KTH ROYAL INSTITUTE
OF TECHNOLOGY

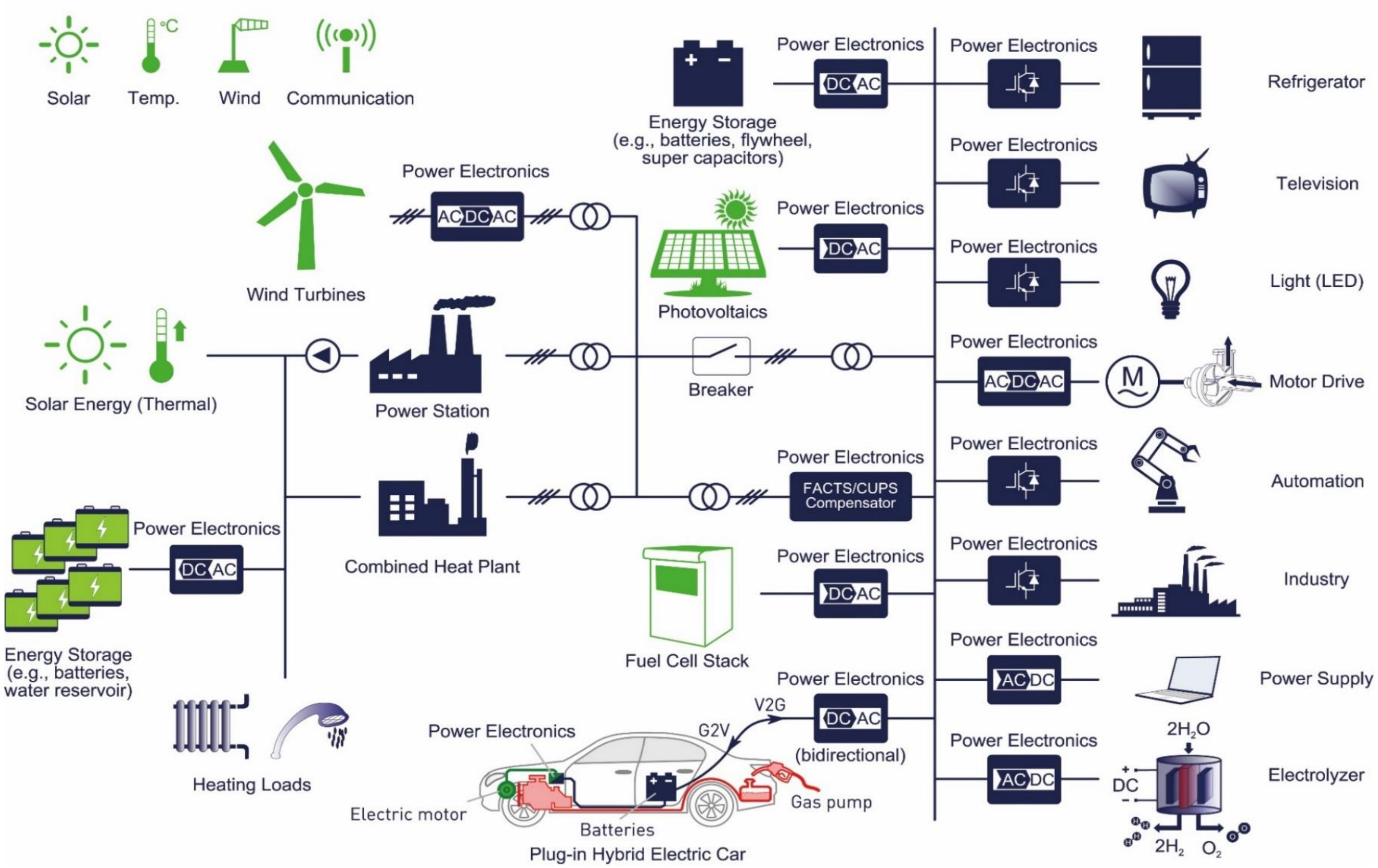
Powering the Future: Grid-Forming Converter Technology and Implementation

Xiongfei Wang

Revolutionizing Energy Systems with Power Electronics

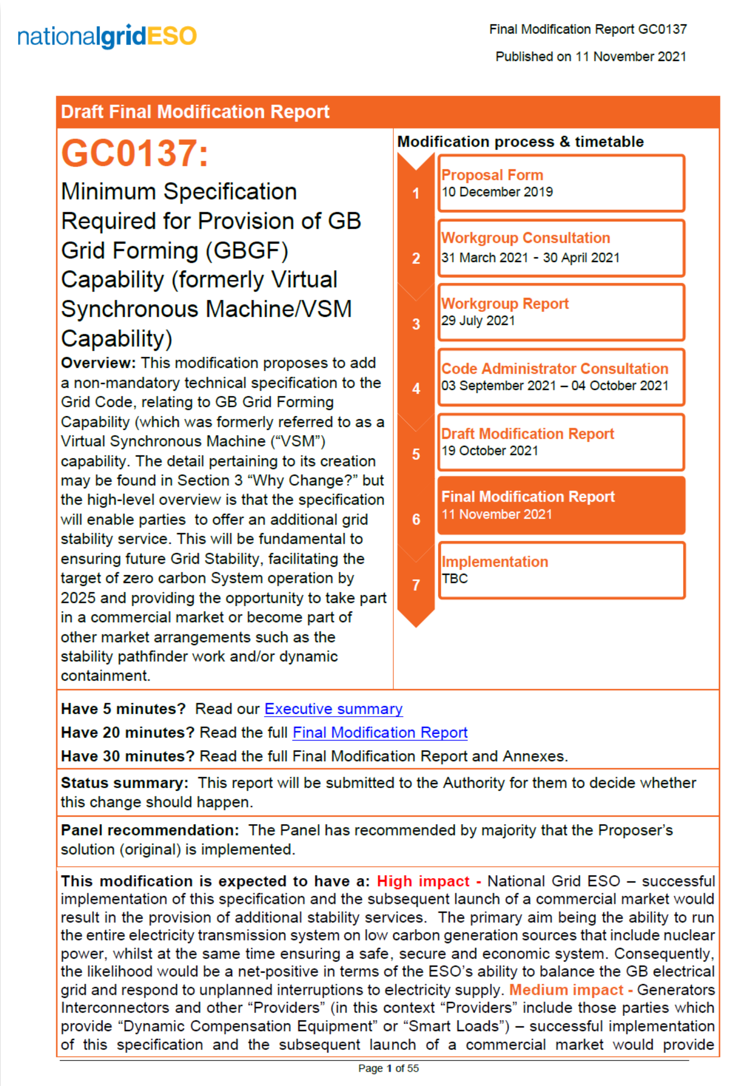
Power-electronic-based power systems

- **Less physics-governed but**
  more control-dependent dynamics
- **Wide-timescale interactions**
  bring more stability problems
- **Vendor-specific black-box**
  inverter control & protection
- **Large-scale power-to-X plants**
  ride through grid disturbances
- **Evolving grid structure with**
  challenges and opportunities



Grid-Forming Capability Requirements

Grid code, report, white paper



nationalgridESO

Final Modification Report GC0137

Published on 11 November 2021

Draft Final Modification Report

GC0137:

Minimum Specification Required for Provision of GB Grid Forming (GBGF) Capability (formerly Virtual Synchronous Machine/VSM Capability)

Overview: This modification proposes to add a non-mandatory technical specification to the Grid Code, relating to GB Grid Forming Capability (which was formerly referred to as a Virtual Synchronous Machine ("VSM") capability. The detail pertaining to its creation may be found in Section 3 "Why Change?" but the high-level overview is that the specification will enable parties to offer an additional grid stability service. This will be fundamental to ensuring future Grid Stability, facilitating the target of zero carbon System operation by 2025 and providing the opportunity to take part in a commercial market or become part of other market arrangements such as the stability pathfinder work and/or dynamic containment.

Modification process & timetable

1. Proposal Form
10 December 2019
2. Workgroup Consultation
31 March 2021 - 30 April 2021
3. Workgroup Report
29 July 2021
4. Code Administrator Consultation
03 September 2021 – 04 October 2021
5. Draft Modification Report
19 October 2021
6. Final Modification Report
11 November 2021
7. Implementation
TBC

Have 5 minutes? Read our Executive summary

Have 20 minutes? Read the full Final Modification Report

Have 30 minutes? Read the full Final Modification Report and Annexes.

Status summary: This report will be submitted to the Authority for them to decide whether this change should happen.

Panel recommendation: The Panel has recommended by majority that the Proposer's solution (original) is implemented.

This modification is expected to have a: High impact - National Grid ESO – successful implementation of this specification and the subsequent launch of a commercial market would result in the provision of additional stability services. The primary aim being the ability to run the entire electricity transmission system on low carbon generation sources that include nuclear power, whilst at the same time ensuring a safe, secure and economic system. Consequently, the likelihood would be a net-positive in terms of the ESO's ability to balance the GB electrical grid and respond to unplanned interruptions to electricity supply. Medium impact - Generators Interconnectors and other "Providers" (in this context "Providers" include those parties which provide "Dynamic Compensation Equipment" or "Smart Loads") – successful implementation of this specification and the subsequent launch of a commercial market would provide

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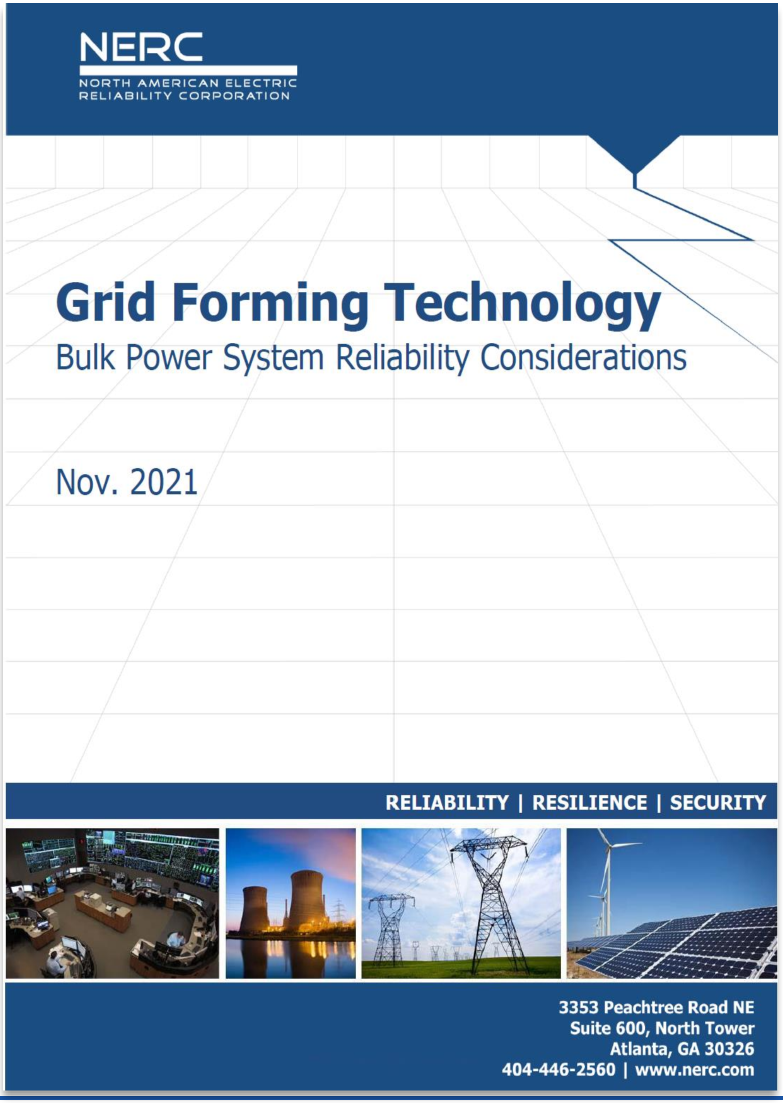

NERC

NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

Grid Forming Technology

Bulk Power System Reliability Considerations

Nov. 2021

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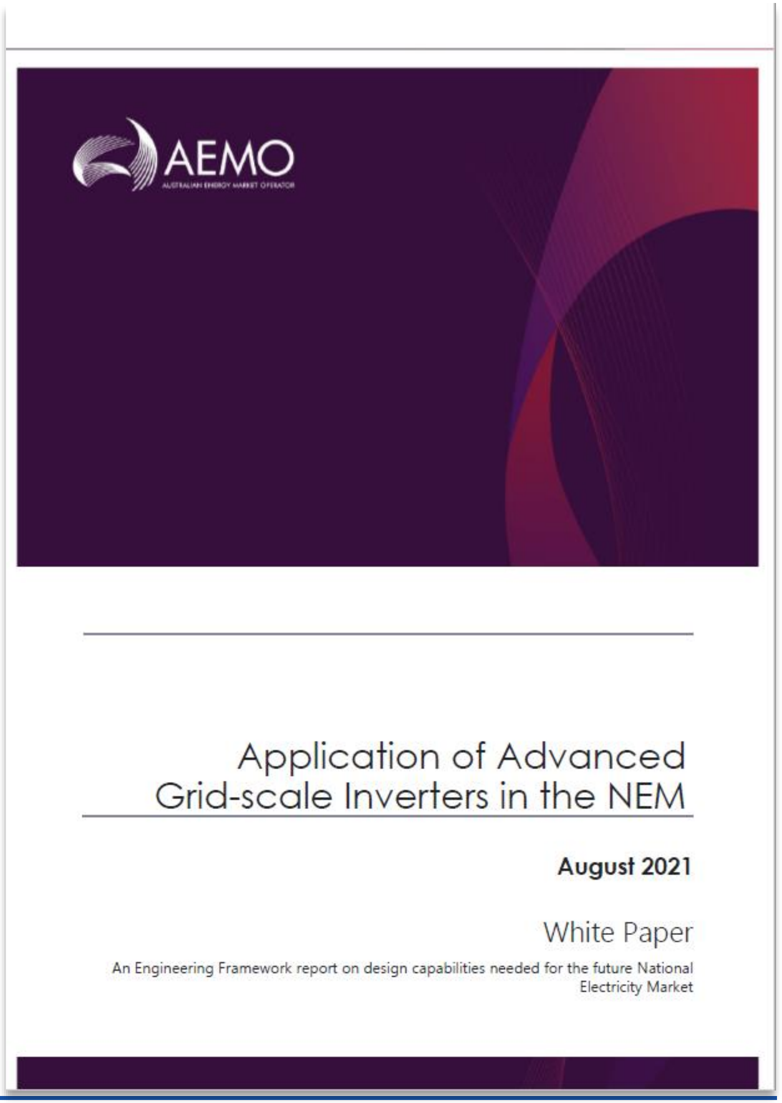


AEMO

AUSTRALIAN ENERGY MARKET OPERATOR

Application of Advanced Grid-scale Inverters in the NEM

August 2021

White Paper

An Engineering Framework report on design capabilities needed for the future National Electricity Market

Grid-Forming Capability Requirements

From European Network of TSOs (ENTSO-E)

Ideal resource to power system

- **Creating (form) system voltage**
- Contributing to fault level (short-circuit power)
- Contributing to total system inertia
- Support system survival to enable the effective operation of low frequency demand disconnection for rare system splits
- Acting as a sink to counter harmonics and inter-harmonics in system voltage
- Acting as a sink to counter any unbalance in system voltage
- Prevent adverse control system interactions

[2] ENTSO-E, “Grid-forming capabilities: towards system level integration,” Mar. 2021.

High Penetration of Power Electronic Interfaced Power Sources and the Potential Contribution of Grid Forming Converters

Technical Report

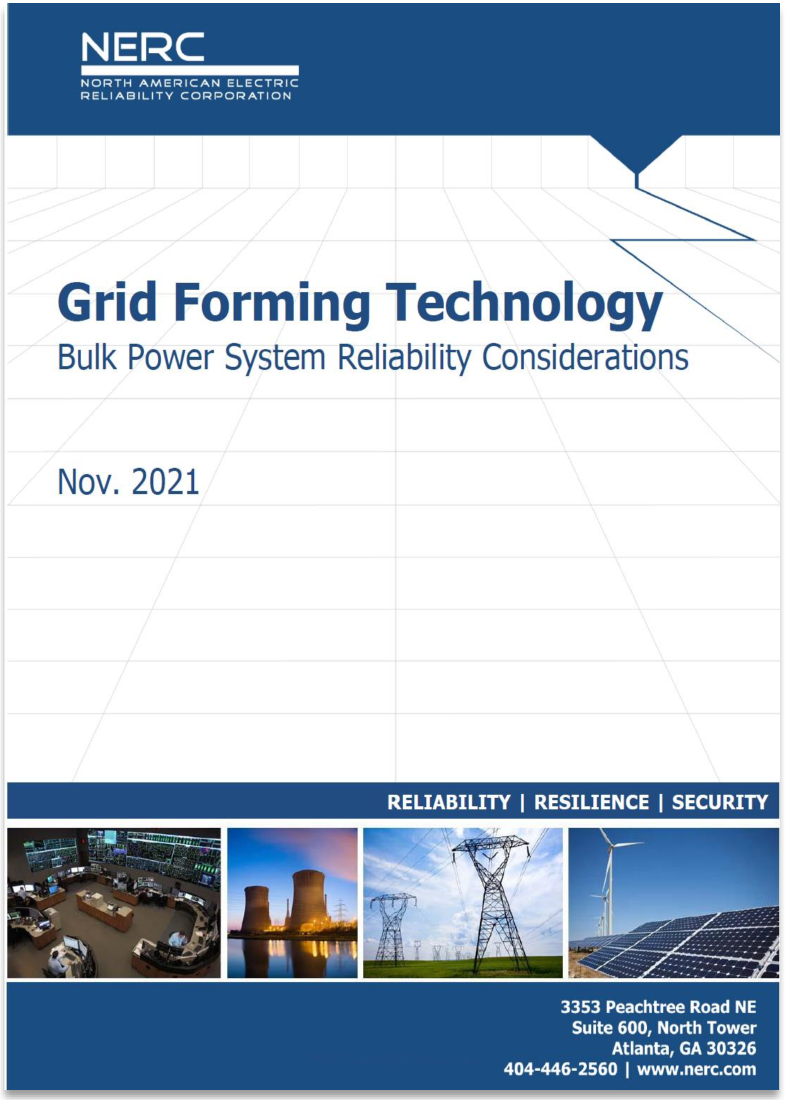
ENTSO-E Technical Group on High Penetration of Power Electronic Interfaced Power Sources

Grid-Forming Capability Requirements

From NERC

Essential requirement: internal voltage source

- **Maintaining an internal voltage phasor:**
  - Being constant or nearly constant in the sub-transient to transient time frame
  - Maintain synchronism with other devices
  - Regulate active and reactive power appropriately
- Islanding operation
- Arresting the decline or increase of frequency, and contributing the subsequent recovery of frequency
- Reactive power support and voltage regulation, aiding fast and stable post-fault voltage recovery
- Reduce adverse control interactions
- Providing the prescribed level of oscillation damping
- Active low-order harmonic cancellation
- Black-start capability



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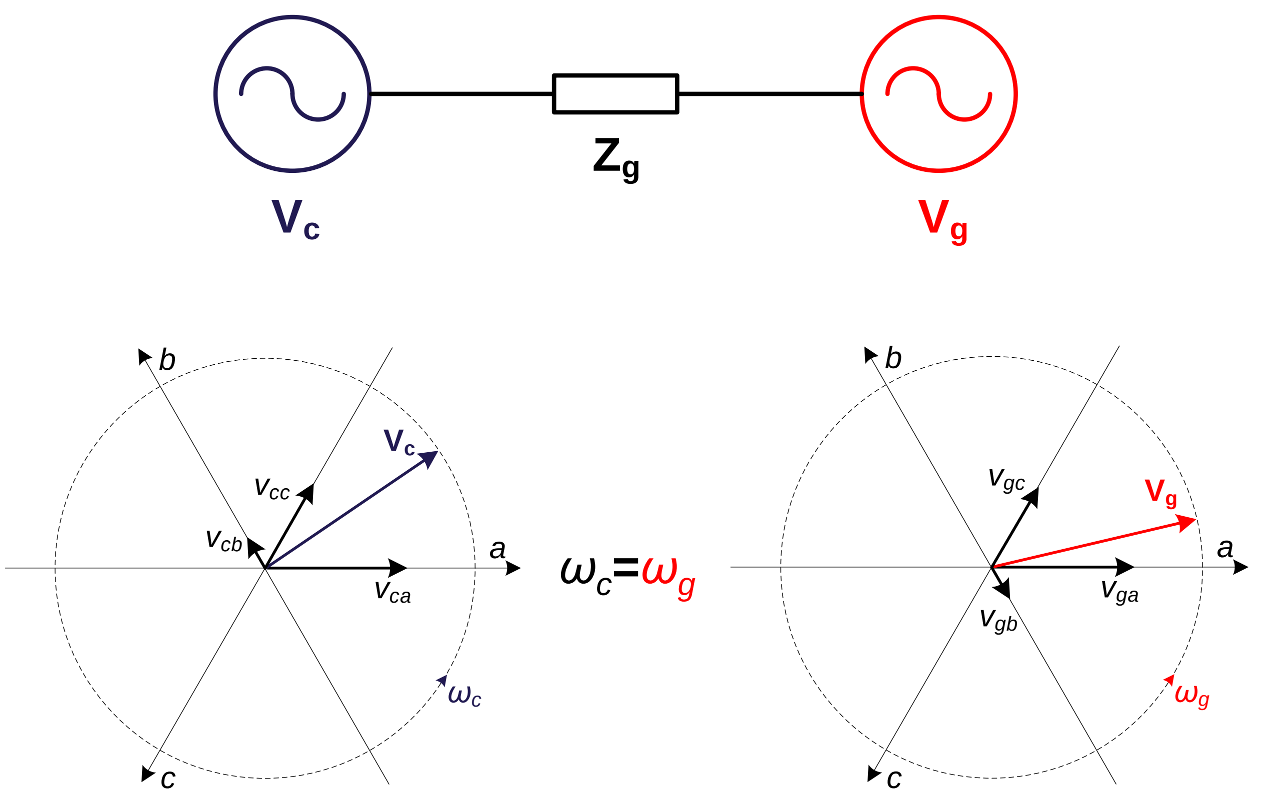
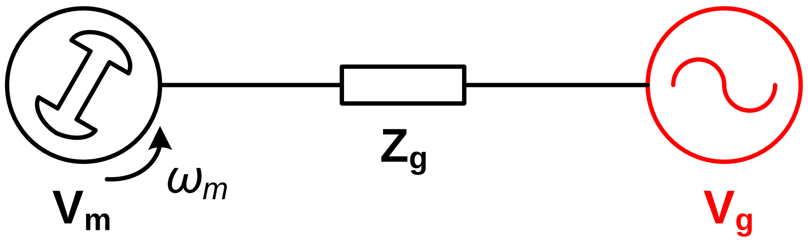
[3] NERC, "Grid forming technology: bulk power system reliability considerations," Nov. 2021.

Grid-Forming Converter Technology

Synchronization is the foundation of ac systems

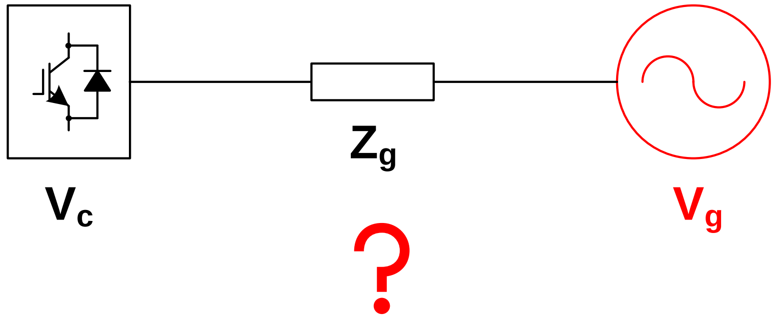


$\omega_c=\omega_g$



Electromechanical (swing) equation

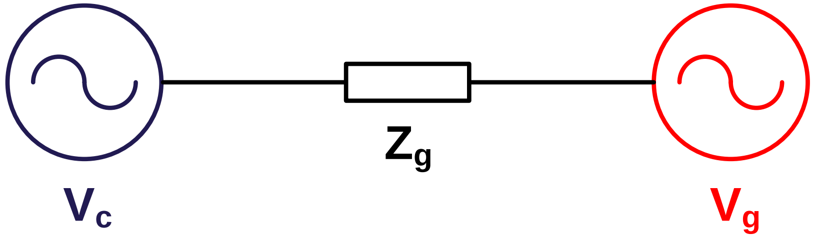
$$J\dot{\omega}_m + D\omega_m = \tau_m - \tau_e$$

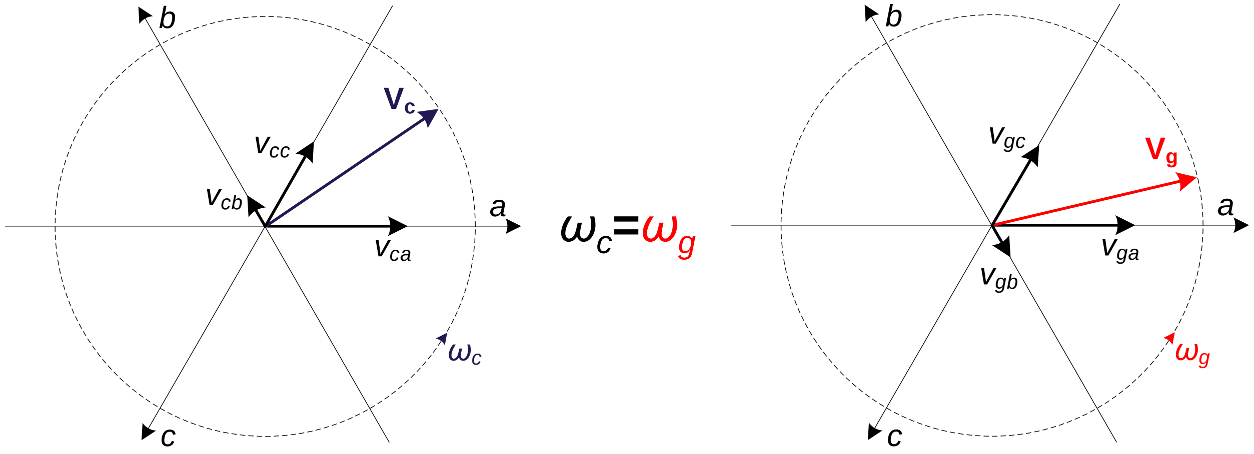


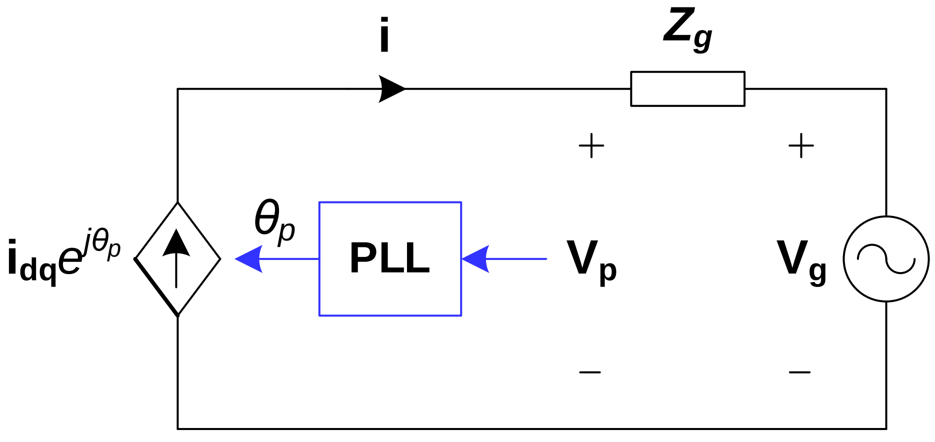
[4] X. Wang, M. Taul, H. Wu, Y. Liao, F. Blaabjerg and L. Harnefors “Grid-synchronization stability of converter-based resources–an overview” *IEEE Open Jour. Ind. Appl.*, vol. 1, pp. 115–134, 2020.

Grid-Forming Converter Technology

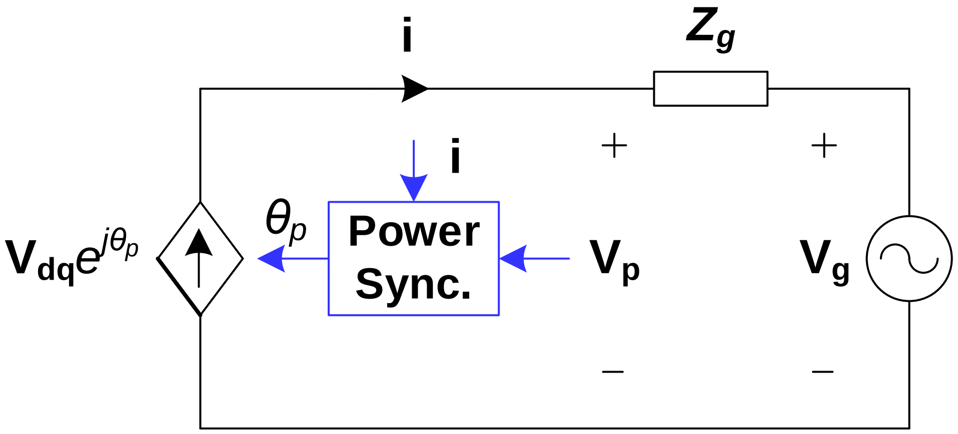
Two fundamental synchronization principles







Voltage-based synchronization

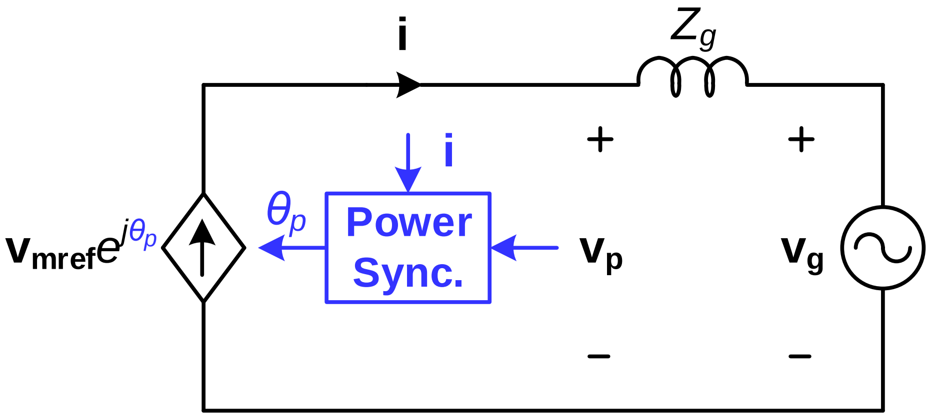


Power-based synchronization

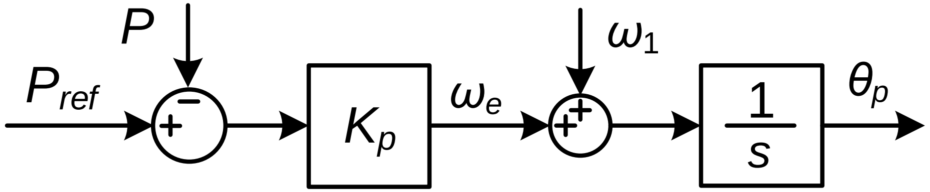
[4] X. Wang, M. Taul, H. Wu, Y. Liao, F. Blaabjerg and L. Harnefors “Grid-synchronization stability of converter-based resources–an overview” *IEEE Open Jour. Ind. Appl.*, vol. 1, pp. 115–134, 2020.

Grid-Forming Converter Technology

Basics of power-based synchronization control



Power-based synchronization



Active power-frequency droop control

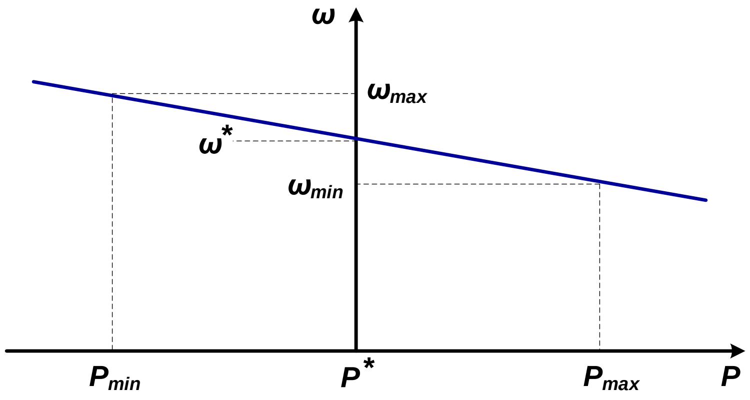
***P*-*ω* controller options**

- **P**: Droop Control & Power Synchronization Control
- **Low-pass filter** (swing equation): Inertia and damping provision, yet with limited *P-f* droop gain
- **PI**: Zero static error under grid frequency deviation, inertia and damping, yet no *P-f* droop characteristic
- **Lead-lag filter**: flexible *P-f* droop gain, inertia and damping coefficients

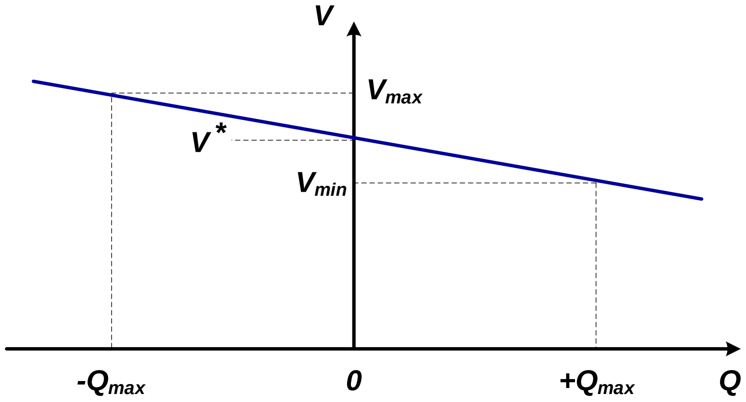
Grid-Forming Converter Technology

Basics of power-based synchronization control

1. Power Sharing

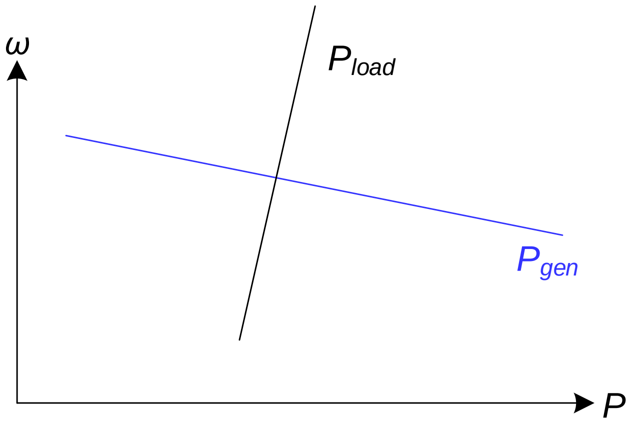


P-ω Droop

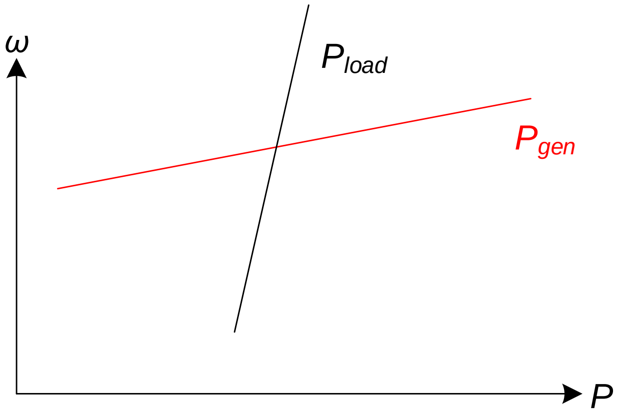


Q-V Droop

2. Load frequency control



Stable active power-frequency control



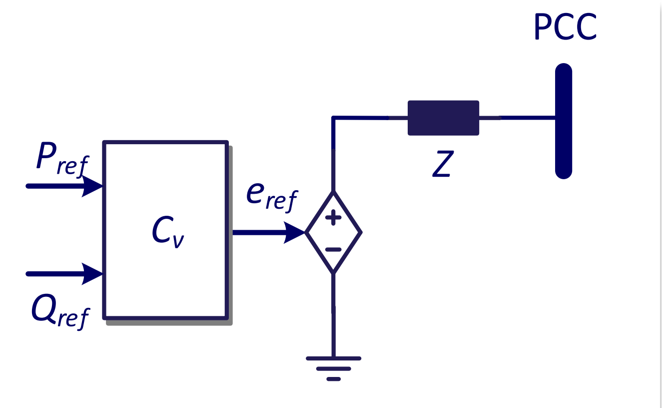
Unstable active power-frequency control

[5] X. Wang, J. Guerrero, F. Blaabjerg, and Z. Chen “A review of power electronics based microgrids,” Jour. Power Electron., vol. 12, pp. 181-192, 2012.

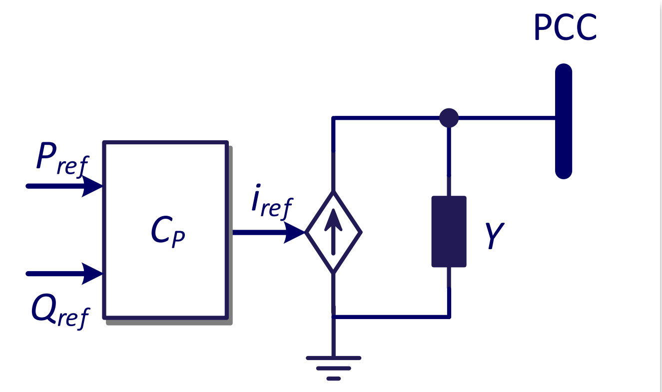
Grid-Forming Converter Technology

Need of current control with Grid-Forming?

- Low-frequency resonance and non-minimum phase
- Full control of current (harmonics, fault, etc.)



Grid-Forming Control

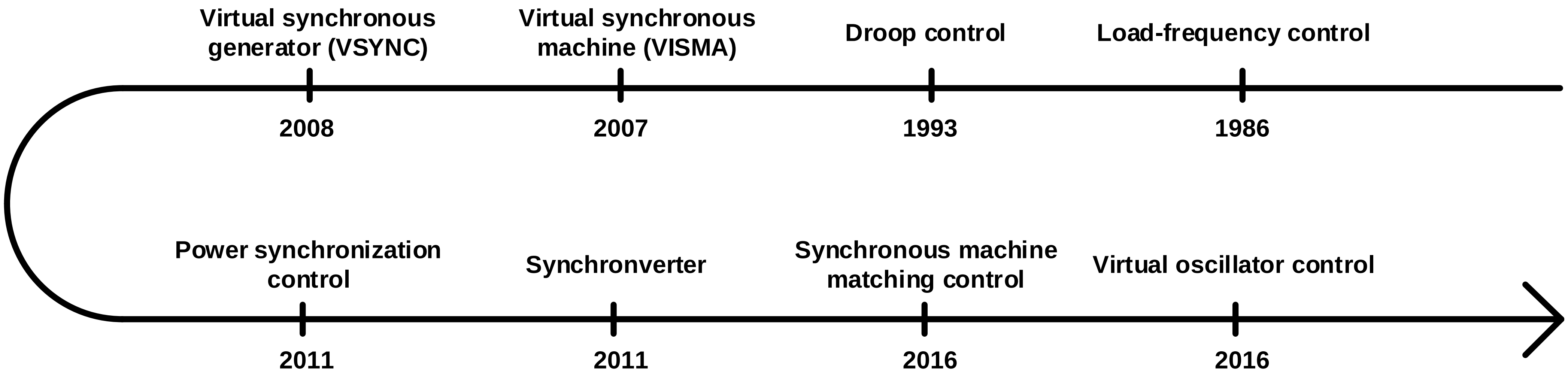


Grid-Following Control

- Instability and dynamic couplings in low SCR grids
- Less control interactions in the high-frequency range

Grid-Forming Converter Technology

Historical review of grid-forming control



Virtual synchronous generator (VSYNC) 2008

Virtual synchronous machine (VISMA) 2007

Droop control 1993

Load-frequency control 1986

Power synchronization control 2011

Synchronverter 2011

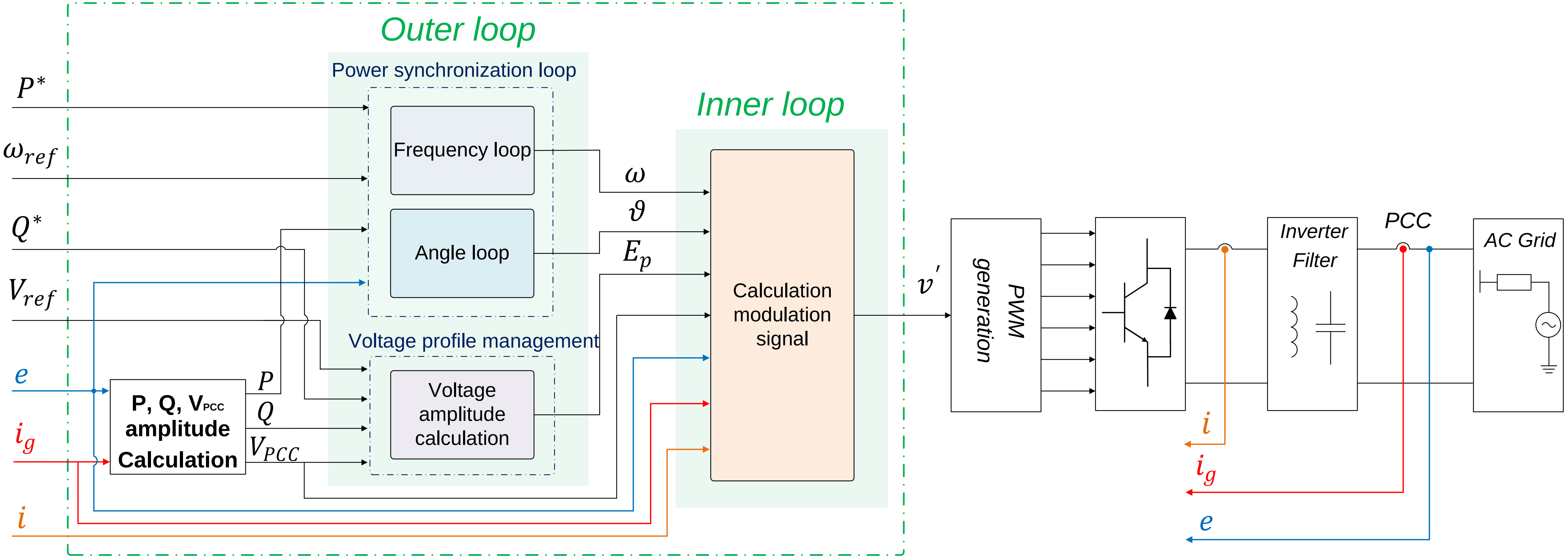
Synchronous machine matching control 2016

Virtual oscillator control 2016

[6] X. Wang and D. Yang, “Design-oriented stability analysis and control of power converters in weak grids,” IEEE PEAC Tutorial, 2018.

Grid-Forming Converter Technology

Many control options yet grid code not ready yet



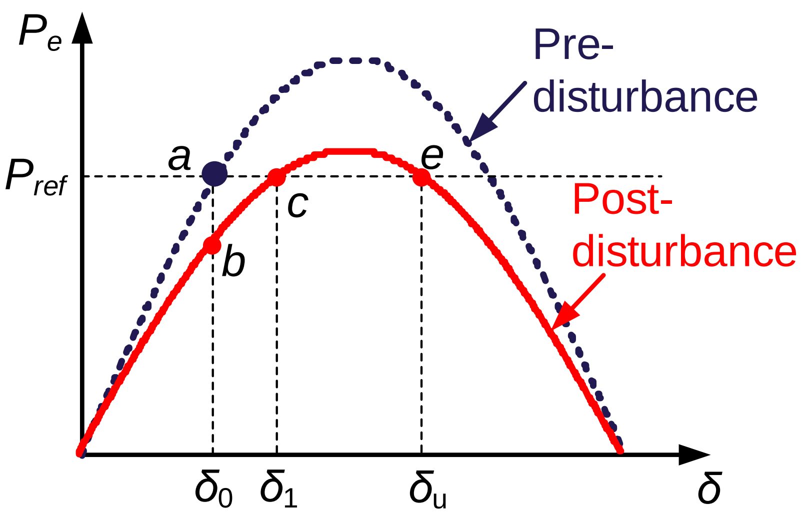
[8] R. Rosso, X. Wang, M. Liserre, X. Lu, S. Engelken, “Grid-forming converters: control approaches, grid-synchronization, and future trends – a review,” *IEEE Open Jour. Ind. Appl.*, vol. 2, pp. 93 - 109, 2021.

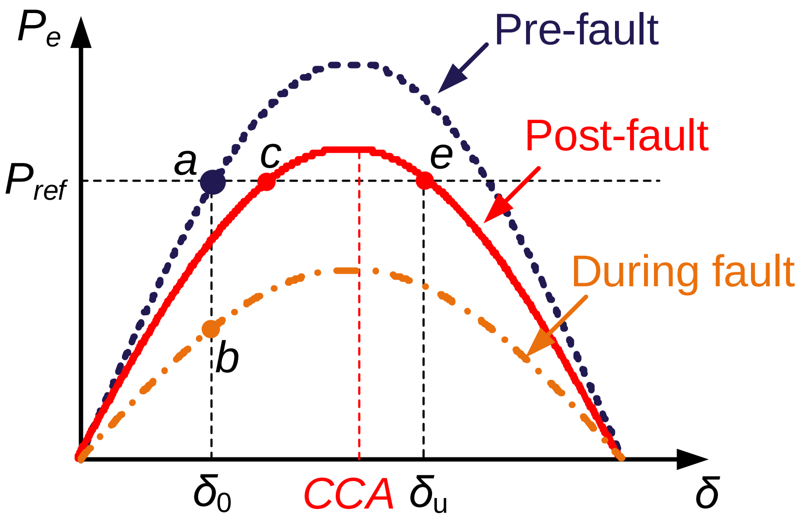
Large-Disturbance Withstand Capability

Transient stability of grid-forming converter

Virtual Synchronous Machine (VSM) – swing dynamics

$$P_{ref} - P_e - D\dot{\delta} = 2H\ddot{\delta}$$





Stable equilibrium point (SEP) *c*

Unstable equilibrium point (UEP) *e*

- Before SEP *c*, $P_m > P_e$, ω_{VSM} increases
- After SEP *c*, $P_m < P_e$, ω_{VSM} decreases
- Loss of synchronization (LOS) if $\omega_{VSM} > \omega_g$ at UEP *e*

Critical clearing angle (CCA)

Critical clearing time (CCT)

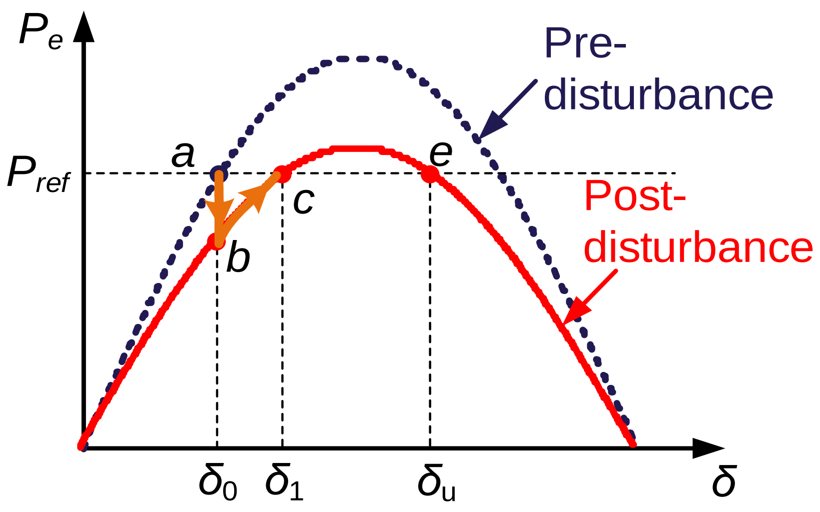
- LOS if fault clearing time > CCT

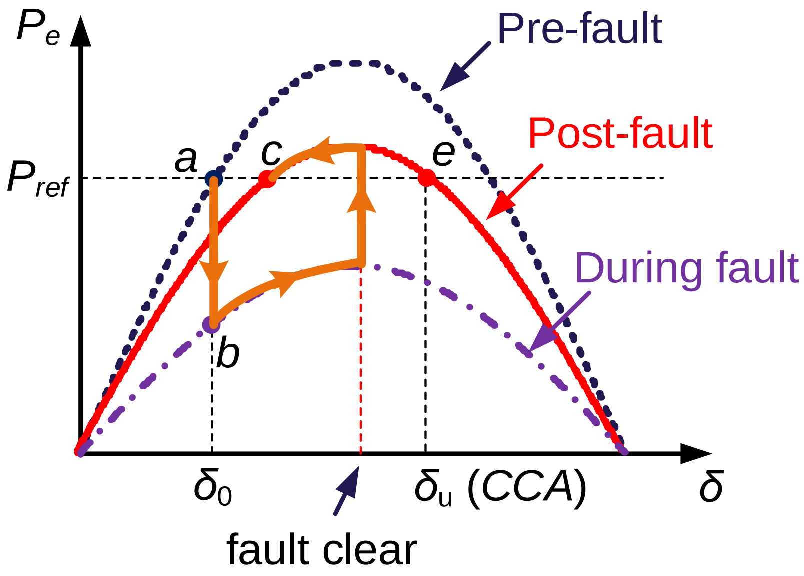
Large-Disturbance Withstand Capability

Transient stability of grid-forming converters

Inertia-less droop control

$$\dot{\delta} = K_i \left(P_{ref} - P_e \right)$$





- Converge to SEP *c* without overshoot
- Inertia-less control better than VSM

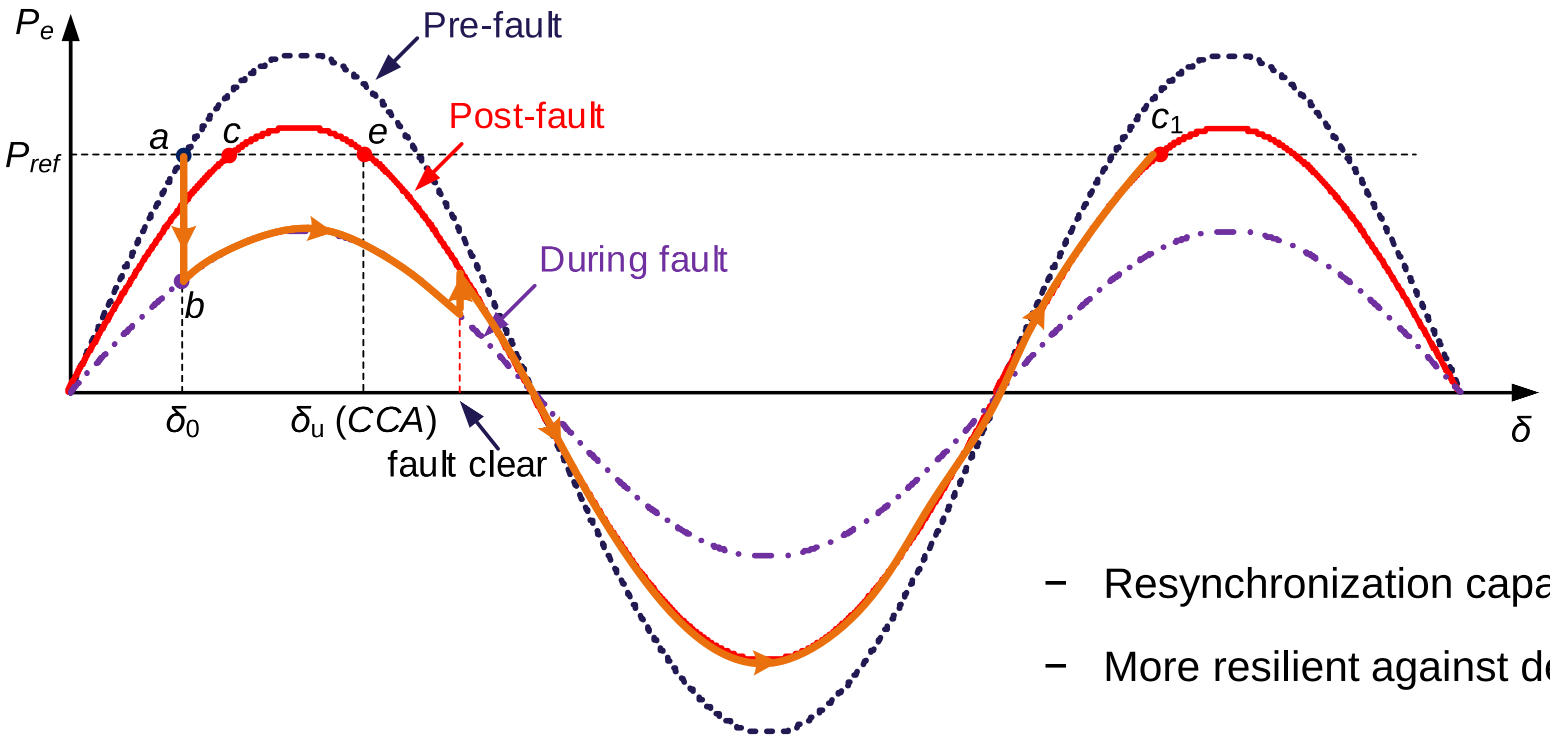
- Constant critical clearing angle (CCA) fixed to UEP *e* $CCA = \delta_u$

Large-Disturbance Withstand Capability

Transient stability of grid-forming converters

Inertia-less droop control

$$\dot{\delta} = K_i \left(P_{ref} - P_e \right)$$

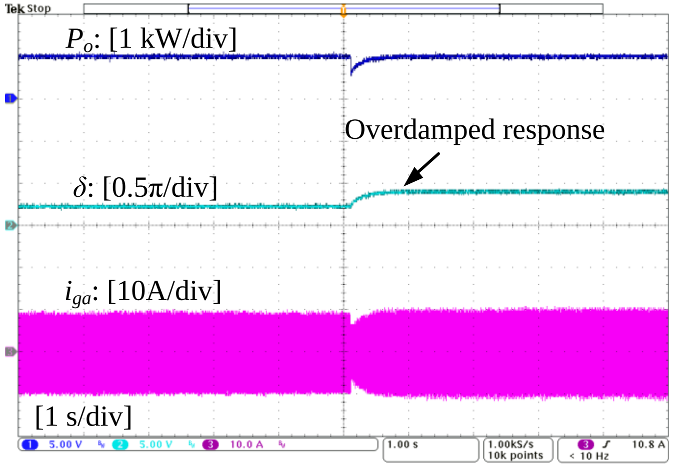
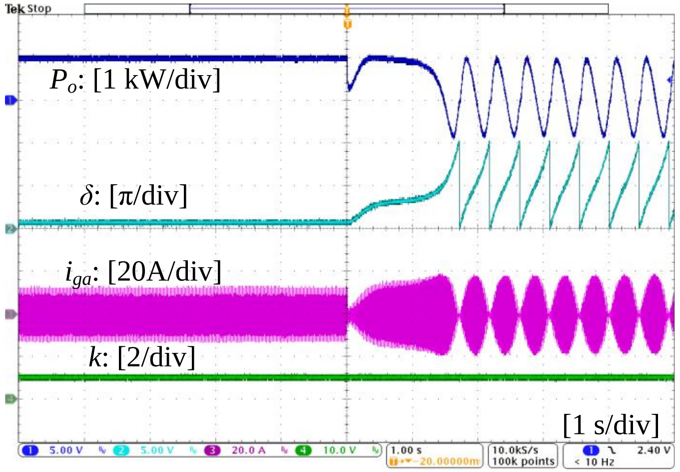
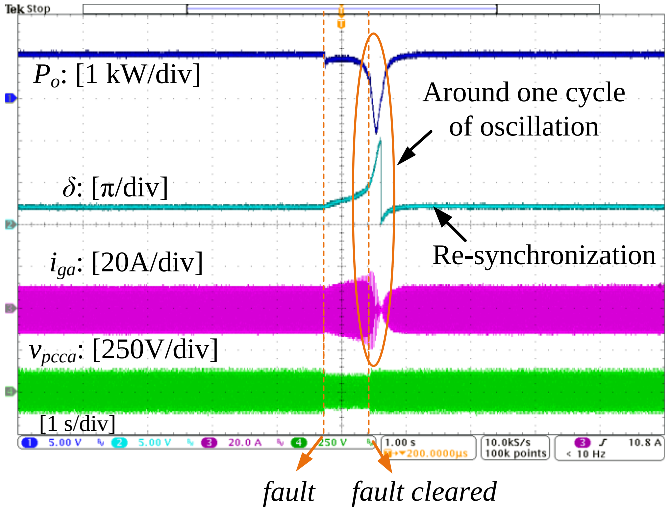
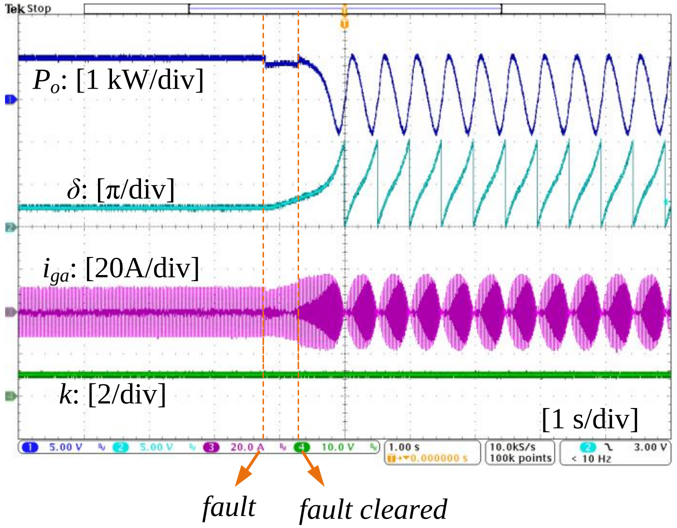


- Resynchronization capability
- More resilient against delayed fault clearance

[10] H. Wu and X. Wang, “Design-oriented transient stability analysis of grid-connected converters with power synchronization control,” *IEEE Trans. Ind. Electron.*, vol. 66, no. 8, pp. 6473–6482, Aug. 2019.

Large-Disturbance Withstand Capability

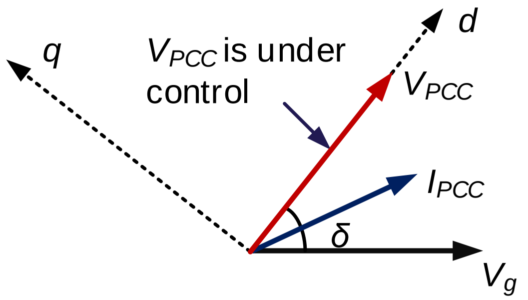
Inertia is not always good nor needed

Post-disturbance	First-order *P-ω* (droop) control	Second-order *P-ω* (VSM) control
With Equilibria	 Overdamped response	
No Equilibria (FCT>CCT)	 Around one cycle of oscillation Re-synchronization	

Large-Disturbance Withstand Capability

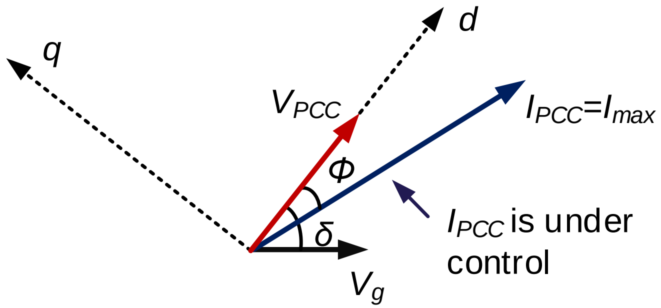
Current limiting control affects transient stability

Voltage control mode

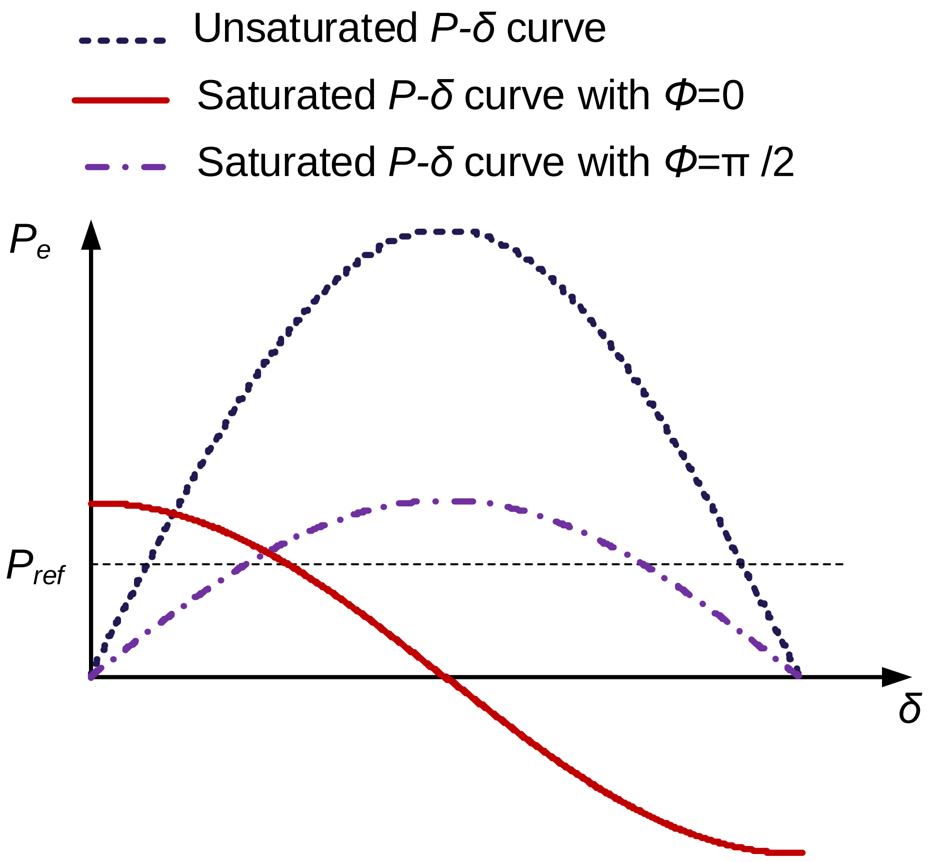


$$P_e = \frac{3V_{PCC}V_g}{2X_g}\sin\delta$$

Current limiting mode



$$P_e = \frac{3}{2} I_{max} V_g \cos(\delta - \phi)$$



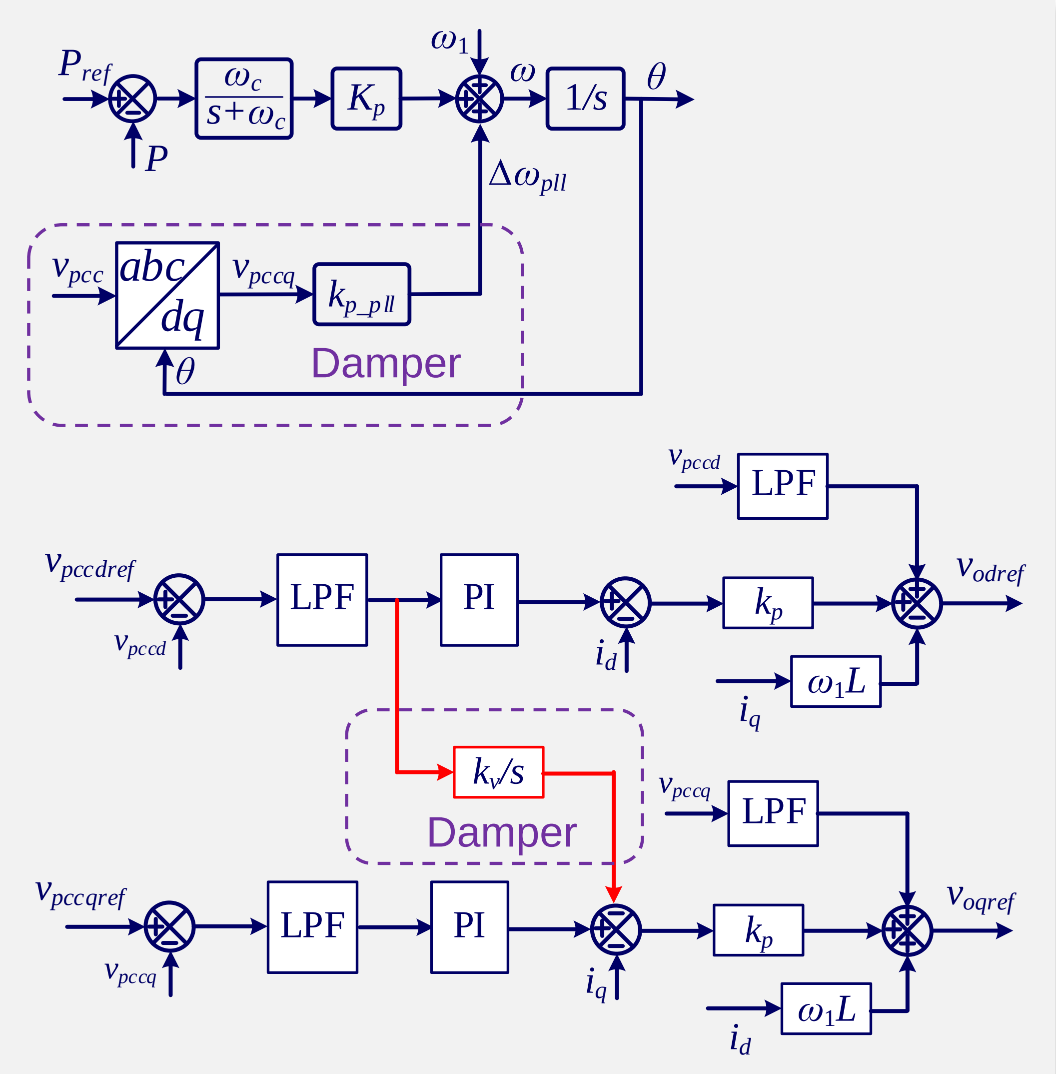
[11] E. Rokrok, T. Qoria, A. Bruyere, B. Francois and X. Guillaud, "Transient stability assessment and enhancement of grid-forming converters embedding current reference saturation as current limiting strategy," *IEEE Trans. Power Syst.*, vol. 37, pp. 1519-1531, Mar. 2022.

Small-Signal Stability Robustness

Breaking the limit of short-circuit ratio (SCR)

Flexibly configurable voltage and current sources

- Hybrid power- and voltage-based synchronization
- Dual-loop voltage and current control
- Voltage controller: virtual admittance or PI
- Voltage-based sync. as damper
- Asymmetrical virtual admittance for active damping
- Current control as damper
- High stability robustness with no SCR limit



[12] L. Harnefors, J. Kukkola, M. Routimo, M. Hinkkanen and X. Wang, “A universal controller for grid-connected voltage-source converters,” *IEEE Jour. Emer. Sel. Top. Power Electron*., vol. 9, pp. 5761-5770, Oct. 2021.

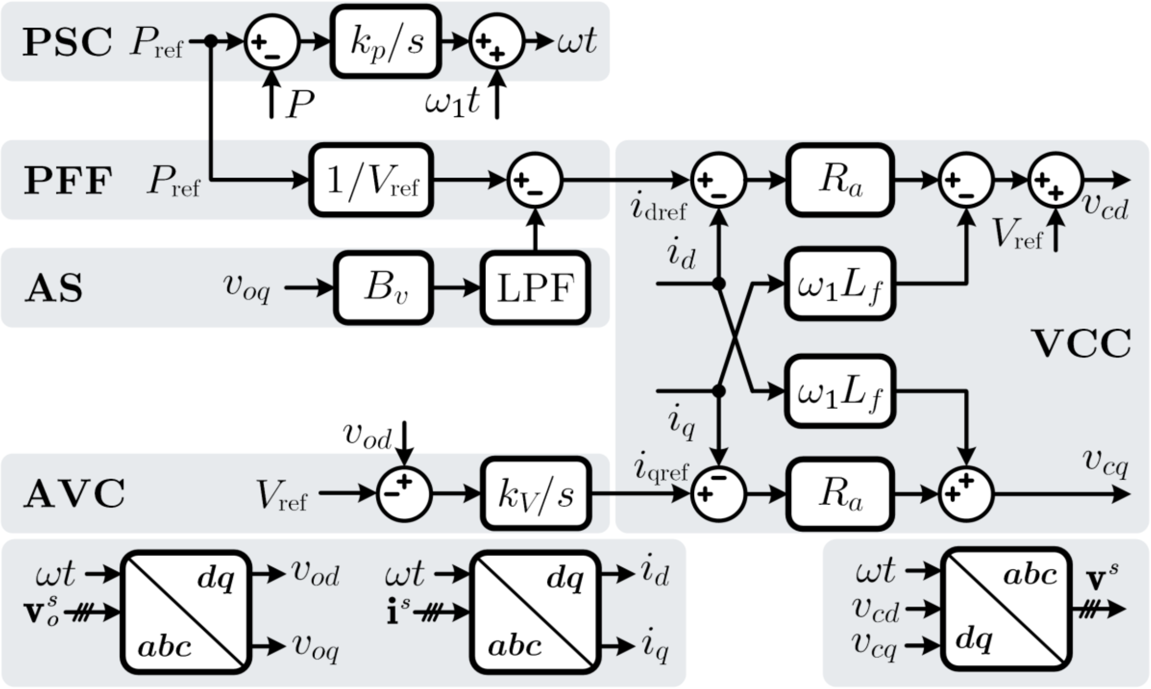
[13] T. Liu and X. Wang, “Physical insight into hybrid-synchronization-controlled grid-forming inverters under large disturbances,” *IEEE Trans. Power Electron*., vol. 37, pp. 11475-11480, Oct. 2022.

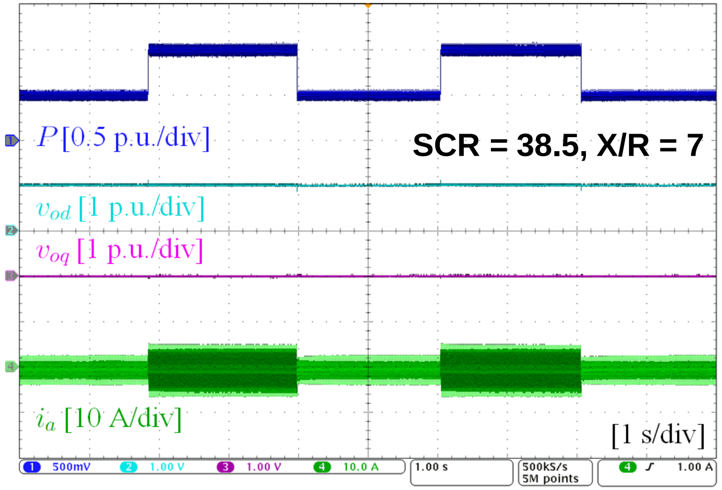
Small-Signal Stability Robustness

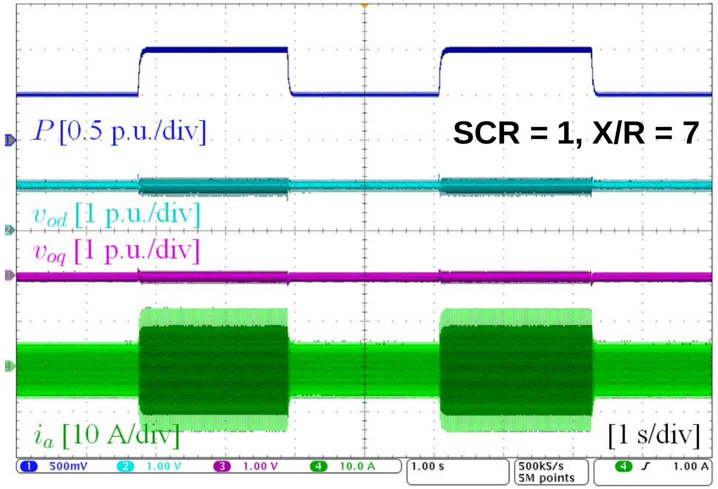
Breaking the limit of short-circuit ratio (SCR)

Enhanced Grid-Forming control with active susceptance (AS)

- Using power synchronization control only
- AS for voltage-oriented vector control and enhanced damping



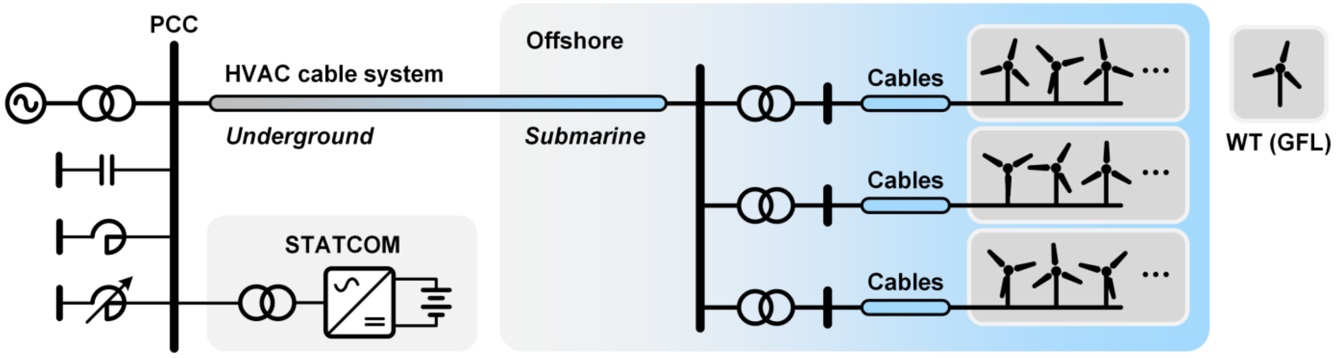




[14] F. Zhao, X. Wang, Z. Zhou, Y. Sun, L. Harnefors and T. Zhu, "Robust Grid-Forming Control With Active Susceptance," *IEEE Trans. Power Electron.*, vol. 38, no. 3, pp. 2872-2877, Mar. 2023.

Grid-Forming STATCOM for Wind Power Plants

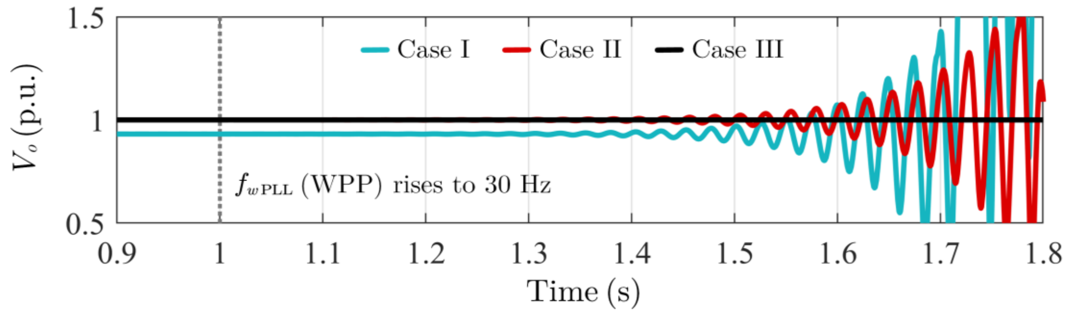
Interaction analysis and small-signal stability enhancement



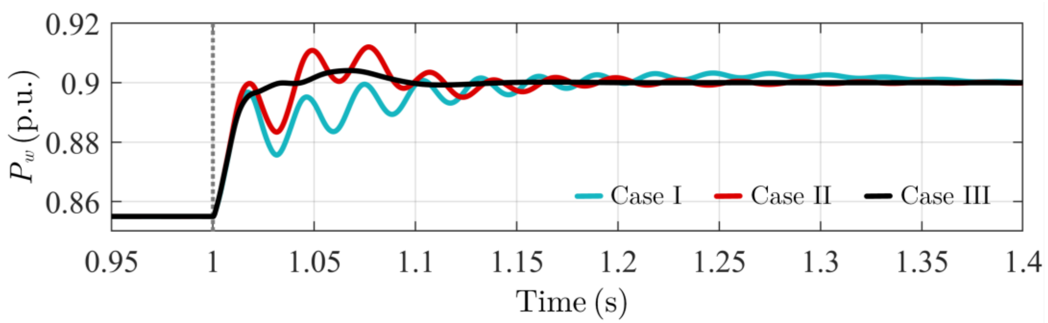
Static synchronous compensator (STATCOM) Grid-Following (GFL) or Grid-Forming (GFM)?

- Case I – GFL-WPP
- Case II – GFL-WPP + GFL-STATCOM
- Case III – GFL-WPP + GFM-STATCOM
- Which case is the most robust under small disturbance

Comparison of PCC voltage mag. ***(WT-PLL bandwidth increases)***



Comparison of active power ***(Power reference step responses)***



[15] 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, p. 108449, Nov. 2022.

[16] F. Zhao, X. Wang, Z. Zhou, L. Harnefors, J. R. Svensson, , Ł. Kocewiak, and M. Gryning, "Control Interaction Modeling and Analysis of Grid-Forming Battery Energy Storage System for Offshore Wind Power Plant," *IEEE Trans. Power Syst*., vol. 37, no. 1, pp. 497-507, Jan. 2022.