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Considerations for Microgrid Co-Design: Performance Verification Approach, Metrics, and Interoperability

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Outline

1. Microgrid Controller Performance Verification Approaches
2. Metrics for Evaluating Microgrid Controller Performance
3. Considerations for Microgrid Control Co-Design

Microgrid Controller System Basic Functionality

- **Local objective**: manage generation, storage, and loads within microgrid boundaries to meet the needs of the local system
- **POI objective**: manage power flow, power quality, and provided ancillary services at the point of interconnection (POI)
- **Core Functions [1]:**
  - Transition
  - Dispatch

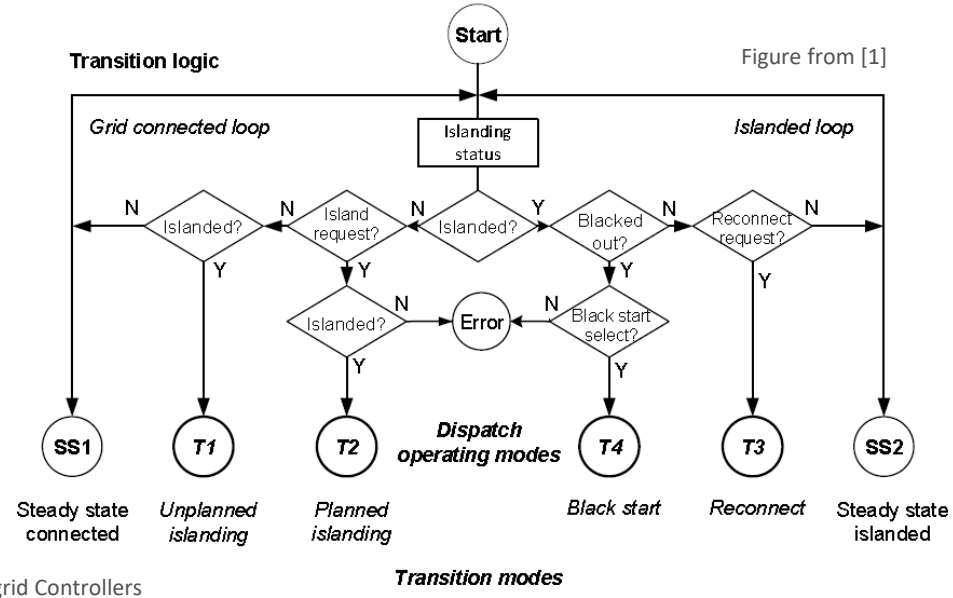


Figure from [1]

[1] IEEE Std 2030.7-2017, IEEE Standard for the Specification of Microgrid Controllers

Microgrid Control System Implementation Challenges

- The Microgrid Control System (MGCS) must successfully interact with many control devices:
  - Inverter, Generator, or Load controllers; Battery Management Systems
  - Protective relays
  - Distribution Management Systems
  - Supervisory Control and Data Acquisition systems
- Considerations:
  - Interoperability with many control devices
  - Reconfigurability to accommodate various microgrid designs
  - Robust to added, removed, or non-responsive assets
  - Local and POI objectives may be competing
  - Cyber security

DOE/NREL Microgrid Controller Procurement Challenge

- **Motivation**: advance a standardized and systematic approach to evaluating microgrid controllers to:
  - Allow developers, operators, and key stakeholders to objectively understand MGCS performance and make informed decisions
  - Promote increased transparency in microgrid technology functionality
  - Advance nascent microgrid standards
  - Spur further microgrid controller innovation

- **Summary**: In 2017-2018, NREL hosted a dual-stage microgrid controller procurement challenge in which commercial vendors were invited to participate in a multi-round competition to demonstrate the best-performing microgrid controller. The winner's controller was purchased for permanent installation in NREL's microgrid research platform.

MGCS Validation Approaches

NREL MCPC Stage 1

MIT LL Microgrid Symposium 2017 [3]

NREL MCPC Stage 2

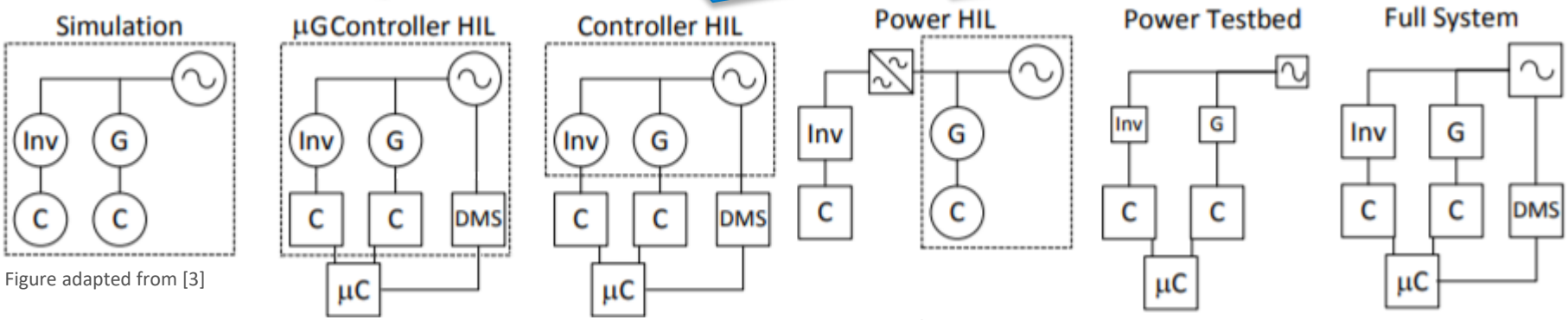


Figure adapted from [3]

- Trade-offs:
  - Coverage
  - Fidelity
  - Complexity/Safety concerns
  - Cost

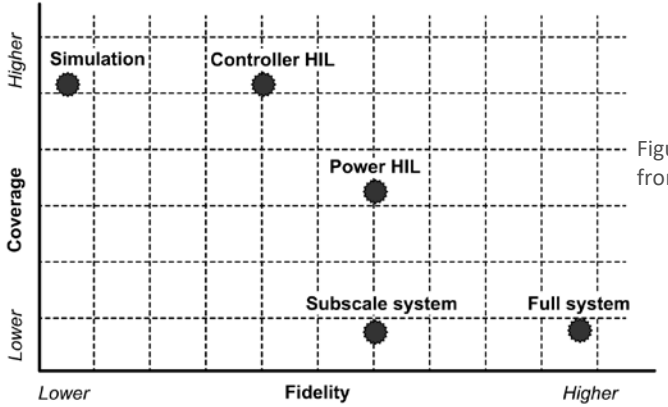


Figure from [2]

[2] IEEE Std 2030.8-2018, IEEE Standard for the Testing of Microgrid Controllers

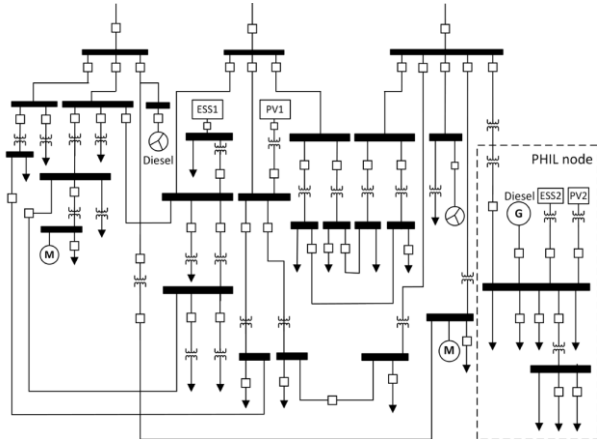
[3] R. O. Salcedo et al., "Development of a Real-Time Hardware-in-the-Loop Power Systems Simulation Platform to Evaluate Commercial Microgrid Controllers," Technical Report 1203, MIT Lincoln Laboratory, 2016.

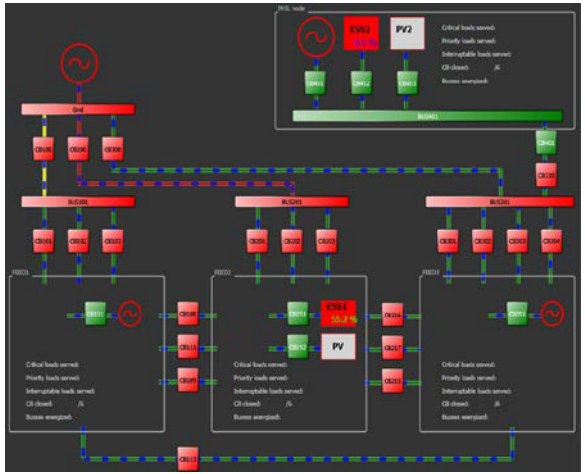
GHOST

- The microGrid Hardware-in-the-loop Open Source Testbed (GHOST) was developed at NREL to evaluate MCPC controllers
- Implements CHIL and PHIL stages
- Expands upon a validated, open source microgrid power system model for an industrial facility developed by MIT LL [3] – NREL added smart DER models, additional PHIL node with smart controllable DER assets for the MCPC
- Implements multiple test scenarios that go beyond the standardized framework test conditions (e.g., [2]) to evaluate important cost and operation factors for practical microgrids under challenging scenarios
- Key performance parameters (KPPs) are utilized to evaluate aggregate performance - relative weights adjusted based on industry focus group input
- All models, scenarios, code, etc. are now open source and available: https://github.com/PowerSystemsHIL/EPHCC

[2] IEEE Std 2030.8-2018, IEEE Standard for the Testing of Microgrid Controllers
[3] R. O. Salcedo et al., "Development of a Real-Time Hardware-in-the-Loop Power Systems Simulation Platform to Evaluate Commercial Microgrid Controllers," Technical Report 1203, MIT Lincoln Laboratory, 2016.

GHOST RT-HIL Model and HMI



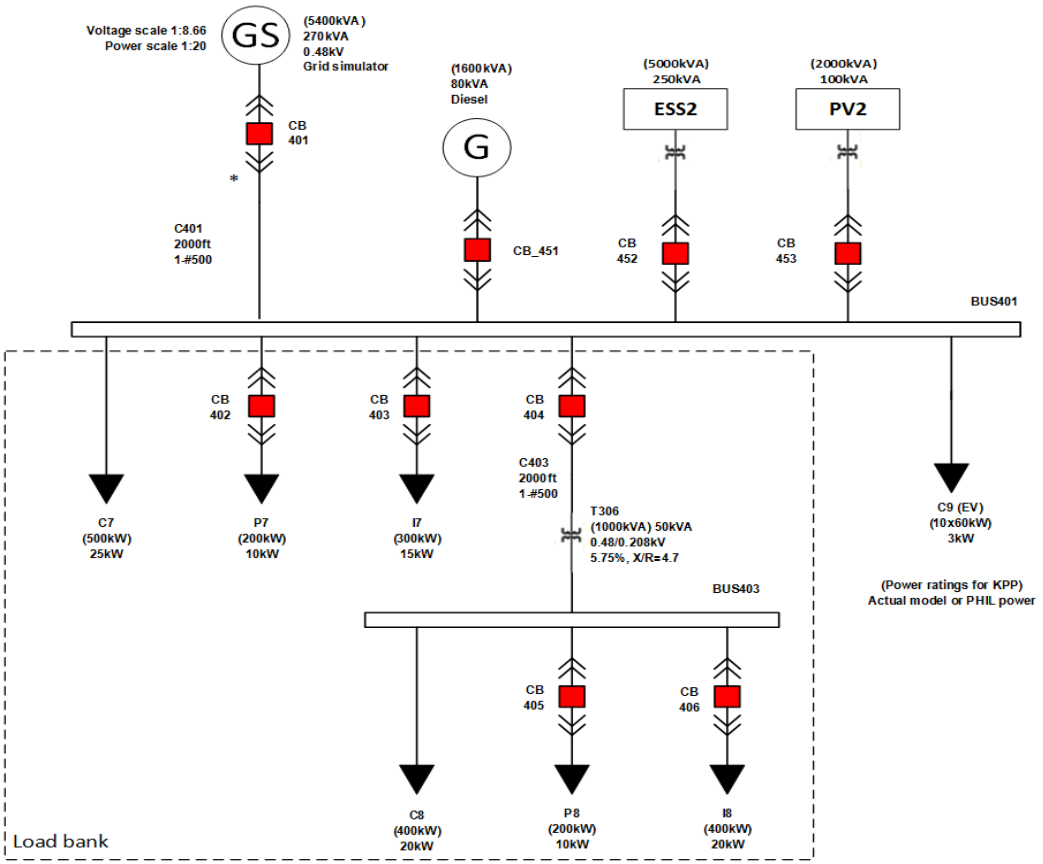


- Three feeders, overall peak 16.5 MW
- Distribution at MV (13.8 kV) and LV (4.16 kV, 2.4 kV, 208 V)
- (25) loads: 9 critical, 8 priority, 8 interruptible
- (2) large induction motors
- (3) Synchronous Generators (4, 3.5, 1.5 MVA) with controls
- (2) PV inverters (5, 2 MW) with controls
- (2) ESS inverters (5, 2 MVA) with controls
- Inverter control: grid-forming, grid-following, with seamless transition and droop functionalities
- (49) circuit breakers with protective relays, IEC 61850, Modbus
- (1) DMS interface
- Single phase nodes: 291
- RT Simulation on Opal RT OP6500 – 12 cores, Ts = 100µs
- Controller interface: based on ethernet only
  - 50 IEC61850 GOOSE interfaces
  - 56 Modbus TCP interfaces

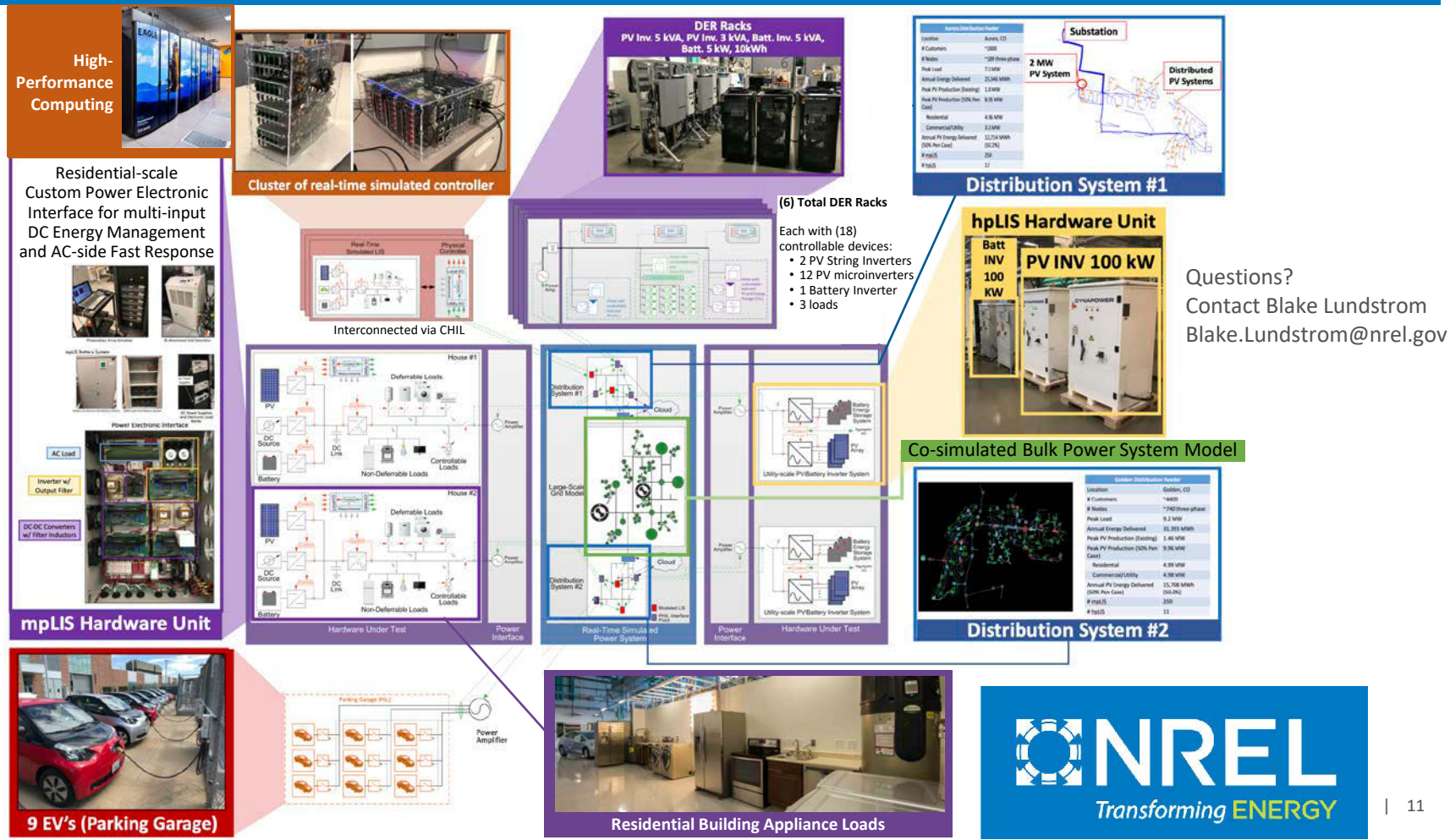
GHOST PHIL Configuration

Real power hardware:

- 270 kVA Grid Simulator
- 100 kVA PV Inv.
- 250 kW PV simulator
- 250kVA ESS inverter
- 250 kW emulated battery (bi-directional DC supply)
- 250 kW load bank
- ABB Circuit Breaker
- 80 kW diesel generator
- Electric Vehicle



NREL Distribution Scale PHIL + CHIL Evaluation Platform



Questions?
Contact Blake Lundstrom
Blake.Lundstrom@nrel.gov

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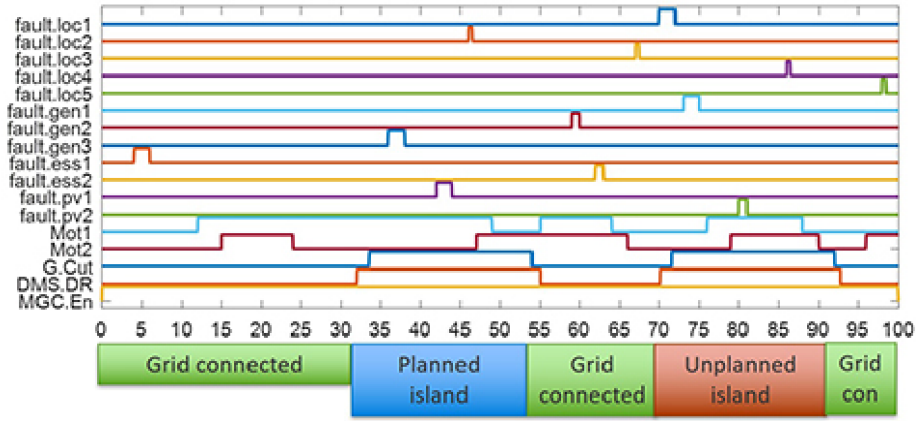
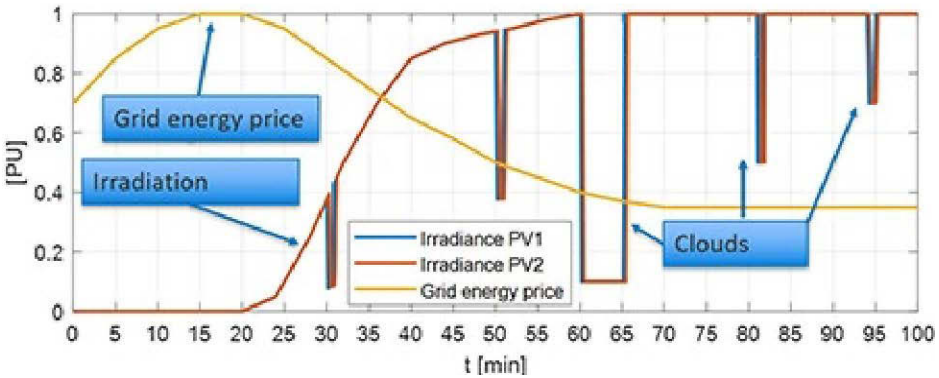
GHOST Example Test Sequence (100 min)





- Mimic real microgrid operation scenarios with events that allow accelerated testing of multiple functionalities, including dispatch and transition
- Evaluate microgrid controllers' ability to respond to real-time variability of load, generation, and energy pricing as well as respond to multiple contingencies:
  - Motor startup
  - Motor trip-off
  - Loss of various generation assets
  - Line faults

Steady-state Performance Metrics

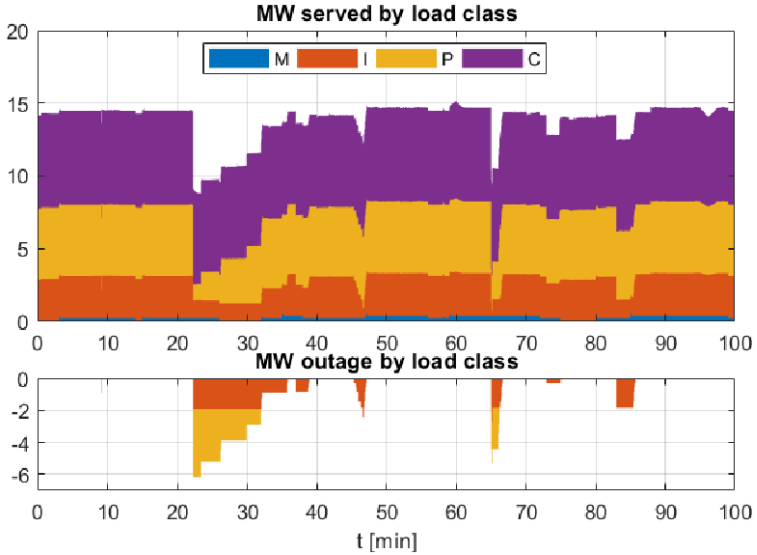
KPP1 – Resiliency and Reliability

Measured by calculating the energy delivered to predetermined categories of load. A penalty will be added for any outage on critical loads.

$$\mathrm{KPP1} = E_C P_{11} + E_P P_{12} + E_I P_{13} - E_{CO} P_{15} - E_{PO} P_{16} + E_{ESS} P_{17}$$

where:

Energy [kWh]		Unit cost [$/kWh]
Energy delivered to Critical loads	E_C	P_{11} = 1.00
Energy delivered to Priority loads	E_P	P_{12} = 0.90
Energy delivered to Interruptible loads	E_I	P_{13} = 0.85
Energy Critical loads Outage	E_{CO}	P_{15} = 4.50
Energy Priority loads Outage	E_{PO}	P_{16} = 2.25
Energy left in ESS at the end of the sequence compared to beginning	E_{ESS}	P_{17} = 1.00



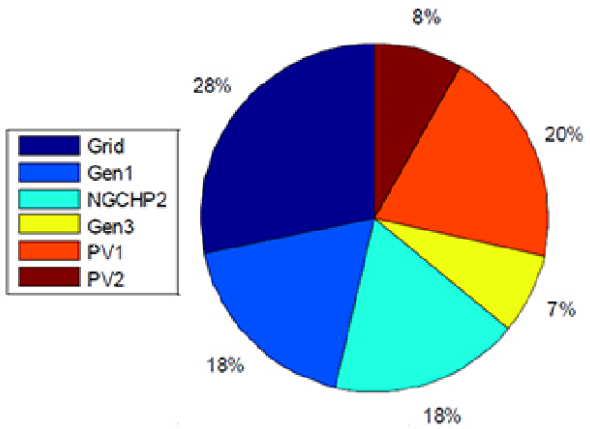
Loads served (top) and outages (bottom) during a test sequence measuring KPP1

Load types:
M = motor, I = interruptible,
P = priority, C = critical

Steady-state Performance Metrics

KPP2 – Fuel Costs
The cost of fuels to run generators with a credit for heat delivered

Used Fuel - Diesel	F_D [gal]	P_{21} = 74.55 [$/gal]
Used Fuel- Natural Gas	F_{NG} [m^3]	P_{22} = 4.18 [$/$m^3$]
Energy delivered as Heat	E_H [MBtu]	P_{28} = 147.00 [$/MBtu]



The breakdown of energy resources used by a microgrid controller under evaluation. Solar PV and grid energy were prioritized in this evaluation, as their respective costs were lower than energy generation from on-site generators.

Steady-state Performance Metrics

KPP3 – Interconnection Contract

- Accounts for cost of power exchange with the grid, including the variable price of energy during the sequence
- Penalty for exceeding active and reactive power export and import limits

Exported Energy	E_E [kWh]	P_E [$/kWh]
Exported Energy Over limit	E_{E0} [kWh]	P_{EO} [$/kWh]
Energy imported from grid	E_B [kWh]	P_B [$/kWh]
Energy imported over limit	E_{BO} [kWh]	P_{BO} [$/kWh]
Reactive power over limit penalty	E_{RP} [kVArh]	P_{33} = 0.50 [$/kVArh]

KPP4 – Grid Services

Incentivizes controllers to support the grid by following DMS commands and autonomously responding to detected grid contingency events (e.g., underfrequency)

Meeting dispatch command premium (DP). Power imported from Grid to µG	T_{DP} [min]	P_{41} = 23.60 [$/min]
Meeting demand command premium (DM). Power exported from µG to Grid	T_{DM} [min]	P_{41} = 23.60 [$/min]
Following Volt/Var support premium (VV)	T_{VV} [min]	P_{43} = 290.00 [$/min]
Following Demand response curve (Freq/kW, FkW)	T_{FkW} [min]	P_{44} = 149.50 [$/min]
Meeting power factor request (PF)	T_{PF} [min]	P_{46} = 11.21 [$/min]
Violating planned disconnect request (DR)	T_{DR} [min]	P_{45} = 19.50 [$/min]
Unplanned disconnect – failure to disconnect (UD)	T_{UD} [min]	P_{47} = 26.40 [$/min]

Steady-state Performance Metrics

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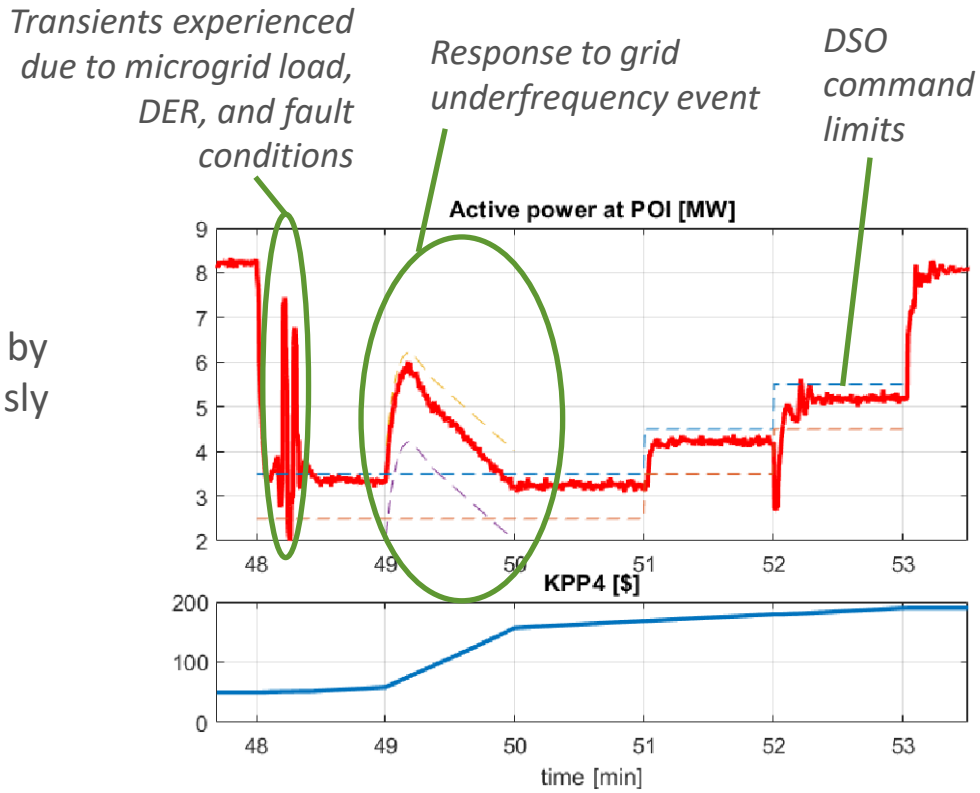


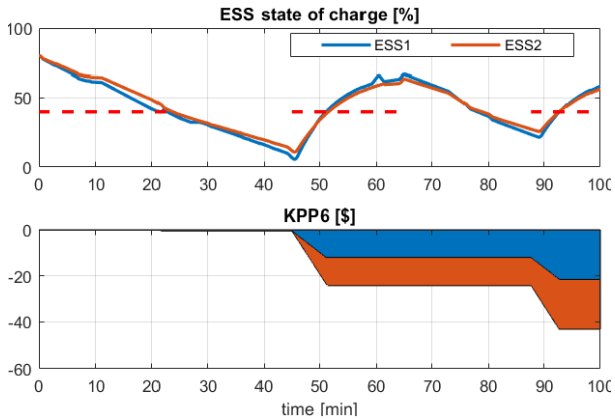
Steady-state Performance Metrics

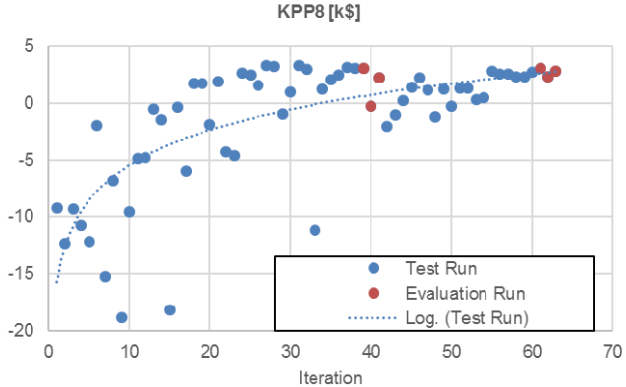
KPP5 – Power Quality
Voltage and frequency monitored at all nodes and deviations violating IEEE 1547a-2014 clearing times (Tables 1 and 2 of the standard) are penalized

KPP6 – Microgrid Survivability
Allowing battery State of Charge (SoC) below the predetermined level during grid connected conditions results in a penalty

KPP7 – Operation and Maintenance
Accounts for microgrid component use that will result in component degradation, including generator starting, battery cycling, CB switching, and overcurrent conditions

KPP8 – Economic Operation
Dollar sum of KPP1 to KPP7 allowing for overall comparison of various controllers under test

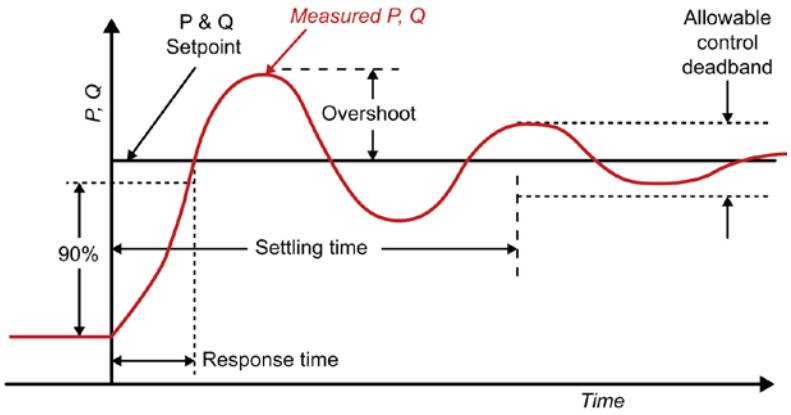


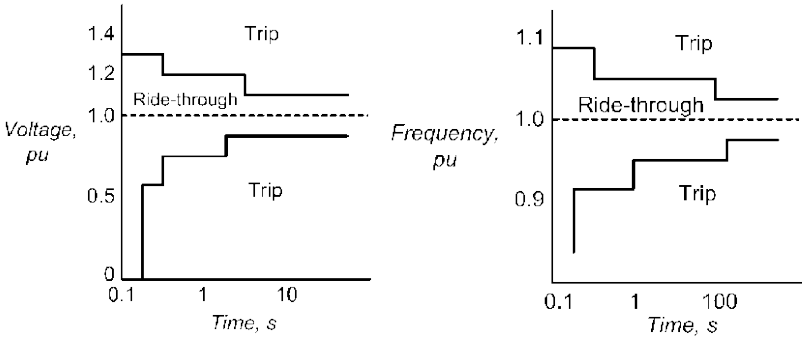


MCPC controller performance improvement through design iteration

Dynamic Performance Metrics

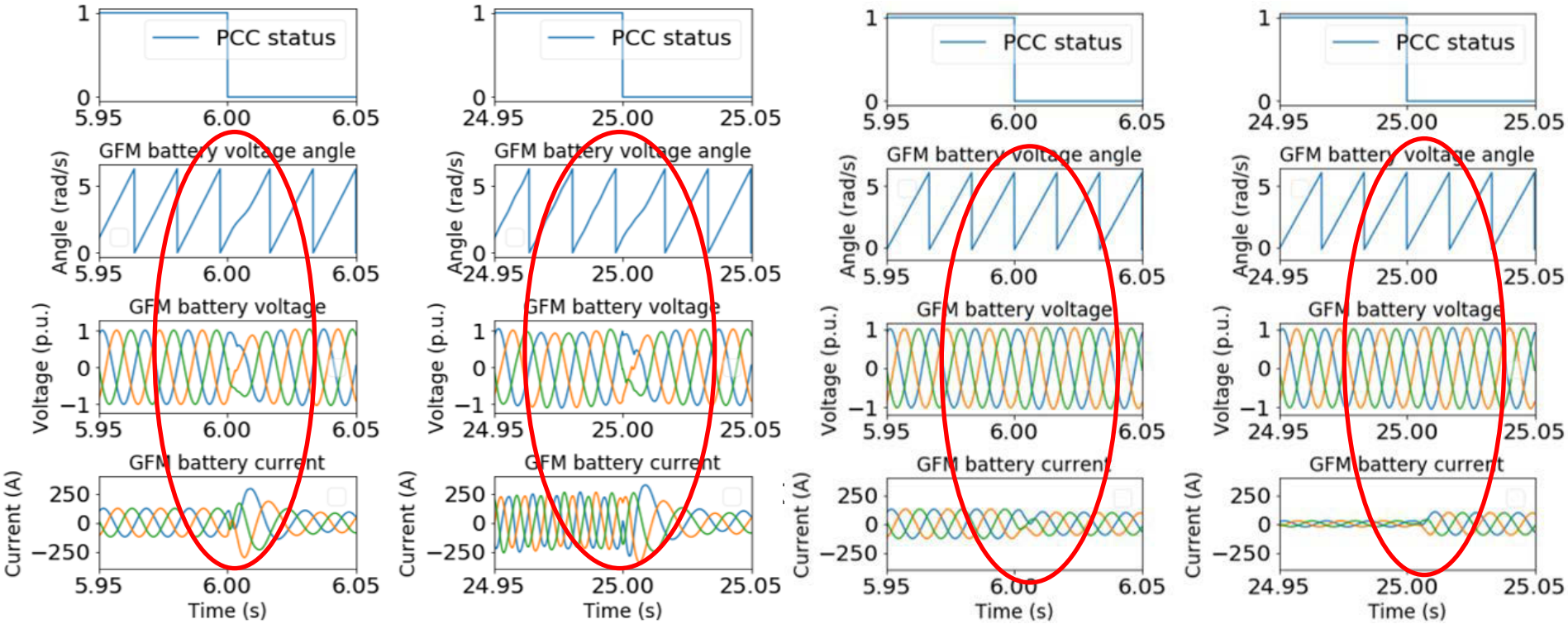
- Approach in IEEE Std 2030.8 [2]:
  - Evaluated at transition to unplanned island, planned island, and reconnection
  - V, f, P, Q settling time, overshoot, and steady-state values within contractual limitations





Figures from: [2] IEEE Std 2030.8-2018, IEEE Standard for the Testing of Microgrid Controllers

Unintentional Islanding Event Performance Example



Traditional method

Improved method [4]

[4] J. Wang, B. Lundstrom, A. Bernstein, "Design of a Non-PLL Grid-forming Inverter for Smooth Microgrid Transition Operation," in *IEEE PES General Meeting*, 2020.

Considerations for Microgrid Control Co-design

- For practical implementations, microgrid control system performance and value are dependent on a wide array of metrics—both dynamic and steady-state—that may be challenging to co-optimize, especially for multiple microgrid configurations
  - Local and POI objectives are frequently competing
  - The relative importance of performance metrics may vary widely by region and owner
- A standard set of metrics *and evaluation scenarios* is critical for objective comparison and validation of MGCS performance
- HIL is a valuable, cost-effective tool for rapid, iterative design and evaluation

Considerations for Microgrid Control Co-design

- Contemporary microgrid controllers are highly optimized for a particular configuration to provide the maximum value. This makes it difficult to avoid recurring engineering cost.
- Microgrid assets and controllers from multiple vendors are often used to minimize overall cost and due to vendor specialization. Standardization and interoperability are critical to support this approach, but may conflict with control co-design

Thank You

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