Power HIL validation of a MW-scale grid-forming inverter's stabilization of otherwise unstable cases of the Maui transmission system

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Panel Session: Grid Forming Converter Technology and Applications
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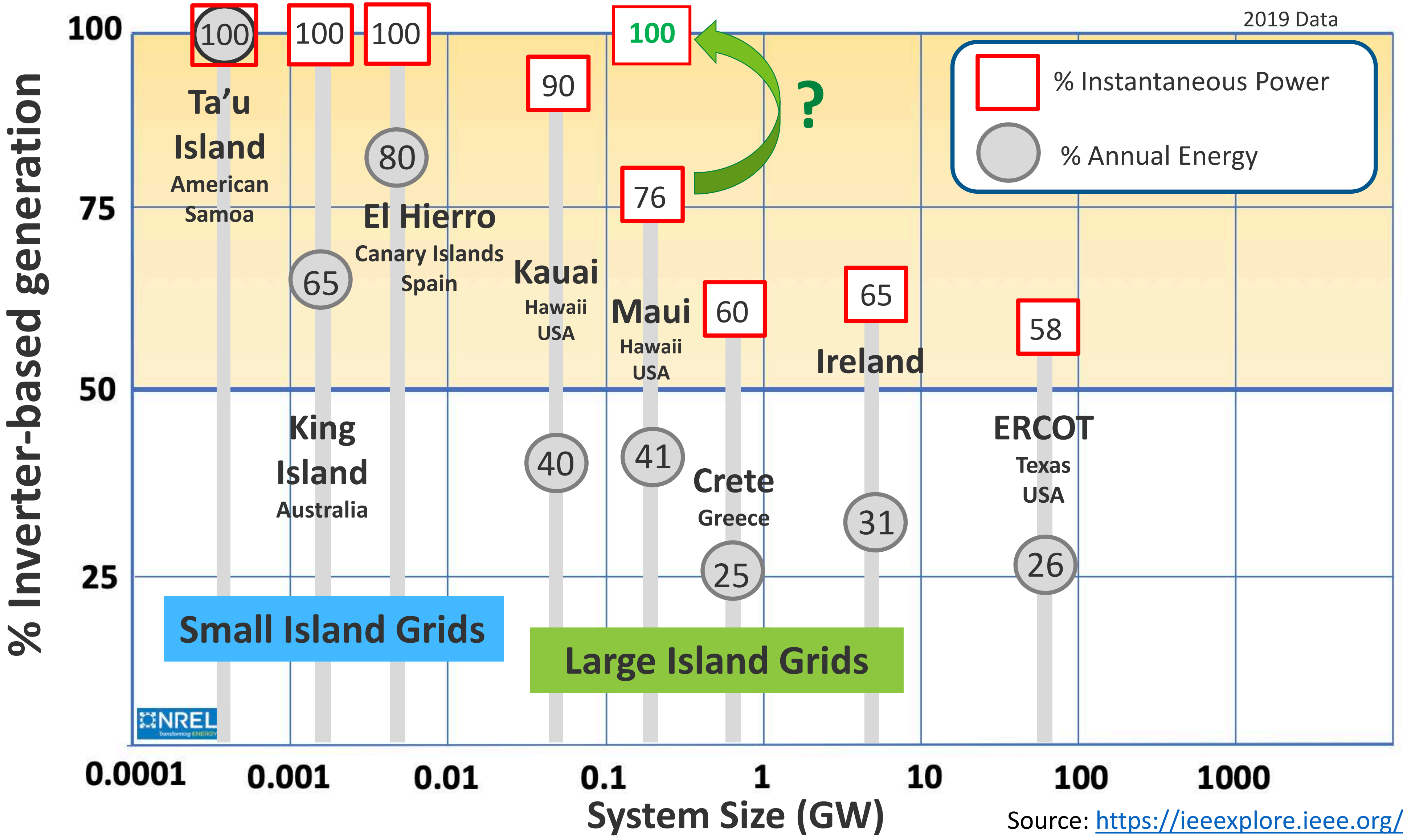
Wind and Solar in Synchronous AC Power Systems as a Percentage of Instantaneous Power and Annual Energy



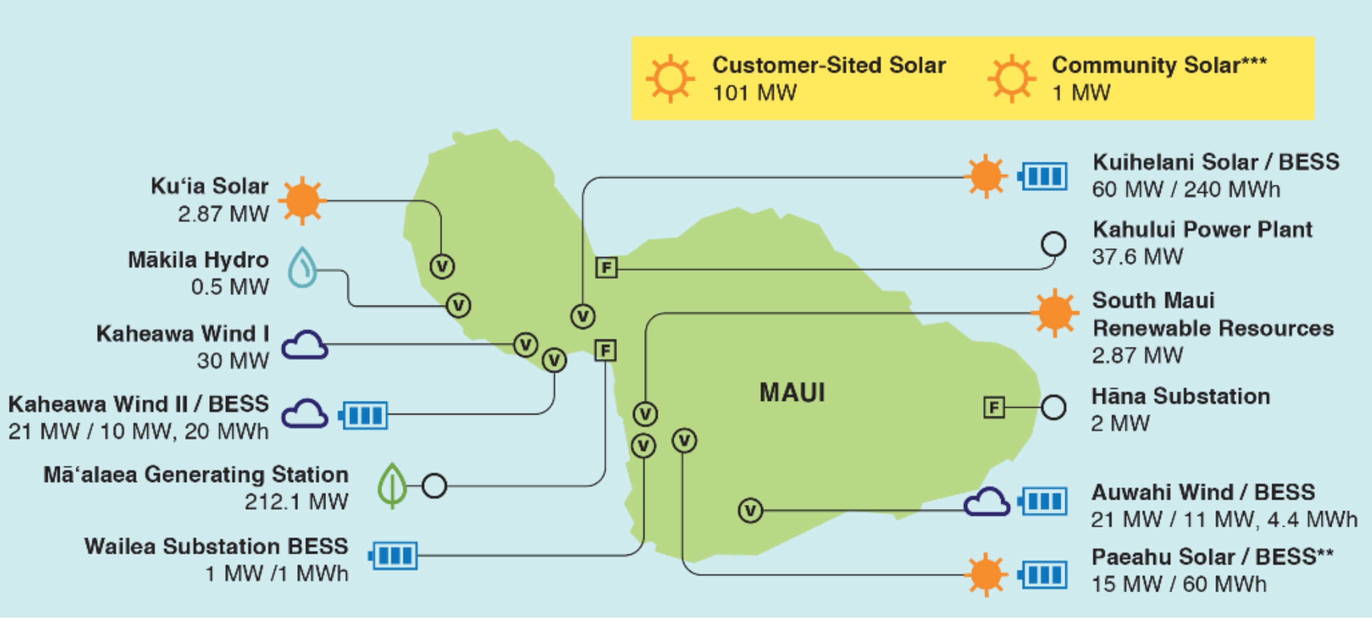
No known power system large enough to have a transmission system has operated with 100% inverter-based resources (IBRs)

Will likely require grid-forming (GFM) inverters

Source: https://ieeexplore.ieee.org/abstract/document/9371251/

Background and Motivation

- Hawaiian Electric expects Maui to be their first large island to be capable of operating with 100% inverter-based power resources
  - 2020 peak: ~89.5% IBR (DER and wind)
  - **100% IBR operation expected to possible for certain hours by 2023**, from an energy balance perspective
- Maui would be the first interconnected power system of its size (~200 MW peak) with highly distributed utility-scale generation and 69 kV voltage levels to reach this milestone

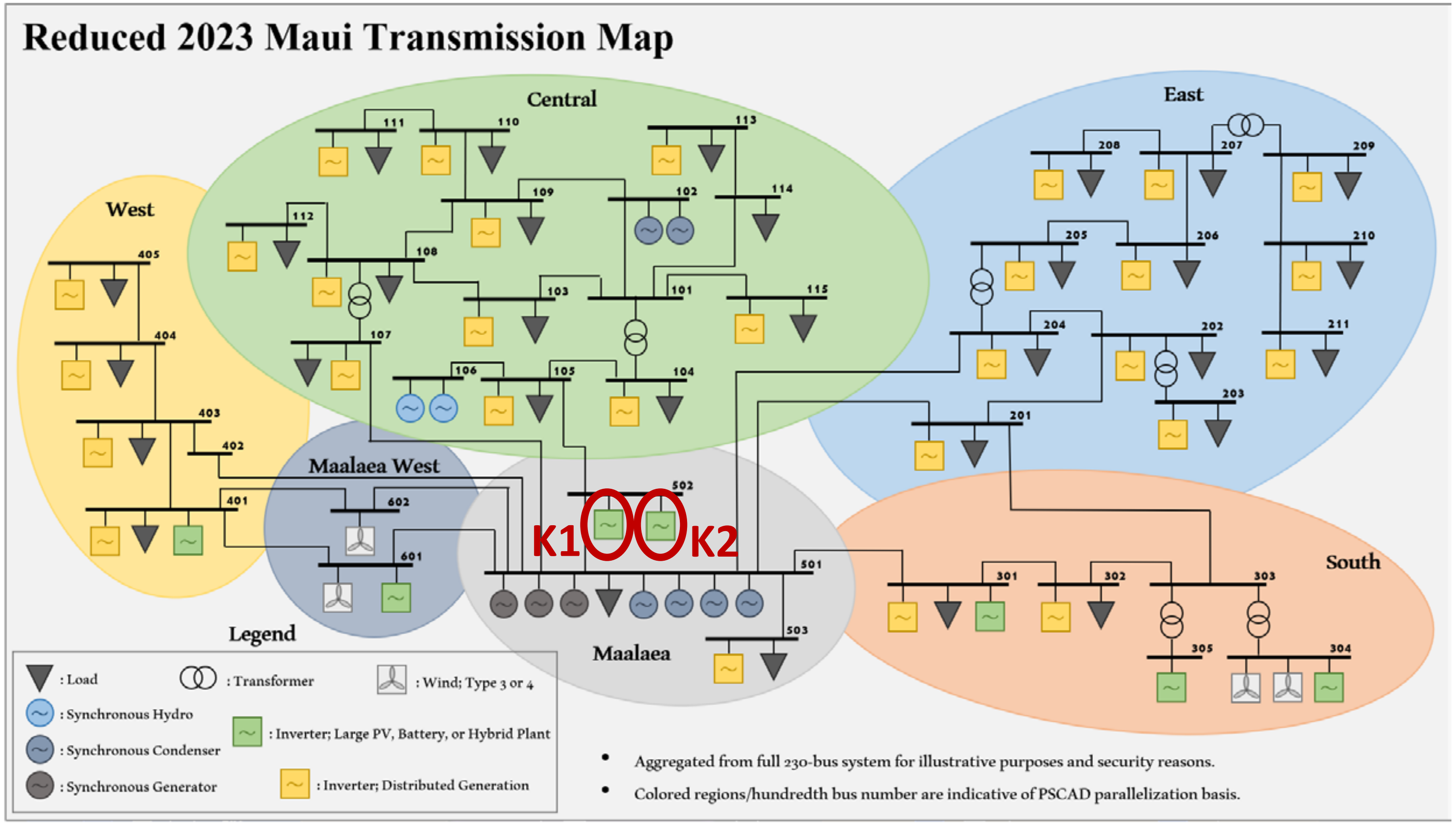


- NREL EMT study (PSCAD): System can be stable from an oscillation damping perspective (generic IBR models)
- Electranix PSCAD study: GFM inverters can operate stably with rest of system (actual IBR plant models)
- **In this presentation: Power hardware-in-the-loop tests linking real hardware GFM inverter to real-time EMT model of Maui (RSCAD)**
- These are just steps in a complex due-diligence process towards operating Maui in an unprecedented way

2023 Maui Power System

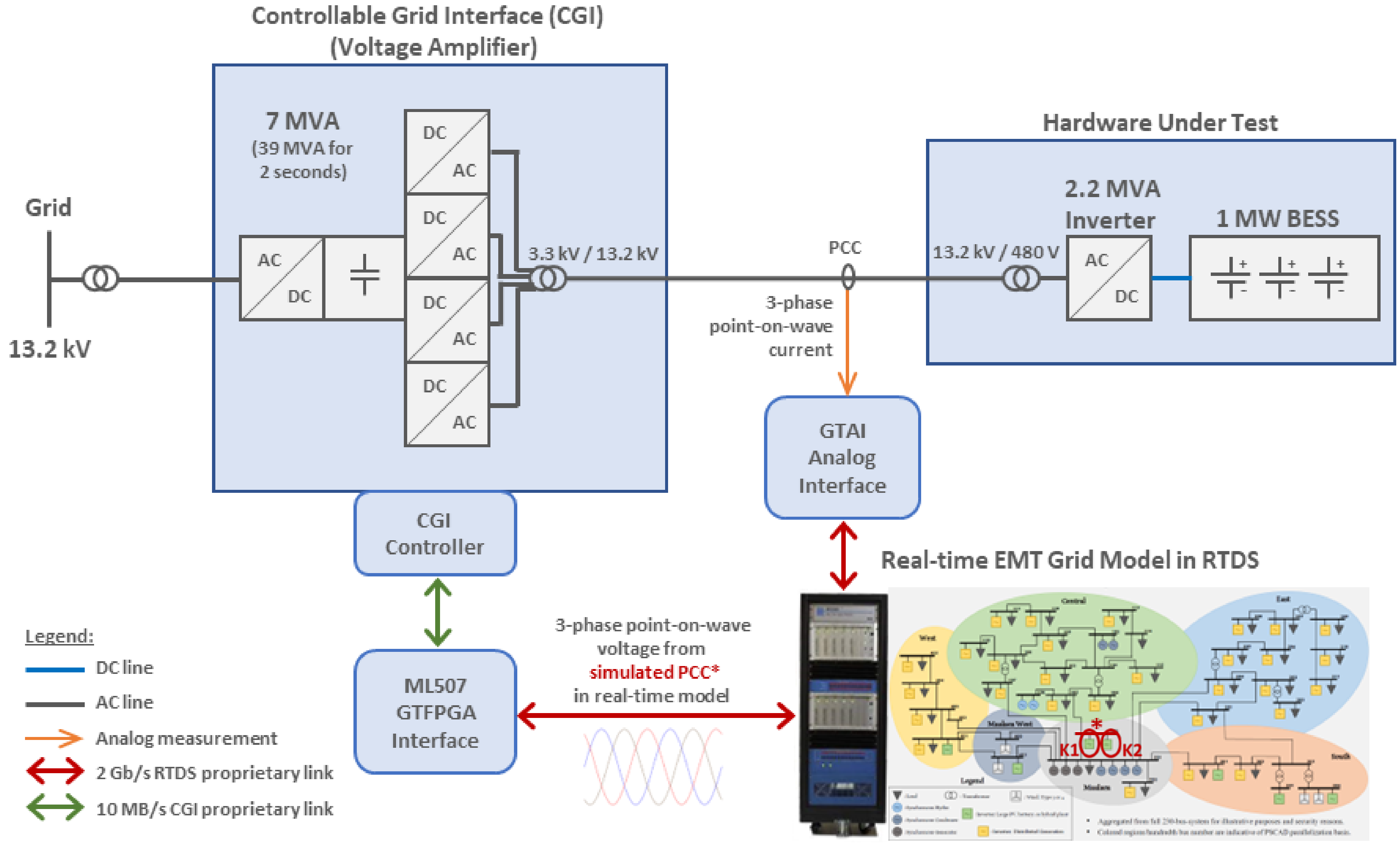
Day Minimum Dispatch (Scenario S1)	
Total load	145.2 MW
Total generation output	145.9 MW
Total synchronous generation output	5.7 MW
Total synchronous condenser capacity	136.4 MVA
Total synchronous inertia	370 MVA·s
Inertia constant (H)	0.97 s
Distributed PV output	104.3 MW
Utility-scale PV output (2 plants)	5.3 MW
Wind output (4 plants)	24.9 MW
Utility-scale PV-BESS output (3 plants)	5.7 MW
Minimum voltage level	0.48 kV
Maximum voltage level	69 kV

Configuration shown here reflects a planning case from 2020. Current plan differs.



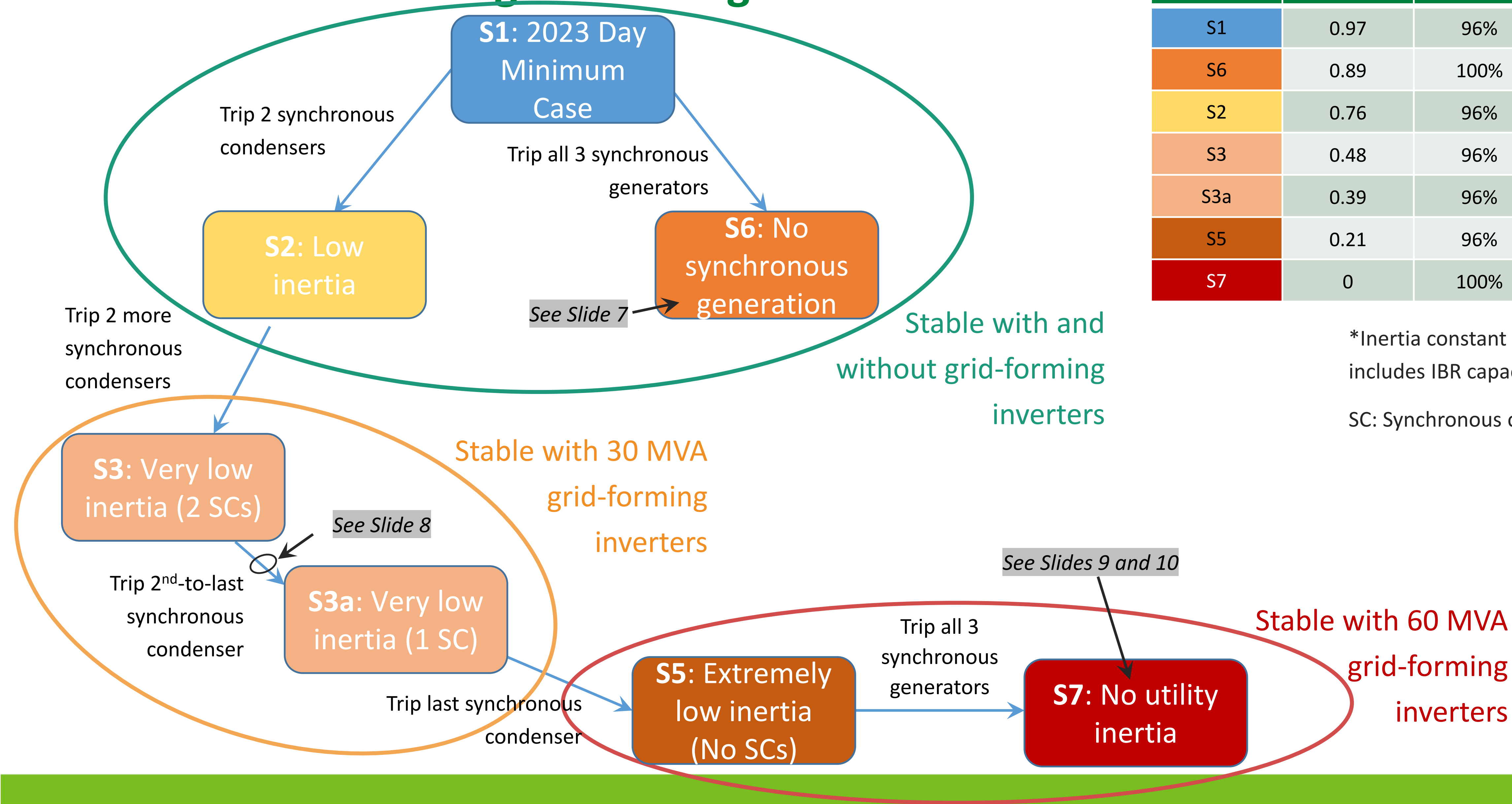
- No grid-forming inverters in base case
- Significant system strength from synchronous condensers
- Electromagnetic transient (EMT) model validated against field data
- K1 and K2 are two 30 MW segments of planned 60 MW PV-BESS plant

Power Hardware-in-the-loop Test Setup



- 30 MVA K1 PV-BESS plant replaced by real 2.2 MVA inverter with 1 MVA BESS
  - Instantaneous inverter output scaled 30x and injected into real-time model in PHIL
  - Inverter able to operate in GFM or GFL mode
- Rest of system represented in RTDS/RSCAD model
  - Includes 30 MVA K2 plant, also able to be GFL or GFM
  - All other IBRs always GFL

Summary of Maui stability in PHIL experiments with and without grid-forming inverters



Scenario	Inertia constant "H" (s)*	Generation from IBR (% of generation output)	GFM IBR capacity to stabilize (% of total online capacity)
S1	0.97	96%	0
S6	0.89	100%	0
S2	0.76	96%	0
S3	0.48	96%	12%
S3a	0.39	96%	12%
S5	0.21	96%	27%
S7	0	100%	29%

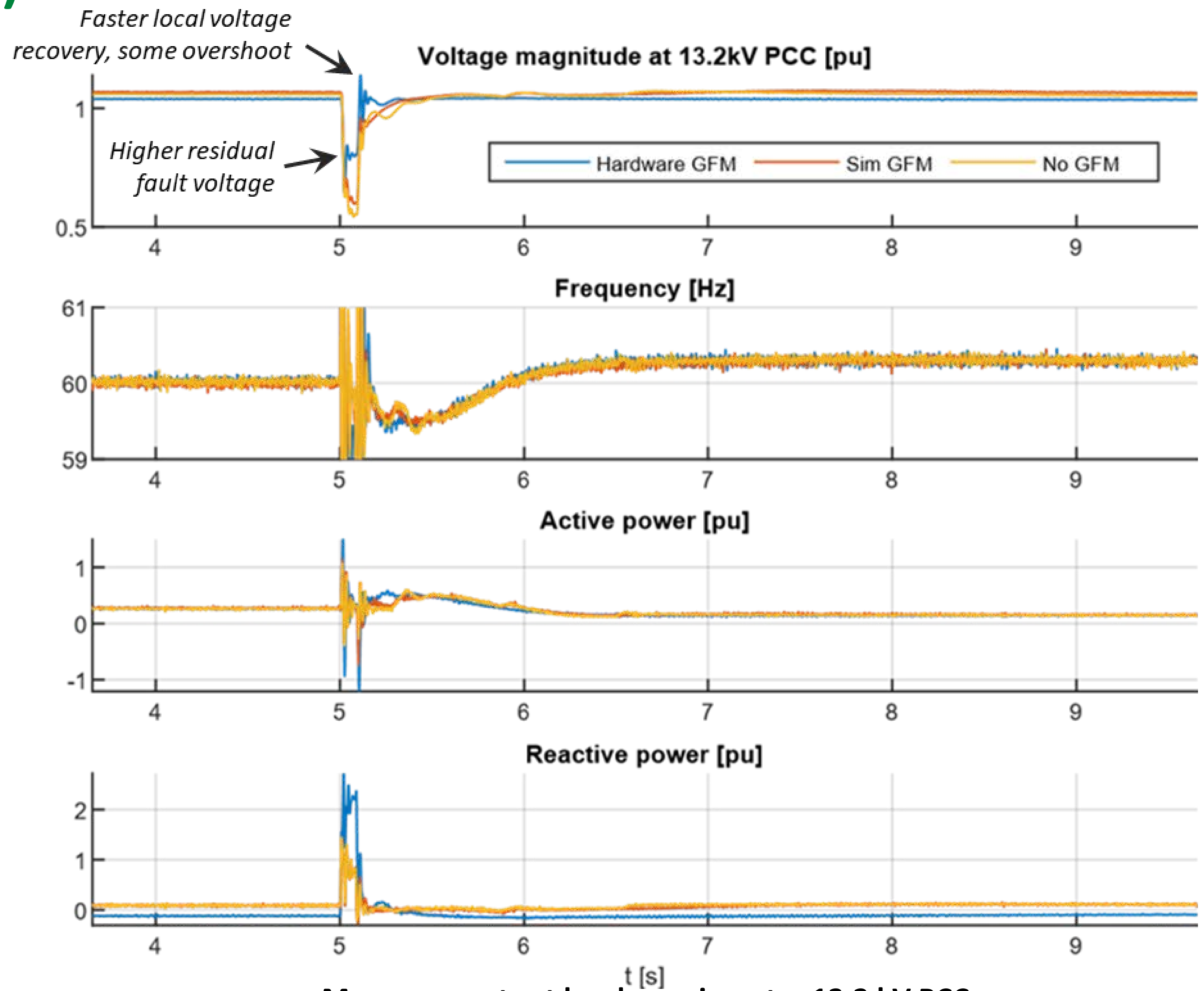
*Inertia constant calculation includes IBR capacity in MVA base

SC: Synchronous condenser

Zero synchronous generation: Scenario 6 Event E1 (fault at low-SCR bus)

- Zero sync generation system is robust to severe fault with or without grid-forming
  - System has 317 MVA-s of sync condensers; H = 0.89 s
  - Frequency measurement during fault is unreliable due to severe voltage distortion
  - Potential DER momentary cessation not modeled; GFM (or other fast active power source) may be needed to mitigate

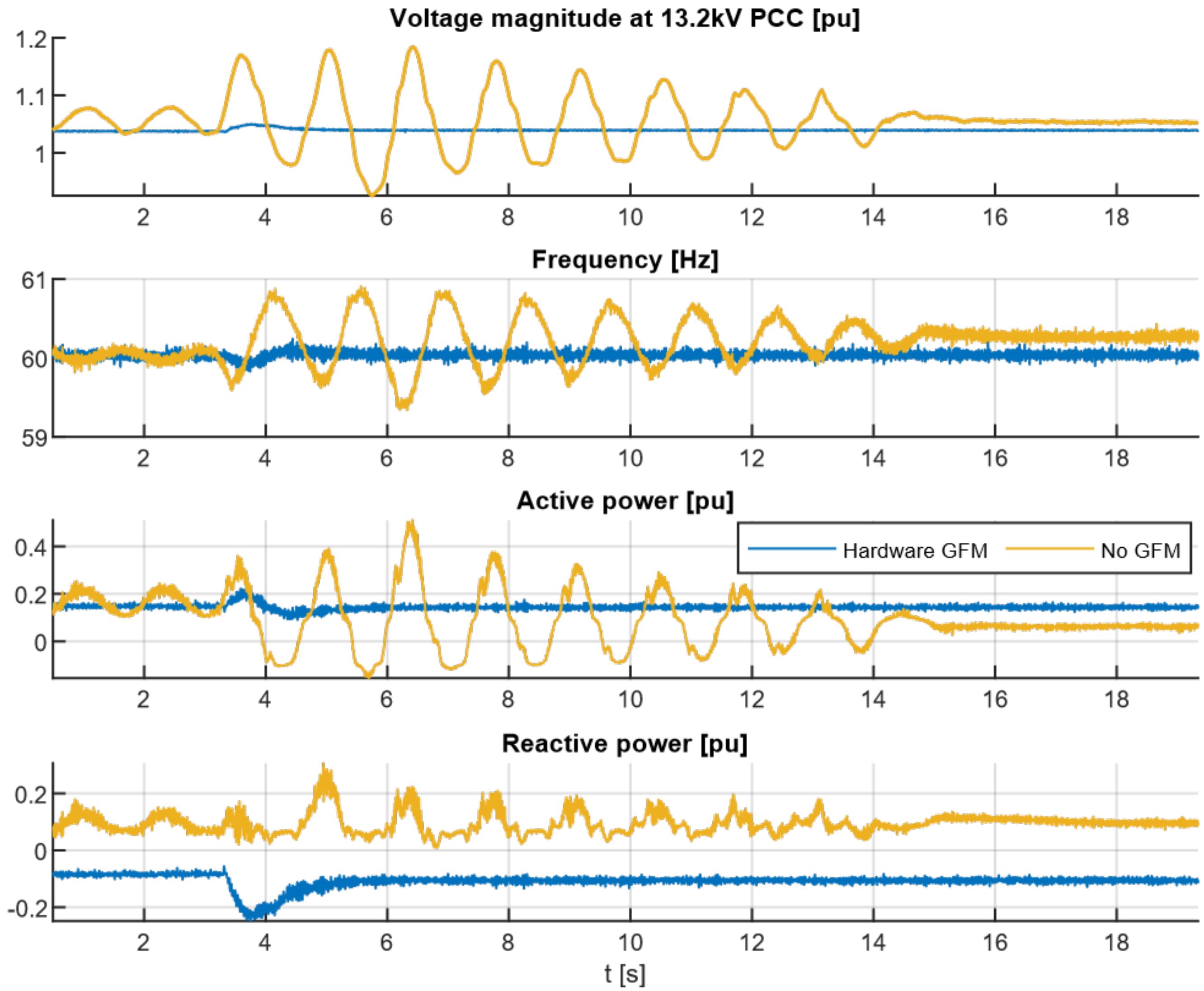
- Scenarios S1 and S2 are very similar, with and without GFM



Measurements at hardware inverter 13.2 kV PCC

Stability boundary: Scenario 3 to 3a transition (loss of 2nd-to-last sync. condenser)

- Without GFM, severe voltage and frequency oscillations; would have resulted in DER tripping and system crash
  - Note oscillations already present before disturbance
- With 30 MVA of GFM, system recovers quickly and is stable
- The resulting one-GFM, one-condenser system (S3a) is also robust to fault and generation loss (not shown)

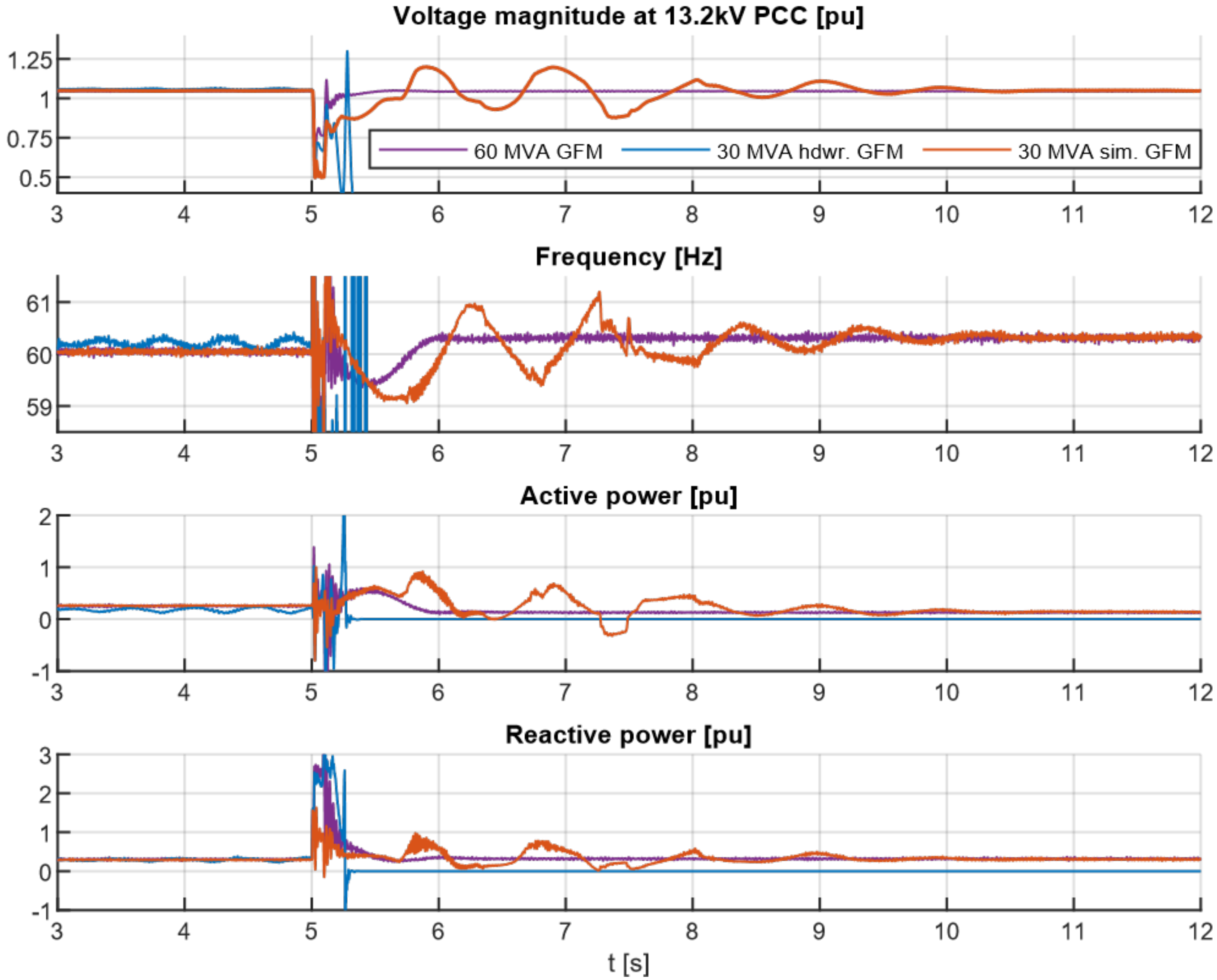


Measurements at hardware inverter 13.2 kV PCC

Zero inertia system: Scenario 7
Fault event

- Without GFM, scenario cannot be reached
  - Voltage instability occurs as soon as last condenser is removed (not shown)

- With 30 MVA of GFM (hardware), system crashes post-fault
- With 30 MVA of GFM (simulated), system has severe voltage and frequency deviations; would have tripped DERs and crashed
- With 60 MVA of GFM capacity, system is stable and recovers quickly

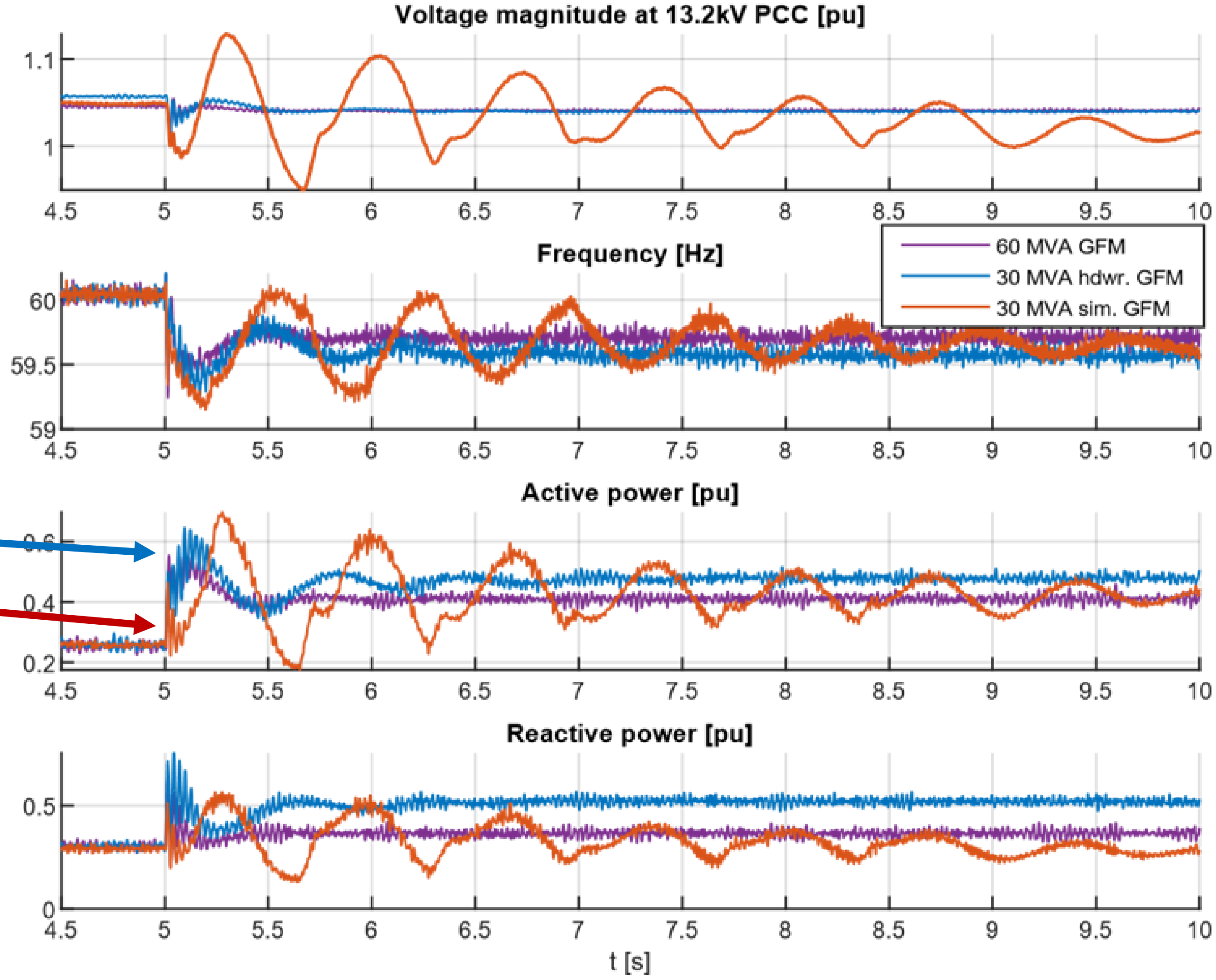


Measurements at hardware inverter 13.2 kV PCC

Zero inertia system: Scenario 7
N-1 generation trip event

- All events potentially survivable
- 60 MVA GFM case has best damping

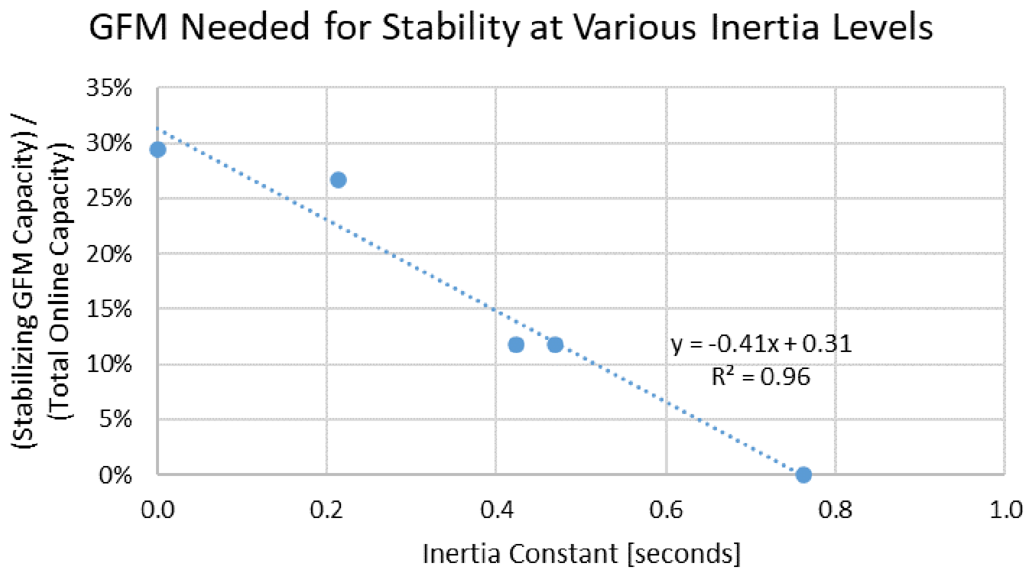
- Note difference in hardware inverter response speed immediately after event when in GFM mode (blue) vs GFL mode (red)
  - Illustrates a fundamental difference between GFL (reacts via droop) and GFM (inherently does what's needed to stabilize terminal voltage angle)



Measurements at hardware inverter 13.2 kV PCC

Conclusions and questions:

- **A real hardware GFM inverter can stabilize otherwise unstable cases of a transmission electric power system, including zero-inertia cases**
  - Stabilizes faster modes
  - Mitigates instability of remaining GFLs
  - MW-scale test validates detailed PSCAD simulations
- Modeling inverter control loops (power and current) of GFL devices (including small DERs if their aggregate capacity is large!) is required to detect faster modes in the system response under very weak grid conditions
- Amount of GFM capacity needed (observations):
  - *Does not* necessarily depend on percentage generation from IBRs
  - *Does* depend (inversely) on **capacity of synchronous machines** online
  - This considers oscillatory stability; major nonlinearities such as DER/IBR tripping or momentary cessation may drive higher GFM need



- Note: These simulations focus on transient stability and do not consider other topics necessary for 100% IBR operation, e.g. protection, reserves, resource adequacy…

Hypothesis: Can a simple metric help capture need for voltage forming capacity?

Metrics for future power system stability?

Inertia constant:
(existing metric)

$$\frac{\text{Synchronous machine rotational kinetic energy (MVA-seconds)}}{\text{Total online generation capacity (MVA, including inverter-based resources)}}$$

Voltage forming ratio:
(version 1)

$$\frac{\text{Synchronous machine rotational kinetic energy (MVA-seconds)} + A_1 \cdot \text{Grid-forming IBR capacity of type 1 (MVA)} + \cdots + A_k \cdot \text{Grid-forming IBR capacity of type k (MVA)}}{\text{Total online generation capacity (MVA, including inverter-based resources)}}$$

or…

Voltage forming ratio:
(version 2)

$$\frac{\text{Synchronous machine capacity (MVA)} + B_1 \cdot \text{Grid-forming IBR capacity of type 1 (MVA)} + \cdots + B_k \cdot \text{Grid-forming IBR capacity of type k (MVA)}}{\text{Total online generation capacity (MVA, including inverter-based resources)}}$$

Could such a metric be used to **develop stability constraints for scheduling, dispatch, and capacity planning?**
Can new models (e.g. NREL's MIDAS tool) validate the ability of this approach to ensure stability with high IBRs?

Questions welcome

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