



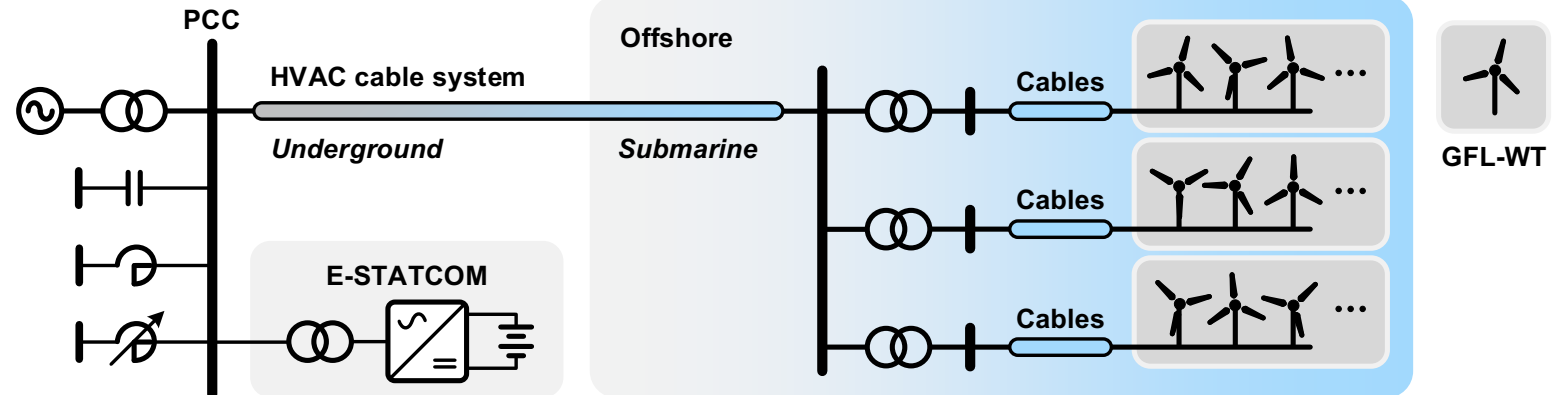
System Services from GFM Wind and STATCOMs

Xiongfei Wang, KTH Royal Institute of Technology, Sweden

Grid-Forming Wind Power Plants (GFM-WPPs)

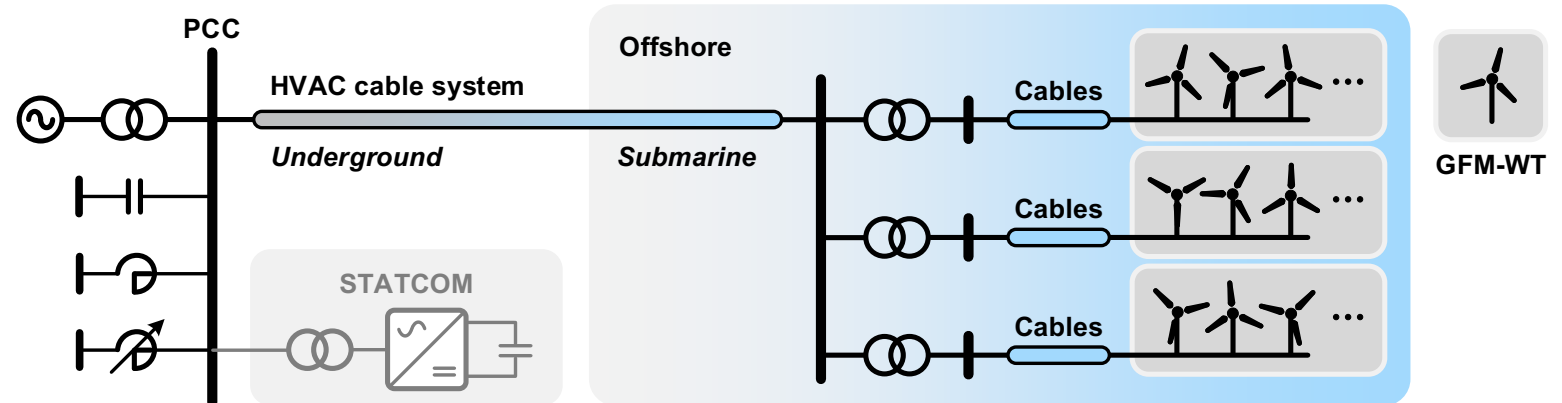
Type I GFM-WPP

- Energy-storage + STATCOM (**E-STATCOM**)
- GFM E-STATCOM
- Grid-Following Wind Turbine (GFL-WT)



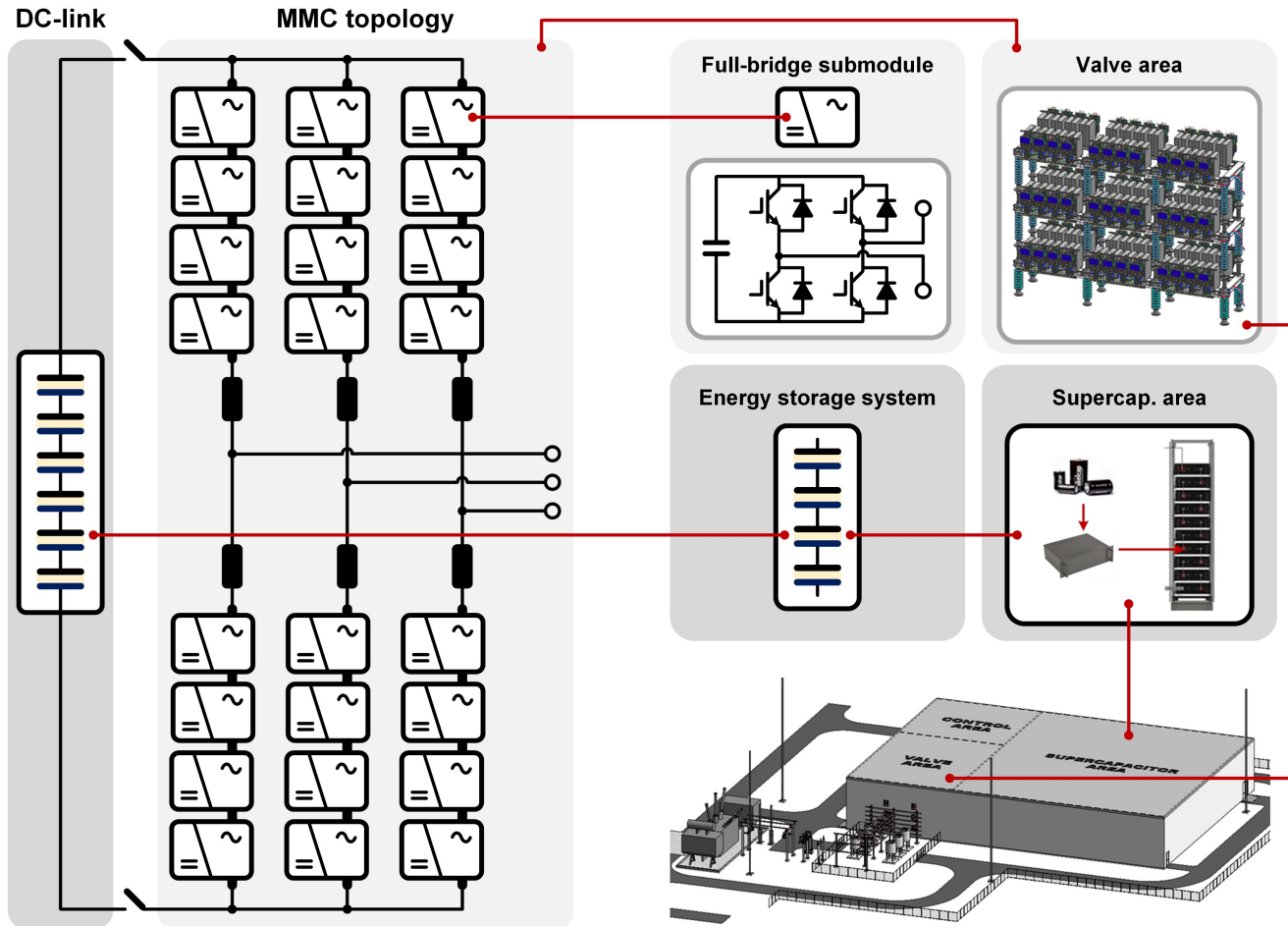
Type II GFM-WPP

- STATCOM (optional)
- GFM Wind Turbine (GFM-WT)
- WPP controller

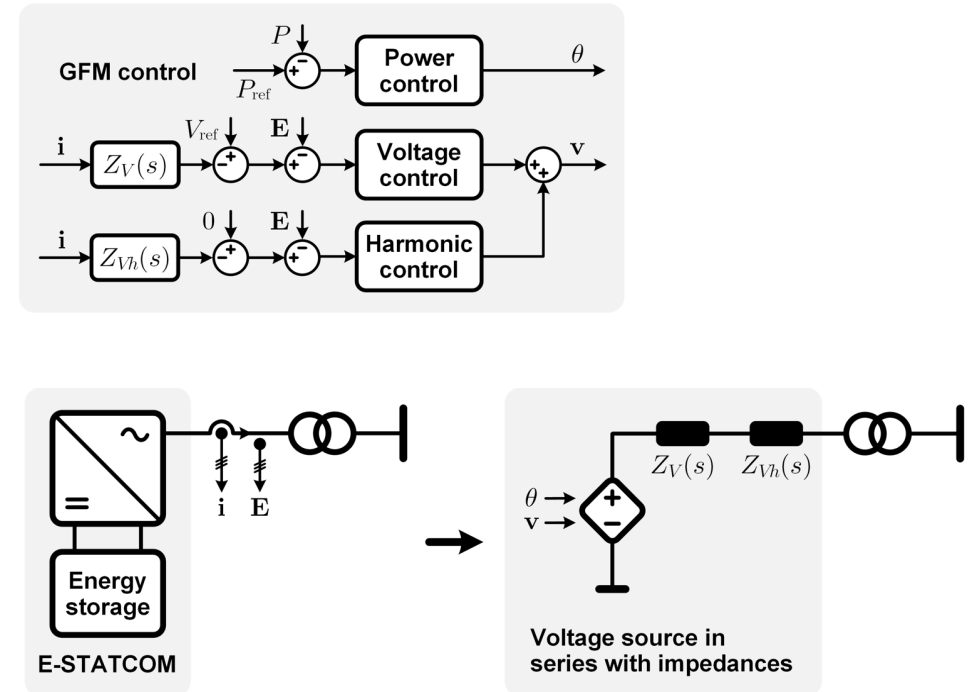


Grid-Forming E-STATCOM

System Hardware

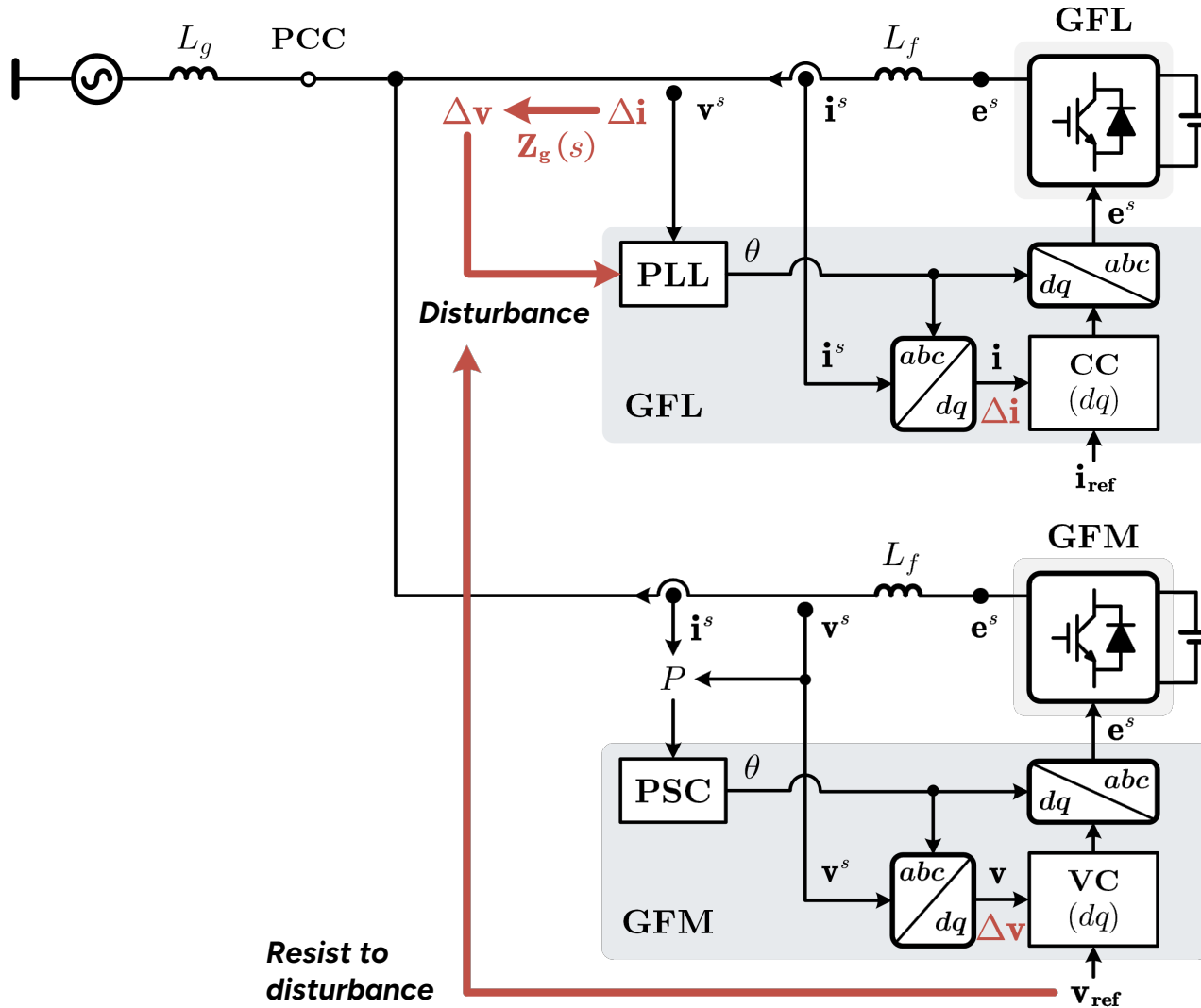


Control Software



[1] F. Zhao, X. Wang, Z. Zhou, L. Meng, J.-P. Hasler, J. R. Svensson, L. Kocewiak, H. Bai and H. Zhang, "Energy-storage enhanced STATCOMs for Wind Power Plants," *IEEE Power Electron. Mag.* 2023.

System Strength (Voltage Stiffness) Support



GFL-WTs

- Voltage-based synchronization (PLL)
- Higher voltage disturbance under *weak-grid* conditions (low short-circuit ratio)

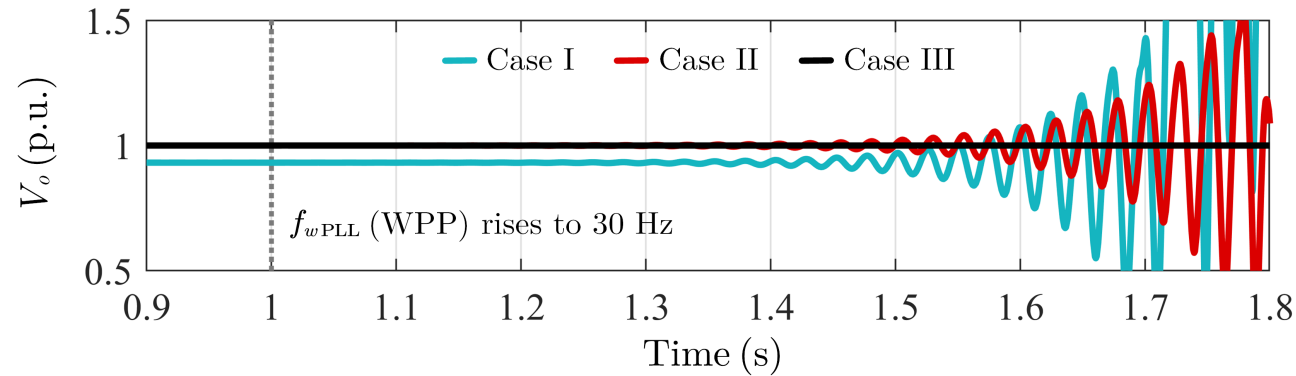
GFM E-STATCOM

- Voltage-source characteristics
- Capability to resist voltage disturbance within voltage control bandwidth
- Small-signal *stability enhancement*

System Strength (Voltage Stiffness) Support

Case I – only GFL-WTs; Case II – GFL-WTs + GFL-STATCOM; Case III – GFL-WTs + GFM E-STATCOM

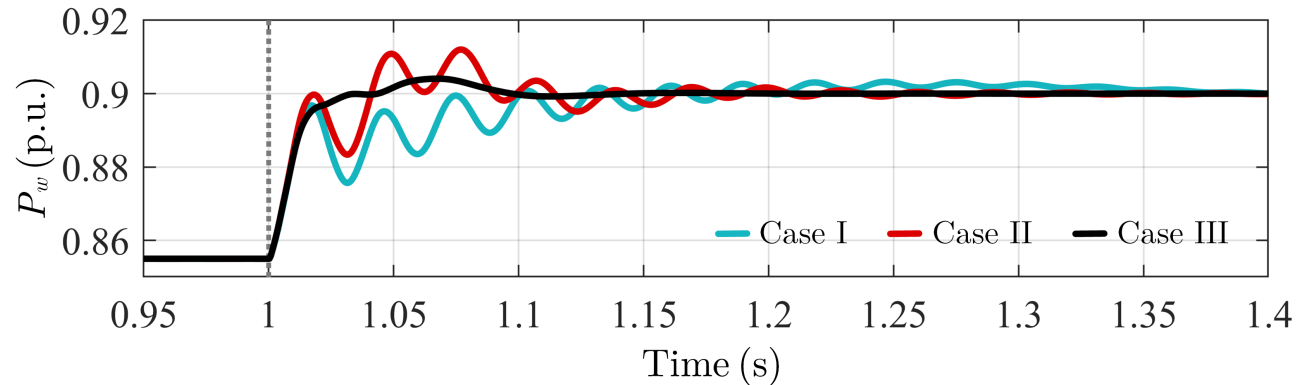
Comparison of PCC voltage magnitude of 3 cases



E-STATCOM stabilizing WPP in weak grids

- Control bandwidth tuned at 1 s
- Short-Circuit Ratio (SCR) = 1.63
- Case I and case II are unstable
- Case III (with E-STATCOM) is stable

Comparison of active power response of 3 cases



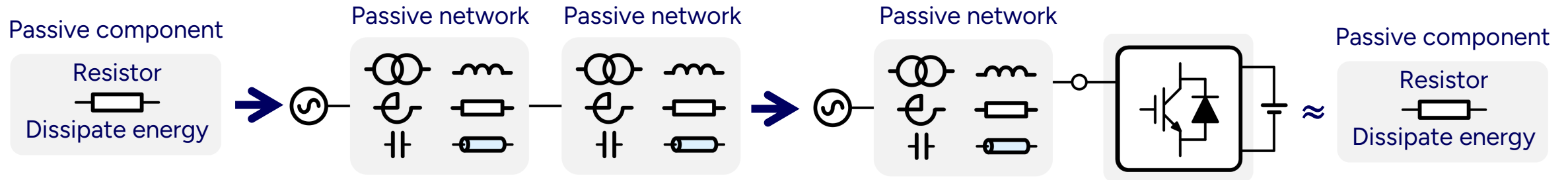
E-STATCOM improving transient dynamics

- Control reference of WPP changed at 1 s
- Case I and case II indicate insufficient damping
- Case III enhanced power controllability

[1] F. Zhao, X. Wang, Z. Zhou, Ł. Kocewiak, and J. R. Svensson, "Comparative study of battery-based STATCOM in grid-following and grid-forming modes for stabilization of offshore wind power plant," *Electric Power Systems Research*, vol. 212, Nov. 2022.

Positive Damping - Impedance Passivity

GFM shall present a non-negative resistance to the grid within 0-300 Hz [1]



Intrinsic non-passive nature of converters

- In low frequency range, GFM (GFL) converter is inherently non-passive at 0 Hz (dq -frame), or 50 Hz ($\alpha\beta$ -frame)
- Nature of constant power operation, e.g., $P = ui$
- Impedance matrix is required for the frequency range below 100 Hz ($\alpha\beta$ -frame)
- Insufficient, unnecessary stability criterion

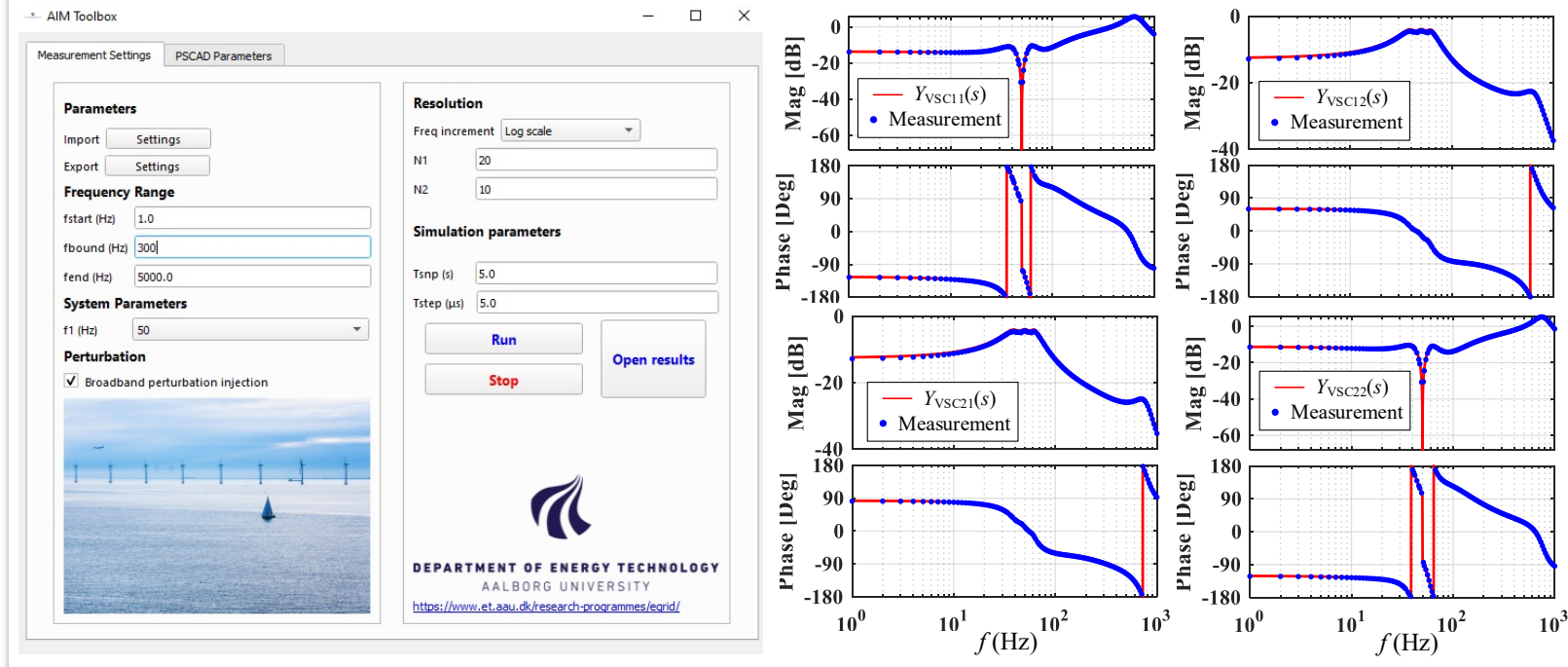
GFM shall present a non-negative resistance to the grid within 0-47 Hz and 53-250 Hz [2]

[1] NERC, "Grid forming functional specifications for BPS-connected battery energy storage systems," Sept. 2023.

[2] FINGRID, "Specific study requirements for grid energy storage systems," Jun. 2023.

Positive Damping - Impedance Measurement

Impedance measurement software – commercialized



Software users

TRANSNET BW

tennet
Taking power further

YONSEI
UNIVERSITY

상명대학교
SANGMYUNG UNIVERSITY

- Fully automated, PSCAD/EMT compatible
- Impedance matrix in different reference (dq or $\alpha\beta$) frame
- Used by Europe's leading TSOs in multiple commercial projects

- For more information, visit our spinoff www.aistability.dk

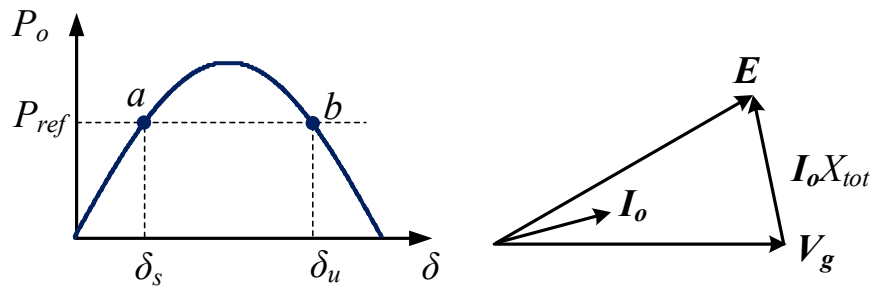
AI STABILITY

Nearly Constant Voltage Source

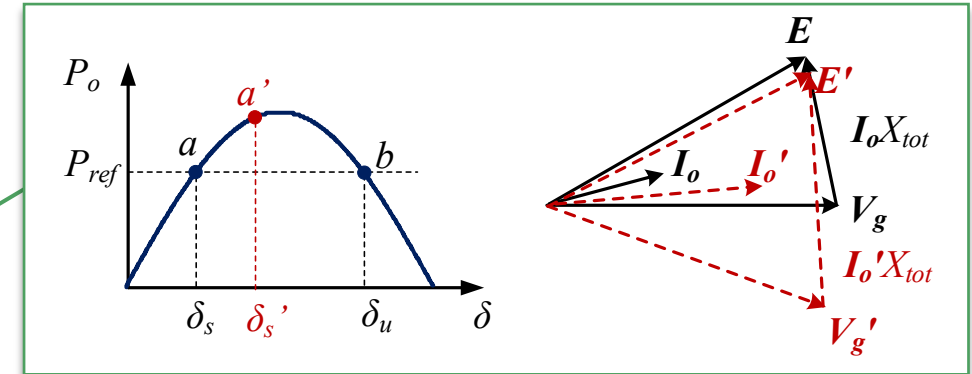
GFM shall maintain a nearly constant (slow) internal voltage source in the sub-transient timeframe [1]

Enhanced voltage stiffness under small phase jump

- Within current limit
- Transient stability (keep synchronism)

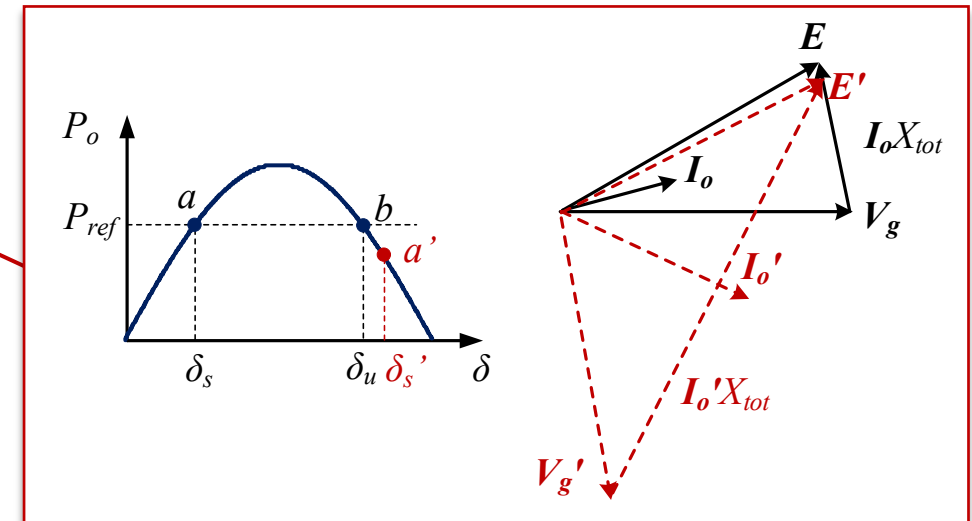


Small phase jump



Jeopardized transient stability with large phase jump

- Triggering current limit
- Transient instability (loss of synchronism)



[1] NERC, "Grid forming functional specifications for BPS-connected battery energy storage systems," Sept. 2023.

[2] H. Wu and X. Wang, "Control of Grid-Forming VSCs: A Perspective of Adaptive Fast/Slow Internal Voltage Source," *IEEE Trans. Power Electron.*, vol. 38, pp. 10151-10169, Aug. 2023.

Nearly Constant Voltage Source

4.3. The Control 5Hz Bandwidth Limit

For the avoidance of doubt the following applies:

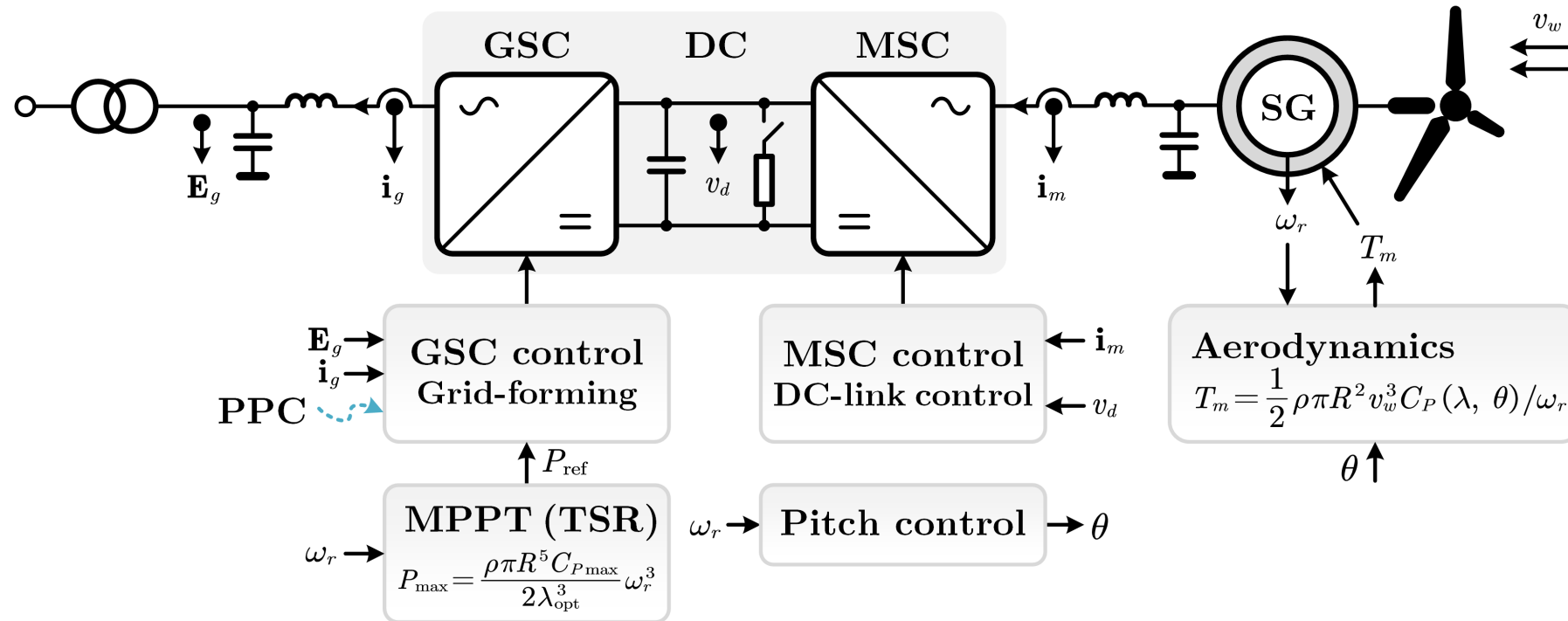
- a) For a GBGF-I system operating in the **Normal Mode**, all control functions are allowed, including items (1), (2) and (3) in this Section 4.3 provided **their control action conforms to the 5 Hz bandwidth limitation** as listed in Grid Code ECC.6.3.19.3.(v).(d).
- b) For a GBGF-I system operating in the **Withstand Mode**, all control functions are allowed, including items (1), (2) and (3) in this Section 4.3 with **no limit on their bandwidth** as listed in the proposed revision to Grid Code ECC.6.3.19.3.(v).(d).



[1] National Grid ESO, "Great Britain grid forming best practice guide," Apr. 2023.

[2] H. Wu and X. Wang, "Control of Grid-Forming VSCs: A Perspective of Adaptive Fast/Slow Internal Voltage Source," *IEEE Trans. Power Electron.*, vol. 38, pp. 10151-10169, Aug. 2023.

GFM-WTs under Small Phase Jump

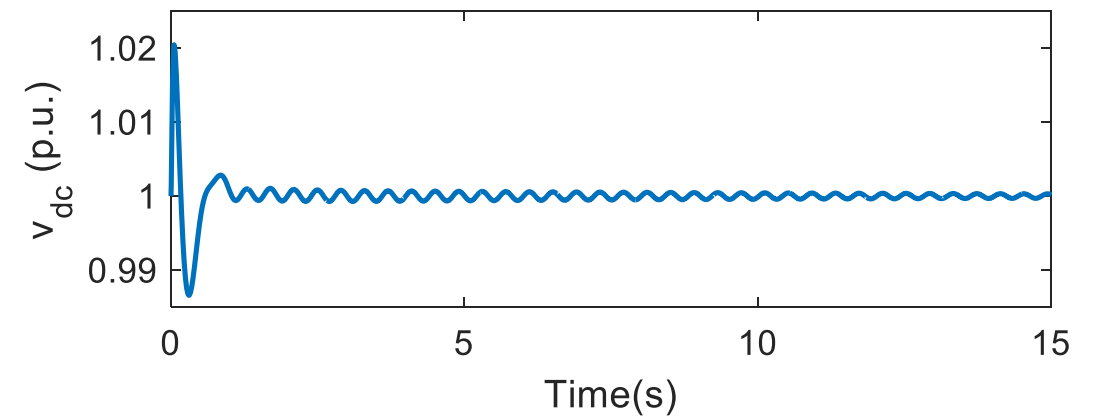
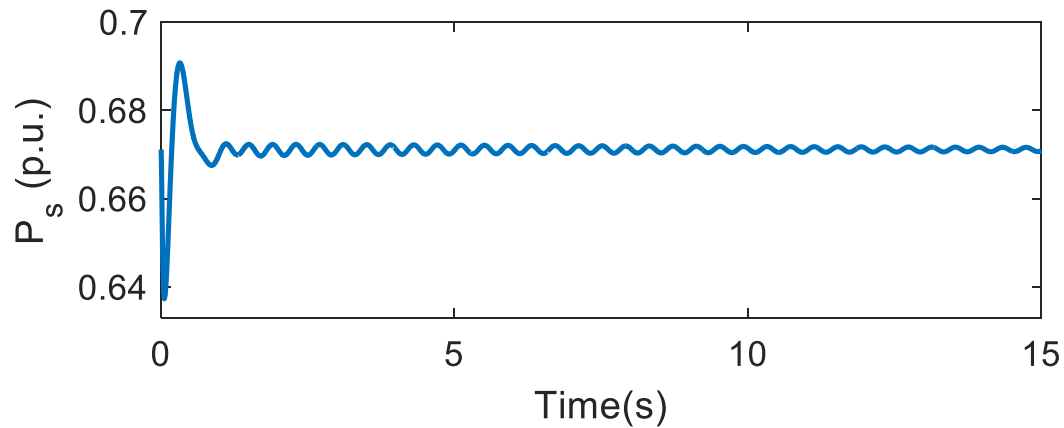
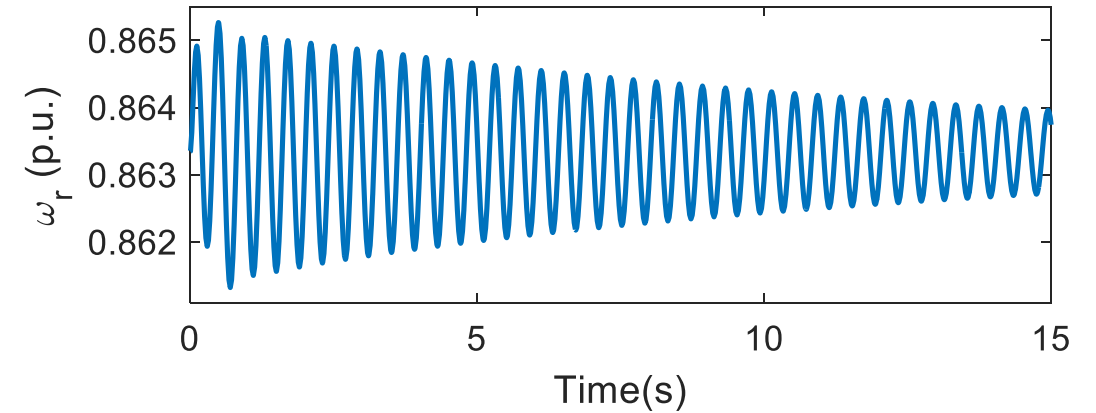
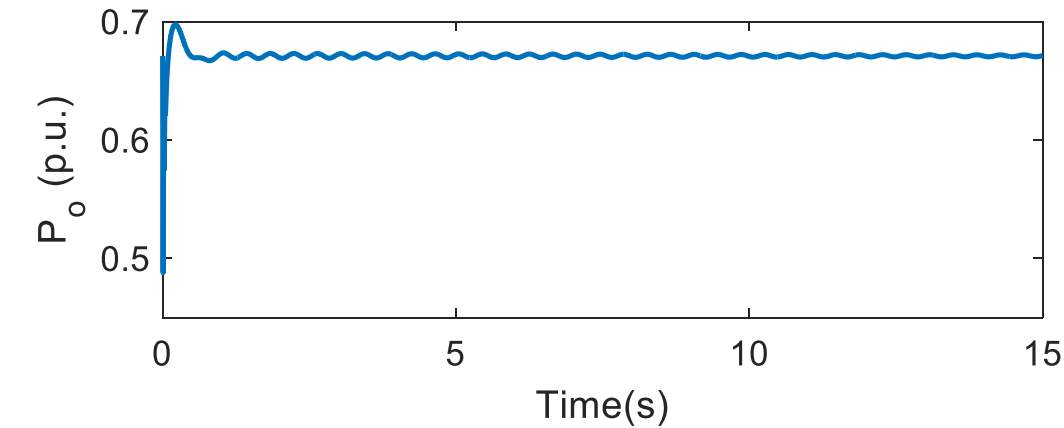


Electromechanical dynamics coupling between turbine shaft and power grid

- Power control reference of grid-side converter (GSC) is generated from aerodynamics
- Grid disturbances propagate through DC-link to machine-side converter (MSC) and drivetrain

GFM-WTs under Small Phase Jump

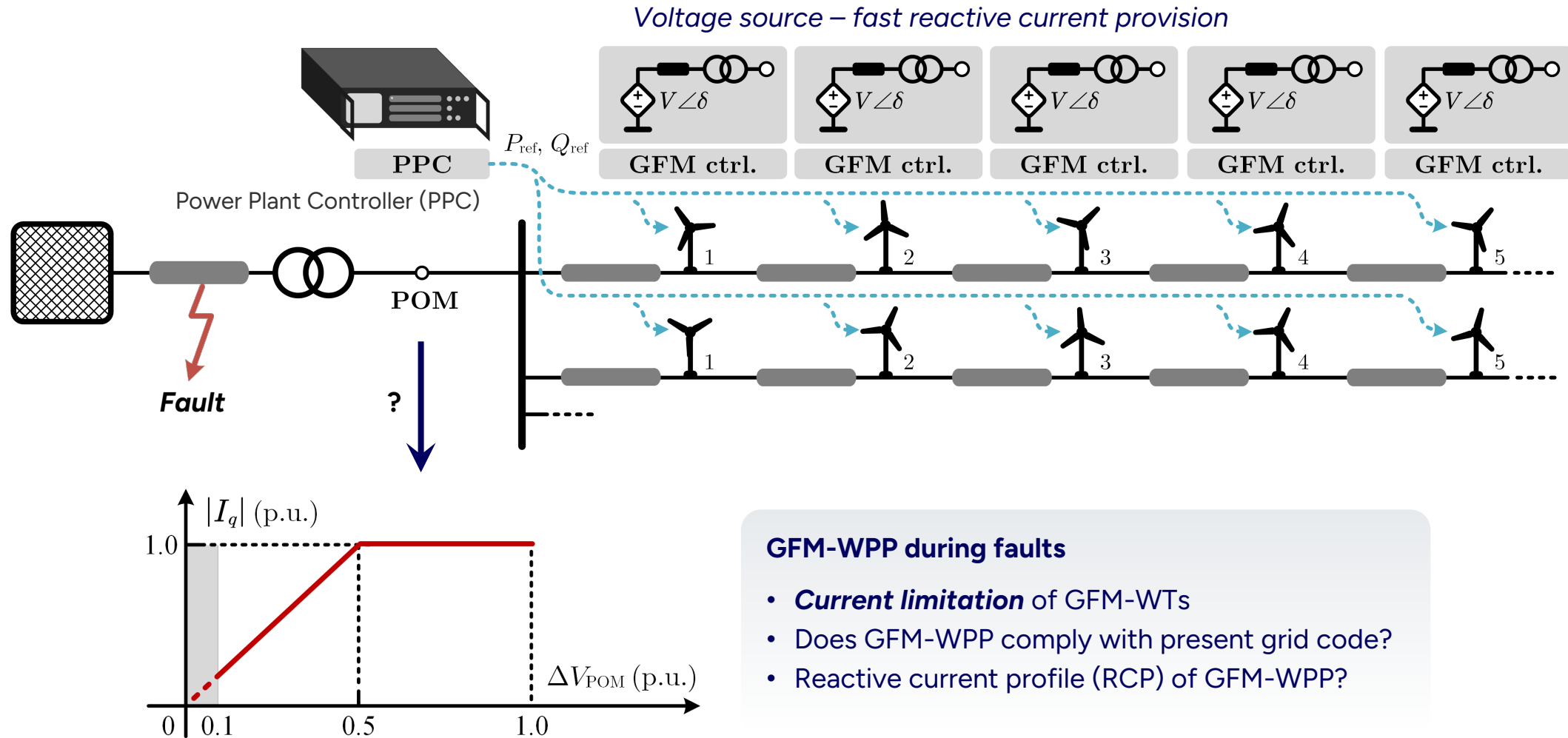
System responses (P_o , P_s , ω_r and v_{dc}) under $+2^\circ$ phase step in the grid voltage (with 2-mass drivetrain) [1]



P_o : output active power of GSC; P_s : input power of MSC; ω_r : rotating speed of drivetrain; v_{dc} : dc-link voltage.

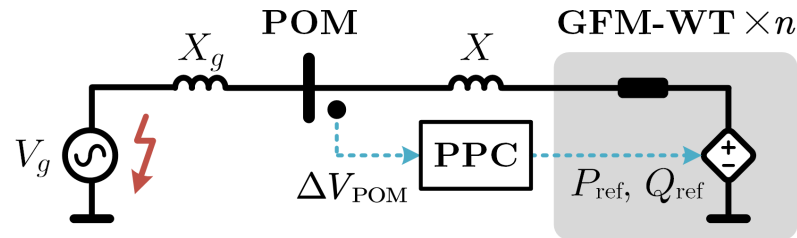
[1] S. Liu, H. Wu, X. Wang et al., "Torsional Vibration Analysis of Grid-Forming PMSG Wind Turbine," *Proc. Wind and Solar Integration Workshop*, Sept. 2023.

Reactive Current Profile of GFM-WPP



Reactive Current Profile of GFM-WPP

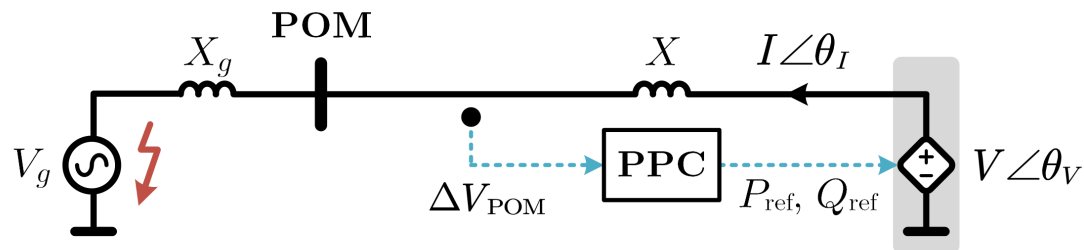
Analytical model of aggregated WPP – equivalent circuits based on general GFM characteristic



1. Voltage source when current is not limited

- Fundamental GFM characteristic

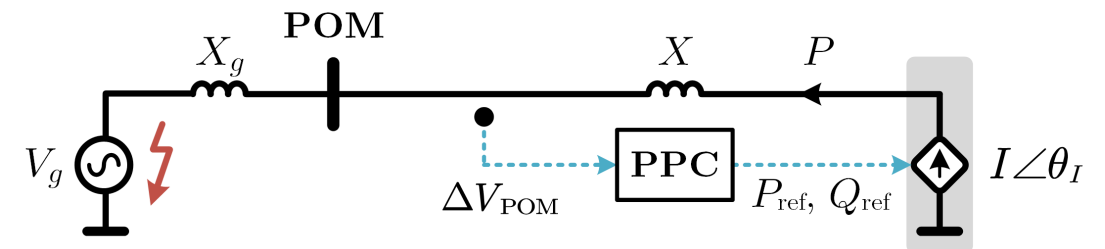
$$V = 1 \text{ p.u.}, \forall I < I_{\max}$$



2. Power-based synchronization when current is limited

- Phase-forming during faults (does not switch to PLL)

$$I \approx I_{\max}, P \approx P_{\text{ref}}$$



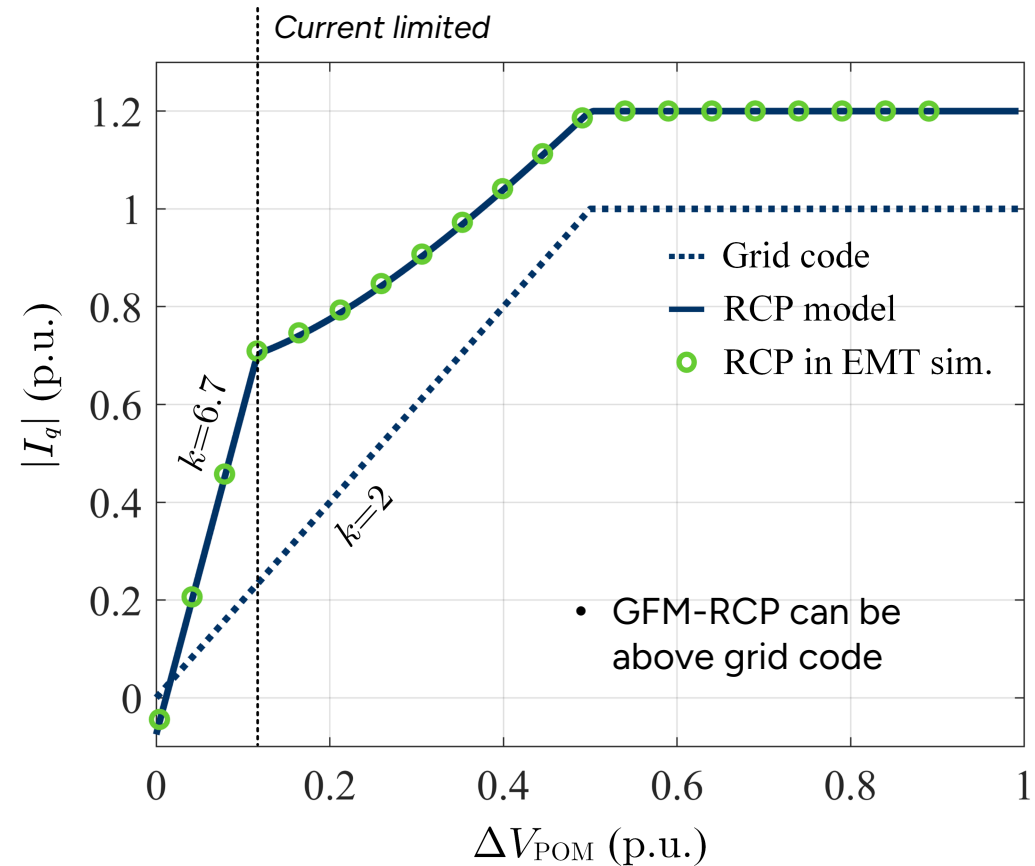
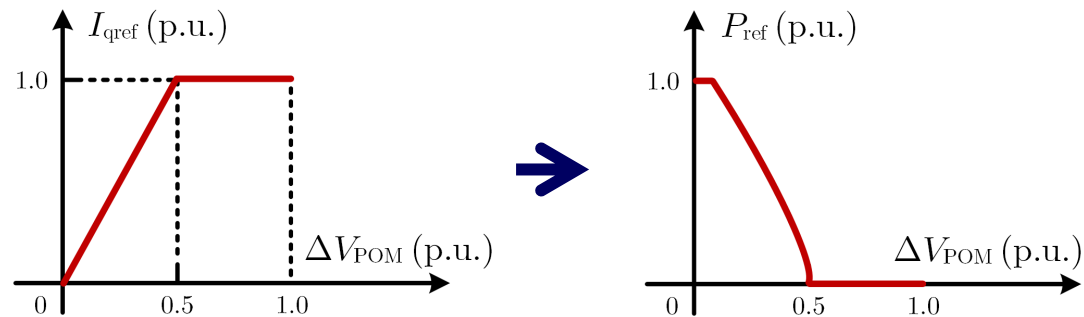
Reactive Current Profile of GFM-WPP

Adjusting active power reference (P_{ref}) to prioritize reactive current support [1]

P_{ref} decreases in respect to voltage dip $P_{\text{ref}} = \sqrt{S_f^2 - Q_{\text{ref}}^2}$

S_f Available apparent power during fault

Q_{ref} Reactive power reference following grid code



Takeaways

- **System strength support – voltage stiffness**
 - GFM E-STATCOM can enhance voltage stiffness under small disturbances
 - Yet, GFM capability – nearly constant (slow) voltage source can jeopardize transient stability
 - Further, even small disturbances can challenge GFM wind turbines, e.g., torsional vibrations of drivetrain
- **Impedance passivity – an effective indicator for positive damping of GFM in high frequency range**
 - Non-dissipative behavior of GFM converters around the fundamental frequency
 - Impedance matrix is necessary for low-frequency (within 100 Hz) dynamics analysis
- **Reactive current profile of GFM-WPPs can meet the present grid code**