Microgrid Controller Hardware-in-the-Loop Demonstration Platform

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Homeland Security
Science and Technology

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

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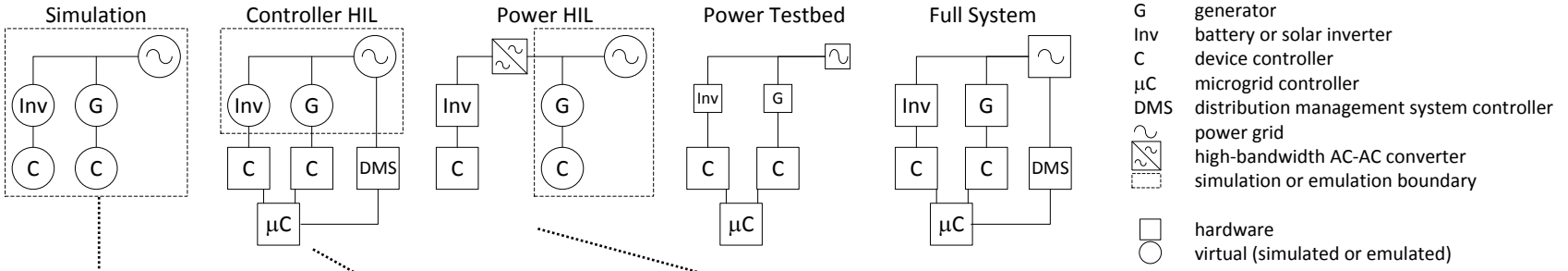
How Do We Accelerate Microgrid Deployment?

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



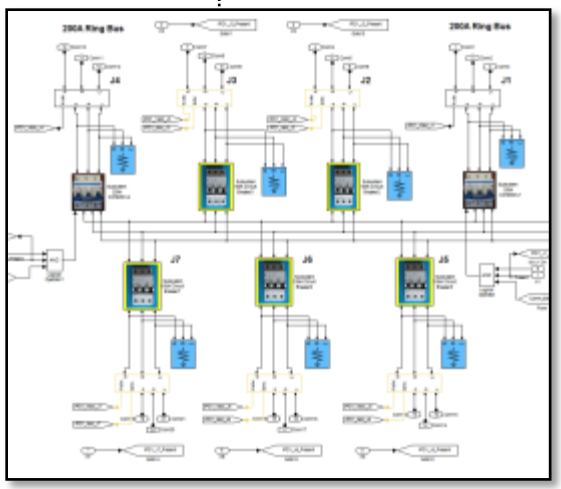
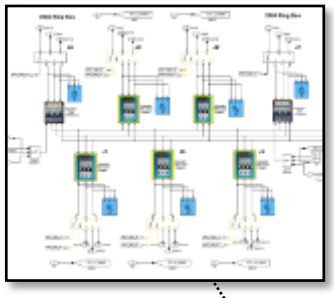


Image: Florida State Univ. CAPS

Power Simulation: Flight Simulator Analogy

Matlab SimPowerSystems simulation (not real-time)



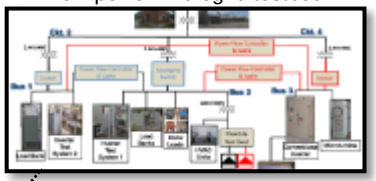
Actual device and microgrid controller with real-time simulation

(Microgrid controller HIL)

Real-time simulation coupled with power electronics testbed

(Florida State CAPS facility)

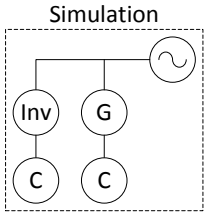
Low-power microgrid testbed

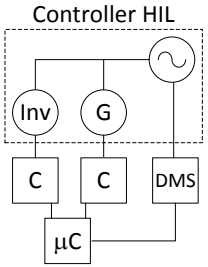


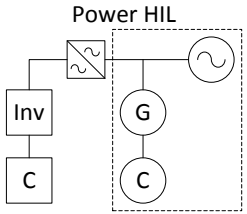
(DECC Microgrid Lab)

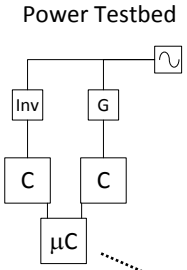
Actual microgrid

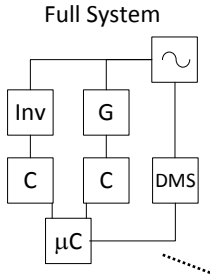
(Princeton U. cogen plant)











Legend

G	generator
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

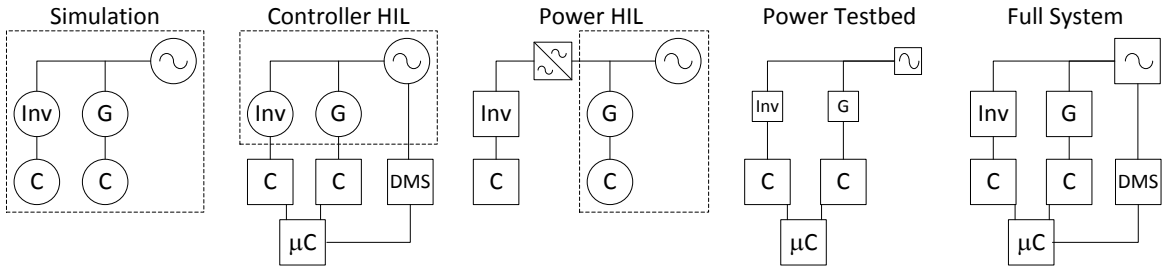
Moving cockpit, field-of-view visualization

Trainer aircraft

Passenger-carrying aircraft

Microgrid Controller Hardware-in-the-Loop (HIL) Testbed

Types of Controller Testbeds



Testbed Cost					
Test Fidelity					
Test Coverage					

Legend

G	generator
Inv	battery or solar inverter
C	device controller
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Microgrid Controller Hardware-in-the-Loop (HIL) Testbed

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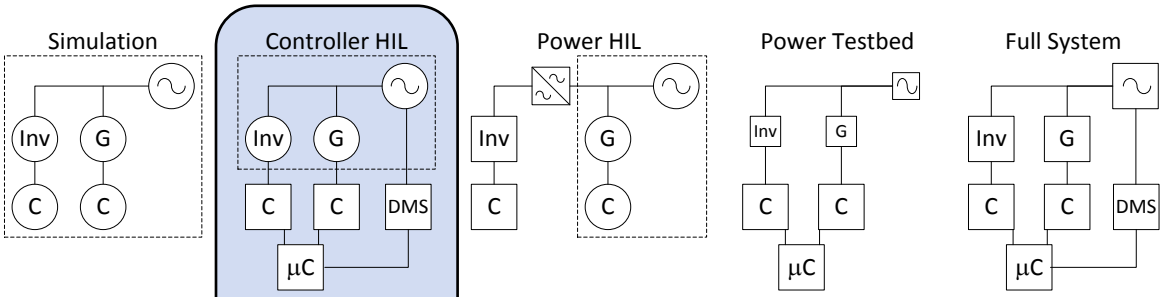


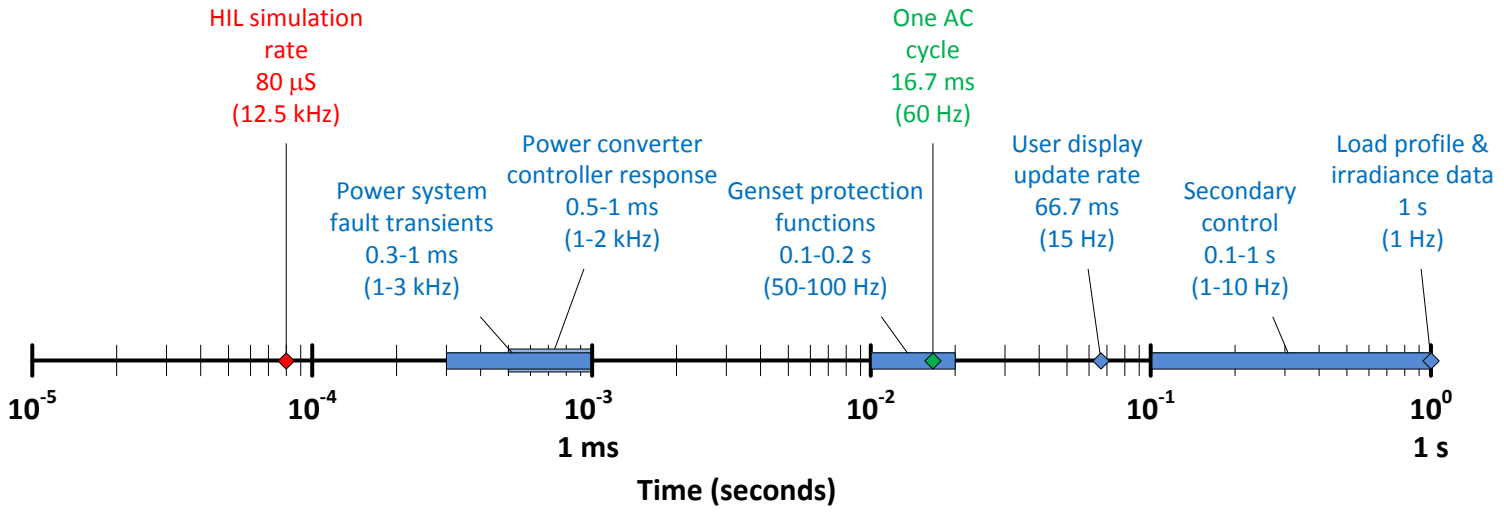
	Simulation	Controller HIL	Power HIL	Power Testbed	Full System
Testbed Cost					
Test Fidelity					
Test Coverage					

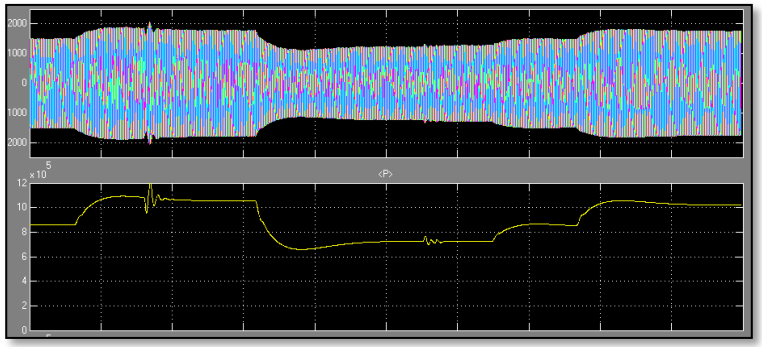
Legend

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)

High-fidelity Real-time Simulation

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

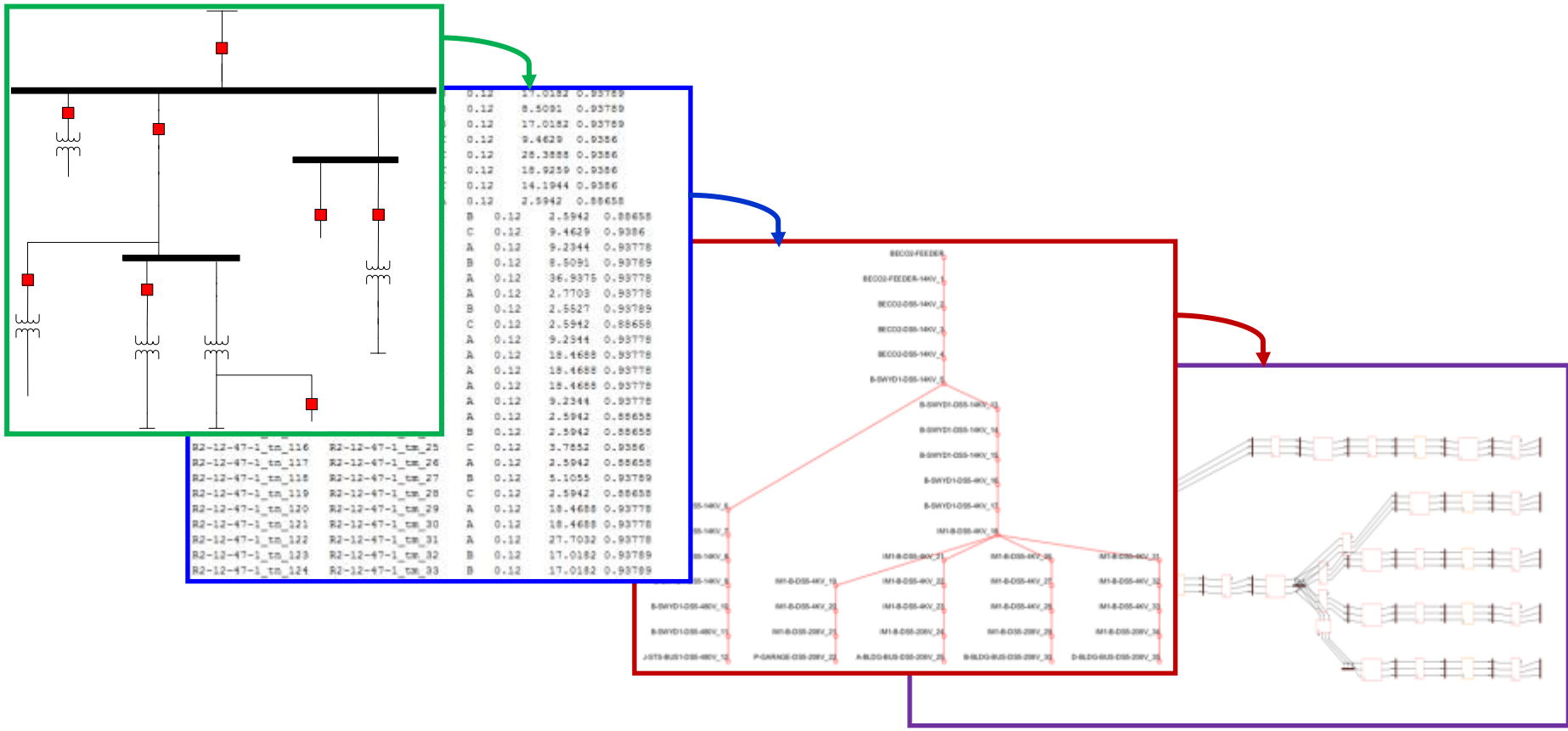




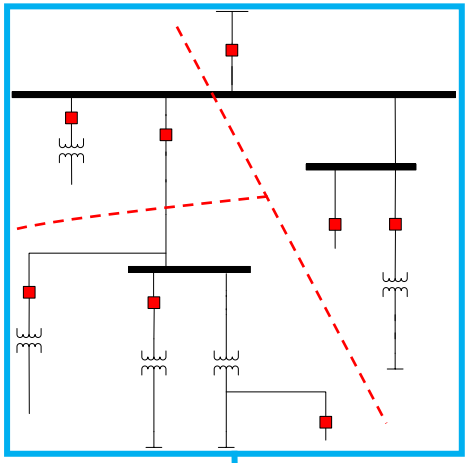
Construction of Detailed Microgrid Test Feeder Model

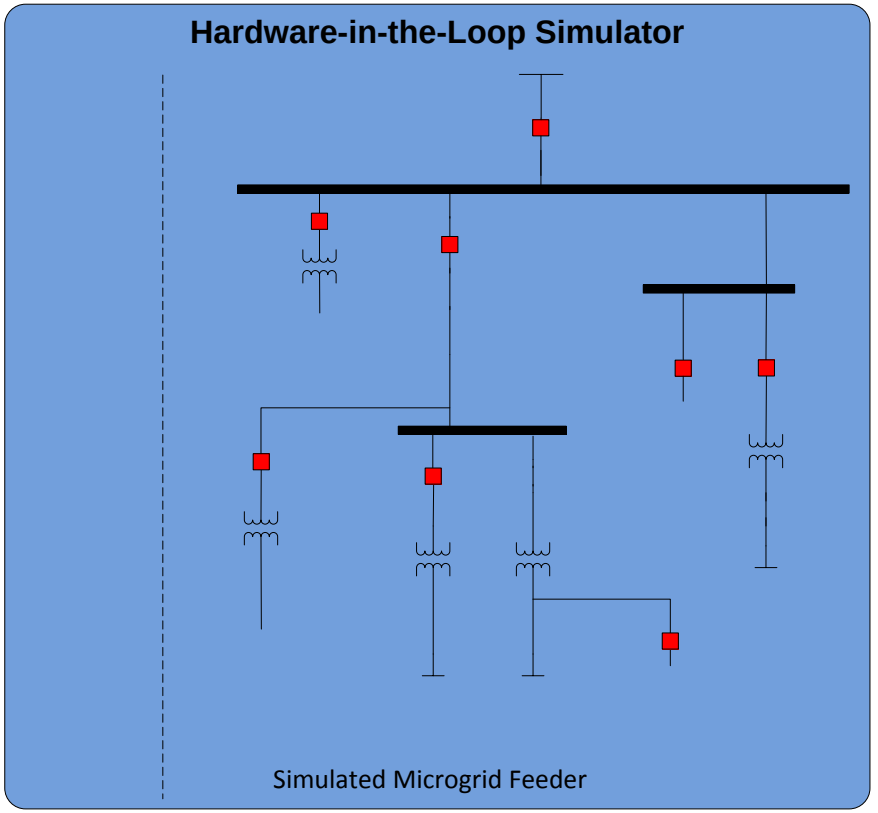
Automated with scripting

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



Elements of the Microgrid Controller HIL Platform

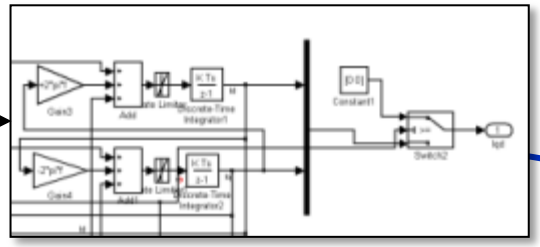




Load the feeder model into the HIL simulator "target"

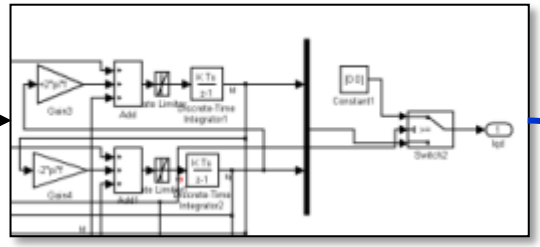
Elements of the Microgrid Controller HIL Platform

Solar Inverter



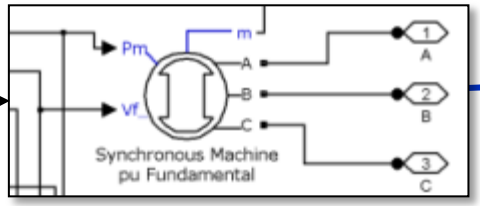
Power Electronics Model

Bidirectional Power Converter

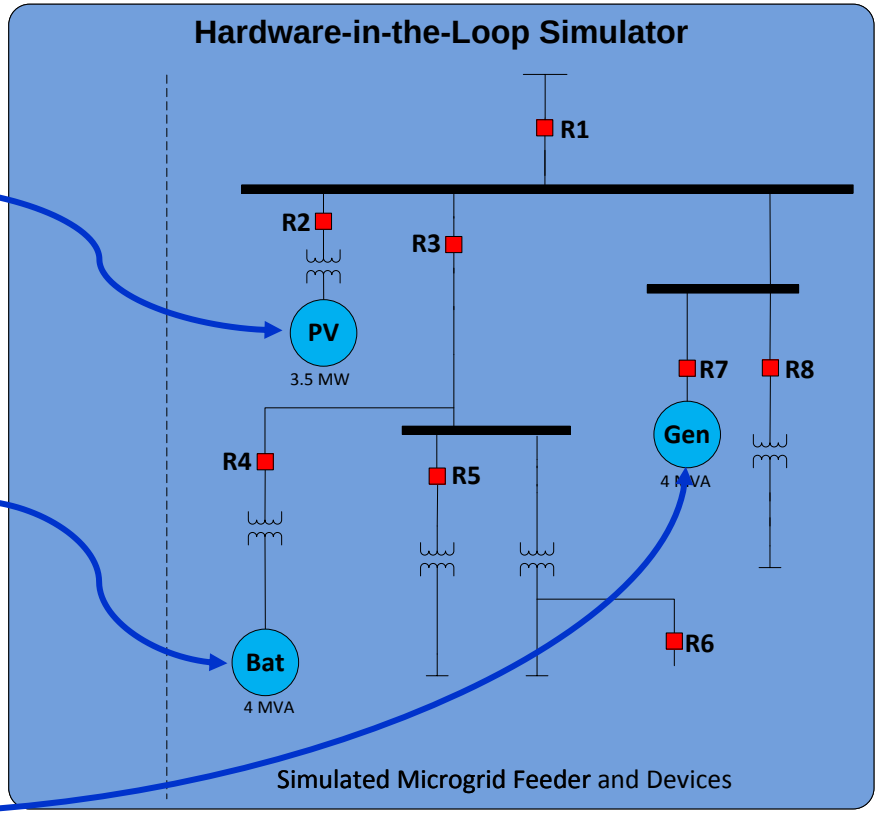


Power Electronics Model

Genset

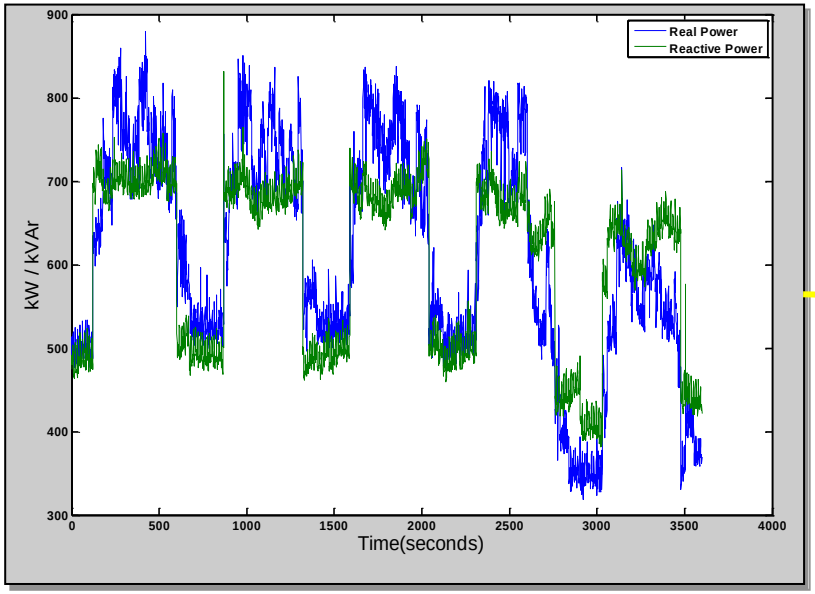


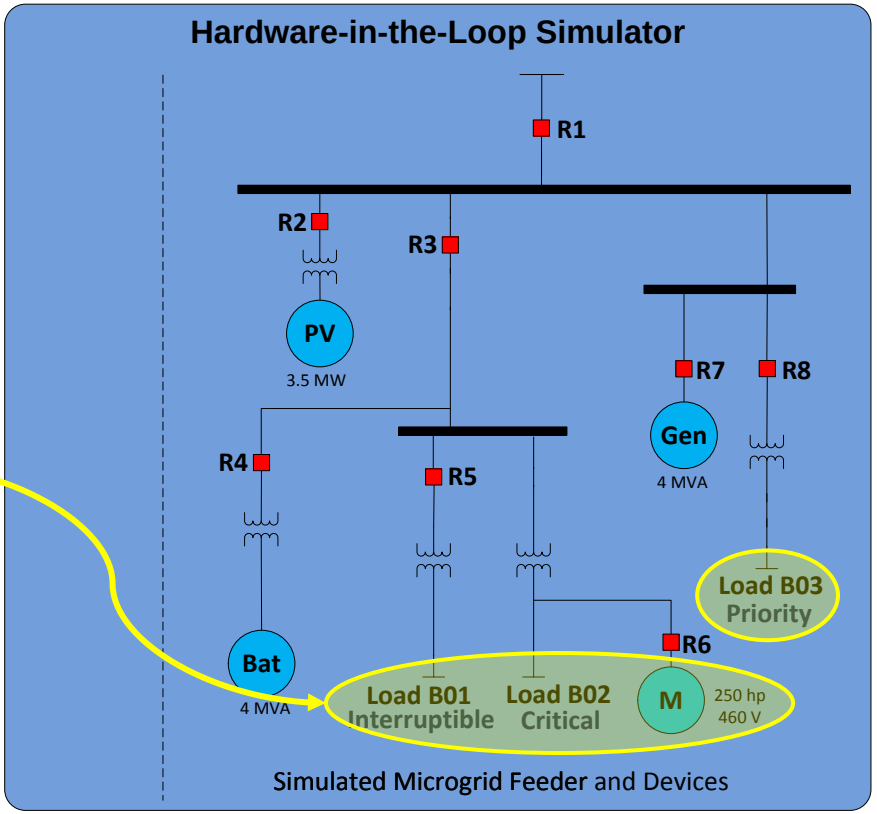
Machine Model

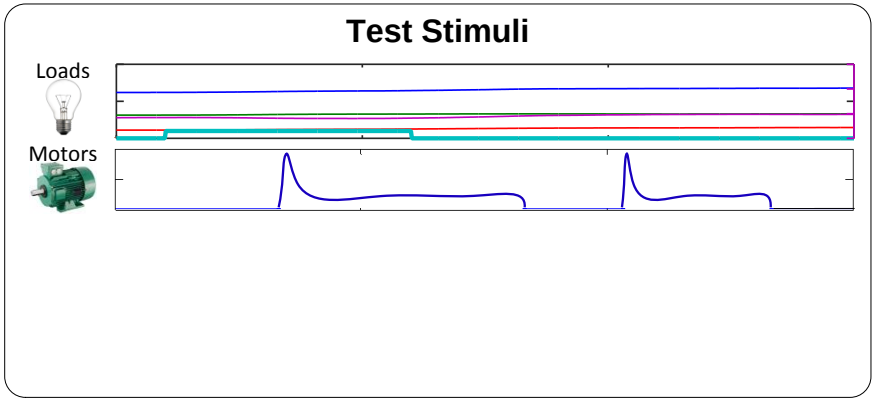


Create detailed models of the DER devices

Elements of the Microgrid Controller HIL Platform



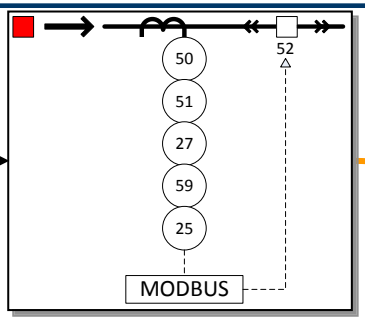




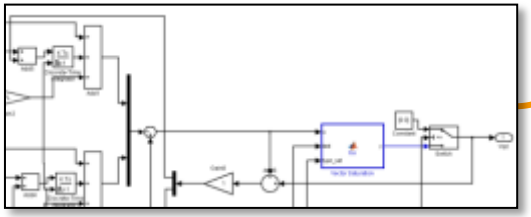
Add load profiles and assign load priorities

Elements of the Microgrid Controller HIL Platform

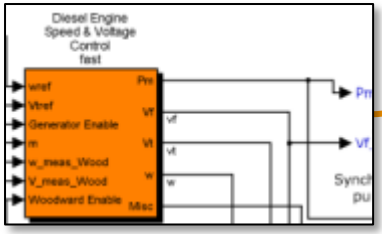
Relay



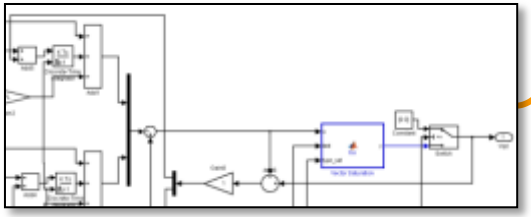
Relay Protection Functions



Inverter Control

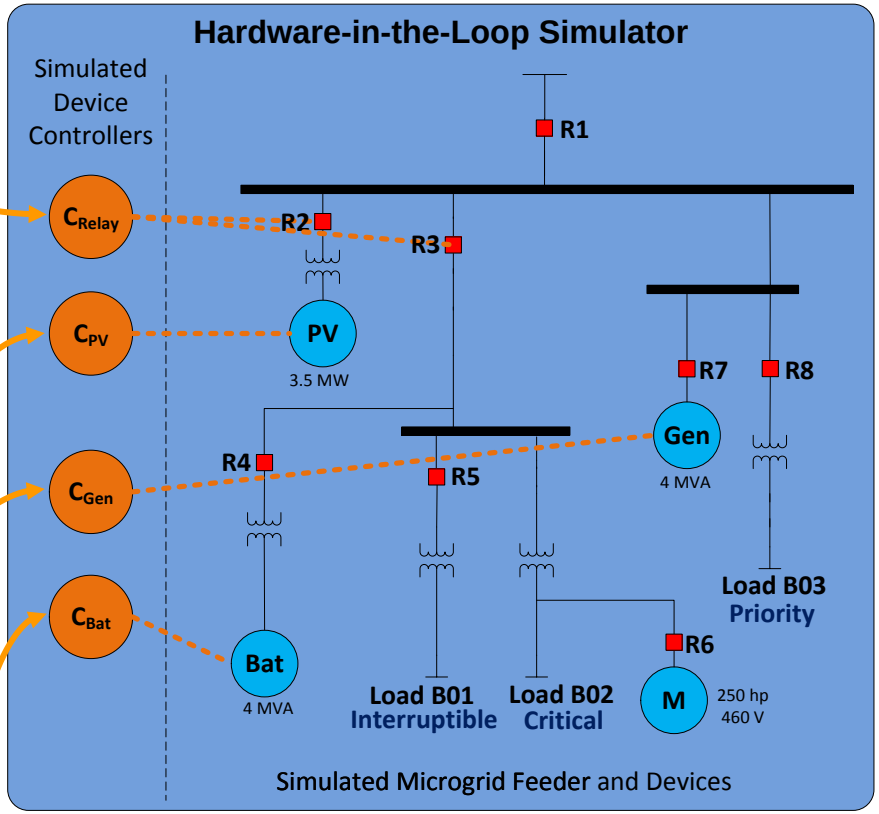


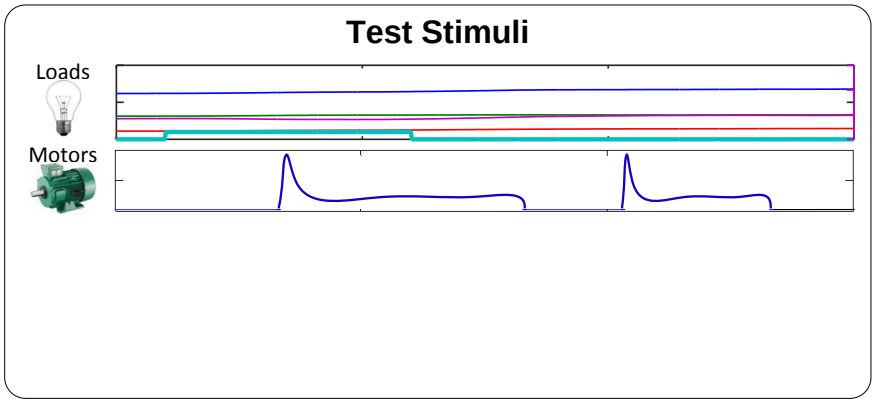
Genset Primary & Secondary Control



Bidirectional Power Converter Control

Implement DER control algorithms





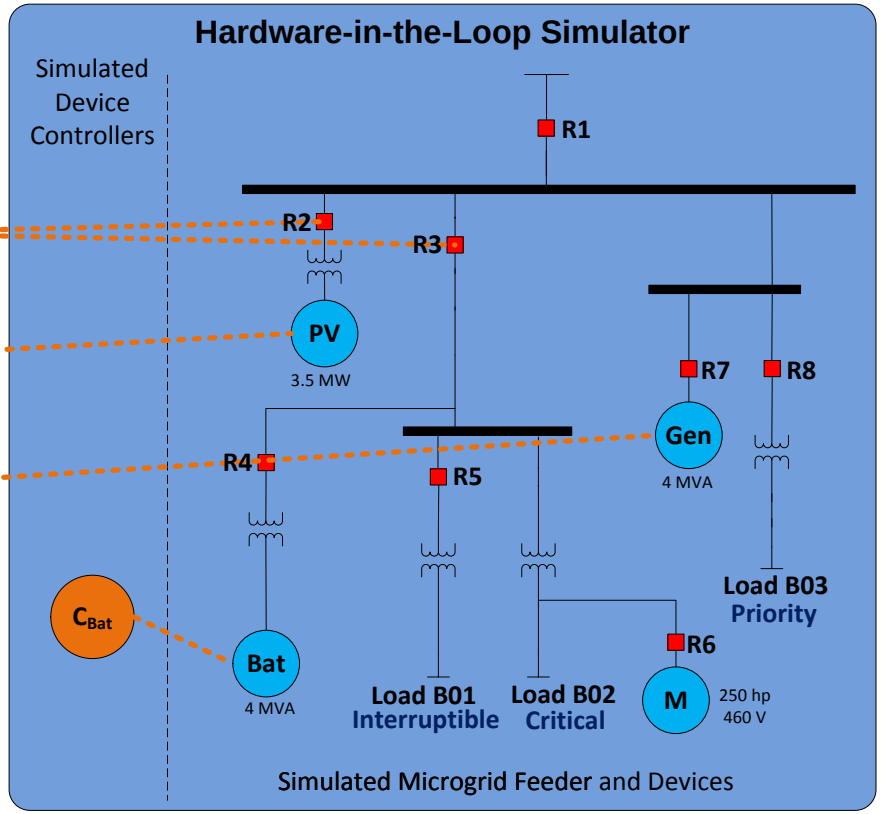
Elements of the Microgrid Controller HIL Platform

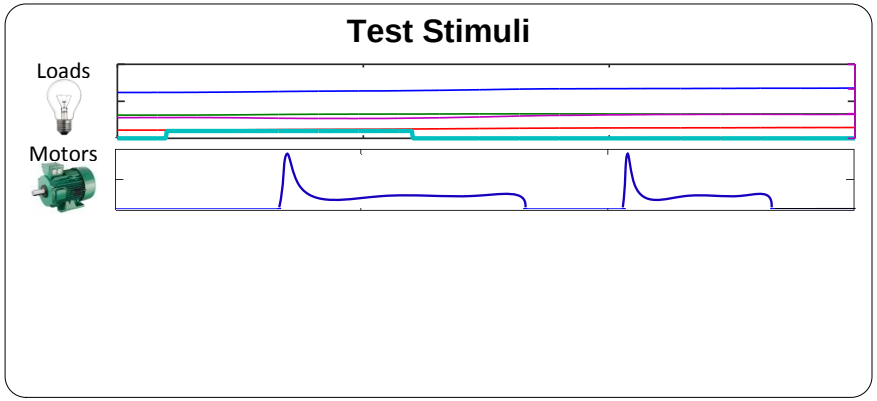
Physical Device Controllers

SEL 787 Relay

Acme Energy PV Inverter Controler

Woodward easYgen 3000 Genset Controller





Replace simulated device controllers with vendors' commercial device controllers

Elements of the Microgrid Controller HIL Platform

Physical Device Controllers

SEL 787 Relay

Acme Energy PV Inverter Controler

Woodward easYgen 3000 Genset Controller

Hardware-in-the-Loop Simulator

Simulated Device Controllers

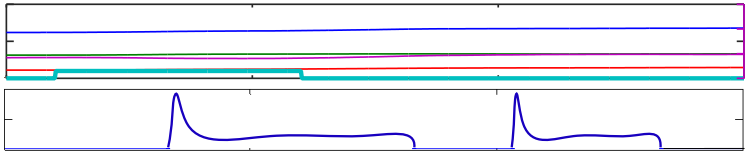
R1
R2
R3
PV
3.5 MW
R7
R8
Gen
4 MVA
R4
R5
C_{Bat}
Bat
4 MVA
Load B03
Priority
R6
Load B01
Interruptible
Load B02
Critical
M
250 hp
460 V

Simulated Microgrid Feeder and Devices

Test Stimuli

Loads

Motors



Manually control the microgrid

Elements of the Microgrid Controller HIL Platform

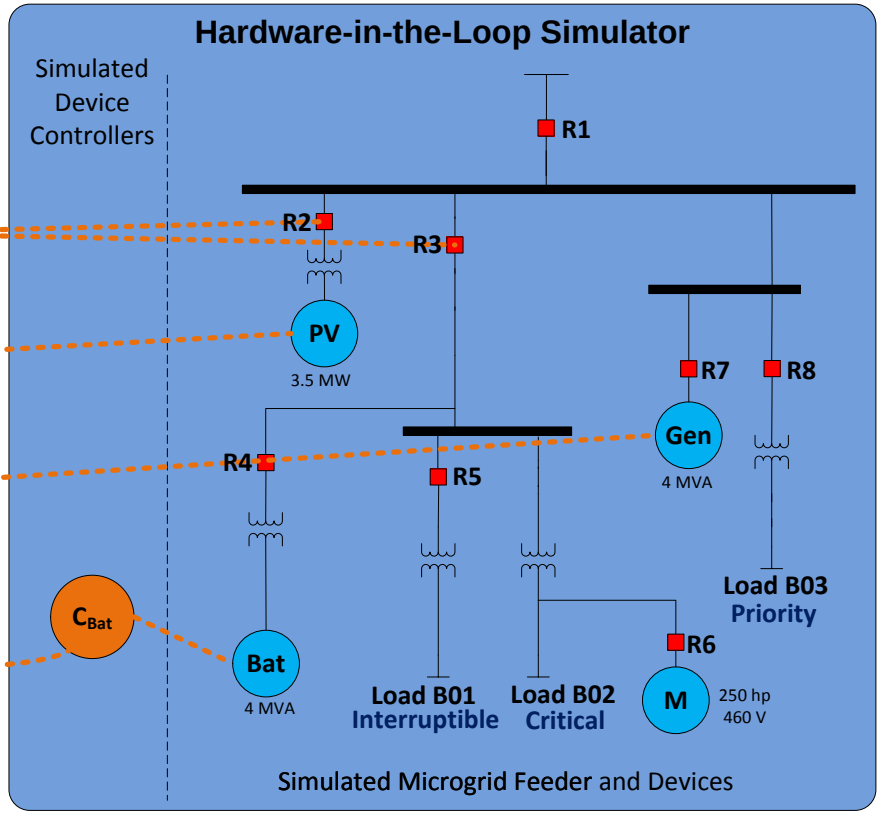
Physical Device Controllers

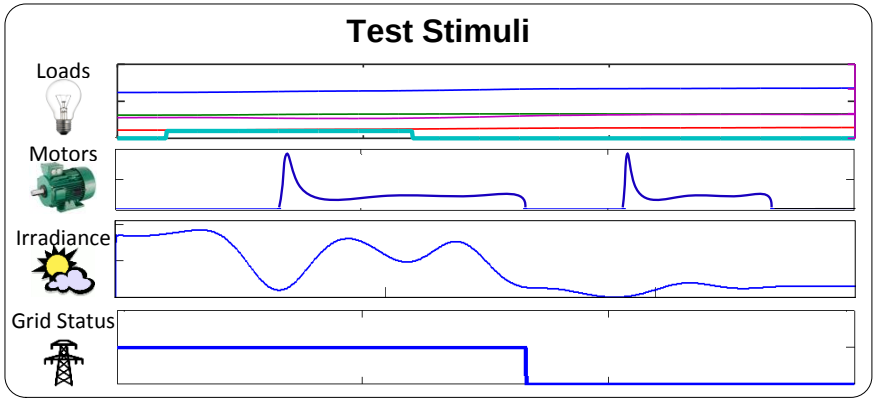
SEL 787 Relay

Acme Energy PV Inverter Controler

Woodward easYgen 3000 Genset Controller

Add more test stimuli…. overwhelm the human operator.





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Elements of the Microgrid Controller HIL Platform

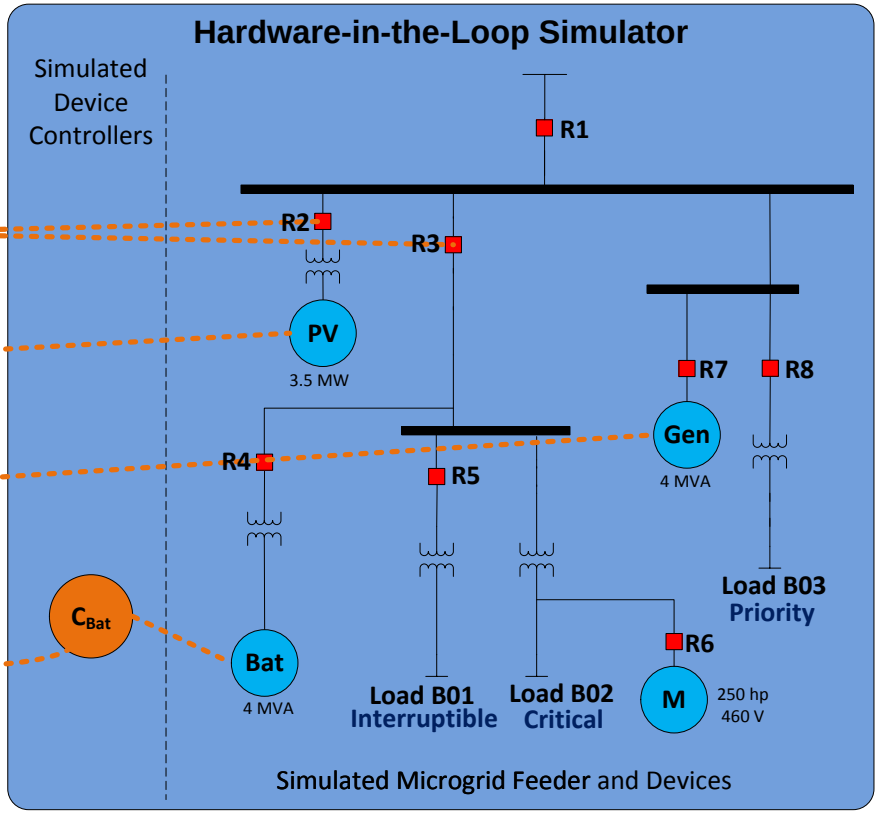
Schneider Microgrid Controller

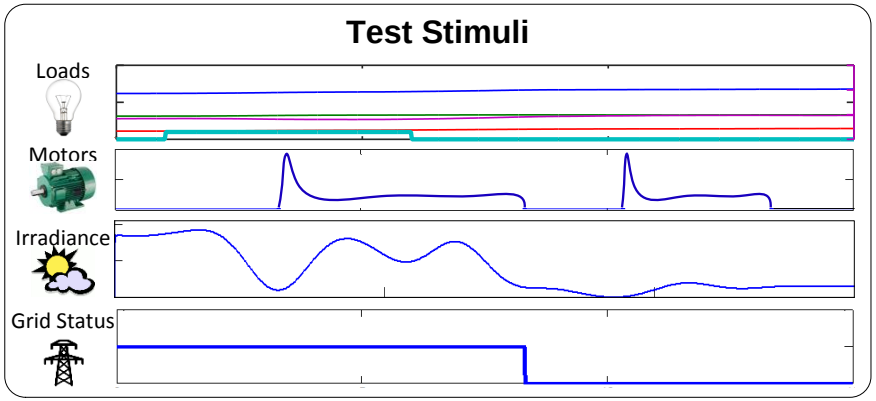
Physical Device Controllers

SEL 787 Relay

Acme Energy PV Inverter Controler

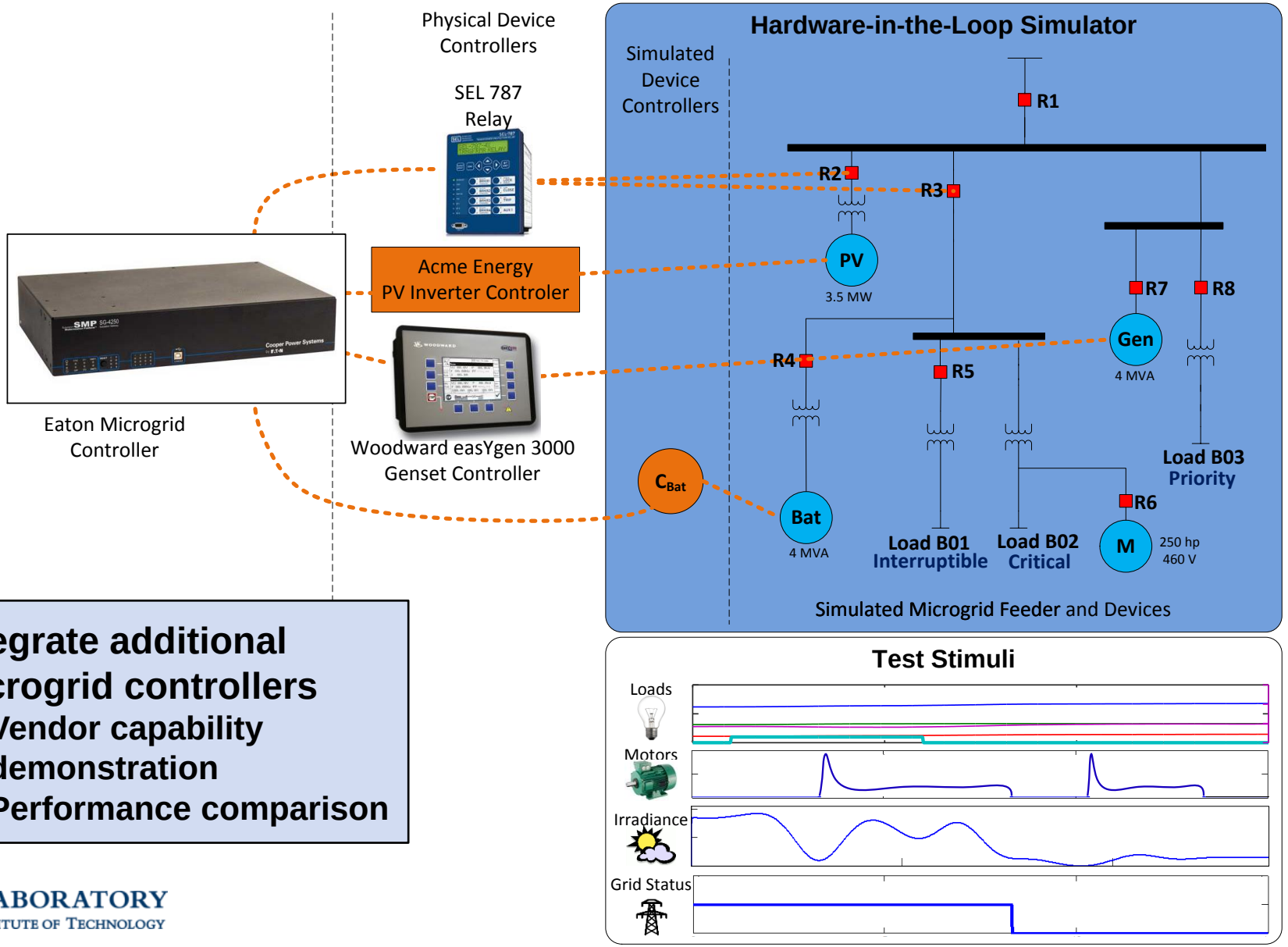
Woodward easYgen 3000 Genset Controller





Integrate microgrid controller

Elements of the Microgrid Controller HIL Platform



Integrate additional microgrid controllers

- Vendor capability demonstration
- Performance comparison

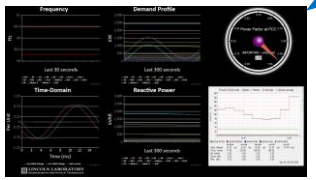
Elements of the Microgrid Controller HIL Platform

Physical Device Controllers

Woodward easYgen 3000 Genset Controller

Add data visualization, collection, and post-processing

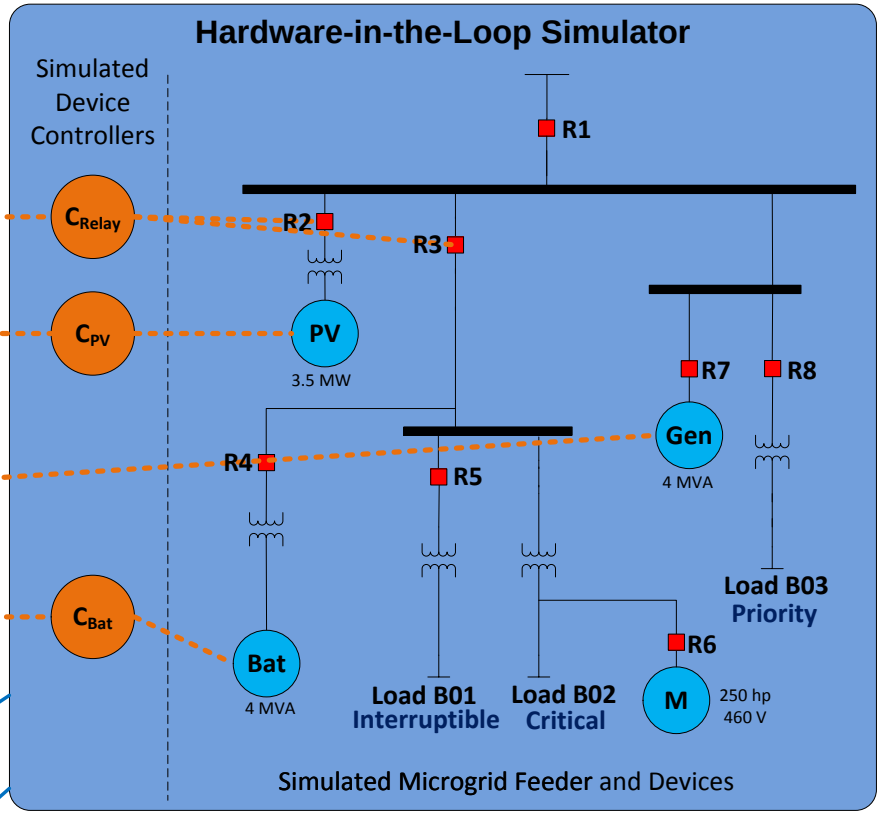
- Real-time operation
- Performance analysis

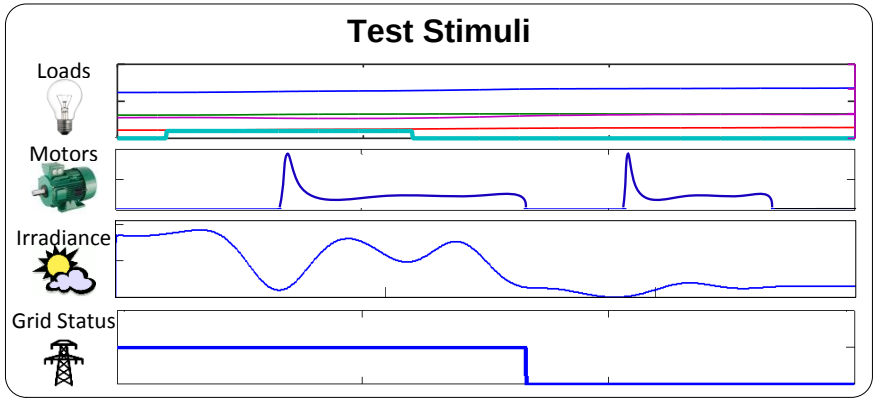


Real-time Data Visualization

Data Collection & Post-processing

UDP



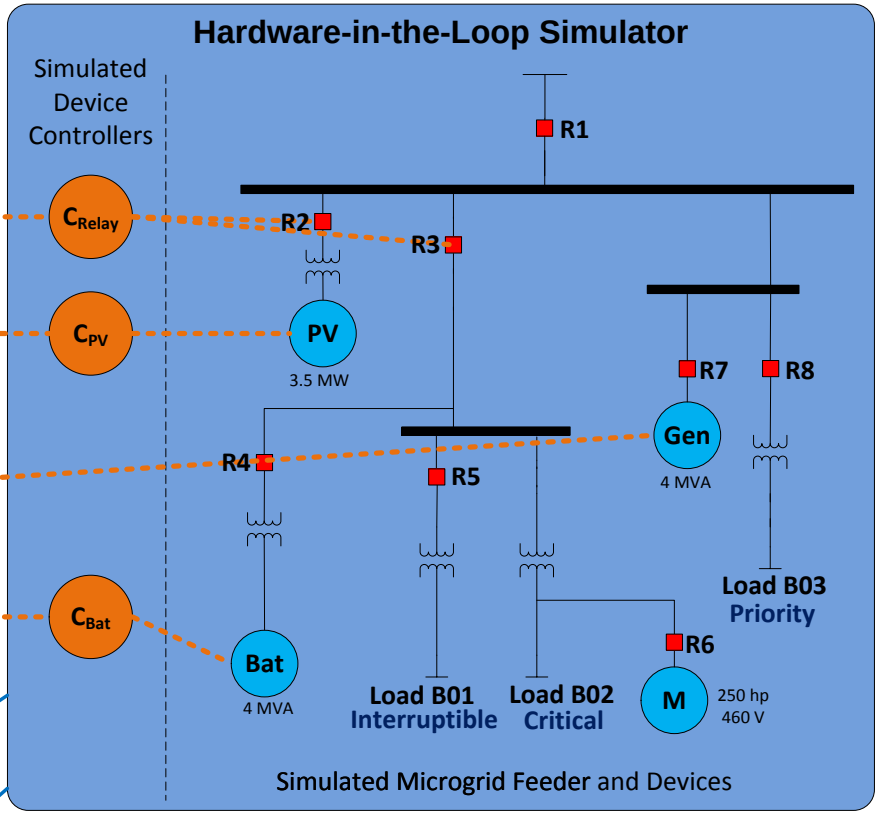


Microgrid Controller HIL Platform

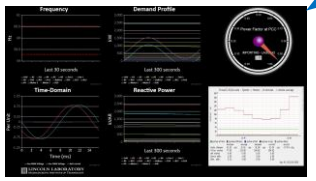
Schneider Microgrid Controller

Woodward easYgen 3000 Genset Controller

Physical Device Controllers

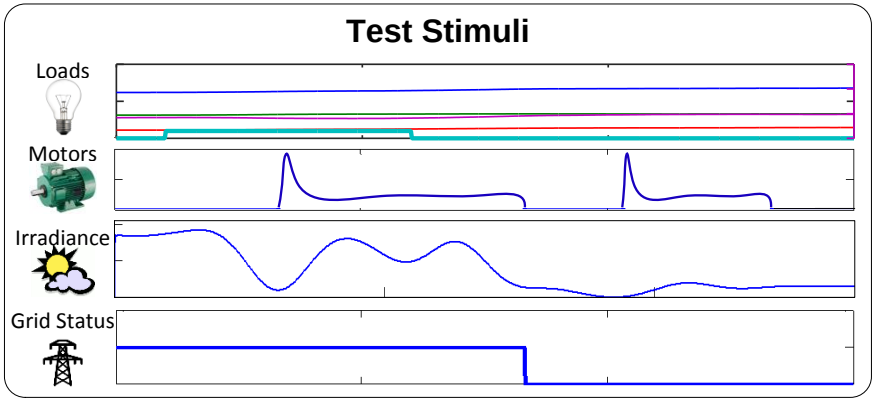


UDP

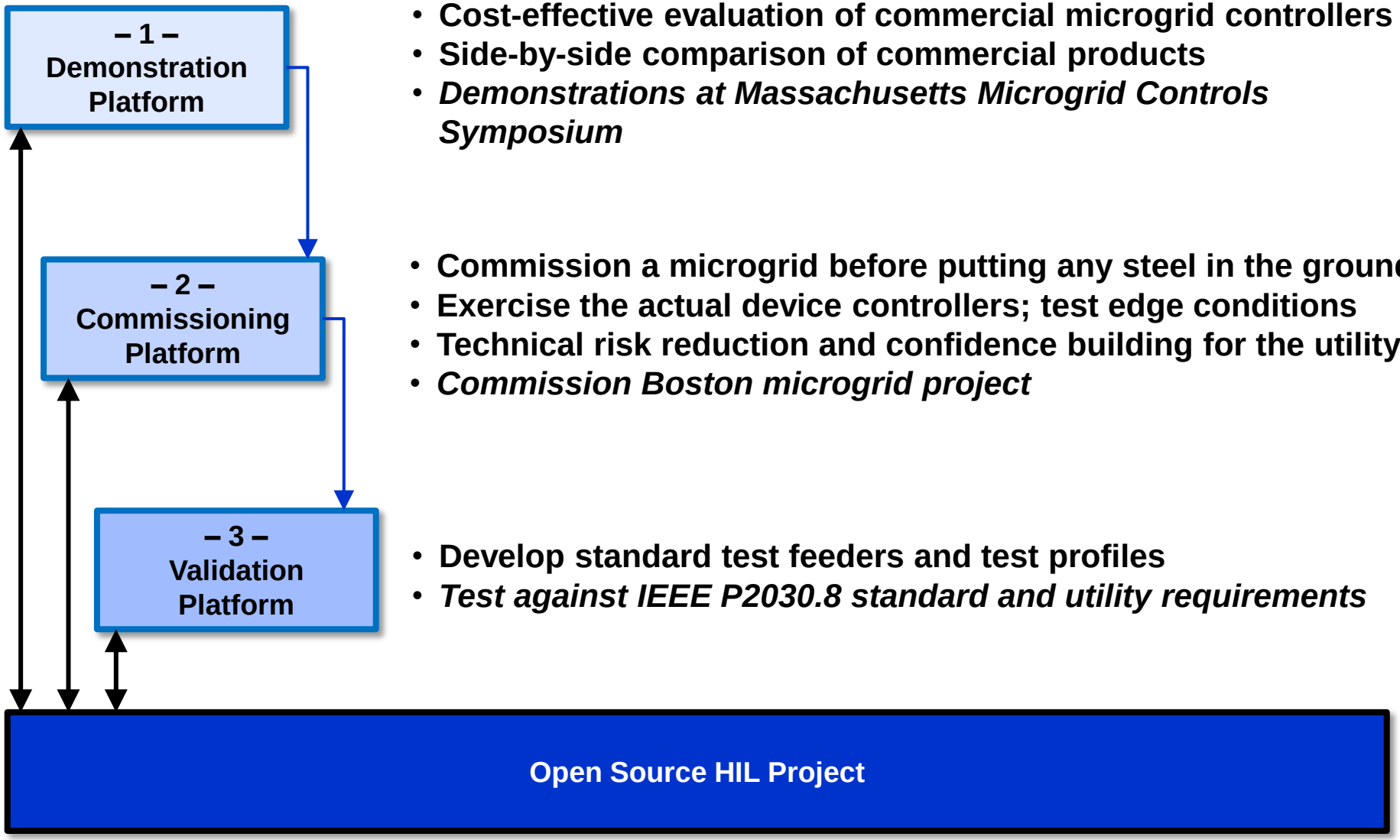


Real-time Data Visualization

Data Collection & Post-processing



Vision for the Microgrid Controller HIL Platform



- Cost-effective evaluation of commercial microgrid controllers
- Side-by-side comparison of commercial products
- *Demonstrations at Massachusetts Microgrid Controls Symposium*

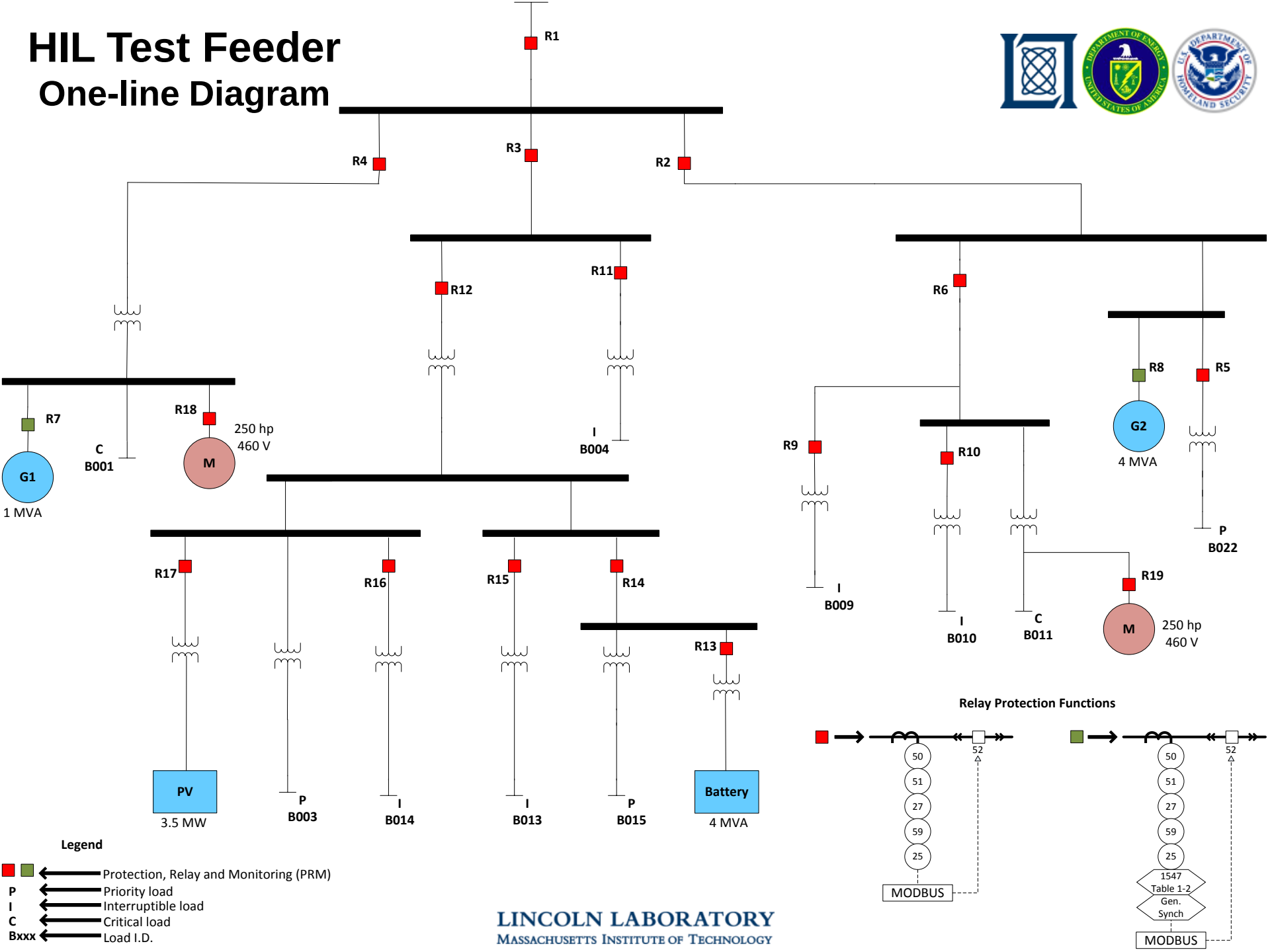
- Commission a microgrid before putting any steel in the ground
- Exercise the actual device controllers; test edge conditions
- Technical risk reduction and confidence building for the utility
- *Commission Boston microgrid project*

- Develop standard test feeders and test profiles
- *Test against IEEE P2030.8 standard and utility requirements*

Outline

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

HIL Test Feeder
One-line Diagram



Relay Protection Functions

Legend

- Protection, Relay and Monitoring (PRM)
- **P** — Priority load
- **I** — Interruptible load
- **C** — Critical load
- **Bxxx** — Load I.D.

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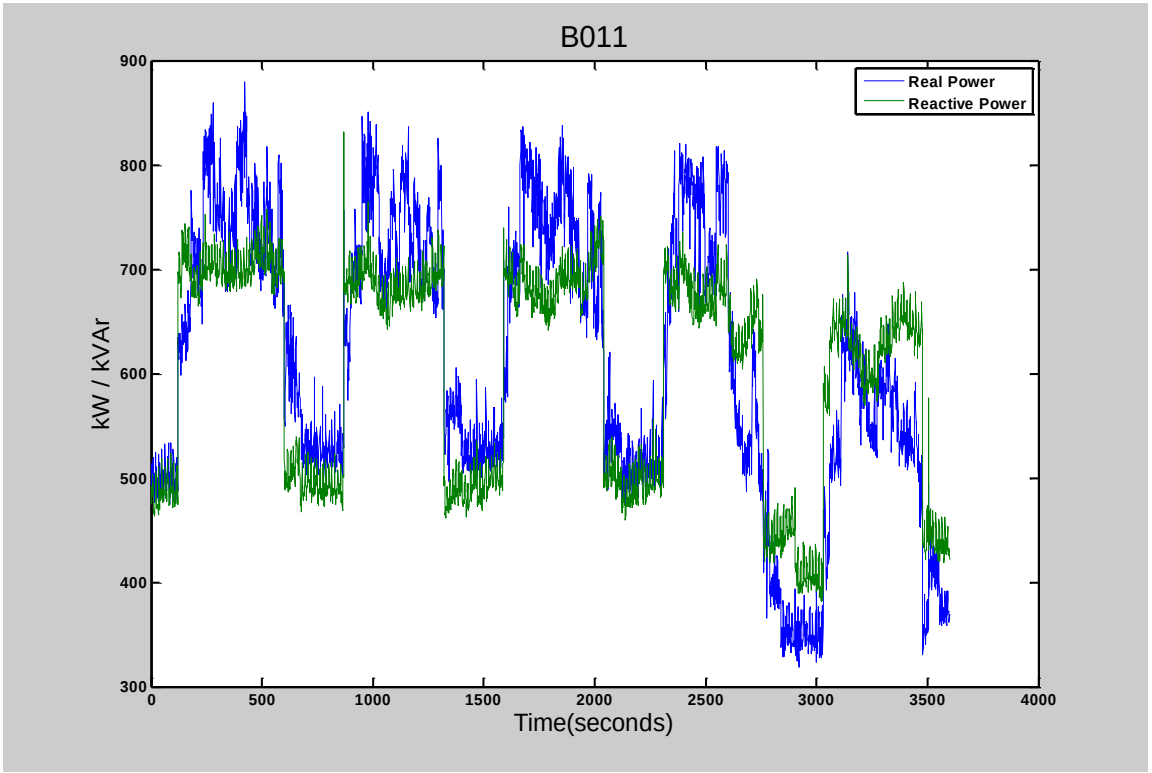
Example Load (B011)



- **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

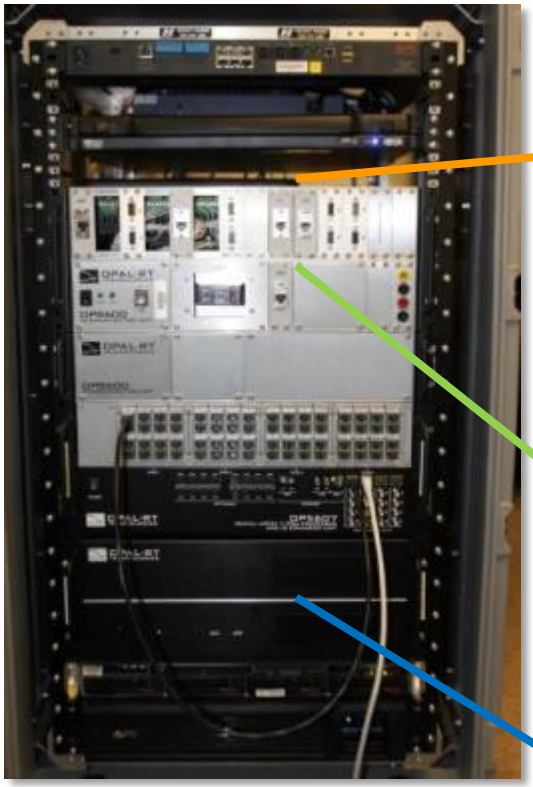
Opal-RT HIL Target

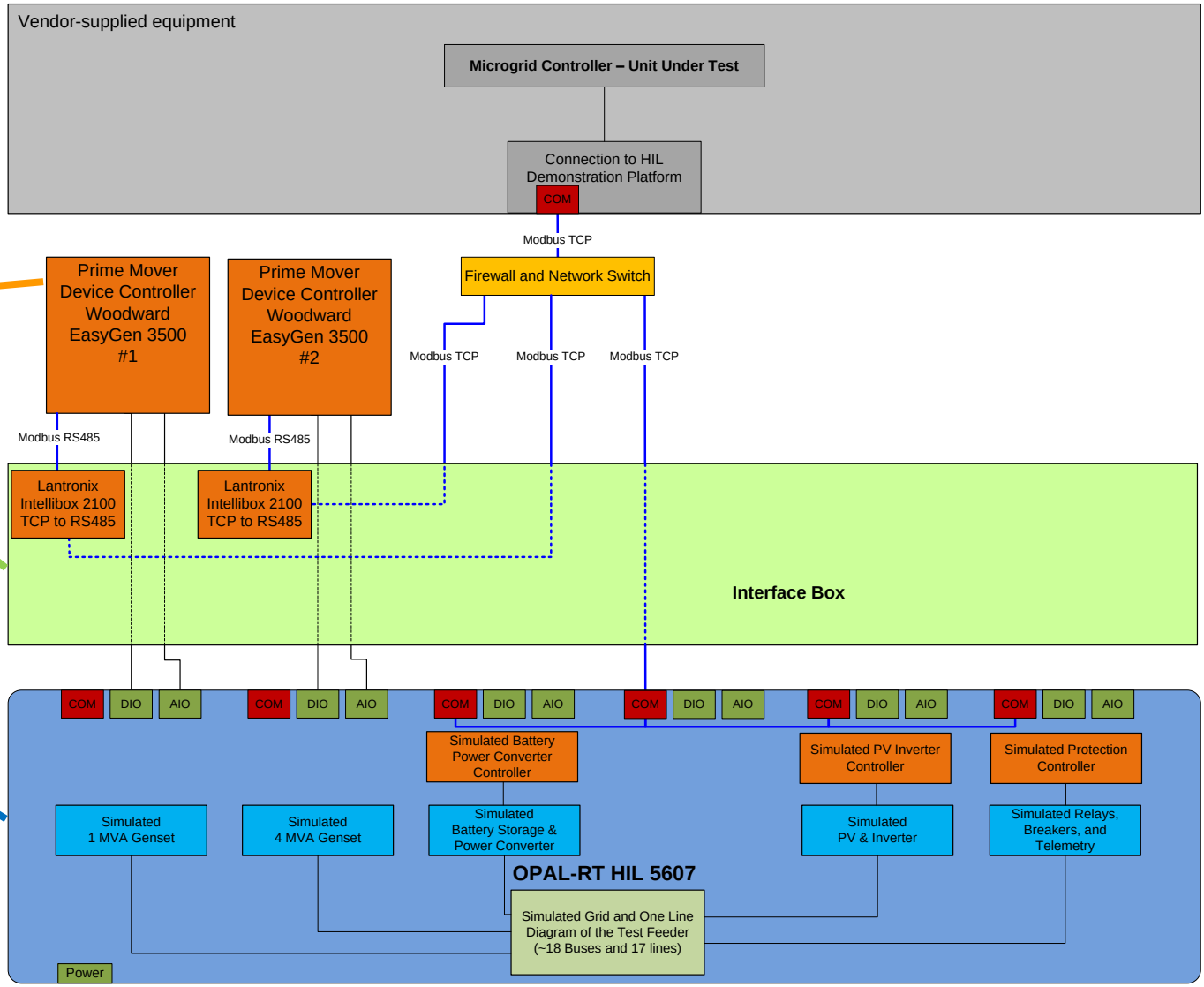
MIT Lincoln Lab Windows Server

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

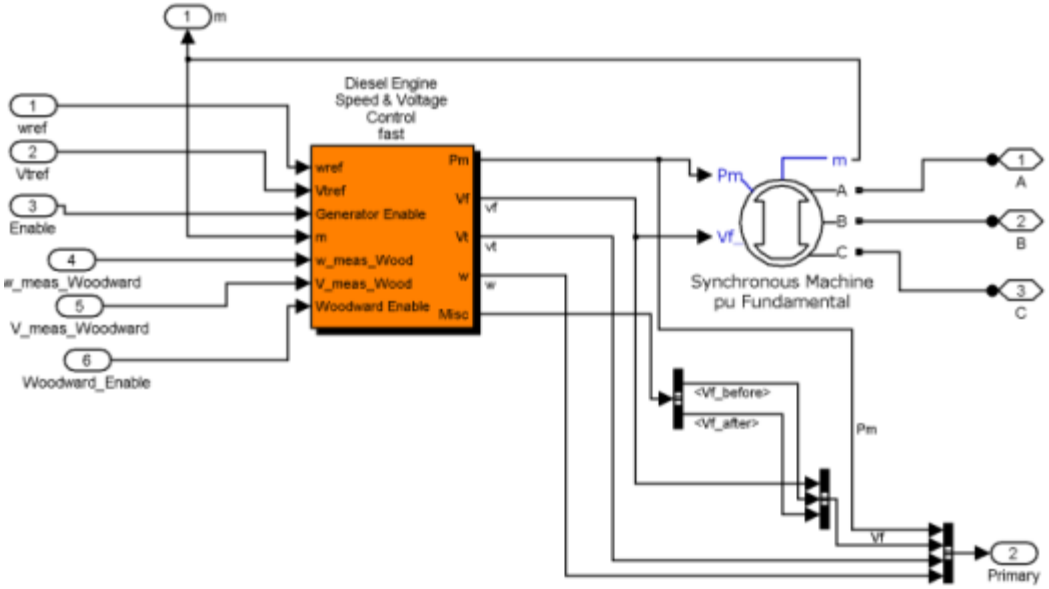
Parameter	Units	Notes
Real Power Command	kW	(-) discharge; (+) charge
Reactive Power Command	kVAR	(+) capacitive; (-) inductive
Modbus Enable	0/1	1 to indicate active Modbus connection.
Fault Status		Phase A Over Current Phase B Over Current Phase C Over Current DC Link Overvoltage PLL Loss of Sync Vrms 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

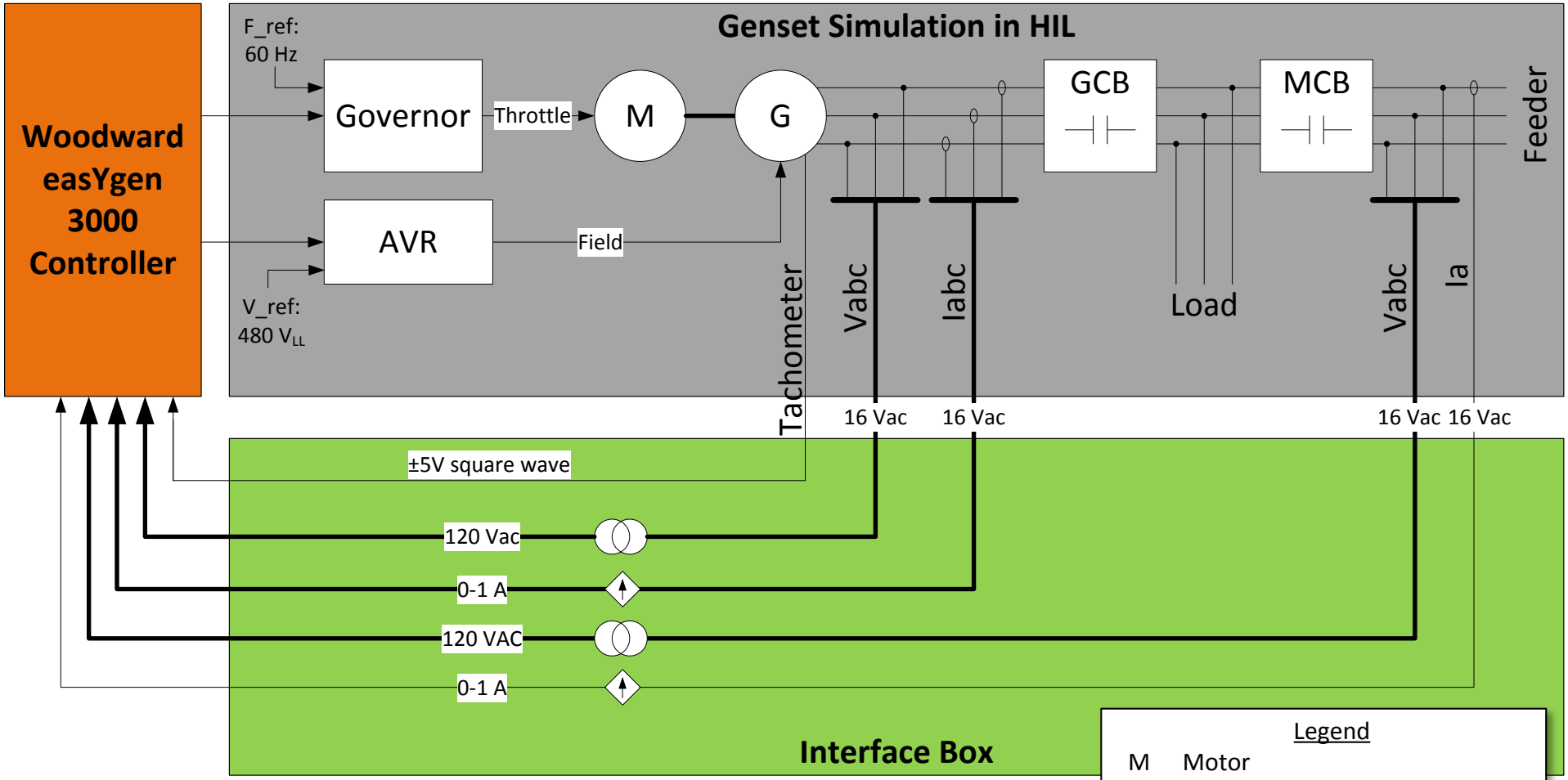
	1 MW Genset	4 MW Genset
Manufacturer / Model	CAT C32	CAT C175-20
Rating (kVA)	1,000	4,000
Power Factor	TBD	TBD
Voltage (V)	480	13,800
Frequency (Hz)	60	60
Speed (RPM)	1800	1800
Minimum Output Power	25kW	100kW
Startup Time	<10 sec	<15 sec

Genset ratings and characteristics



Synchronous Machine, Governor, and AVR Models

Device Controller Integration: Woodward easYgen 3000



Simulated Relay: SEL-787 Transformer Protection Relay

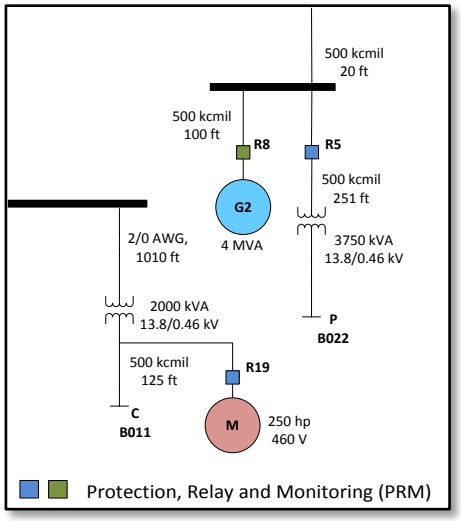
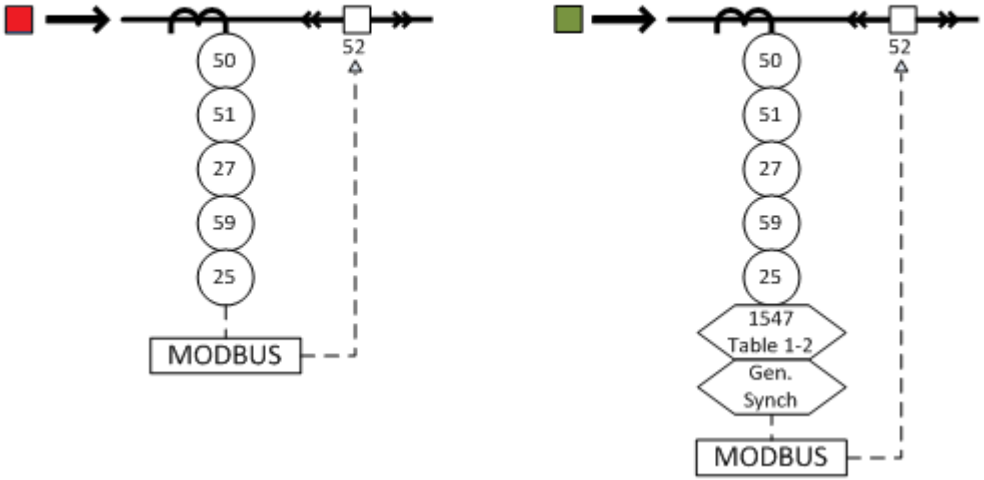


Image: Schweitzer Engineering

Relay Protection Functions



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

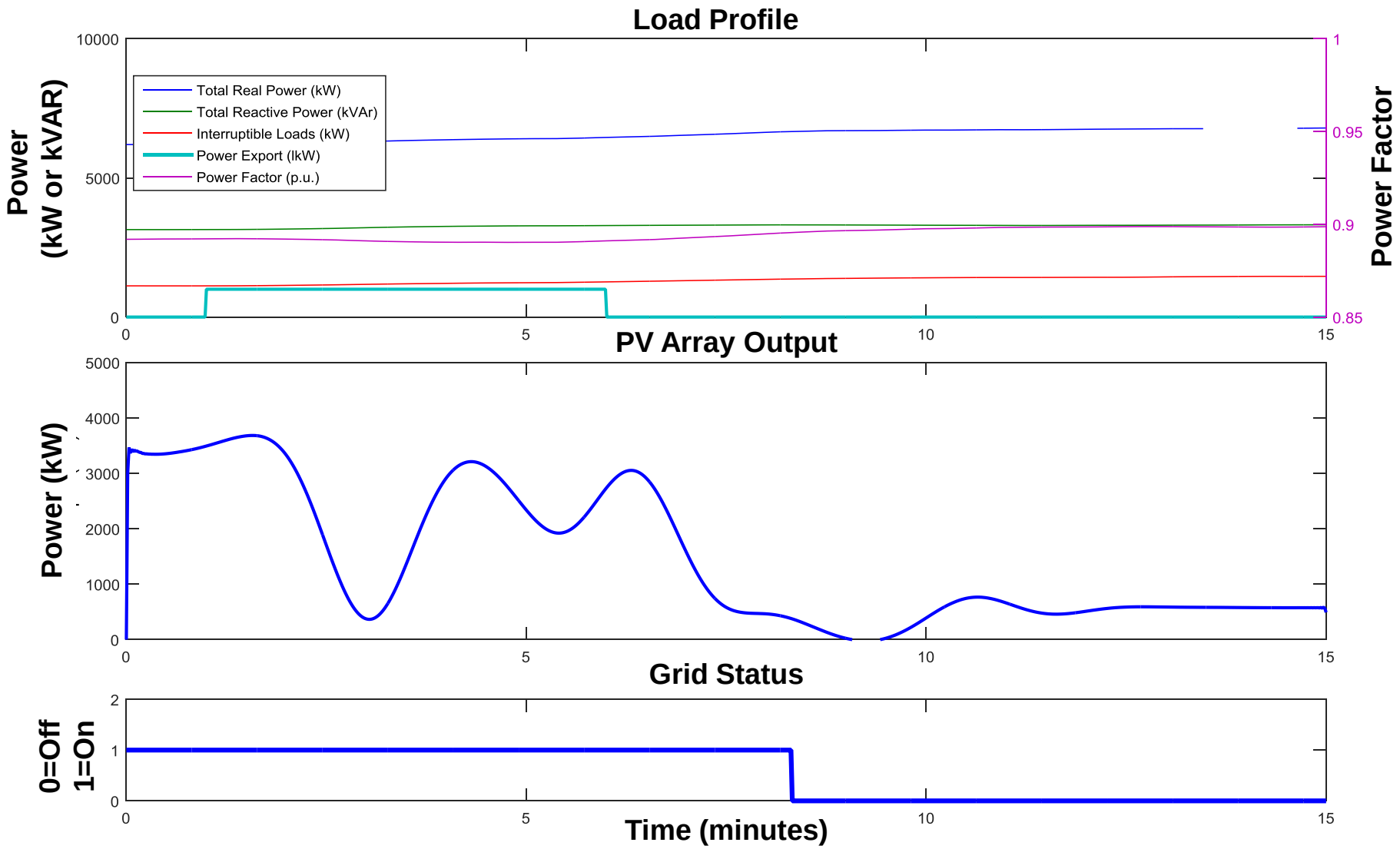
Demonstration against ORNL/EPRI Microgrid Functional Use Cases

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

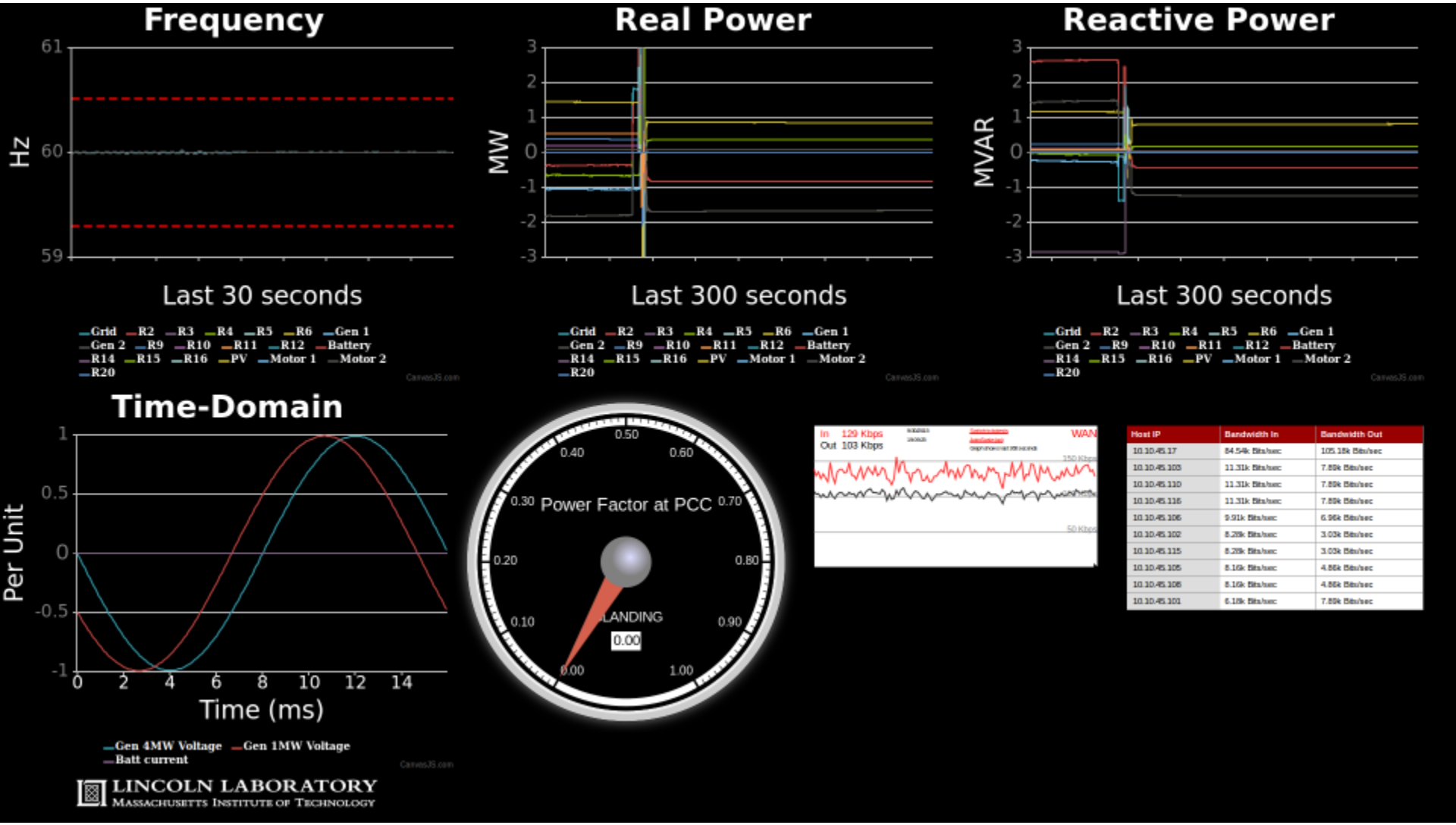
Demonstration against ORNL/EPRI Microgrid Functional Use Cases (cont.)

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

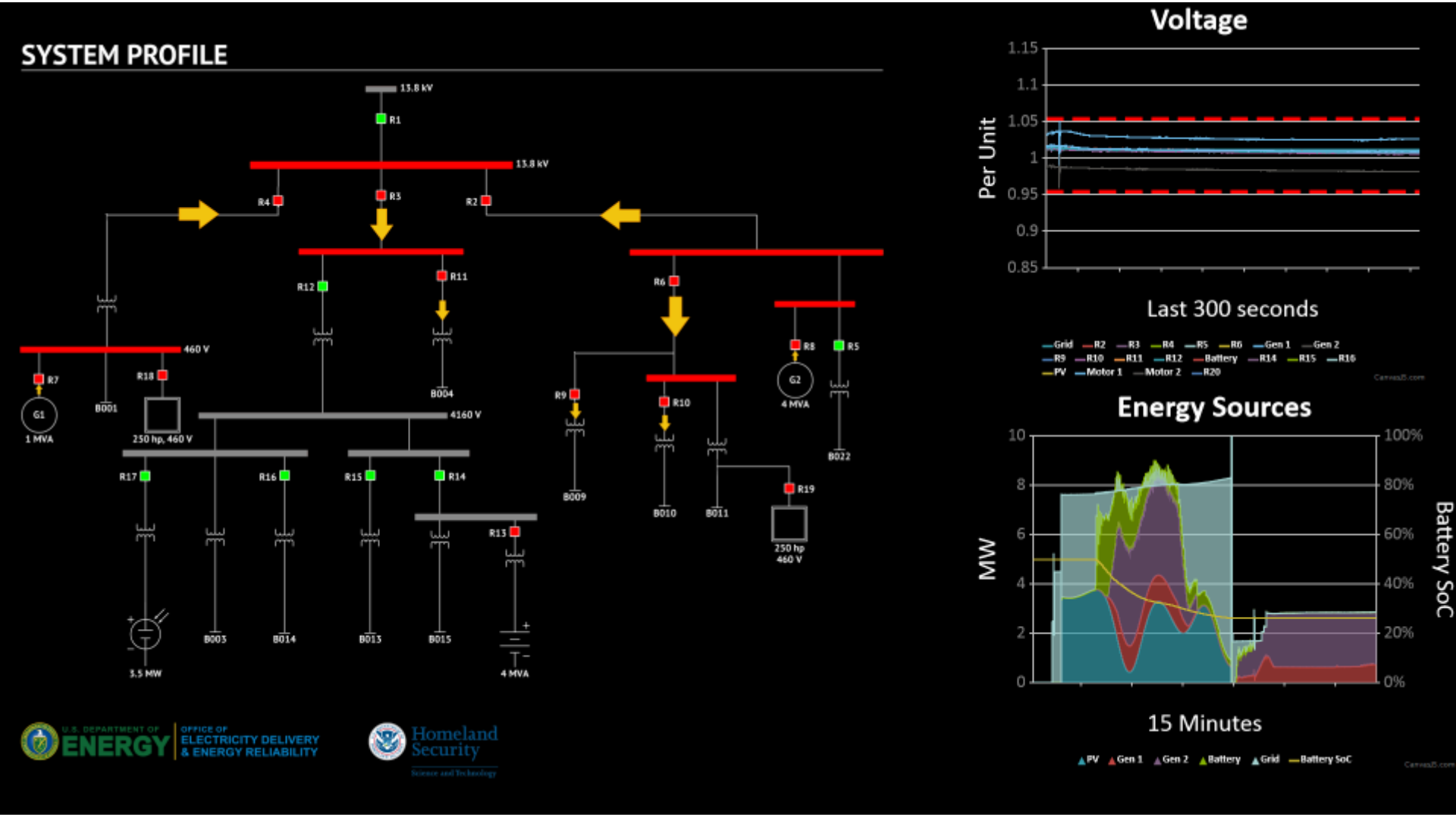
15-minute Demonstration Sequence



Heads-up Display (screen 1)



Heads-up Display (screen 2)



Anonymized Results of Demonstration Runs

Energy Consumption

	Grid-tied			Islanded
	Fuel Used (gal.)	Energy Imported (kWh)	Energy Exported (kWh)	Fuel Used (gal.)
Sequence 1	5.9	311	13	4.9
Sequence 2				
Sequence 3				

Load-not-Served (kWh) while Islanded

	Critical	Priority	Inter.
Sequence 1	79	466	143
Sequence 2			
Sequence 3			

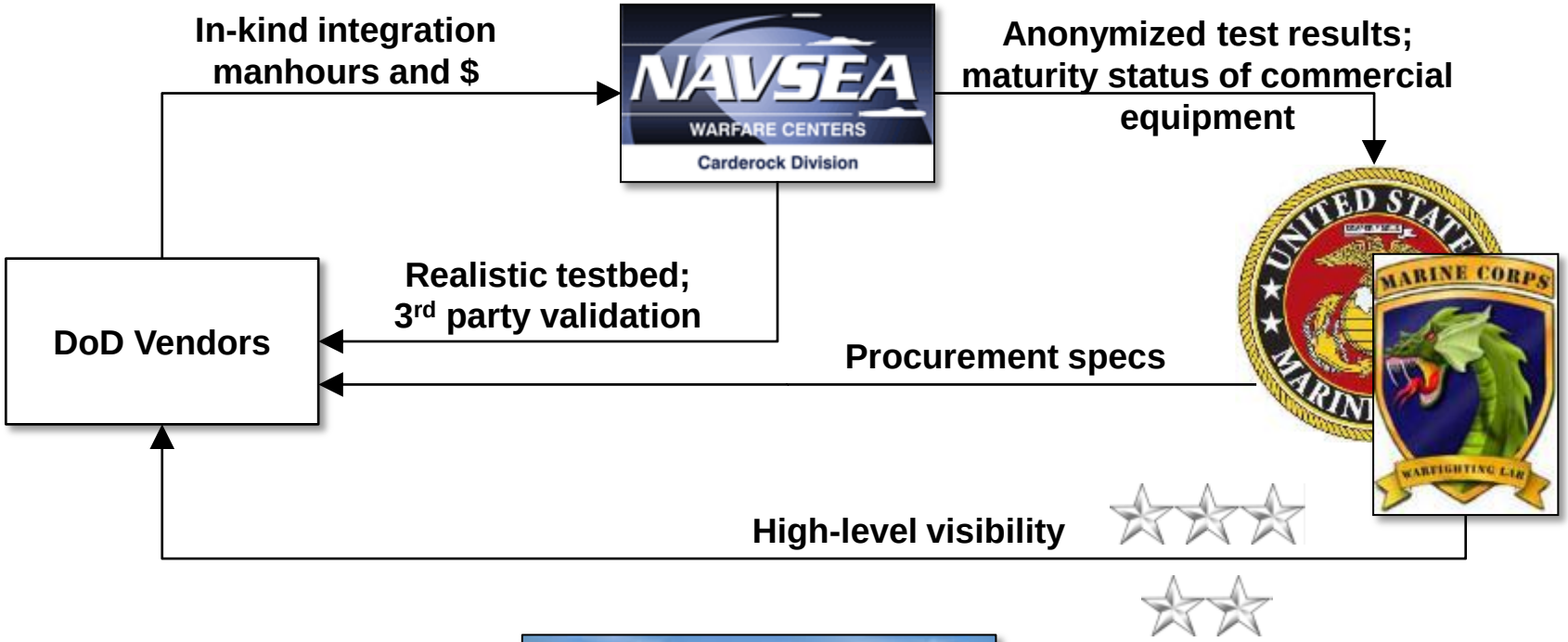
Voltage Profile (sec exceeding ±5%)

	Grid-tied	Islanded
Sequence 1	0	3.6
Sequence 2		
Sequence 3		

Outline

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

USMC ExFOB Example

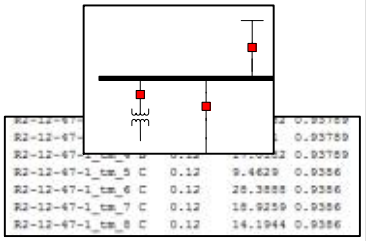


ExFOB 2013 – Twentynine Palms

Elements of the Open Source HIL Repository

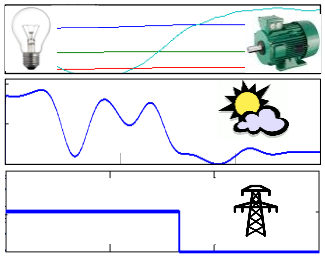
Microgrid Test Repository

Microgrid Test Feeders



Netlists

Standard Test Stimuli

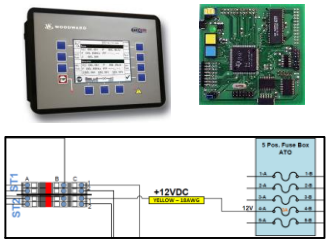


Load profiles, irradiance profiles, grid outages, faults

Post-processing Scripts for Test Results

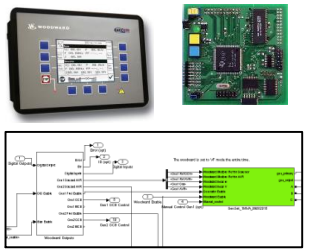
Controller-in-the-Loop Repository

Interface Circuitry for Device Controllers



Circuit schematics, bills of materiel

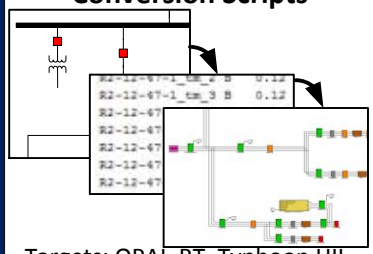
Interface Code for Device Controllers



Communications Interface Translation Code

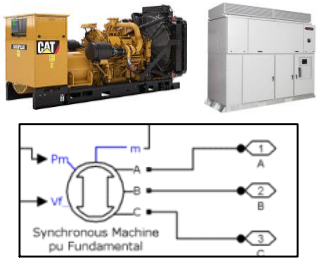
HIL Platform Repository

HIL Target Platform Conversion Scripts



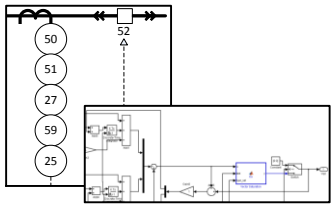
Targets: OPAL-RT, Typhoon HIL, RTDS, NI, and others

Validated Device Models



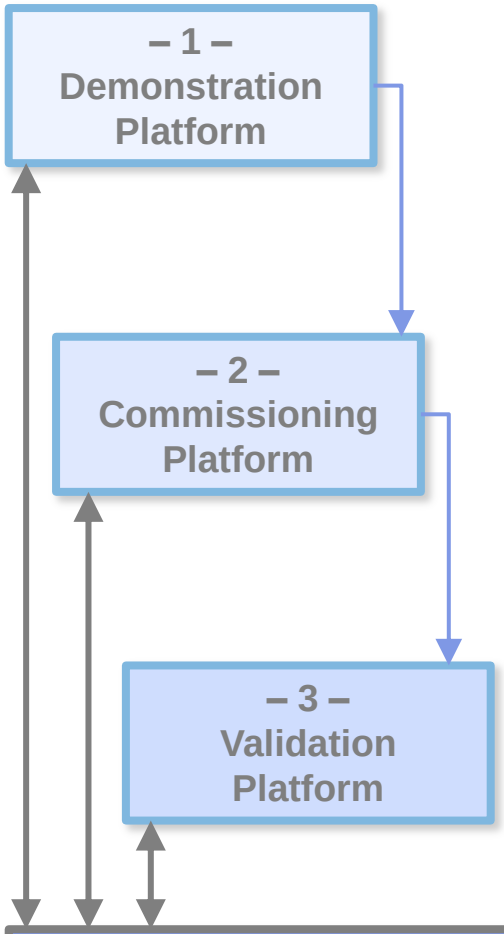
Motor-generators, power converters / inverters, and relays

Validated Device Controller Software



Genset controllers, power converter controllers, relay protection functions

Vision for Microgrid HIL Open-source Repository



- **Goals:**
  - **Accelerate and reduce risk of microgrid deployment**
    - **Enable software development and integration work to be 95% done at the start of commissioning, not 50%**
  - **Enable rapid proof-of-concepts to reduce utility engineers' perceived risk**
- **Agnostic to real-time simulation platform**
  - **NI, OPAL-RT, RTDS, Typhoon, or any other target**
- **Validated DER device models provided by vendors**
- **Standard test benches**
  - **Reference microgrid feeders**
  - **Test scripts / test stimuli**
  - **Post-processing software for compliance verification**

Interested in participating? Contact MIT-LL.

Vision for Eventual HIL Capabilities

Host Utility's Distribution Management System (DMS)

Actual Controllers for DER Deployed in the Microgrid

Service Provider

Microgrid Controller Under Test

Industry-standard Test Platform

Multiple Real-time Digital Sim. Platforms

RTDS
Opal-RT
Typhoon HIL
National Instruments

Validated Controller Models

Vendor-validated Device Models

C_{Relay}
C_{PV}
C_{Gen}
C_{Bat}

R1
R2
R3
R4
R5
R6
R7
R8

PV
3.5 MW

Gen
4 MVA

Bat
4 MVA

Load B01
Interruptible

Load B02
Critical

Load B03
Priority

M
250 hp
460 V

Multiple Standard Test Feeders

Test Stimuli per IEEE P2030.8 and Host Utilities

Loads

Motors

Irradiance

Grid Status

LINCOLN LABORATORY
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