Megapack Grid-Forming

Enabling Simplicity and Flexibility in BESS Projects

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TESLA

Tesla Grid-Forming Approach

Tesla GFM battery operates as a standalone voltage-frequency source, containing two paths:

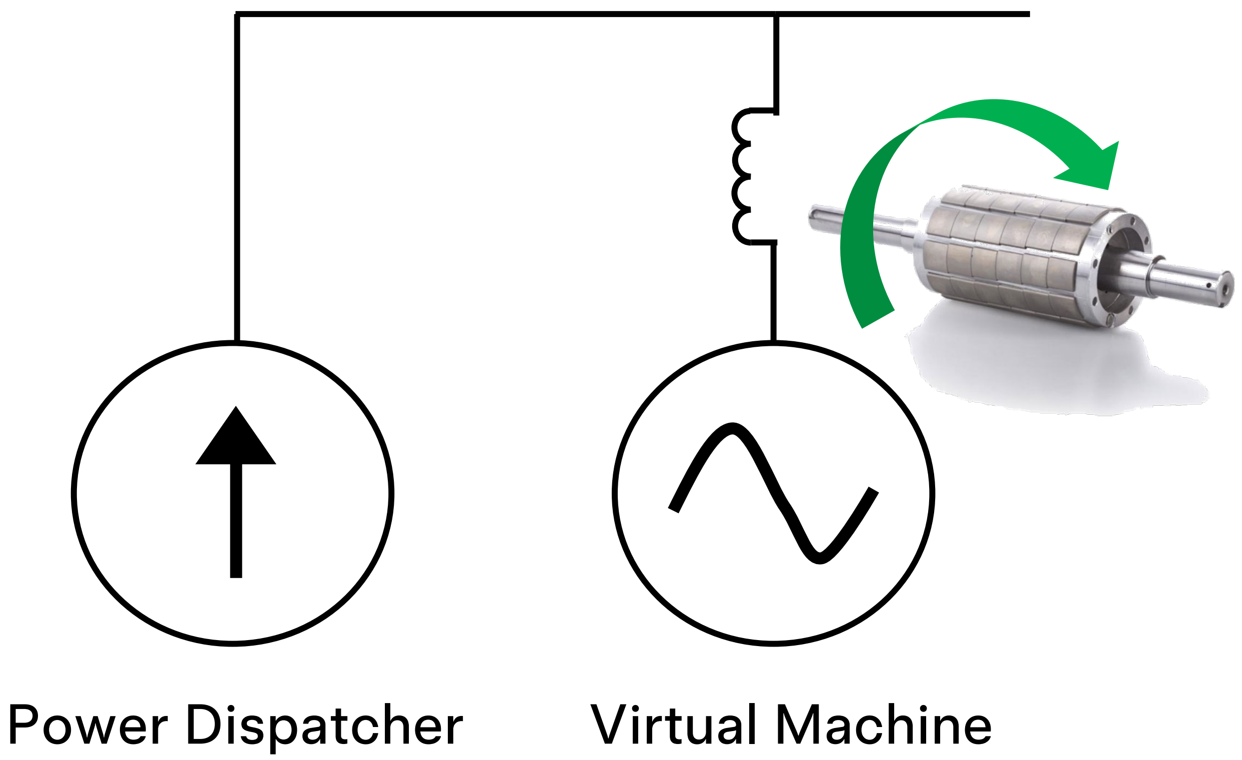
- **Power Dispatcher** responds to real and reactive power setpoints from the Tesla System Controller
- **Virtual Machine** in series with a virtual impedance responds to voltage and frequency references from the Tesla System Controller through exciter and swing equation controls.

In Tesla GFM, the inverters autonomously respond on a sub-cycle basis to maintain the voltage and frequency to the references at their AC output terminals.

This control method resembles REGFM_C1 & REPCGFM_C1
(WECC generic grid-forming models in the process of approval, model specification approved)

Power Dispatcher Path

- P/Q dispatch
- Frequency market
- Plant level voltage control
- Automatic generator control (AGC)
- Voltage and frequency droop



Virtual Machine Path:

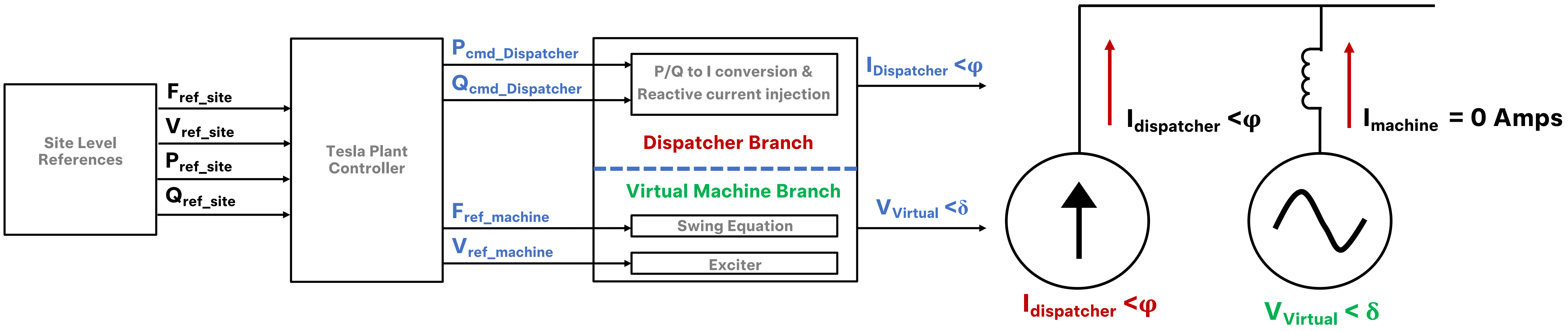
- Inertial power response
- Phase jump power response
- Maintains synchronism with other generators
- Blackstart
- Shapes voltage waveform (subcycle)
- Provides system strength

Tesla Grid-Forming Dispatch Architecture

Within Tesla's architecture, dispatch can be achieved in two ways:

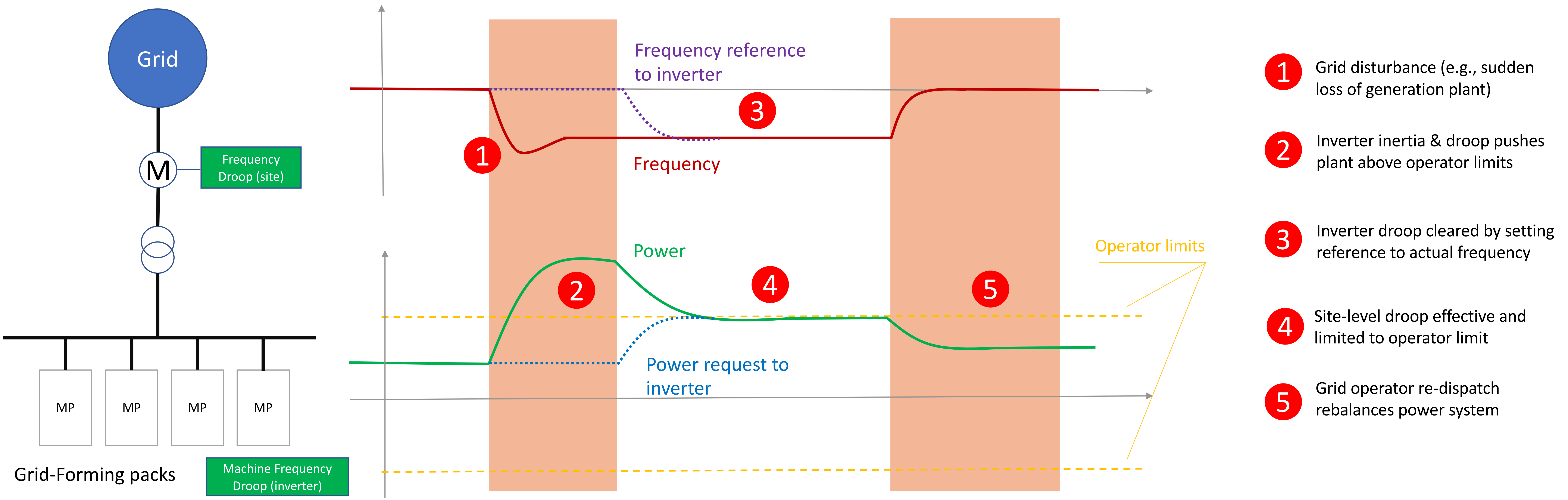
- **Manipulating frequency and voltage references** to the Virtual Machine
- **Direct power commands to the Power Dispatcher:**
  - **Less secondary controller complexity:** Avoids the need for reverse droop math and slope coordination.
  - Machine current in steady state is zero, initializing the machine load angle to zero
    - **Improved transient stability behavior.**

During Steady State $I_{machine}$ is zero



Transient and Steady-State Response Management

- Ensures plant-level goals are met while respecting operational limits.
- Initial response to grid disturbances comes from the inverter's Virtual Machine inertia and droop response.
- Subsequently adjusts inverter voltage/frequency references and active/reactive power commands to transition output from the Virtual Machine to the Power Dispatcher.

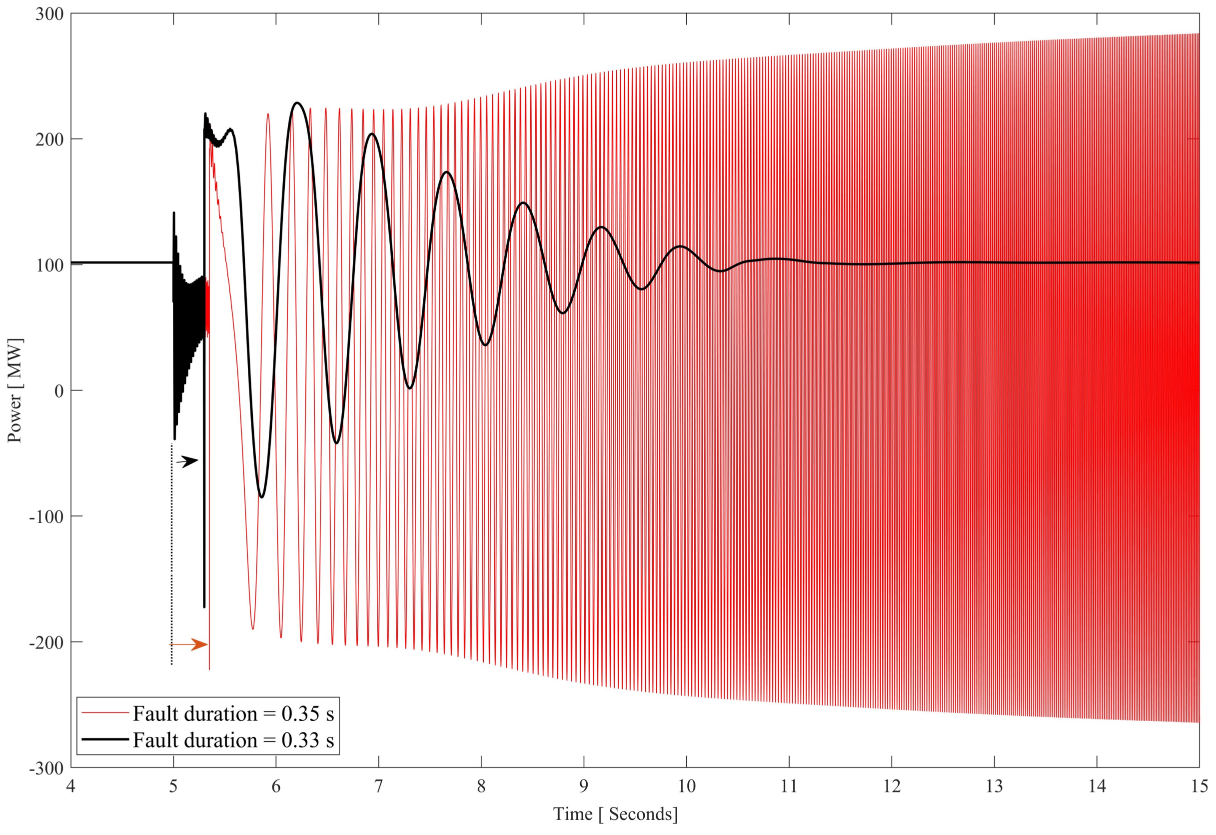


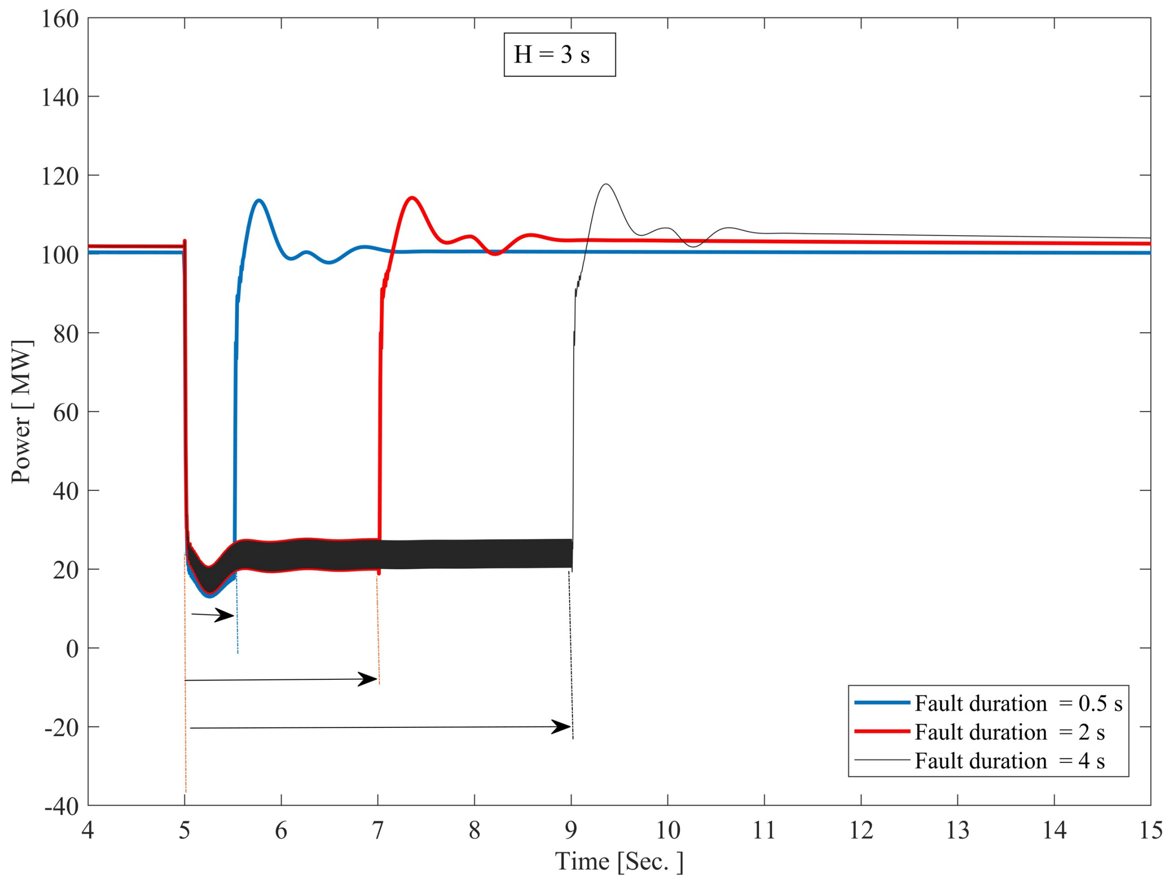
Improved Transient Stability

Decoupling Power Dispatch from Virtual Machine:
Tesla's approach separates dispatch power ($Pcmd$) from machine angle acceleration to enhance angle stability over extended periods

Traditional Grid-Forming Approach or Synchronous Machine:
Pcmd to prime mover is non-zero

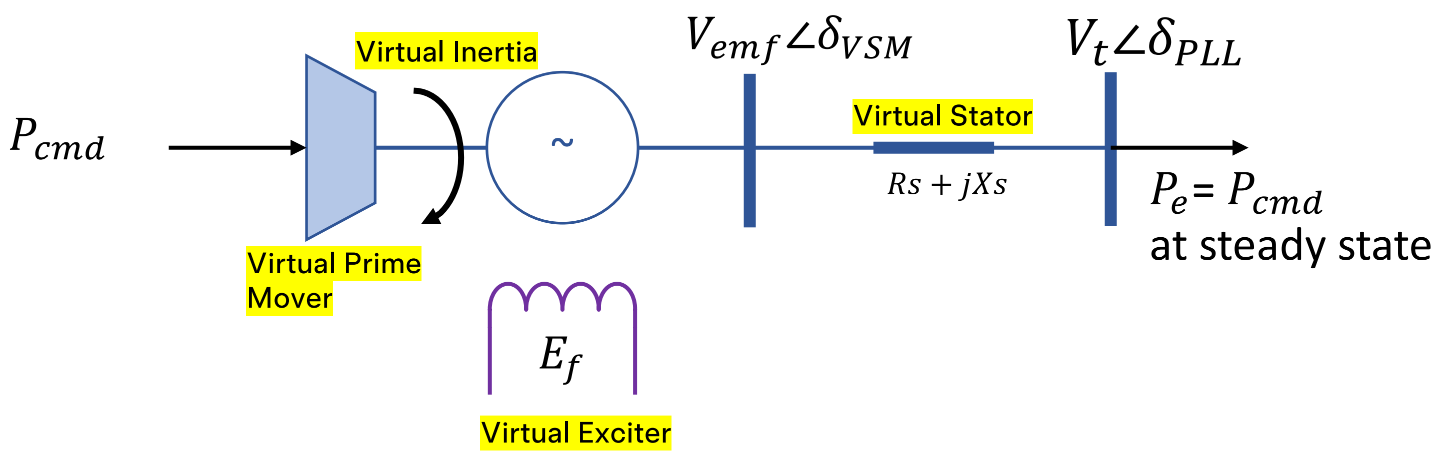
Load angle is not zero

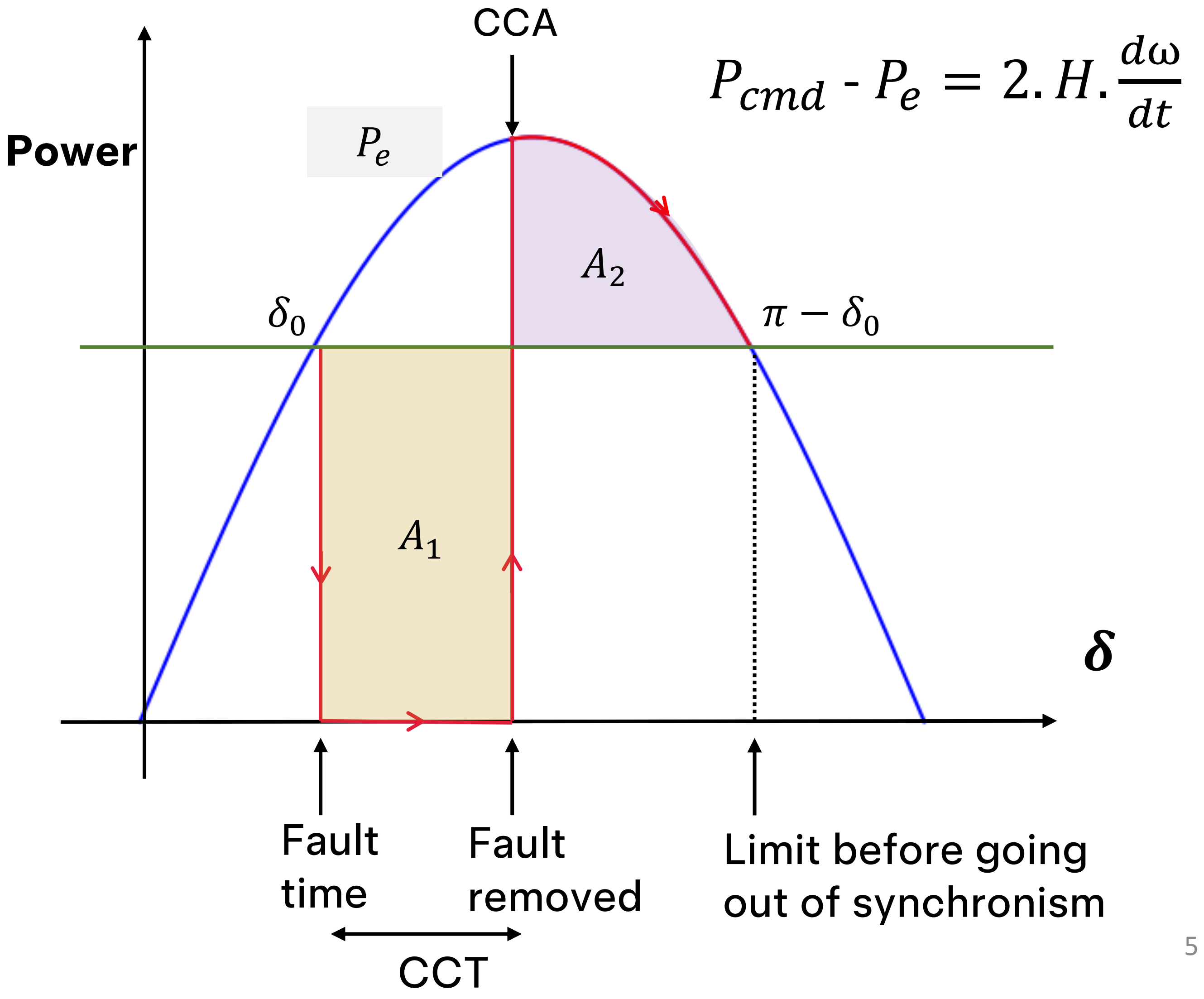




Tesla Approach:
Pcmd to prime mover is zero

Load angle is zero
(Better transient stability)





Demonstrated Utility-Scale Grid-Forming Experience

KIUC – Kauai, HI, USA

13 MW / 52 MWh
Commissioned 2017
Grid-Forming 2018

Hornsdale—AUS

150 MW / 193 MWh
Commissioned 2017, Expanded 2020
Grid-Forming 2022

Wallgrove—AUS

50 MW / 75 MWh
Commissioned 2021
Grid-Forming 2021

KES—Oahu, HI, USA

185 MW / 565 MWh
Commissioned 2023
Grid-Forming & Blackstart 2023

Riverina & Darlington—AUS

150 MW / 300 MWh
Commissioned 2023
Grid-Forming 2023

Kupono– Oahu, HI, USA

42 MW / 168 MWh
Commissioned 2024
Grid-Forming 2024

Lessons Learned:
Controls Testing to Ensure No Surprises

Key Takeaway: Controller Hardware-in-the-Loop (CHIL) testing validates controls and settings ahead of deployment

Issue

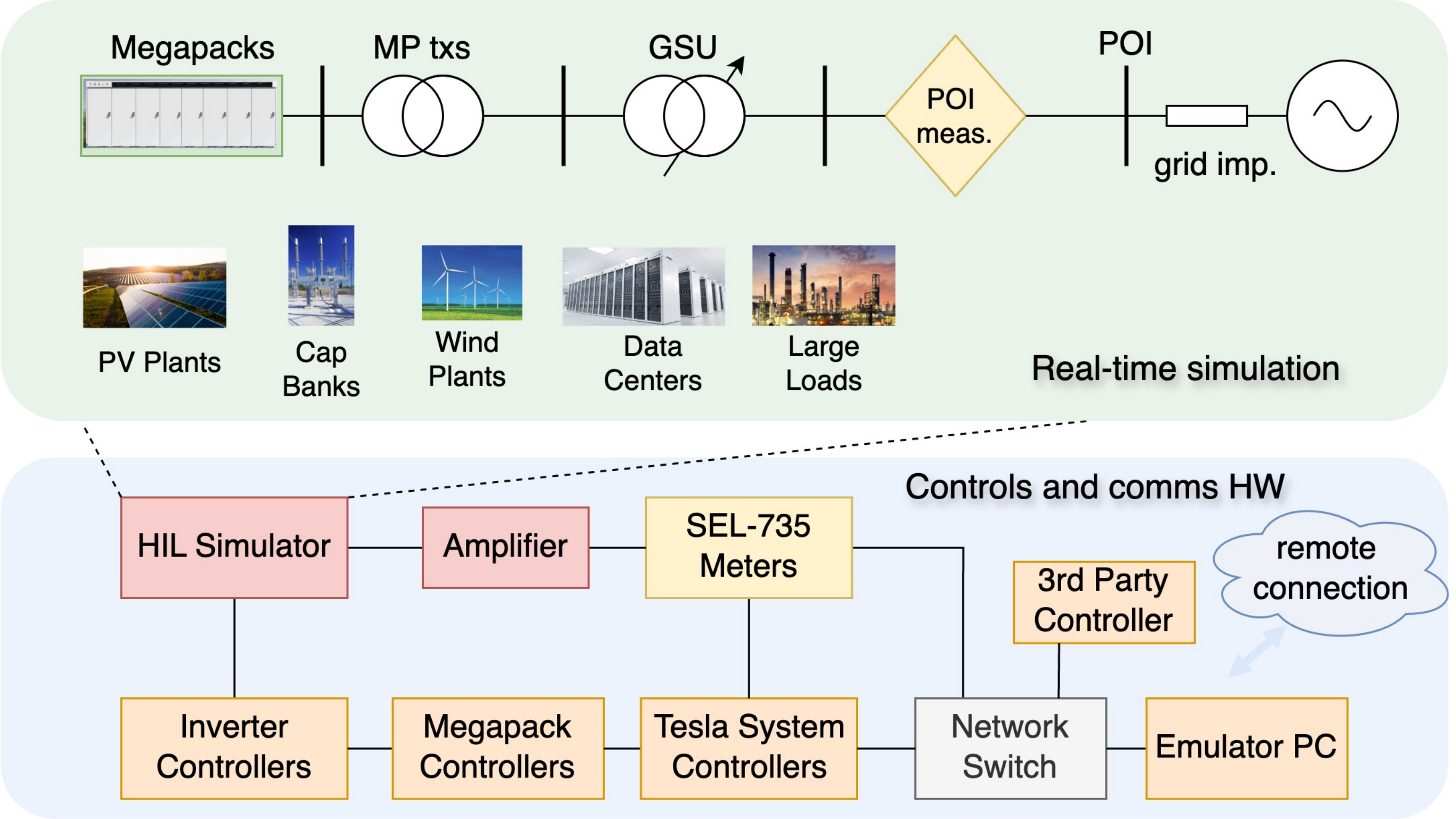
- Communication & controls issues with 3rd party controllers found first on-site during commissioning
    - Nominal behavior often not working, including common edge cases like MIAs & device restarts
- Bad behaviors manifest once site is already operating

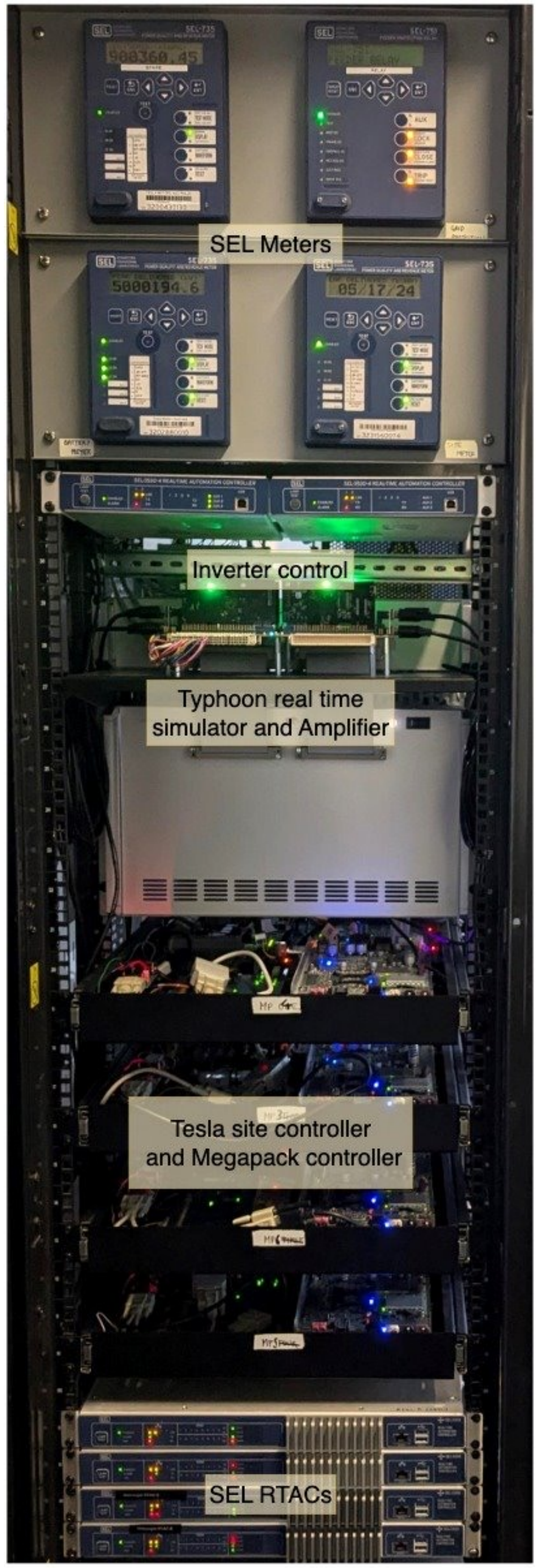
Cause

- Many devices in critical path for controls
- Once commissioning, goal to operate site ASAP

Solution

- Pre-commissioning testing with critical path devices





Lessons Learned: Model/Plant Benchmarking Achieves Expected Behavior

Key Takeaway: Plants' actual and modelled behavior can differ unless explicitly verified with grid events

Issue

- Modelled, expected behavior not achieved during grid events
- Difficult to stage disturbances with GFM during commissioning

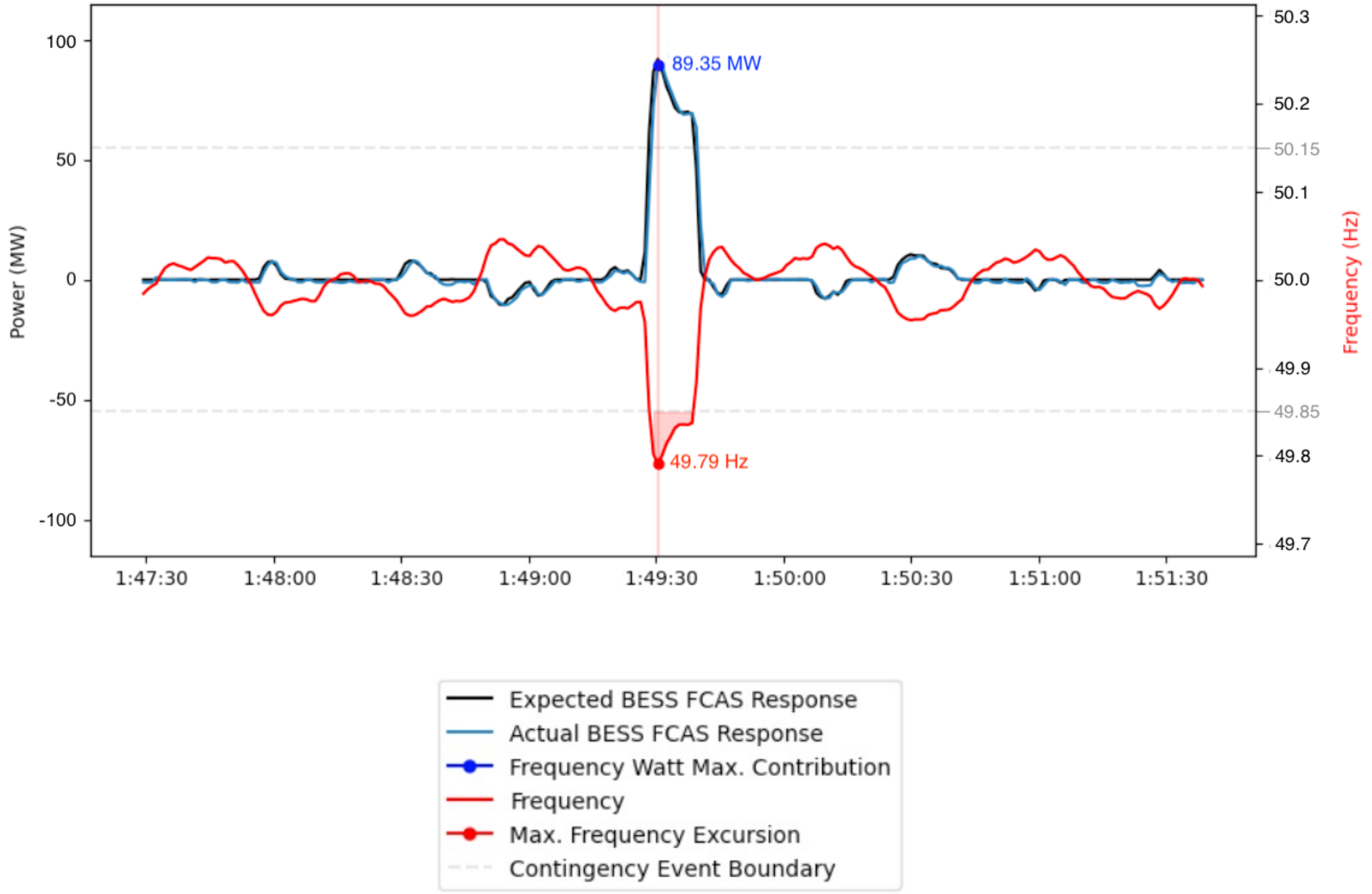
Cause

- Behavior at commissioning not be maintained for life of project
- Plant issues can be hidden when performing staged tests
    - ex Overriding meter frequency hides issues with meter

Solution

- Use actual grid events to demonstrate compliance
    - NERC MOD-027-1 allows for data from frequency excursion to be used to periodically verify behavior.

Expected vs. Actual Behavior of Plant During Grid Frequency Event



Lessons Learned:
Edge Case Behaviors Matter

Key Takeaway: Grid-critical facilities need understood and tested failure mode behavior

Issue

- Unexpected behaviors can manifest once site is already operating

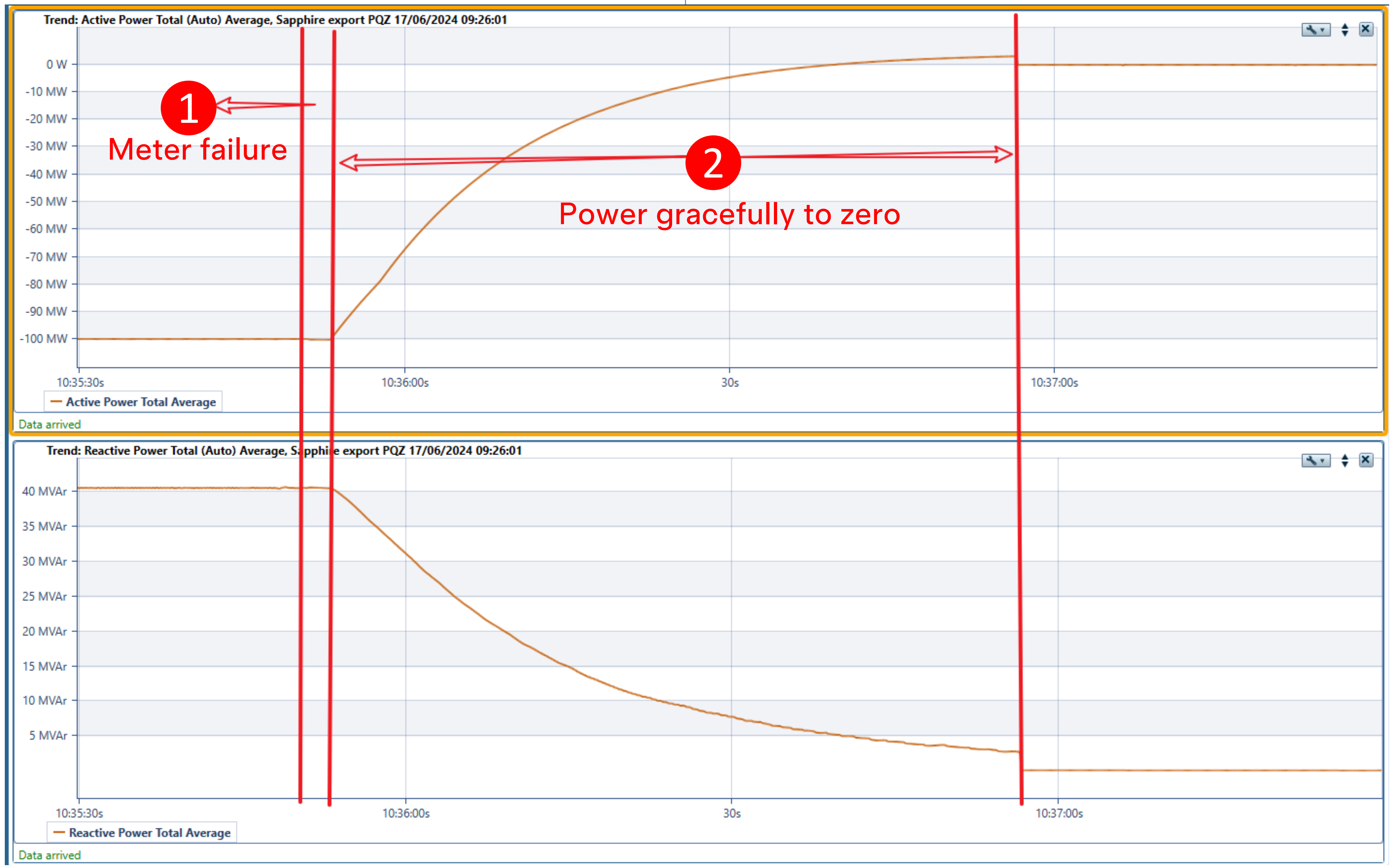
Cause

- "Edge cases" like communication loss, loss of controller power can happen
- Many devices in critical path for controls which have likely not been tested together

Solution

- Explicit test plan with behavior expectations
- Pre-commissioning tests with critical devices

Elspec P and Q Trace at the POI Showing Ramp 0MW/0MVAr After Meter Failure

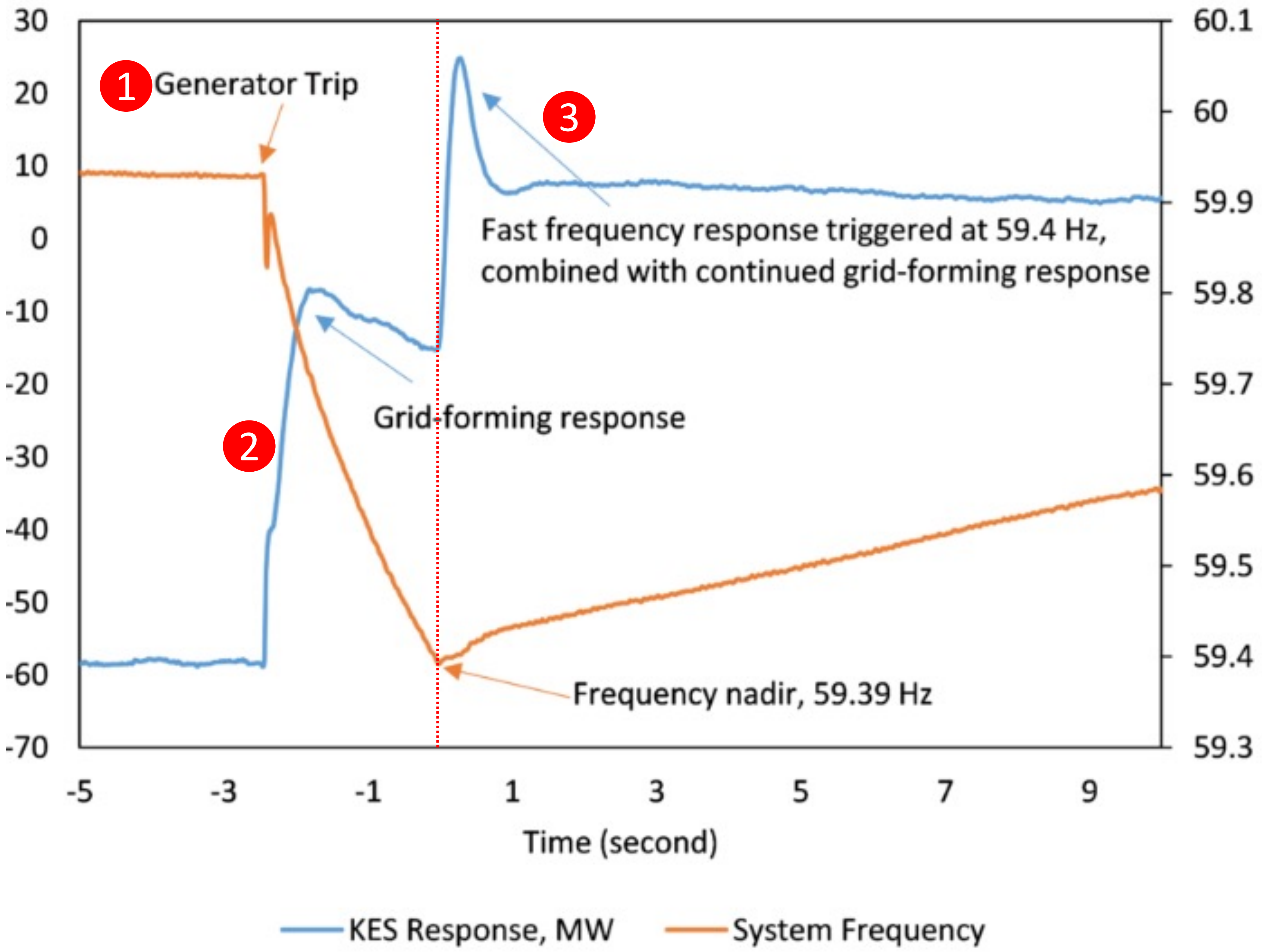


Case Study: Kapolei Energy Storage (KES)

The Kapolei facility operates Megapacks in Grid-Forming mode to mimic traditional power plants' inertial response, while also providing Fast Frequency Response (FFR).

February 2024 Grid Event

1. 208 MW power plant tripped
2. KES Grid-Forming responds to grid rate-of-change-of-frequency
3. FFR triggers at 59.4 Hz



https://www.esig.energy/an-innovative-clean-energy-integrated-grid-plan-for-hawaii/