Multi-PCC Electric Distribution System Power Hardware-in-the-Loop

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Contents

Background

The IEEE 8,500-Node Test Feeder

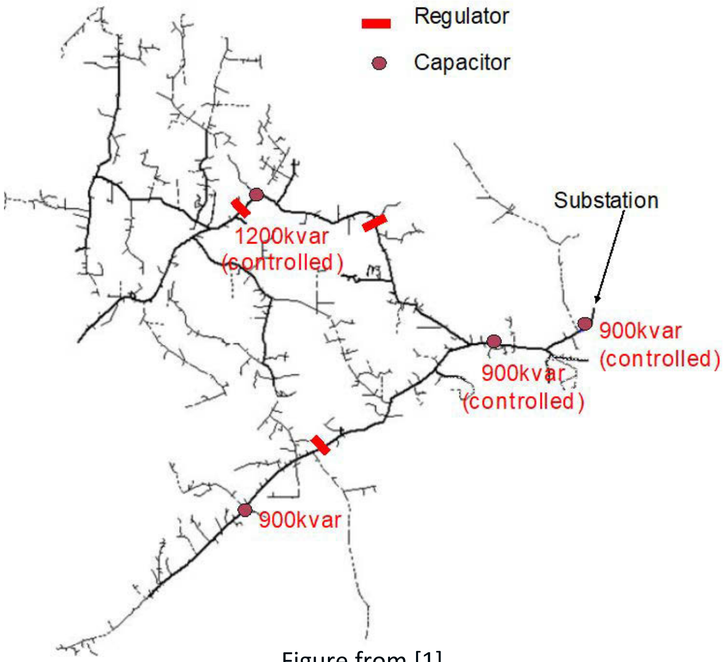
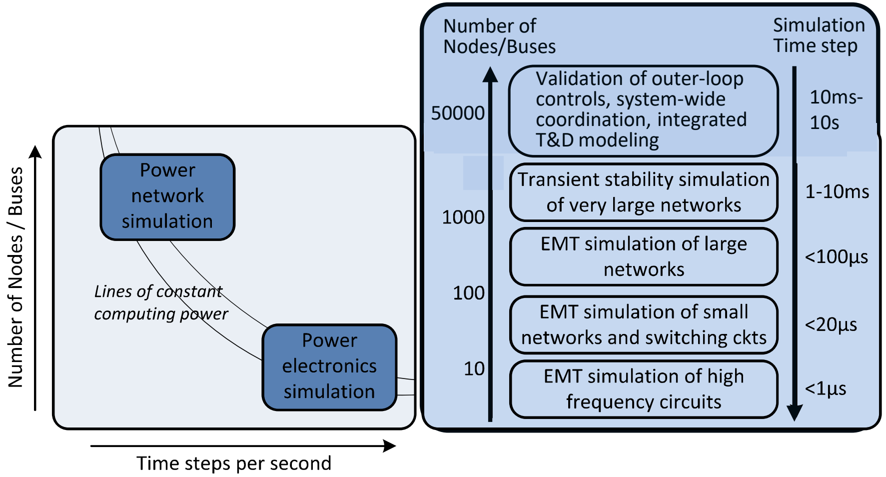


Figure from [1]

- Differences in distribution system RT simulation
  - More nodes
  - More devices with more sophisticated models
  - Unbalanced power flow
  - Different assumptions.

1. R.F. Arritt and R.C. Dugan, "The IEEE 8500-Node Test Feeder," presented at the IEEE PES T&D 2010, New Orleans, LA, 2010, 1–6.

Applications vs. Common Implementation

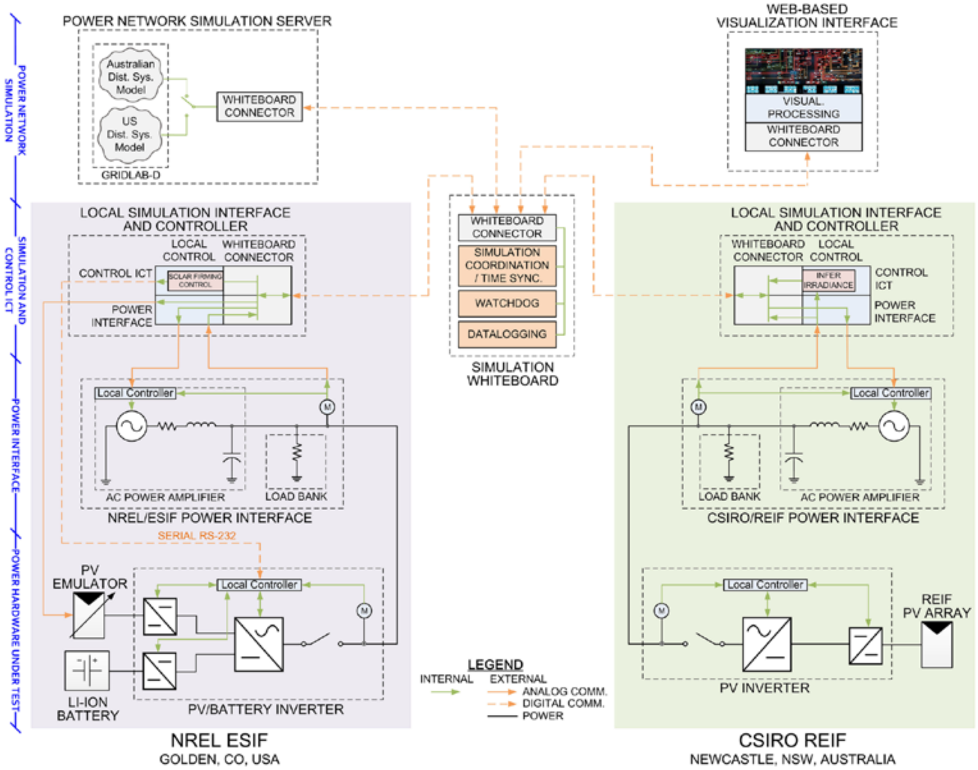


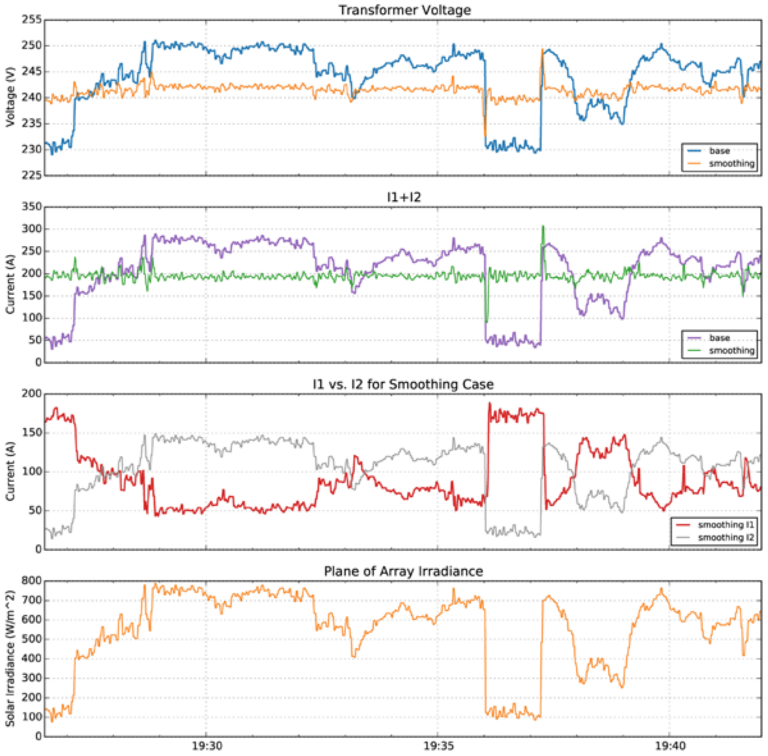
Updated version of figure from [2]

- Quasi-static time-series (QSTS) simulation
  - **Model scale**: full system
  - **Purpose**: study of system voltages, voltage regulation equipment, system-wide coordination.
- Dynamic/electromechanical transient simulation
  - **Model scale**: reduced order
  - **Purpose**: study of system/device interaction, system frequency response, combined distribution/bulk power system dynamics.

2. M.O. Faruque et al., "Real-Time Simulation Technologies for Power Systems Design, Testing, and Analysis," *IEEE Power and Energy Technology Systems Journal* 2, no. 2 (June 2015): 63–73.

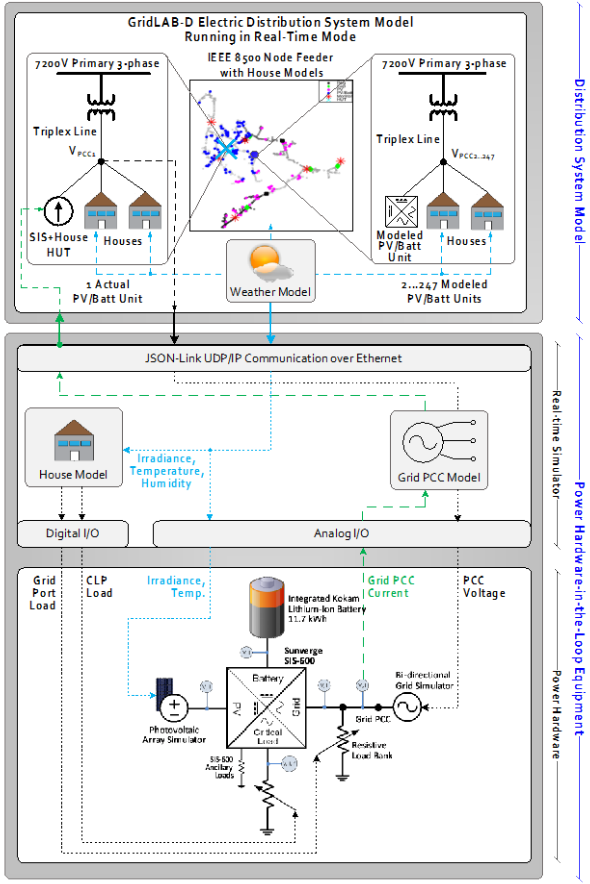
QSTS Examples: Multisite Cosimulation and Coordinated Control

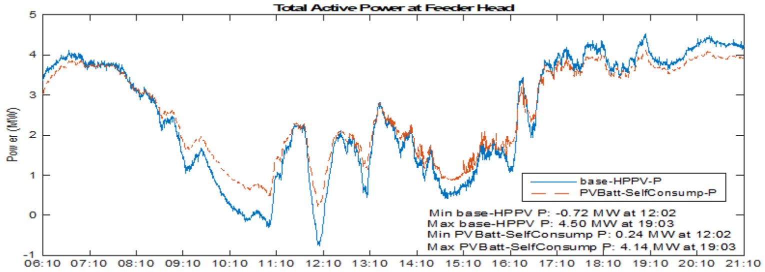


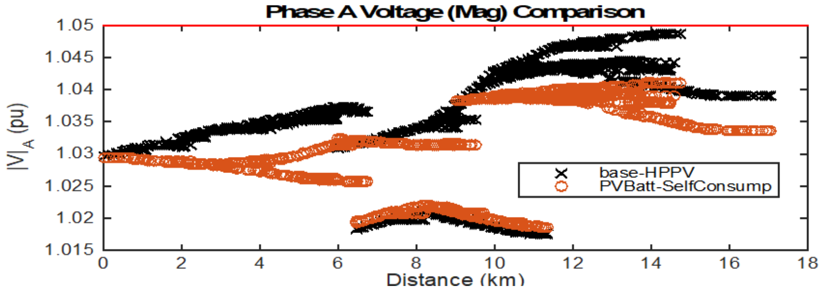


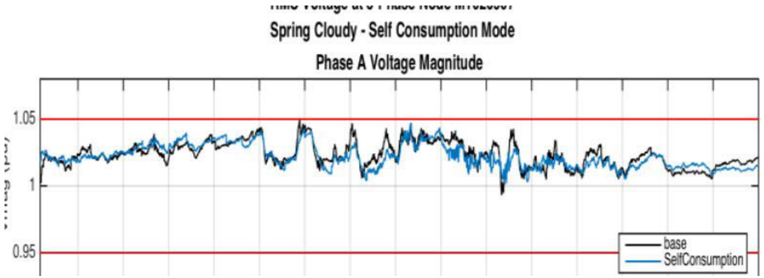
3. B. Lundstrom, B. Palmintier, D. Rowe, J. Ward, and T. Moore, “Trans-Oceanic Remote Power Hardware-in-the-Loop: Multi-Site Hardware, Integrated Controller, and Electric Network Co-simulation,” *IET Generation, Transmission, and Distribution* (Dec. 2017).

QSTS Examples: System Impacts of DER Autonomous Control



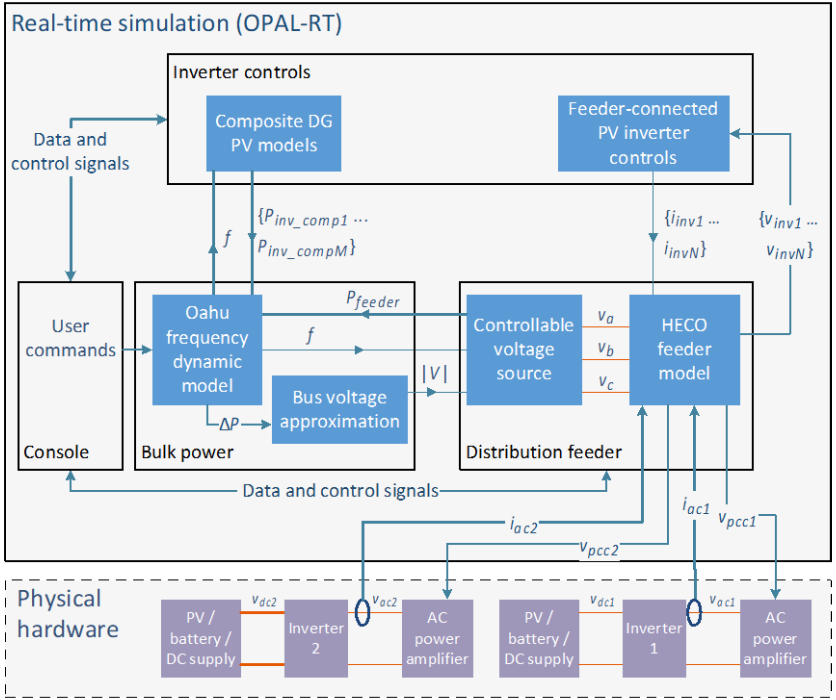


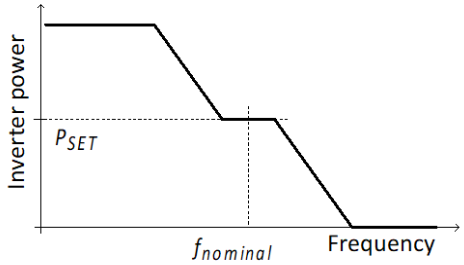


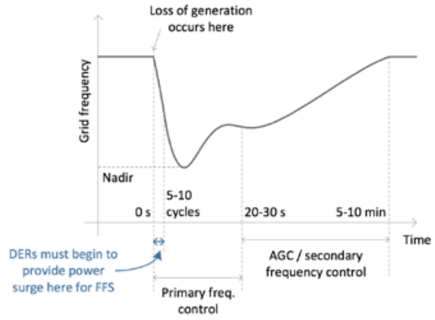


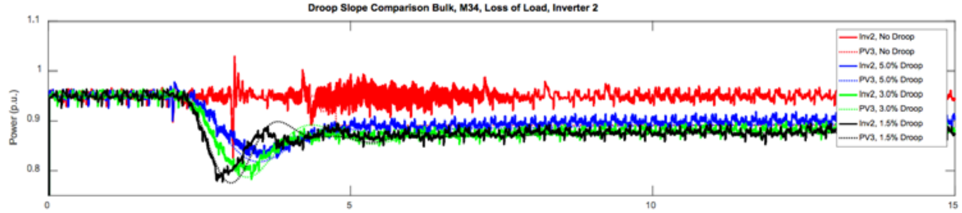
4. B. Lundstrom and P. Gotseff, “Analyzing the Impact of Widespread DERs on Power Systems Using Data-Driven Models, Automated Scenario Building, and Integrated Power Hardware,” *IET Generation, Transmission, and Distribution* (submitted).

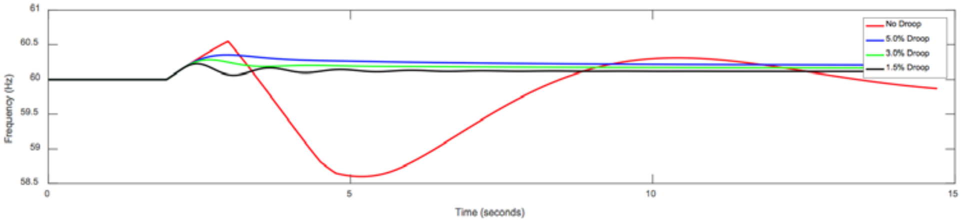
Dynamic Examples: Oahu Frequency Response





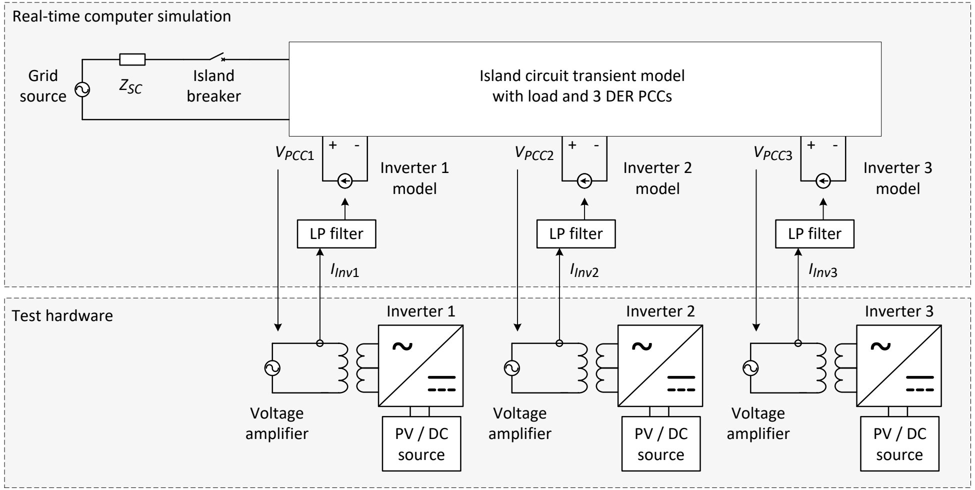


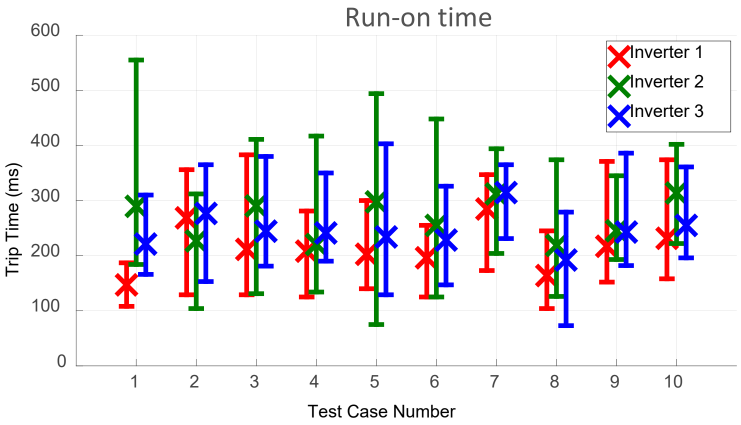




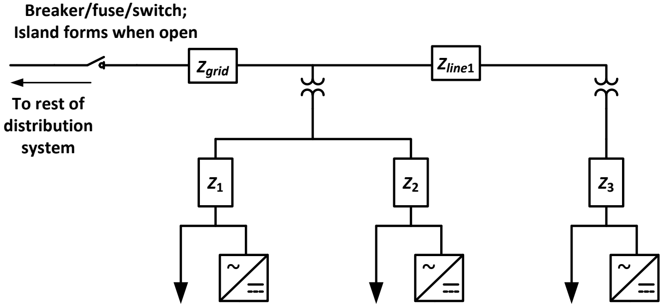
5. A. Nelson, A. Nagarajan, K. Prabakar, V. Gevorgian, B. Lundstrom, S. Nepal, A. Hoke, M. Asano, R. Ueda, J. Shindo, K. Kubojiri, R. Ceria, and E. Ifuku, *Hawaiian Electric Advanced Inverter Grid Support Function Laboratory Validation and Analysis* (NREL/TP-5D00-67485) (Golden, CO: National Renewable Energy Laboratory, 2016).
6. A. Nelson, K. Prabakar, A. Nagarajan, S. Nepal, A. Hoke, et. al, "Power Hardware-in-the-Loop Evaluation of PV Inverter Grid Support on Hawaiian Electric Feeders," presented at the IEEE ISGT, 2017.
7. A. Hoke, M. Elkhatib, A. Nelson, J. Johnson, J. Tan, R. Mahmud, V. Gevorgian, J. Neely, C. Antonio, D. Arakawa, and K. Fong, *The Frequency-Watt Function: Simulation and Testing for the Hawaiian Electric Companies* (NREL/TP-5D00-68884) (Golden, CO: National Renewable Energy Laboratory, July 2017).

Dynamic Examples: Anti-Islanding of Multiple Inverters with GSF





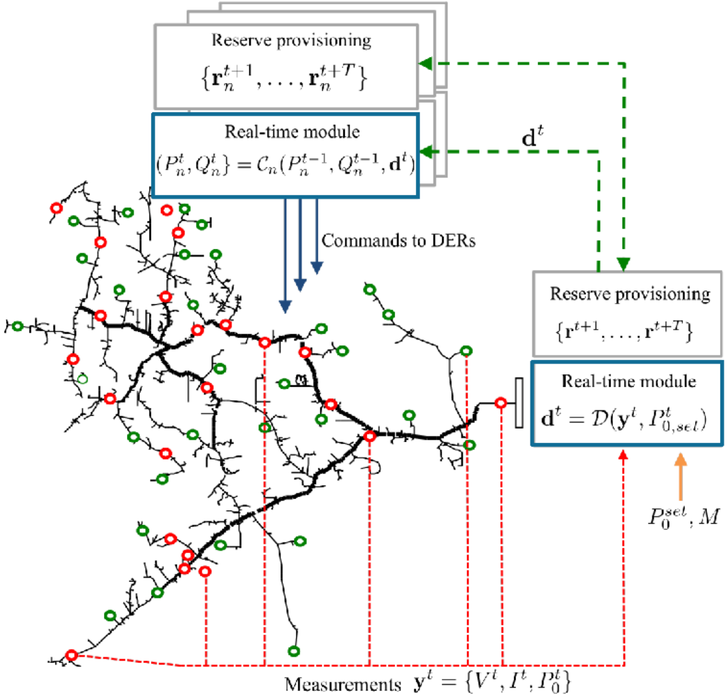
Topology 3:
Two inverters on one transformer and one on a second



Test Case	Circuit Topology and Impedances		
	# Transformers	# Overhead Lines	# Underground Lines
1	1	0	3
2	1	3	0
3	3	0	3
4	3	3	0
5	3	1	2
6	3	2	1
7	2	0	3
8	2	3	0
9	2	1	2
10	2	2	1

8. A. Hoke et al., "An Islanding Detection Test Platform for Multi-Inverter Islands Using Power HIL," *IEEE Transactions on Industrial Electronics* 65, no. 10 (Oct. 2018): 7944–7953.
9. A. Hoke, A. Nelson, B. Miller, S. Chakraborty, F. Bell, and M. McCarty, *Experimental Evaluation of PV Inverter Anti-Islanding with Grid Support Functions in Multi-Inverter Island Scenarios* (NREL/TP-5D00-66732) (Golden, CO: National Renewable Energy Laboratory, 2016).
10. S. Chakraborty, A. Hoke, and B. Lundstrom, "Evaluation of Multiple Inverter Volt-VAR Control Interactions with Realistic Grid Impedances," presented at the IEEE PES GM, 2015.

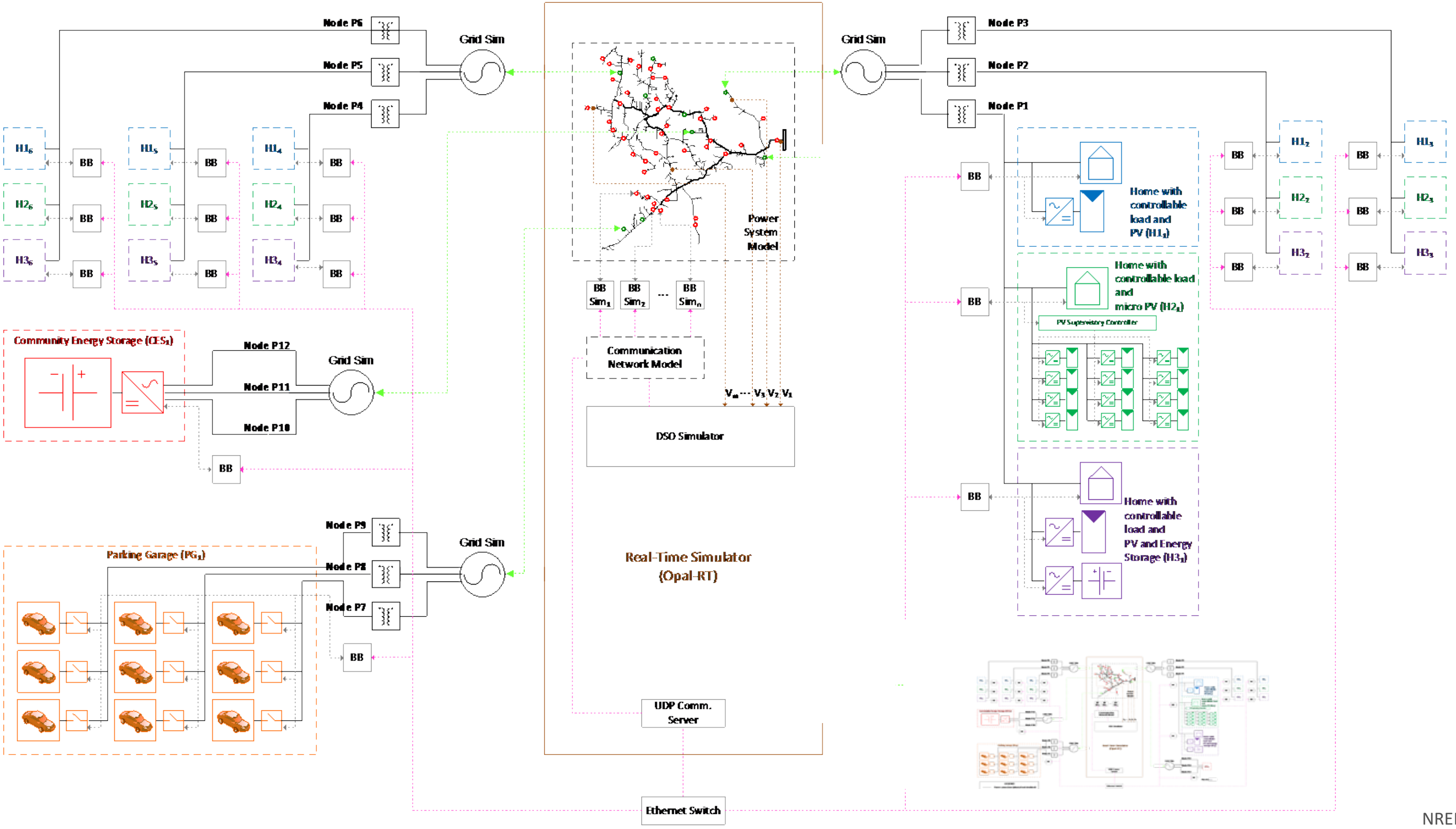
Next Applications



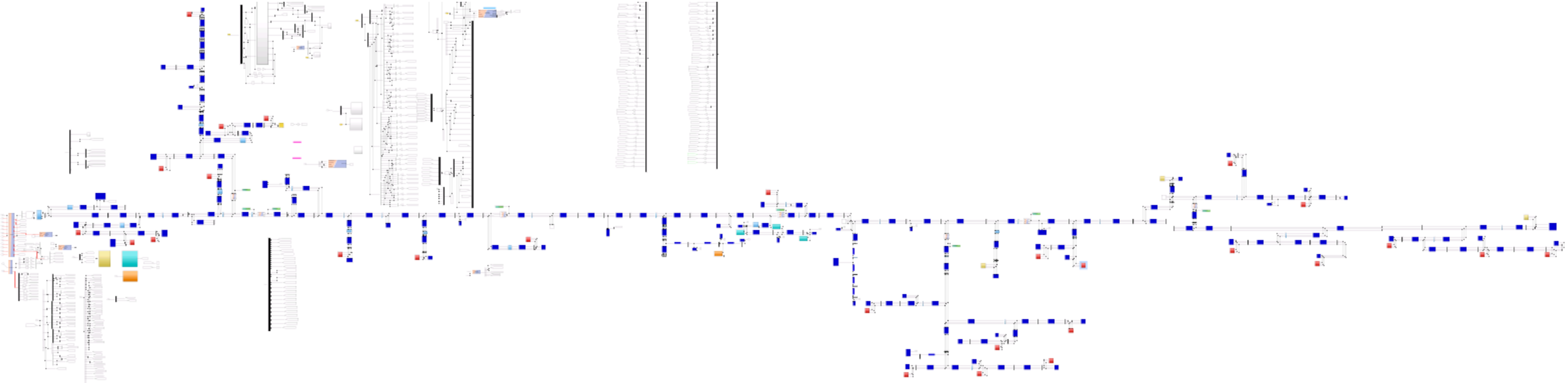
- Maximize customer and system operator objectives while respecting system limits
- Inertial response
- Primary frequency response
- Secondary frequency response
- Follow dispatch signals.

- Distributed control applications requiring full-scale models at dynamic timescale
- More power devices under test (100+)
- More control devices under test (100+)
- More PHIL PCCs
- Larger distribution + bulk power system networks.

Power- and Controller-Hardware-in-the-Loop Test Platform

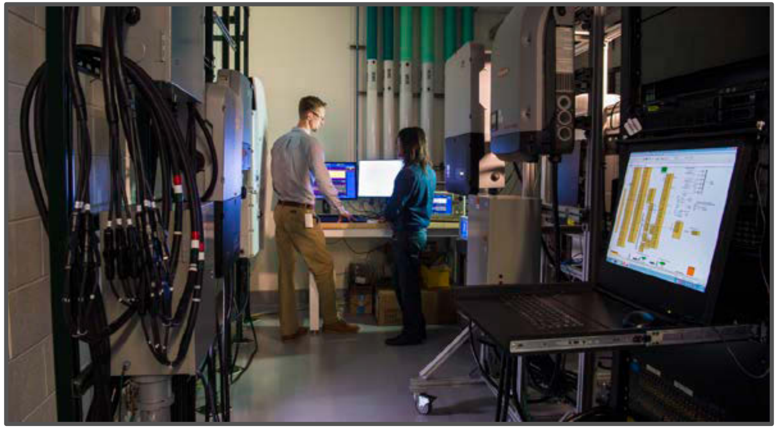


Implementation Aspects

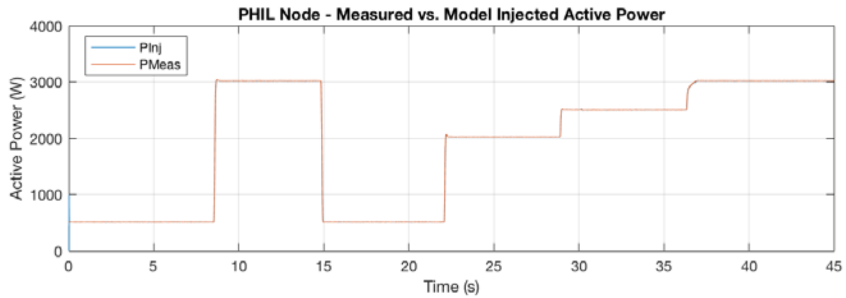


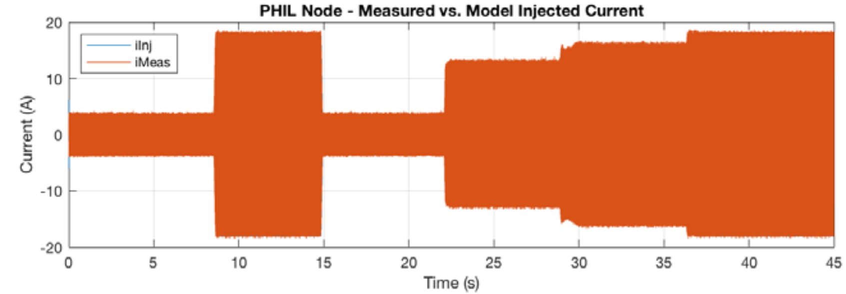
- Real-world distribution system model from Southern California Edison with 366 single-phase nodes, 100+ DER models, real-time load and generation inputs, running at 50–200 us time step using SSN solver
- 100+ powered hardware devices and 20+ controllers in (5) disparate lab locations
  - PV string inverters
  - PV microinverters
  - Battery inverters
  - EVSE + EV
  - Controllable load, including residential appliances
  - Community-scale hybrid power system
  - Beaglebone Black and Raspberry PI microcontrollers.
- Sensing: 200 kHz+ LEM voltage and current sensors
- Grid Sim: Various—Ametek RS and MX, and Chroma families
- Distribution of analog I/O via fiber.

Photo by Dennis Shroeder, NREL
NREL PIX54238

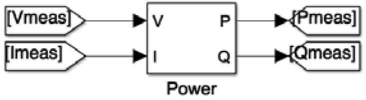


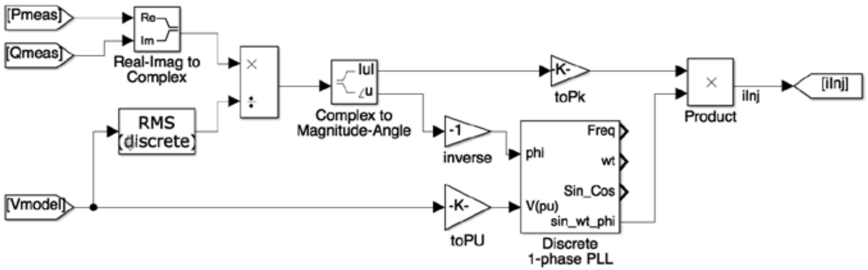
Power-Hardware-in-the-Loop Interface



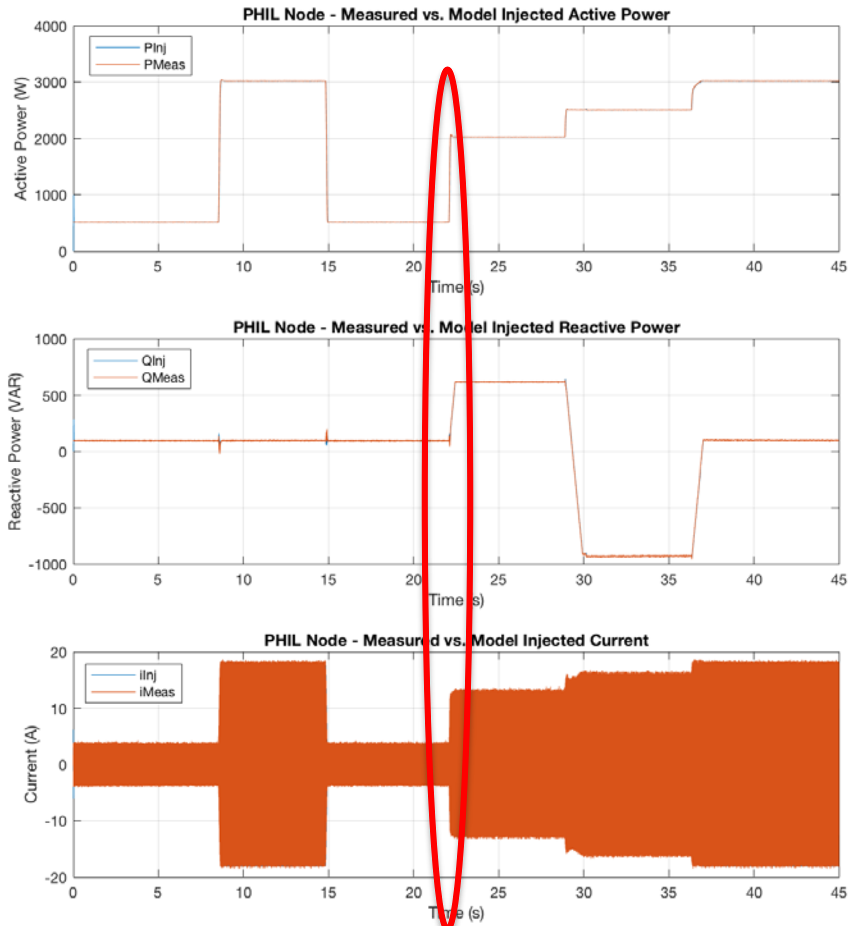


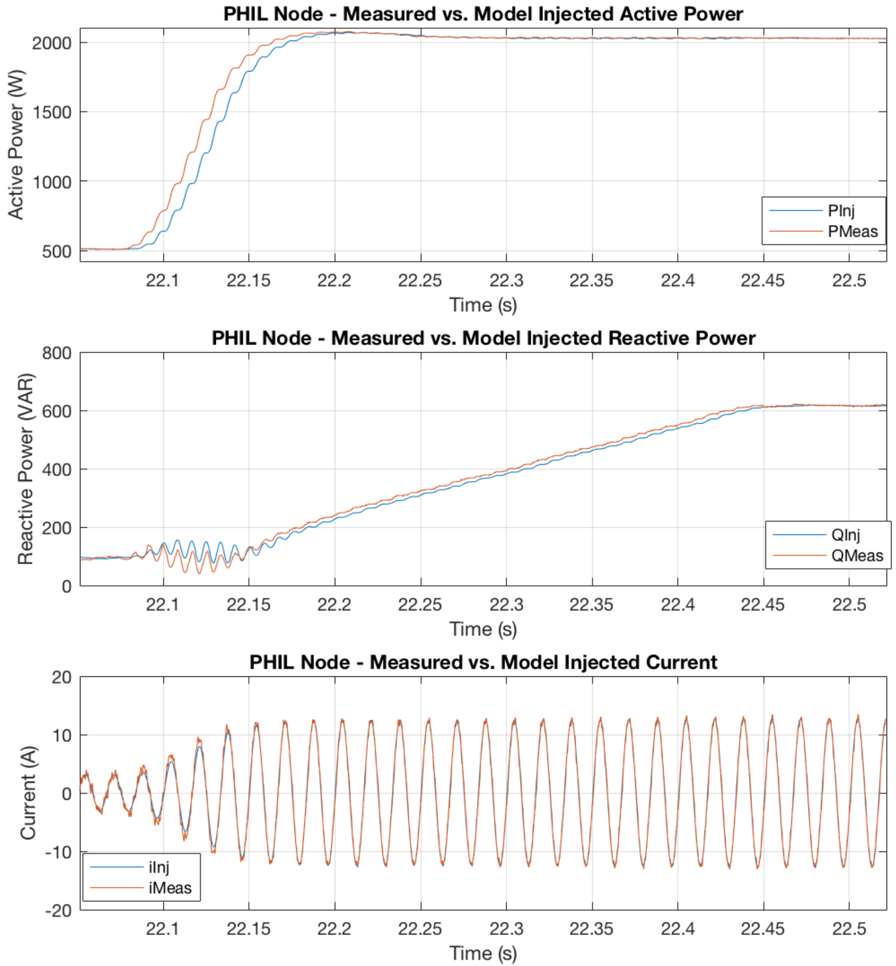
- Closed-loop control of voltage at device under test terminals using PR0 + delay compensation controller
- VITM-type interface algorithm leveraging power computation of the form:



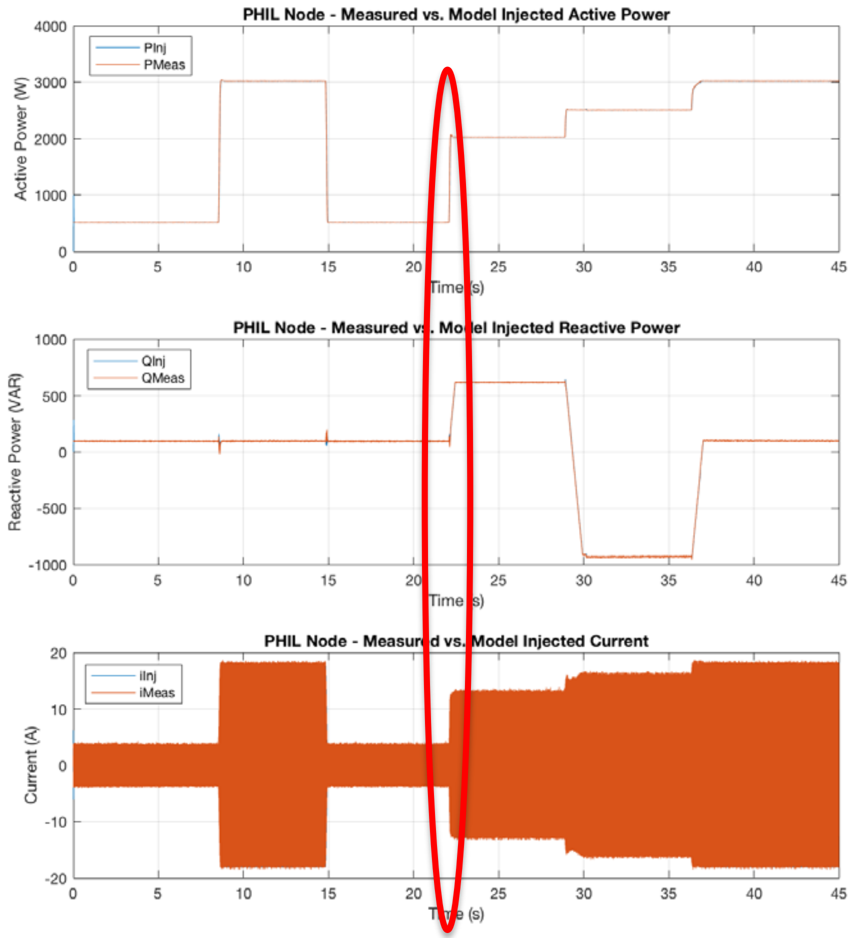


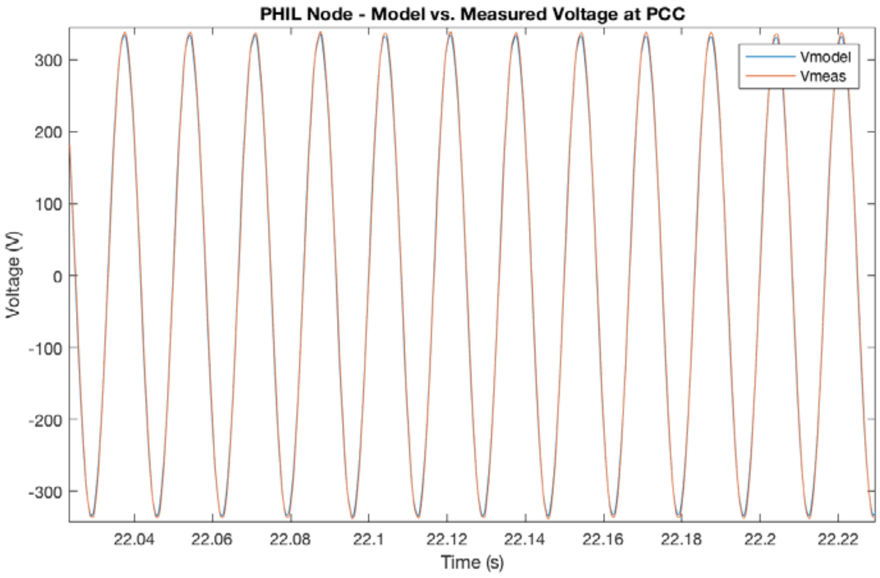
Power-Hardware-in-the-Loop Interface: Current, Power Tracking





Power-Hardware-in-the-Loop Interface: Voltage Tracking





Thank you

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