This study was based on the results obtained from a project commissioned by the New Energy and Industrial Technology Development Organization (NEDO), no. JPNP19002.

擬似慣性機能付きインバータのPHIL試験

PHIL Testing for Inverters with Virtual Inertia Capabilities

RTDS Japan User Group Meeting
@J-POWER ビジネスサービス 本店
October 4, 2023

喜久里 浩之、産業技術総合研究所
KIKUSATO Hiroshi, AIST

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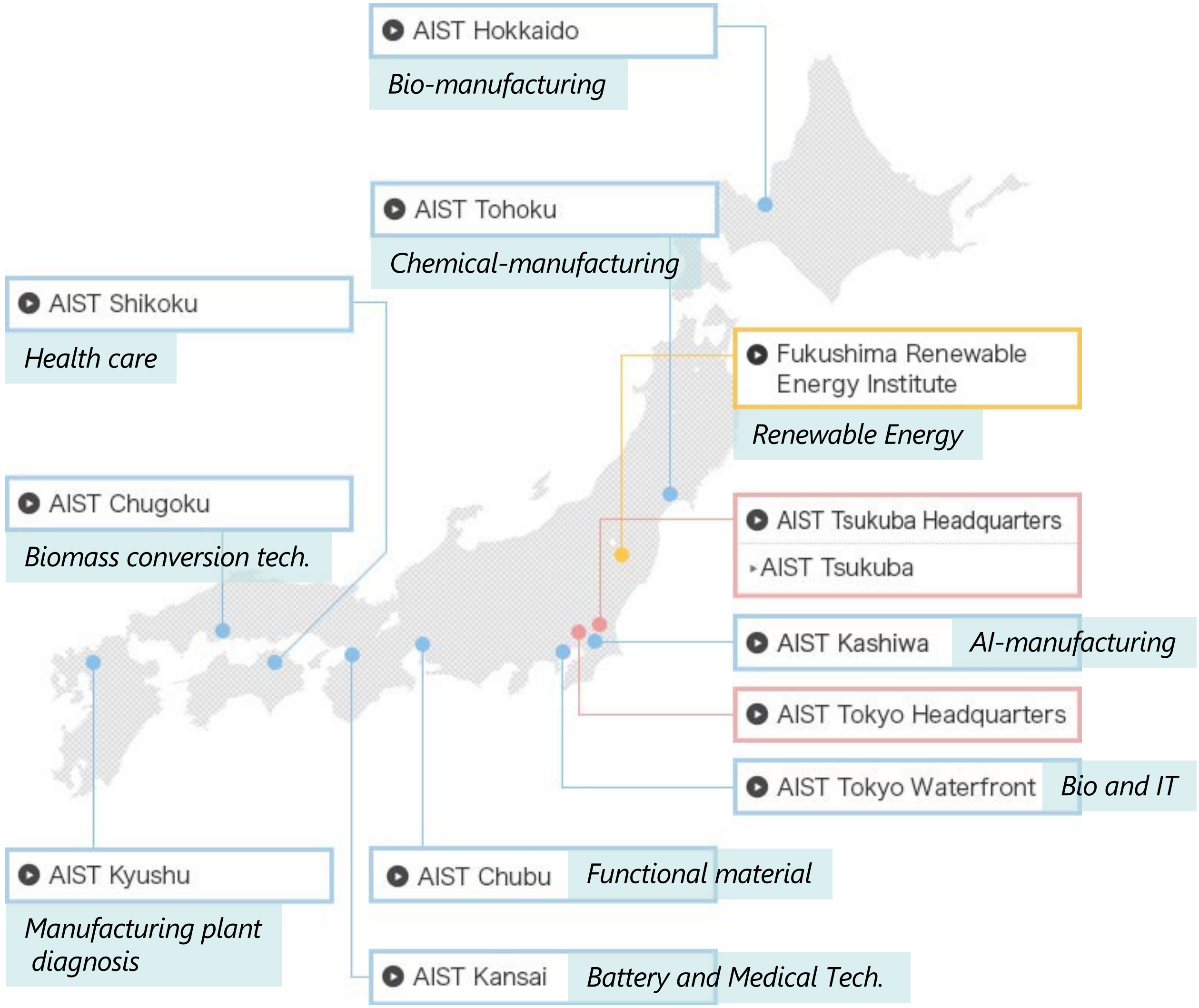
AIST (National Institute of **A**dvanced **I**ndustrial **S**cience and **T**echnology)

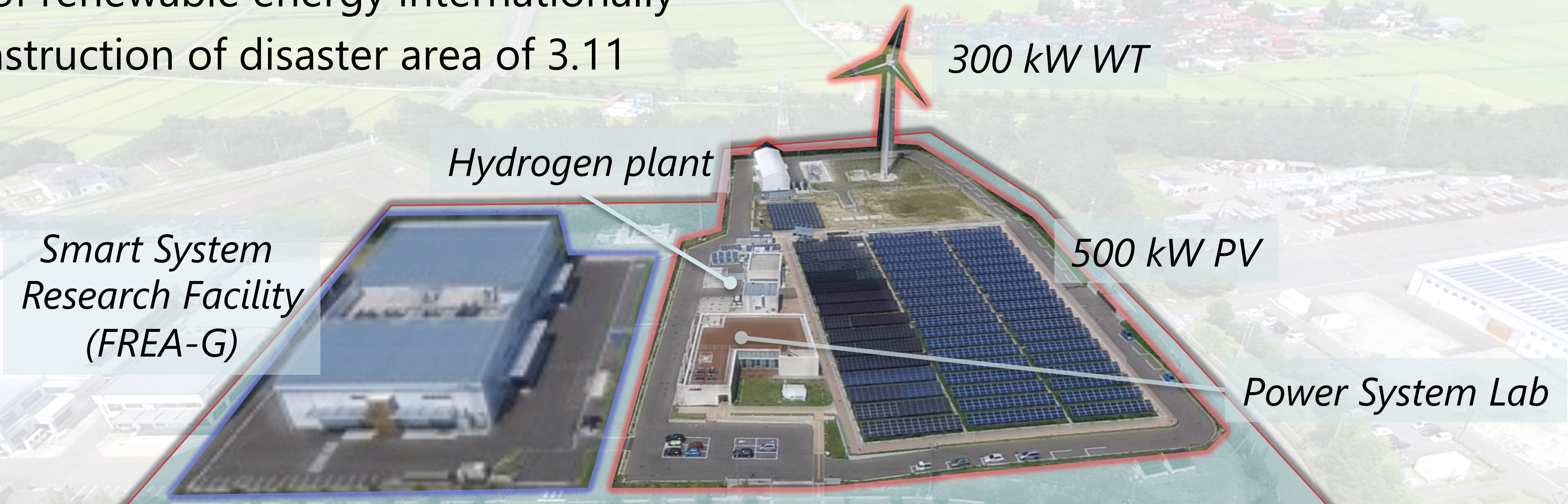
- Established in 2001 by reorganizing 16 institutes under METI
- Total income: 110 billion JPY
  - 90%: Government, 10%: Industry
- 2901 employees (as of July. 2022)
  - 2214 researchers
  - 687 administrative employees
  - + executives, visiting researchers, postdocs, technical staff
- 7 research departments



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



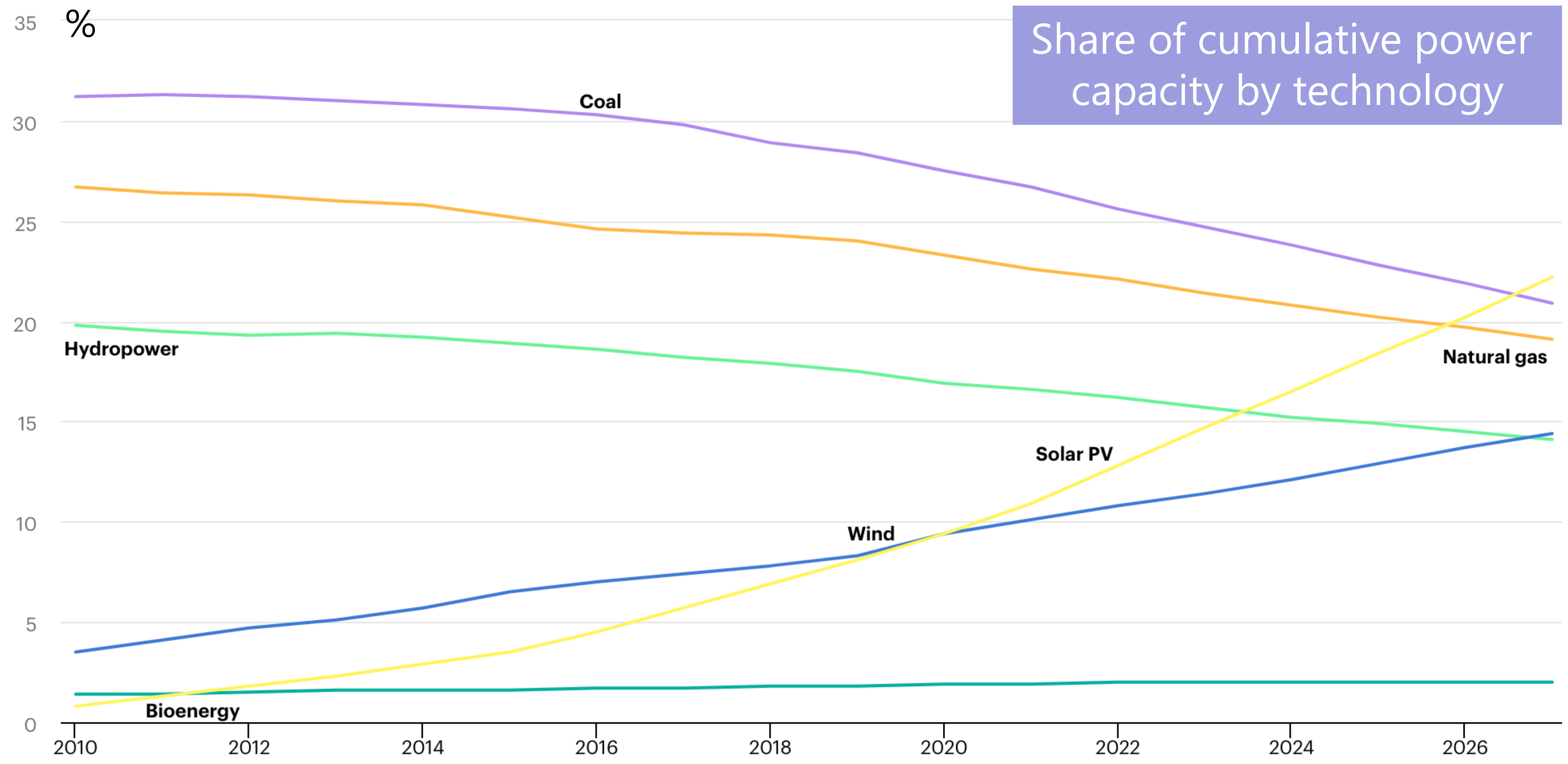
- Has over 200 researchers in 9 research teams

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

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

Why PHIL Testing for Power Systems?

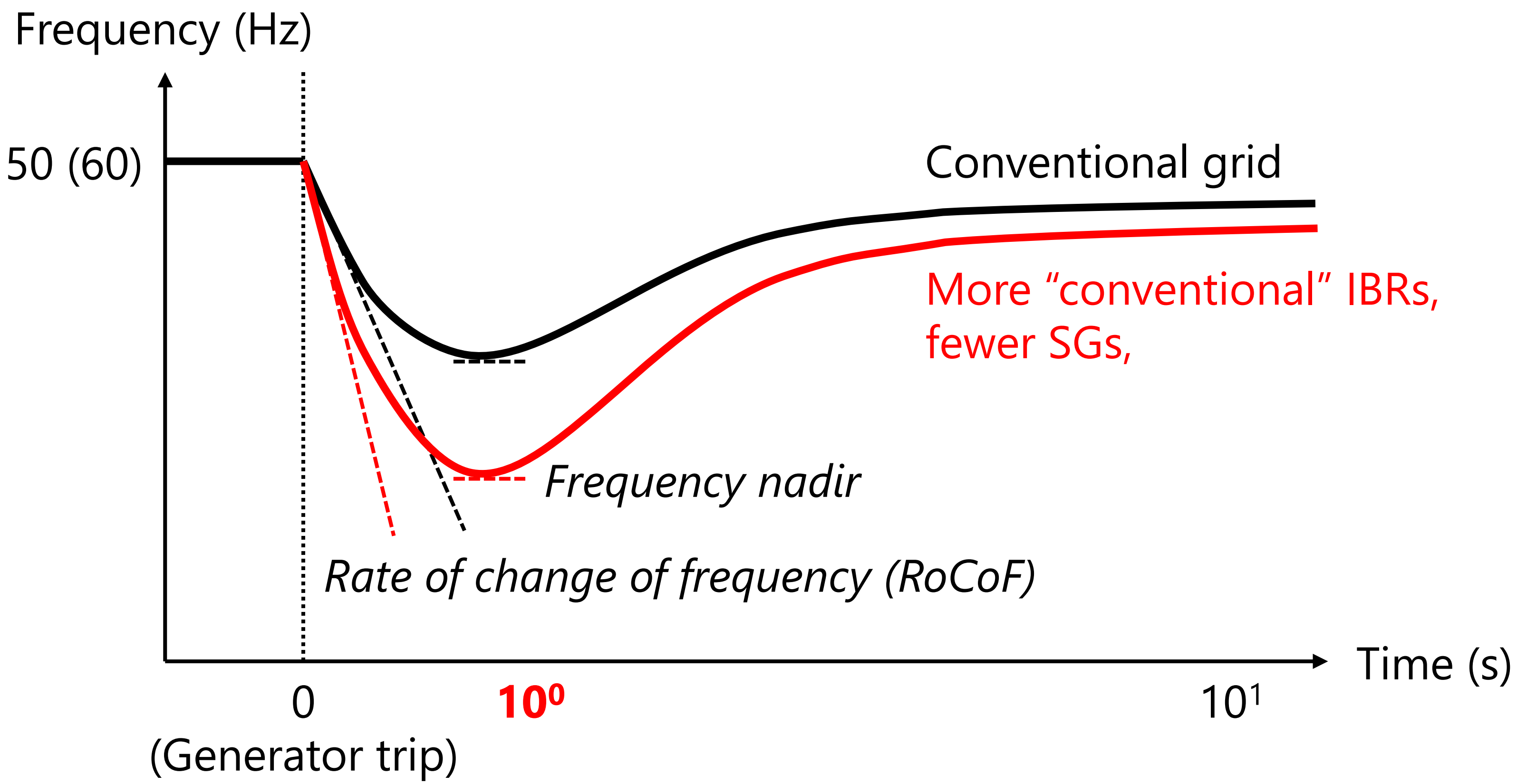
Inverter-based resources (IBRs) will increase, and synchronous generators (SGs) will decrease.



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, IEA. Licence: CC BY 4.0

IBRs are expected to replace some of services provided by SGs

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



AIST FREA

Changes in technical requirements due to increase in IBRs

Evolution of grid support functions

Low

IBR penetration

High

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

AIST FREA

Significant increase in inverter test items

1547 Content Growth

	1st Edition		2nd Edition
1547 technical content:	13 pages	→	127 pages
1547.1 technical content:	54 pages	→	256 pages

New/significantly modified 1547-2018 content in red:

4. General interconnection technical specifications and requirements
- 4.2 Reference points of applicability
- 4.3 Applicable voltages
- 4.4 Measurement accuracy
- 4.5 Cease to energize performance requirement
- 4.6 Control capability requirements
- 4.7 Prioritization of DER responses
- 4.8 Isolation device
- 4.9 Inadvertent energization of the Area EPS
- 4.10 Enter service
- 4.11 Interconnect integrity
- 4.12 Integration with Area EPS grounding
- 4.13 Exemptions for Emergency Systems and Standby DER

5. Reactive power capability and voltage/power control requirements
- 5.2 Reactive power capability of the DER
- 5.3 Voltage and reactive power control
- 5.4 Voltage and active power control

6. Response to Area EPS abnormal conditions
- 6.2 Area EPS faults and open phase conditions
- 6.3 Area EPS reclosing coordination
- 6.4 Voltage
- 6.5 Frequency
- 6.6 Return to service after trip

7. Power quality
- 7.1 Limitation of dc injection
- 7.2 Limitation of voltage fluctuations induced by the DER
- 7.3 Limitation of current distortion
- 7.4 Limitation of overvoltage contribution

8. Islanding
- 8.1 Unintentional islanding
- 8.2 Intentional islanding

9. DER on distribution secondary grid/area/street (grid) networks and spot networks
- 9.1 Network protectors and automatic transfer scheme requirements
- 9.1 Distribution secondary grid networks
- 9.2 Distribution secondary spot networks

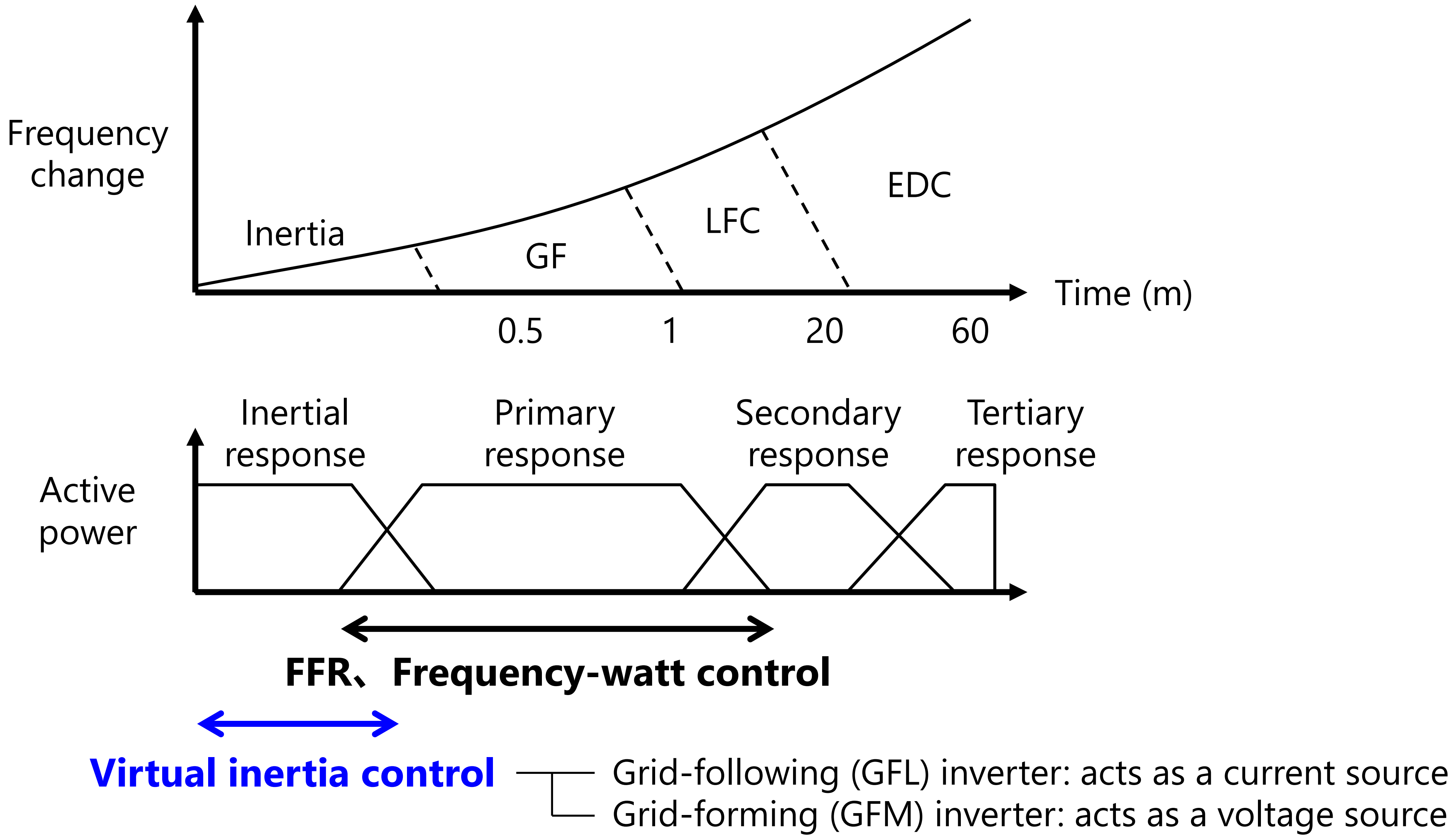
10. Interoperability, information exchange, information models, and protocols
- 10.1 Interoperability requirements
- 10.2 Monitoring, control, and information exchange requirements
- 10.3 Nameplate information
- 10.4 Configuration information
- 10.5 Monitoring information
- 10.6 Management information
- 10.7 Communication protocol requirements
- 10.8 Communication performance requirements
- 10.9 Cyber security requirements

11. Test and verification requirements
- 11.2 Definition of test and verification methods
- 11.3 Full and partial conformance testing and verification
- 11.4 Fault current characterization

NREL | 5

Source: A. Hoke, "DER Testing and Verification - Overview of IEEE P1547.1," PJM Technical Workshop on DER Integration, 2019

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

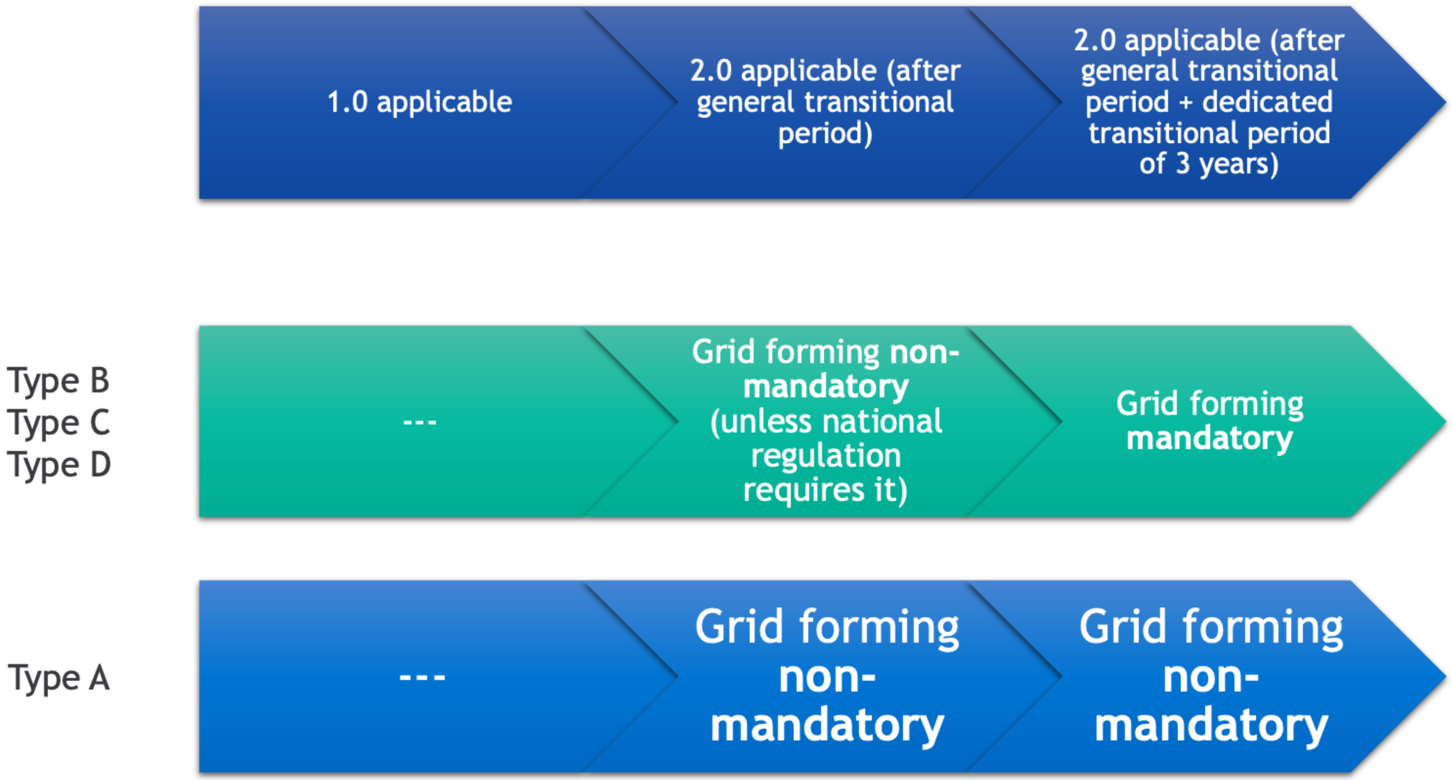


AIST FREA

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

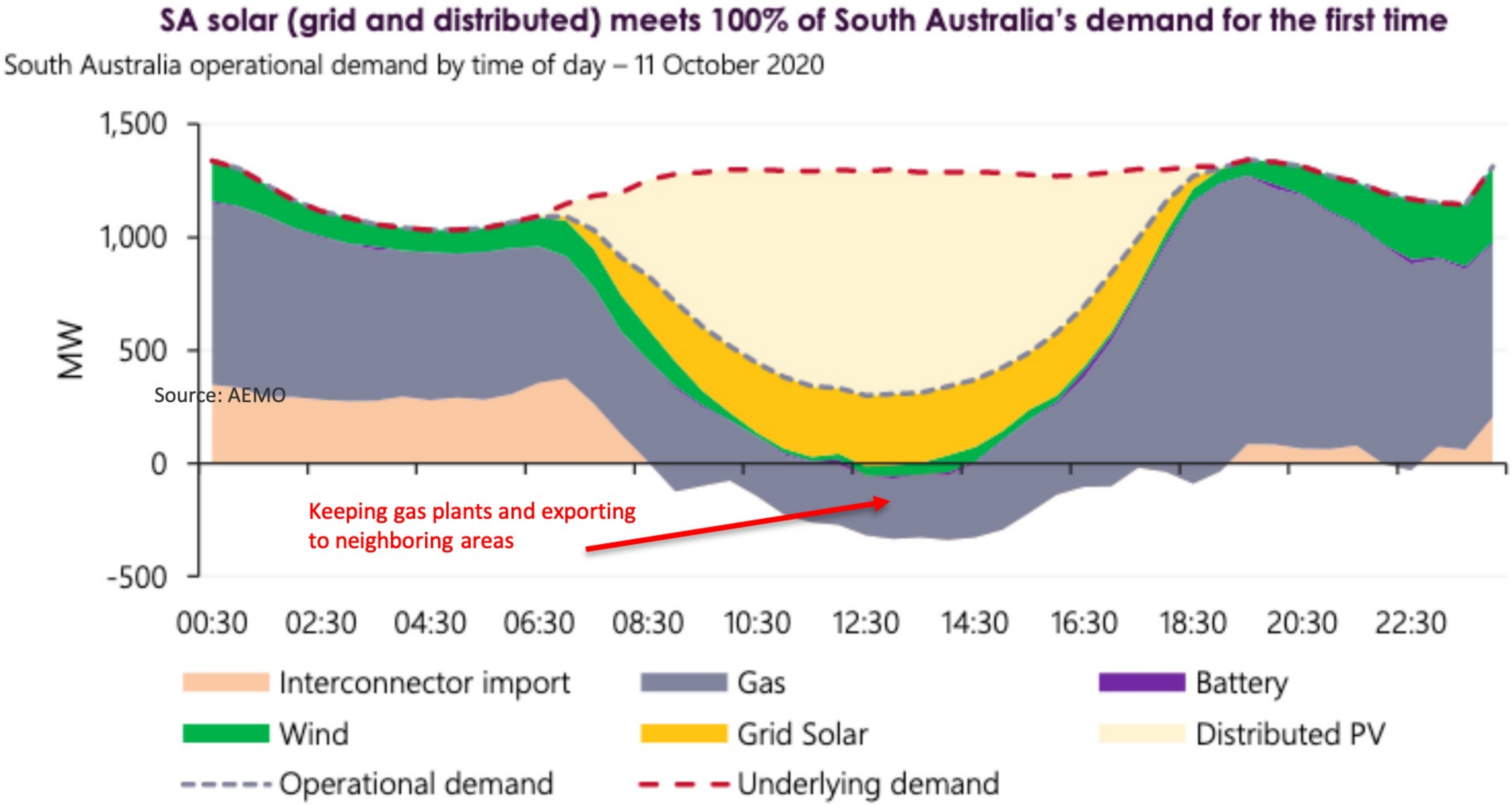
NC RfG 2.0 / Grid forming new Article



entsoe 6

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

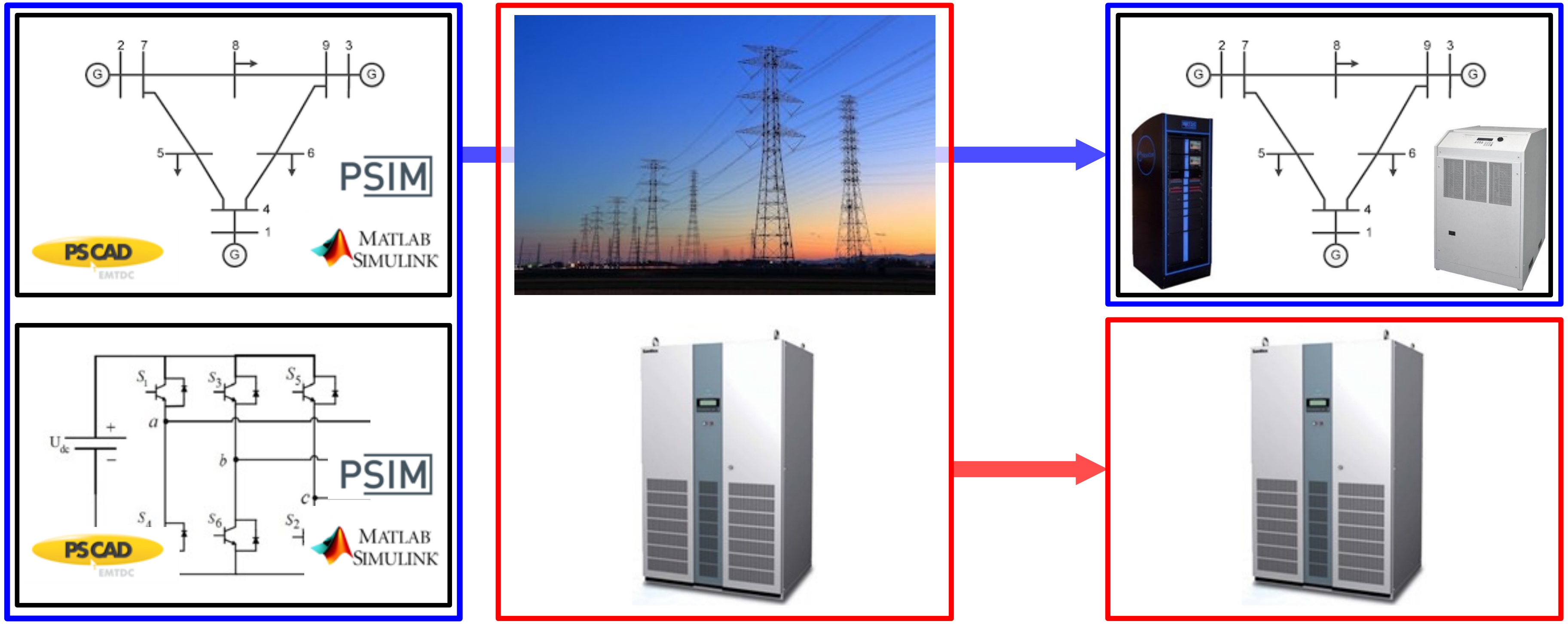
South Australia – Already at 100% IBR (but…)



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

PHIL testing is a flexible and reliable testing method

	Simulation	Demonstration	**Power hardware-in-the-loop (PHIL) testing**
Grid			
Inverter			



	Simulation	Demonstration	PHIL testing
Flexibility (Grid)	**High**	Low	High
Fidelity (Inverter)	Low	**High**	High

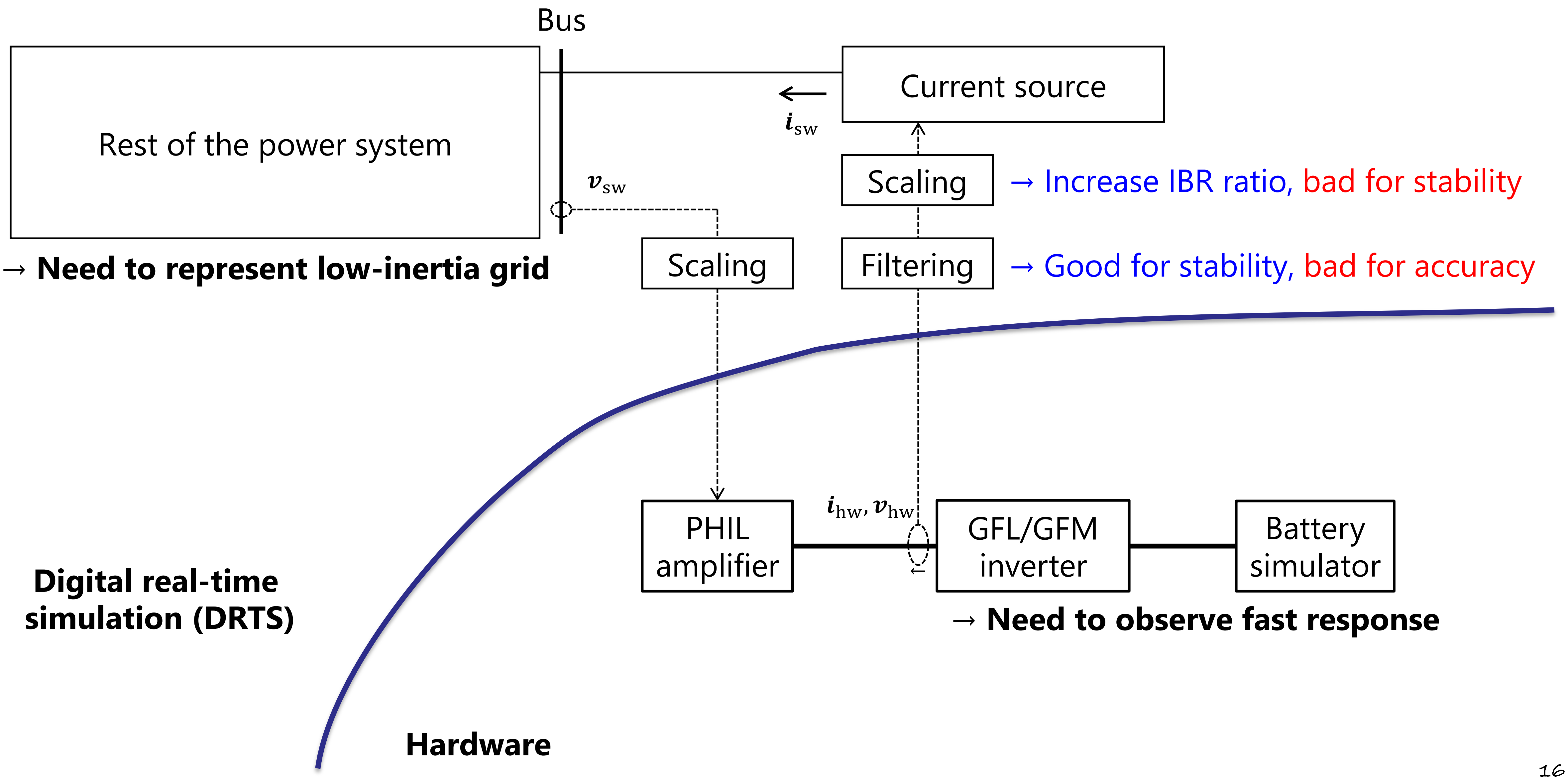
PHIL Testing for GFL and GFM Inverters with Virtual Inertia

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 f-P droop	df/dt-P droop f-P droop	VSM Q-V droop	P-f droop Q-V droop	VSM Q-V droop
Rated capacity (kVA)	20	49.9	12	20	50
Rated AC voltage (V)	200	200	420	200	440



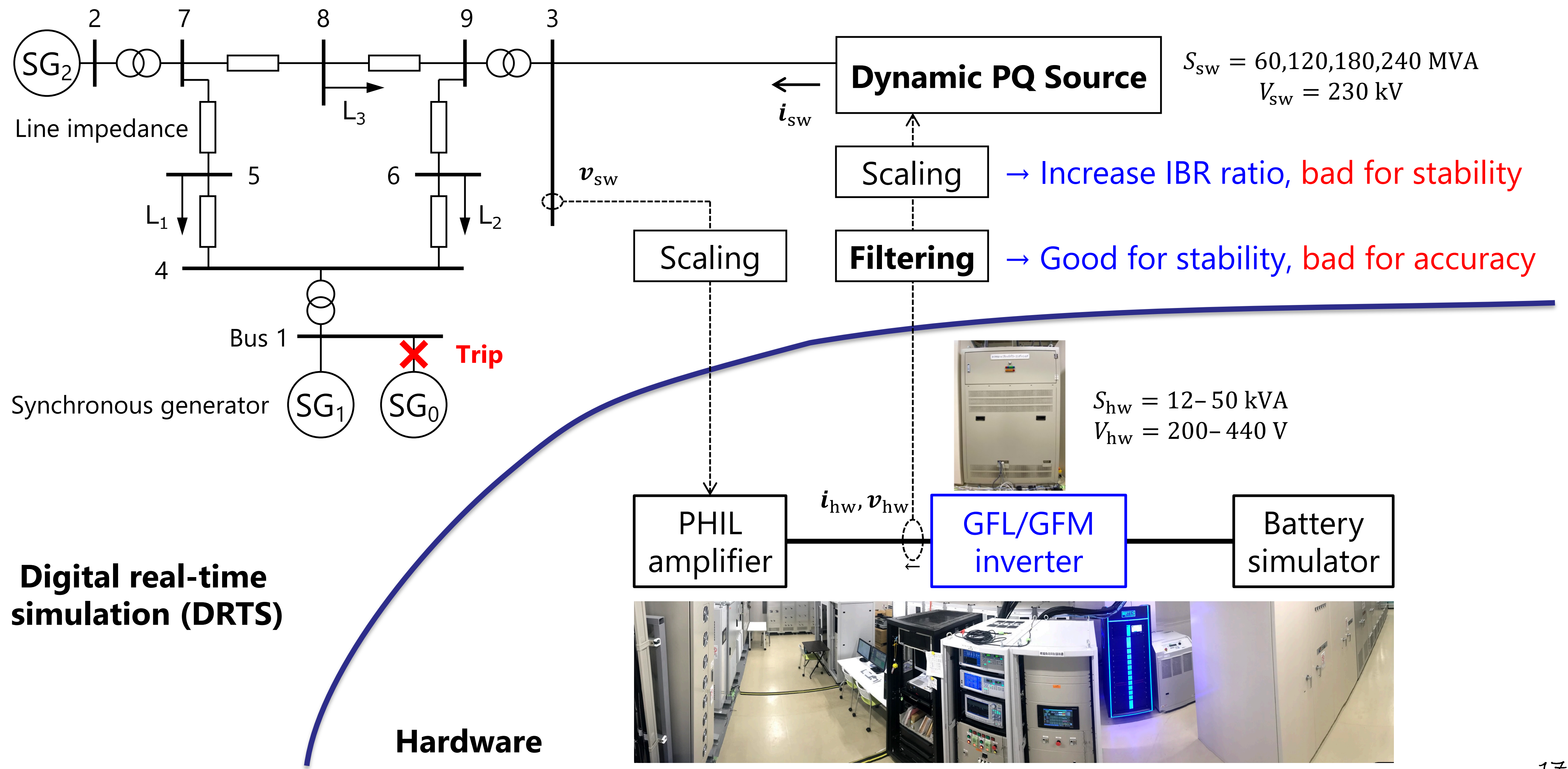

Challenge to build stable and accurate PHIL environment of low-inertia grid



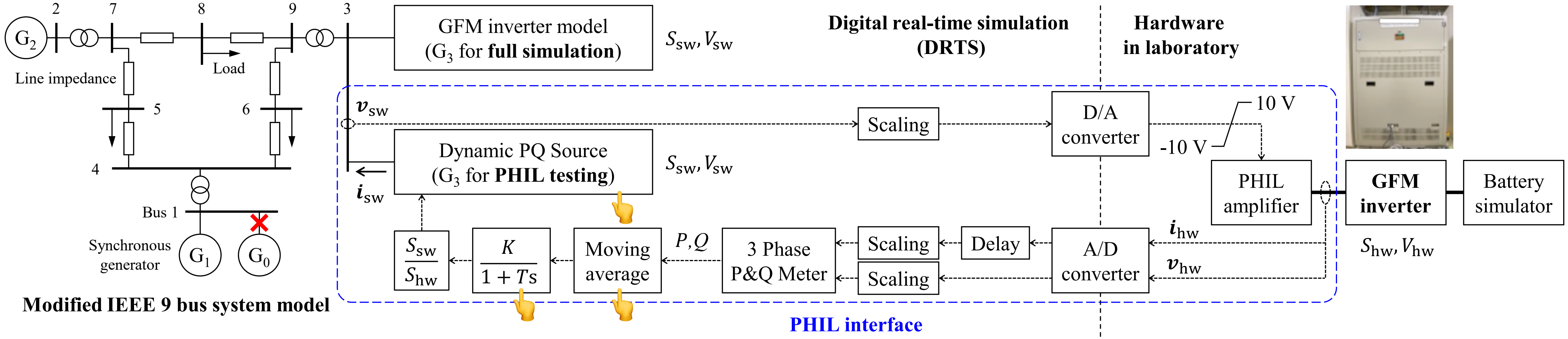
AIST FREA

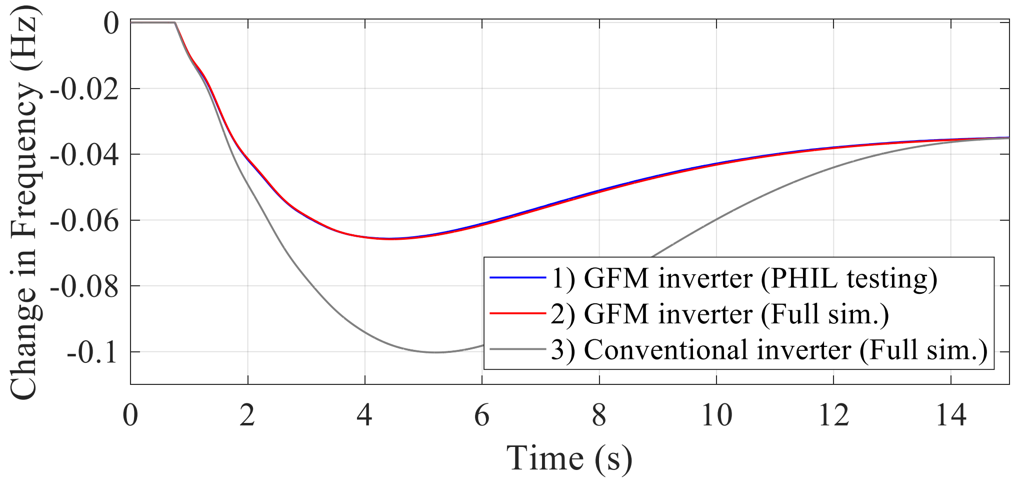
Test setup for GFL/GFM inverters using modified IEEE 9-bus system model

Modified IEEE 9-bus system model (300 MW)

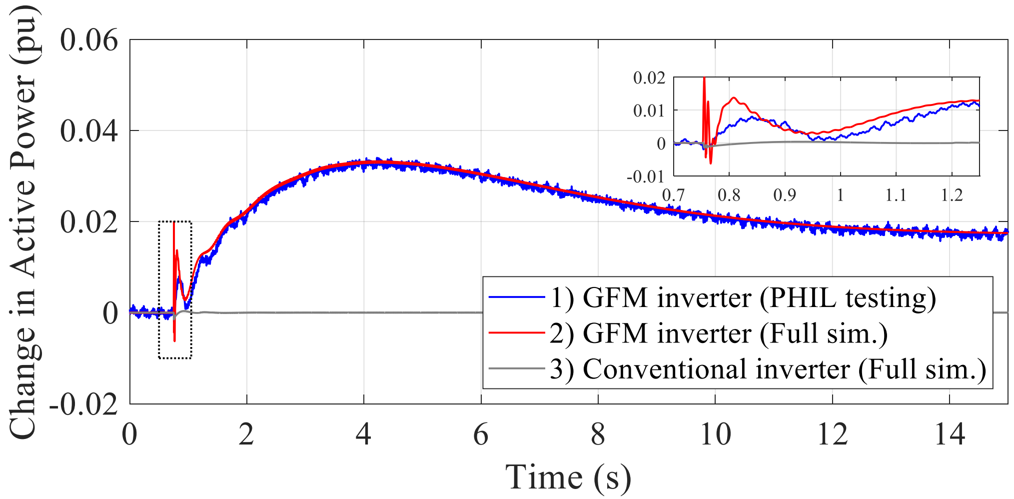


PHIL testing can be conducted stably in most cases with adequate accuracy





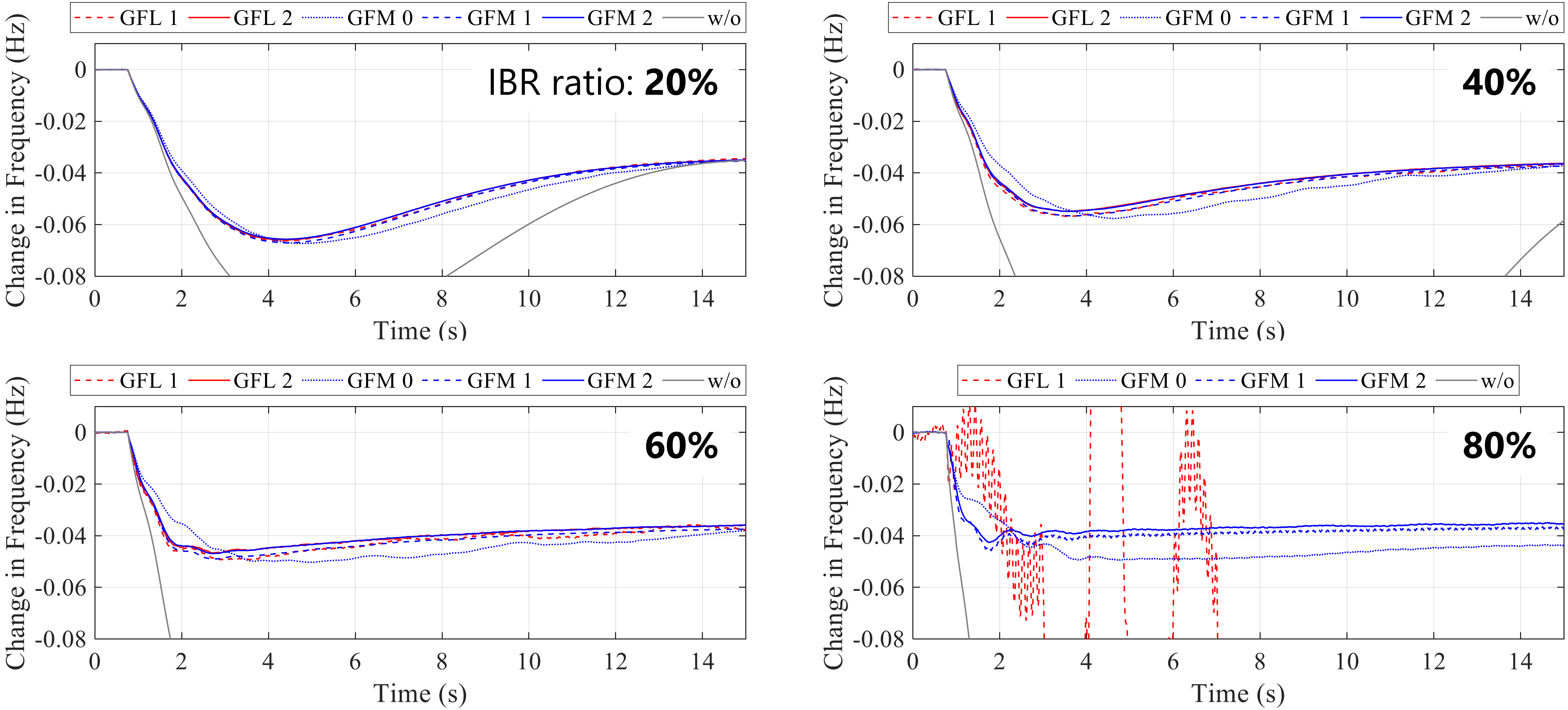
Frequency



Active power

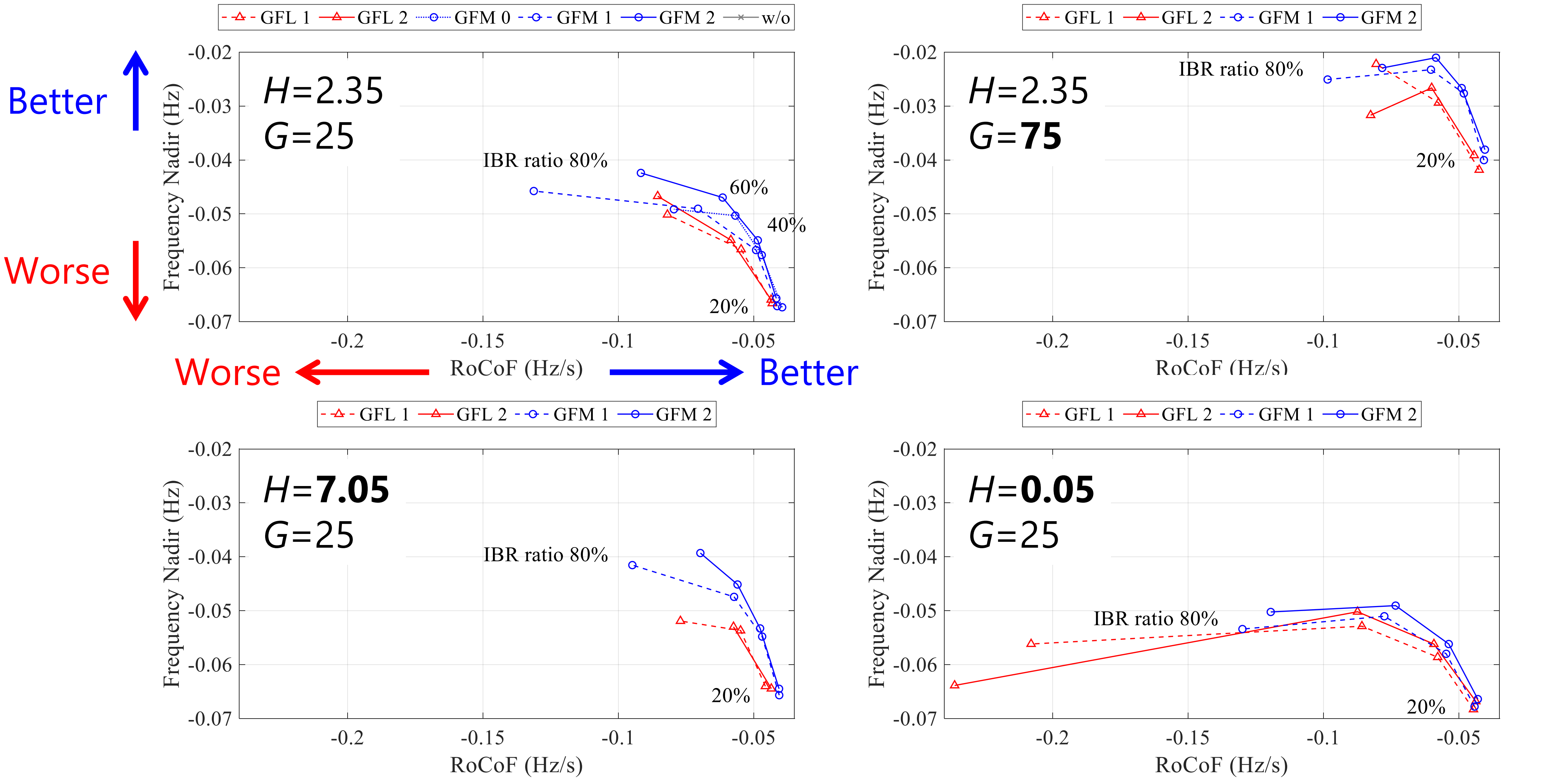
Source: H. Kikusato, et al., "Verification of Power Hardware-in-the-Loop Environment for Testing Grid-Forming Inverter," Energy Reports 2023, 9 (supplement 3), 303–311.

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



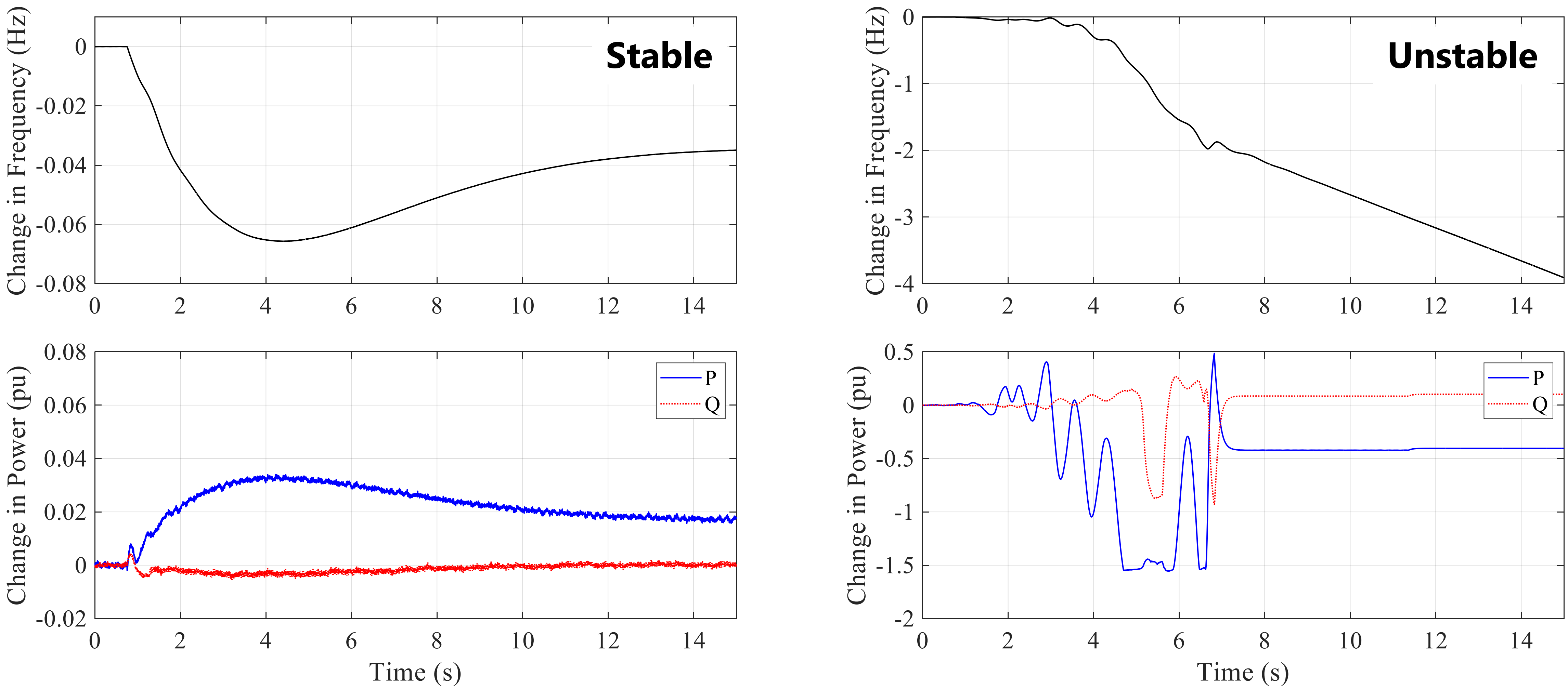
Source: H. Kikusato, et al., "Performance Evaluation of Grid-Following and Grid-Forming Inverters on Frequency Stability in Low-Inertia Power Systems by Power Hardware-in-the-Loop Testing," Energy Reports 2023, 9 (supplement 1), 381–392.

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.

Interference occurs between islanding detection and frequency stabilization capability in GFM inverter

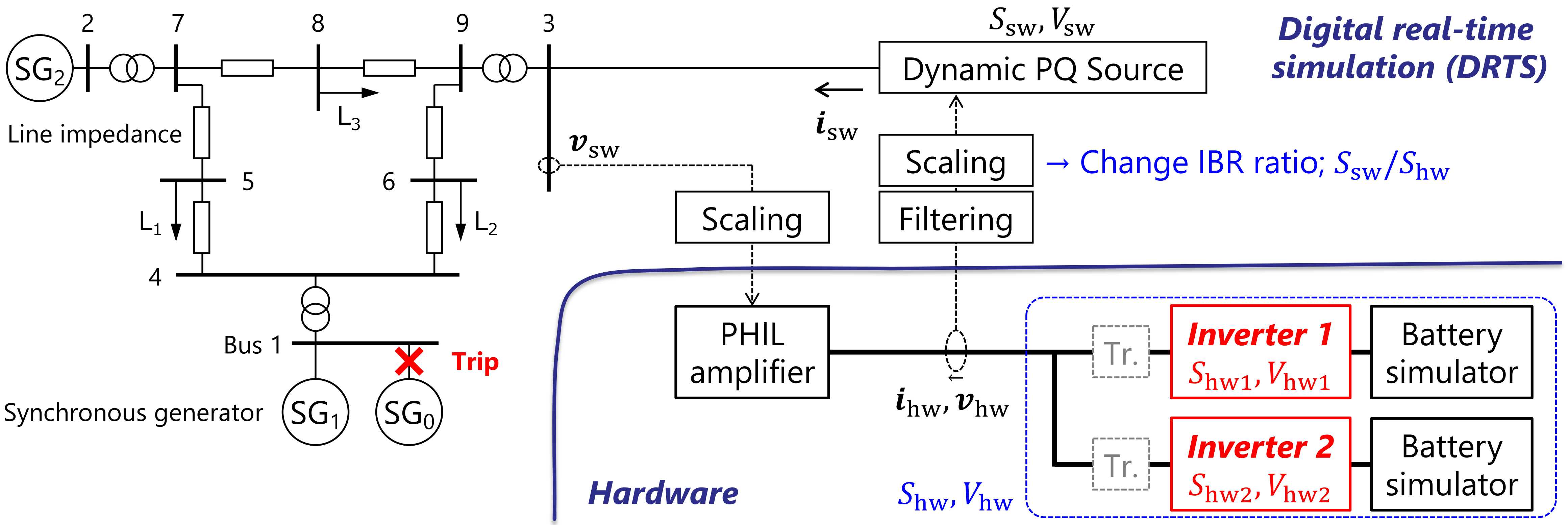


Disable islanding detection

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.

PHIL testing for multiple inverter combinations



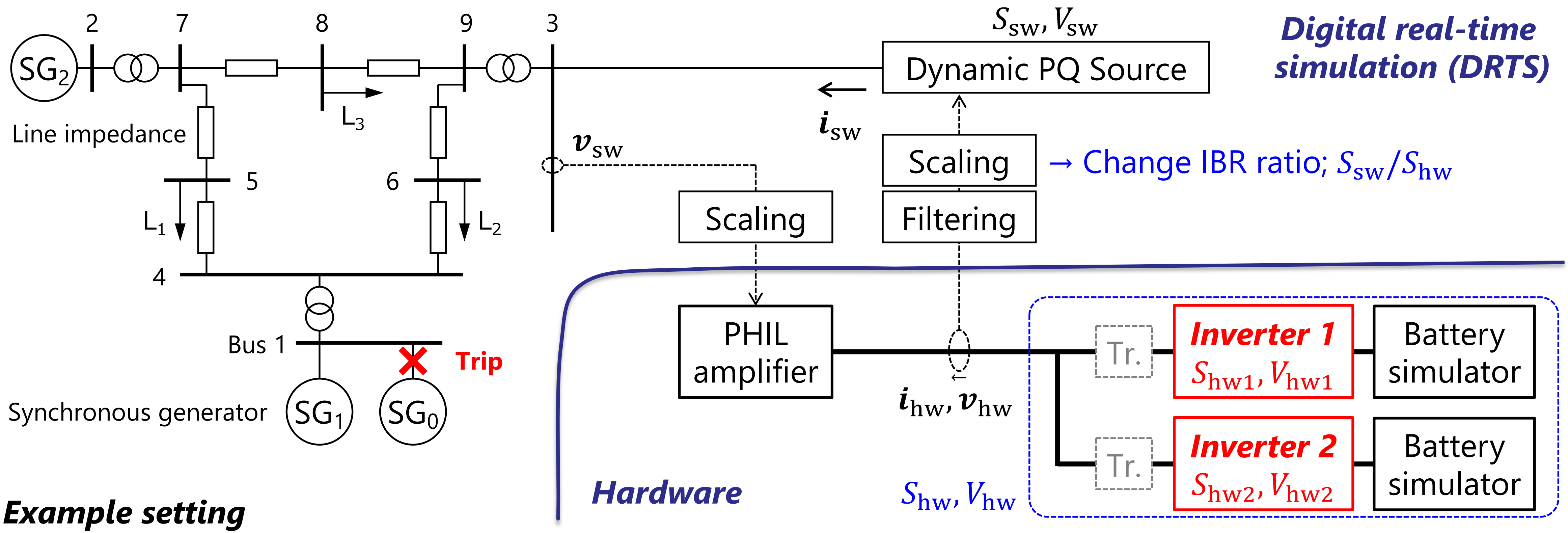
How do we test multiple inverters with different ratings?

▼

Equalize rated capacities, voltages, and control parameters

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.

Configuration of PHIL testing for multiple inverters

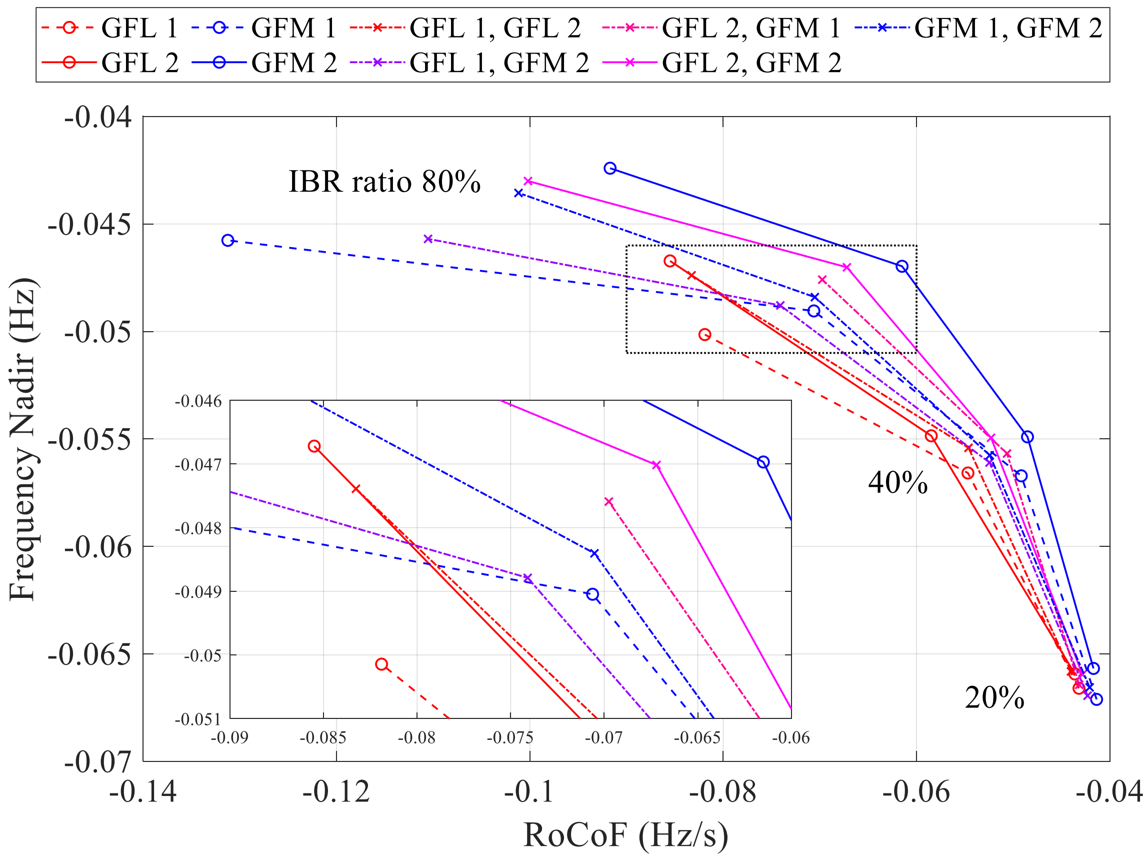


Example setting

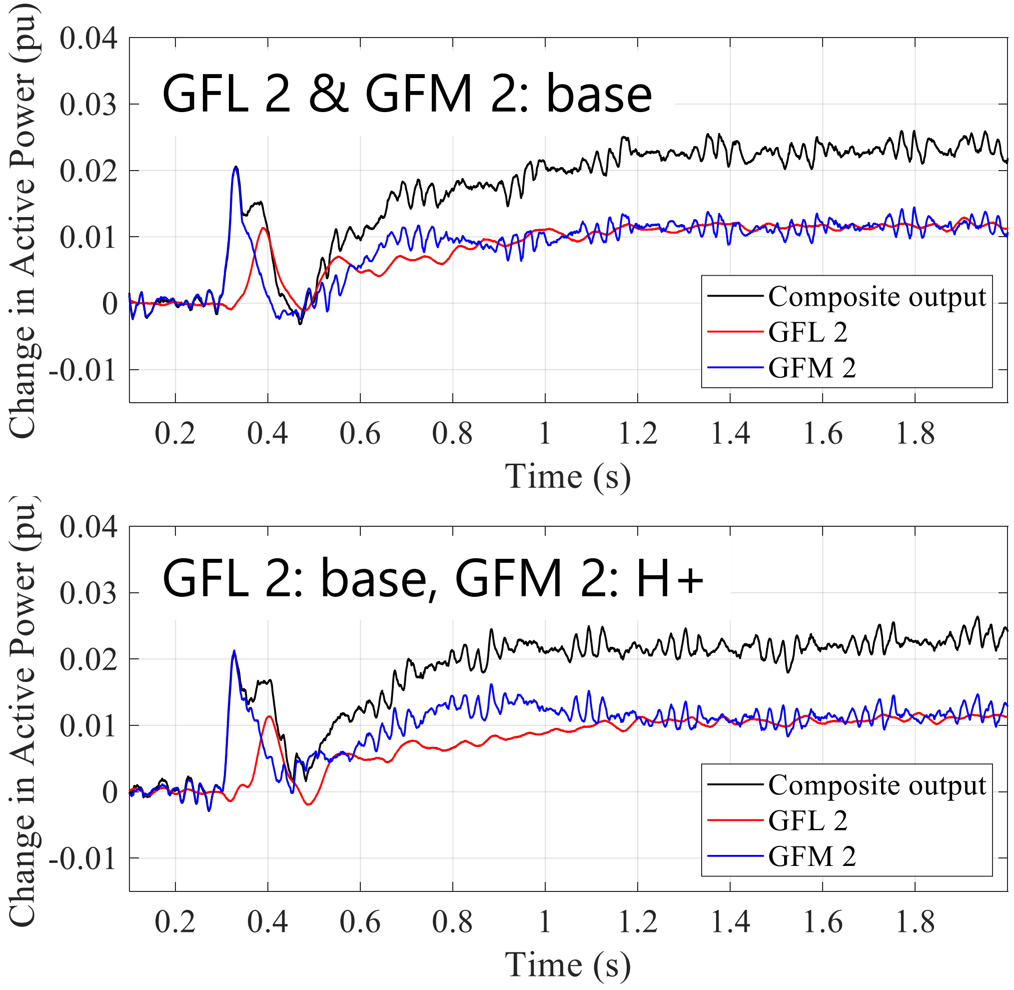
Inverter 1	$S_{hw1} = 20\ \text{kVA} \Rightarrow S'_{hw1} = 20\ \text{kVA}$	$V_{hw1} = 200\ \text{V} \Rightarrow$ use Tr.	$H'_1 = \frac{S'_{hw1}}{S_{hw1}} \times H_1, G'_1 = \frac{S'_{hw1}}{S_{hw1}} \times G_1$
Inverter 2	$S_{hw2} = 50\ \text{kVA} \Rightarrow S'_{hw2} = 20\ \text{kVA}$	$V_{hw2} = 440\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

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.

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.

Summary

- PHIL testing is a powerful evaluation method for IBR dominant power systems
  - Can observe the interaction between IBRs and power systems
  - Can model various power systems and test inverter hardware (flexibility & fidelity)

- Conducted PHIL testing with IEEE 9-bus system model for five GFL and GFM inverters from different manufacturers
  - As the IBR ratio increased, frequency change increased for conventional IBR, decreased for GFL and GFM inverters. GFM inverters were stable at 80%.
  - No inverter combination caused interference that significantly worsened the grid frequency stability. Combined inverters' performance was intermediate between the performance of each inverter alone.

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

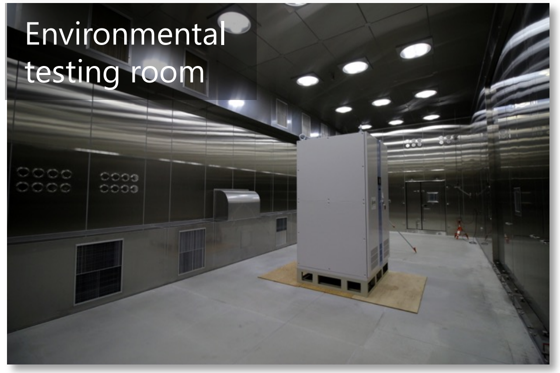
Appendix

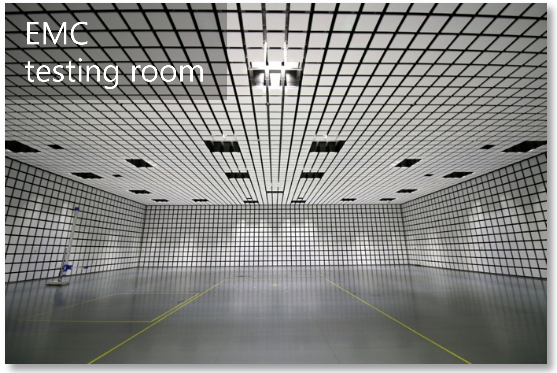
Related Works

- 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.

Smart System Research Facility called "FREA-G"

- Established in 2016 for testing large-size grid-connected inverters
- Testing capability
  - Grid simulator: AC 5 MVA (1.67 MVA × 3 units)
  - PV/battery simulator: DC 3.3 MVA, 2000 V
  - Grid interconnection testing room (L, M, S)
  - Environmental testing room: -40 to +85°C, 30 to 90%RH
  - EMC testing room: 34 m×34 m×7.8 m, largest in Japan





Source: https://www.aist.go.jp/fukushima/ja/outline/smart_system/index.html

Power System Laboratory (Movie)

- AC source
  - Grid simulator: 500 kVA, 30 kVA
- DC source
  - PV simulator: 600 kW
  - Batter simulator: 207 kW
  - Lithium-ion battery: 16 kWh
- Inverter
  - GFM (VSG control)
  - GFL (smart inverter, virtual inertia, etc.)
- Digital real-time simulator (DRTS)
  - RTDS Technologies: NovaCor, PB5
  - Typhoon HIL: HIL604
- RLC load: 200 kVA
- Data acquisition system
- Connectivity to demonstration field