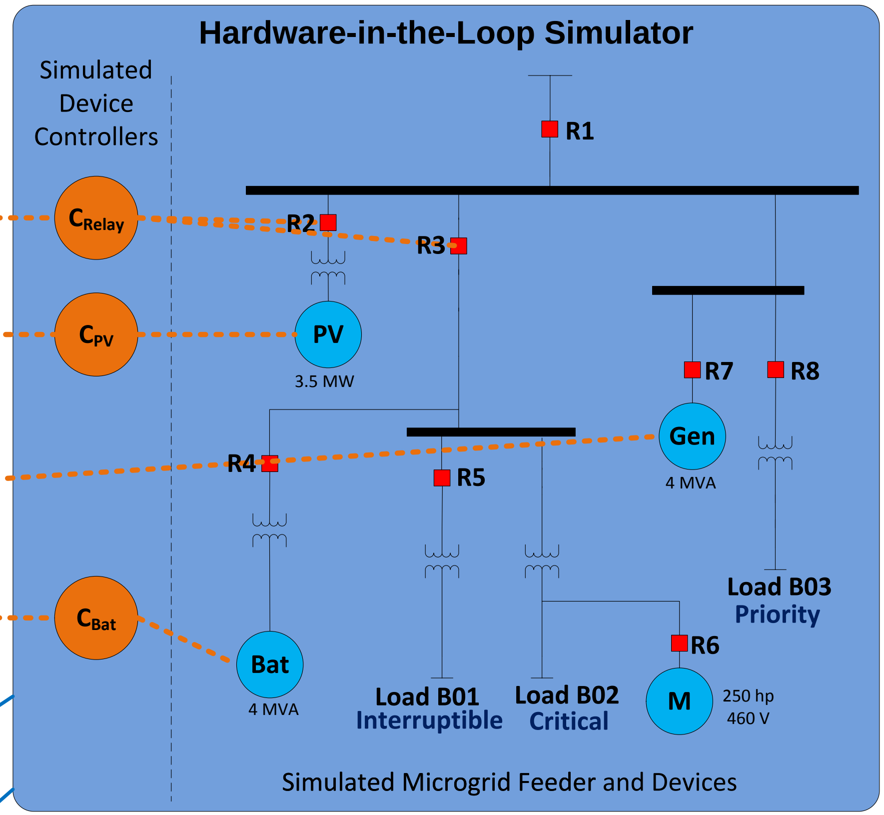
Integrate additional microgrid controllers
- **Vendor capability demonstration**
- **Performance comparison**

Elements of the Microgrid Controller HIL Platform

Physical Device Controllers

Add data visualization, collection, and post-processing

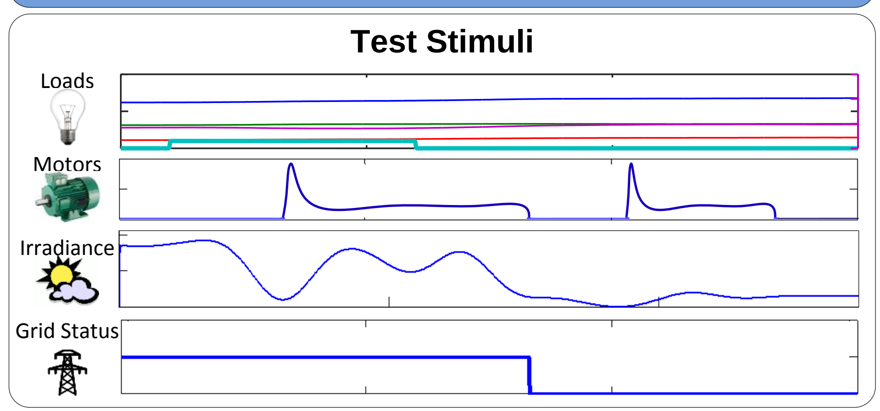
- **Real-time operation**
- **Performance analysis**



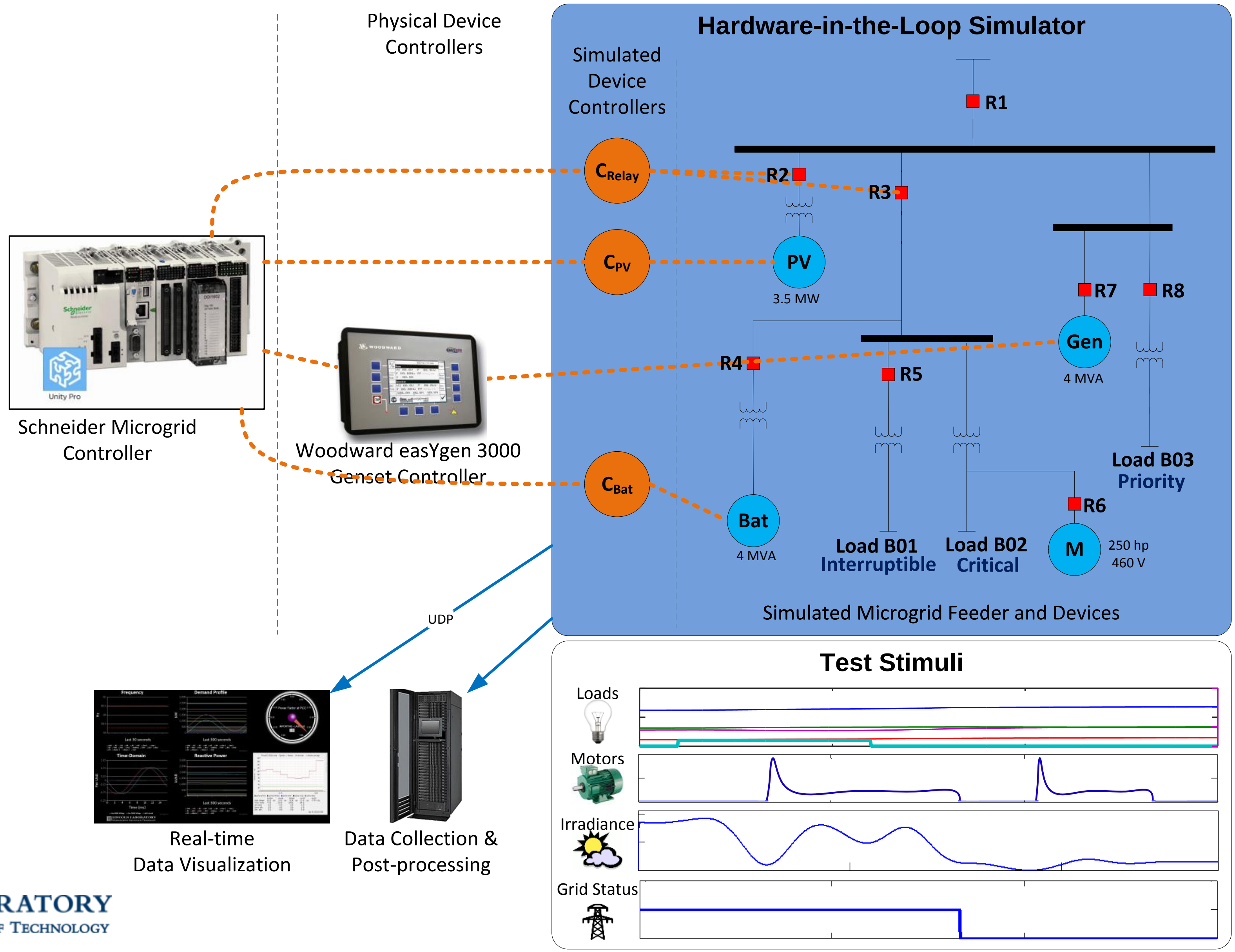
UDP

Real-time
Data Visualization

Data Collection &
Post-processing



Microgrid Controller HIL Platform



Vision for the Microgrid Controller HIL Platform

– 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

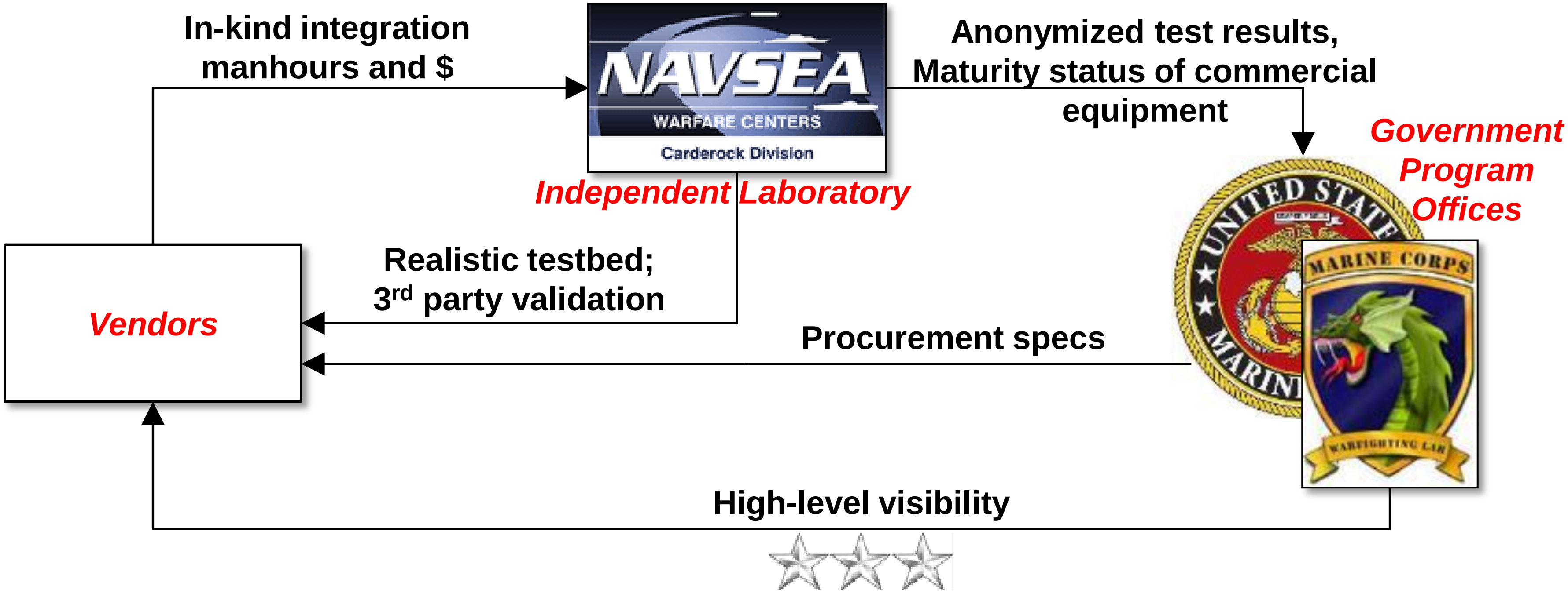
- Industry-standard test platform for new power systems
- *Test against IEEE P2030.8 standard and utility requirements*

– 4 –
Electric Power Controls Consortium (EPCC) Shared Repository

October 1 Massachusetts Microgrid Controls Symposium

Demo-centric Tech. Evaluation

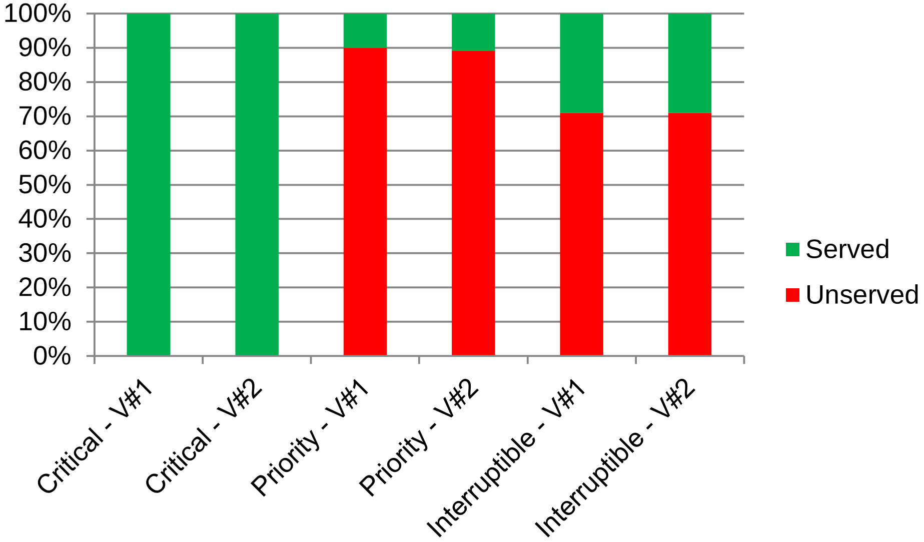
U.S. Marine Corps' ExFOB Example



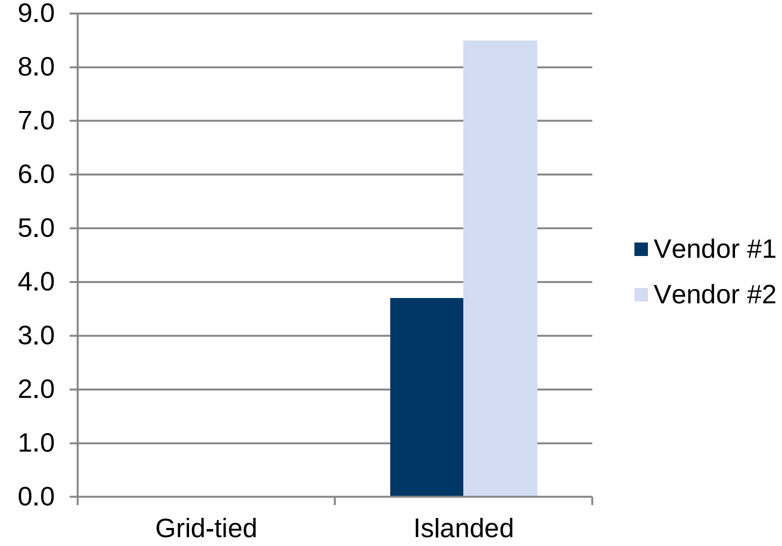
ExFOB 2013 – Twentynine Palms

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

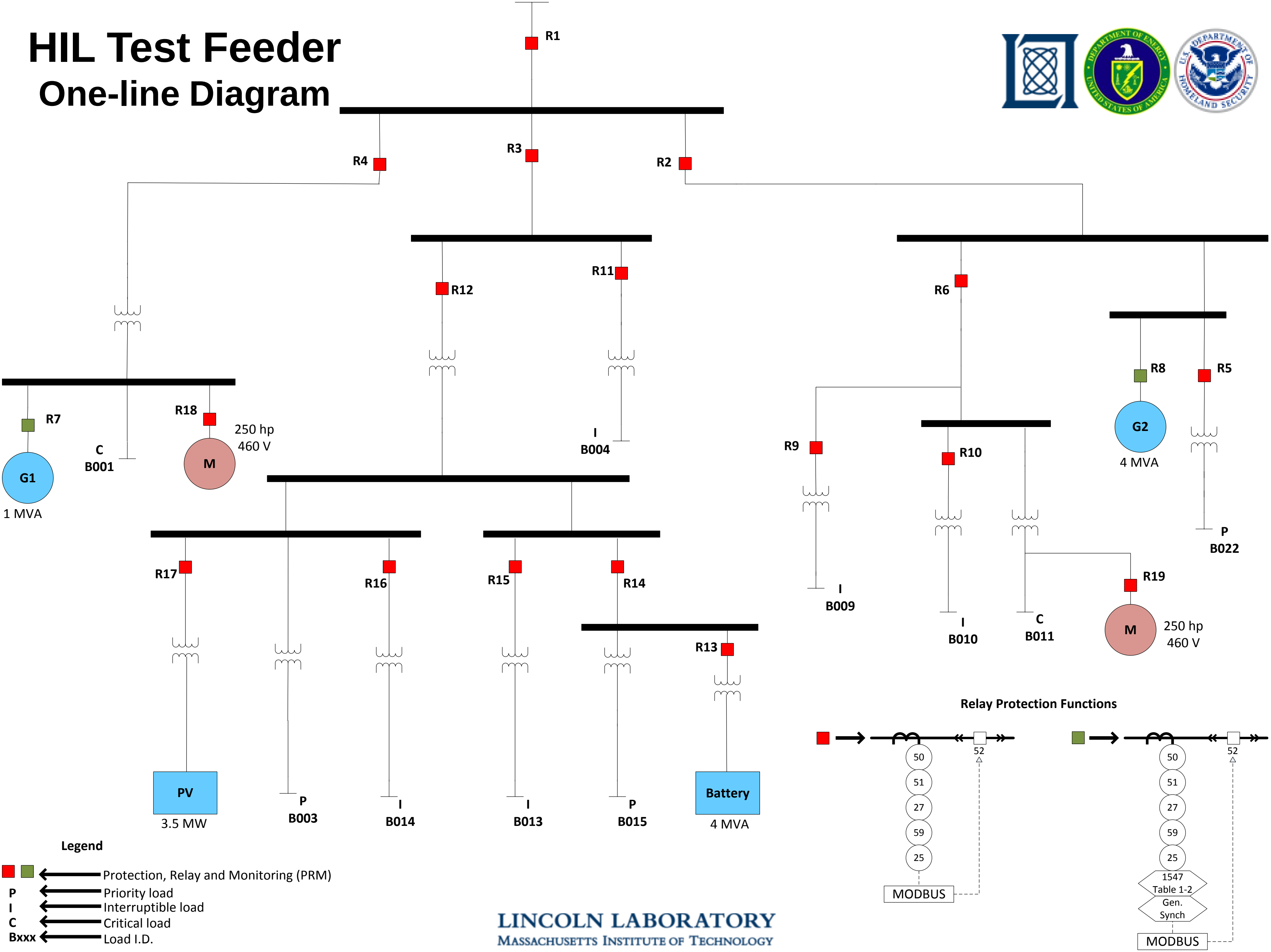
	Grid-tied			Islanded
	Fuel Used (gal.)	Energy Imported (kWh)	Energy Exported (kWh)	Fuel Used (gal.)
Vendor #1	**5.7**	**317**	**14**	**5.0**
Vendor #2	**6.3**	**272**	**38**	**5.9***
Difference	***+11%***	***-14%***	***+170%***	***+18%***

* 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

HIL Test Feeder
One-line Diagram



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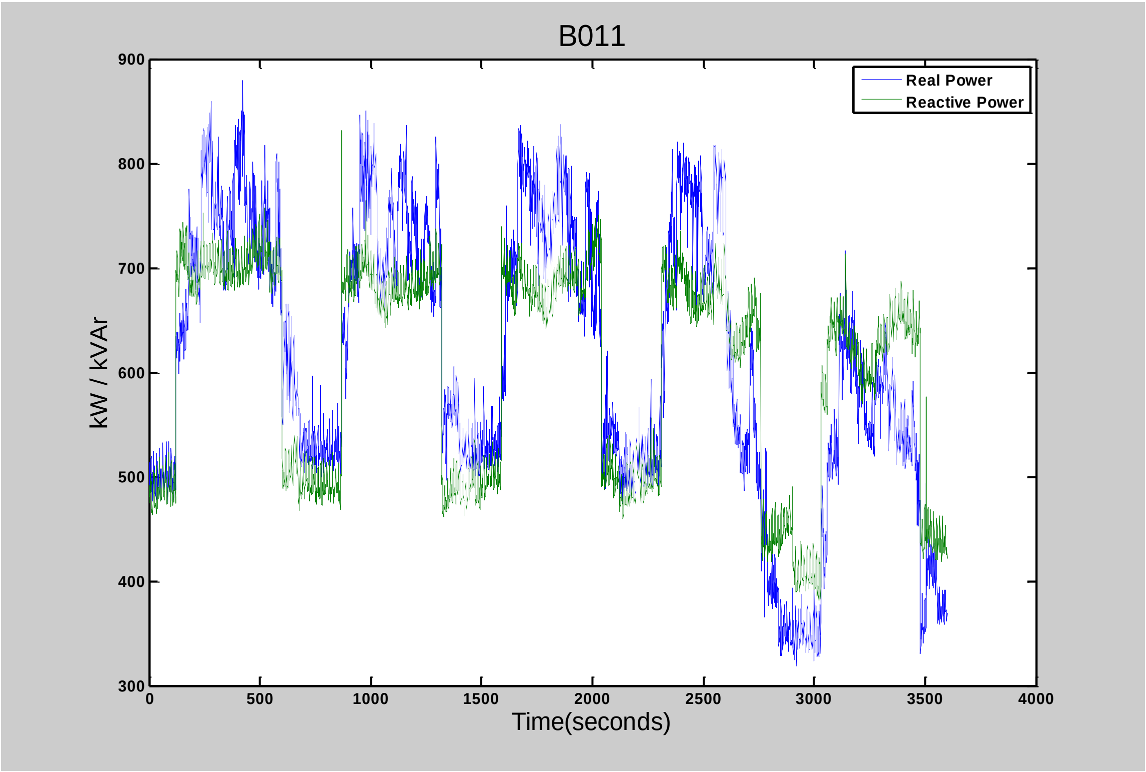
Example Load (B011)



- **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

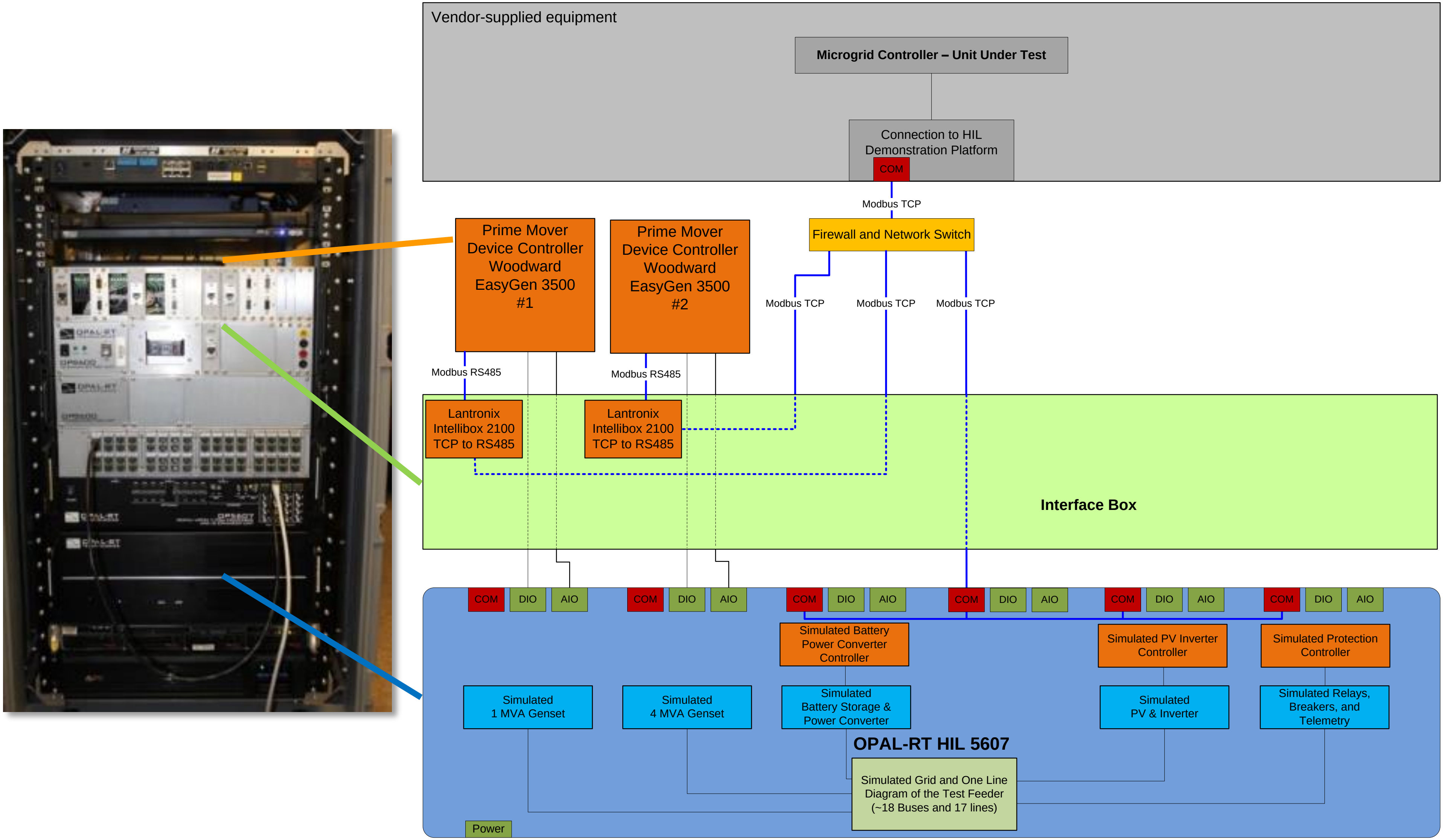
Opal-RT HIL Target

MIT Lincoln Lab Windows Server

Power Supply

Two integrated Woodward easYgen 3000 genset controllers

HIL Platform Block Diagram



Device Address List

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

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

	Battery Rating	PV Rating
AC Power Rating (kVA)	4,000	3,500
Storage (kWh)	500	n/a
Cycle Life	∞	n/a
Voltage (V)	2,400	2,400
Frequency (Hz)	60	60
Ramp Rate	8 MW/s	2.5 MW/min

Battery and PV system ratings and characteristics

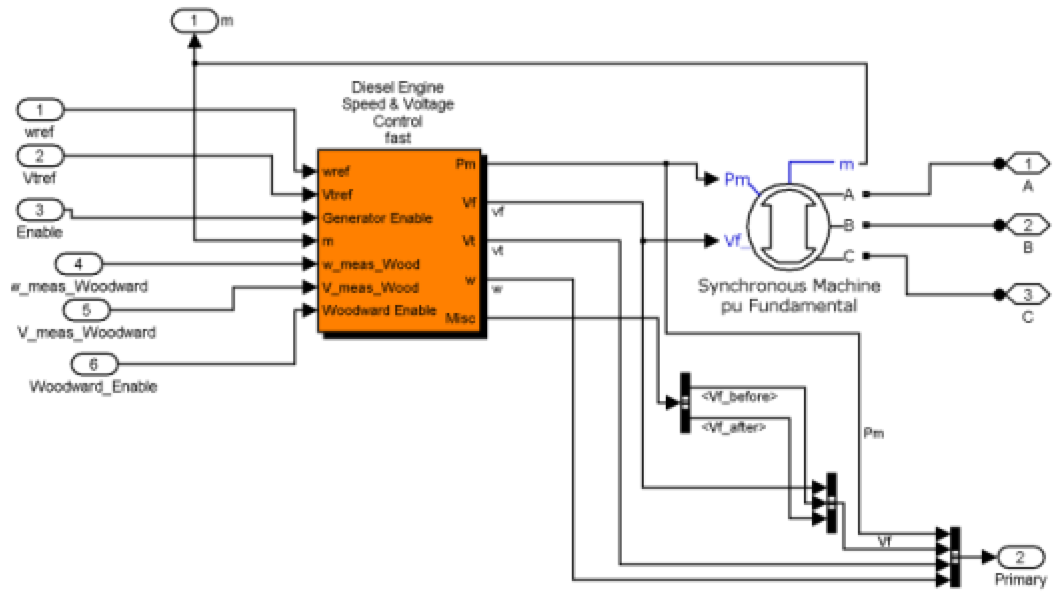
Parameter	Units	Notes
Real Power Command	kW	(-) discharge; (+) charge
Reactive Power Command	kVAR	(+) capacitive; (-) inductive
Modbus Enable	0/1	1 to indicate active Modbus connection.
Fault Status		Phase A Over Current Phase B Over Current Phase C Over Current DC Link Overvoltage PLL Loss of Sync Vrms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

Register list for battery system device controller

Simulated Genset Block

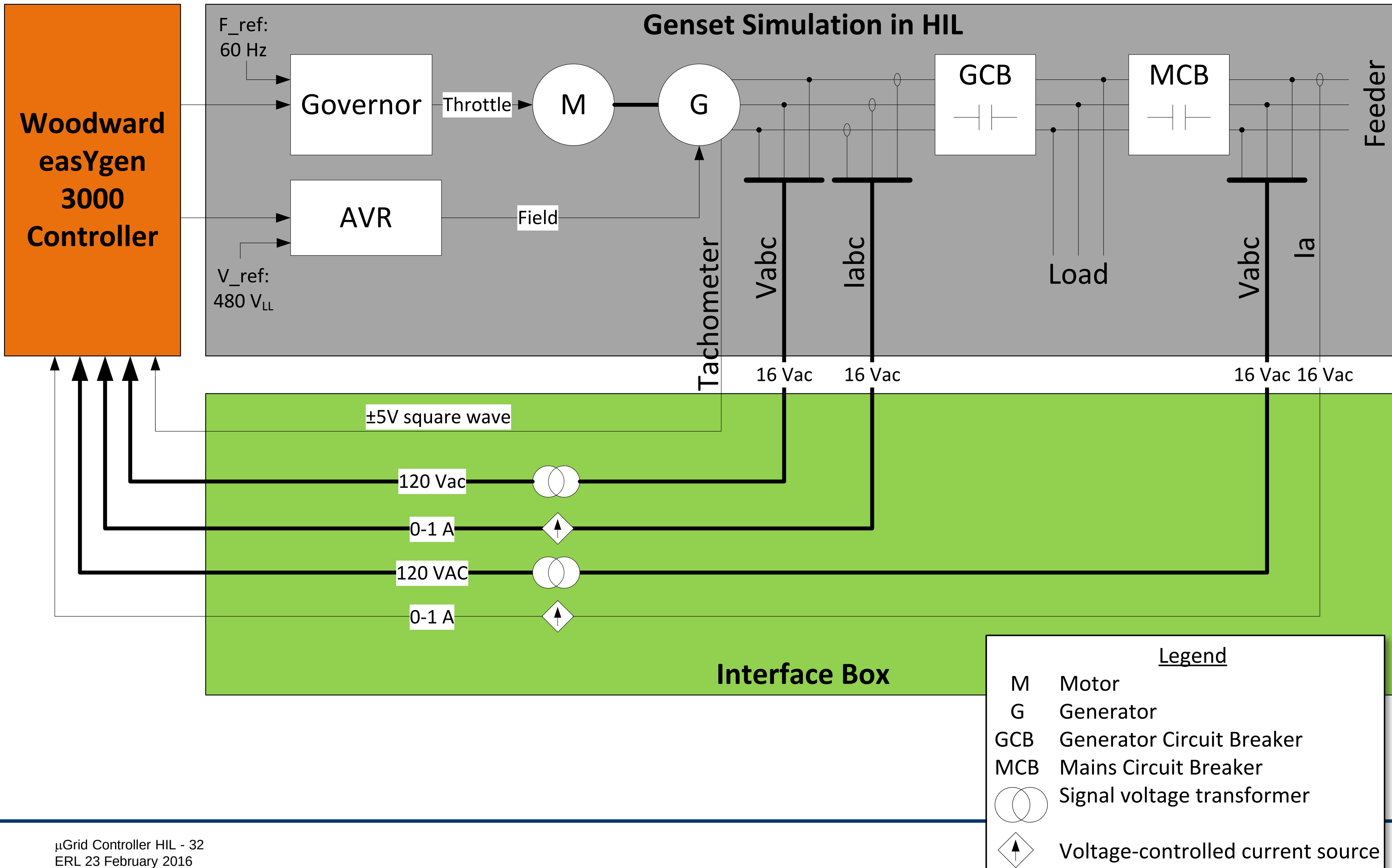
	1 MW Genset	4 MW Genset
Manufacturer / Model	CAT C32	CAT C175-20
Rating (kVA)	1,000	4,000
Power Factor	TBD	TBD
Voltage (V)	480	13,800
Frequency (Hz)	60	60
Speed (RPM)	1800	1800
Minimum Output Power	25kW	100kW
Startup Time	<10 sec	<15 sec

Genset ratings and characteristics



Synchronous Machine, Governor, and AVR Models

Device Controller Integration: Woodward easYgen 3000



Simulated Relay: SEL-787 Transformer Protection Relay

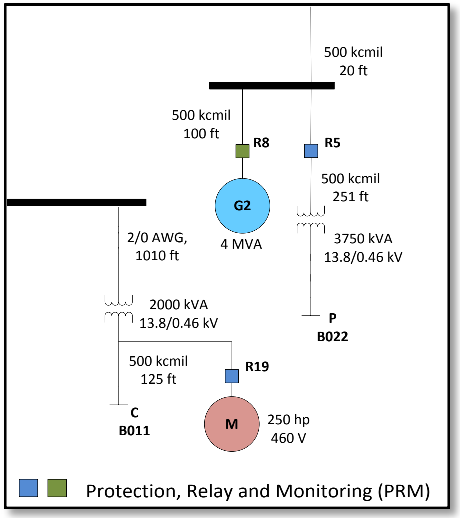
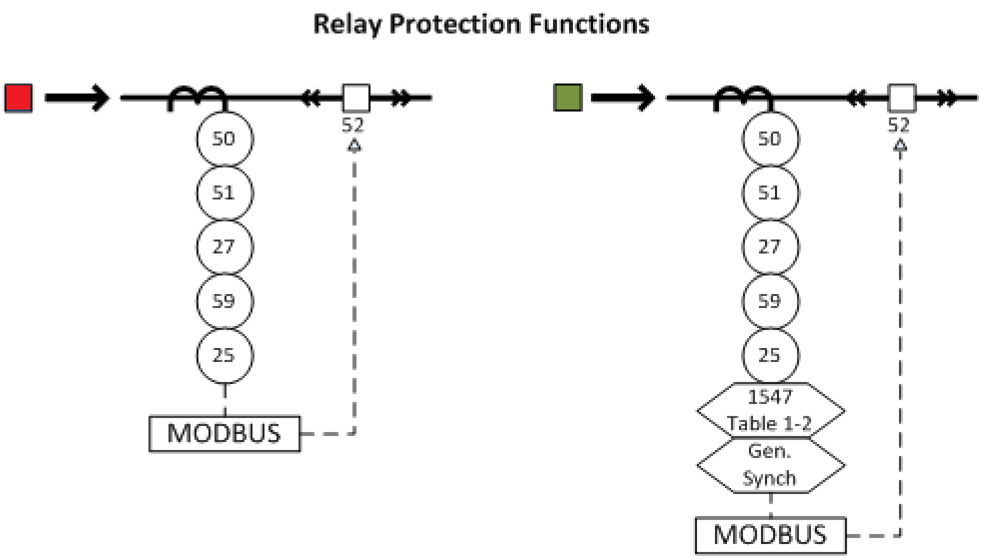


Image: Schweitzer Engineering



Protection Function	
ANSI 50	Inst. overcurrent
ANSI 51	Avg. overcurrent
ANSI 27	Undervoltage
ANSI 59	Overvoltage
ANSI 25	Synchronism-check
1547 Tables 1&2	Abnormal V & f
Gen. Synch	Generator synch
ANSI 52	AC Circuit Breaker

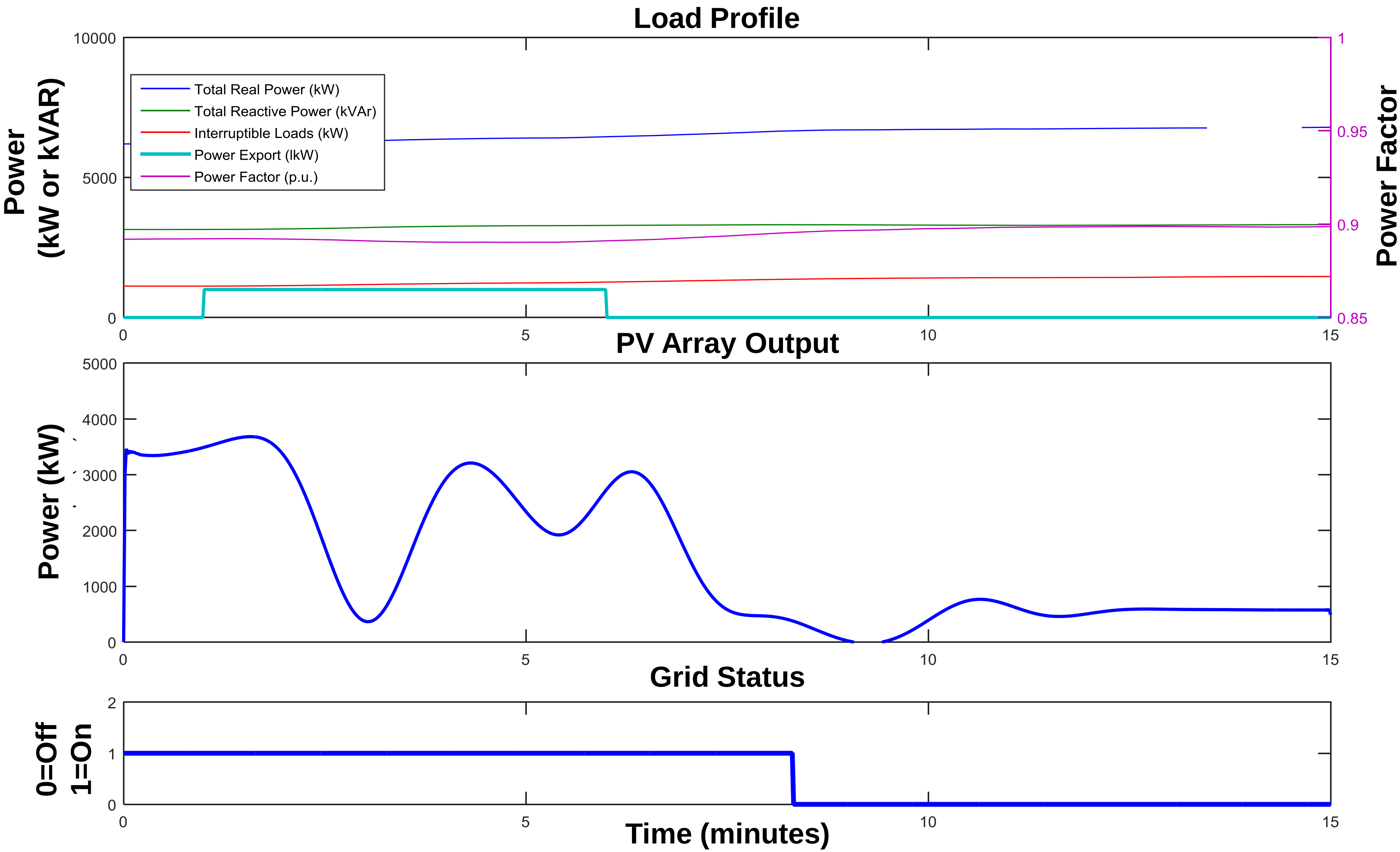
Demonstration against ORNL/EPRI Microgrid Functional Use Cases

Functional Use Case	Description	Demonstration
F-1 Frequency Control	Selection of grid-forming, -feeding, and -supporting energy sources to maintain stability; sub-second control to maintain stable frequency while islanded	The microgrid controller selects from among the two gensets and battery DERs.
F-2 Voltage Control	Regulate voltage at the microgrid point of common coupling	No demo
F-3 Intentional Islanding	Planned disconnect from area electric power system (AEPS)	Islanding will be initiated by the microgrid controller
F-4 Unintentional Islanding	Fast disconnect from AEPS upon large disturbance to provide continuous supply to loads	No demo due to battery and PV inverter controller PLL instability
F-5 Transition from Islanded to Grid-tied	Resynchronize and reconnect to AEPS	Initiated by microgrid controller once generators and grid synchronize

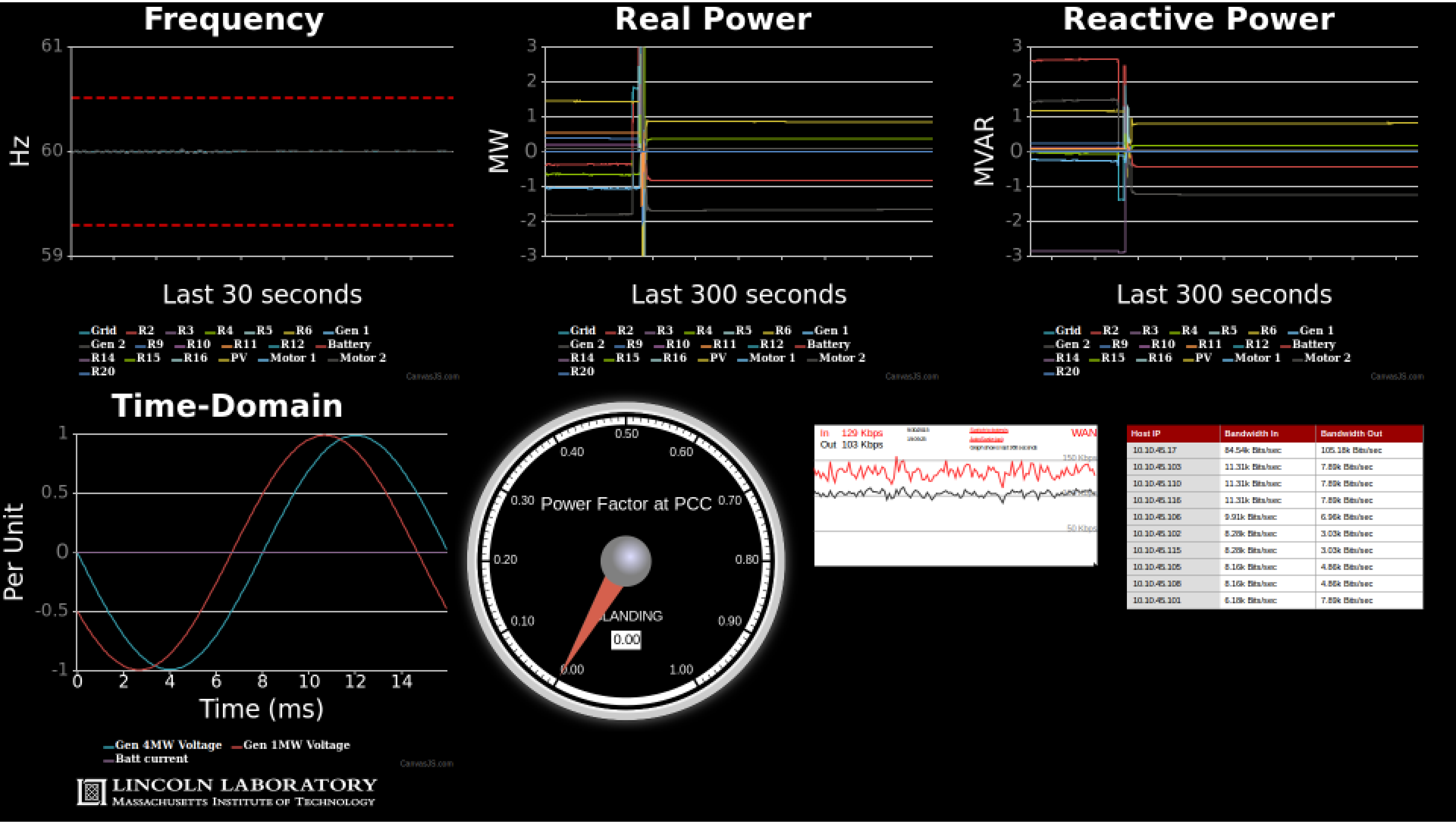
Demonstration against ORNL/EPRI Microgrid Functional Use Cases (cont.)

Functional Use Case	Description	Demonstration
F-6(a) Energy Management: grid-tied	Coordinate generation, load, & storage dispatch, to participate in utility operation and energy market activities	The microgrid controllers target a power export value for a defined period, and should also shave peak demand.
F-6(b) Energy Management: islanded	Coordinate generation, load, & storage dispatch, to optimize islanded operation (fuel consumption, islanding duration)	Fuel consumption and service of critical and priority loads are measured during islanded operation.
F-7 Microgrid Protection	Configure protection devices for different operating conditions	DER and relay protection are implemented, but are not configurable.
F-8 Ancillary Services: regulation	Provide frequency regulation, generation reserves, reactive power support, and demand response to AEPS	Demand response to hit a target power export value; Reactive power support to maintain unity power factor at PCC
F-9 Microgrid Blackstart	Restore islanded operation after a complete shutdown	Likely limited by present genset control capabilities
F-10 User Interface, Data Collection	Organize, archive, and visualize real-time and non-real-time data	Data collection and visualization performed by MIT-LL, not µC

15-minute Demonstration Sequence

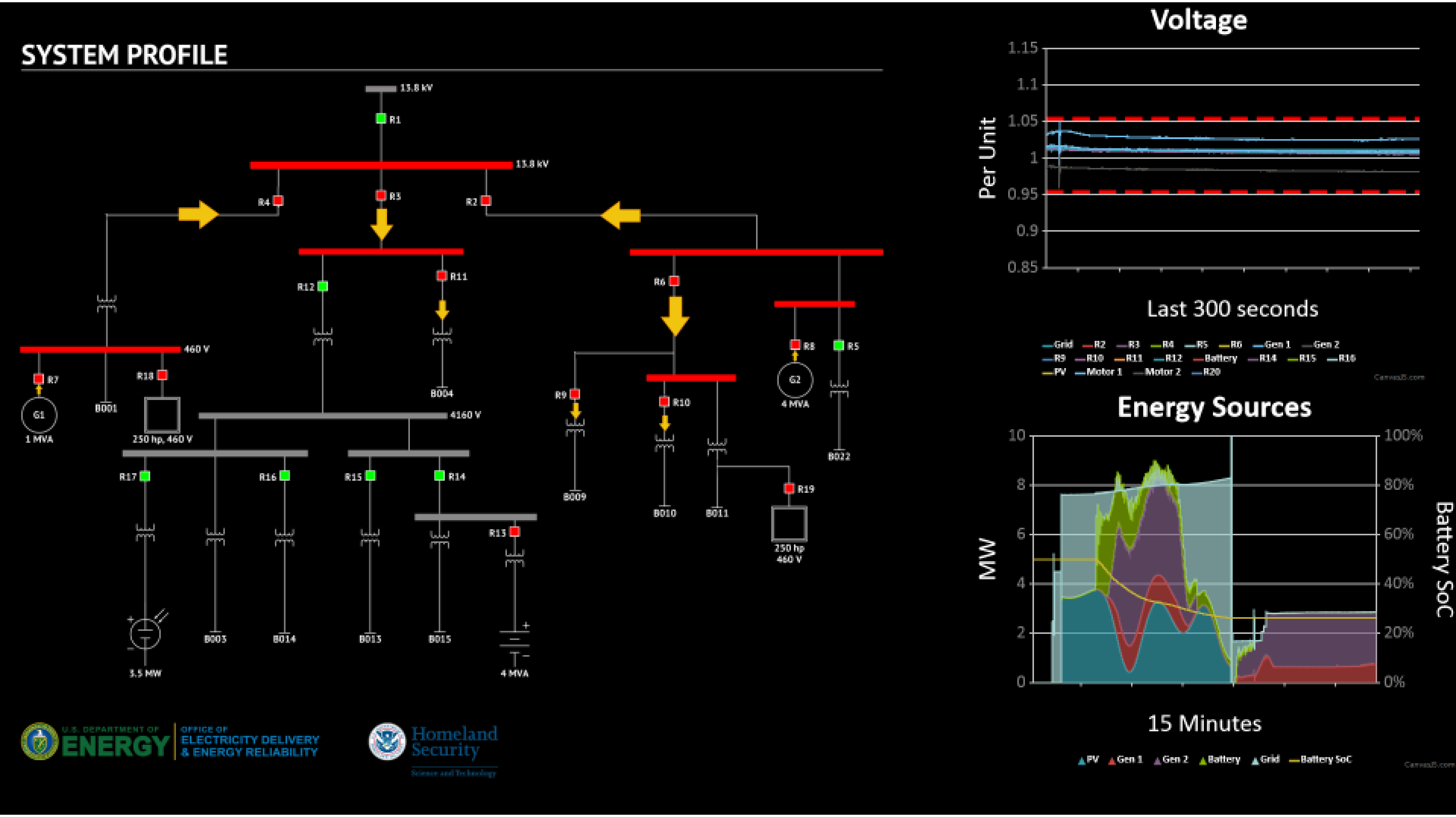


Heads-up Display (screen 1)



Host IP	Bandwidth In	Bandwidth Out
10.10.45.17	84.54k Bits/sec	105.18k Bits/sec
10.10.45.103	11.31k Bits/sec	7.89k Bits/sec
10.10.45.110	11.31k Bits/sec	7.89k Bits/sec
10.10.45.116	11.31k Bits/sec	7.89k Bits/sec
10.10.45.106	9.91k Bits/sec	6.96k Bits/sec
10.10.45.102	8.28k Bits/sec	3.03k Bits/sec
10.10.45.115	8.28k Bits/sec	3.03k Bits/sec
10.10.45.105	8.16k Bits/sec	4.86k Bits/sec
10.10.45.108	8.16k Bits/sec	4.86k Bits/sec
10.10.45.101	6.18k Bits/sec	7.89k Bits/sec

Heads-up Display (screen 2)



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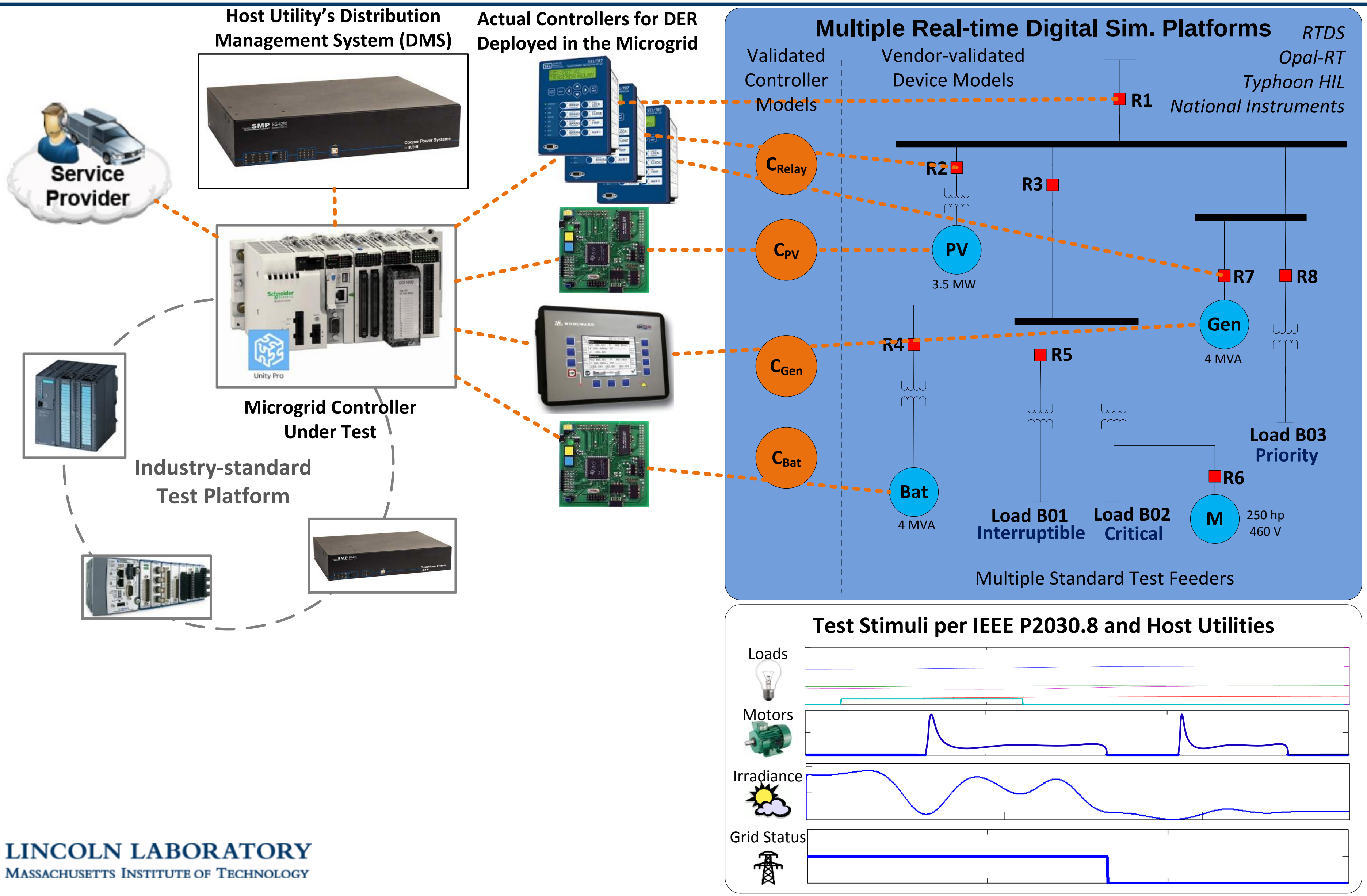
Outline

- **Introduction to Controller Hardware-in-the-Loop**
- **Orientation to Today's Demonstration**
- **Way Ahead**

Vision for Eventual HIL Capabilities



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

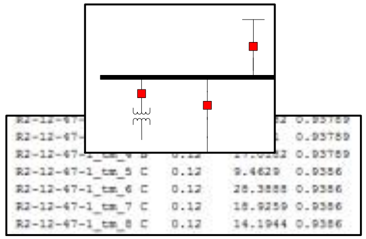
- Industry-standard test platform for new power systems
- *Test against IEEE P2030.8 standard and utility requirements*

– 4 –
Electric Power Controls Consortium (EPCC) Shared Repository

Elements of the EPCC Shared Repository

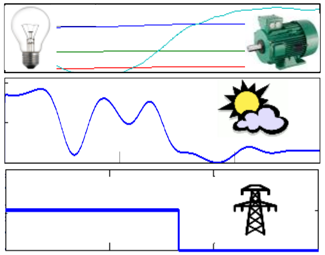
Microgrid Test Repository

Microgrid Test Feeders



Netlists

Standard Test Stimuli

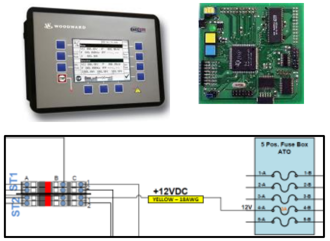


Load profiles, irradiance profiles, grid outages, faults

Post-processing Scripts for Test Results

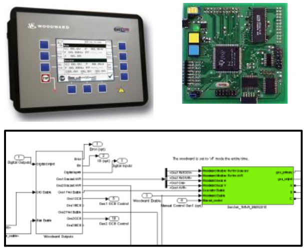
Controller-in-the-Loop Repository

Interface Circuitry for Device Controllers



Circuit schematics, bills of materiel

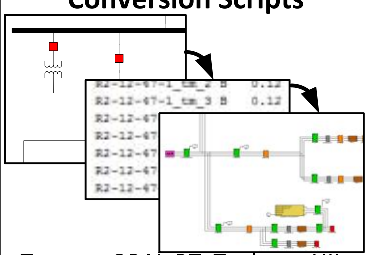
Interface Code for Device Controllers



Communications Interface Translation Code

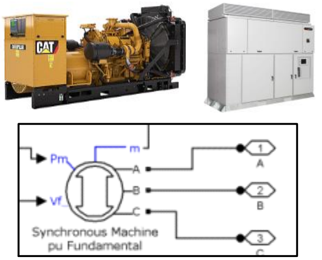
HIL Platform Repository

HIL Target Platform Conversion Scripts



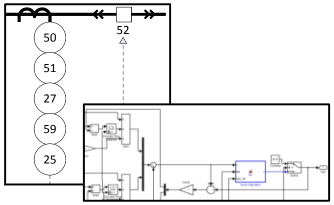
Targets: OPAL-RT, Typhoon HIL, RTDS, NI, and others

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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Power Systems HIL Platform