Retrofit grid-following converter control to grid-forming control using the same hardware/sensors

NERC Inverter-based Resource Performance Subcommittee (IRPS)

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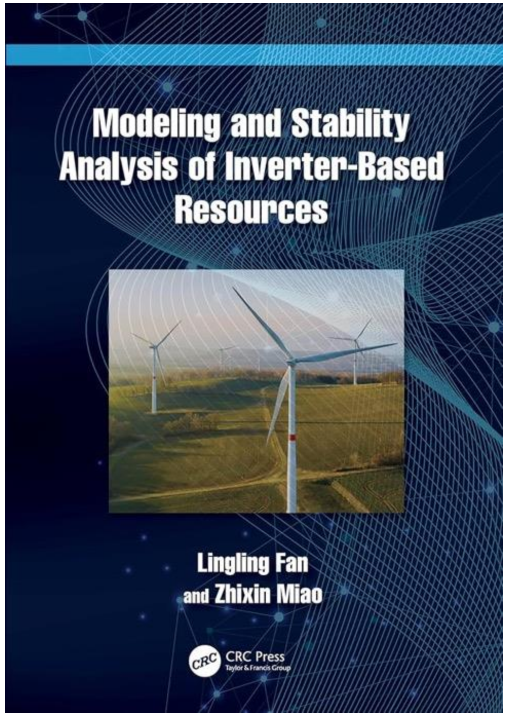
DE-EE0011474
SPRING: Stability Prediction for IBR-Penetrated Grids Enabled by Digital Twins

References:

- 📌A book
- H. Ding, R. Kar, Z. Miao and L. Fan, **"A Novel Design for Switchable Grid-Following and Grid-Forming Control,"** *IEEE trans. Sustainable Energy*. [IEEE Xplore link](), [preprint pdf]()
- L. Fan, Z. Miao and H. Ding, **"Enabling Technology for Energy Sustainability: Power Electronic Converter Control for Renewables,"** under review, *IEEE Energy Sustainability Magazine.*
- Univ. of South Florida Technology Innovation*: 24T248 "**A Novel Grid-Forming Control Design**" (L. Fan and Z. Miao)*
  - *https://usf.technologypublisher.com/techcase/24T248*



Chapter 4-5: GFL
Chapter 6: GFM
Features: per unit-based analysis; Bode diagrams; EMT simulation results.

Outline

Overview: PLL-based inverter control

Retrofit

GFM control **not suitable for retrofitting**

Test 1:

Weak grid low-voltage ride through

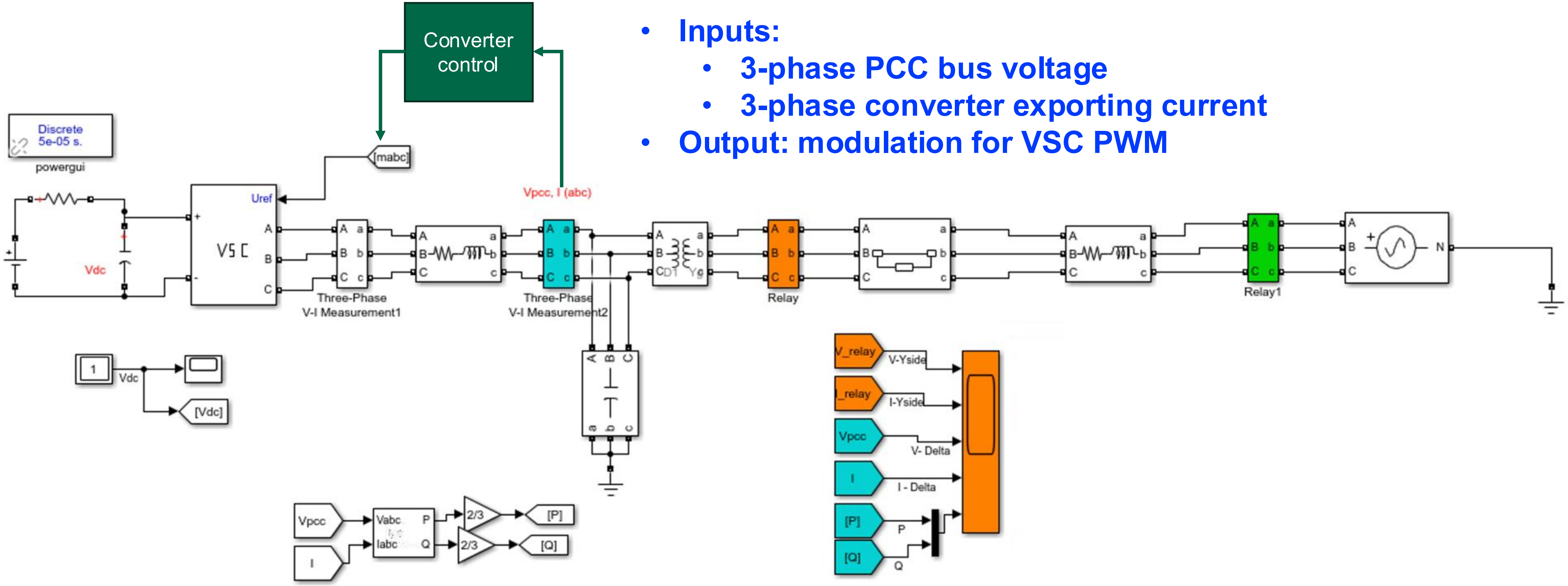
Test 2 :

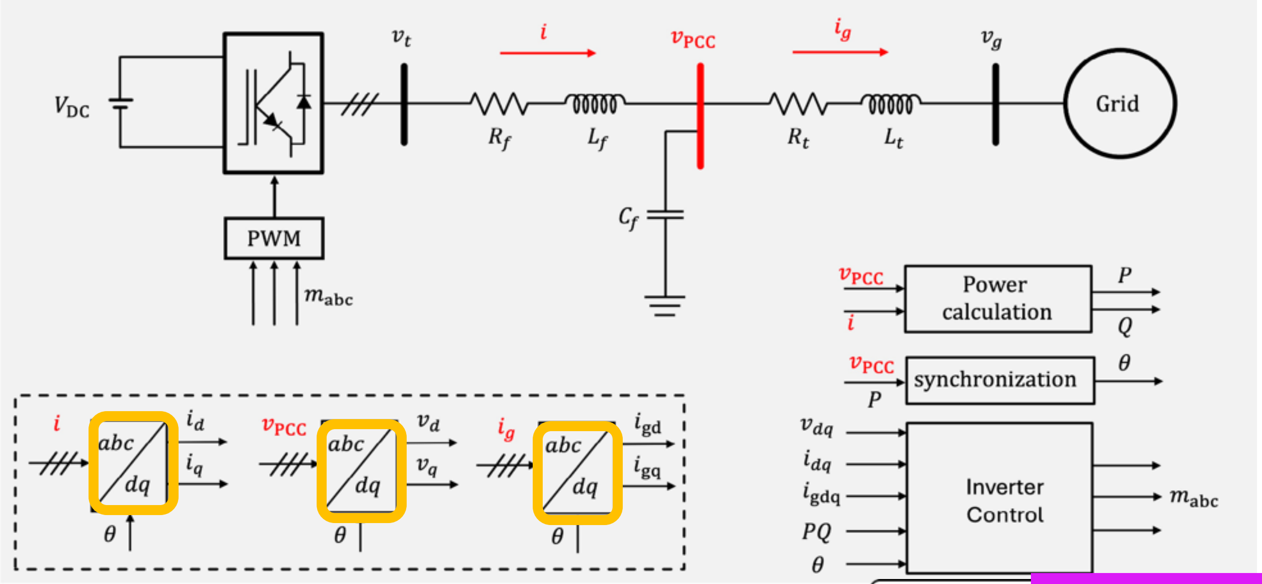
Operating in a series compensated network

Inverter control: three layers

Electromagnetic transient simulation

- **Inputs:**
  - **3-phase PCC bus voltage**
  - **3-phase converter exporting current**
- **Output: modulation for VSC PWM**





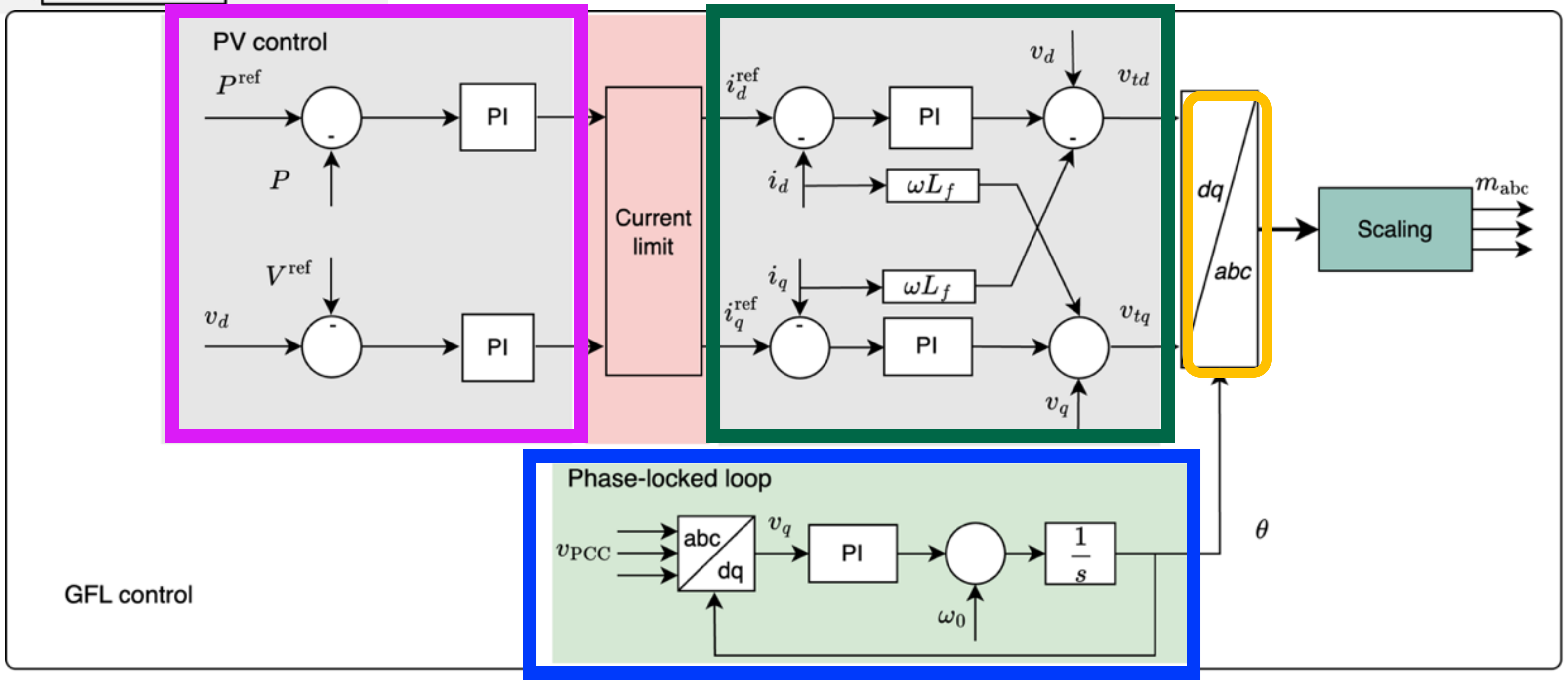
dq-frame control:

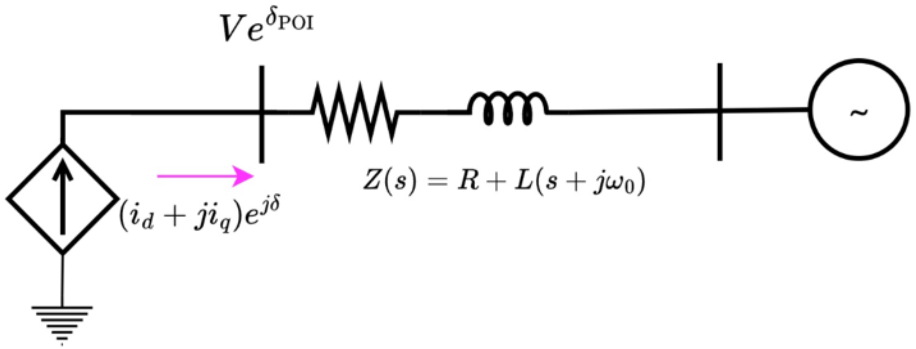
The frame aligns with the point of common coupling (PCC) voltage space vector at steady state.

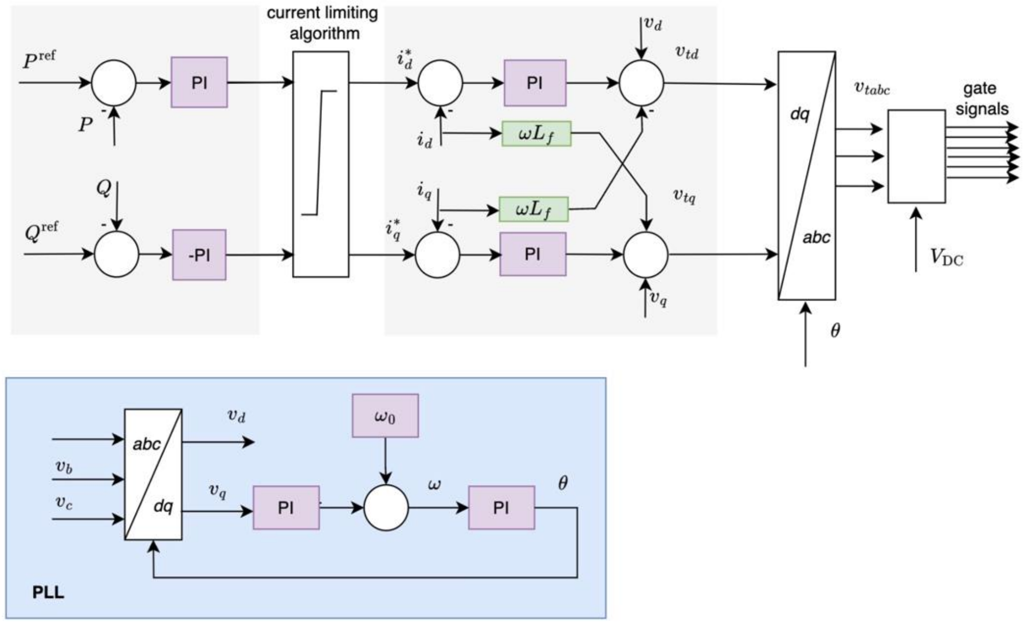
Voltage-based synchronization: PLL

Inner current control (very fast)

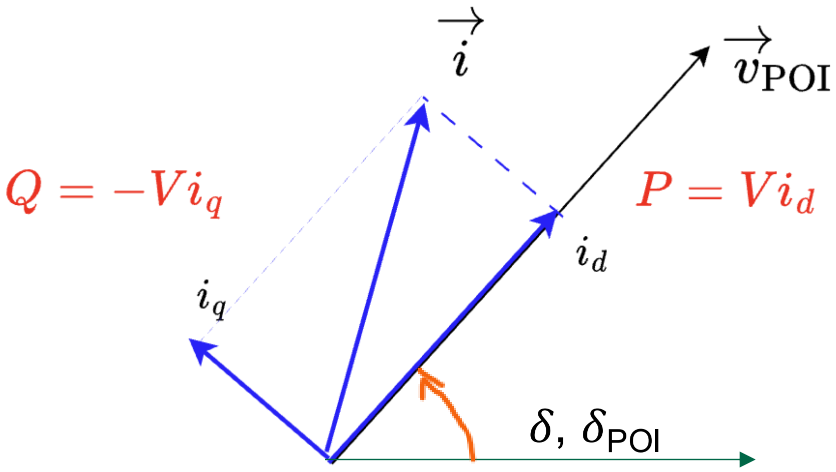
Outer power control (slow)







Decoupled vector control adapted from field-oriented control for AC motors (1968): Technische Universität Darmstadt's K. Hasse and Siemens' F. Blaschke

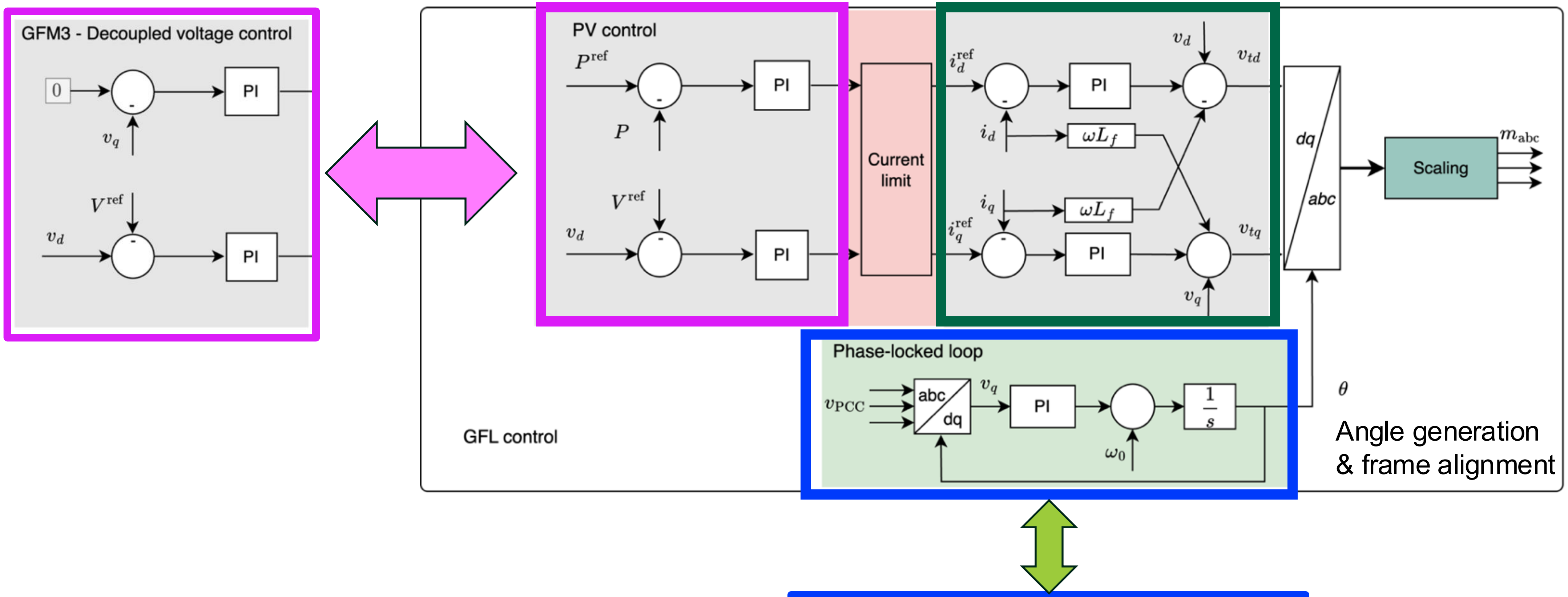


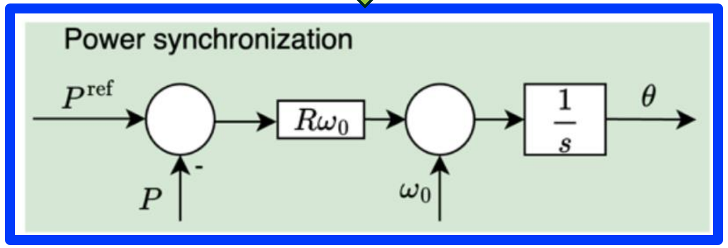
- Setup a dq frame aligned with the POI voltage through a PLL.
- Decompose a current vector to dq components.
- Regulate P through id; regulate Q through iq.

Retrofitting:
provide frequency support

dq-frame control:
The frame aligns with the point of common coupling (PCC) voltage space vector at steady state.

frame alignment

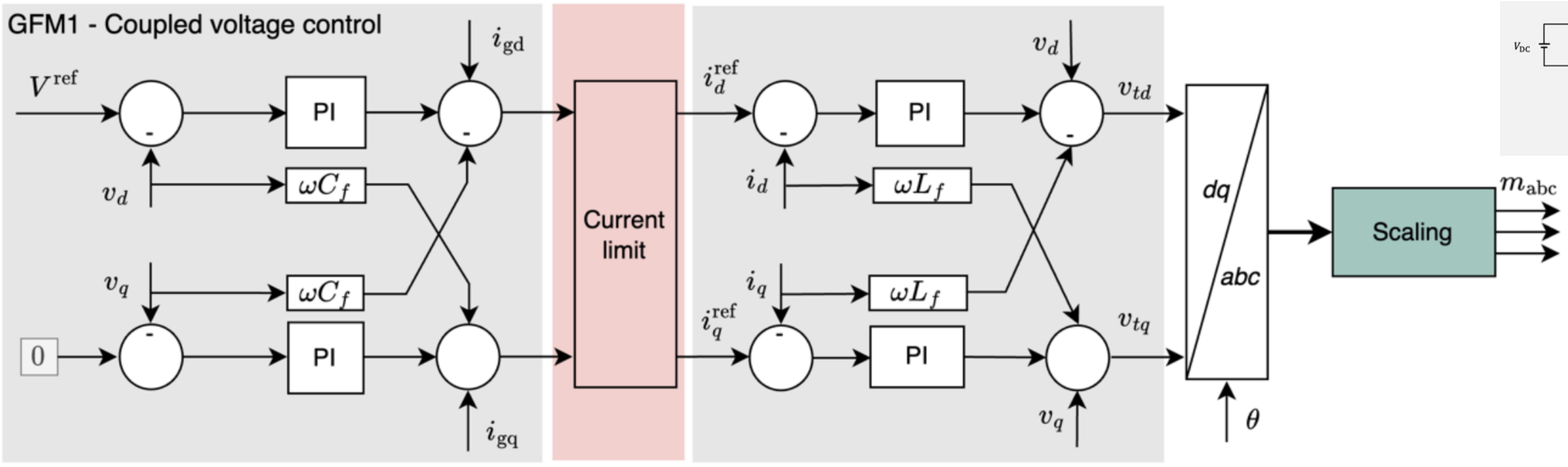


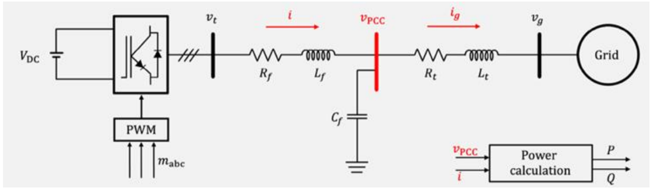


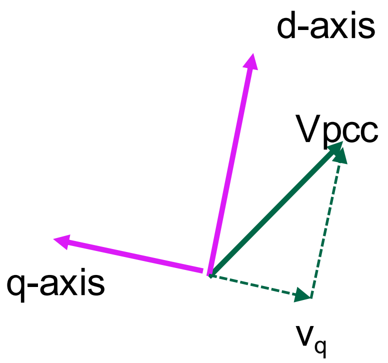
Angle generation & power regulation

1. Replace voltage-based PLL by power-based synchronization.
2. D-axis outer control enforces the dq-frame aligned with the PCC voltage space vector

GFM control not suitable for retrofitting



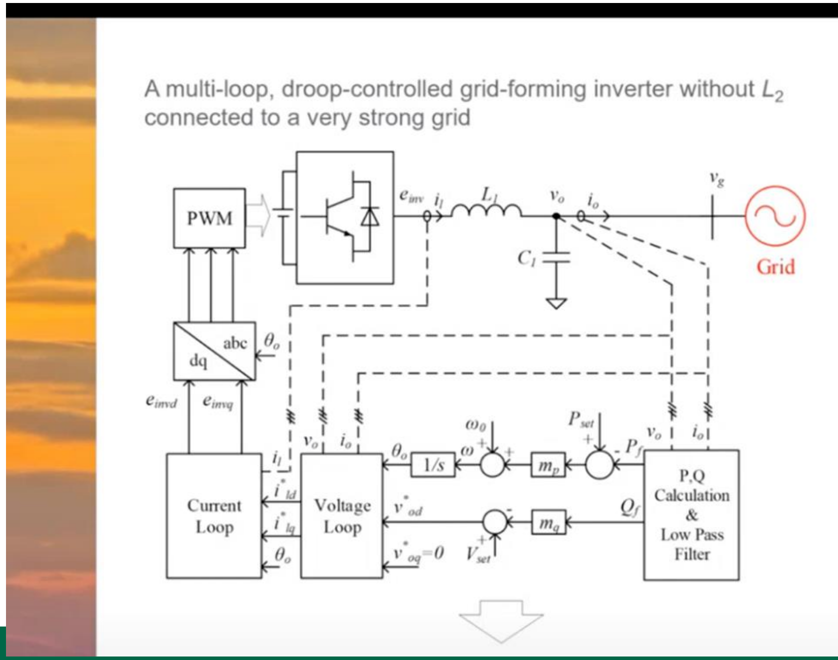




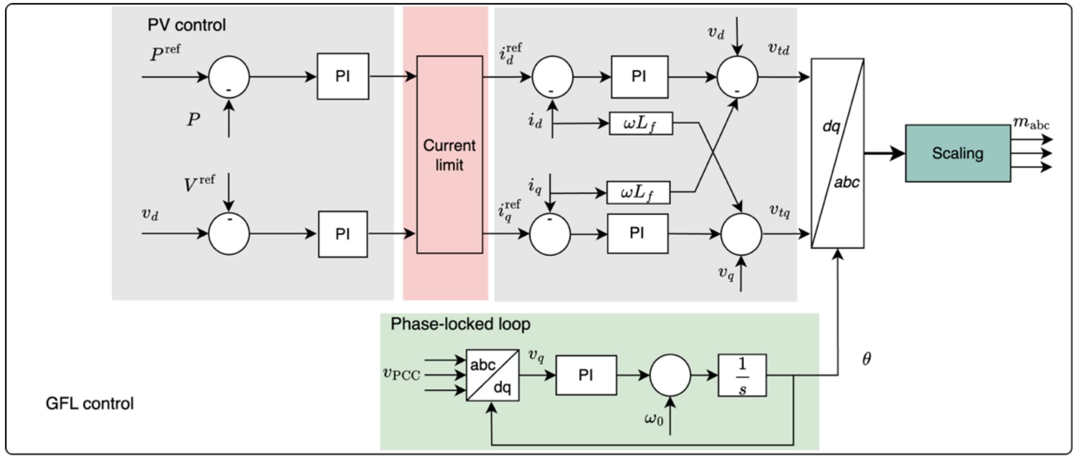
•N. Pogaku, M. Prodanovic, and T.C. Green. "Modeling, analysis and testing of autonomous operation of an inverter-based microgrid." *IEEE Transactions on power electronics* 22, no. 2 (2007): 613-625.

This control structure requires an additional current sensor.

Low-voltage ride-through: If Vd dips, real current order will be increased. This is not good for low-voltage ride through.
Inherent instability mechanism: if vq < 0 (the synchronizing angle is ahead of the PCC bus voltage angle), iq order increases or reactive current decreases. This leads to voltage reduction➔ real power reduction➔ more sync angle increase➔ instability.

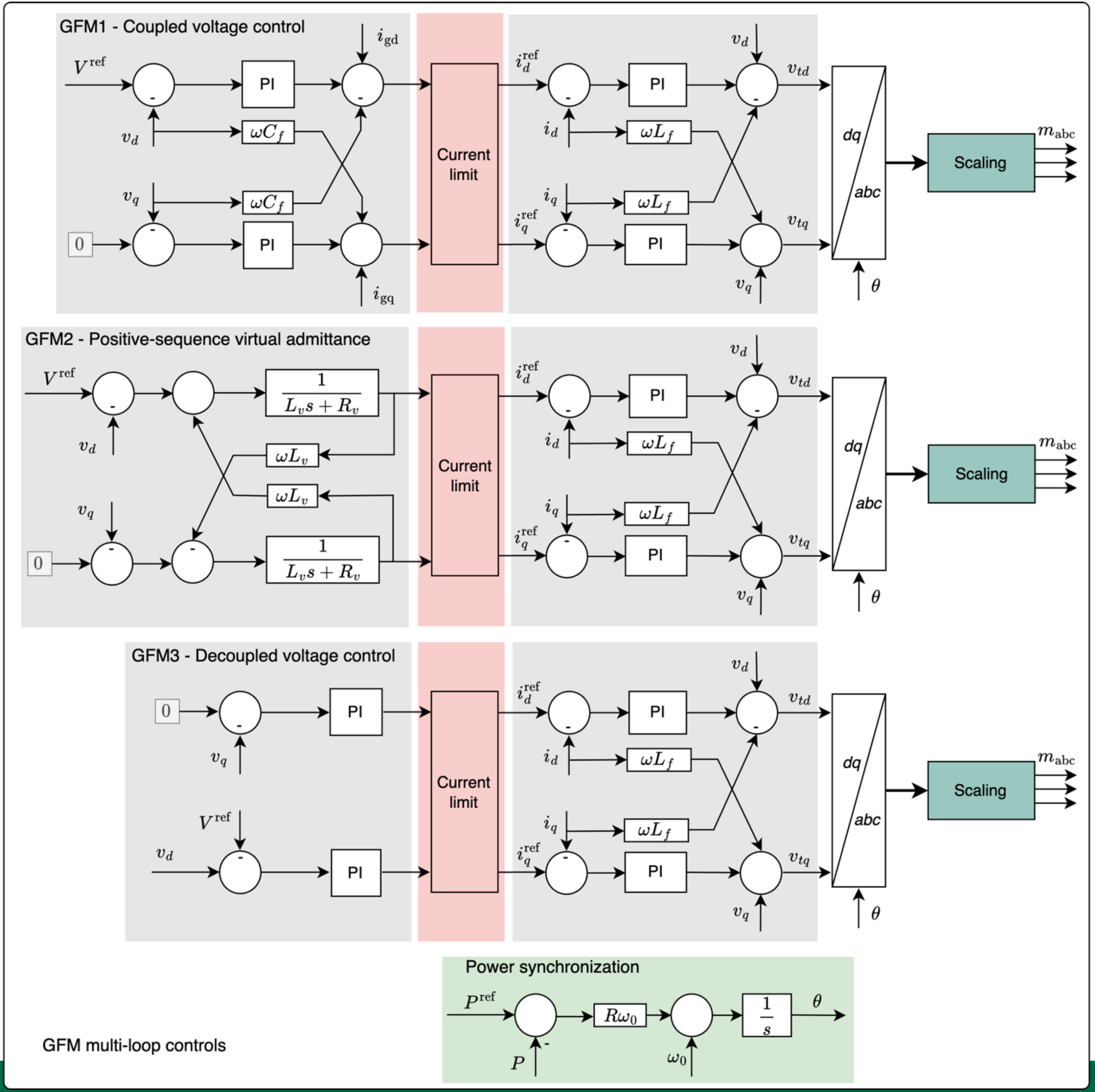


Comparison: weak grid low-voltage ride-thru tests

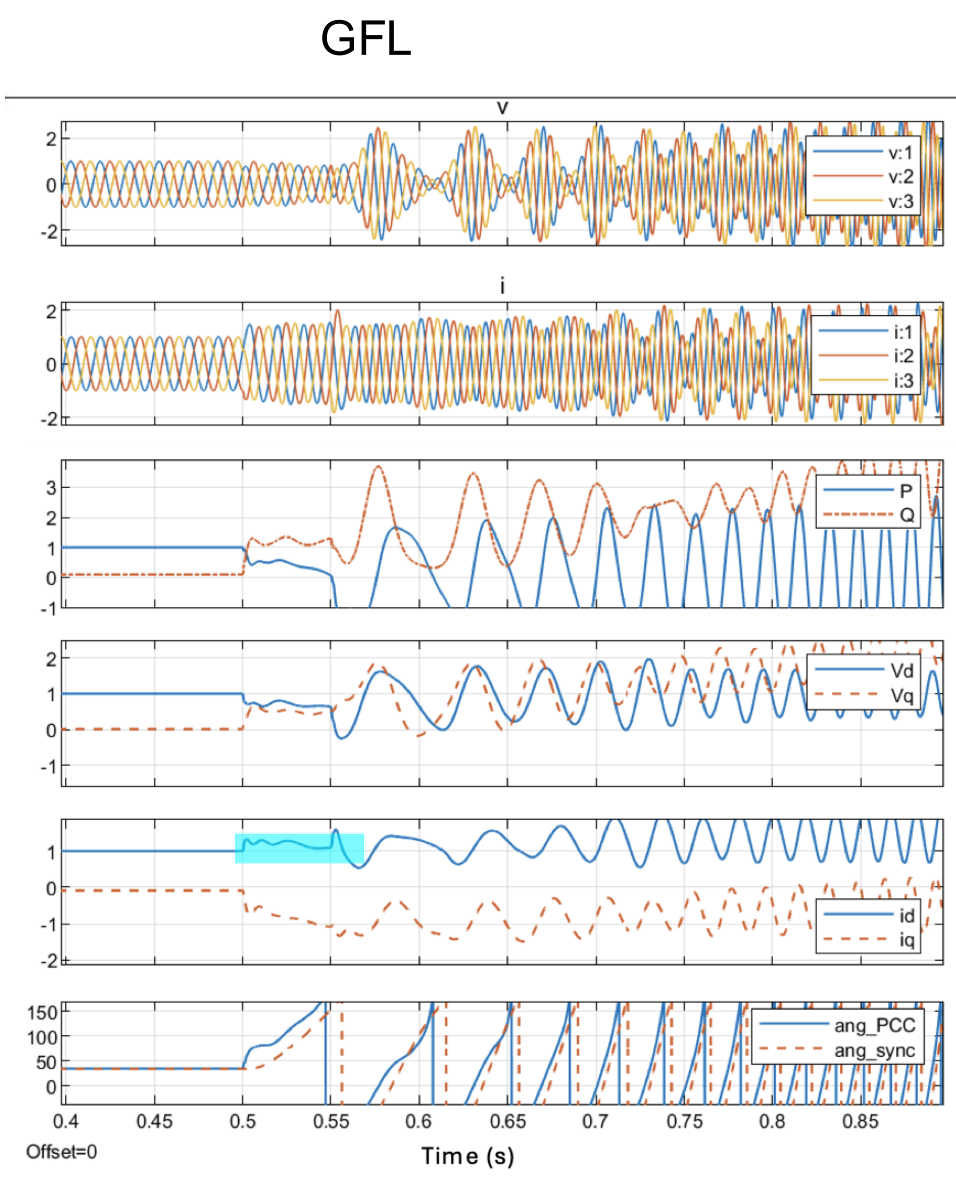


- (a) GFL
- (b) GFM with coupled voltage control
- (c) GFM with decoupled voltage control
- (d) GFM with virtual admittance* (**also good for retrofitting**)

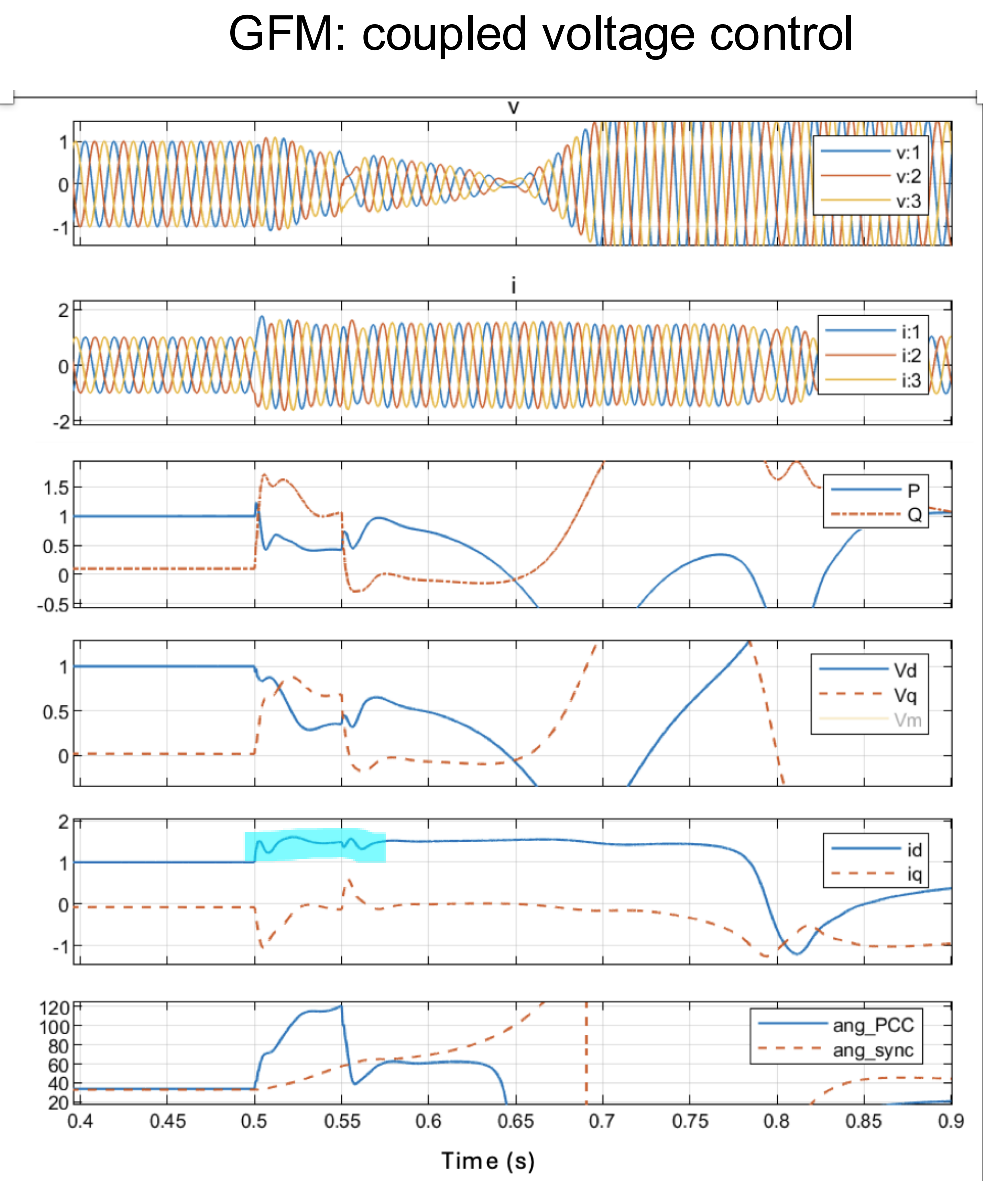
*G.Postiglione, et al, "An improved modular statcom topology equipped with short- time energy storage and grid forming control for hv network voltage and frequency," CIGRE 2024 Paris Session, 2024.



L. Fan, Z. Miao, H. Ding, "Enabling Technology for Energy Sustainability: **Power Electronic Converter Control for Renewables.**"

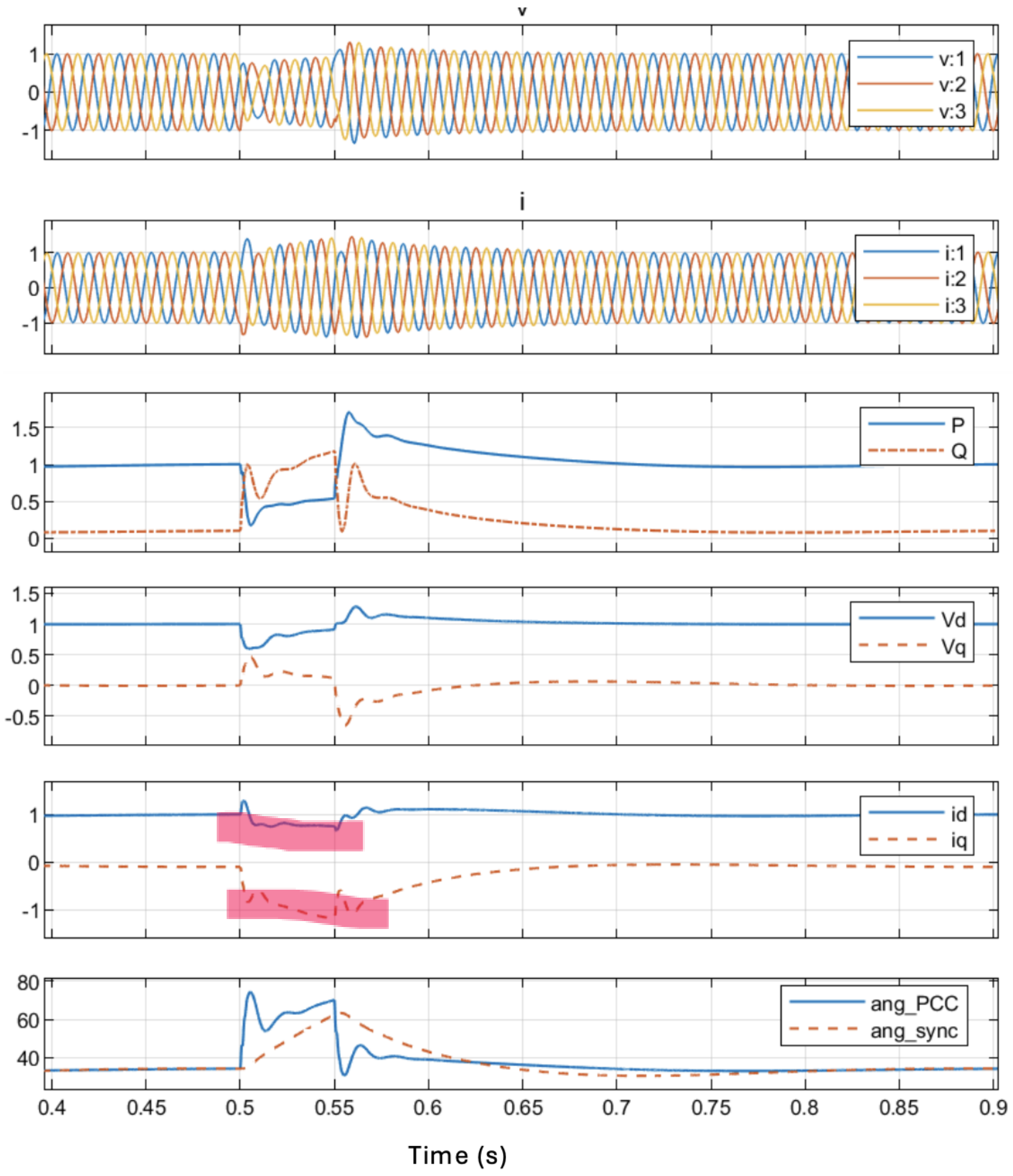


(a)

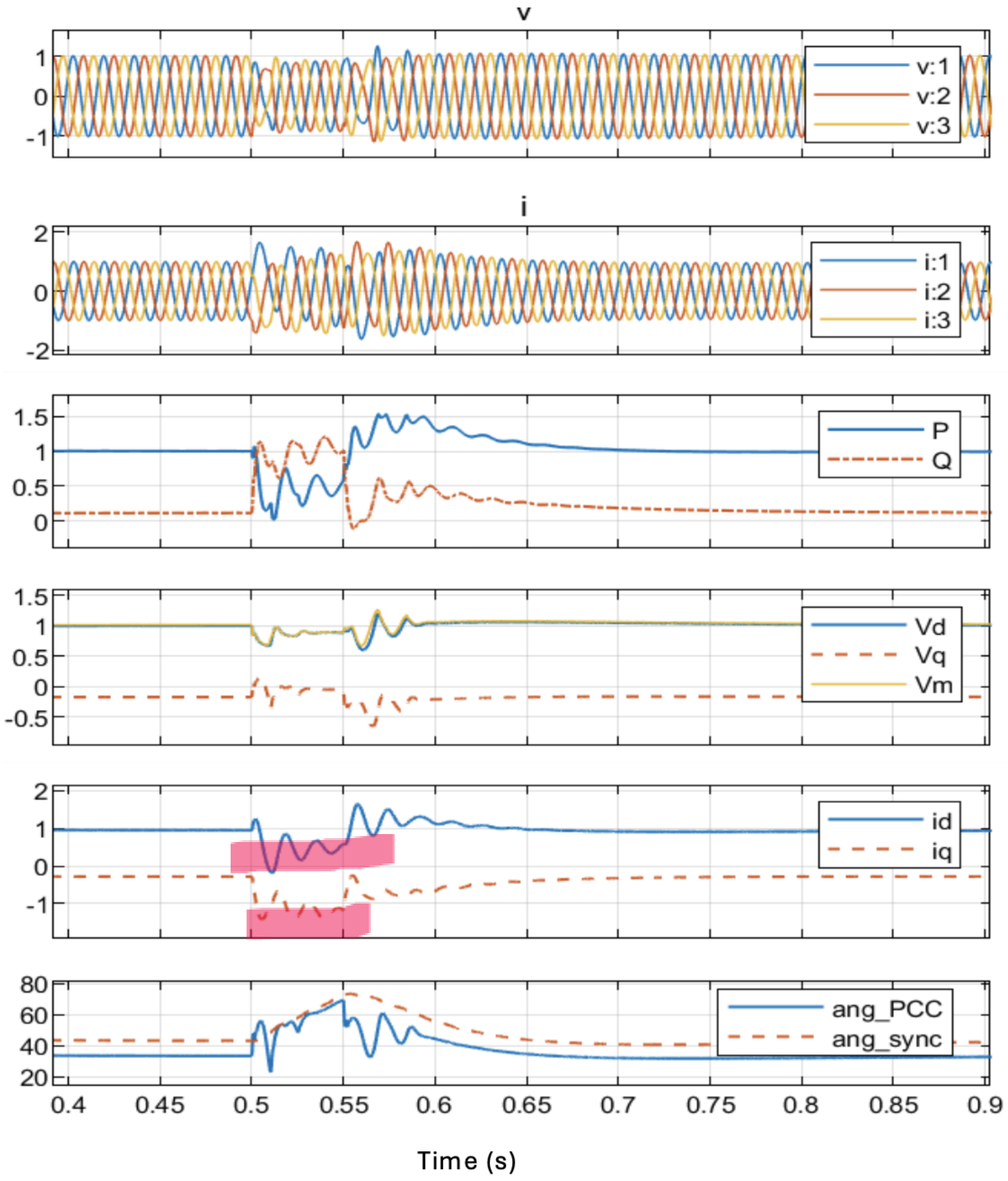


(b)

Low-voltage ride-through tests for four IBRs: 75% grid voltage dip; grid strength: SCR at 2



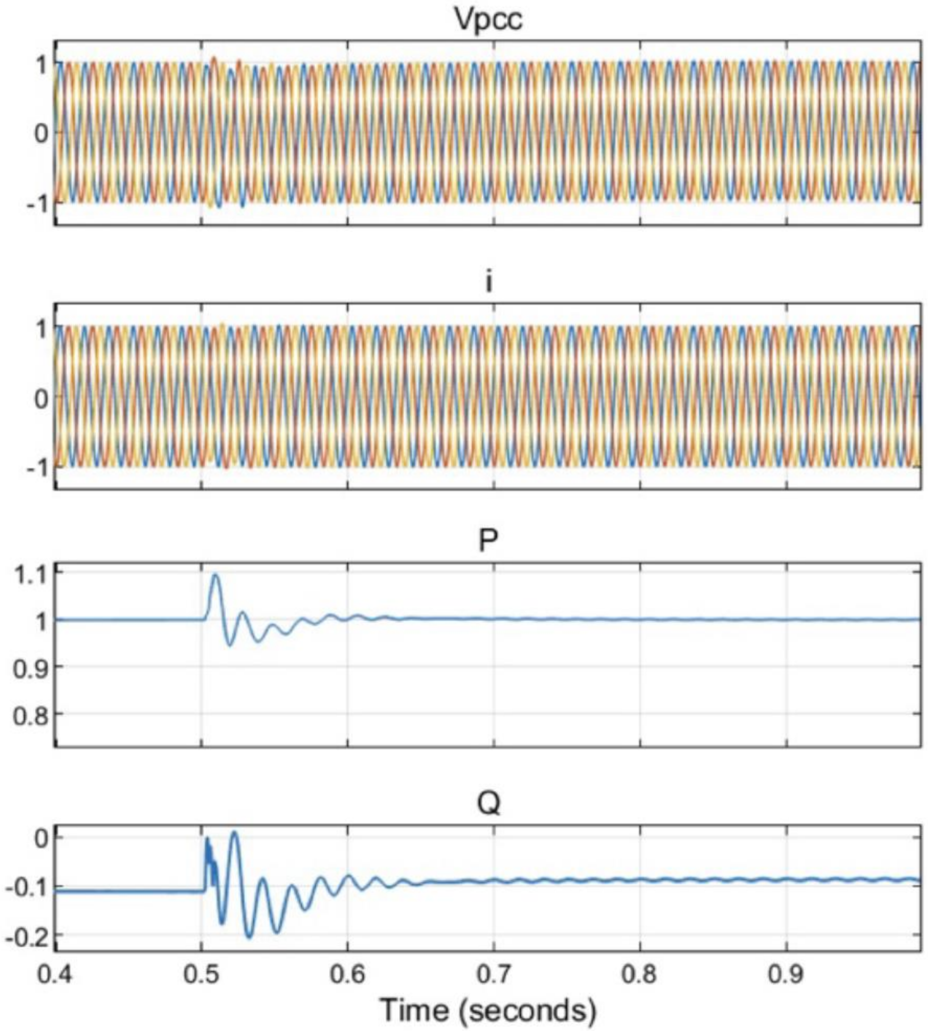
(c) GFM: decoupled control



(d) GFM: virtual admittance

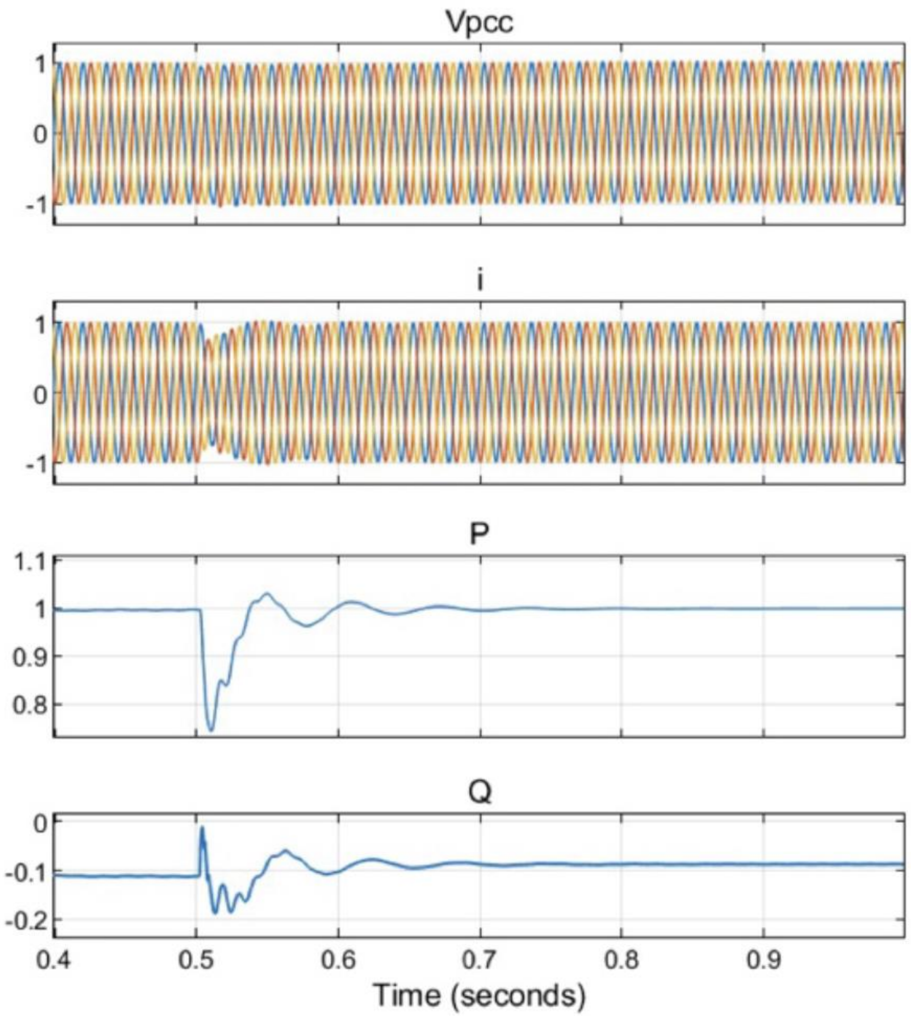
Low-voltage ride-through tests for four IBRs: 75% grid voltage dip; grid strength: SCR at 2

Comparison: Radial connection with a series compensated line



(a)

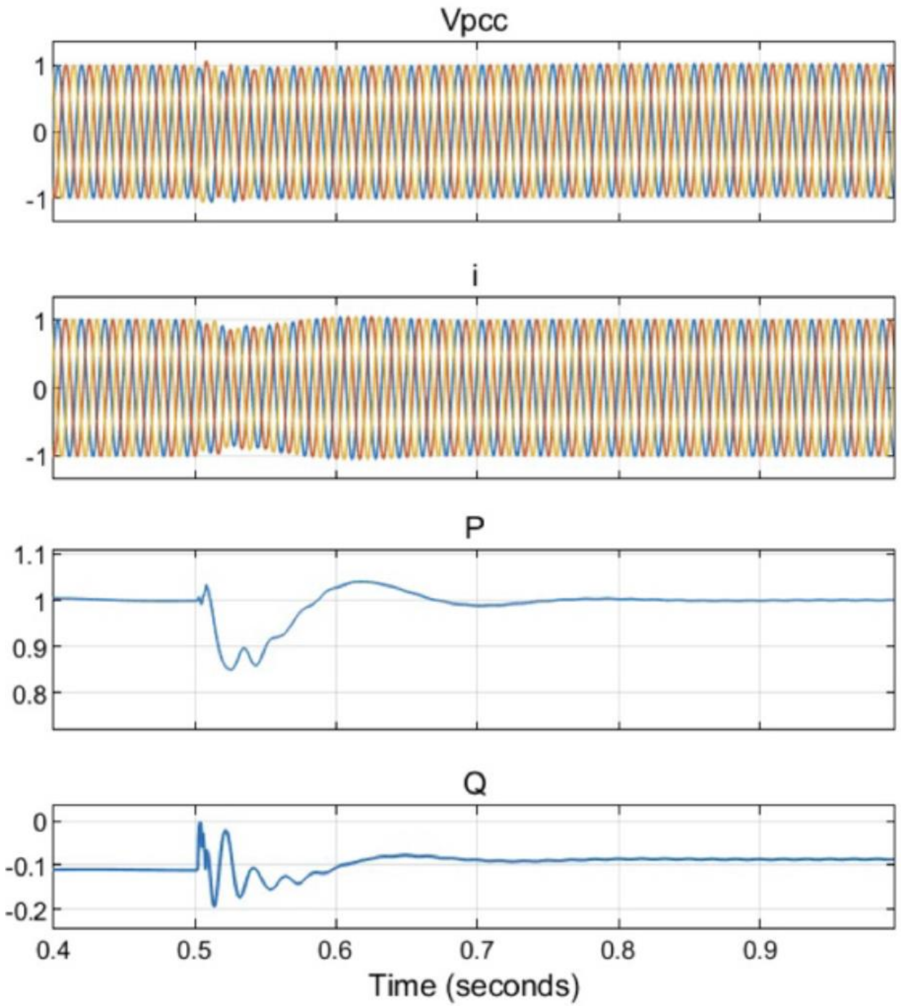
GFL



(b)

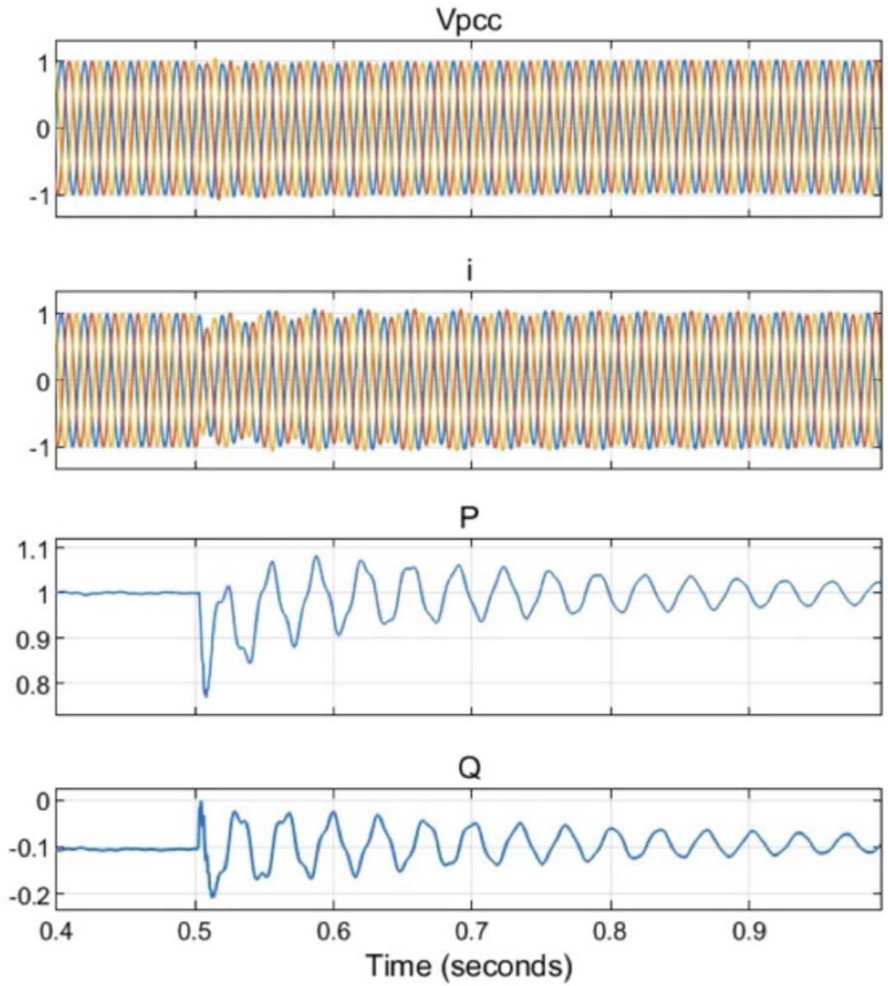
GFM: coupled voltage control

EMT simulation results of an IBR radially connected to a 50% compensated line at 0.5 s. (a) GFL. (b) Coupled voltage GFM. (c) Decoupled voltage GFM. (d) Virtual admittance GFM.



(c)

GFM: decoupled control



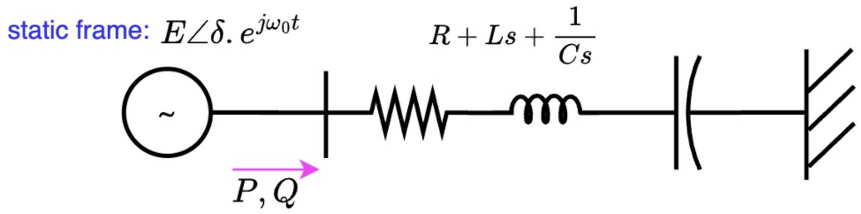
~28 Hz oscillations

(d)

GFM: virtual admittance

Voltage source like IBRs are more prone to LC mode instability.

Xc = 0.25; XL = 0.5, Xv = 0.3; comp level = 30%.

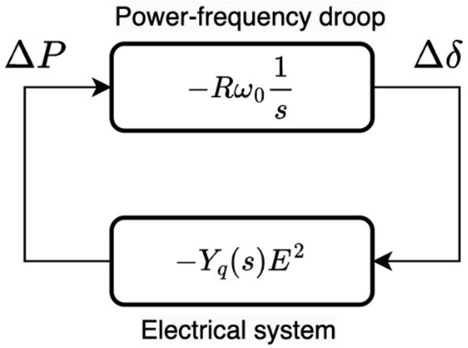


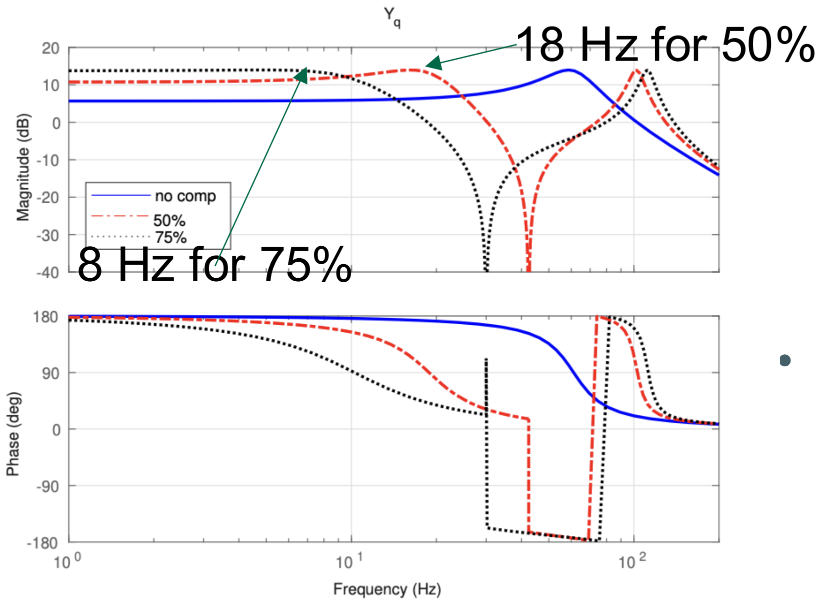
dq frame: $E\angle\delta$

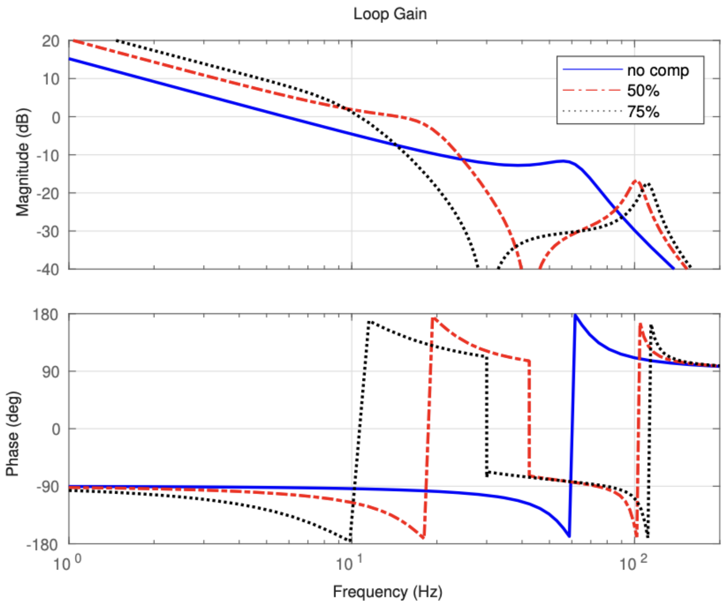
$$Z(s) = R + L(s + j\omega_0) + \frac{1}{C(s + j\omega_0)}$$

$$Y(s) = \frac{1}{Z(s)} = Y_d(s) + jY_q(s)$$

(a)

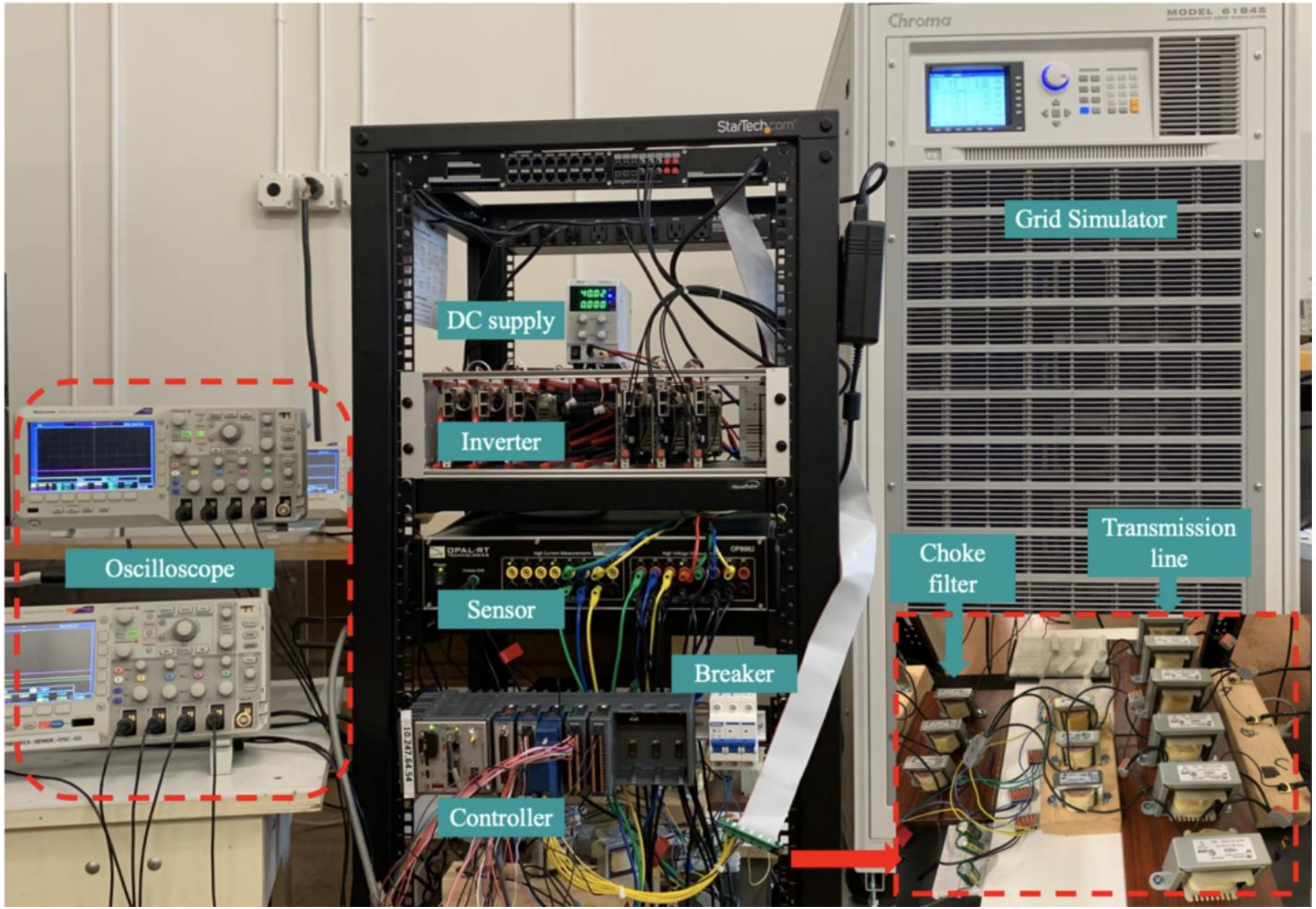






- Series compensation introduce phase lag in subsynchronous region.
- For power-based synchronization, more phase lag leads to SSOs at the complimentary frequency: 60-f_LC.
- This is similar to torsional interaction (SSTI) mechanism.

Other benefits: smooth control mode switching



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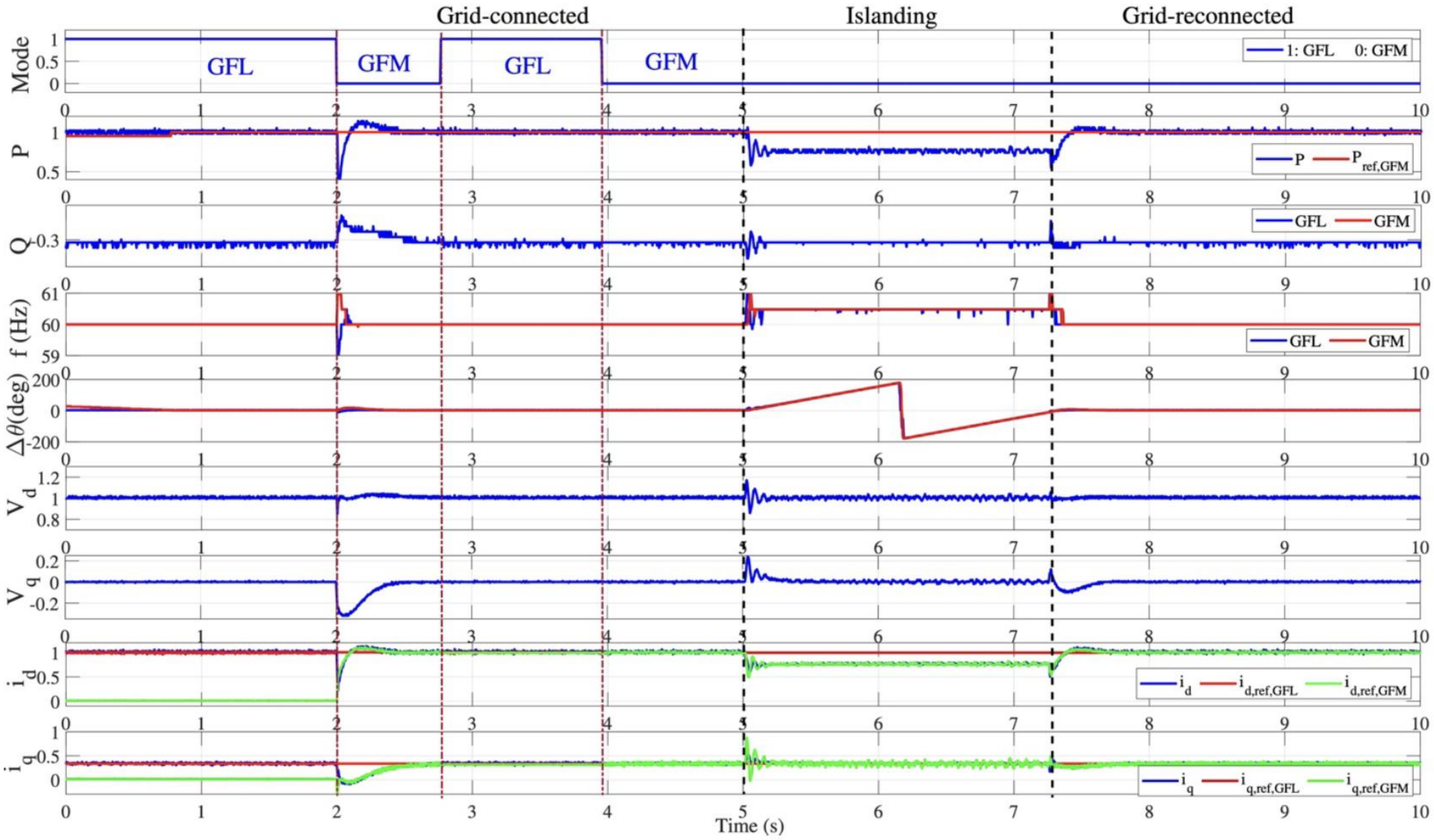

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Major takeaways

- Retrofitting controllers is feasible. With same sensors, **multiple control structures** can be implemented in one chip – cost saving**.**

	Retrofitting	Freq support	Weak grid LVRT	Series compensation
Grid-following control			x	√
GFL with frequency support	√	√	√*	√
GFM: coupled control	x	√	x	√
GFM: vector control	√	√	√	√
GFM: virtual admittance	√	√	√	X

*Potential oscillations due to PLL, f-P droop, delay.

L. Fan, Z. Miao and D. Ramasubramanian, "IBR Power Plant Frequency Control Design Consideration," in IEEE Transactions on Sustainable Energy, vol. 15, no. 4, pp. 2405-2416, Oct. 2024, doi: 10.1109/TSTE.2024.3420940.

S. Dong et al., "A Twin Circuit Theory-Based Framework for Oscillation Event Analysis in Inverter-Dominated Power Systems With Case Study for Kaua'i System," in IEEE Transactions on Circuits and Systems I: Regular Papers, doi: 10.1109/TCSI.2024.3524251.