This study was based on the results obtained from a project commissioned by the New Energy and Industrial Technology Development Organization (NEDO), no. JPNP19002. We would like to thank the inverter manufacturers, M. Suzuki, S. Sugahara, and M. Takahashi, for their grateful cooperation in the testing.

Performance Analysis of Grid-Forming Inverters in Existing Conformance Testing

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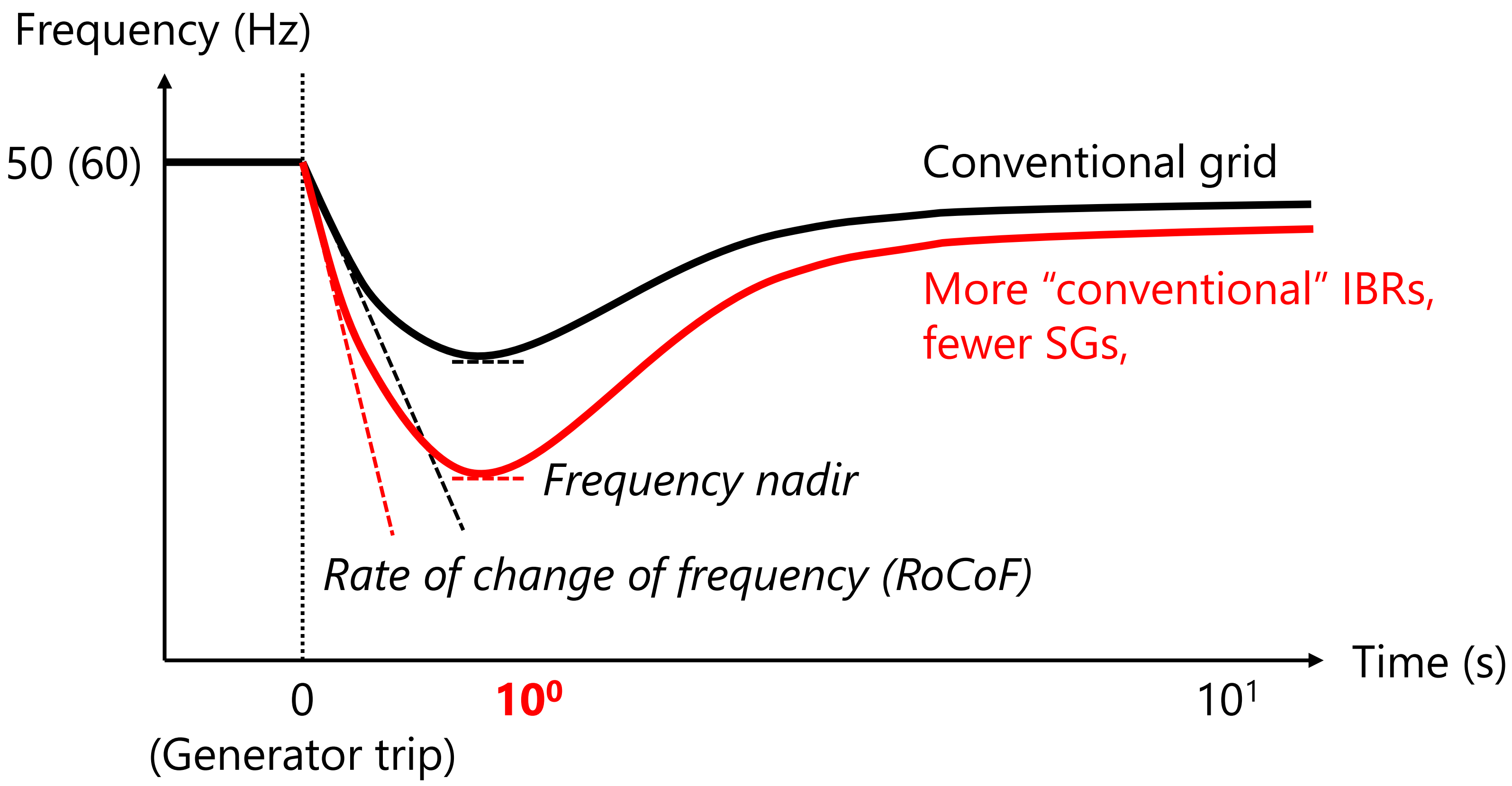
IBR is Alternative to Provide FFR Capability in Low-Inertia Grid

- Fast frequency response (FFR) capability of synchronous generator (SG) needs to be alternated in power system with high penetration of inverter based-resources (IBRs)
- IBR itself is expected as an option to provide FFR



IBR's FFR Capability may Conflict with Protective Functions

- FFR capability of IBR
  - Responds to changes in grid voltage (V, f, ϕ)
    - Grid-following (**GFL**) inverter acts as a **current source** and responds to **frequency** changes
    - Grid-forming (**GFM**) inverter acts as a **voltage source** and responds to changes in **grid voltage (V, f, ϕ)**
  - Has fast response time within 1 s
    - Overlap with operating times of its protective functions
    - *Cf.* response time of smart inverter is a few to a few tens of seconds

- **Conventional conformance testing for protective functions has not been amended considering FFR capabilities**
  - *Cf.* IEEE 2800-2020 → IEEE P2800.2

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Applied Existing Japanese Conformance Testing on GFL and GFM inverter prototypes with FFR Capabilities

	GFL 1	GFL 2	GFM 0	GFM 1	GFM 2
FFR capability	df/dt-P droop f-P droop	df/dt-P droop f-P droop	VSM	P-f droop	VSM
Rated capacity (kVA)	20	49.9	12	20	50
Rated AC voltage (V)	200	200	420	200	440
Current limiting function	w/	w/	w/	w/o	w/

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Tests with Changes in Voltage Magnitude, Frequency, and Phase Angle

- **GFL** Inverters: Almost **Conformance** in All Tests
- **GFM** Inverters: **Non-Conformance** in Most Tests, **Three Issues** are 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.

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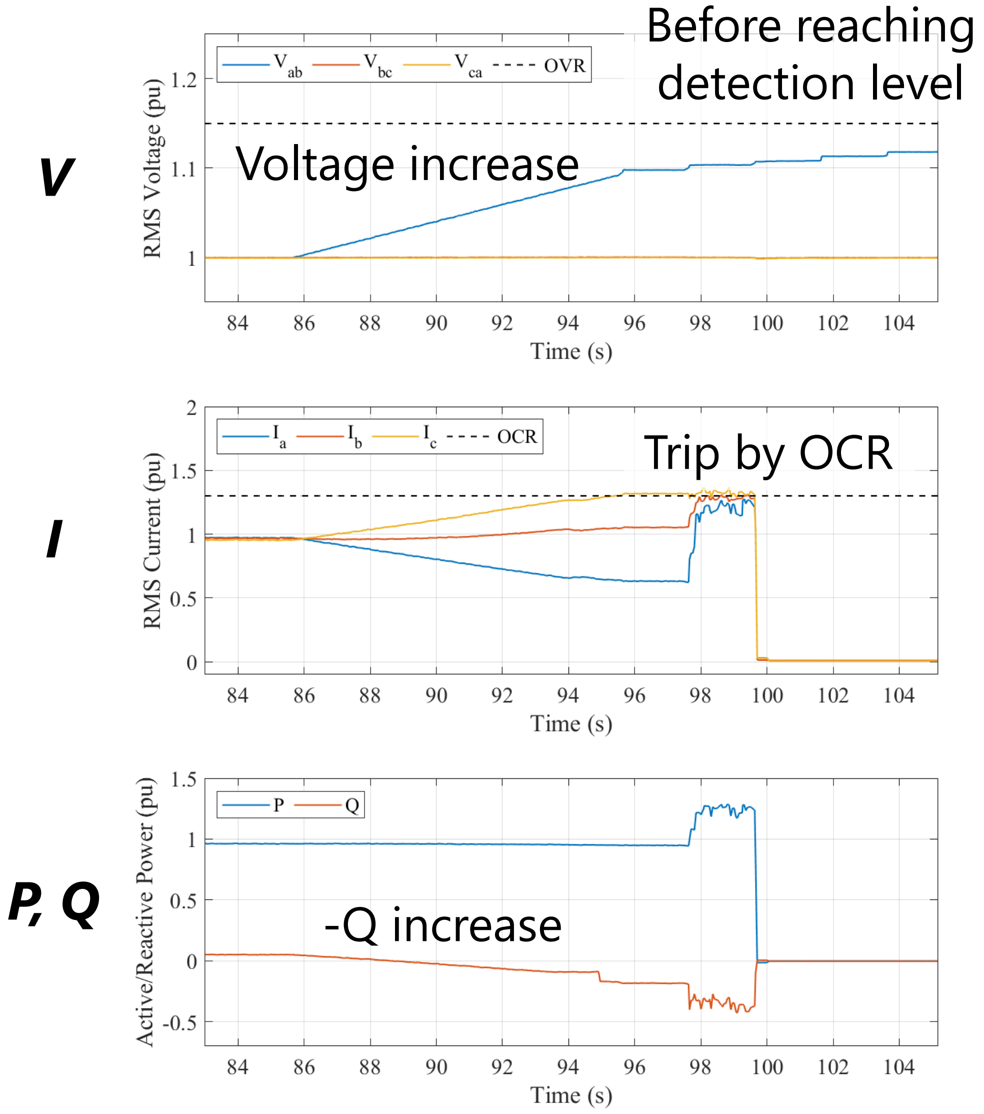
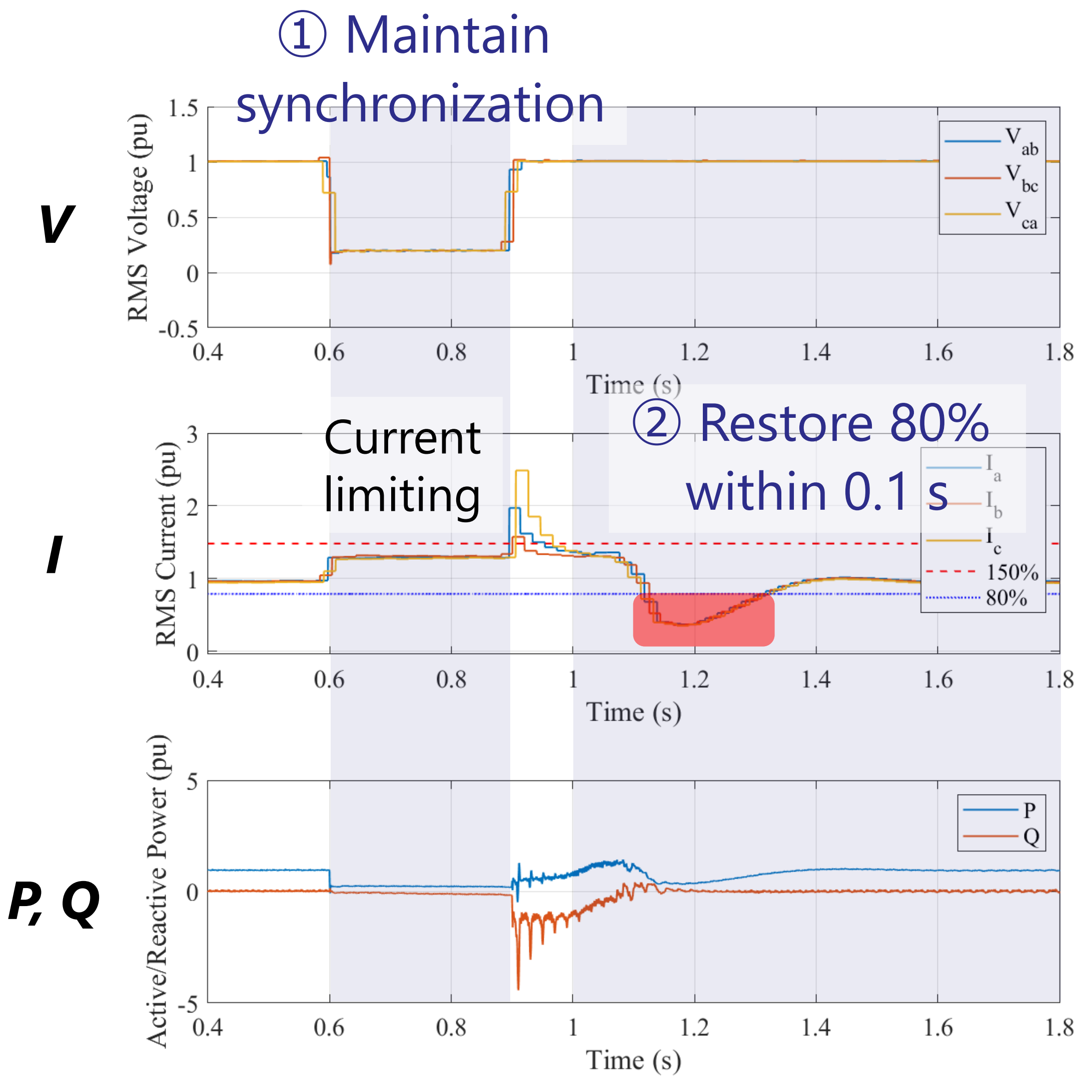
Issue 1: Unwanted Tripping by OCR due to Change in Grid Voltage



Test for over-voltage trip (GFM 0)

- Reason for non-conformance
  - Trip before initial state: #1, 2
  - Operation cannot continue: #4~7
- Reason for tripping due to OCR
  - GFM's voltage-source characteristic
  - No/short-term current limiting function
  - Initial P output setting was 1.0 pu
- Solution
  - Longer current limiting function
  - Decrease initial P output setting
  - Change control parameters

Issue 2: Active Power Swing after Recovery from Voltage Sag



Low-voltage ride-through test (GFM 0)

- Reason for non-conformance
  - ② is not satisfied
- Reason for active power swing
  - GFM's voltage-source characteristic
- Solution
  - Change control logic/parameters
  - **Change conformance criteria**
- Cf. Conformance criteria of active power swing after voltage recovery
  - Acceptable: IEEE 1547, IEEE 2800, National Grid
  - Not noted: EN50549

Issue 3: Coexistence of Grid Stabilization Capability and Islanding Detection

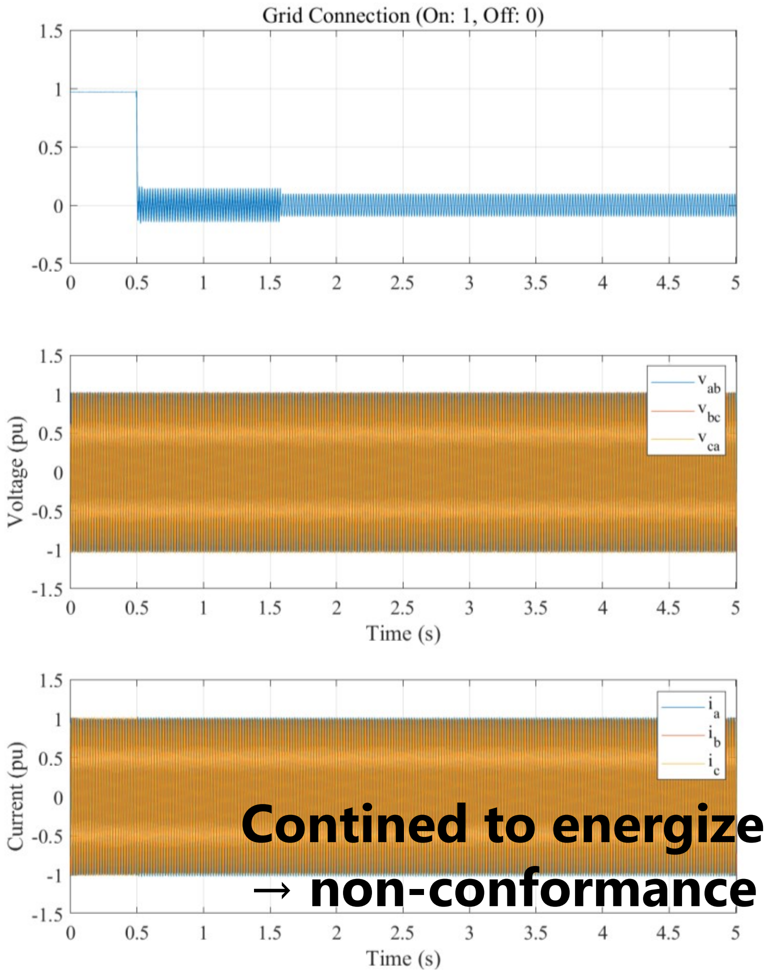
- **GFM 0**: not implemented, **GFM 1**: non-conformance but frequency was stabilized, **GFM 2**: conformance but frequency wasn't stabilized

Grid connection state

Unintentional islanding test result

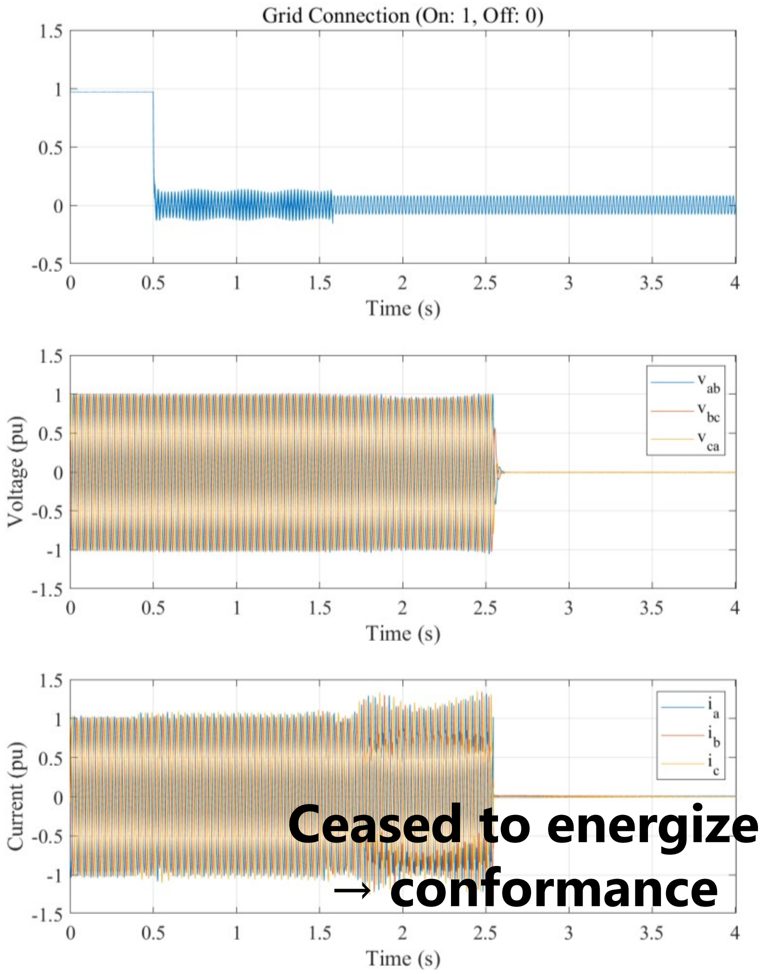
v

i



Contined to energize → non-conformance

GFM 1



Ceased to energize → conformance

GFM 2

Issue 3: Coexistence of Grid Stabilization Capability and Islanding Detection

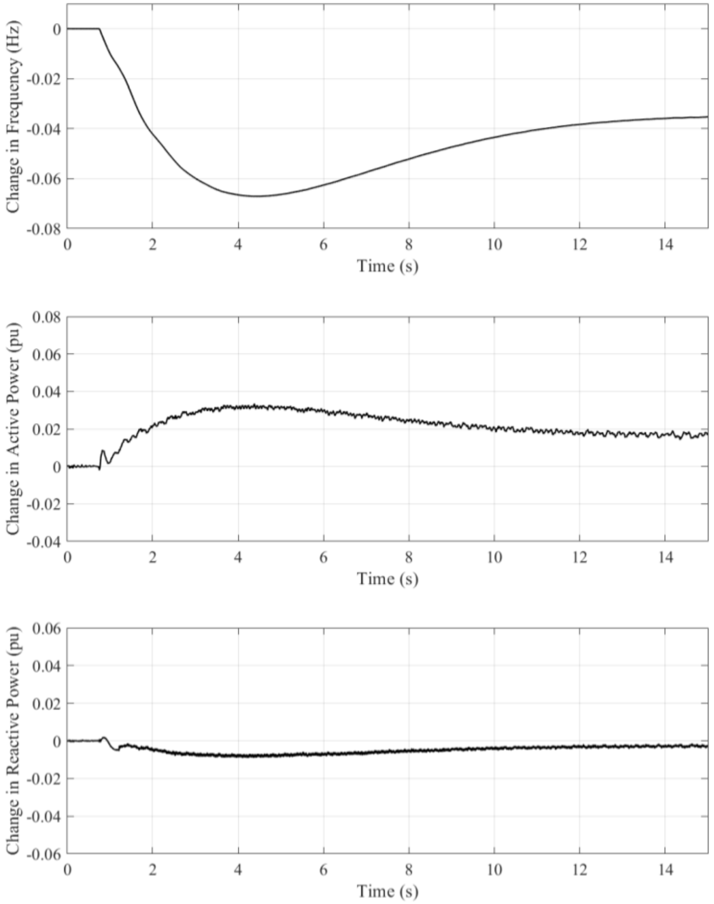
- **GFM 0**: not implemented, **GFM 1**: non-conformance but frequency was stabilized, **GFM 2**: conformance but frequency wasn't stabilized

PHIL test results activating IDM (Kikusato et at., 2022)

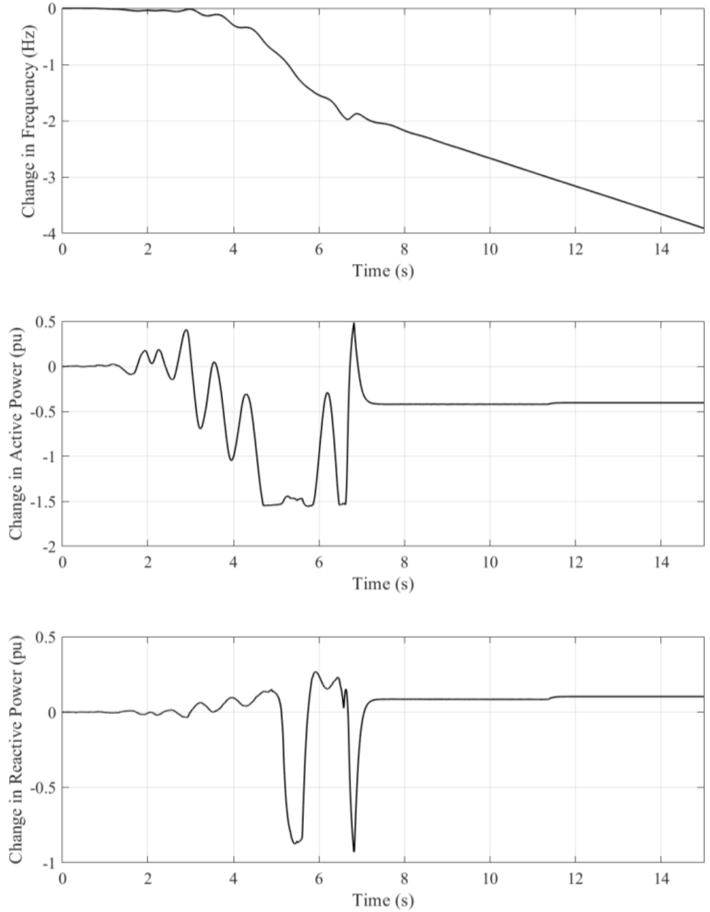
f

P

Q



GFM 1
Frequency was stable



GFM 2
Frequency was unstable

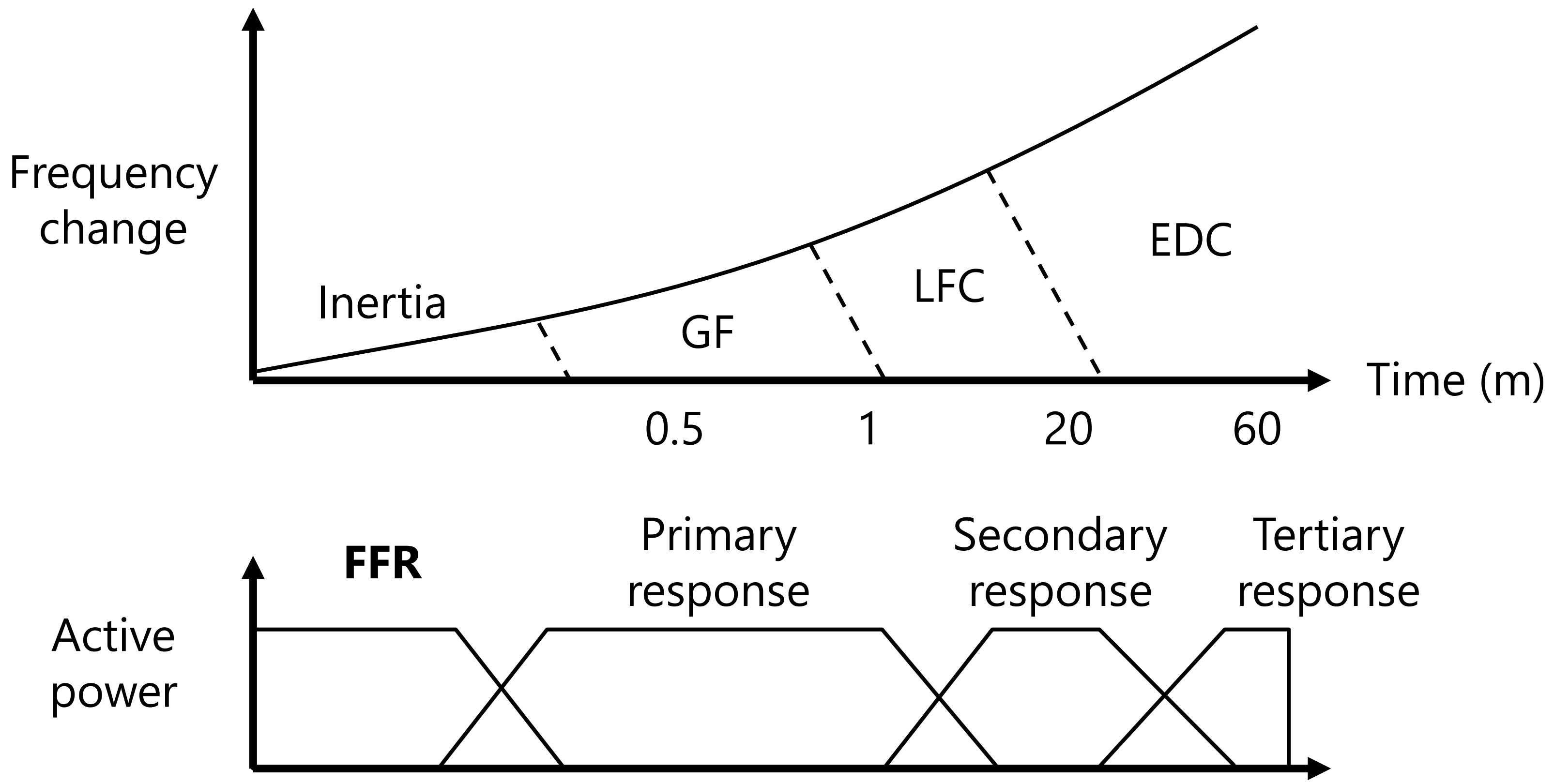
Summary

- Verified the effect of GFL/GFM inverters' FFR capabilities on protective functions
  - Conducted existing conformance testing with changes in grid voltage (V, f, ϕ)
  - **In most cases, CFLs were conformance, and GFMs were non-conformance**
- Identified **three issues on GFM inverters**
  - Issue 1: Unwanted tripping by OCR due to change in grid voltage
  - Issue 2: Active power swing after recovery from voltage sag
  - Issue 3: Coexistence of grid stabilization capability and islanding detection
- **GFM inverters, which have voltage source characteristics, were not considered in the existing conformance test**
  - Technical requirements and verification methods for GFM inverters should be determined
  - Protective functions developed for GFL inverters may be modified for GFM inverters

Appendix

GFMI is an Alternative to Provide FFR Capability in Low-Inertia Grid

- Fast frequency response (FFR) capability of synchronous generator (SG) needs to be alternated in power system with high penetration of inverter based-resources (IBRs)
- Grid-forming inverter (GFMI) is an option for providing FFR



GFL and GFM inverters' transient response after grid voltage change

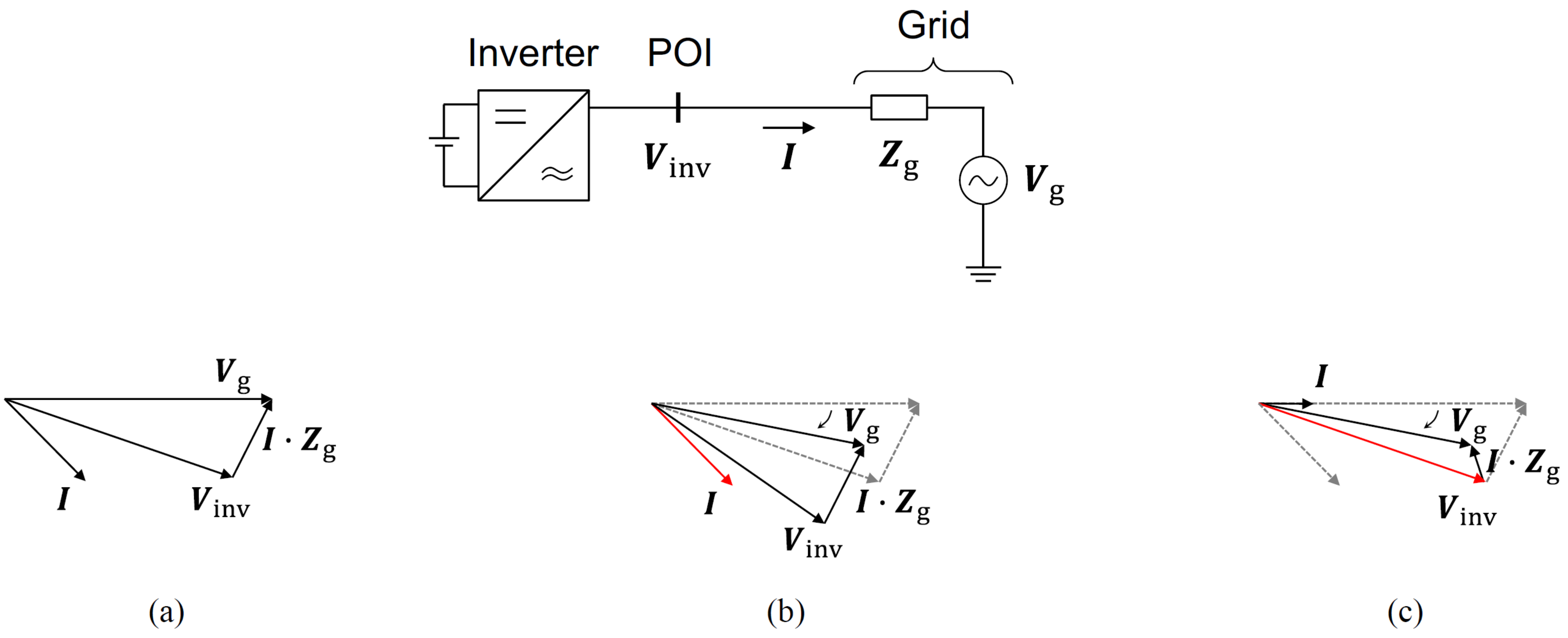


Fig. 2. Phase angle diagram of (a) both types of inverters in stable condition before a change in grid voltage; (b) a GFL inverter during and immediately after a change in grid voltage; (c) a GFM inverter during and immediately after a change in grid voltage.

FFR Capabilities of GFL and GFM inverters

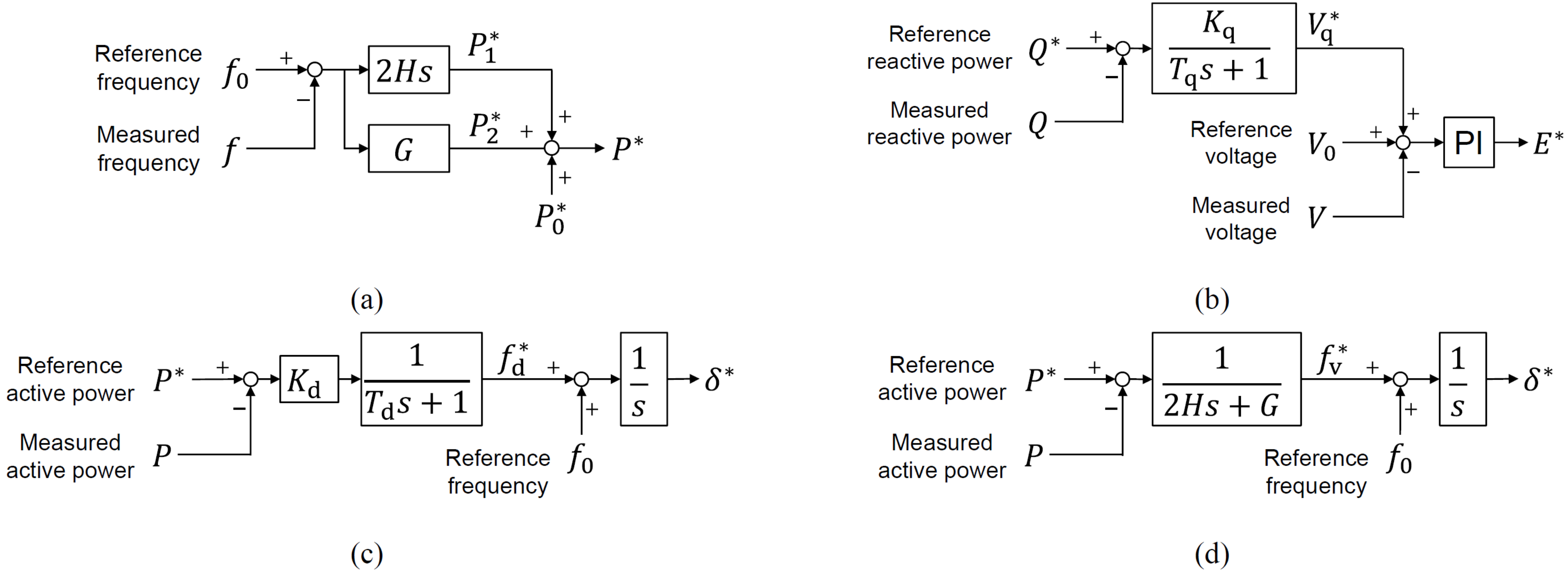


Fig. 4. Generalized control block diagrams of (a) the frequency control implemented in GFL 1 and GFL 2; the voltage phase angle control implemented in (b) GFM 0, GFM 2; and (c) GFM 1; (d) the voltage magnitude control implemented in GFM 0, GFM 1, and GFM 2.

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

Test Setup

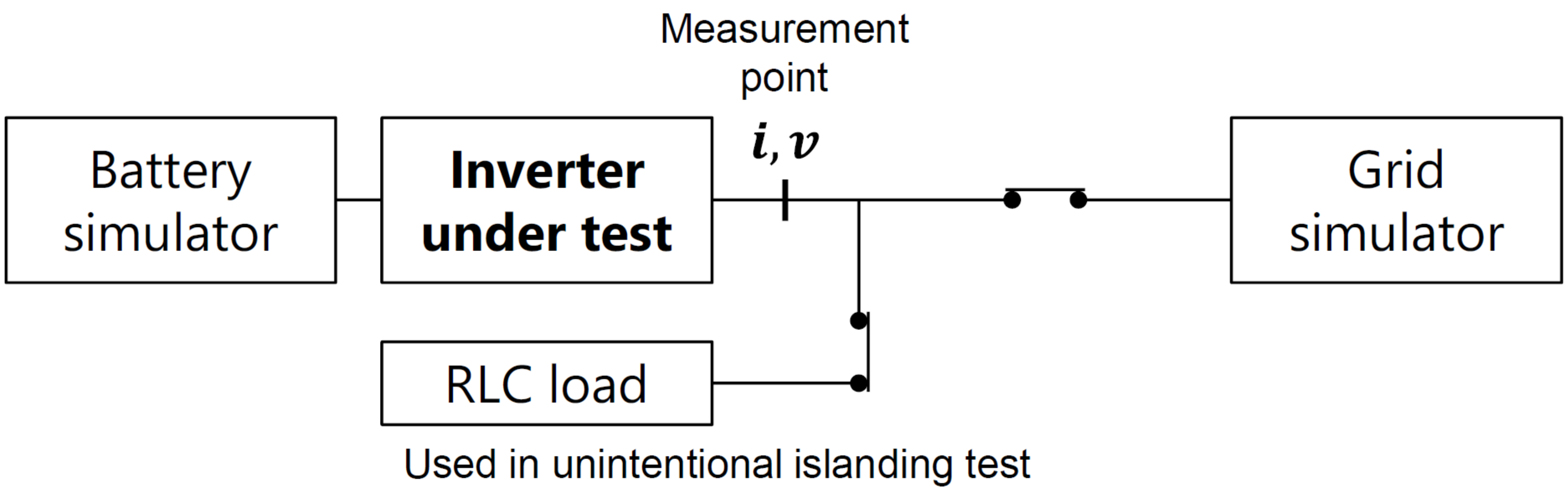
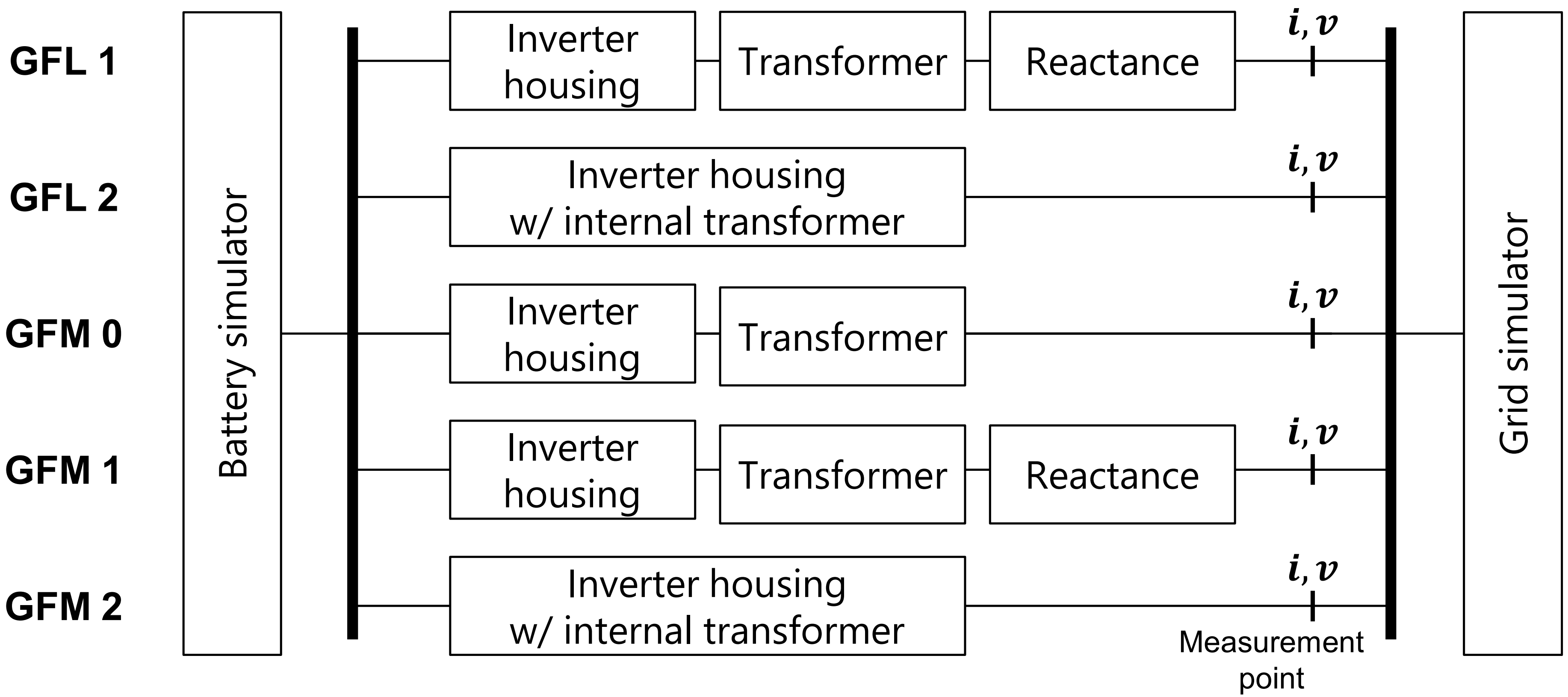


Fig. 5. Schematic diagram of the device connection configuration.

Detailed Connection Configuration of Each Inverter Under Testing



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Laboratory Photos