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# Performance Evaluation of Grid-Following and Grid-Forming Inverters with Virtual Inertia Controls

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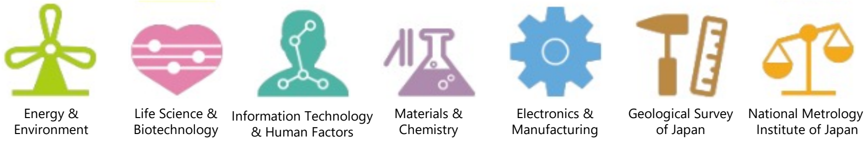
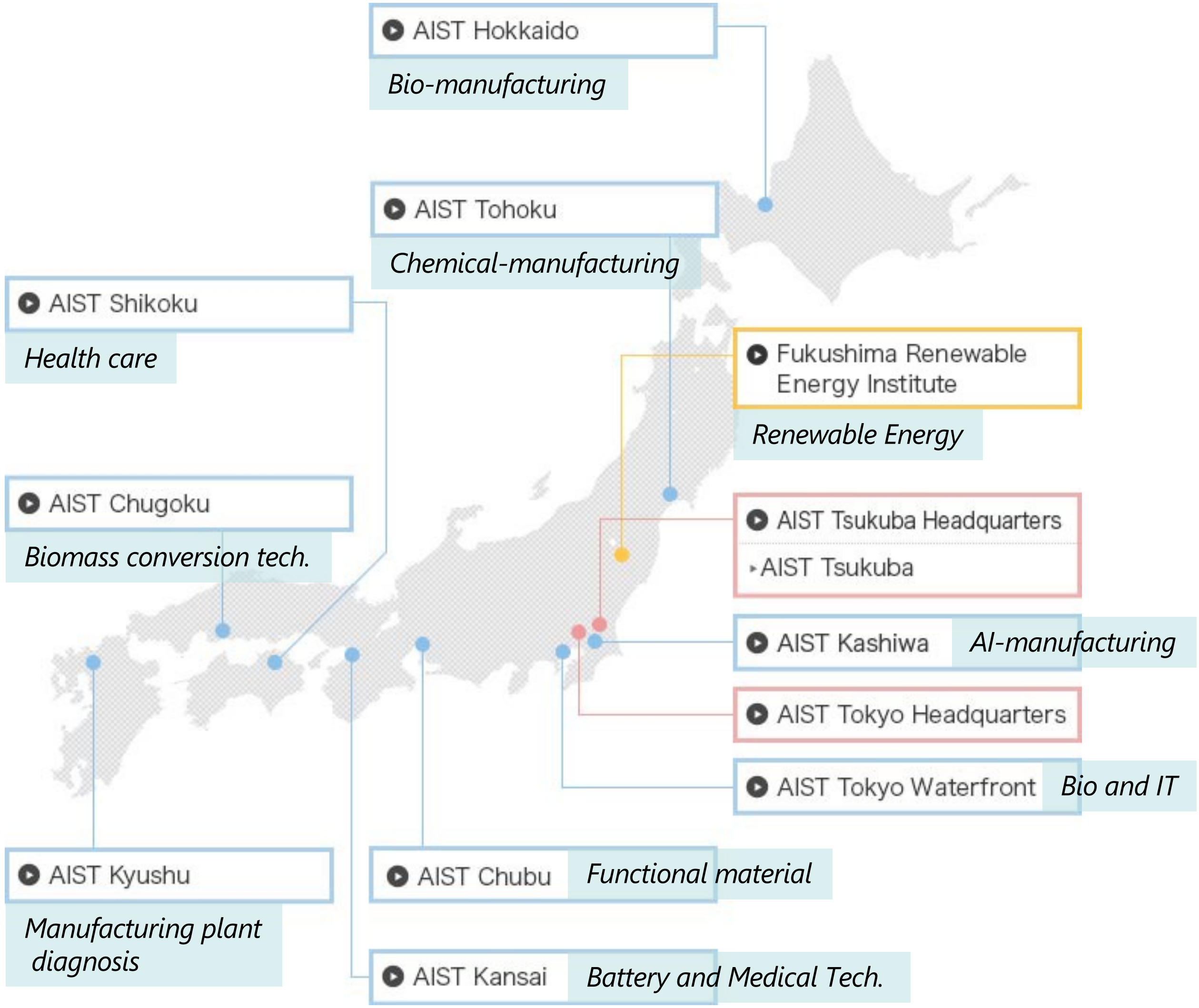
# AIST (National Institute of **A**dvanced **I**ndustrial **S**cience and **T**echnology)

- Established in 2001 by reorganizing 16 institutes under METI
- Total income: 110 billion JPY
  - 90%: Government, 10%: Industry
- 2901 employees (as of July. 2022)
  - 2214 researchers
  - 687 administrative employees
  - + executives, visiting researchers, postdocs, technical staff
- 7 research departments

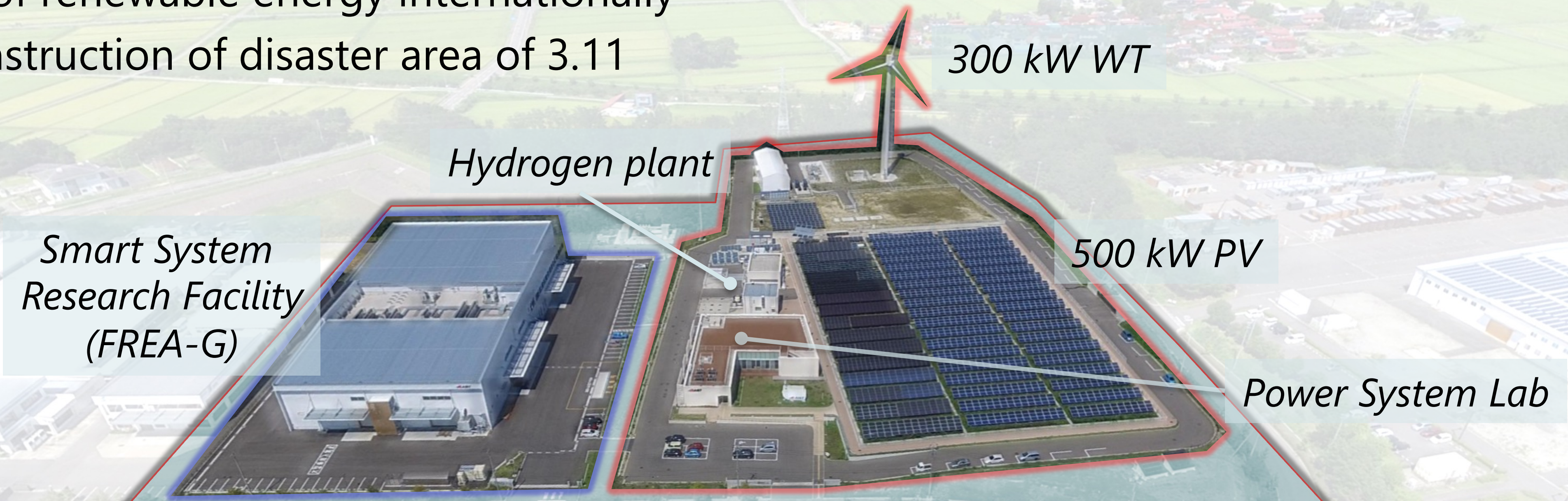



Source: AIST, JP) https://www.aist.go.jp/ , EN) https://www.aist.go.jp/index_en.html

# FREA (**F**ukushima **R**enewable **E**nergy Institute, **A**IST)

- Established in Koriyama, Fukushima in 2014 for promoting
  - R&D of renewable energy internationally
  - Reconstruction of disaster area of 3.11

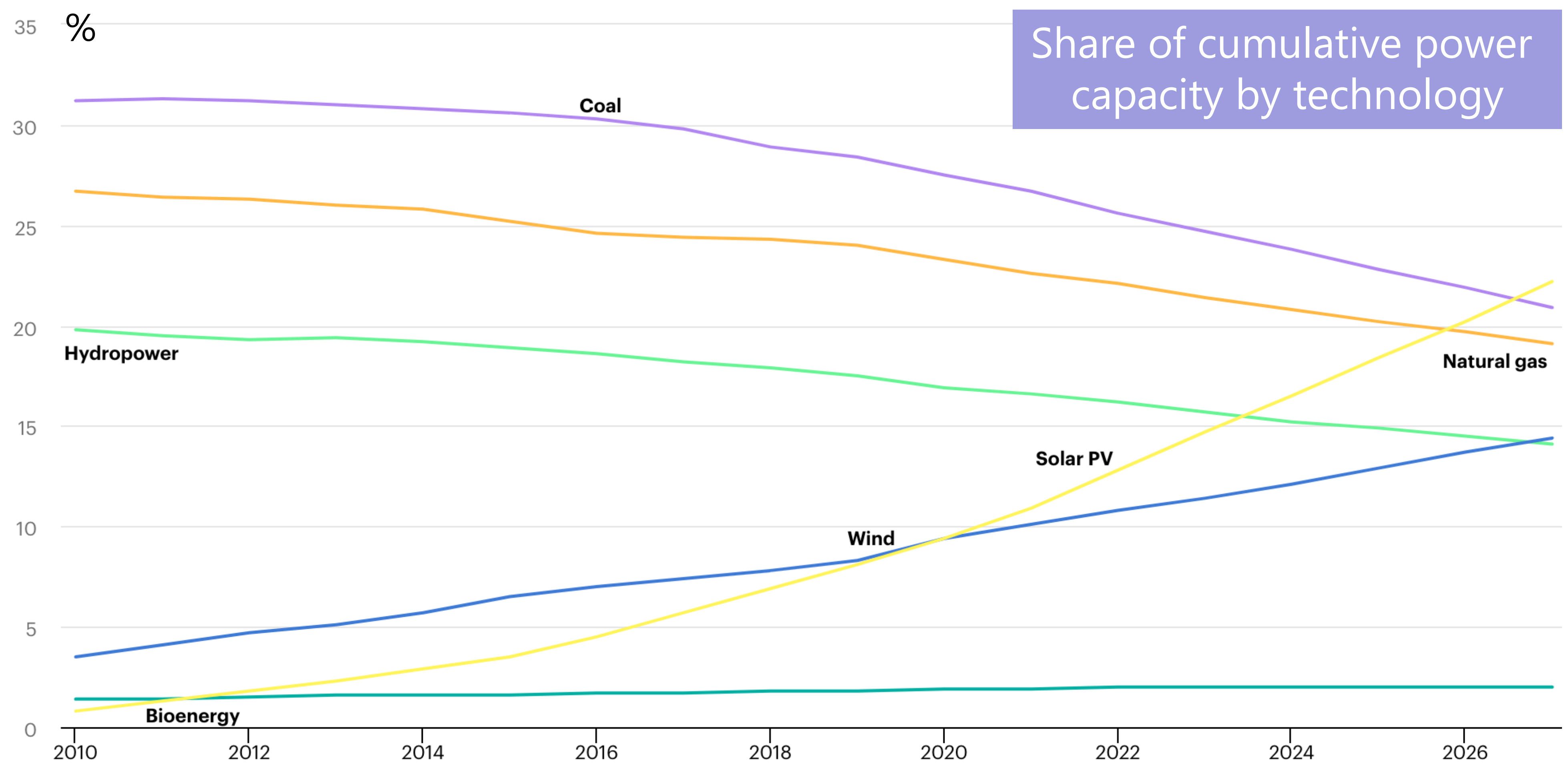



- Has over 200 researchers in 9 research teams

***Energy Network*** | *Hydrogen* | *Photovoltaic* | *Wind Power* | *Geothermal* | *Shallow Geothermal*

Source: FREA https://www.aist.go.jp/fukushima/

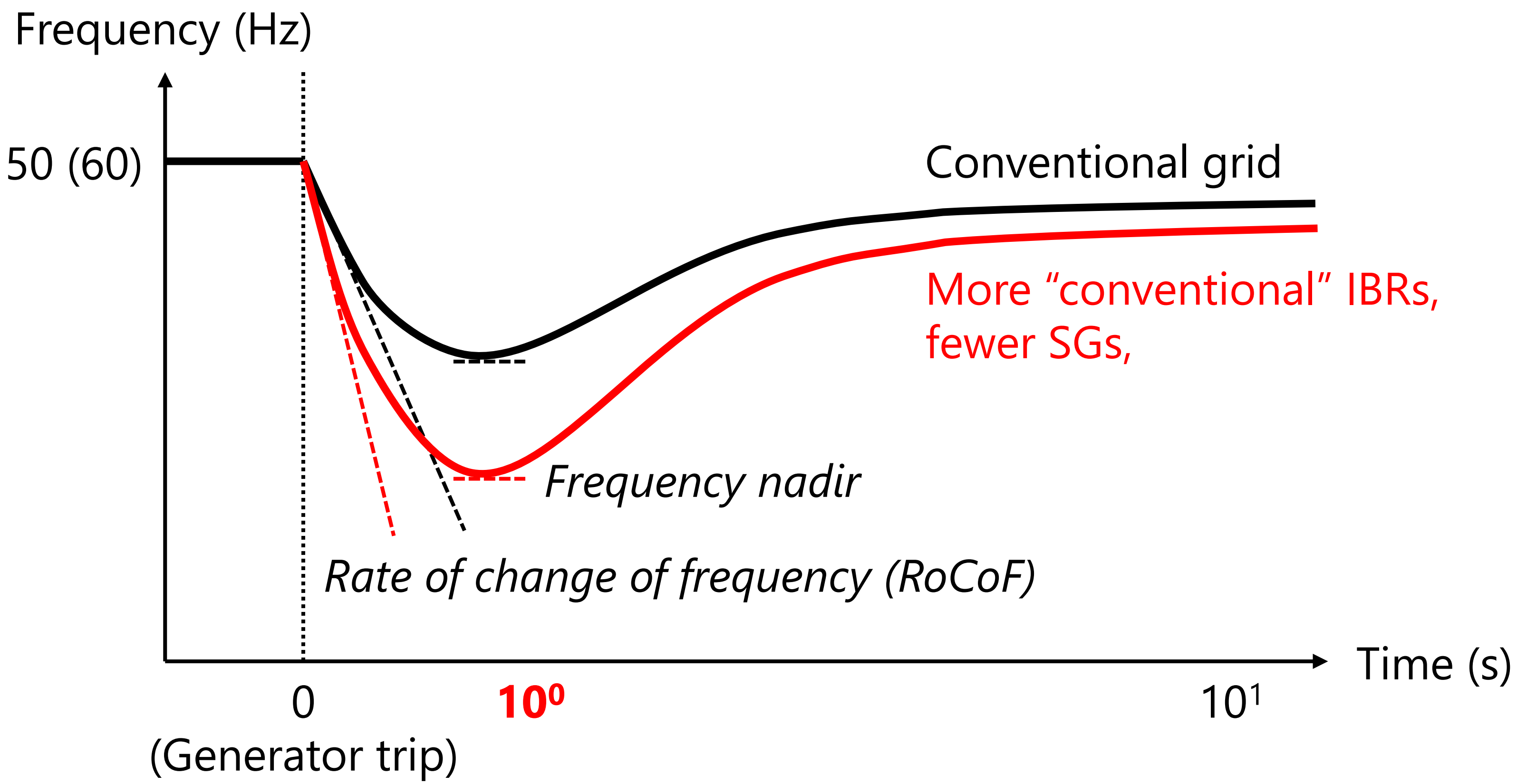
# Inverter-based resources (IBRs) will increase, and synchronous generators (SGs) will decrease.




Source: IEA, Share of cumulative power capacity by technology, 2010-2027, IEA, Paris https://www.iea.org/data-and-statistics/charts/share-of-cumulative-power-capacity-by-technology-2010-2027, 

# IBRs are expected to replace some of services provided by SGs

- Reducing the number of synchronous generators (SGs) decline grid frequency stability
- Frequency control including **inertial response** is required for inverter based-resources (IBRs)



# Changes in technical requirements due to increase in IBRs

## Evolution of grid support functions

IBR penetration: Low → High

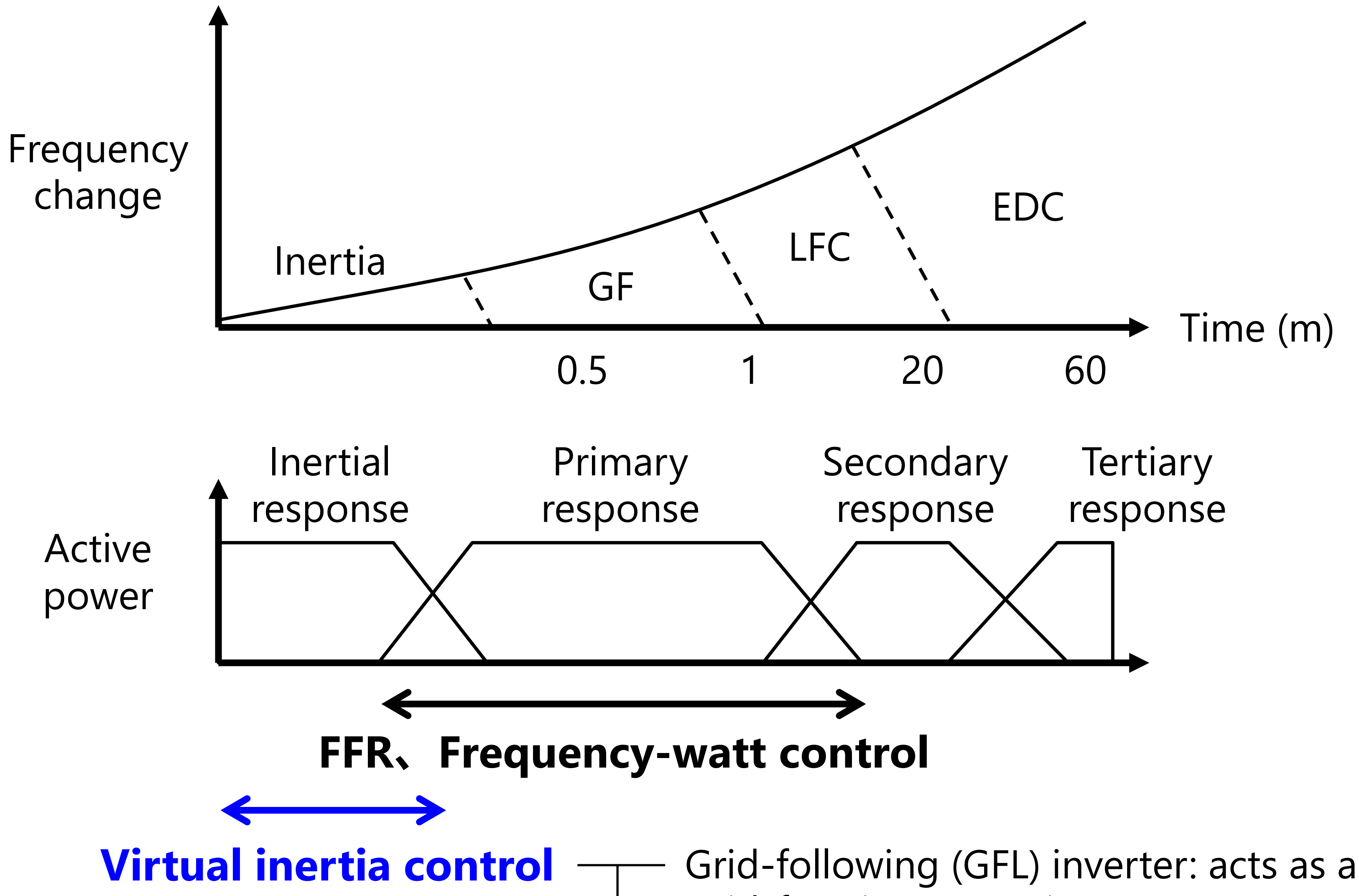
| | |
| --- | --- |
| IEEE Std 1547-2003 | • **Shall NOT** actively regulate voltage<br>• **Shall** trip on abnormal voltage/frequency |
| IEEE Std 1547a-2014 (Amendment 1) | • **May** actively regulate voltage<br>• **May** ride through abnormal voltage or frequency<br>• **May** provide frequency response |
| IEEE Std 1547-2018 | • **Shall be capable of** actively regulating voltage<br>• **Shall** ride through abnormal voltage/frequency<br>• **Shall be capable of** frequency response |

Source: NREL

IEEE STANDARDS ASSOCIATION　IEEE

Source: C. Stice, et al., "IEEE Std 1547-2018," NERC SPIDER WG Meeting, 2019

# Faster response is required for IBRs in low-inertia power systems



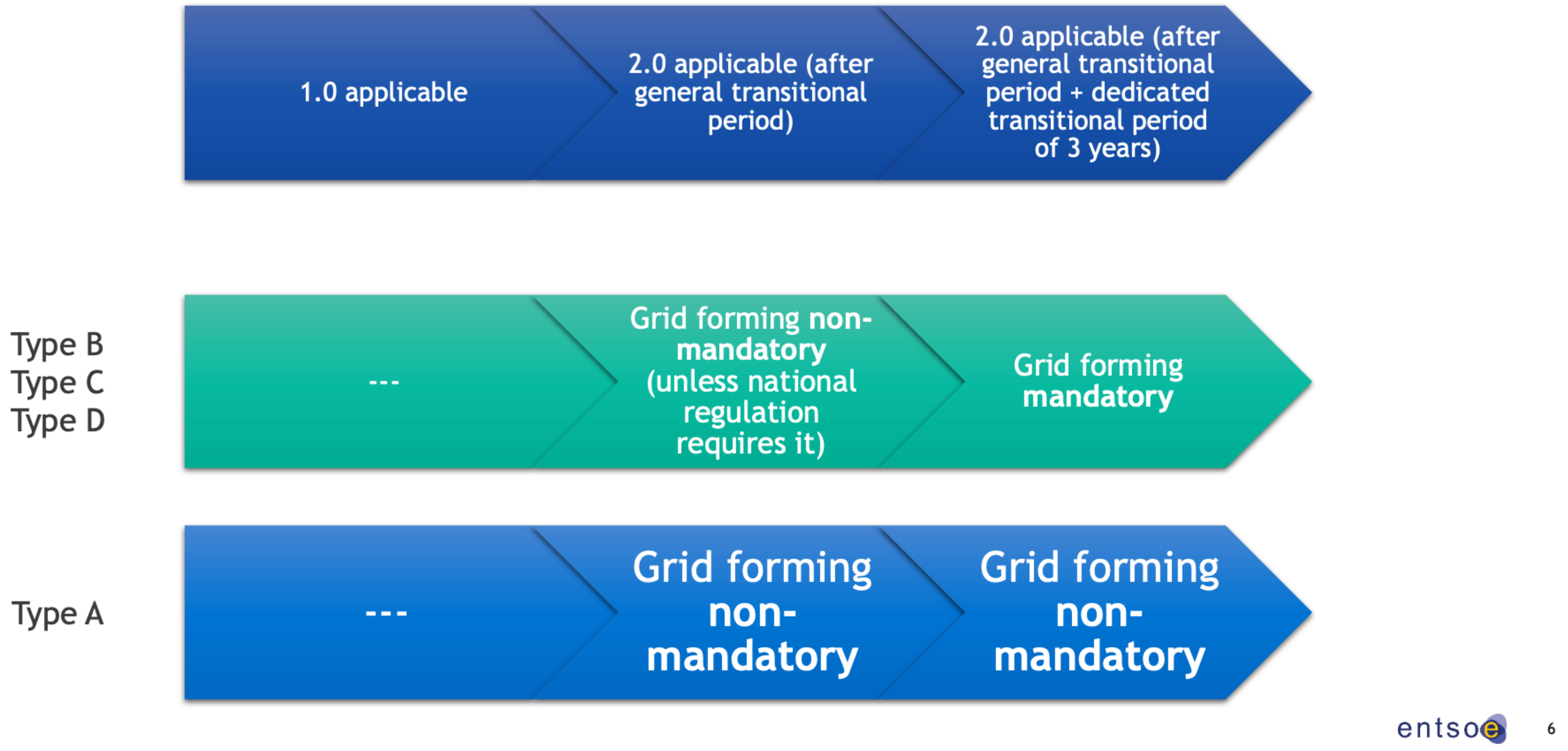

Grid-following (GFL) inverter: acts as a current source
Grid-forming (GFM) inverter: acts as a voltage source

AIST FREA

# Implementation of GFM capability is just around the corner

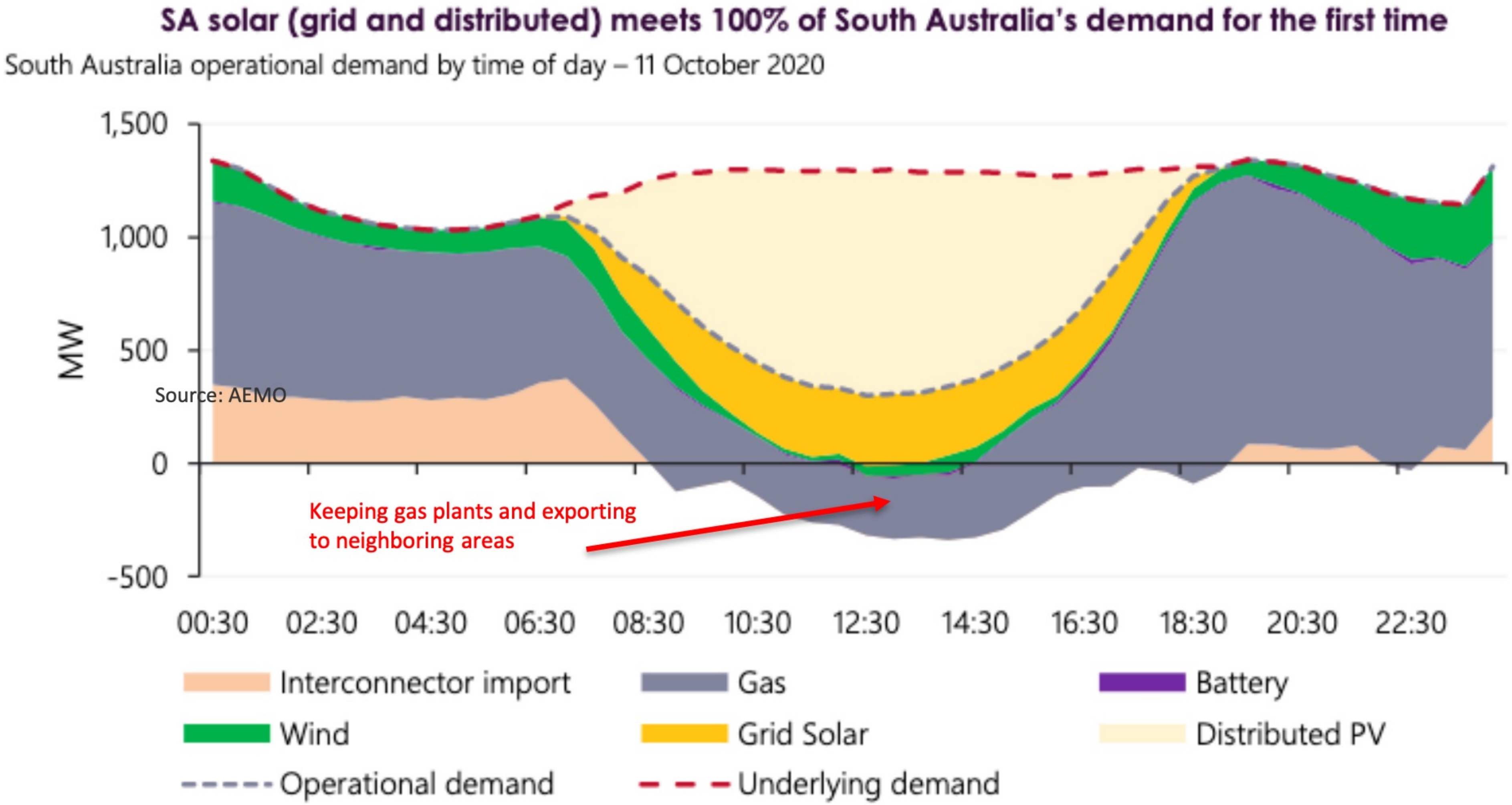
- NC RfG 2.0 with GFM requirement will enter in force in 2024 and will be reflected in national grid codes within three years

## NC RfG 2.0 / Grid forming new Article




Source: "ENTSO-E amendment proposal for NC RfG: on Grid Forming Capability," ENTSO Public Workshop, 2022

# South Australia – Already at 100% IBR (but…)


Source: B. Kroposki, "The Need for Grid-forming (GFM) Inverters in Future Power Systems"
https://research.csiro.au/ired2022/wp-content/uploads/sites/477/2022/11/The-Need-for-Grid-forming-GFM-Inverters-in-Future-Power-Systems.pdf

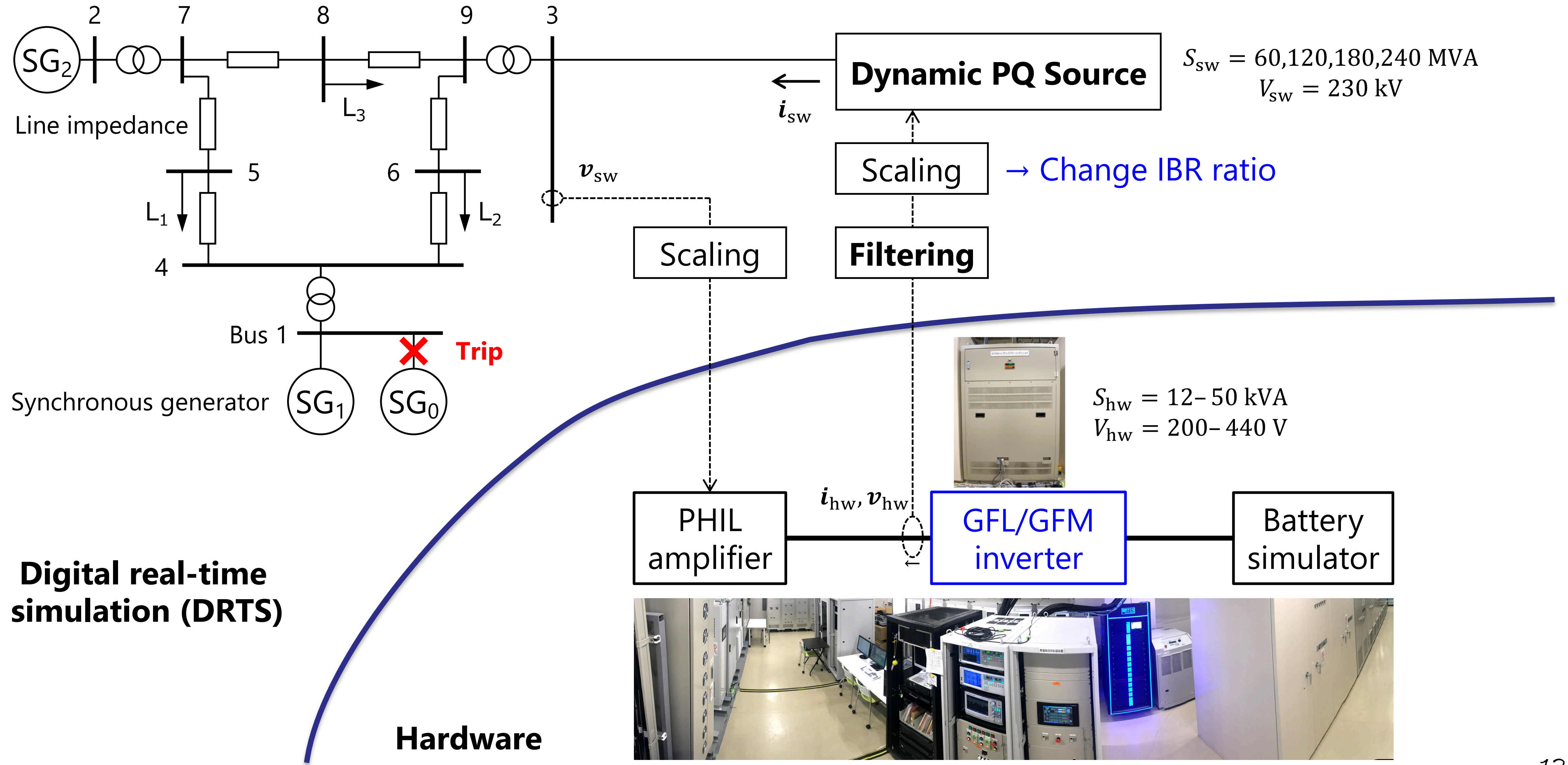
# Tested five inverter prototypes with virtual inertia control

| | Grid-following inverter | | Grid-forming inverter | | |
|---|---|---|---|---|---|
| | GFL 1 | GFL 2 | GFM 0 | GFM 1 | GFM 2 |
| Control function | df/dt-P droop<br>f-P droop | df/dt-P droop<br>f-P droop | VSM<br>Q-V droop | P-f droop<br>Q-V droop | VSM<br>Q-V droop |
| Rated capacity (kVA) | 20 | 49.9 | 12 | 20 | 50 |
| Rated AC voltage (V) | 200 | 200 | 420 | 200 | 440 |



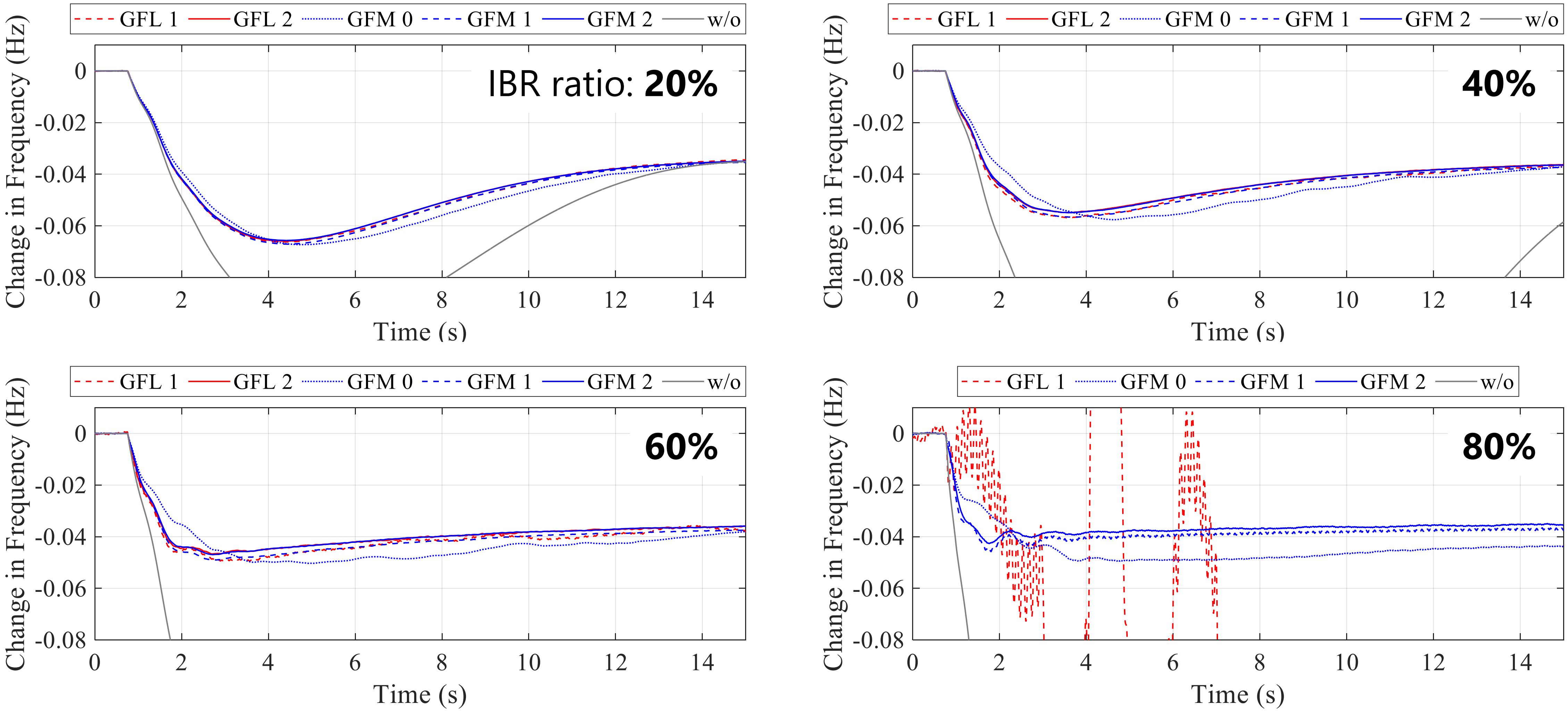

# Test setup for GFL/GFM inverters using modified IEEE 9-bus system model

**Modified IEEE 9-bus system model (300 MW)**




Source: H. Kikusato, et al., "Verification of Power Hardware-in-the-Loop Environment for Testing Grid-Forming Inverter," Energy Reports 2023, 9 (supplement 3), 303–311.

# As IBR ratio increased, frequency change increased for conventional IBR, decreased for GFL and GFM inverters. GFM inverters were stable at 80%.




Source: H. Kikusato, et al., "Performance Evaluation of Grid-Following and Grid-Forming Inverters on Frequency Stability in Low-Inertia Power Systems by Power Hardware-in-the-Loop Testing," Energy Reports 2023, 9 (supplement 1), 381–392.

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# Conducted existing conformance tests with changes in voltage magnitude, frequency, and phase angle. **GFL** inverters were mostly **conformance** in all tests. **GFM** inverters were **non-conformance** in most tests; **3 issues** were identified.

| # | Test | GFL 1 | GFL 2 | GFM 0 | GFM 1 | GFM 2 |
|---|---|---|---|---|---|---|
| 1 | Test for over/under-voltage trip | C* | C | N | N | N |
| 2 | Test for over/under-frequency trip | C* | C | N | N | N |
| 3 | Unintentional islanding test | C* | C* | - | N | C* |
| 4 | Test for voltage magnitude change within continuous operation region | C | C | N | C | C |
| 5 | Test for voltage phase angle change | C | C | C | N | N |
| 6 | Test for low/high-voltage ride-through | C* | C* | N | N | N |
| 7 | Test for low/high-frequency ride-through | C | C | N | N | C |

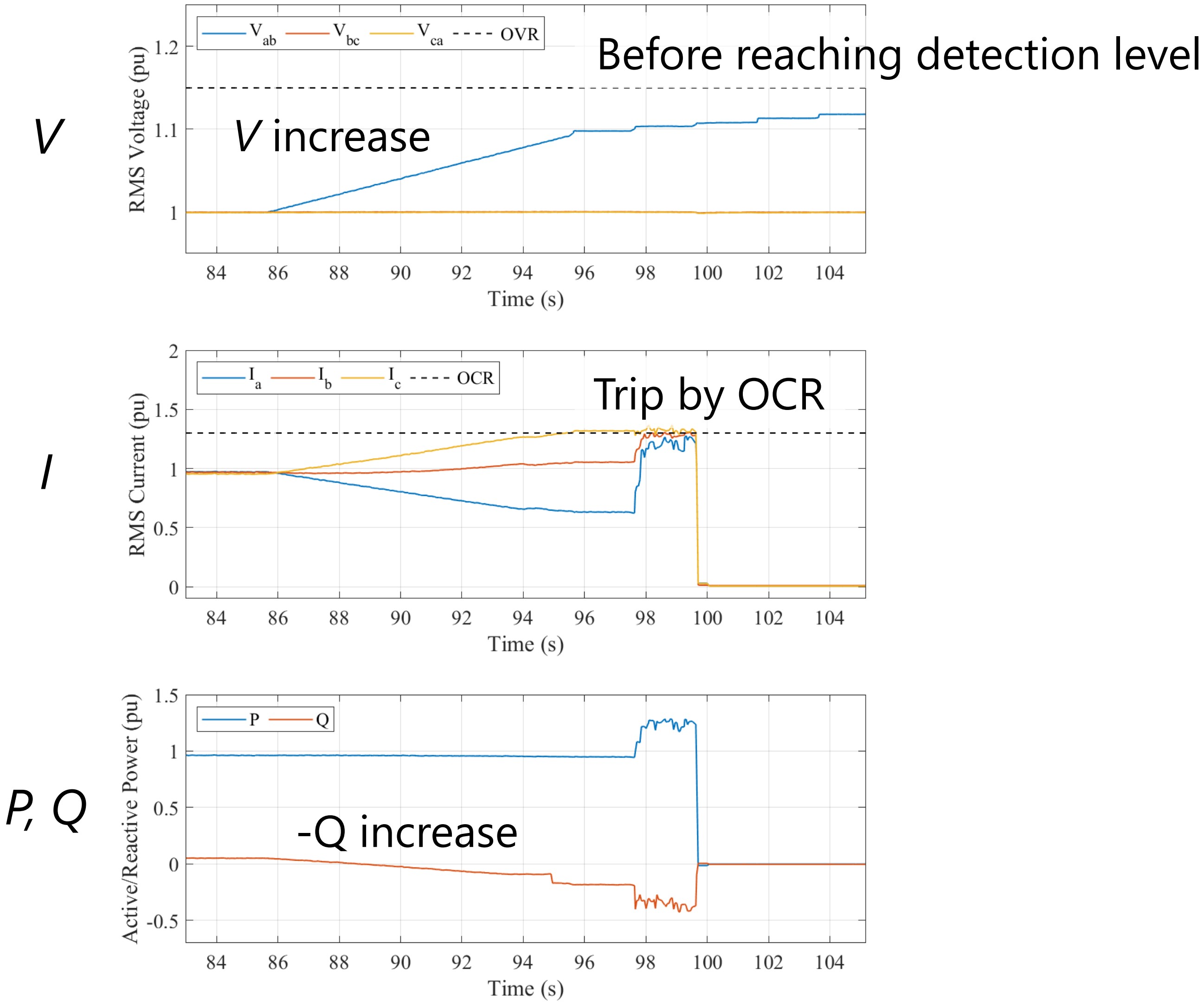
C: Conformance; N: Non-conformance; -: Not conducted

* Conformance can be expected by minor changes to device configuration, control logic, etc.

Source: H. Kikusato, et al., "Performance Analysis of Grid-Forming Inverters in Existing Conformance Testing," Energy Reports 2022, 8 (supplement 15), 73–83.

# Issue 1: Unwanted tripping by OCR due to change in grid voltage

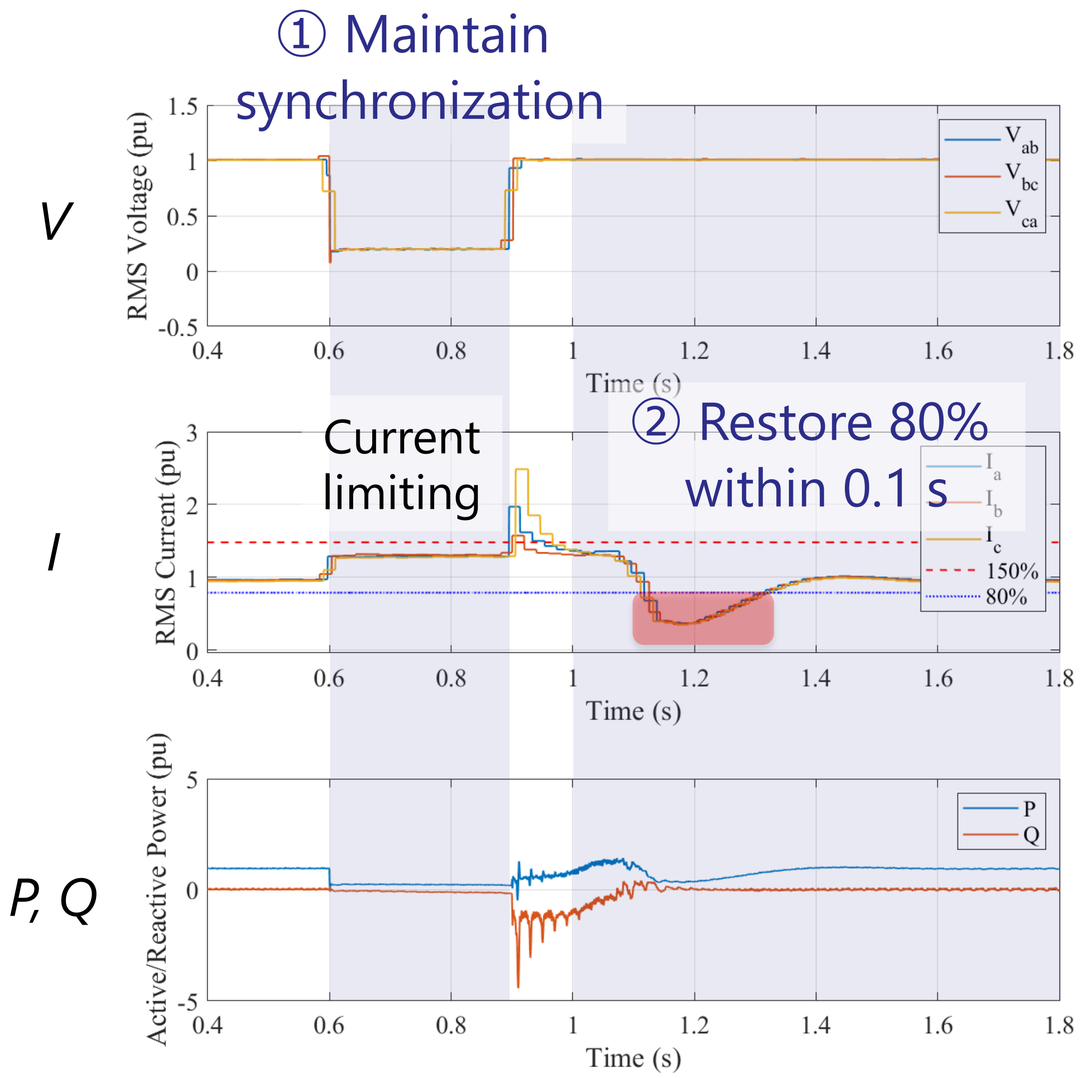
- **Test for over-voltage trip (GFM 0)**




Source: H. Kikusato, et al., "Performance Analysis of Grid-Forming Inverters in Existing Conformance Testing," Energy Reports 2022, 8 (supplement 15), 73–83.

# Issue 2: Active power swing after recovery from voltage sag

- **Low-voltage ride-through test (GFM 0)**

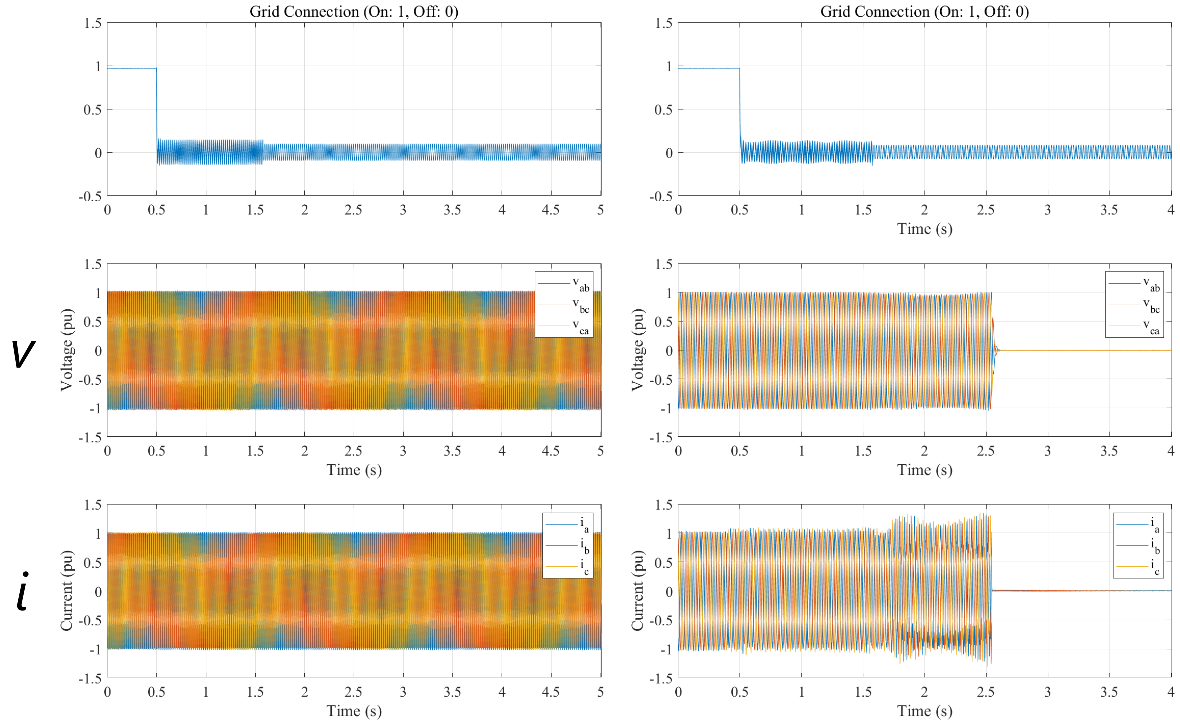



Source: H. Kikusato, et al., "Performance Analysis of Grid-Forming Inverters in Existing Conformance Testing," Energy Reports 2022, 8 (supplement 15), 73–83.

# Issue 3: Coexistence of grid stabilization capability and islanding detection

## ■ Unintentional islanding test

GFM 1 GFM 2

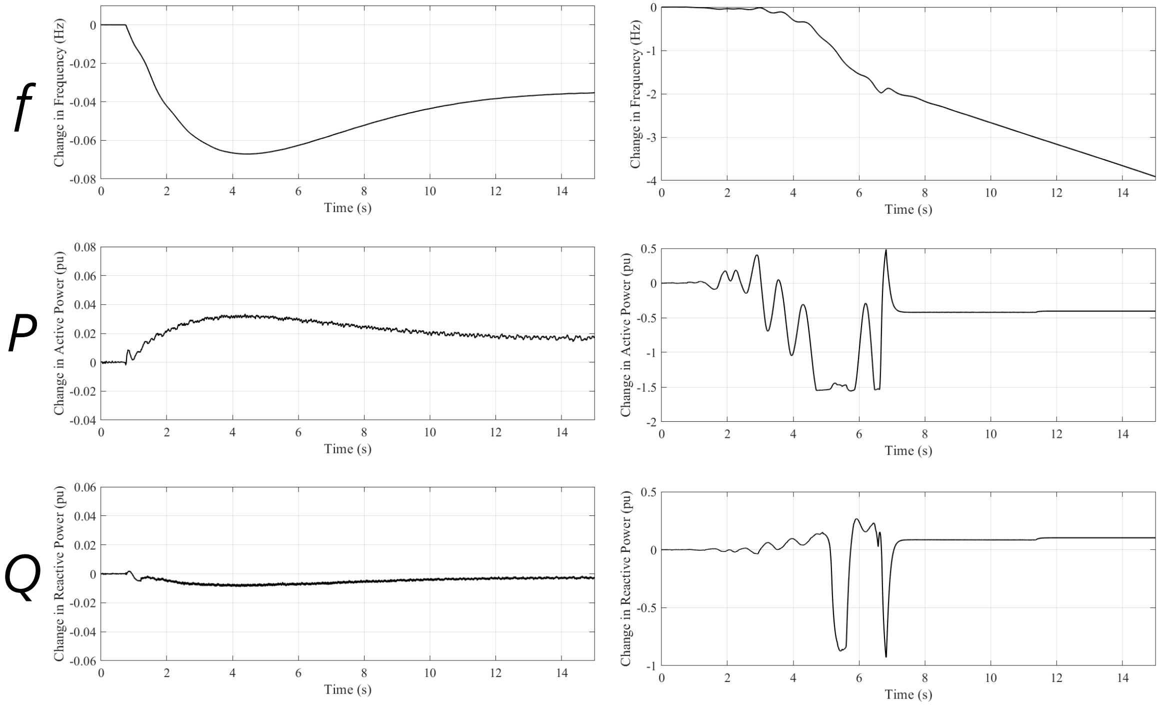



Continued to energize
→ non-conformance

Ceased to energize
→ conformance

## ■ Frequency stability in PHIL testing

GFM 1 GFM 2




Stable

Unstable

Source: H. Kikusato, et al., "Performance Analysis of Grid-Forming Inverters in Existing Conformance Testing," Energy Reports 2022, 8 (supplement 15), 73–83.

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# Summary

- Tested five GFL and GFM inverters from different manufacturers

- PHIL testing with IEEE 9-bus system model
  - As the IBR ratio increased, frequency change increased for conventional IBR, decreased for GFL and GFM inverters
  - GFM inverters were stable at 80%

- Japan's existing conformance testing
  - GFL Inverters were mostly conformance in all tests
  - GFM Inverters were non-conformance in most tests
    - Issue 1: Unwanted tripping by OCR due to a change in grid voltage
    - Issue 2: Active power swing after recovery from voltage sag
    - Issue 3: Coexistence of grid stabilization capability and islanding detection

- Working on a subsequent national R&D project for practical application of GFM inverter

# Appendix

# Related Works

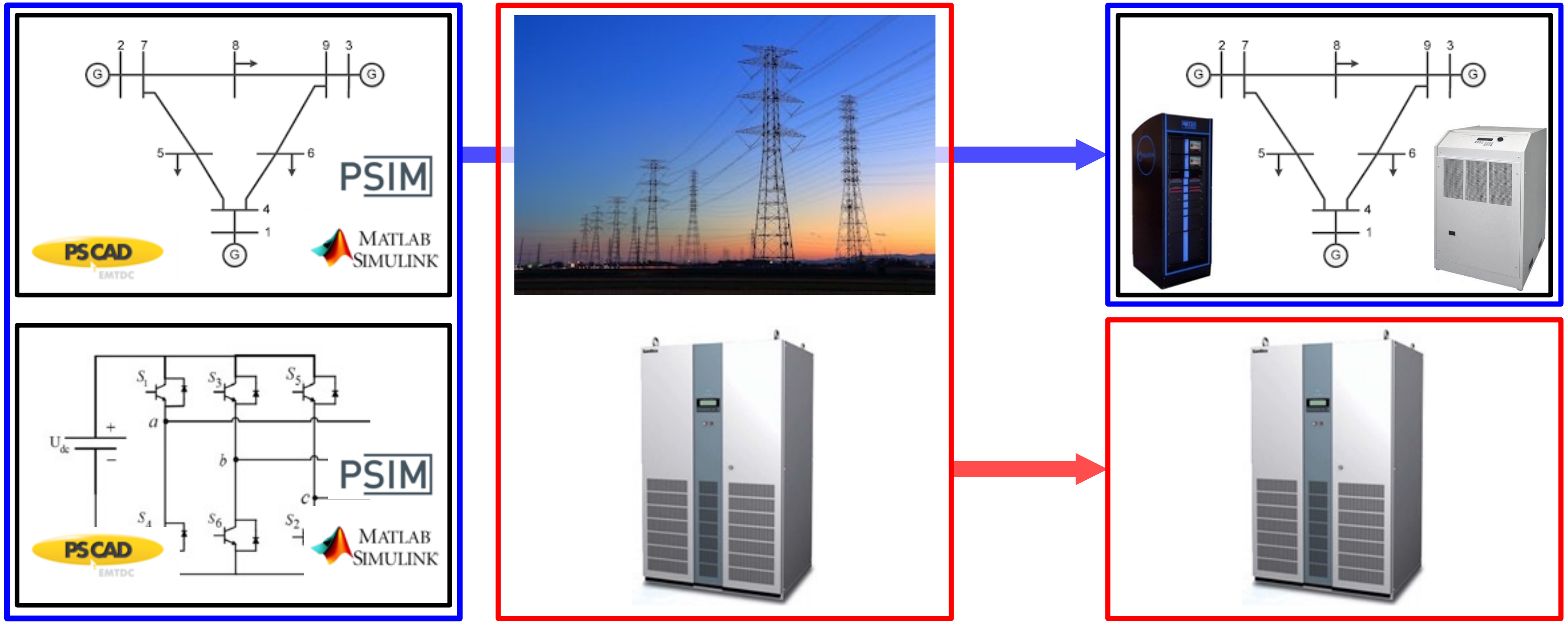

- H. Kikusato et al., "Performance Evaluation of Grid-Following and Grid-Forming Inverters on Frequency Stability in Low-Inertia Power Systems by Power Hardware-in-the-Loop Testing," Energy Reports 2023, 9 (supplement 1), 381–392.
- H. Kikusato et al., "Performance Analysis of Grid-Forming Inverters in Existing Conformance Testing," Energy Reports 2022, 8 (supplement 15), 73–83.
- H. Kikusato et al., "Verification of Power Hardware-in-the-Loop Environment for Testing Grid-Forming Inverter," Energy Reports 2023, 9 (supplement 3), 303–311.
- H. Kikusato et al., "Power Hardware-in-the-Loop Testing for Multiple Inverters with Virtual Inertia Controls," Energy Report 2023, 9 (supplement 10), 458-466.
- D. Orihara et al., "Contribution of Voltage Support Function to Virtual Inertia Control Performance of Inverter-Based Resource in Frequency Stability," Energies 2021, 14, 4220.
- D. Orihara et al., "Internal Induced Voltage Modification for Current Limitation in Virtual Synchronous Machine," Energies 2022, 15, 901.
- J. Hashimoto et al., "Development of df/dt Function in Inverters for Synthetic Inertia," Energy Reports 2023, 9 (supplement 1), 363–371.
- J. Hashimoto et al., "Developing a Synthetic Inertia Function for Smart Inverters and Studying its Interaction with Other Functions with CHIL Testing," Energy Reports 2023, 9 (supplement 1), 435–443.
- T. Takamatsu et al., "Simulation Analysis of Issues with Grid Disturbance for a Photovoltaic Powered Virtual Synchronous Machine," Energies 2022, 15, 5921.
- H. Hamada et al., "Challenges for a Reduced Inertia Power System Due to the Large-Scale," Global Energy Interconnection 2022, 5(3), 266–273.

# PHIL Simulation is a Flexible and Reliable Testing Method

Simulation | Demonstration | **Power hardware-in-the-loop (PHIL) simulation**

Grid

GFMI




| | Simulation | Demonstration | PHIL simulation |
|---|---|---|---|
| Flexibility (Grid) | **High** | Low | High |
| Fidelity (GFMI) | Low | **High** | High |

# Advanced Control of GFL and GFM inverters

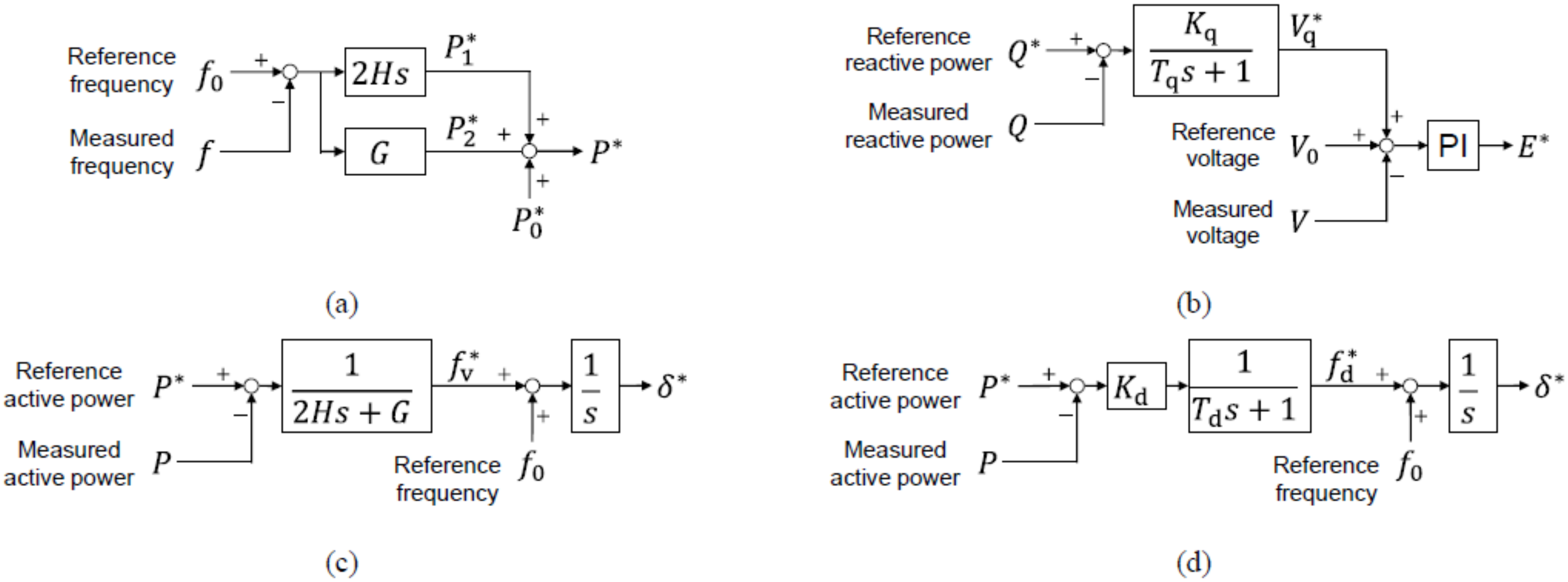


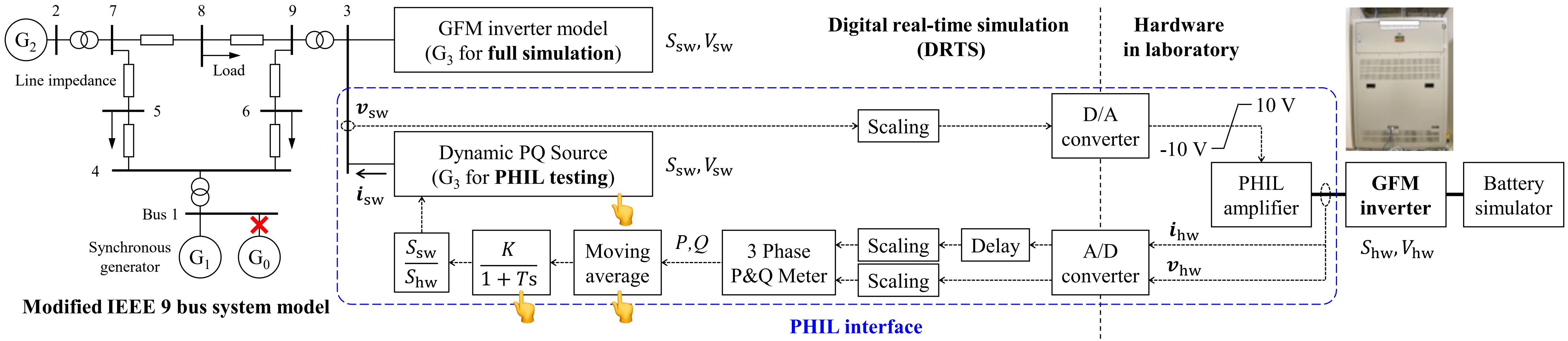

Fig. 2. Generalized control block diagrams of (a) the frequency control implemented in GFL 1 and GFL 2; (b) the voltage magnitude control implemented in GFM 0, GFM 1, and GFM 2; the voltage phase angle control implemented in (c) GFM 0, GFM 2; and (d) GFM 1.

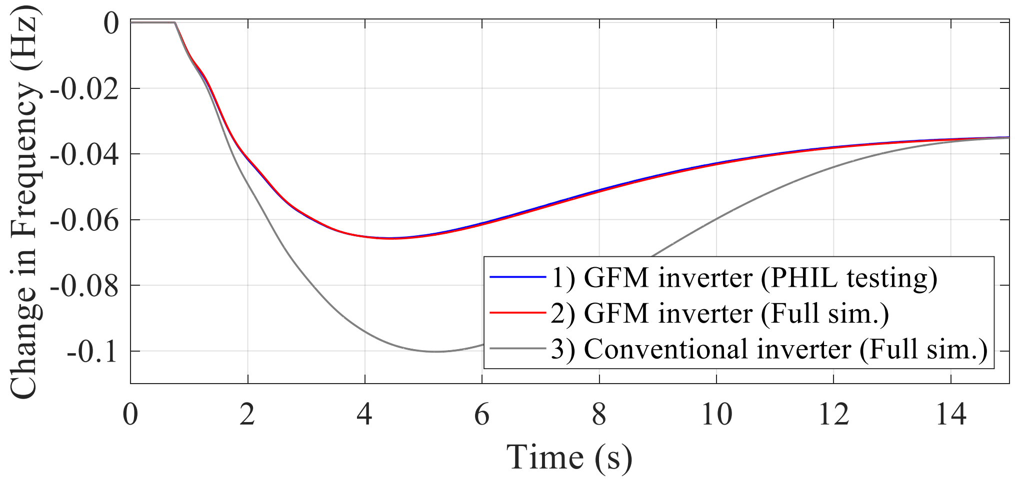
# Specifications of inverters

Table 2. Specifications of inverter prototypes.

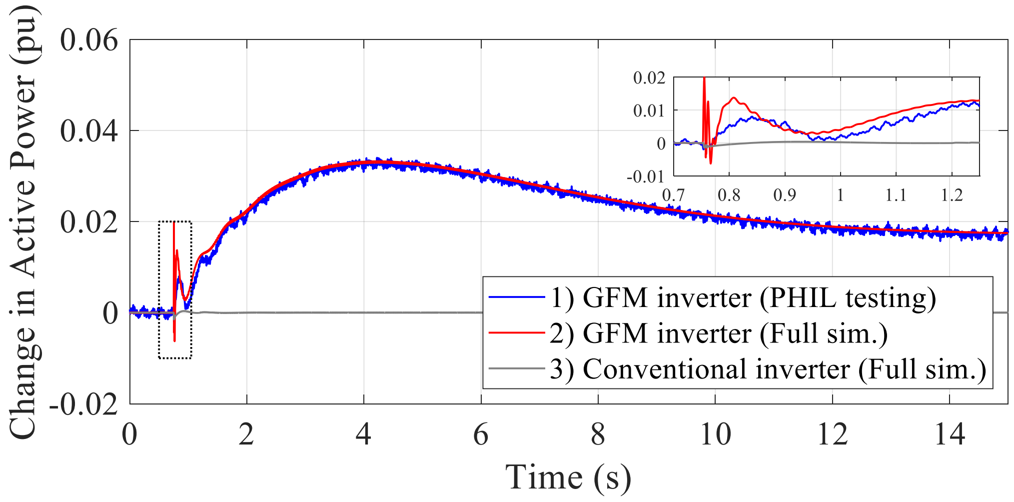
| Name and inverter types | GFL 1 | GFL 2 | GFM 0 | GFM 1 | GFM 2 |
|---|---|---|---|---|---|
| Rated capacity | 20 kVA | 49.9 kVA | 12 kVA | 20 kVA | 50 kVA |
| Advanced control functions | df/dt-P droop, f-P droop | df/dt-P droop, f-P droop | VSM, Q-V droop | P-f droop, Q-V droop | VSM, Q-V droop |
| IDM (reactive method; active method) | Voltage phase angle jump detection; Frequency feedback method with step reactive power injection | RoCoF change detection; Frequency shift method | Unimplemented | Voltage phase angle jump detection; Frequency feedback method with step reactive power injection | Voltage phase angle jump detection; Frequency feedback method with step reactive power injection |
| Current limiting function | w/ | w/ | w/ | w/o | w/ |
| Prototype number | Prototype 1 | Prototype 2 | Prototype 3 | Prototype 1 | Prototype 4 |

# PHIL Testing Can be Conducted Stably in Most Cases with Adequate Accuracy



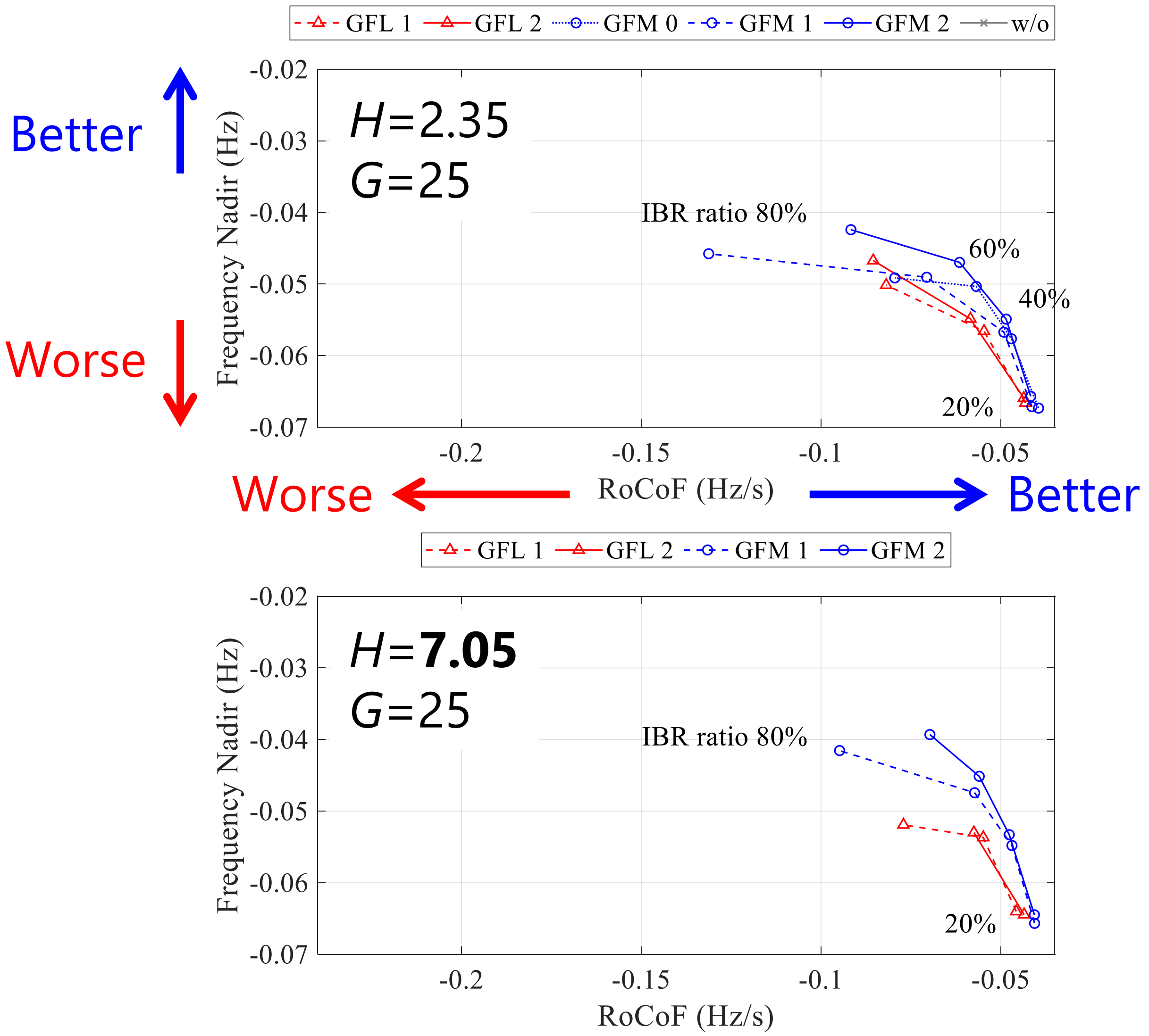

**Frequency**




**Active power**

Source: H. Kikusato, et al., "Verification of Power Hardware-in-the-Loop Environment for Testing Grid-Forming Inverter," Energy Reports 2023, 9 (supplement 3), 303–311.

# Inertia Constant "*H*" Affects RoCoF; Governor Gain "*G*" Affects Frequency Nadir (and RoCoF)




Source: H. Kikusato, et al., "Performance Evaluation of Grid-Following and Grid-Forming Inverters on Frequency Stability in Low-Inertia Power Systems by Power Hardware-in-the-Loop Testing," Energy Reports 2023, 9 (supplement 1), 381–392.

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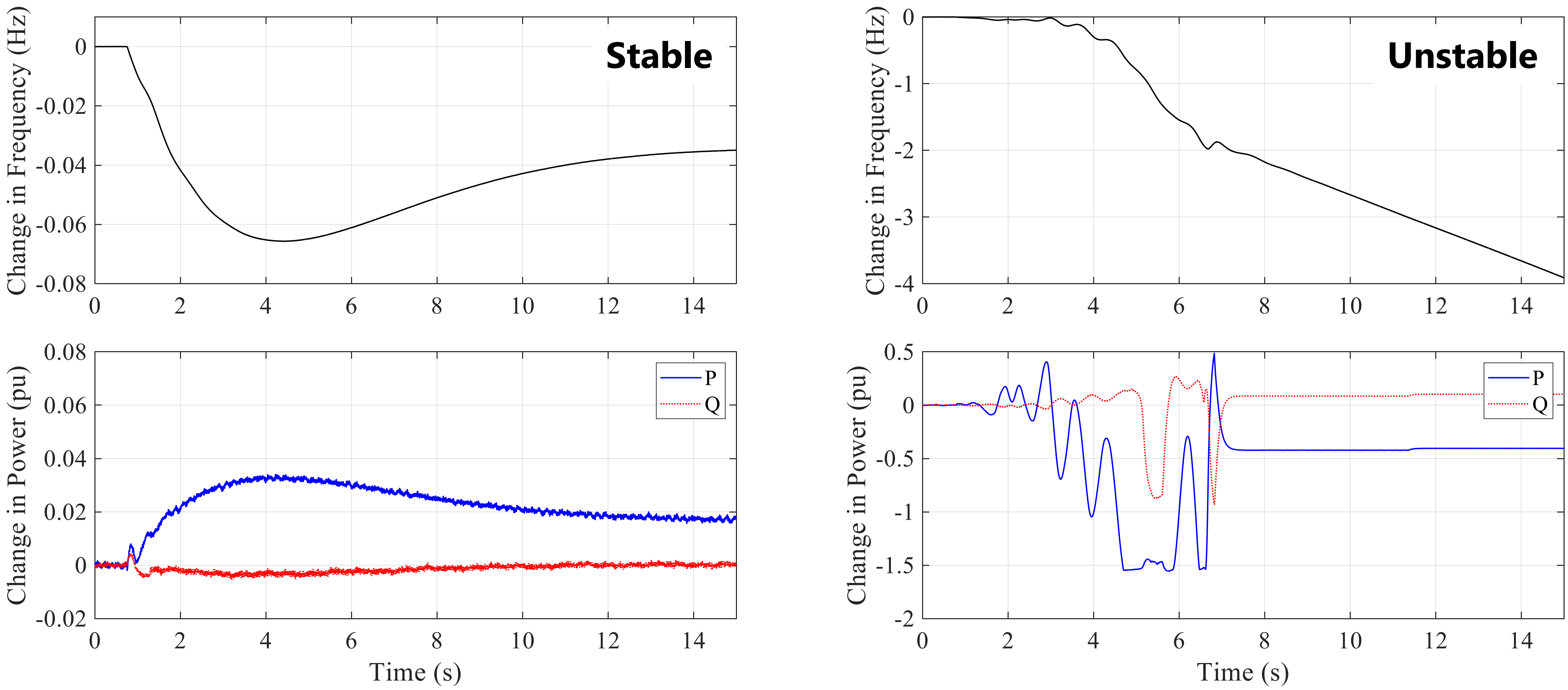
# Interference Occurs between Islanding Detection and Frequency Stabilization Capability in GFM Inverter

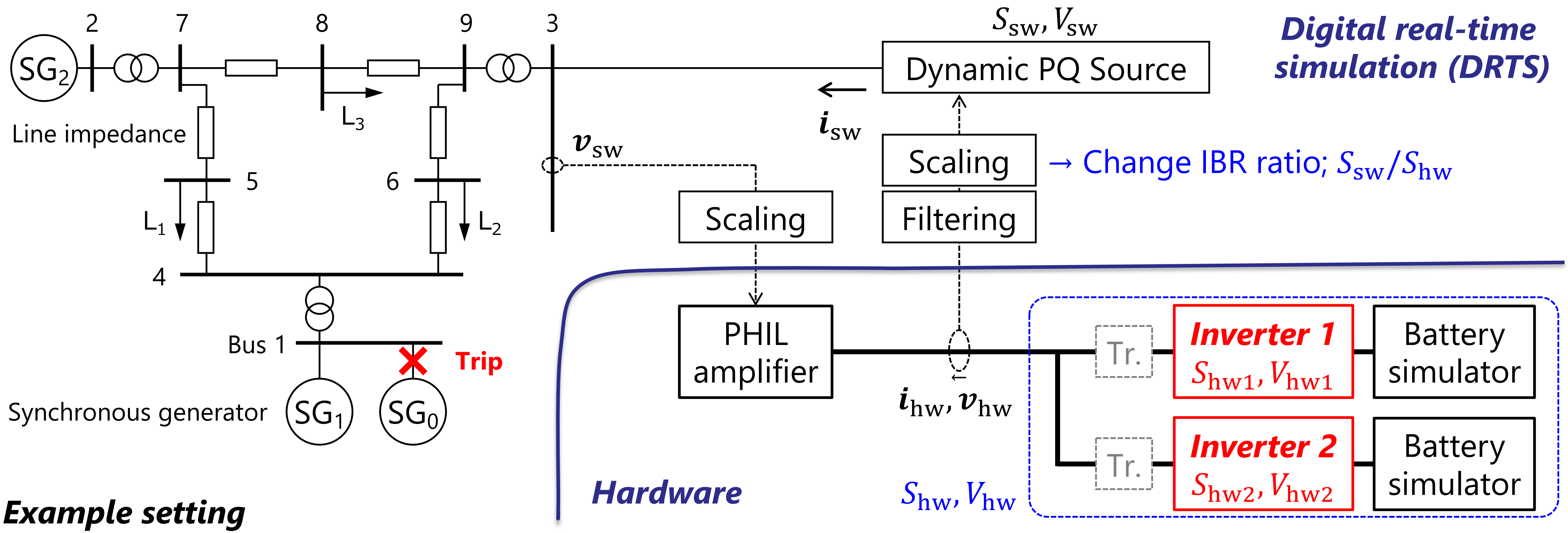



**Disable** islanding detection

**Enable** islanding detection

Source: H. Kikusato, et al., "Performance Evaluation of Grid-Following and Grid-Forming Inverters on Frequency Stability in Low-Inertia Power Systems by Power Hardware-in-the-Loop Testing," Energy Reports 2023, 9 (supplement 1), 381–392.

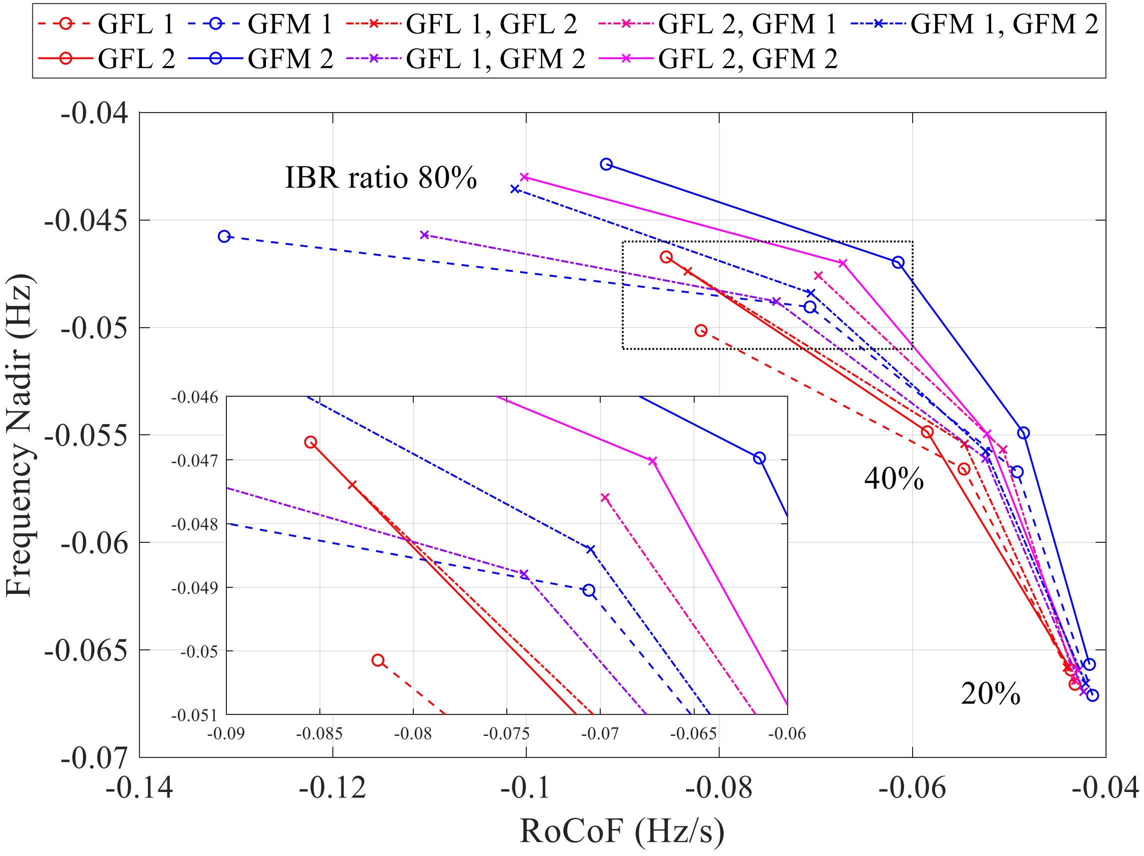
# Configuration of PHIL testing for multiple inverters



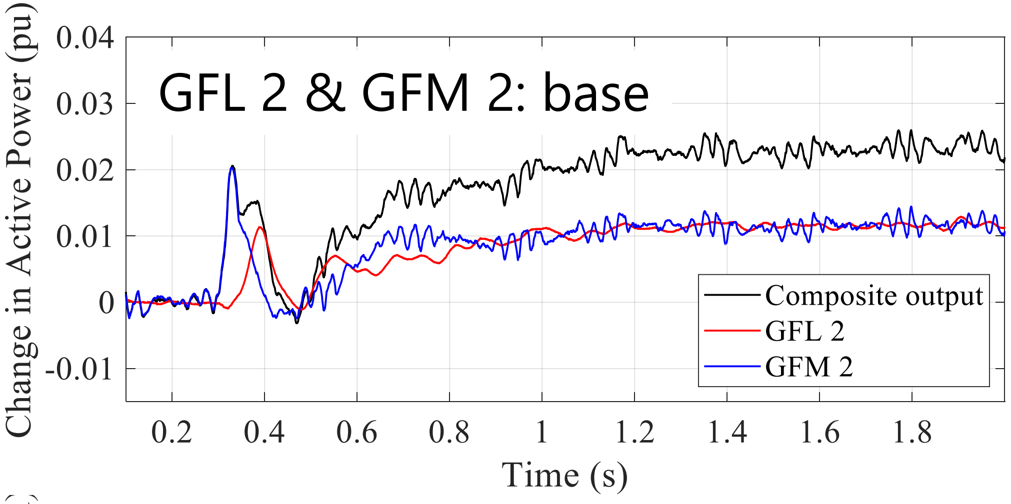

***Example setting***

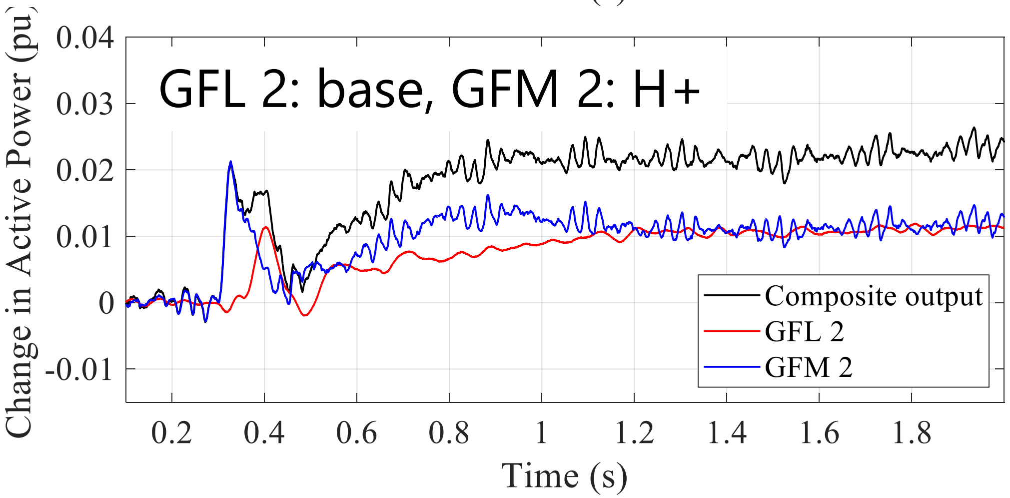
| | | | |
|---|---|---|---|
| ***Inverter 1*** | $S_{hw1} = 20\ \text{kVA} \Rightarrow S'_{hw1} = 20\ \text{kVA}$ | $V_{hw1} = 200\ \text{V} \Rightarrow$ use Tr. | $H'_1 = \frac{S'_{hw1}}{S_{hw1}} \times H_1, G'_1 = \frac{S'_{hw1}}{S_{hw1}} \times G_1$ |
| ***Inverter 2*** | $S_{hw2} = 50\ \text{kVA} \Rightarrow S'_{hw2} = 20\ \text{kVA}$ | $V_{hw2} = 440\ \text{V}$ | $H'_2 = \frac{S'_{hw2}}{S_{hw2}} \times H_2, G'_2 = \frac{S'_{hw2}}{S_{hw2}} \times G_2$ |
| ***Total setting*** | $S_{hw} = S'_{hw1} + S'_{hw2} = 40\ \text{kVA}$ | $V_{hw} = 440\ \text{V}$ | - |

# No inverter combination caused interference that significantly worsened the grid frequency stability. Combined inverters' performance was intermediate between the performance of each inverter alone.




**RoCoF and frequency nadir**



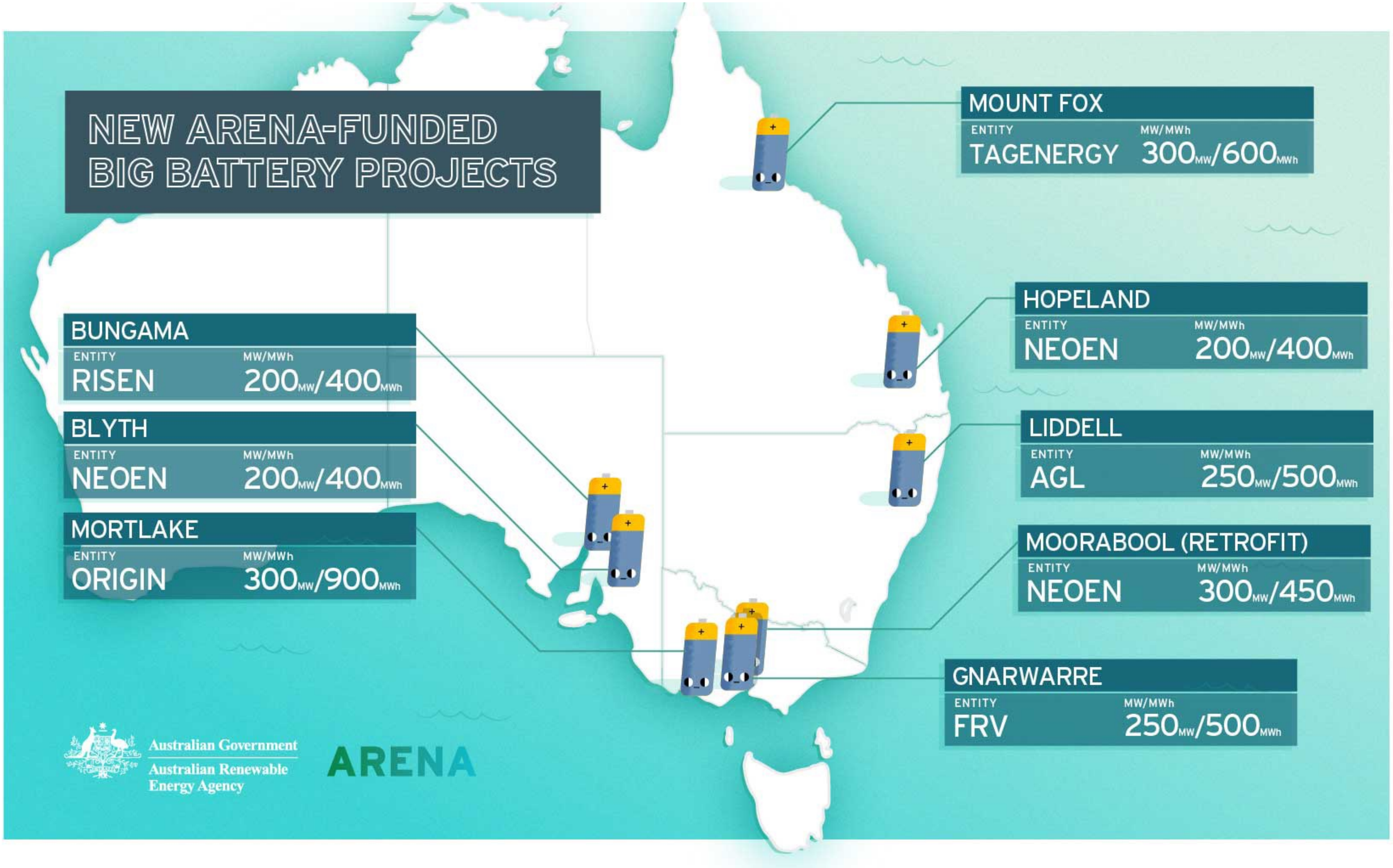




**Active power**



Source: H. Kikusato, et al., "Power Hardware-in-the-Loop Testing for Multiple Inverters with Virtual Inertia Controls," Energy Reports 2023, 9 (supplement 10), 458–466.

# 8 GFM batteries with total capacity of 2.0 GW/4.2 GWh




Source: ARENA, Large Scale Storage Funding Round https://arena.gov.au/news/arena-backs-eight-grid-scale-batteries-worth-2-7-billion/
ARENA https://arena.gov.au/blog/arena-backs-eight-big-batteries-to-bolster-grid/