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Performance Evaluation of Grid-Following and Grid-Forming Inverters on Frequency Stability in Low-Inertia Power Systems by Power Hardware-in-the-Loop Testing

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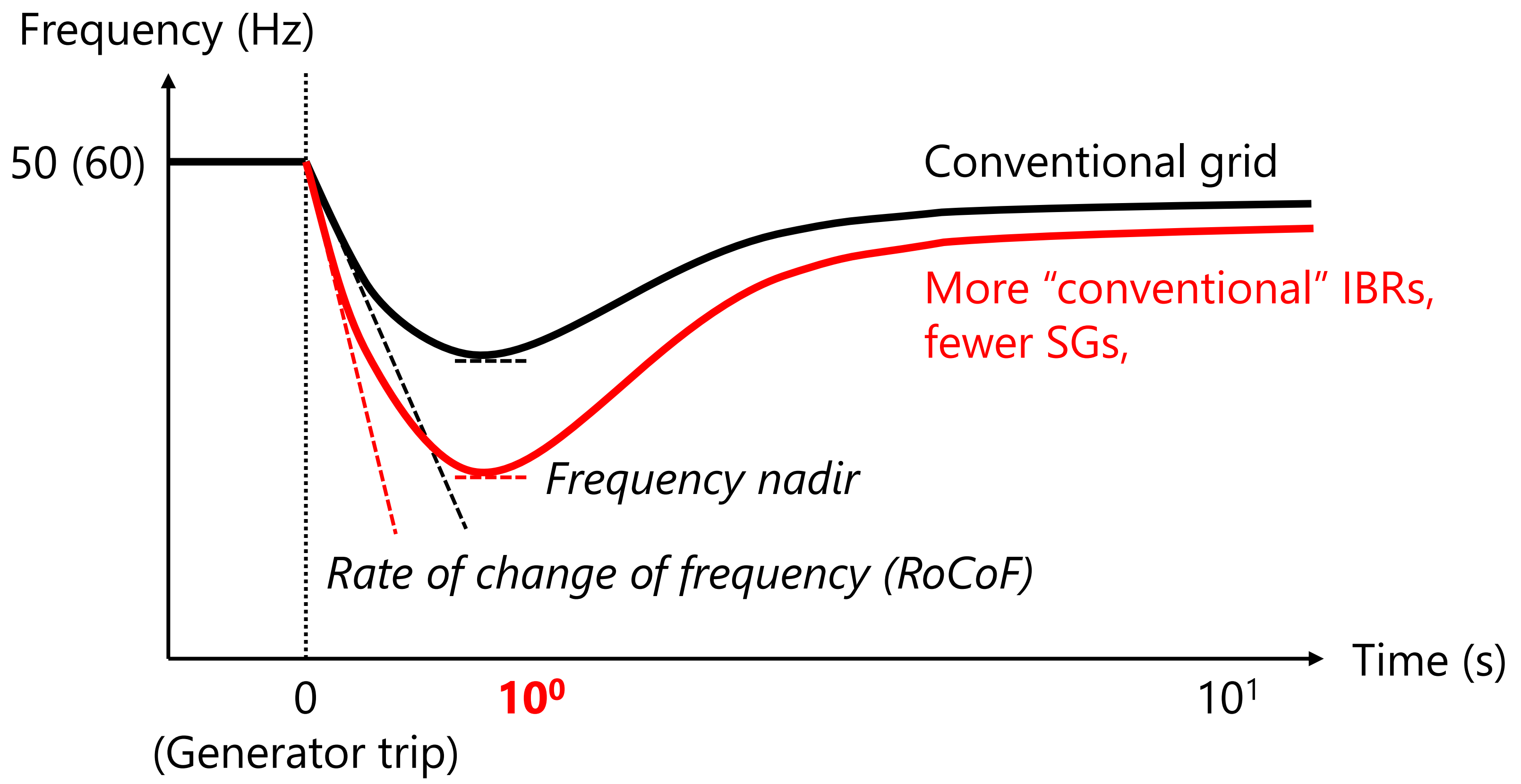
IBR is Expected to Replace Some of Services provided by SG

- Reducing the number of synchronous generators (SGs) decline grid frequency stability
- Frequency control including **inertial response** is required for inverter based-resources (IBRs)
- Their performance in hardware has not been discussed well

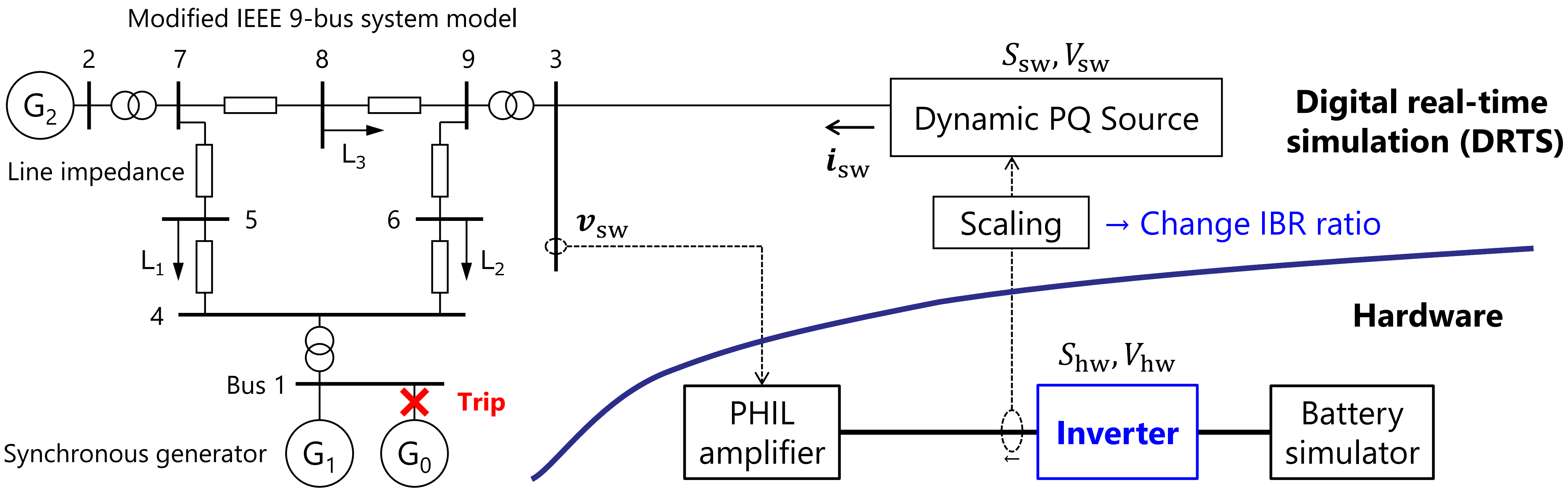


Tested Five Inverter Prototypes with Advanced Control Functions

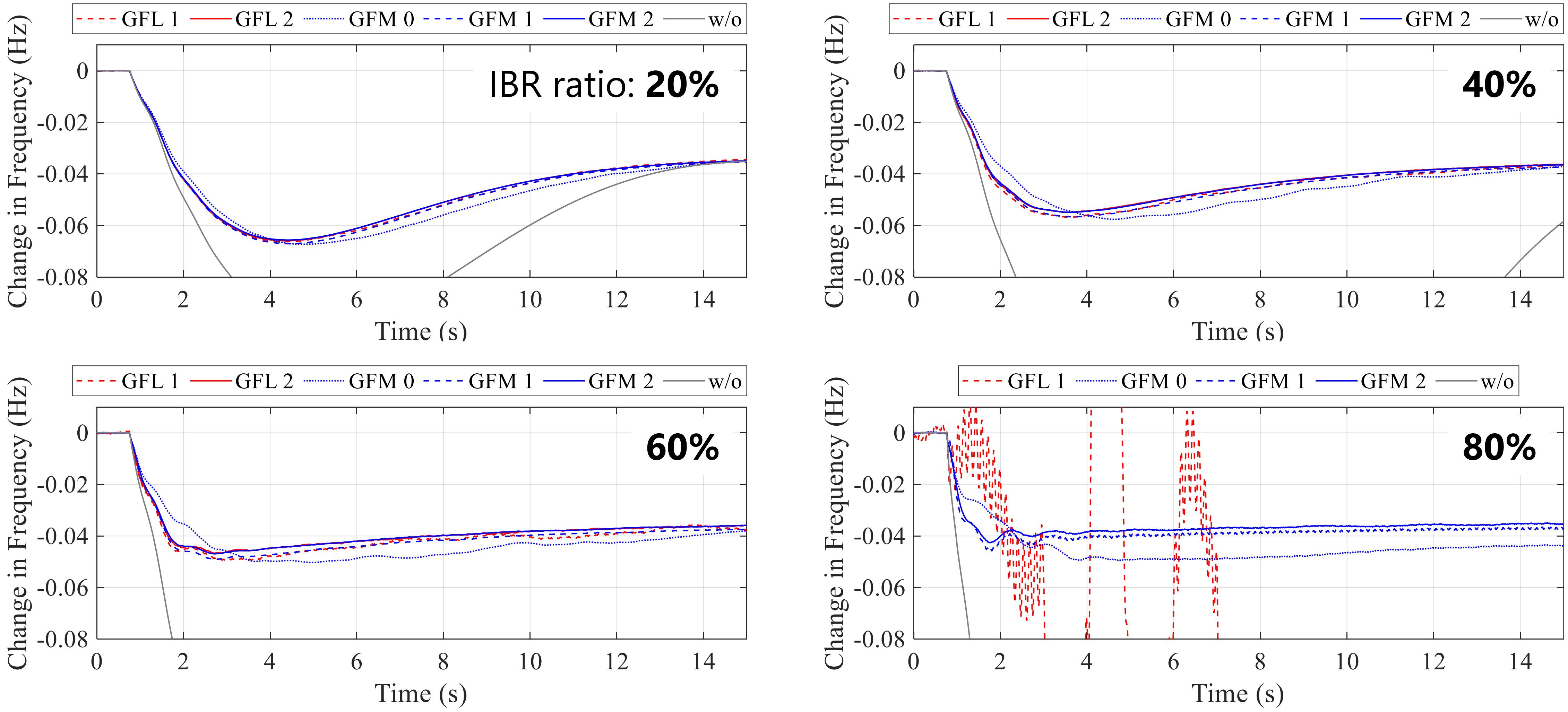
	Grid-following inverter		Grid-forming inverter		
	GFL 1	GFL 2	GFM 0	GFM 1	GFM 2
Advanced control	df/dt-P droop f-P droop	df/dt-P droop f-P droop	VSM Q-V droop	P-f droop Q-V droop	VSM Q-V droop
Rated capacity (kVA)	20	49.9	12	20	50
Rated AC voltage (V)	200	200	420	200	440



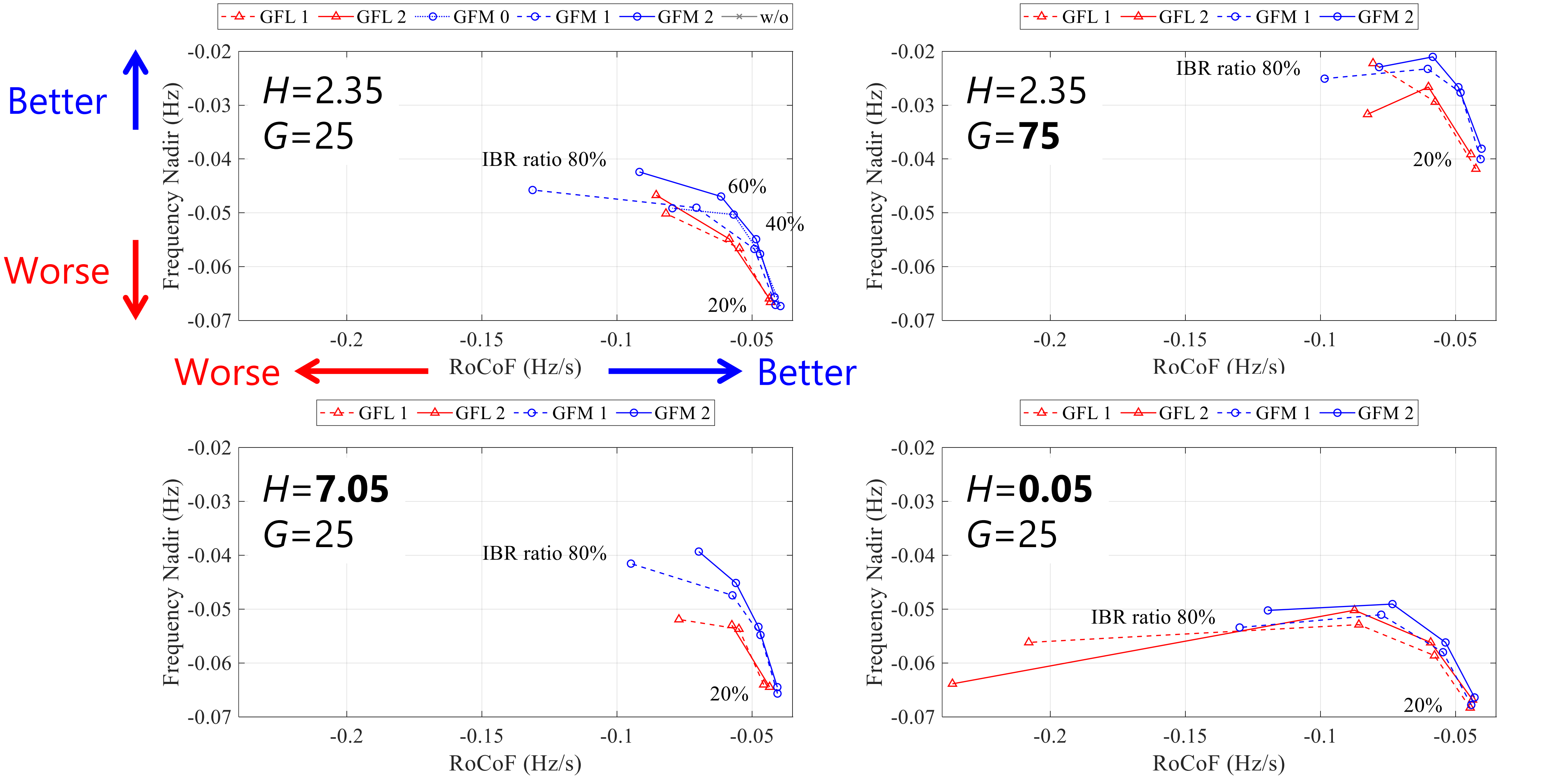

PHIL Test Setup for GFL and GFM Inverters



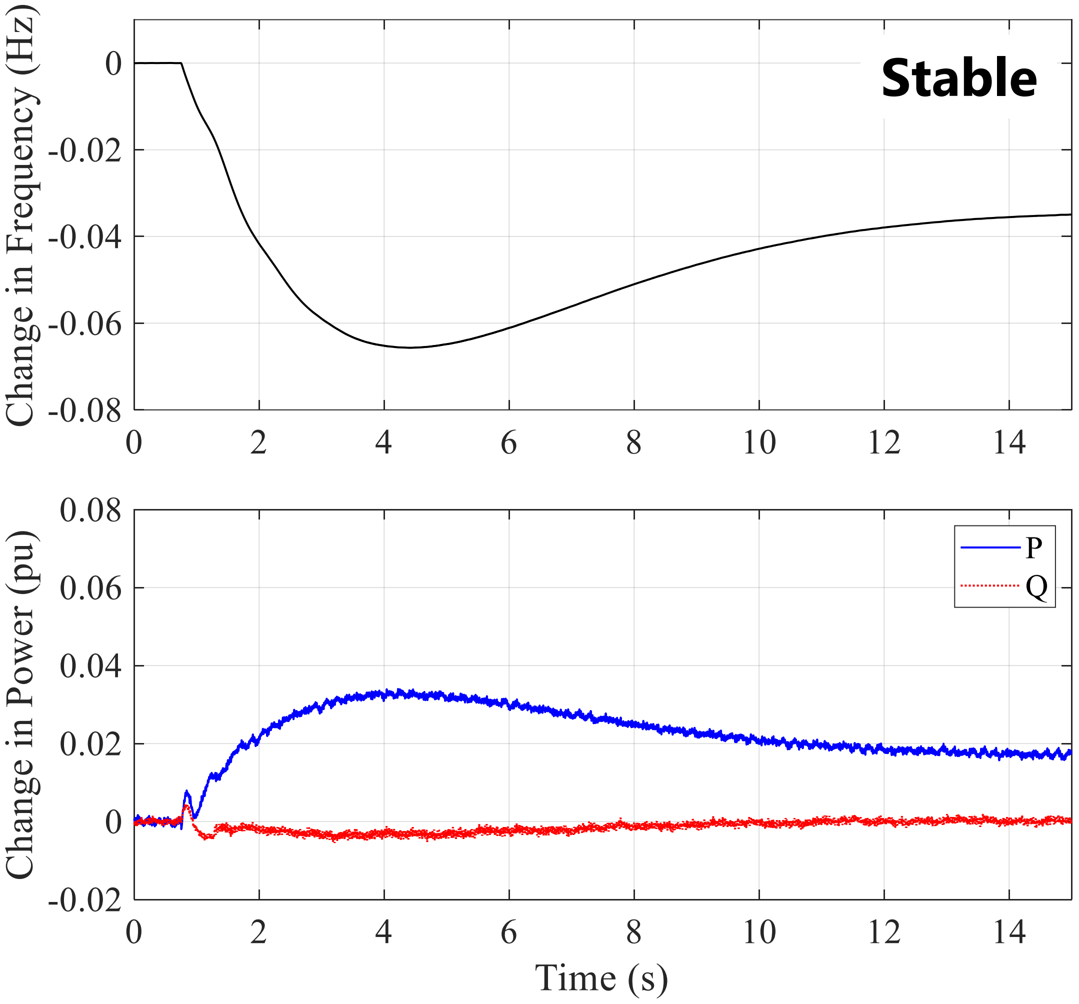
As IBR Ratio Increases, Frequency Change Increase for Conv. IBR, Decrease for GFL and GFM Inverters. GFM Inverters are Stable at 80%.



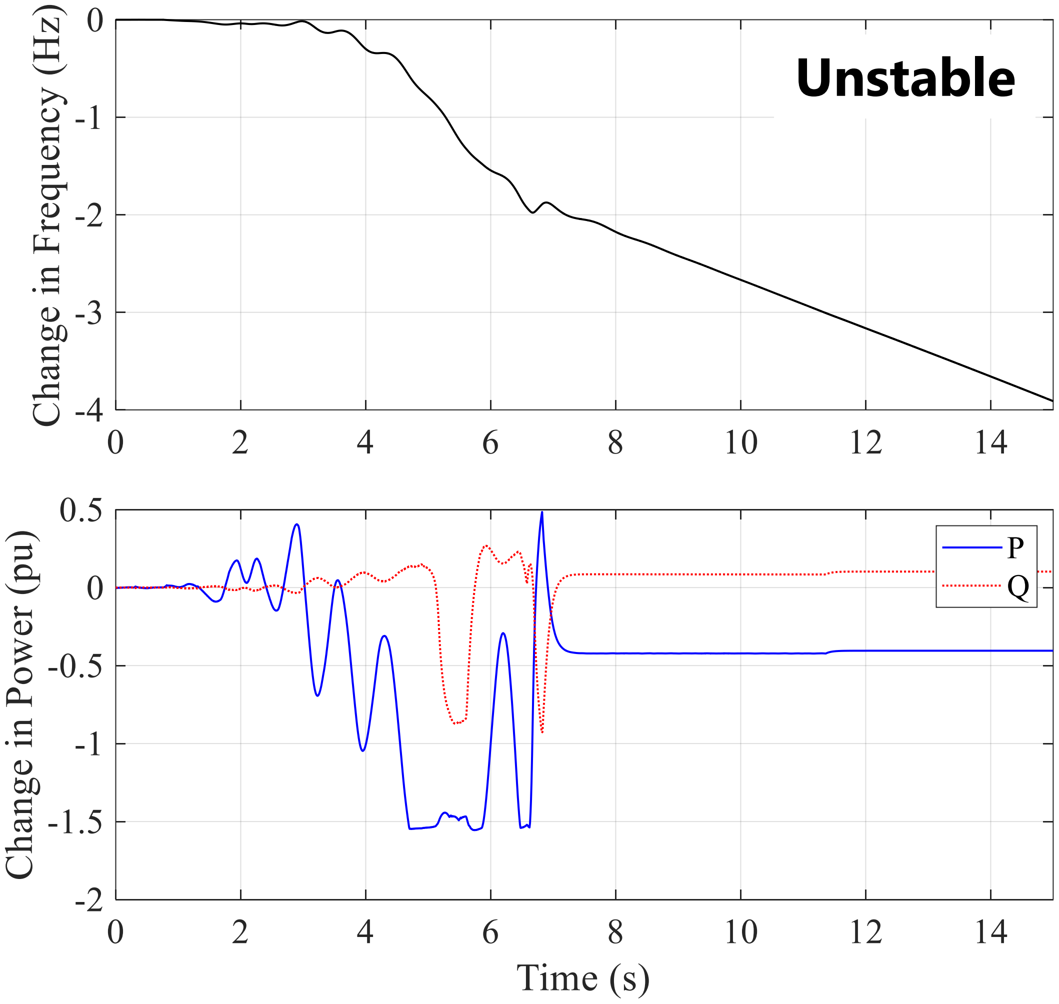
Inertia Constant "*H*" Affects RoCoF; Governor Gain "*G*" Affects Frequency Nadir (and RoCoF)



Interference Occurs between Islanding Detection and Frequency Stabilization Capability in GFM inverter



Disable islanding detection



Enable islanding detection

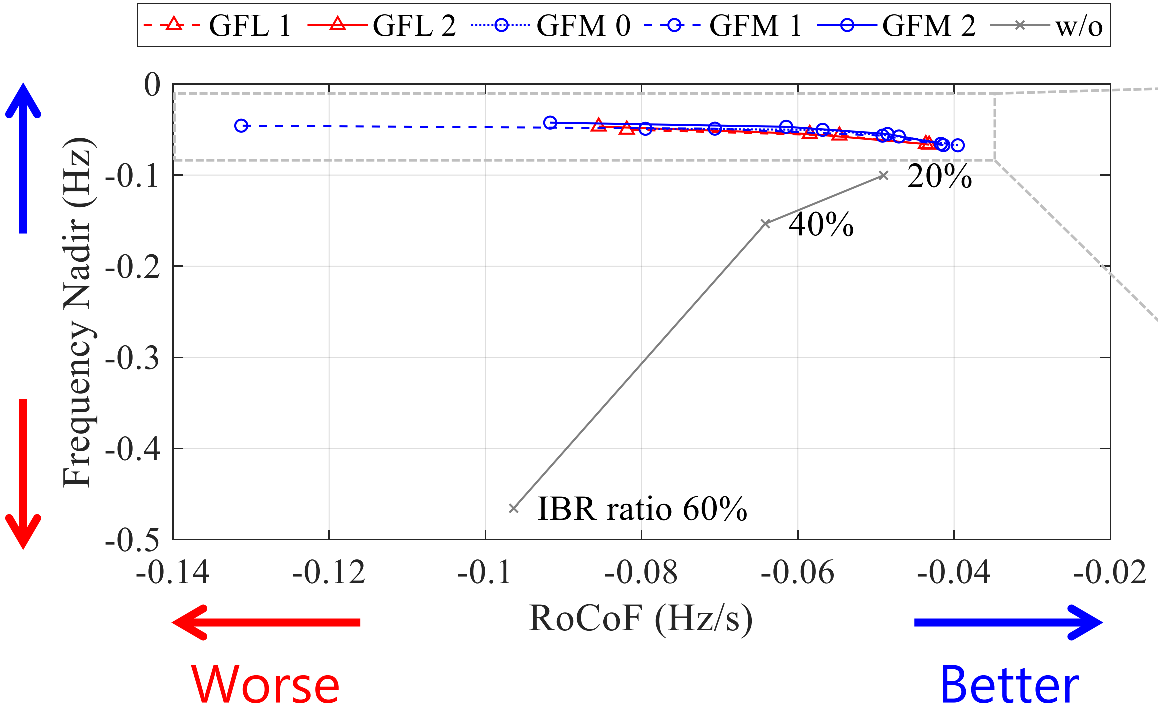
Summary

- Conduced PHIL testing to verify the performance of GFL and GFM inverter prototypes
  - Frequency swing was mitigated by introducing GFL and GFM inverters
  - GFL inverters were stable by IBR ratio at 60%, GFM inverters were stable at 80%
- Confirmed control parameter sensitivity
  - Inertia constant affected RoCoF
  - Governor gain affected Frequency nadir
- Observed interference between islanding detection and frequency stabilization capability of GMF inverter

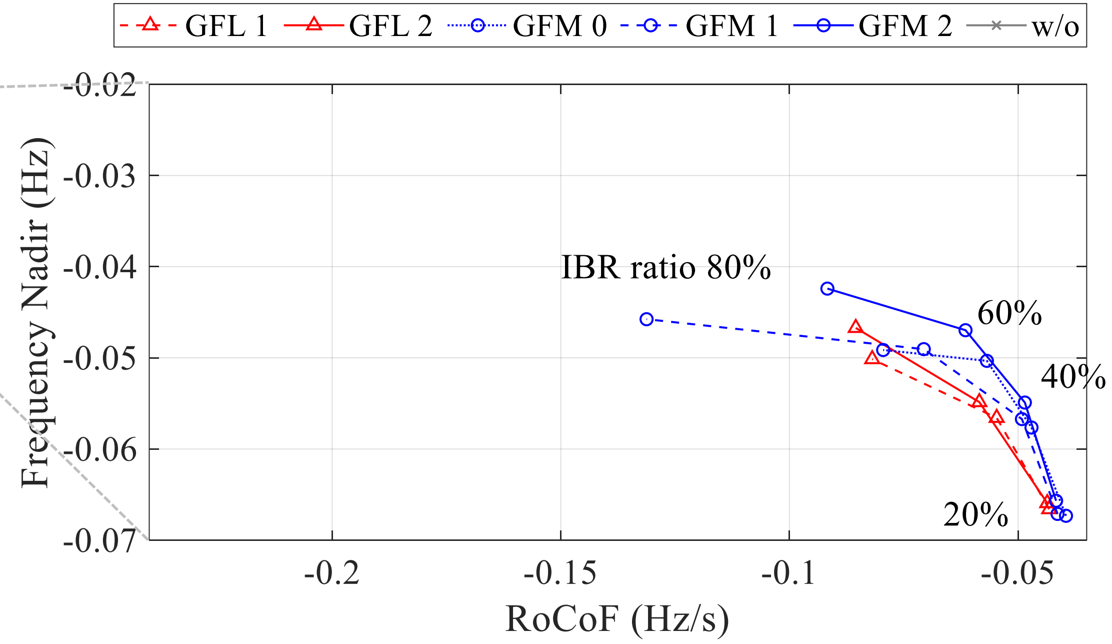
- Future work
  - Evaluate the other power system stabilities
  - Develop islanding detection method for GFM inverters

Appendix

Similar Trends are Observed in Frequency Nadir and RoCoF



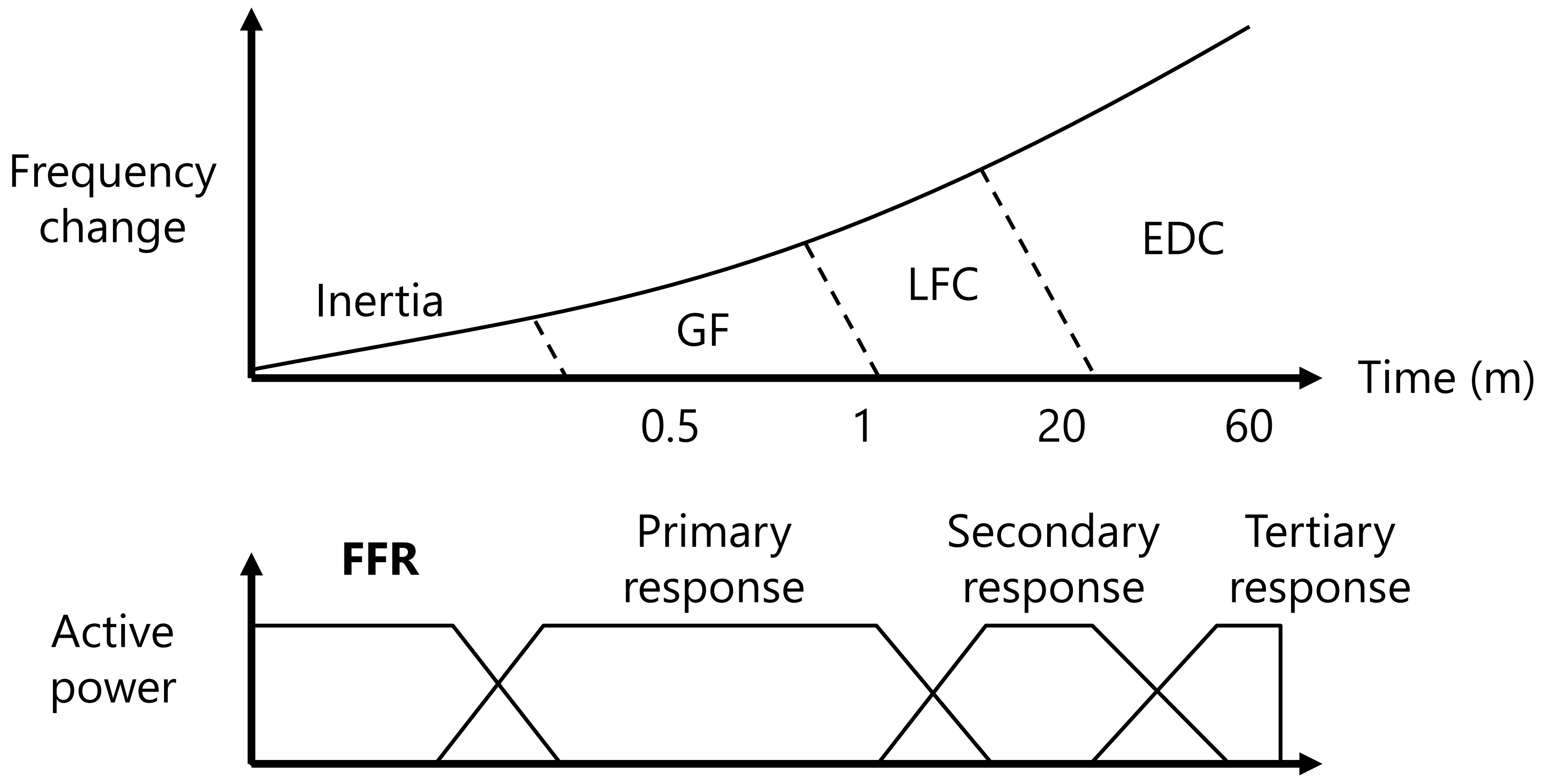
Overall view



Enlarged view

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



Advanced Control of GFL and GFM inverters

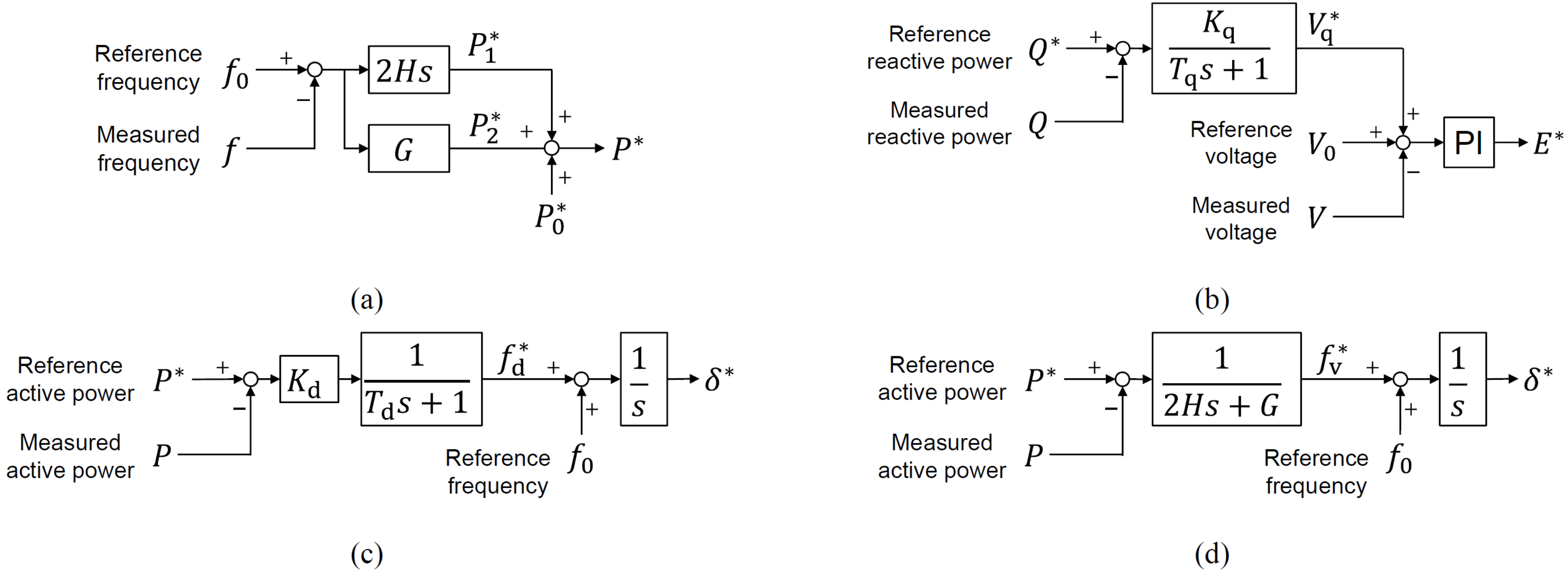


Fig. 4. Generalized control block diagrams of (a) the frequency control implemented in GFL 1 and GFL 2; the voltage phase angle control implemented in (b) GFM 0, GFM 2; and (c) GFM 1; (d) the voltage magnitude control implemented in GFM 0, GFM 1, and GFM 2.

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

Detailed Connection Configuration of Each Inverter Under Testing