Integrated Microgrid Control Platform

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12/1/2022

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SYMPOSIUM
November 29 – December 2, 2022 Arlington, VA

Project Leadership

- Gabor Karsai, PI,
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Problem Statement

- **Problem**: How to rapidly build the control system for *networked microgrids* that use heterogeneous power resources with various communication and control protocols?
- **Current approach**: Commercial offerings are proprietary, engineered solutions designed to centrally control all assets in the microgrid, requiring a single vendor for the entire implementation.
- **Example**: Vendor solution based on vendor control hardware:
  - Coordinates only assets linked to controller hardware
  - Addition of assets to the system requires reconfiguration of the controller
  - Advanced features provided as “black box” solutions
  - Support of advanced communications and control approaches is limited and proprietary

Technical Objectives

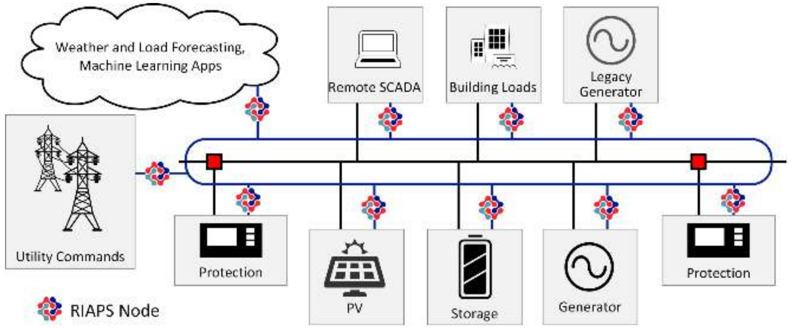
- The main technical objective of the project is to *demonstrate* how foundational technology for microgrid control and integration, developed through Department of Energy ARPA-E funding, can be applied in a field environment.
- The specific goals:
    1. To demonstrate advanced, distributed microgrid control algorithms that solve the dynamic, real-time reconfiguration, and optimal dispatch problem of networked microgrids,
    2. To construct a concrete and functional demonstration based on a distributed software platform: an ‘operating system’ for power grids that serves as a *reference implementation* for future installations.

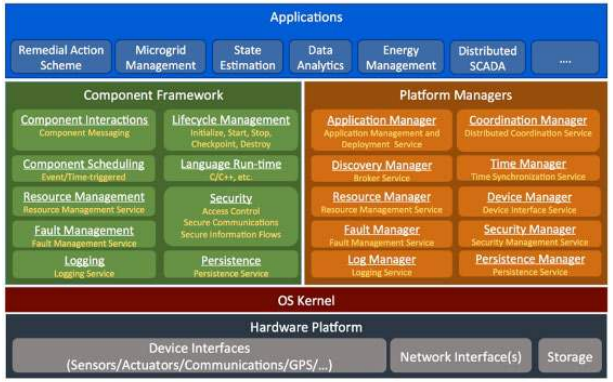
Technology/Methodology Description

To be demonstrated

- **Microgrid control and integration technology:** Advanced microgrid control algorithms implemented as *distributed software applications* running on a network of embedded computing nodes. Each node is interfaced to power resources.
- **Software platform technology:** RIAPS*, a *distributed 'operating system'* that provides the foundation for the applications with fault-tolerance, distributed coordination, resilience, time synchronization, and strong security
- **RIAPS on industrial hardware node**: Inexpensive *embedded computing nodes* to run RIAPS apps, and to replace current, inadequate, non-industrial quality hardware.

*RIAPS: Resilient Information Architecture Platform for the Smart Grid

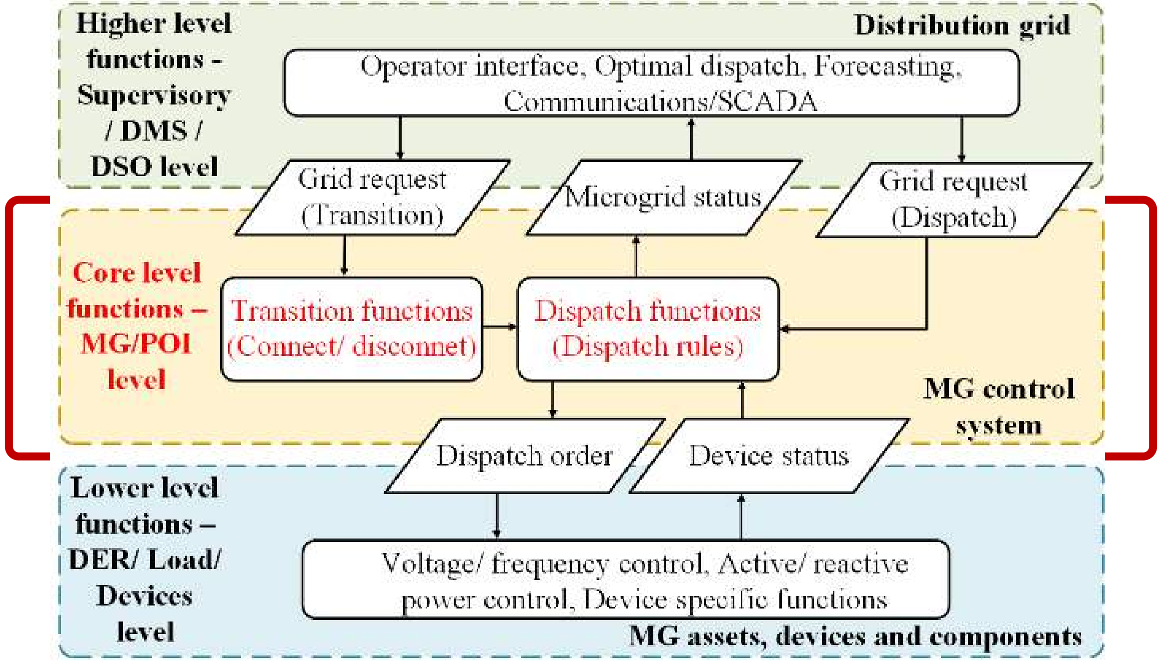




HW Platform:
Beaglebone Black

Technical Approach:
Integrated Microgrid Control Platform (IMCP)

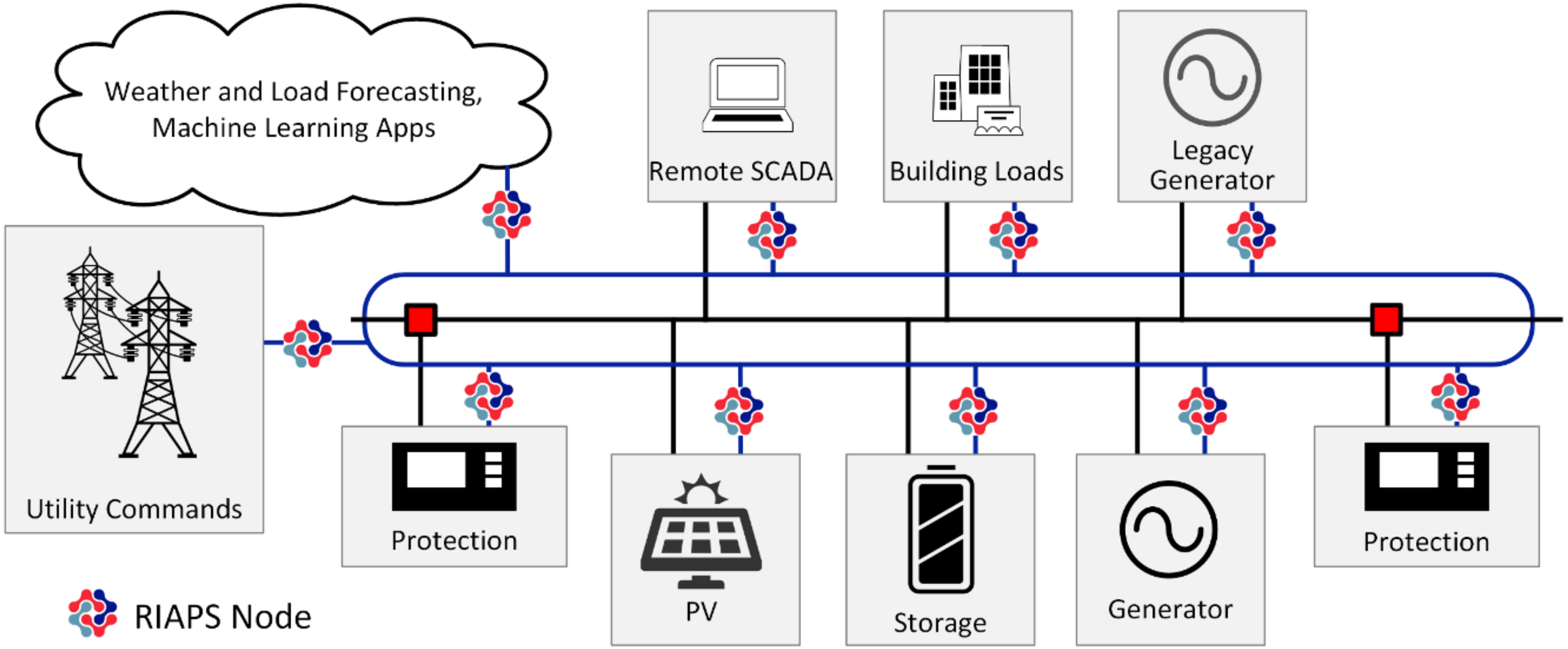
- **State-of-the-art microgrid controllers**
  - Proprietary, closed source
  - Centralized, single point of failure
  - Difficult to network with other controllers
  - Cumbersome DER* integration
- **IMCP provides a re-usable platform**
  - Open source, not proprietary
  - Distributed and resilient
  - Easily configured for nested microgrids
  - Supports plug-and play integration
  - Provides additional intelligence to legacy devices



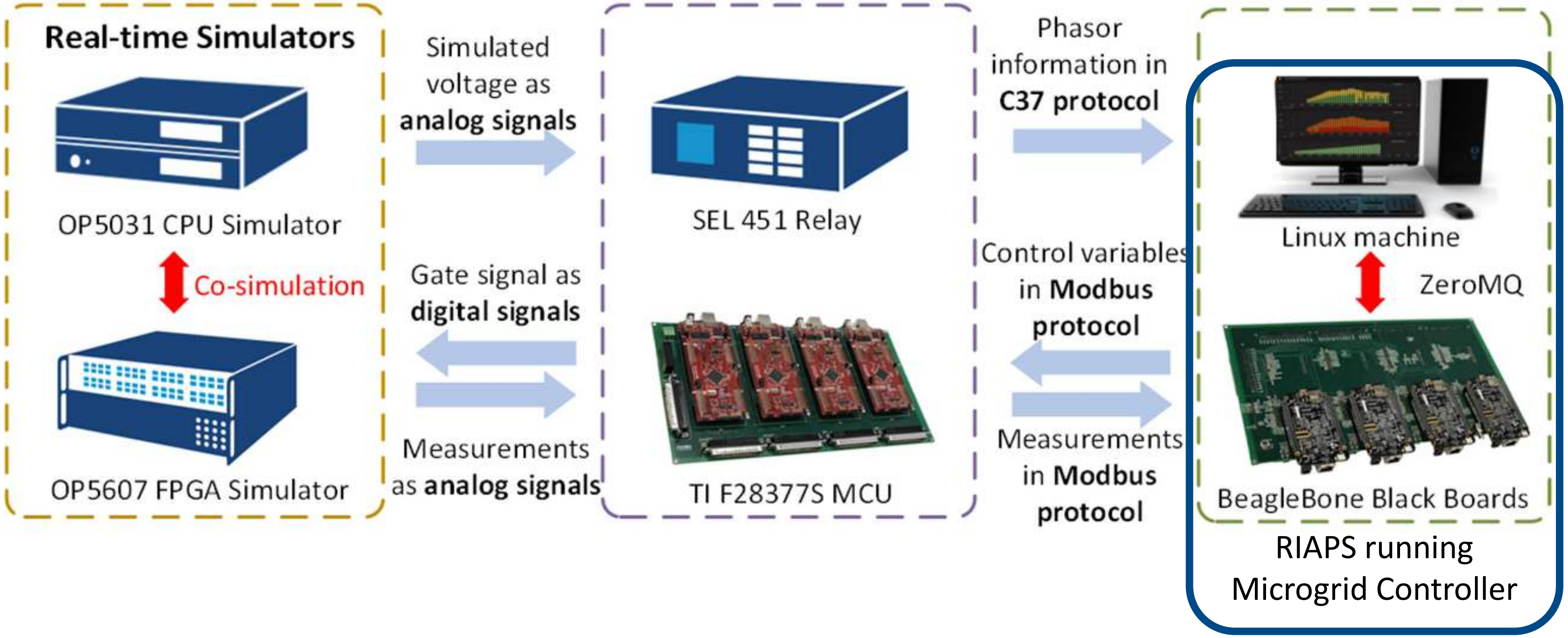
*DER: Distributed Energy Resource

Technical Approach: Reusable and Modular Microgrid Control Solution

- A fully distributed controller operating at the edge of the network delivers a scalable solution for any microgrid
- Reduces barrier to establishing advanced microgrid control



Technical Approach:
Prototype HIL Implementation at NCSU



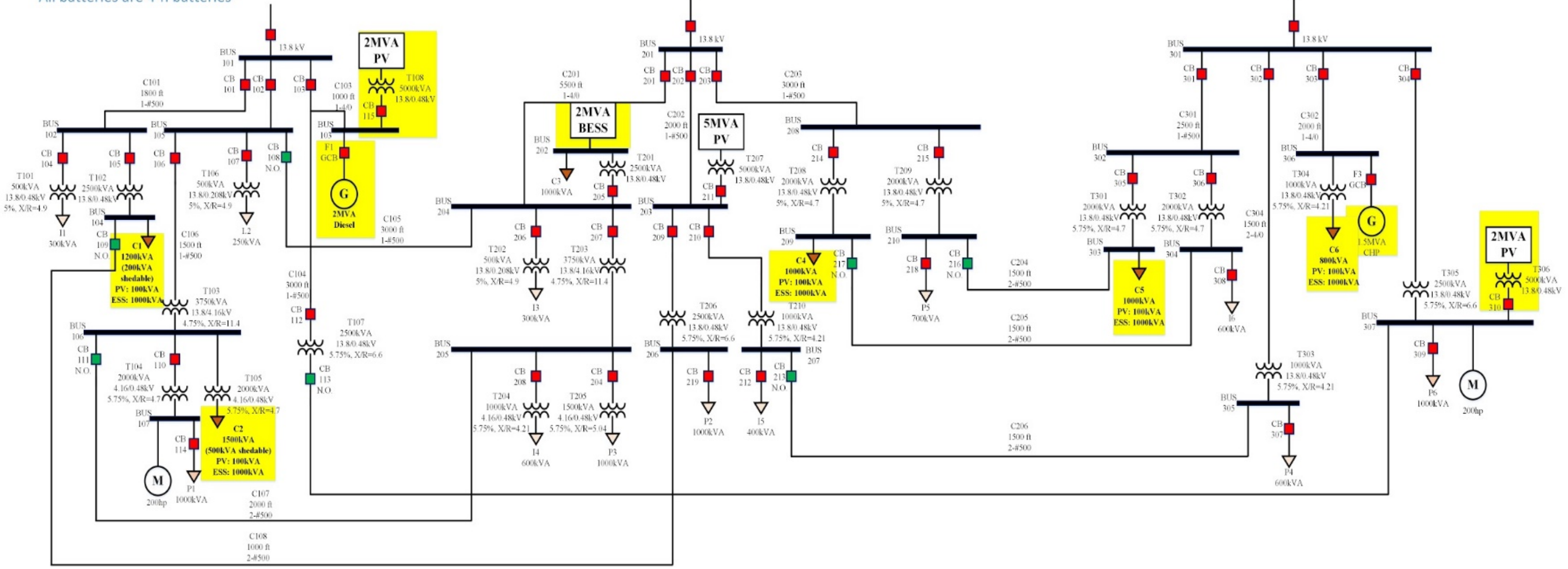
- Opal RT Simulator running switching models of power electronics converters and detailed models of other grid components
- Customized state-of-the-art MCUs* emulate DER controllers
- RIAPS nodes interface with MCUs, relays and simulated grid components

*MCU: Microcontroller Unit

Test and Evaluation Example

- Extended ‘Banshee’ microgrid
  - Three feeders with photovoltaics, gensets, and battery systems on each circuit
  - Can operate as three independent or as one integrated microgrid

All batteries are 4-h batteries



Technical Progress

Demonstration plan – Test details

Grid-connected	Islanded + Grid-to-Island	Island-to-grid	Cyber-security
HIL.1: PQ dispatch	HIL.5: Disconnect command (Planned Islanding)	HIL.9: Reconnect to the main grid	CS.1: Confidentiality
HIL.2: Frequency/Watt Mode Dynamic Reactive Power Support	HIL.6: Unplanned disconnect (Unplanned Islanding)		CS.2: Integrity
HIL.3: PF command	HIL.7: Connect two adjacent microgrids Reconfiguration)		CS.3: Authenticity
HIL.4: Loss of bus (Load Pickup)	HIL.8: Loss of bus (Load pickup)		CS.4: Availability

+1: HIL.10: Comprehensive test

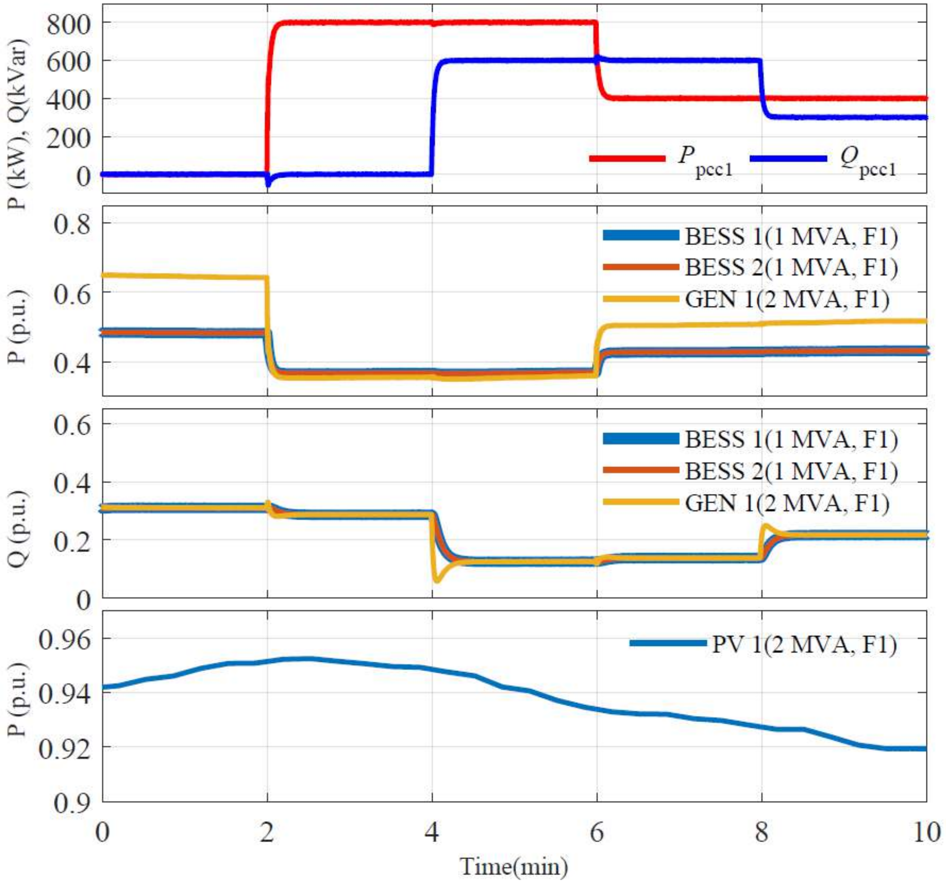
Technical Progress:
Summary of Test Results

Operating mode	Tests	Results
Grid-connected operation	HIL 1 Real and reactive power dispatch at POI	Passed
	HIL 2 Grid support at POI	Passed
	HIL 3 Power factor control at POI	Passed
	HIL4 Loss of bus (Load Pickup)	Passed
Grid-connected to islanded transition	HIL 5 Planned islanding	Passed
	HIL 6 Unplanned islanding	Passed
Islanded operation	HIL 7 Connecting adjacent feeders	Passed
	HIL 8 Disconnecting adjacent Feeders	Passed
Islanded to grid-connected transition	HIL 9 Reconnecting islanded microgrids to the grid	Passed
All	HIL 10 Comprehensive test	Passed

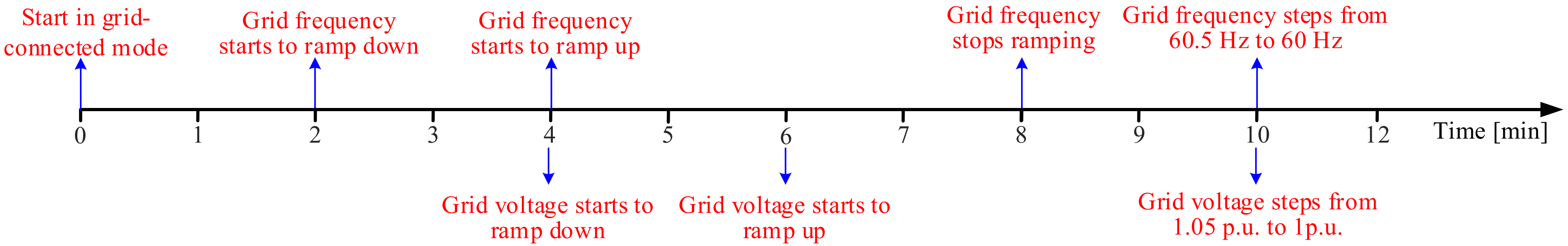
POI: Point of Interconnect

Technical Progress:
HIL1: Power Dispatch at POI - Feeder 1

- POI power is controlled to follow the reference
- Active power is shared among DERs according to cost curve:
  - $C\_dg1 = C\_dg2 = 0.025P^2 + 8$
  - $C\_gen = 0.005P^2 + 20P$
- Reactive power is shared proportionally to the ratings
  - $S\_dg1 = S\_dg2 = 1\ MVA$
  - $S\_gen1 = 2\ MVA$
- PV output is high
  - $S\_pv1 = 2\ MVA$



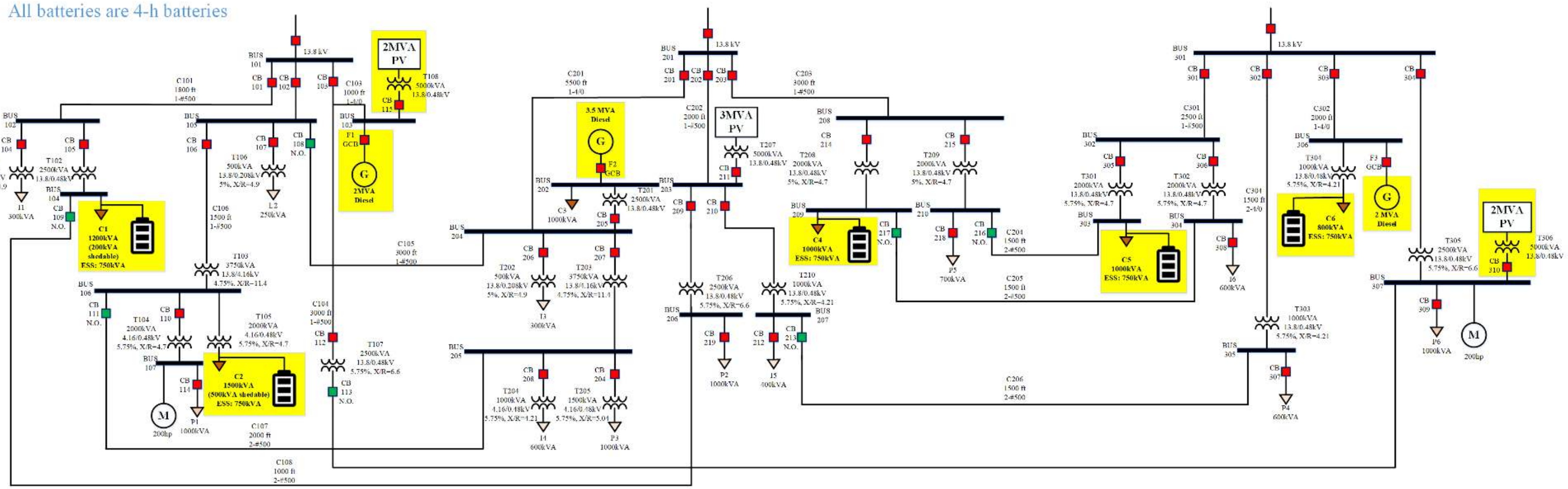
Technical Progress:
HIL 2: Grid Support at POI



The three feeders are connected to the main grid. They operate independently. In our test, the utility grid(115 kV) voltage and the grid frequency vary as follows

- From $t = 2$ min to $t = 4$ min, frequency ramps from 60 to 59.5 Hz
- From $t = 4$ min to $t = 8$ min, frequency ramps from 59.5 to 60.5 Hz
- From $t = 4$ min to $t = 6$ min, voltage ramps from 1 to 0.95 p.u.
- From $t = 6$ min to $t = 10$ min, voltage ramps from 0.95 to 1.05 p.u.
- At $t = 10$ min, f steps from 60.5 to 60 Hz, and V steps from 1.05 to 1 p.u.

Technical Progress: HIL 2: Grid Support at POI


All batteries are 4-h batteries

Scheduled base power $P_{base} = 400$ kW, $Q_{base} = 0$ kVar for each feeder. To support frequency and voltage, the power output at the POI is controlled as

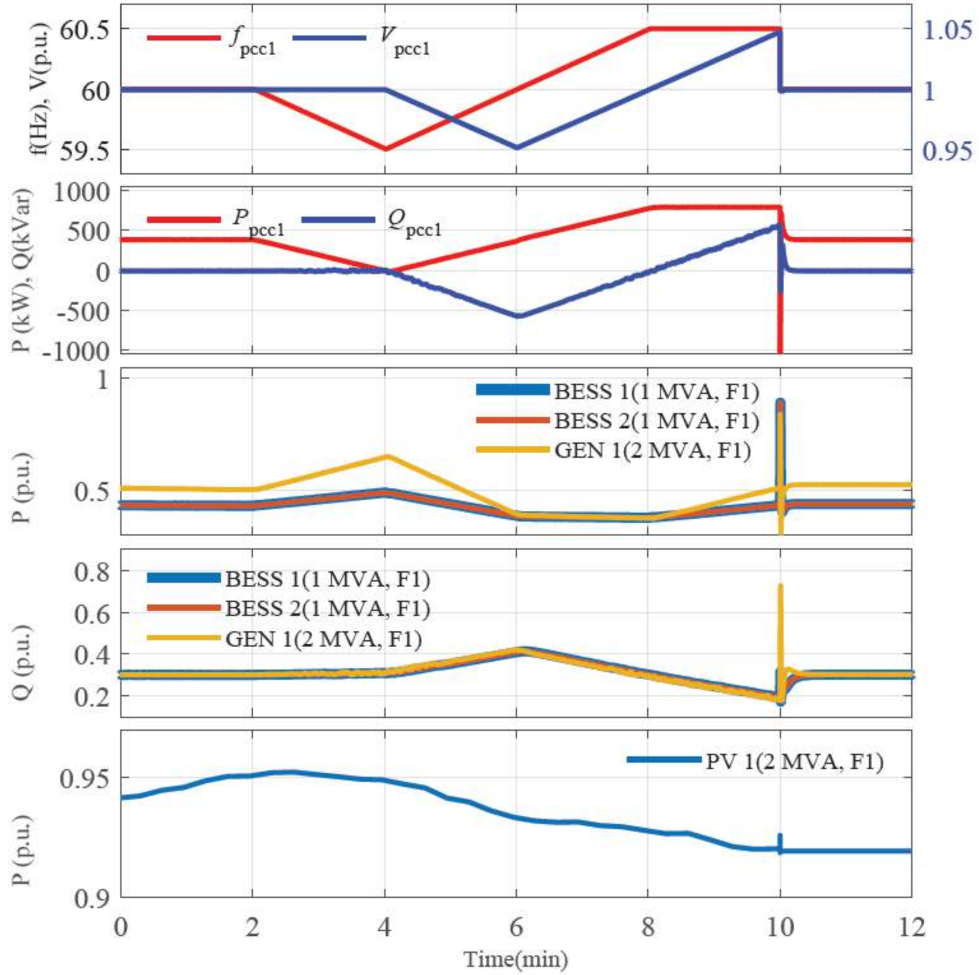
$$P_{POI} = P_{base} + (f - 60\text{ Hz}) \times \frac{400\text{ kW}}{0.05\text{ Hz}} \qquad 0\text{ kW}{\sim}800\text{ kW }(59.5\text{Hz}{\sim}60.5\text{Hz})$$

$$Q_{POI} = Q_{base} + \frac{V - 13.8\text{ kV}}{13.8\text{ kV}} \times \frac{600\text{ kVar}}{0.05\text{ p.u.}} \qquad -600\text{ kVar}{\sim}600\text{ kVar}(0.95\text{p.u}{\sim}1.05\text{p.u})$$

f and V are measured at the POI of each feeder

Technical Progress:
HIL2: Grid support at POI- Feeder 1

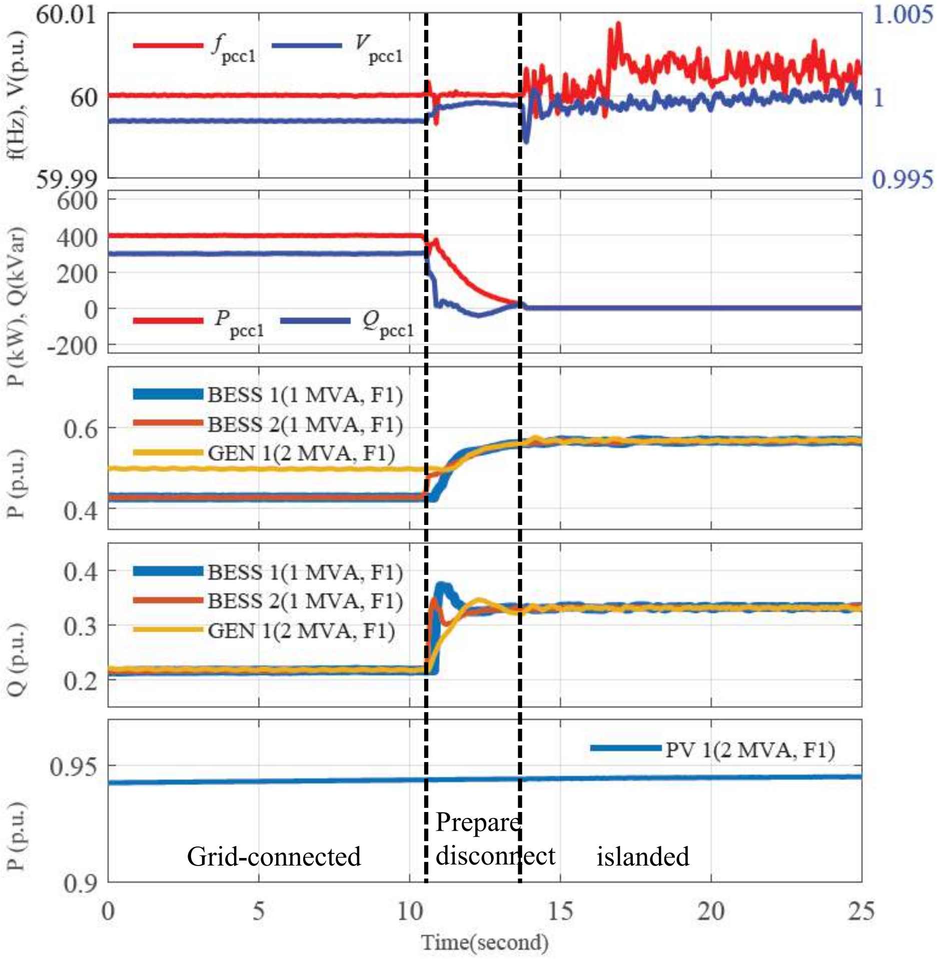
- Measured f and V at POI ,vary as designed
- POI active power and reactive power follow the f and V
- Active power is shared among DERs according to cost curve:
  - $C\_dg1=C\_dg2=0.025P\text{^}2+8P$
  - $C\_gen=0.005P\text{^}2+20P$
- Reactive power is shared proportionally to the ratings
  - $S\_dg1=S\_dg2=1\ MVA$
  - $S\_gen1=2\ MVA$
- PV output is high
  - $S\_pv1=2\ MVA$



PV: Photovoltaic (solar panel)

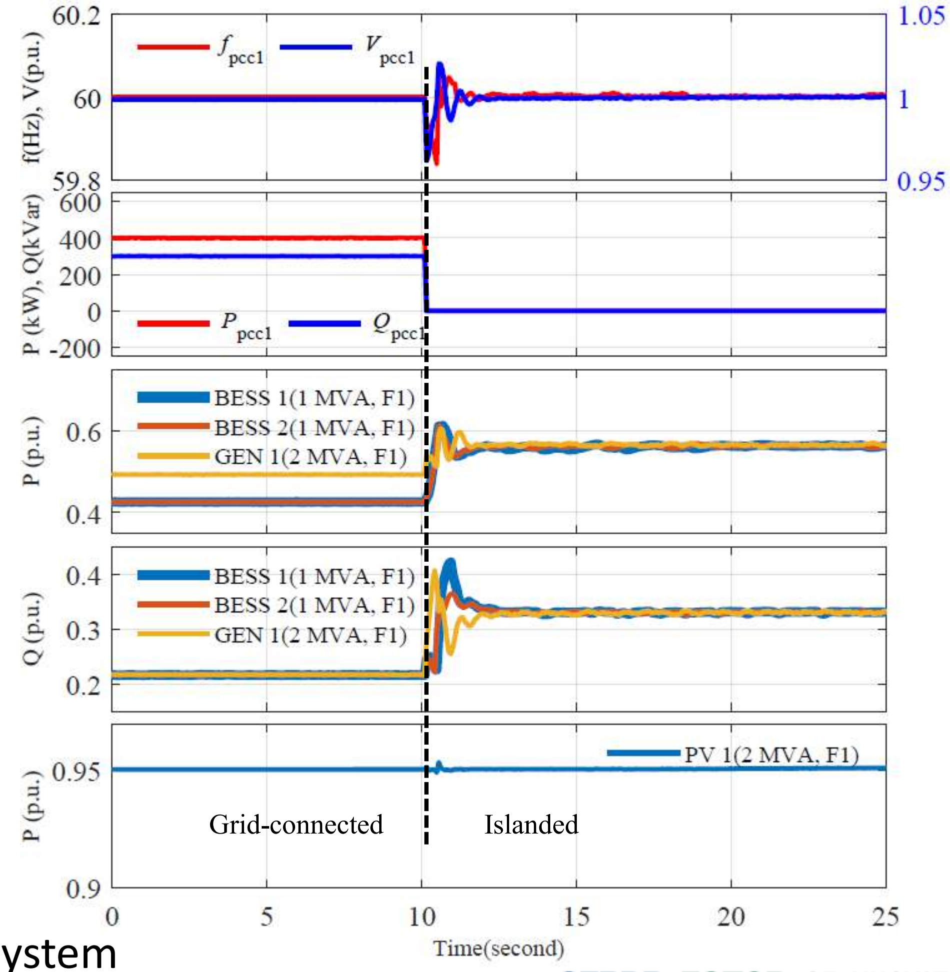
Technical Progress:
HIL 5: Planned Islanding – Feeder 1

- Measured f and V at microgrid POI
- Before islanding, POI active power and reactive power follow the reference $P_{POI}^{*} = 400\ kW$ and $Q_{POI}^{*} = 300\ kVar$.
- During islanding, POI active power and reactive power are regulated to 0.
- Before islanding, active power is shared according to cost curve :
  - $C_{dg1} = C_{dg2} = 0.025P^2 + 8P,\ \ C_{gen} = 0.005P^2 + 20P$
- During/after islanding active power is shared proportionally to the ratings
- Reactive power is shared proportionally to the ratings
  - $S_{dg1} = S_{dg2} = 1\ MVA,\ \ S_{gen1} = 2\ MVA$
- PV output is high
  - $S_{pv1} = 2\ MVA$



Technical Progress:
HIL 6: Unplanned Islanding - Feeder 1

- Measure frequency and Voltage at microgrid POI
- Before islanding, POI active power and reactive power follow the reference $P_{POI}^{*} = 400\ kW$ and $Q_{POI}^{*} = 300\ kVar$
- Before islanding, active power is shared according to a cost curve
- After islanding active and reactive power are shared proportionally
- Reactive power is shared proportionally to the ratings
    - BESS 1,2 =1 MVA
    - Generator 1 =2 MVA



BESS: Battery Energy Storage System

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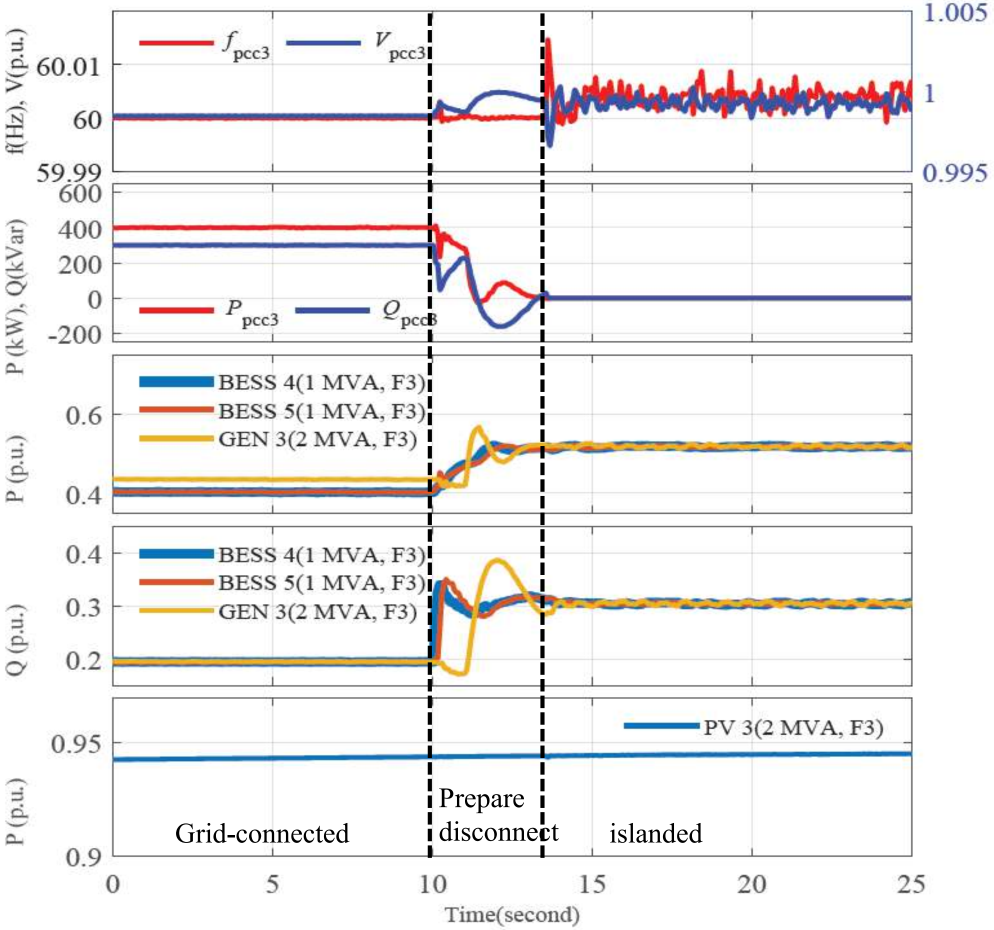
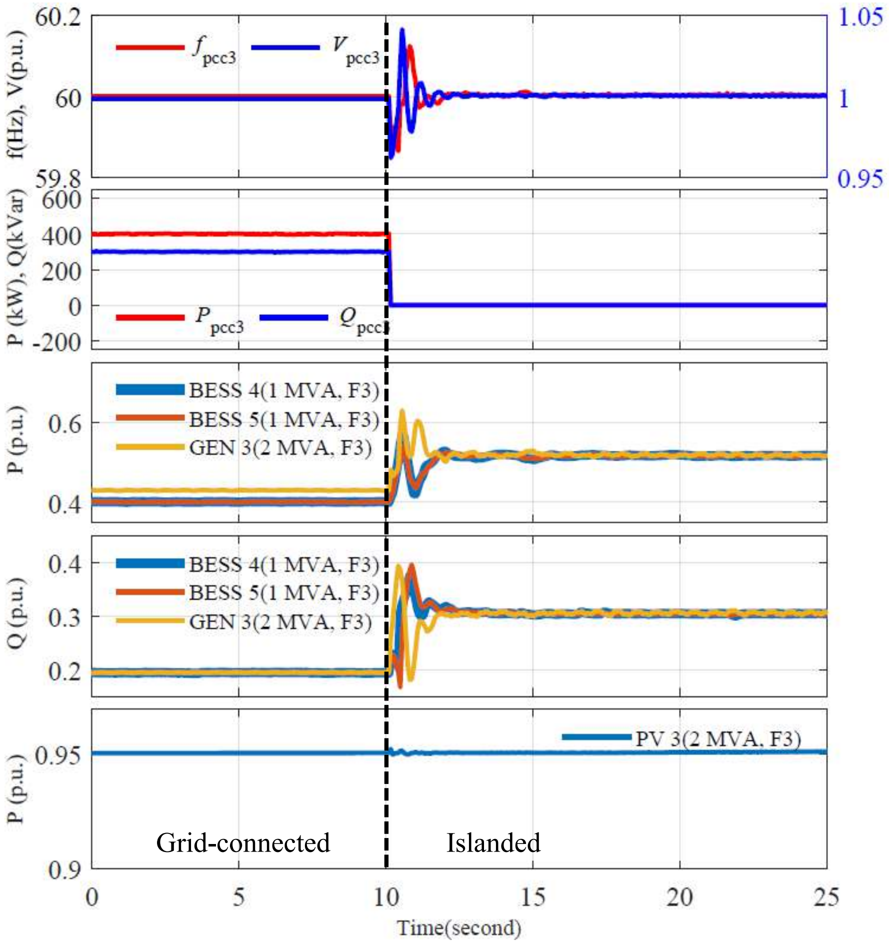
Technical Progress:
Compare Planned and Unplanned Islanding

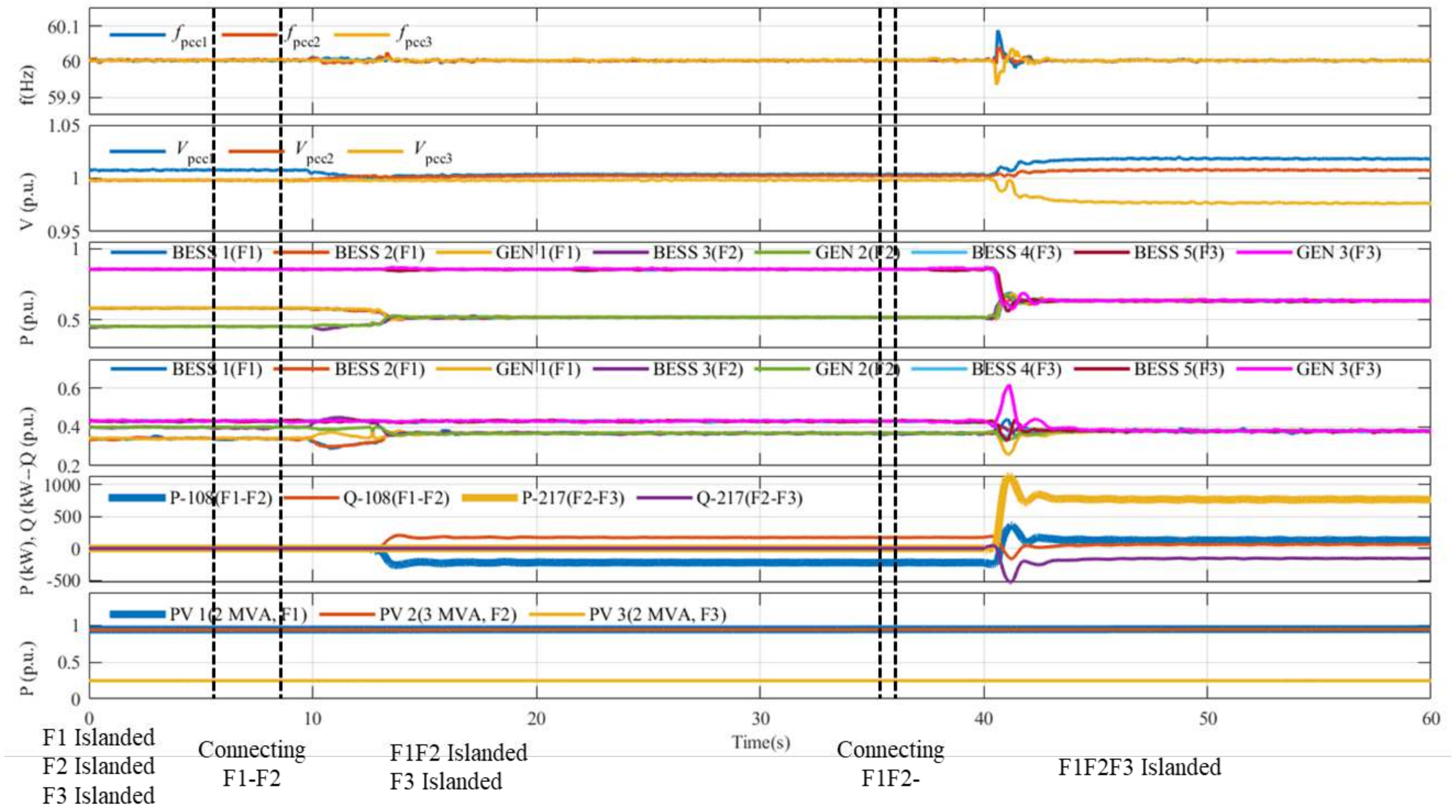


Planned islanding



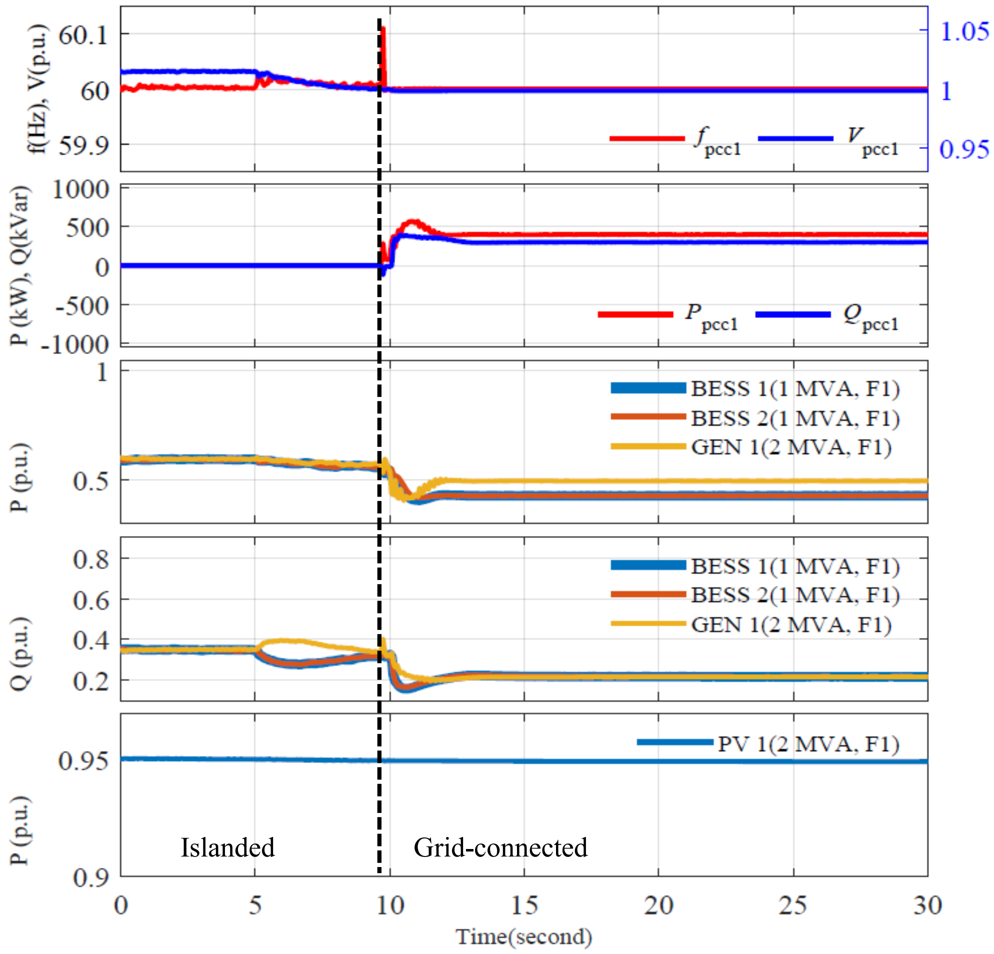
Unplanned islanding

Technical Progress:
HIL 7: Connecting Adjacent Feeders



Technical Progress:
HIL 9: Reconnecting to the grid – Feeder 1

- Measured frequency and voltage at microgrid POI
- After reconnecting, POI active power and reactive power follow the reference $P_{POI}^{*} = 400\ kW$ and $Q_{POI}^{*} = 300\ kVar$.
- Before reconnecting active power is shared proportionally to the ratings
- After reconnecting, active power is shared according to cost curve :
  - $C_{dg1} = C_{dg2} = 0.025P^2 + 8P$
  - $C_{gen} = 0.005P^2 + 20P$
- Reactive power is shared proportionally to the ratings
  - $S_{dg1} = S_{dg2} = 1\ MVA$
  - $S_{gen1} = 2\ MVA$
- PV output is high
  - $S_{pv1} = 2\ MVA$



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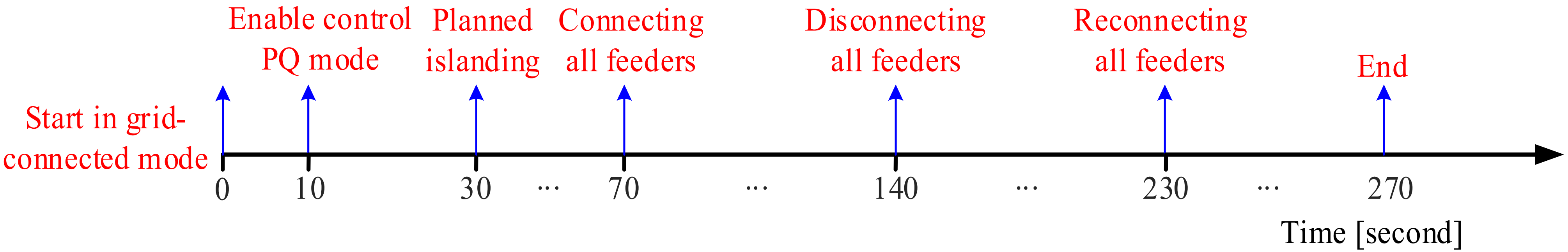
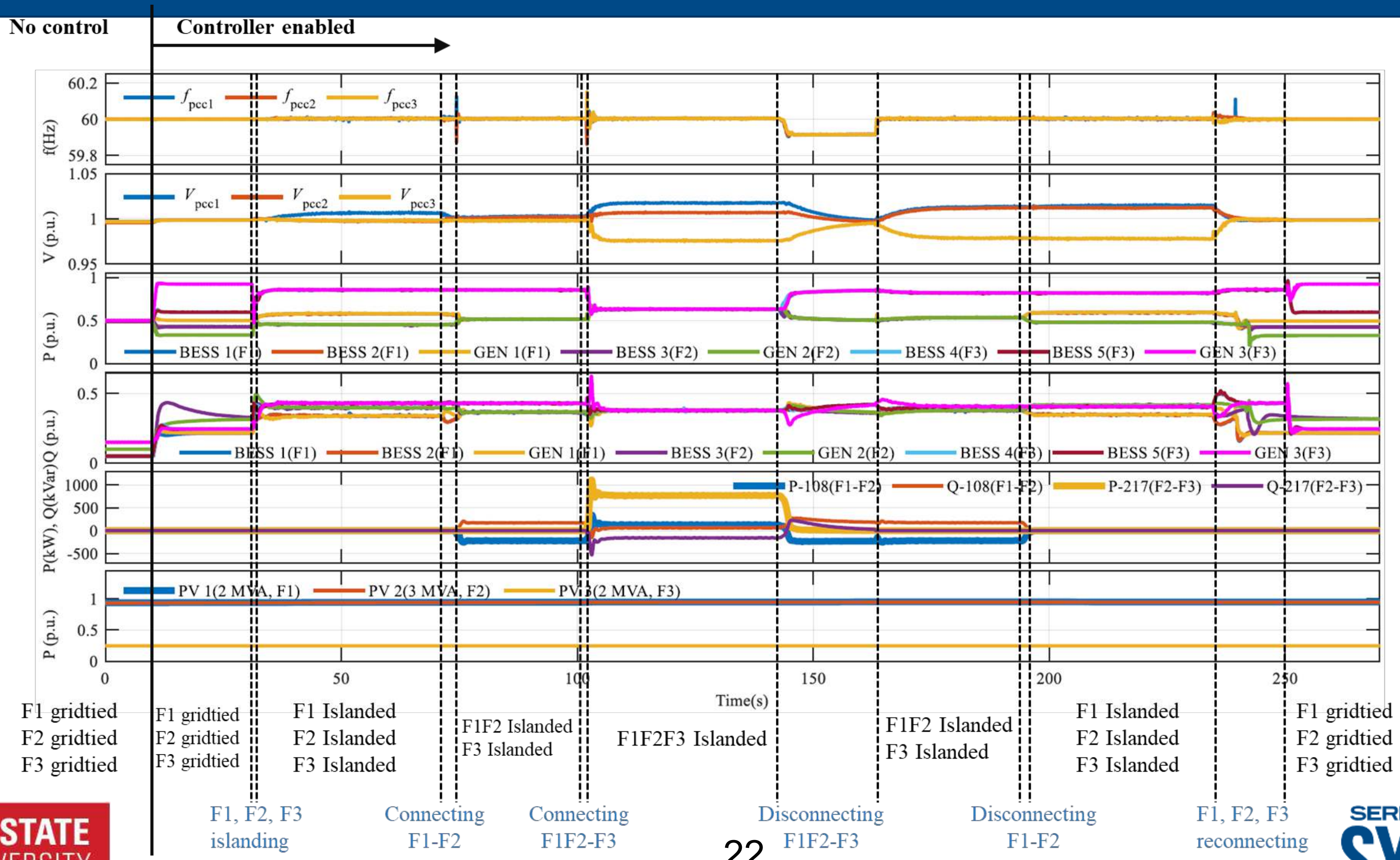
Technical Progress
HIL 10: Comprehensive Test

- Test scenario timeline



PV3 (in Feeder 3) output is set to 500 kW

Technical Progress
HIL 10: Comprehensive Test



Technical Progress
HIL 10: Comprehensive Test - Results

- Frequency and voltage are maintained within the acceptable range during transient
- Frequency and voltage are maintained at rated value during steady operation
- Active power and reactive power are shared economically in grid-connected mode and proportionally in islanded mode
- Transients during relay opening/closing are acceptable
- Transitions between different modes are stable

Remaining Steps

- Improving the resilience of the IMCP code (fault management)
- Cyber-security testing:

Operating mode	Tests	Status
Cyber-security	CS1: Confidentiality	In progress
	CS2: Integrity	
	CS3: Authenticity	
	CS4: Availability	

Expected DoD Benefits

- Benefits
  - Reduced costs – due to reusability of open source code base for algorithms and interfaces
  - More flexible and scalable architecture and optimized operations – due to advanced algorithms and distributed architecture
- Expected number of sites
  - All installations (large and small) wherever a network of microgrids is needed
- Results from demonstration will help DoD evaluate potential benefits of system
- Return-on-Investment:
  - The software engineering/configuration costs of a new microgrid is proprietary information of the system installers, but can be estimated at 10-20%. IMCP is expected to significantly reduce this cost.

Q&A

Questions?

Backup

Backup slides

Summary of Performance Objectives

Performance Objective	Metric	Data Requirement	Success Criteria
Seamless planned and unplanned transitions between operating modes	Transition is seamless?	Voltage and current	Safe transition
Extended Islanded mode	Critical load/s served	Critical load SAIDI* (m/y)	Minimize SAIDI over
System reconfiguration in order to supply maximum critical load	Critical load served	Critical load SAIDI (m/y)	Minimize SAIDI over
Maintain voltage and frequency stability	V/f deviations	Voltage and current	dev < limit
Execution of dispatch rules that optimize system performance	Utilization of local resources	Energy savings	Optimality of dispatch
Cybersecurity features	Resilience to DDoS attacks	Test logs	Maintains control
Engineering cost • to build a controller for a new MG • to integrate two MGs by joining their controllers • to integrate a legacy DER into an MG • to deploy new controls for incremental MG expansion	Man-hours / software development effort	Man-hours effort measured	% Reduction compared to industry baseline

*SAIDI: System Average Interruption Duration Index