Transient Stability of Inverter-Based Resources

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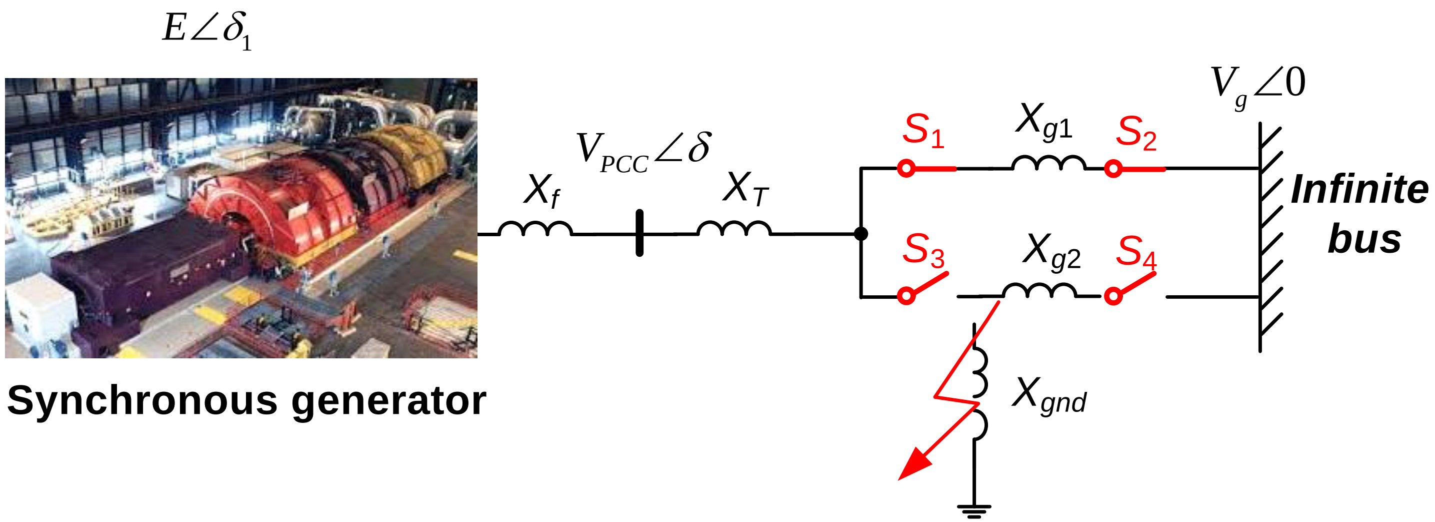
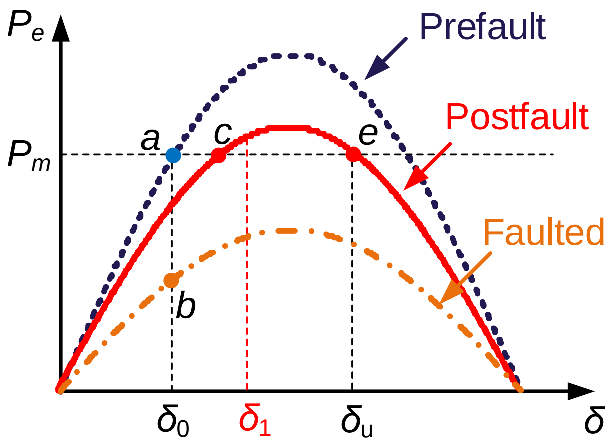
Transient Stability: Keeping Synchronism under Large Disturbances

Presence of equilibrium points (EP) and critical clearing time (CCT)



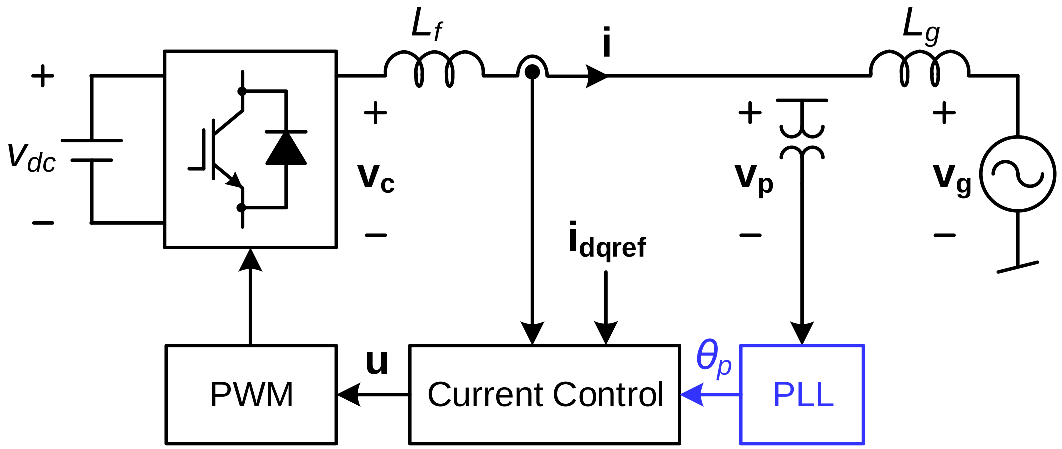
Single-machine infinite-bus power system



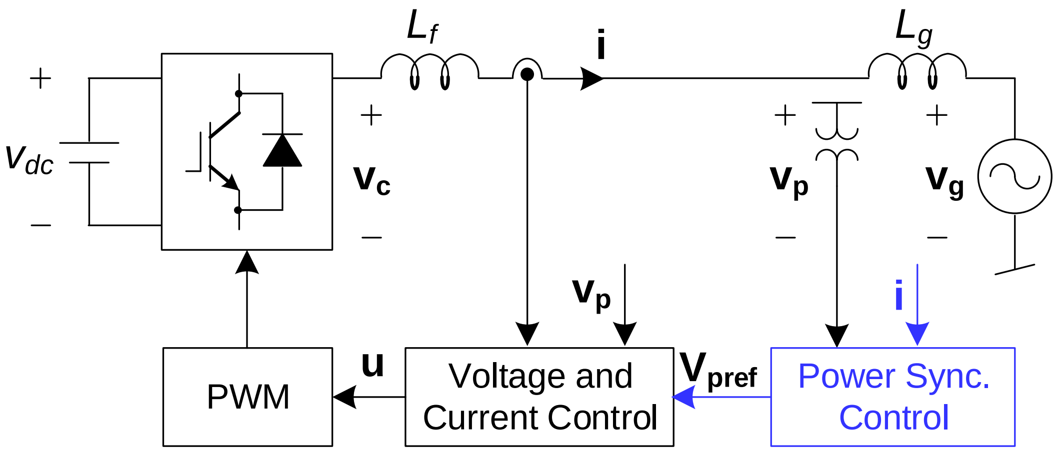
Power-angle curve

- Fault clearing angle: δ_1
- Critical clearing angle (CCA)
- Critical clearing time (CCT)

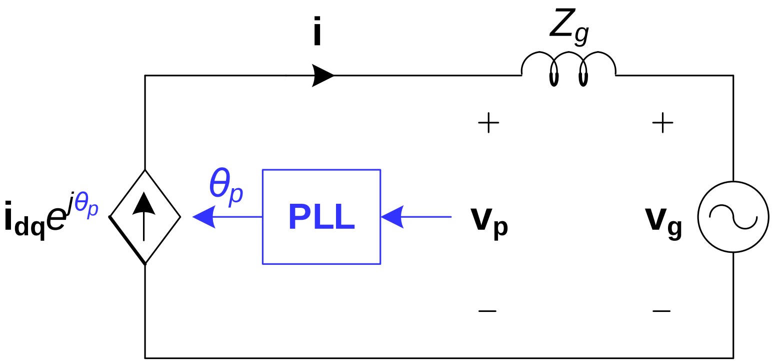
General Control of Inverter-Based Resources
Grid-following inverters and grid-forming inverters



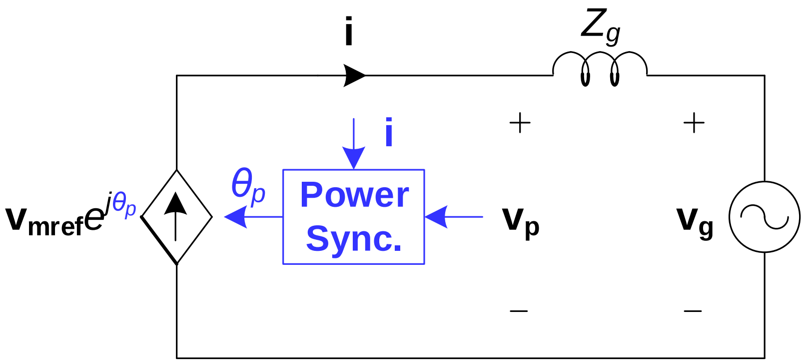
Grid-Following Inverter



Grid-Forming Inverter



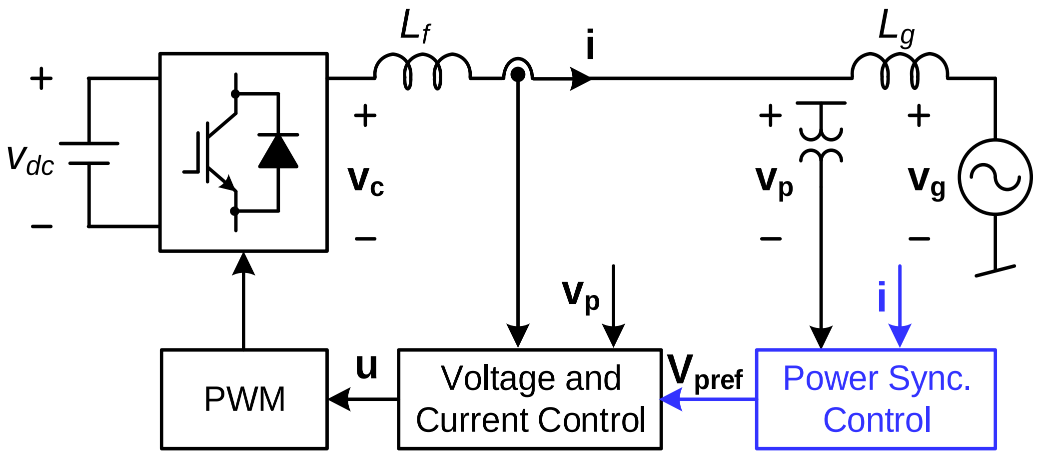
Voltage-based synchronization (stiff grid)



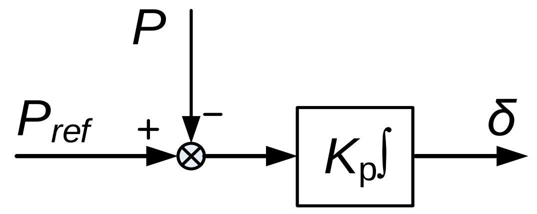
Power-based synchronization (weak grid)

Transient Stability of Grid-Forming Inverters

Droop-based synchronization with constant voltage magnitude



Grid-Forming inverter w/ constant voltage magnitude



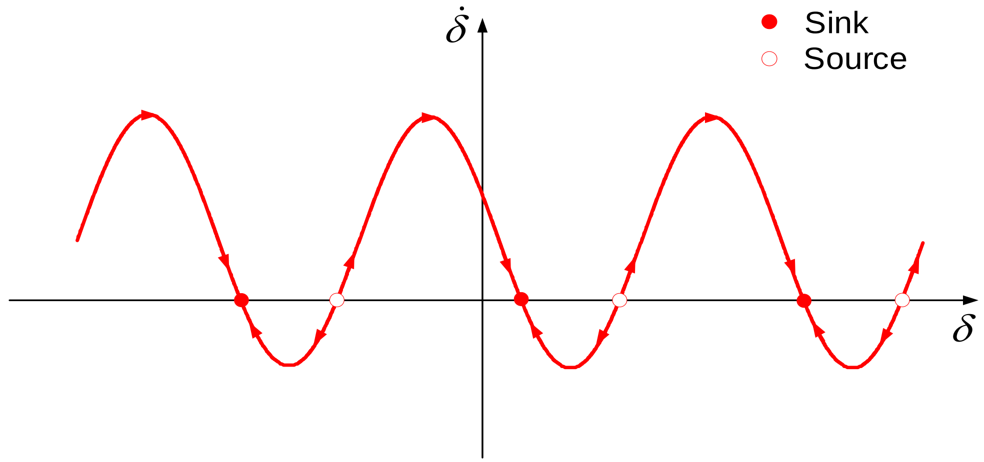
Droop-based synchronization

L. Zhang, L. Harnefors, and H. P. Nee, "Power-synchronization control of grid-connected voltage-source converters," IEEE Trans. Power Syst., 2010.

$$\dot{\delta} = K_p\left(P_{ref} - P\right)$$

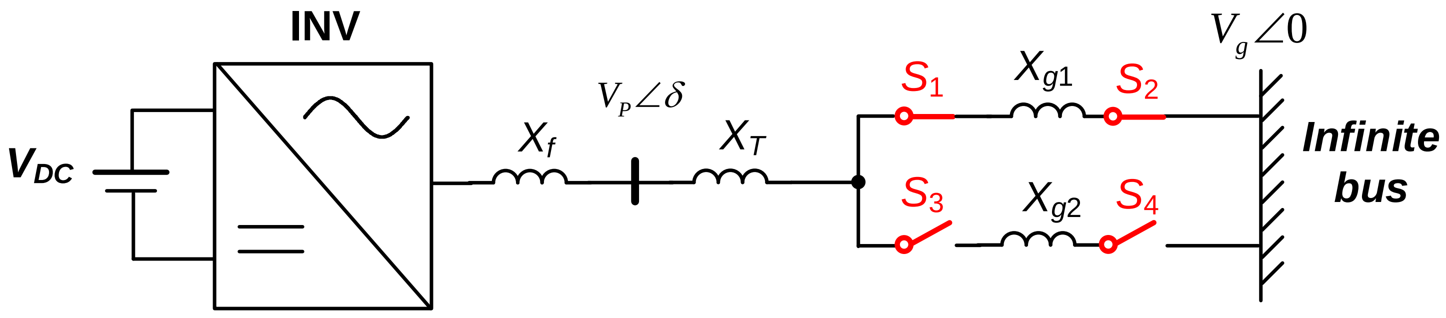
$$P = \frac{3V_P V_g}{2X_g}\sin\delta$$

$$\dot{\delta} = K_p\left(P_{ref} - \frac{3V_P V_g}{2X_g}\sin\delta\right)$$

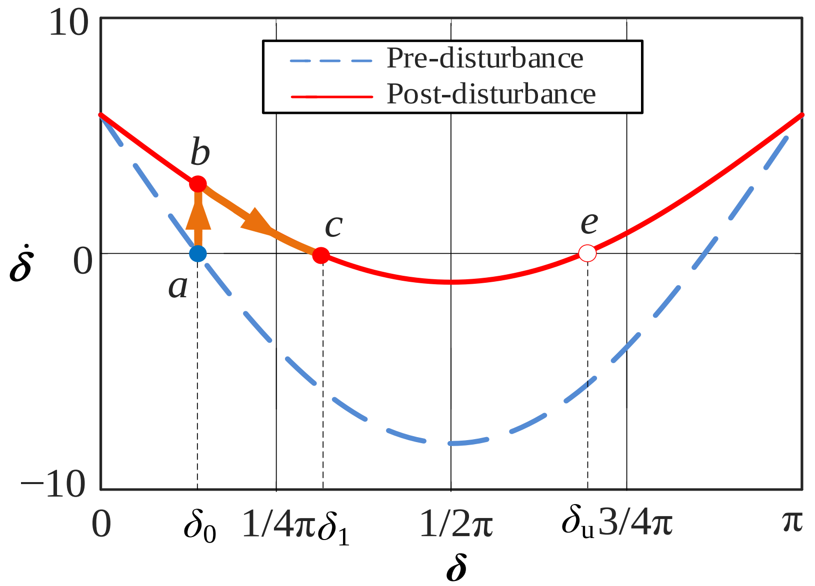


Phase portrait (stable & no overshoot)

Grid-Forming Inverters w/o Triggering Current Limit
Case I - presence of equilibrium points after disturbances



Abrupt disconnection of transmission line X_{g2} ($i_g < I_{limit}$)



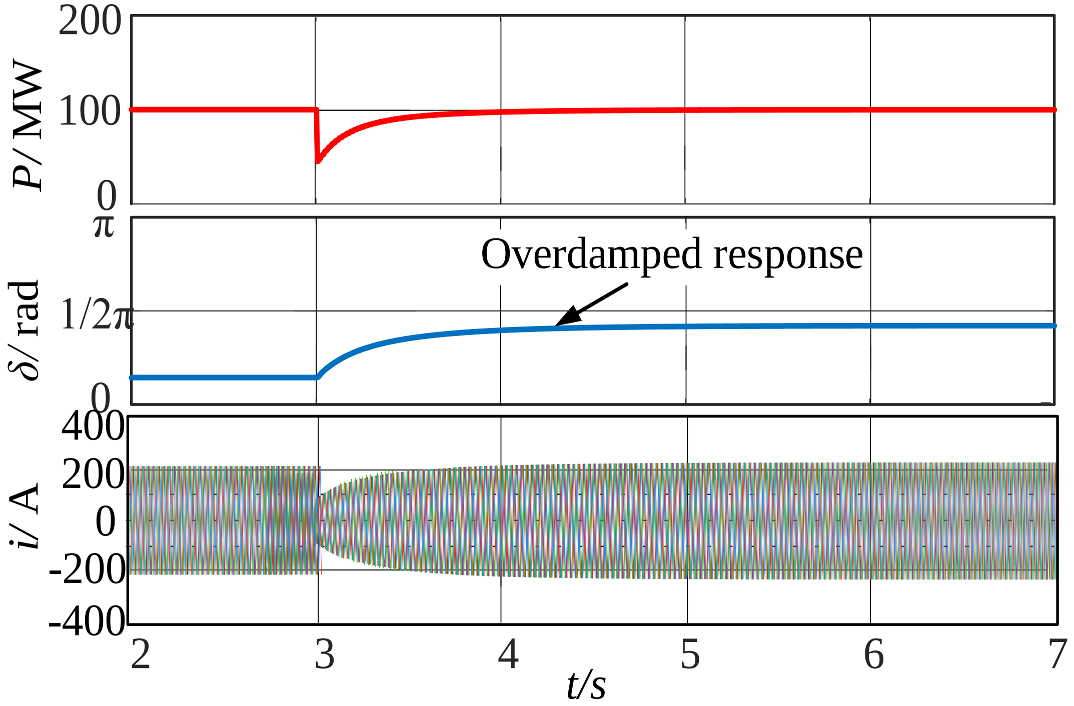
Phase portrait analysis

With equilibrium points after disturbance

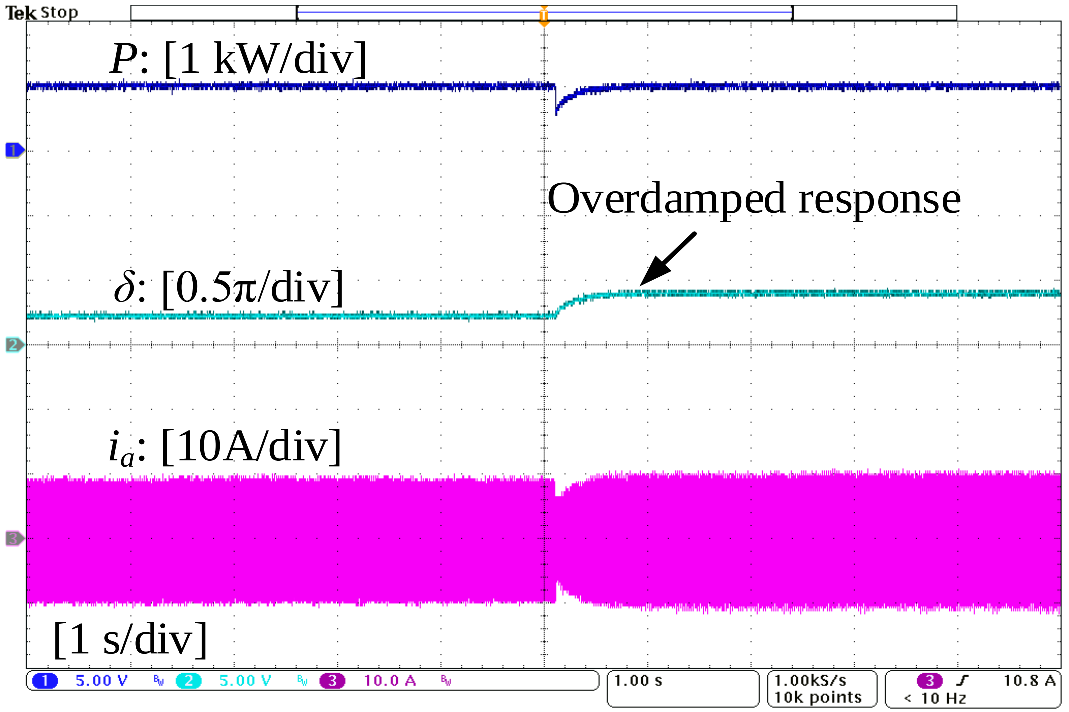
- INV has no transient stability problem
- Overdamped response (zero overshoot)
- Better performance than SG

H. Wu and X. Wang, "Design-oriented transient stability analysis of grid-connected power converters with power synchronization control ," IEEE Trans. Ind. Electron., 2019.

Grid-Forming Inverters w/o Triggering Current Limit
Case I - presence of equilibrium points after disturbances



Simulation results

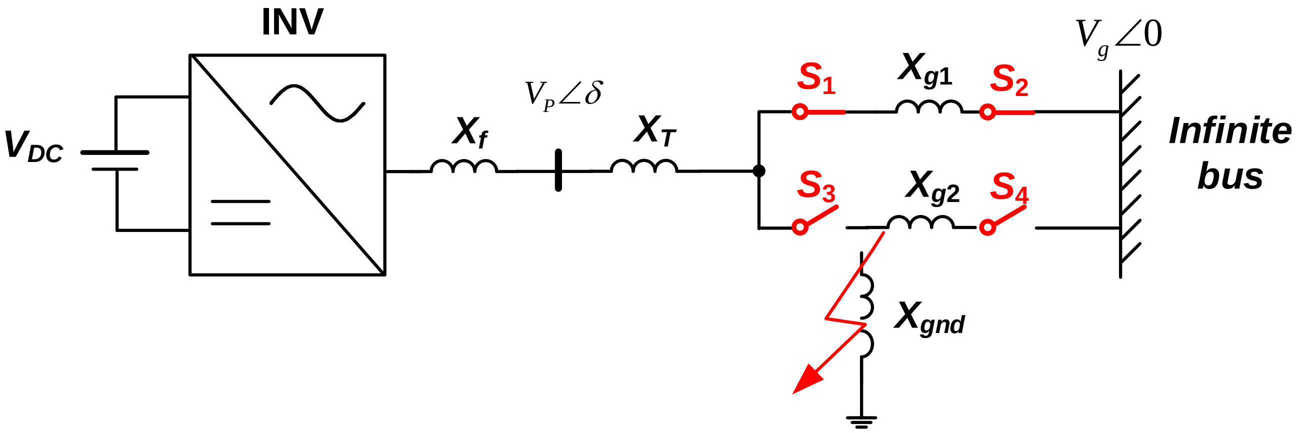


Experimental result

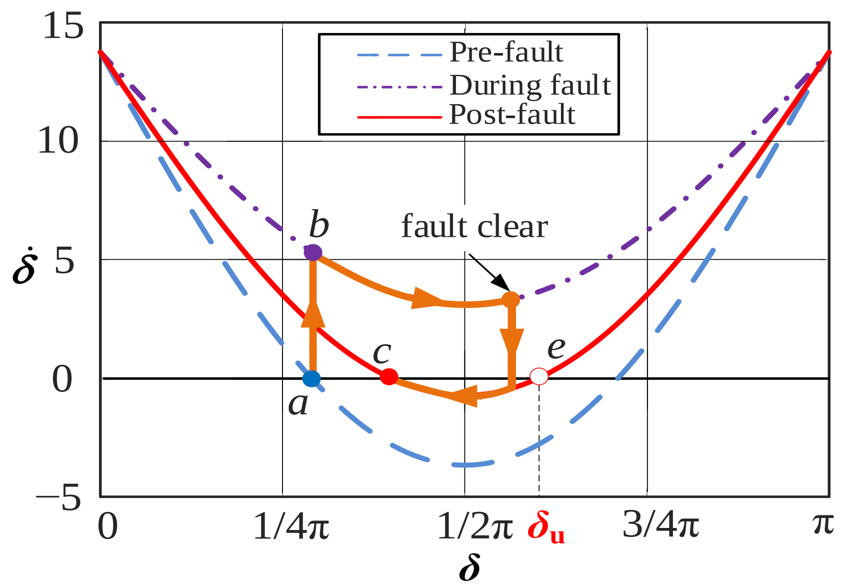
H. Wu and X. Wang, "Design-oriented transient stability analysis of grid-connected power converters with power synchronization control ," IEEE Trans. Ind. Electron., 2019.

Grid-Forming Inverters w/o Triggering Current Limit

Case II - no equilibrium points during grid faults



Grid fault with high short-circuit impedance X_{gnd} ($i_g < I_{limit}$)



Phase portrait analysis

Constant Critical Clearing Angle (CCA)

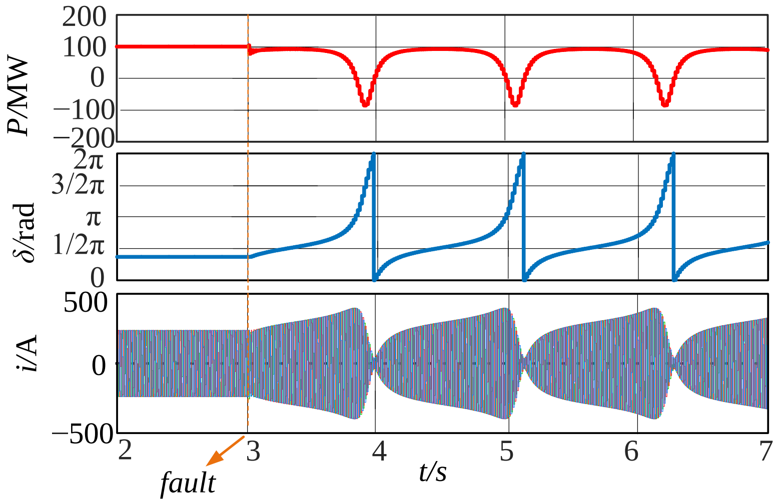
$$CCA = \delta_u$$

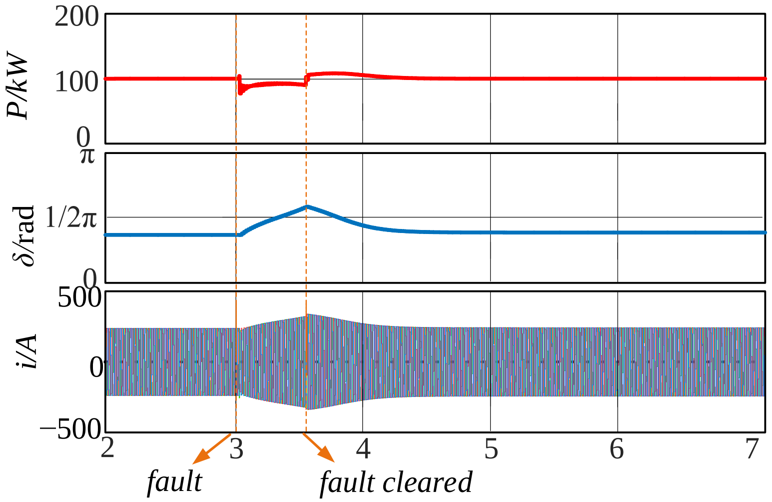
H. Wu and X. Wang, "Design-oriented transient stability analysis of grid-connected power converters with power synchronization control ," IEEE Trans. Ind. Electron., 2019.

Grid-Forming Inverters w/o Triggering Current Limit

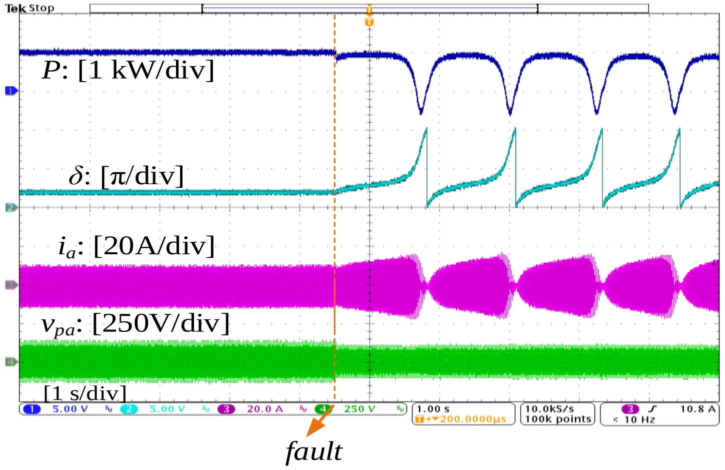
Case II - no equilibrium points during grid faults

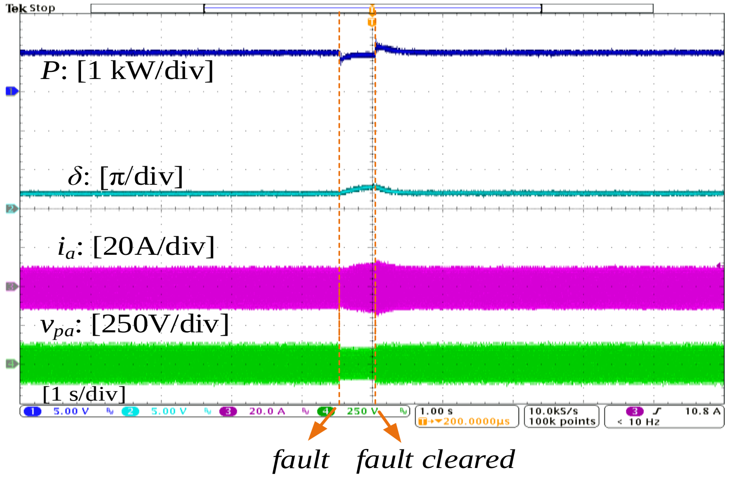
Simulation results





Experimental results



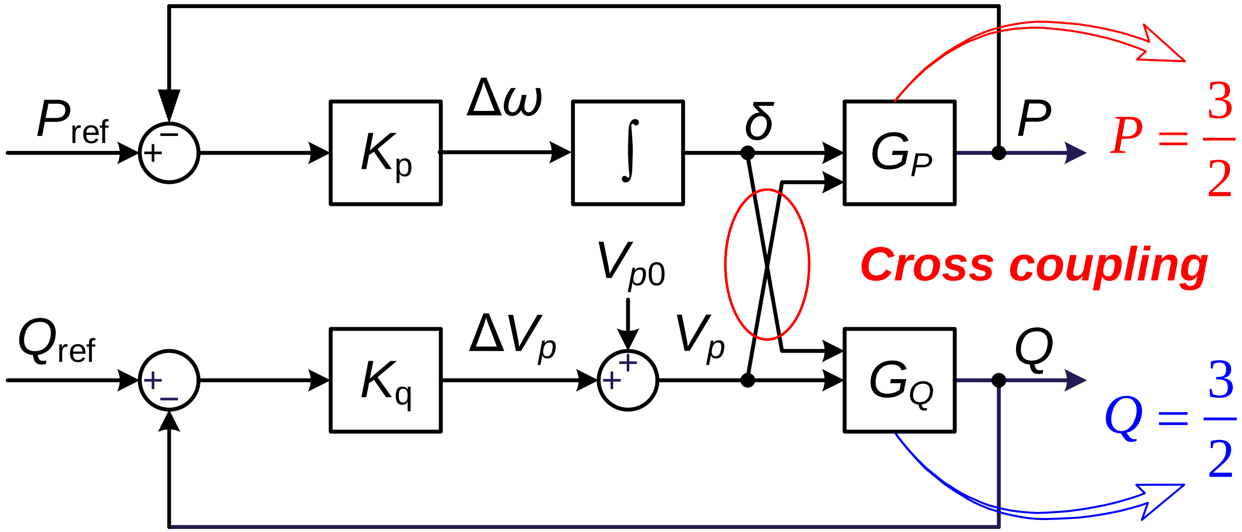


Fault is not cleared - no equilibrium points

Fault clearing time < CCT

Transient Stability of Grid-Forming Inverters

Effect of reactive power-voltage droop control



$$P = \frac{3}{2} \cdot \frac{V_p V_g \sin\delta}{X_g}$$

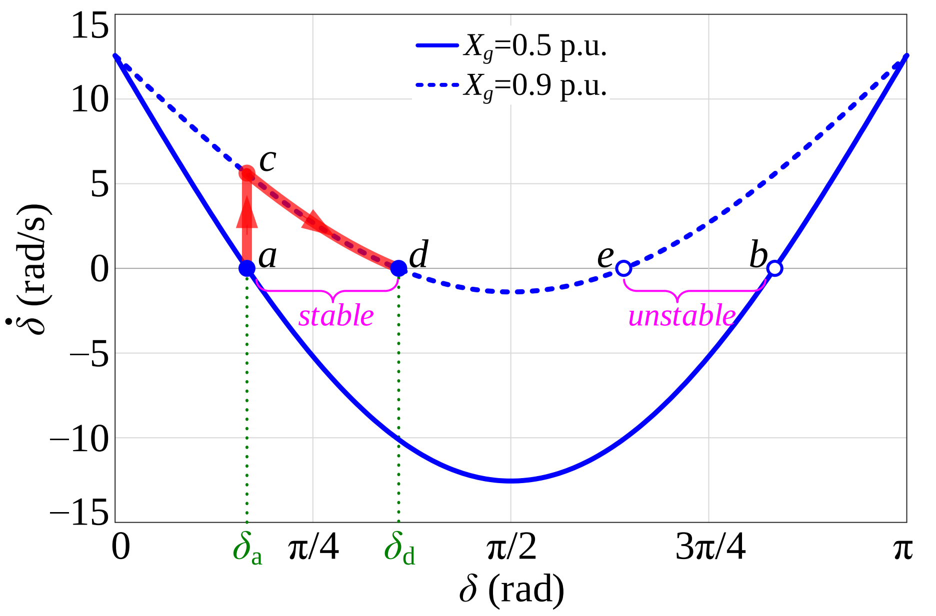
$$Q = \frac{3}{2} \cdot \frac{V_p^2 - V_p V_g \cos\delta}{X_g}$$

Positive Feedback

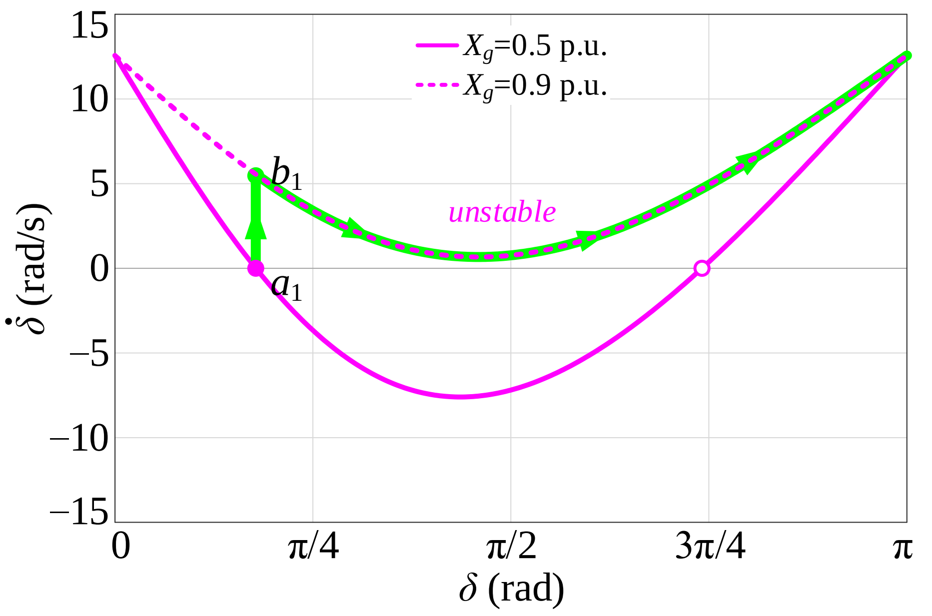
$\dot{\delta} > 0 \Rightarrow \delta \uparrow \Rightarrow Q \uparrow \Rightarrow V_p \downarrow \Rightarrow P \downarrow \Rightarrow \dot{\delta} \uparrow$

Transient Stability of Grid-Forming Inverters

Poorer transient stability of reactive power-voltage droop control



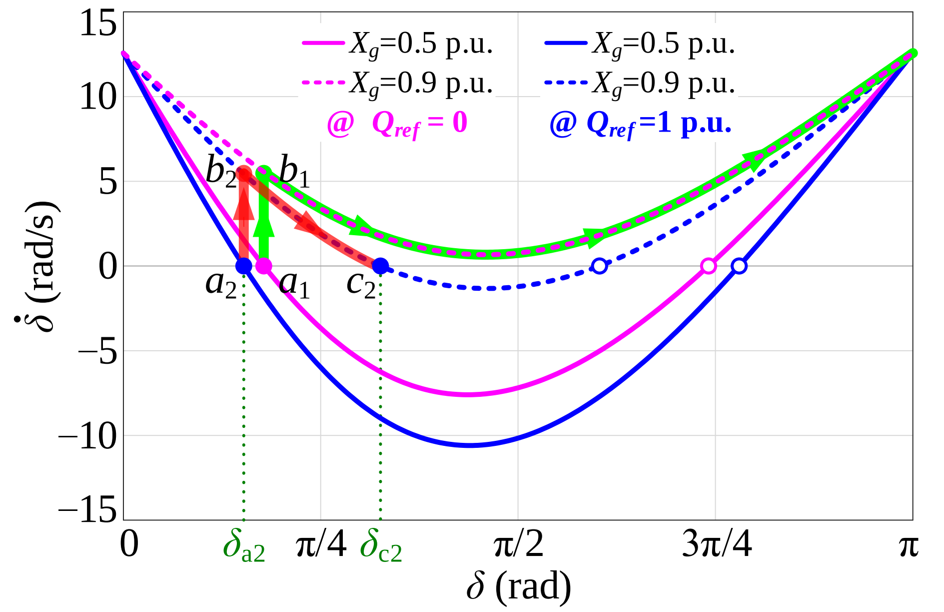
Phase portrait w/ constant V_{p0}



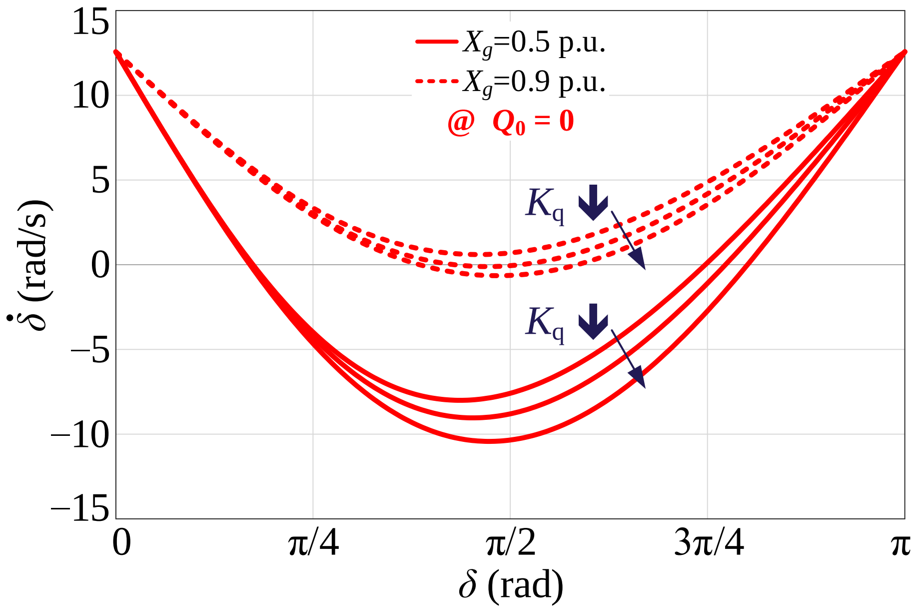
Phase portrait w/ *Q-V* droop control

Transient Stability of Grid-Forming Inverters

Enhanced transient performance with different Q_{ref} and K_q



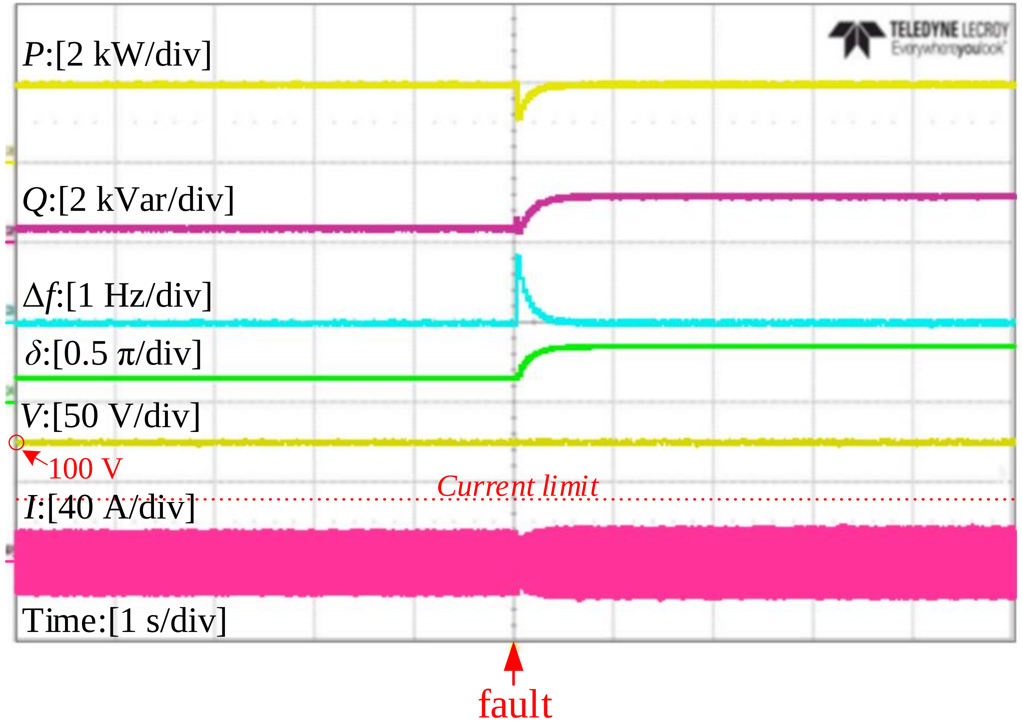
Phase portrait w/ increasing Q_{ref}

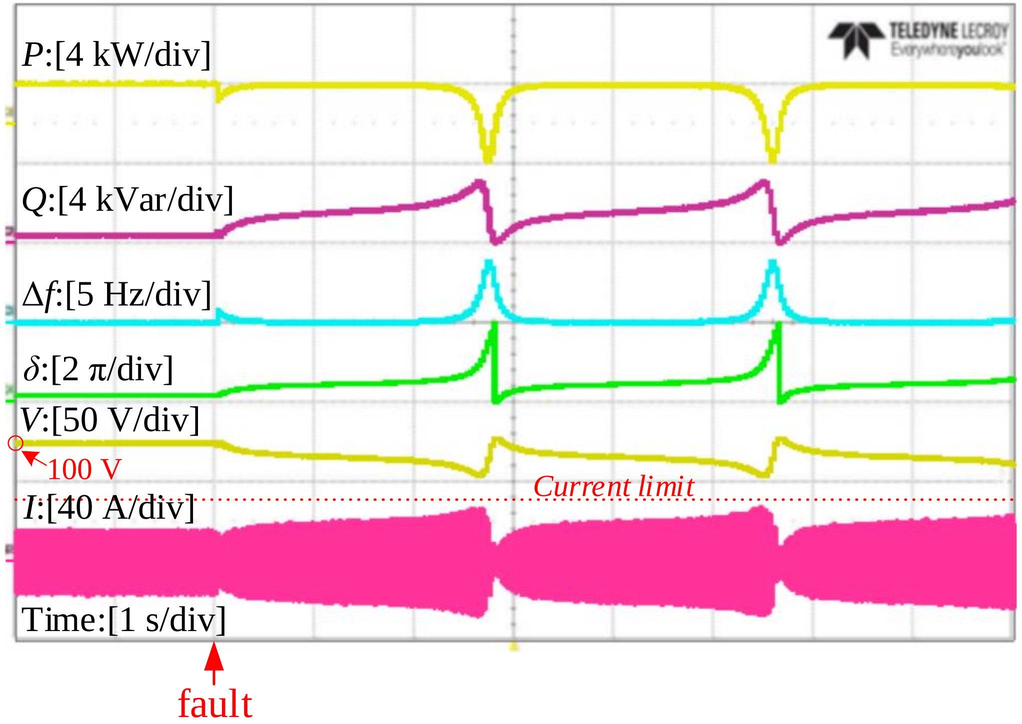


Phase portrait w/ reducing K_q

Transient Stability of Grid-Forming Inverters

Experimental test of transient stability impact of *Q-V* droop

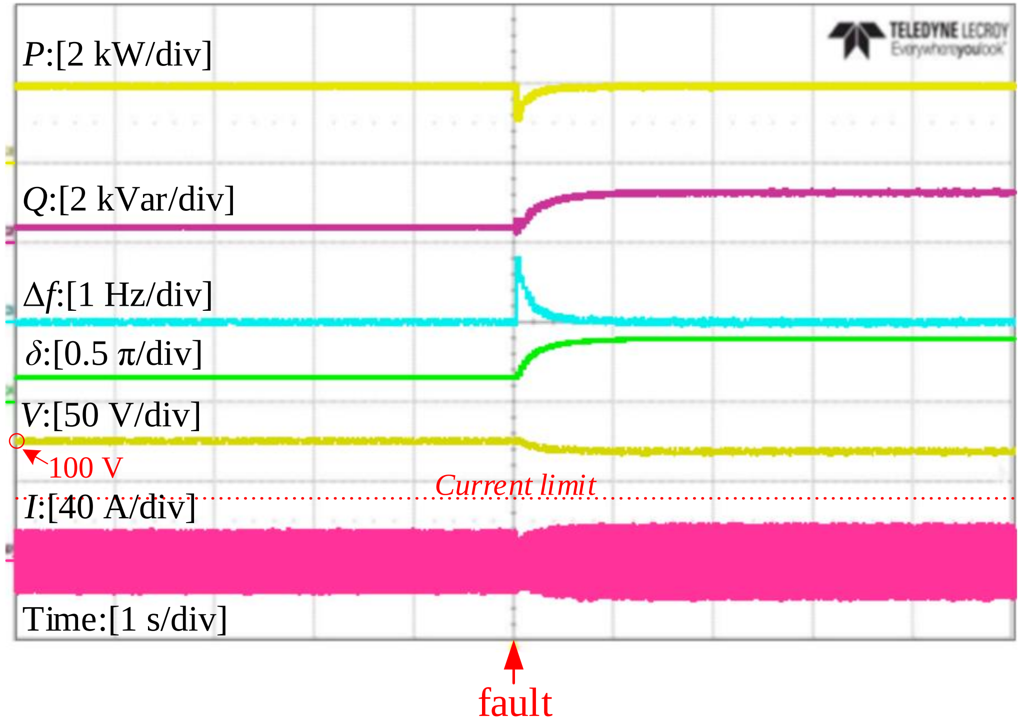




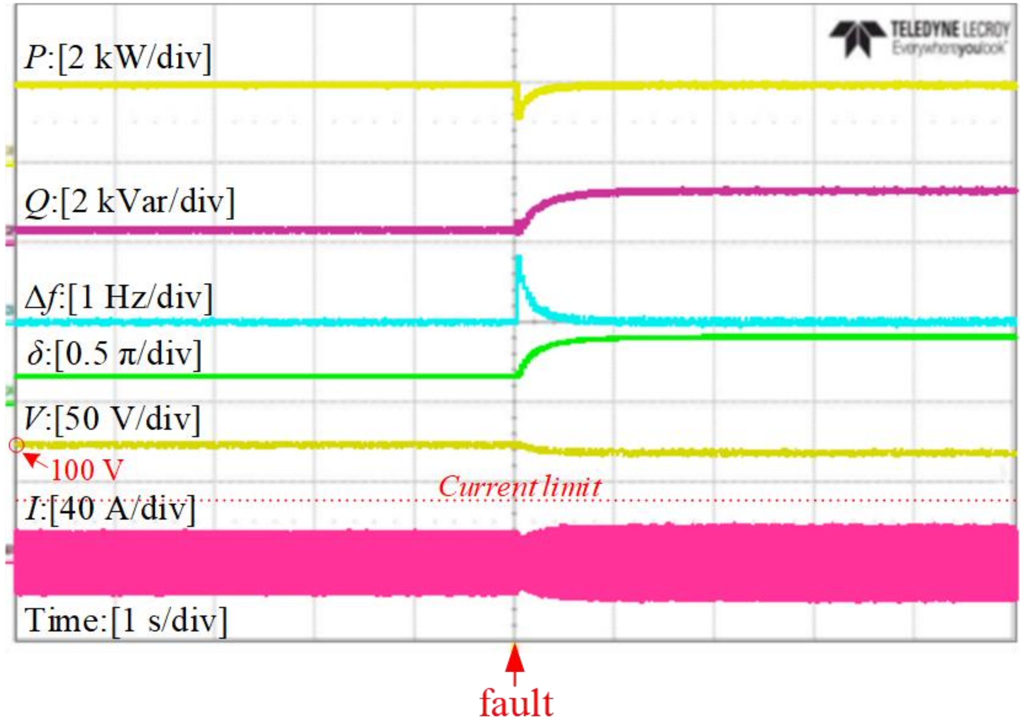
Constant voltage magnitude: $V_p = V_{p0}$

***Q-V* droop control: $Q_{ref} = 0$ and $K_q = 0.15$ p.u.**

Transient Stability of Grid-Forming Inverters
Experimental tests with different Qref and Kq



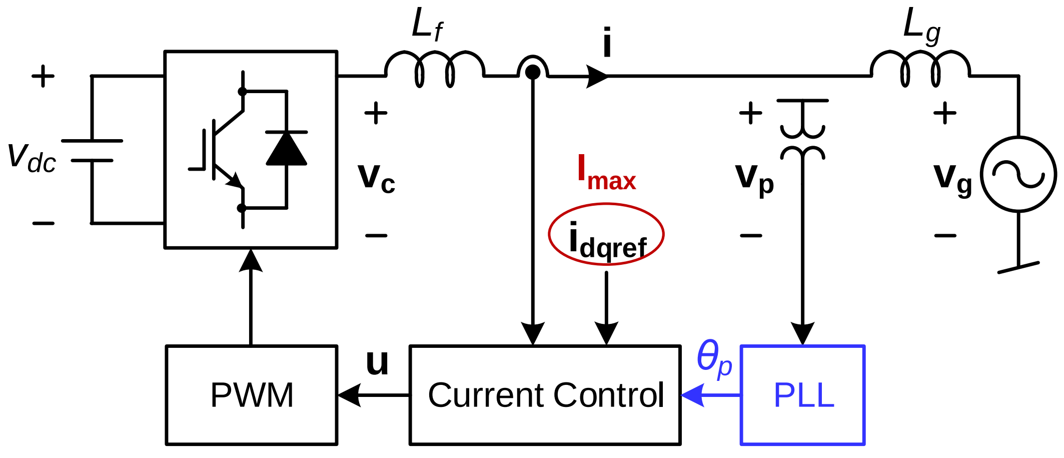
Q-V droop control: Q_{ref} = 0.25 p.u. and K_q = 0.15 p.u.



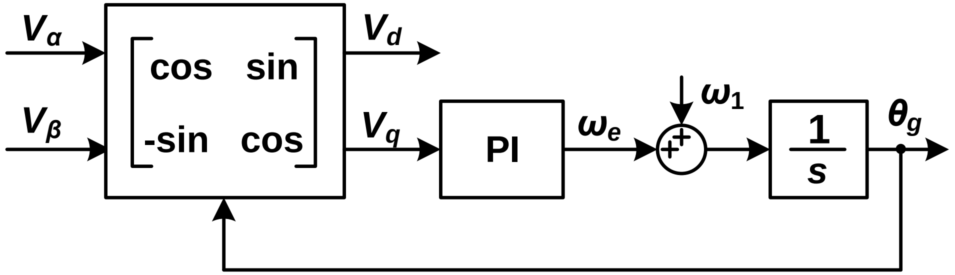
Q-V droop control: Q_{ref} = 0 and K_q = 0.1 p.u.

Grid-Forming Inverters Triggering Current Limit

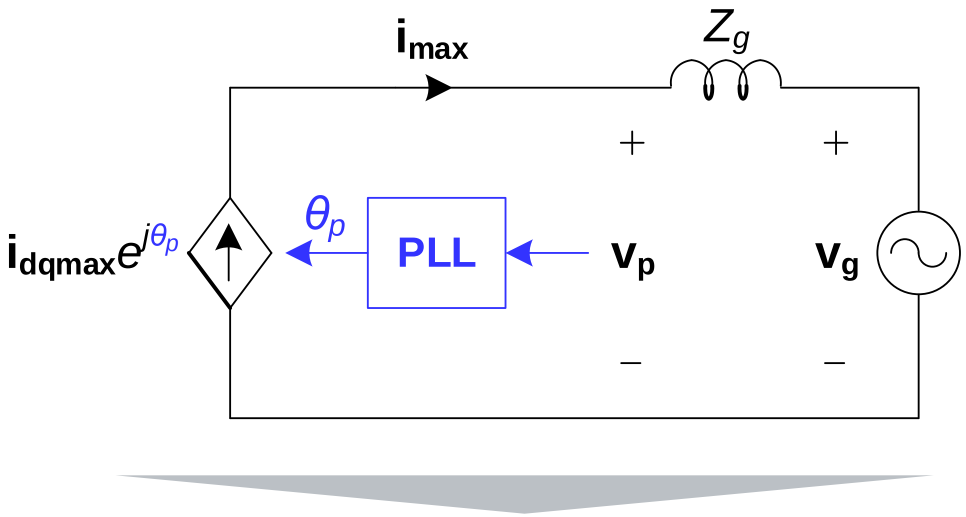
Switched back to grid-following inverters with PLL

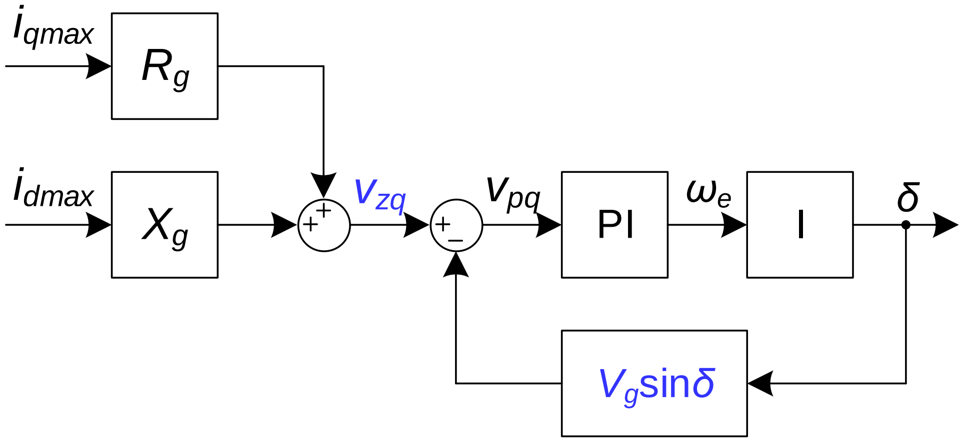


Grid-Following inverter



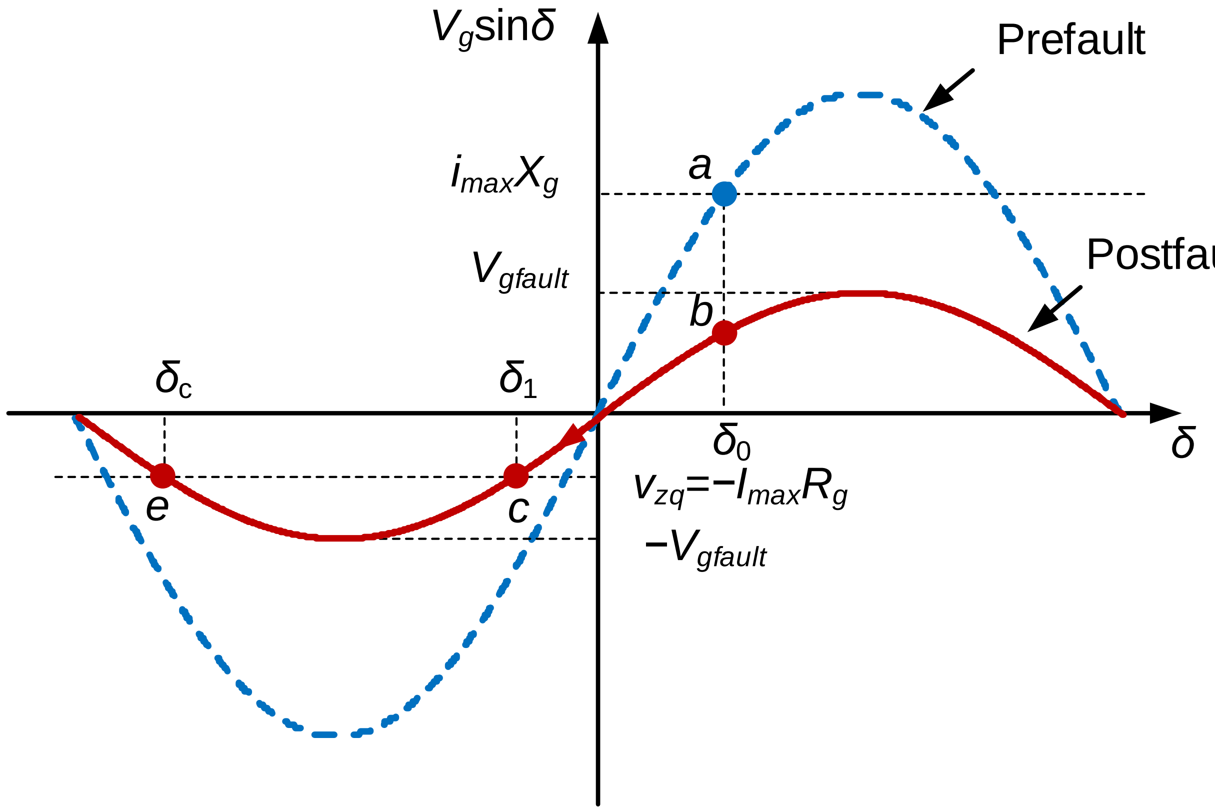
DQ-frame PLL





2nd-order nonlinear dynamic behavior

Transient Stability of Grid-Following Inverters
Second-order swing behaviour of PLL-synchronized current control



Voltage-angle curve

- **Prefault:** $i_{dmax} = I_{max}$, $i_{qmax} = 0$

  Postfault: $i_{dmax} = 0$, $i_{qmax} = -I_{max}$
- $\boldsymbol{V_{zq} = -I_{max}R_g = -V_{gfault}}$

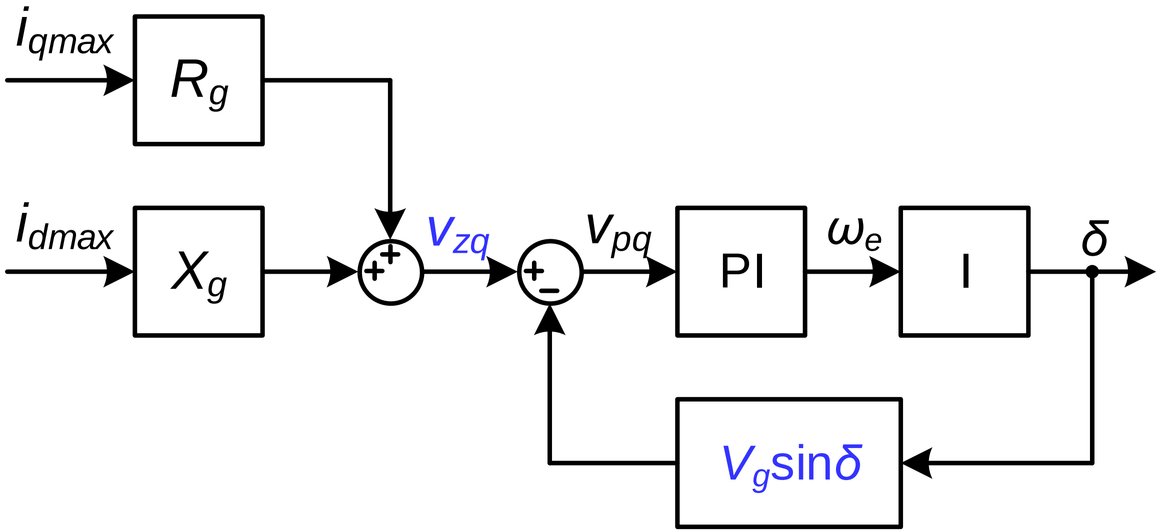
  Unstable equilibrium point (UEP)
- $\boldsymbol{V_{zq} = -I_{max}R_g > -V_{gfault}}$

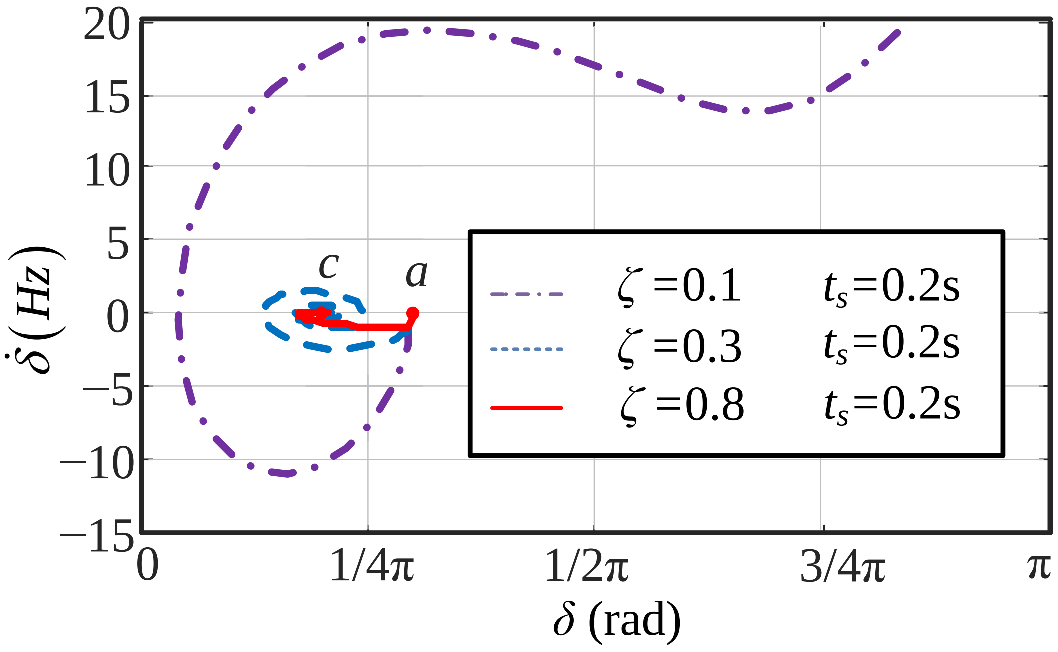
  Two EPs (SEP *c*, UEP e)

H. Wu and X. Wang, “Design-oriented transient stability analysis of PLL-synchronized voltage-source converters,” IEEE Trans. Power Electron., Early Access, 2019.

Transient Stability of Grid-Following Inverters

Case I - two equilibrium points: design-oriented analysis



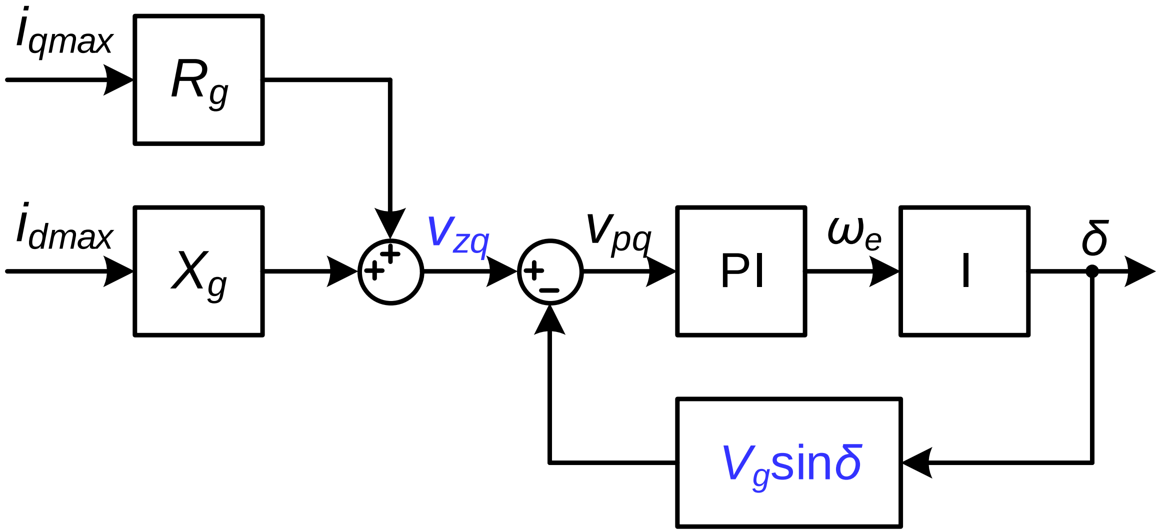


Phase portrait

Damping ratio: $\zeta = \frac{k_p}{2}\sqrt{\frac{V_g}{k_i}}$ **Settling time:** $t_s = \frac{9.2}{V_g k_p}$

- **Larger damping ratio** leads to better transient behavior

Transient Stability of Grid-Following Inverters
Case I - two equilibrium points: design-oriented analysis



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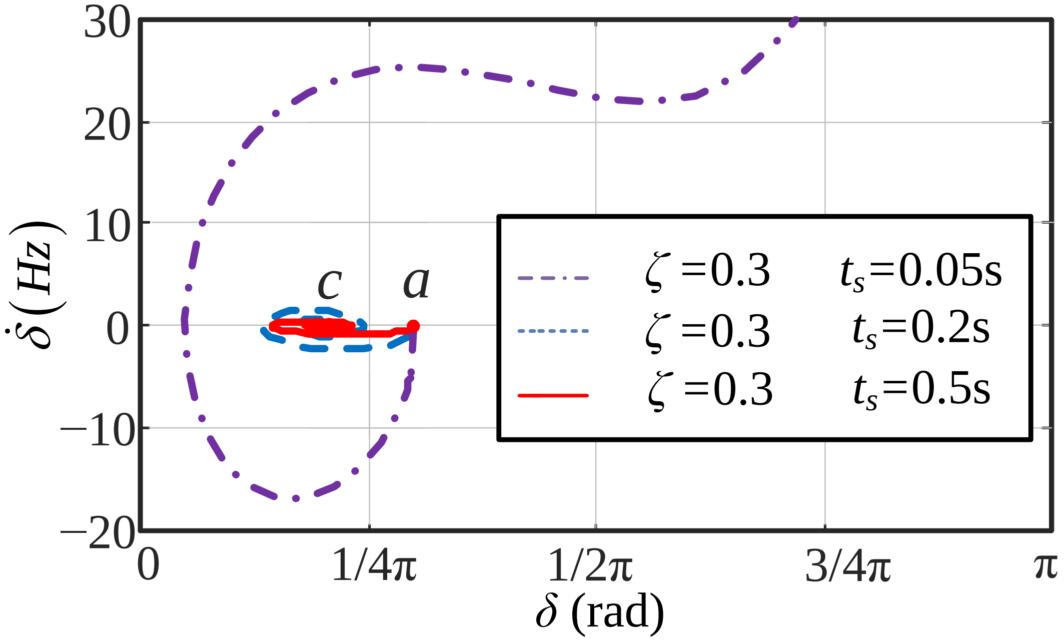
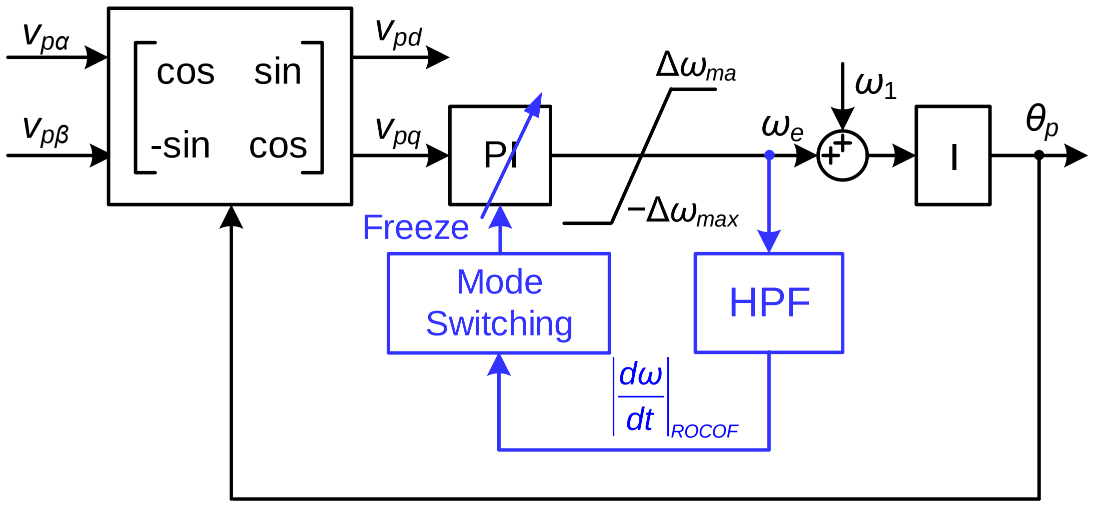


Phase portrait

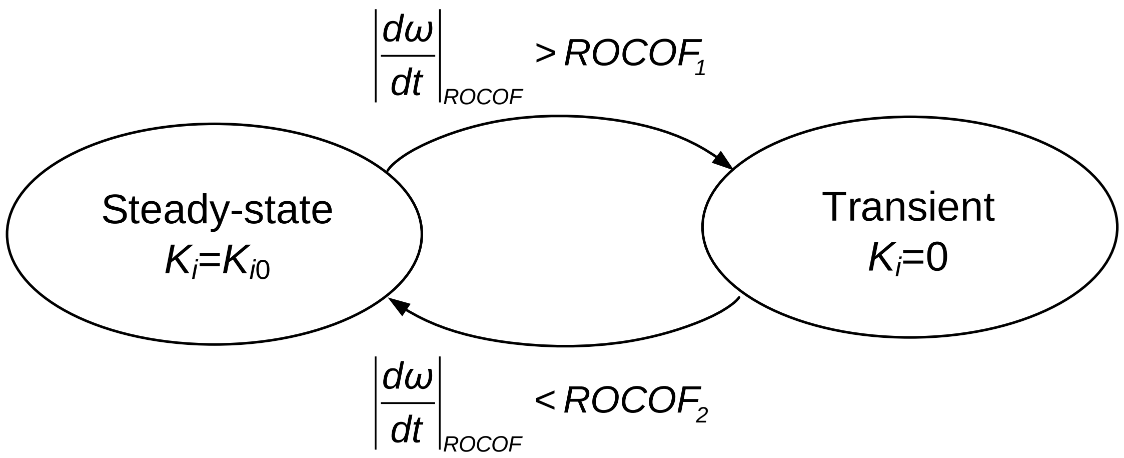
- **Longer settling time** leads to better transient behavior
- With Ki = 0, the PLL is a first-order nonlinear system – always stable

Transient Stability of Grid-Following Inverters

Case II - no equilibrium points: adaptive PLL



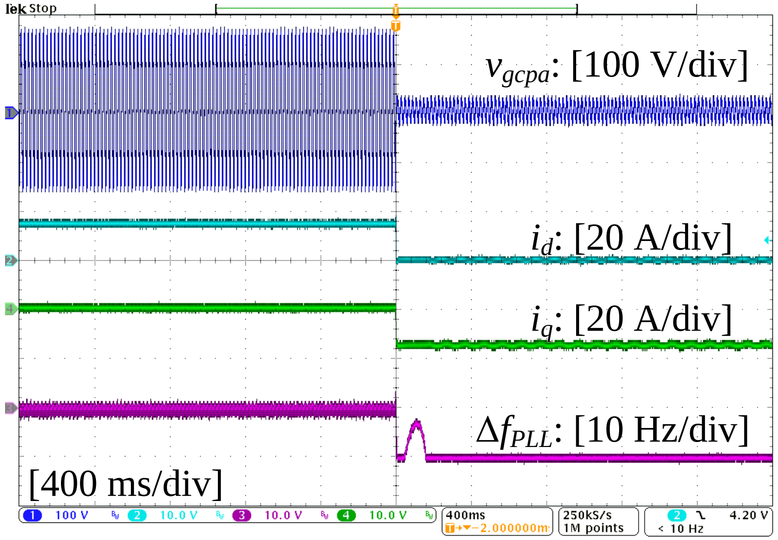
Adaptive PLL for transient stability enhancement



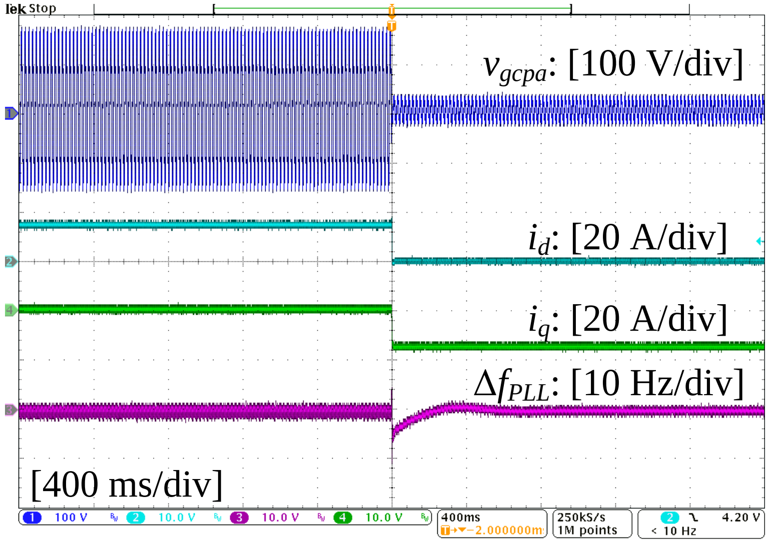
Mode switching logic

Transient Stability of Grid-Following Inverters

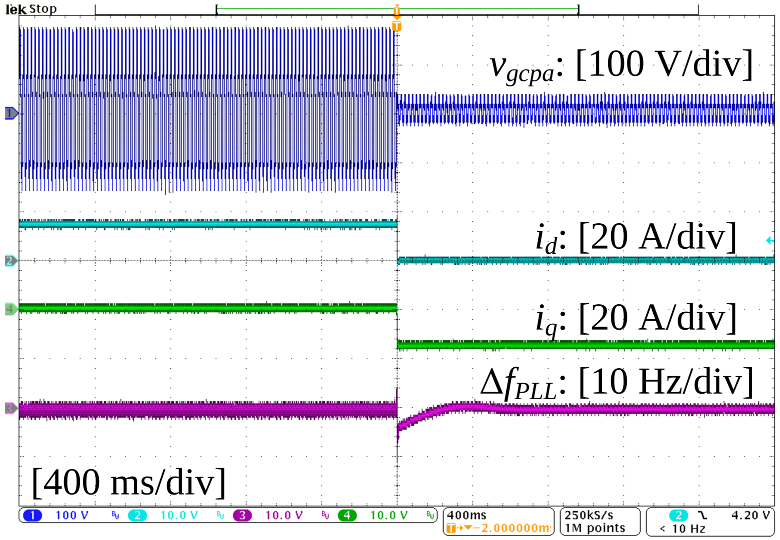
Experimental tests w/ equilibrium points after fault



ζ=0.5, t_s=0.1s, unstable



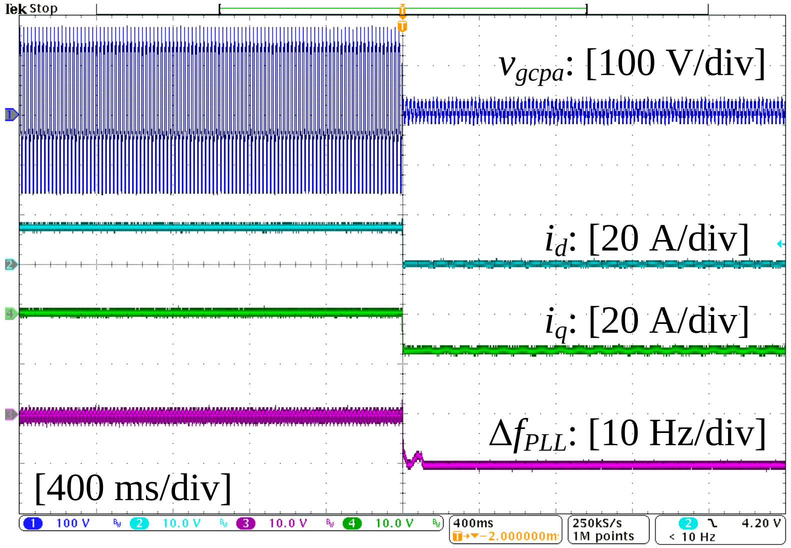
ζ=1.5, t_s=0.1s, stable



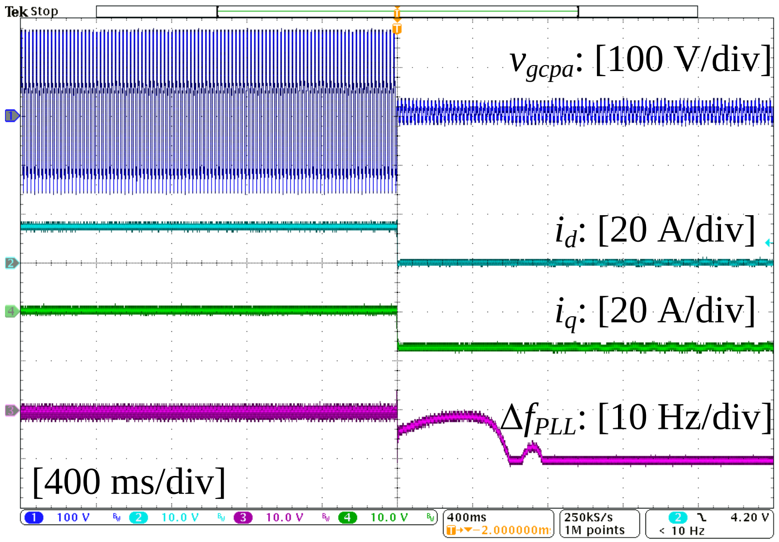
Adaptive PLL, stable

Grid-Forming Inverters Triggering Current Limit

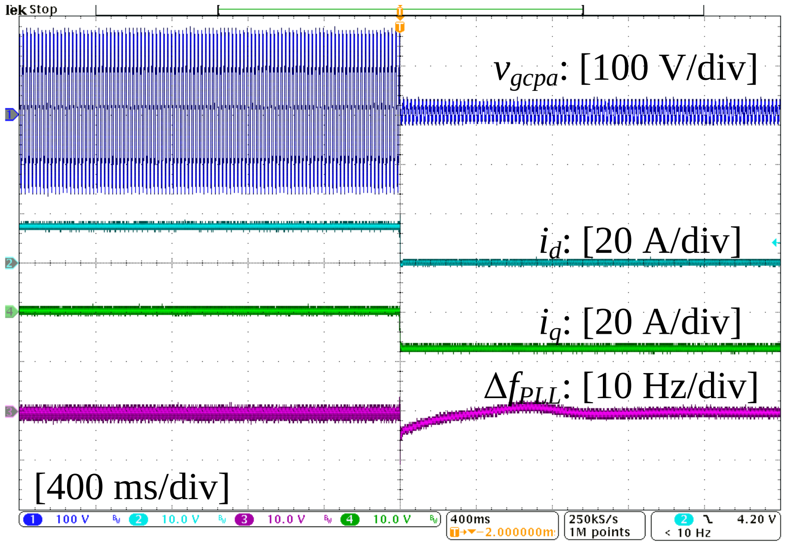
Experimental tests of transient stability w/o equilibrium point after fault



ζ=0.5, t_s=0.1s, unstable



ζ=1.5, t_s=0.1s, unstable



Adaptive PLL, stable

Transient Stability of Grid-Forming Inverters
A comparison with Synchronous Generators (SGs)

Operating Scenarios		Grid-Forming Inverters	Synchronous Generators
With Equilibrium Points		No transient stability problem	May lose synchronization
No Equilibrium Points during the fault	High-impedance fault ($i_g < I_{limit}$)	- Fixed CCA and CCT - Re-synchronize with the grid even if the fault is cleared beyond CCA	- CCA and CCT are dependent on the fault condition - May lead to system collapse if the fault is cleared beyond CCA
	Low-impedance fault ($i_g = I_{limit}$)	- Switching to current-limit control, and the stability is depended on the PLL - Re-synchronize with the grid after the fault is cleared	- Same as high impedance fault

Highlights

- **The first-order nonlinear system with equilibrium points has no transient stability problem**
- For higher-order systems, the controller can be tuned for first-order dynamic during transients
- Control flexibility can bring better stability in power electronic based power systems

Relevant Publications

1. H. Wu and X. Wang, “Transient angle stability analysis of grid-connected converters with the first-order active power Loop,” *IEEE Applied Power Electronics Conference and Exposition (APEC*), 2018.
2. H. Wu and X. Wang, “Transient stability impact of the phase-locked loop on grid-connected voltage source converters,” *IEEE International Power Electronics Conference (IPEC-ECCE Asia*), 2018.
3. H. Wu and X. Wang, “An adaptive phase-locked loop for the transient stability enhancement of grid-connected voltage-source converters,” *IEEE Energy Conversion Congress and Exposition (ECCE),* 2018.
4. H. Wu and X. Wang, “Design-oriented transient stability analysis of grid-connected converters with power synchronization control,” *IEEE Trans. Ind. Electron.*, 2019.
5. H. Wu and X. Wang, “Design-oriented transient stability analysis of PLL-synchronized voltage-source converters,” *IEEE Trans. Power Electron.,* Early Access*, 2*019.
6. D. Pan, X. Wang, F. Liu, and R. Shi, “Transient stability of voltage-source converters with grid-forming control: a design-oriented study,” *IEEE Journal of Emerging and Selected Topics in Power Electronics,* Early Access*,* 2019.
7. D. Pan, X. Wang, F. Liu, and R. Shi, “Transient stability impact of reactive power control on grid-connected converters,” *IEEE Energy Conversion Congress and Exposition (ECCE),* 2019.
8. D. Pan, X. Wang, F. Liu, and R. Shi, “Transient stability analysis of droop-controlled grid-connected converters with inertia emulating low-pass filters,” *IEEE Energy Conversion Congress and Exposition (ECCE),* 2019.