Workshop
DC Grids, Technologies
and Applications
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Transient Stability Analysis of VSC-HVDC Systems

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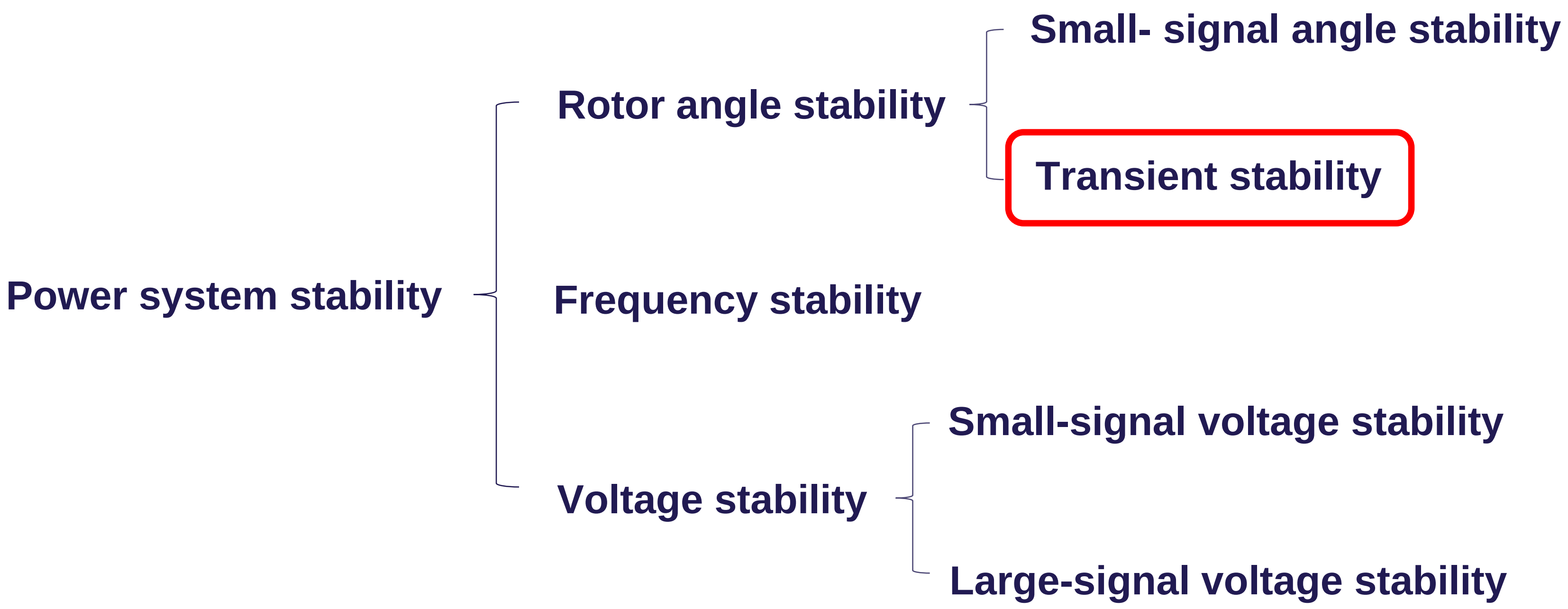
Transient Stability

Synchronization stability under large disturbance

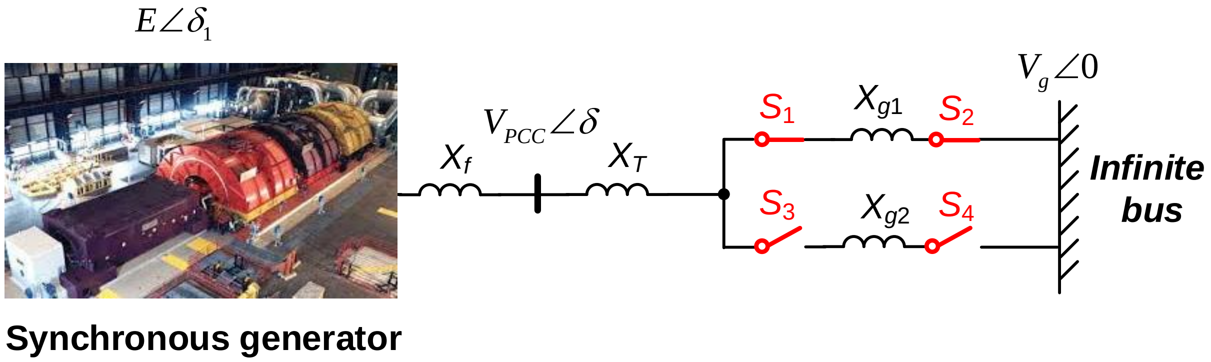


- **Power system stability**
  - **Rotor angle stability**
    - **Small- signal angle stability**
    - **Transient stability**
  - **Frequency stability**
  - **Voltage stability**
    - **Small-signal voltage stability**
    - **Large-signal voltage stability**

Transient stability: Maintain synchronism with the power grid under large disturbance

Transient Stability

Synchronous Generator (SG)



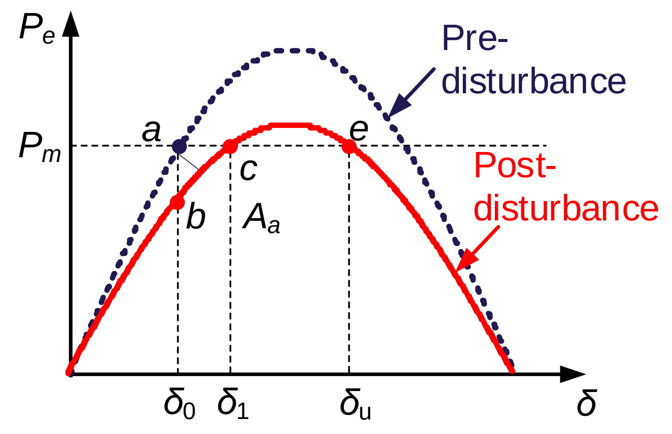
Single-machine infinite-bus power system

Swing equation

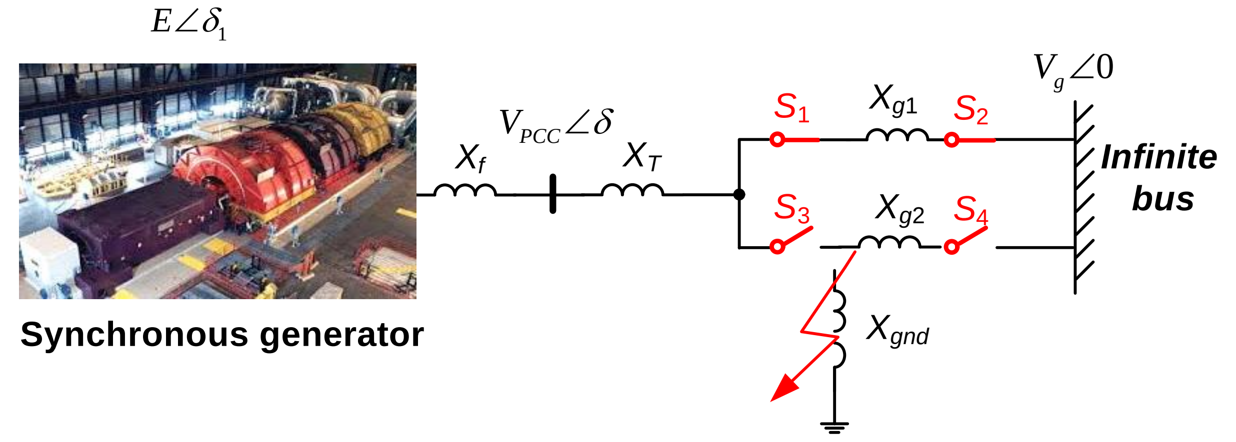
$$P_m - P_e - D\dot{\delta} = H\ddot{\delta}$$

Power equation

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



Transient Stability
Critical fault clearing angle/time

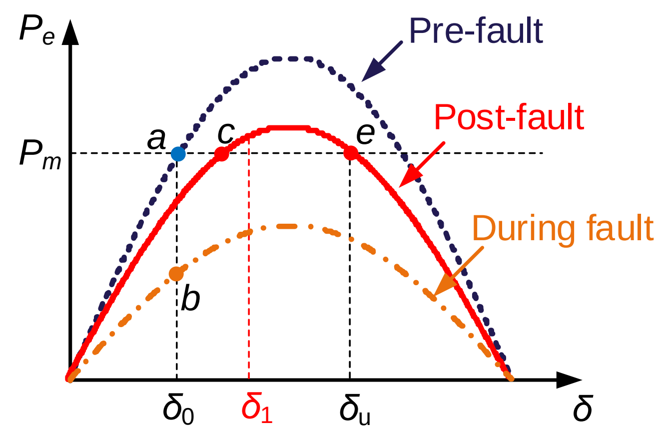


Single-machine infinite-bus power system

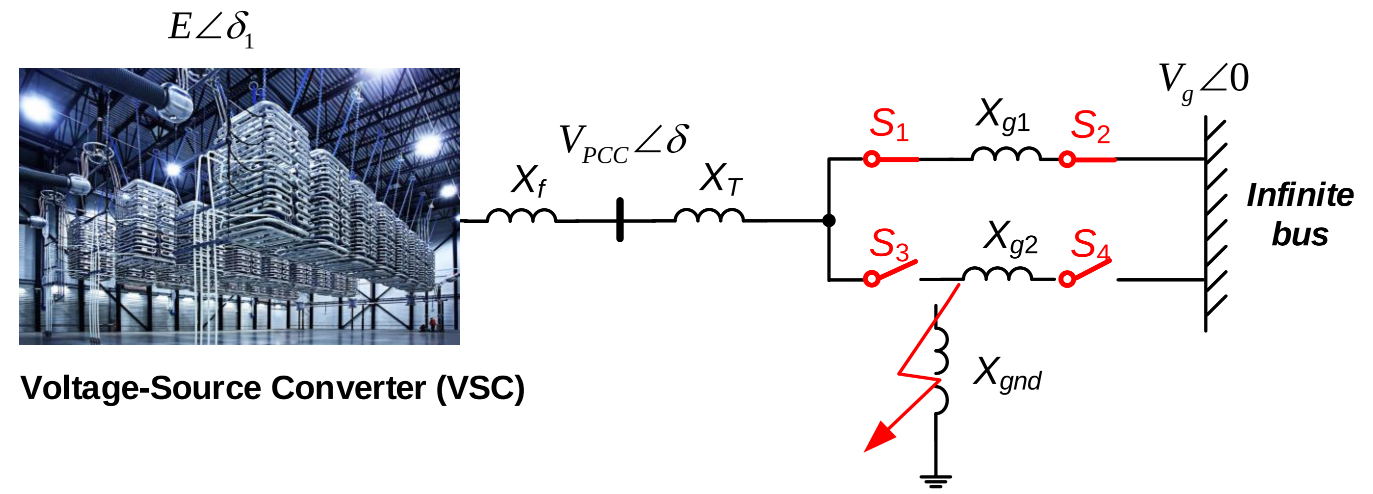
Fault clearing angle: δ_1

Critical clearing angle (CCA)

Critical clearing time (CCT)



Transient Stability
Voltage-Source Converter (VSC)



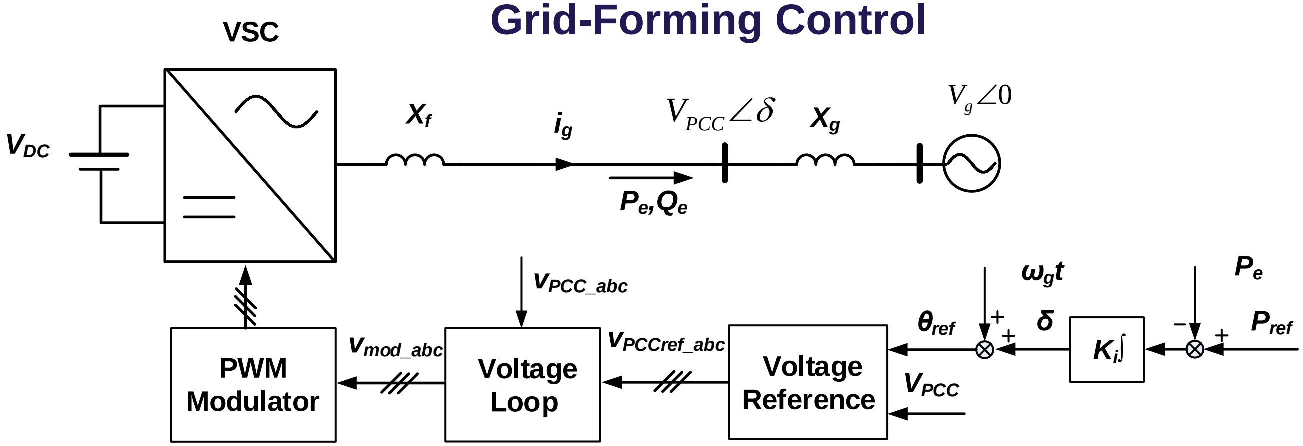
Single-VSC infinite-bus power system

Difference between VSC and SG

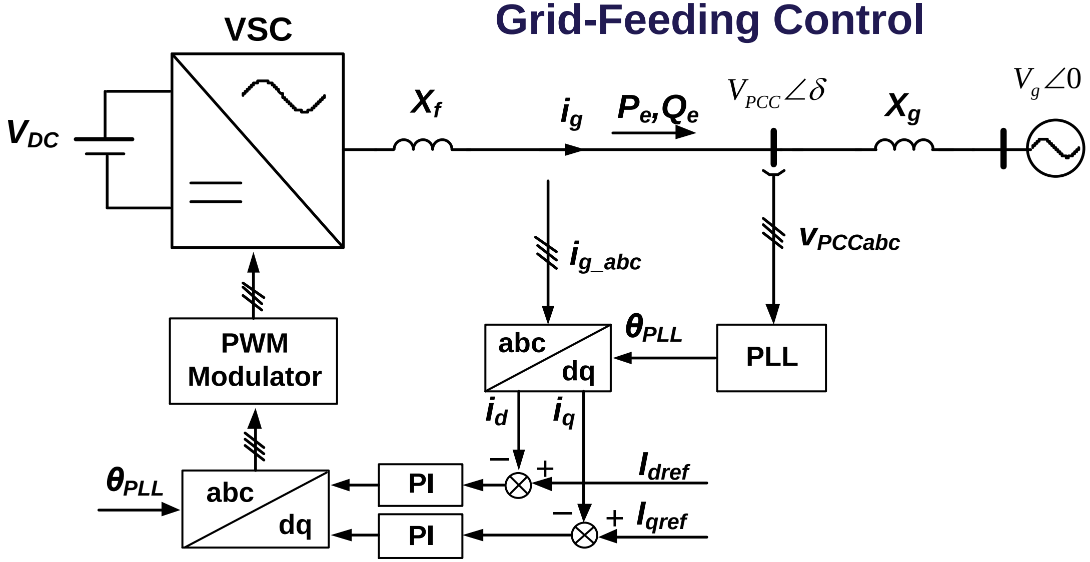
- No natural “rotor speed” response in VSC - lack of physical link with synchronization
- Synchronization is realized by power control and/or Phase-Locked Loop (PLL)
- Limited overcurrent capability - trigger current-mode control

Control of VSC

Grid-Forming Control

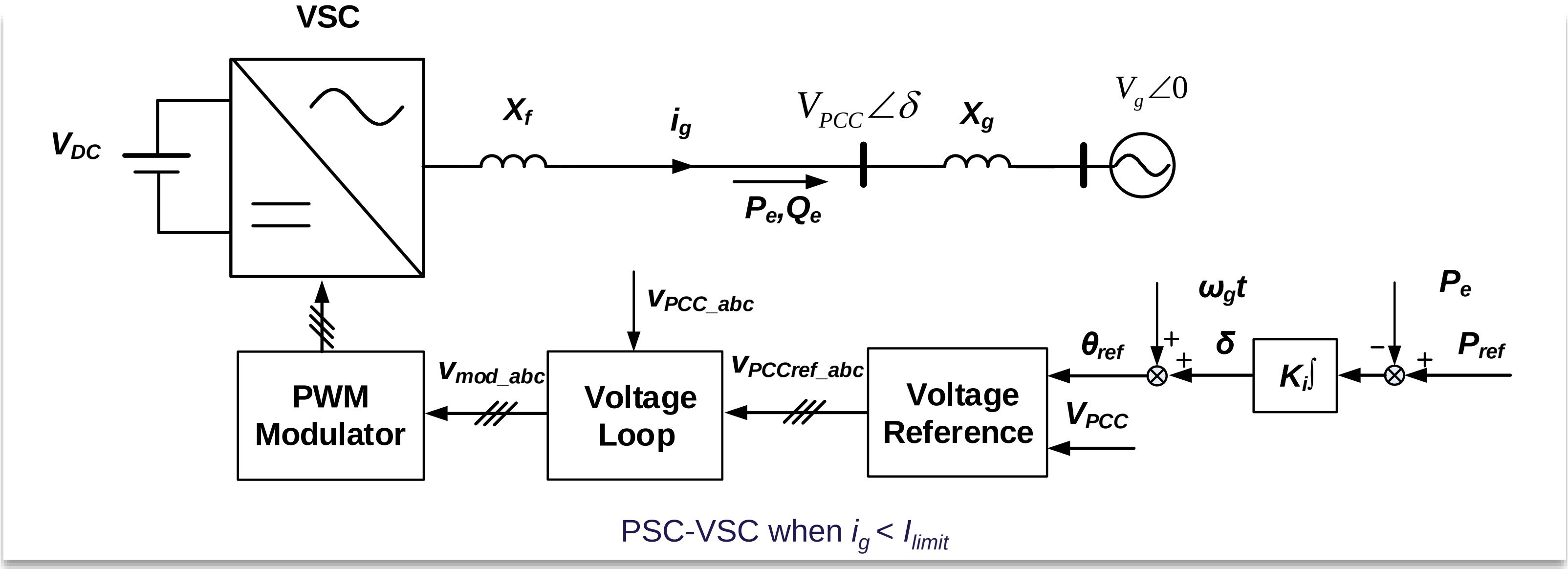


Grid-Feeding Control



Transient Stability

PSC-VSC within overcurrent limit

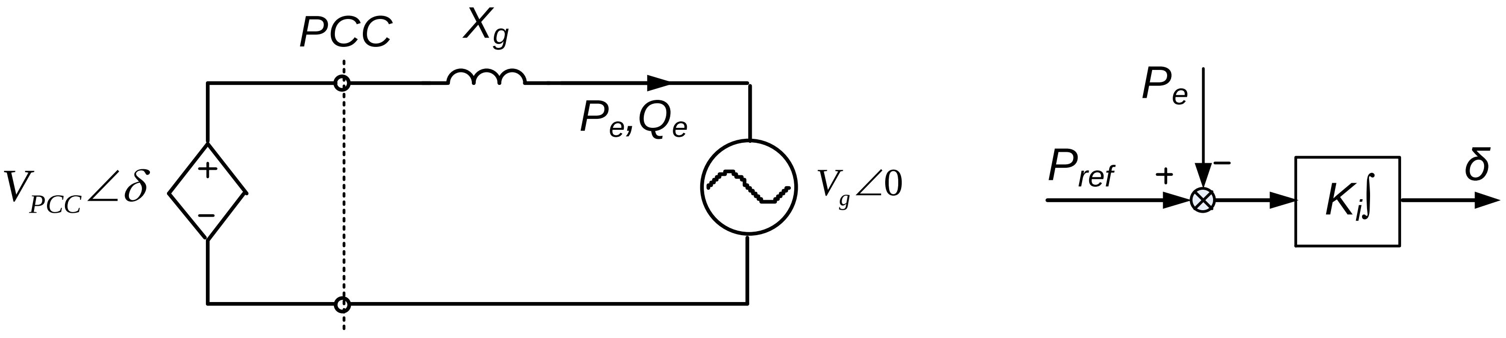


PSC-VSC when $i_g < I_{limit}$

Dynamic representation of PSC-VSC as a Voltage Source

- **Decoupled timescale:** transient stability: 2s ~ 3s, voltage control: 1ms ~ 10ms[1][3]
- Voltage control loop can be simplified as a unity gain
- Only the influence of active power control

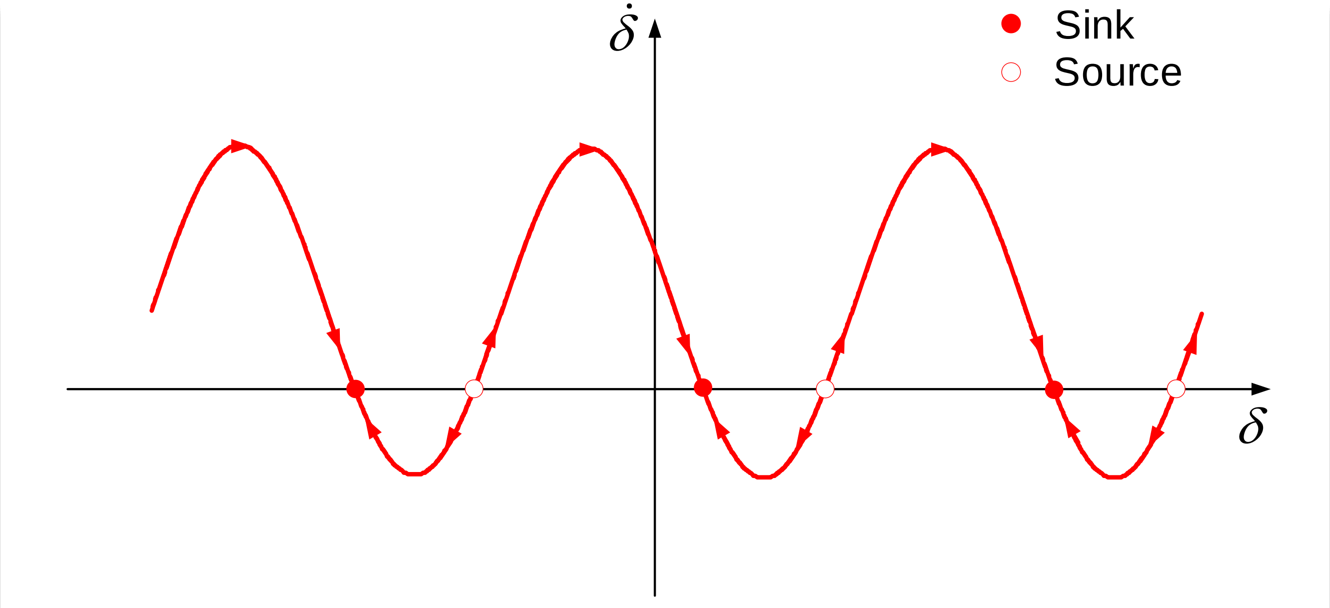
Transient Stability
First-order nonlinear system



Dynamic equivalent of PSC-VSC when $i_g < I_{limit}$

$$\left.\begin{aligned} \dot{\delta} &= K_i\left(P_{ref} - P_e\right) \\ P_e &= \frac{3V_{PCC}V_g}{2X_g}\sin\delta \end{aligned}\right\} \quad \dot{\delta} = K_i\left(P_{ref} - \frac{3V_{PCC}V_g}{2X_g}\sin\delta\right)$$

Transient Stability
Phase-portrait analysis



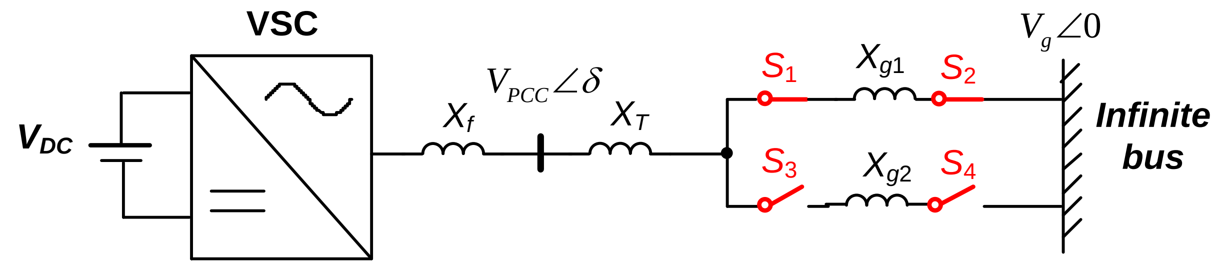
Phase portrait of first-order nonlinear systems

First-order nonlinear system with equilibrium points ($\dot{\delta} = 0$)

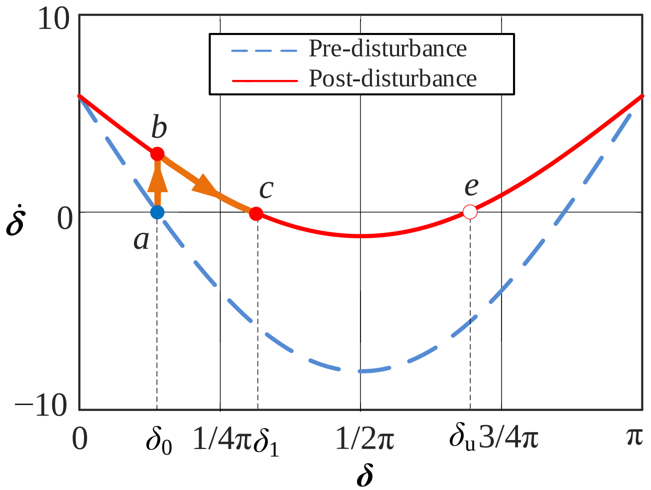
- For any initial conditions, the system is always stabilized at the closest sink point
- Zero overshoot in the dynamic response

Transient Stability

Disconnection of X_{g2} ($i_g < I_{limit}$)



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



Phase portrait analysis

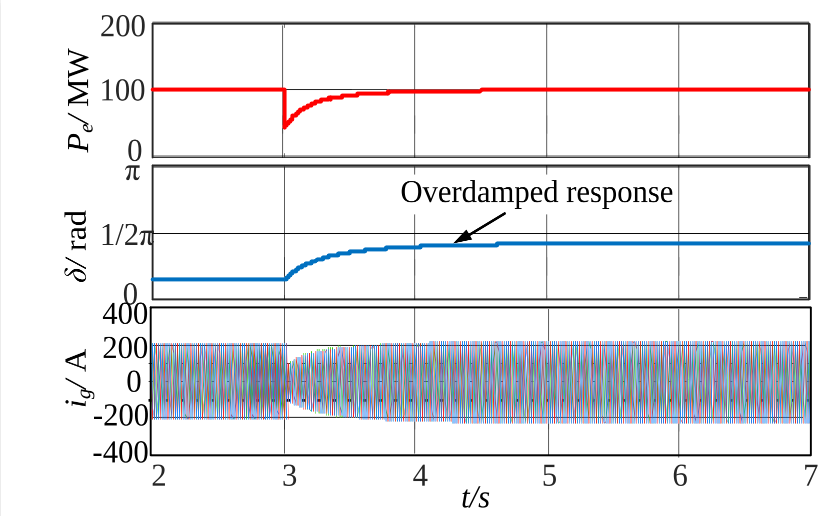
With equilibrium points after disturbance

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

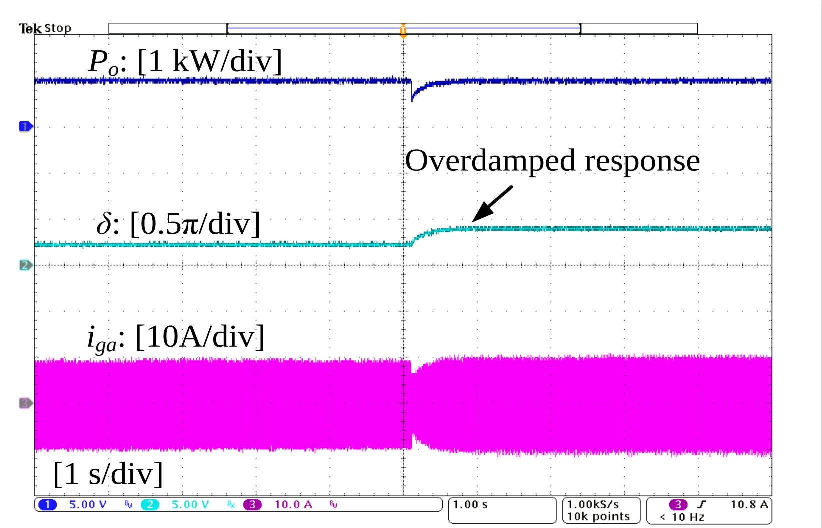
Transient Stability

Disconnection of X_{g2} ($i_g < I_{limit}$)

Simulation and experimental results

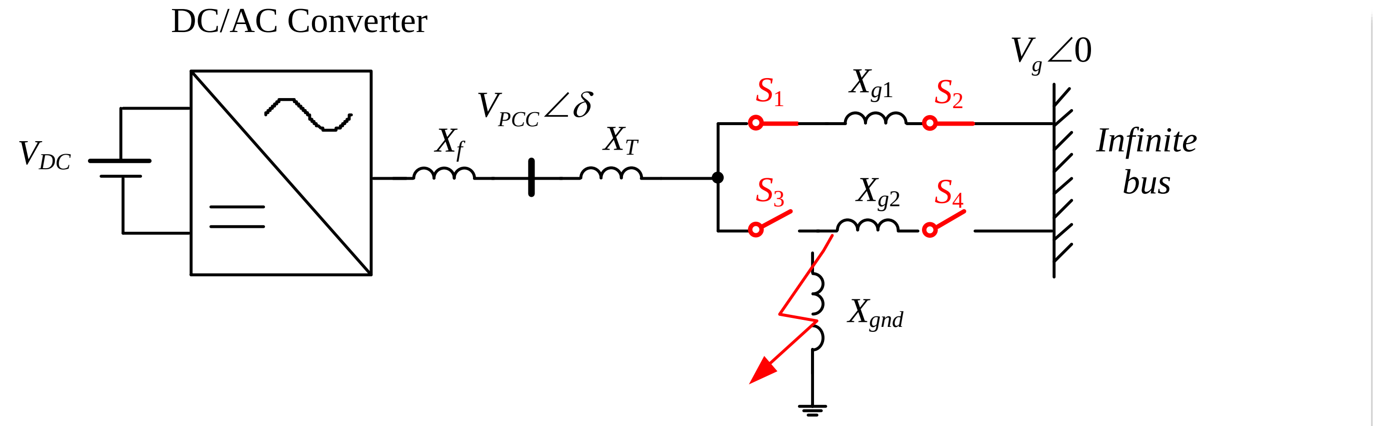


Simulation results

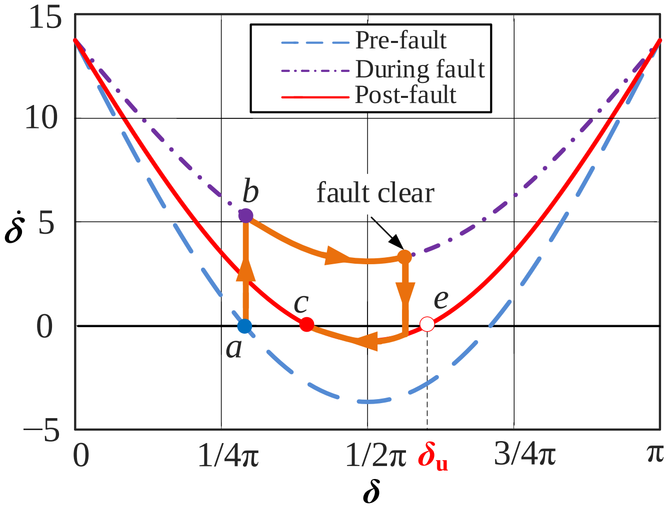


Experimental results

Transient Stability
High-impedance fault - CCA/CCT



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



Phase portrait analysis

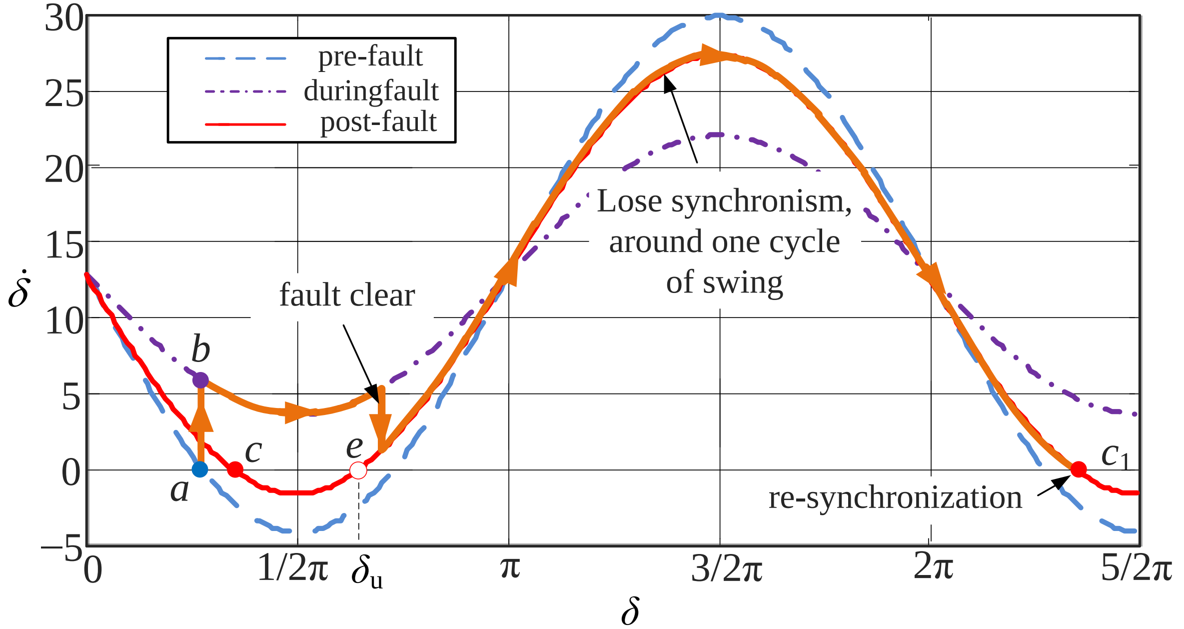
No equilibrium points during fault

Constant CCA and CCT

$$CCA = \delta_u$$

$$CCT = \int_0^{CCT} dt = \int_{\delta_0}^{CCA} \frac{d\delta}{K_i\left(P_{ref} - \frac{3V_{mref}V_g}{2X_g}\sin\delta\right)}$$

Transient Stability
High impedance fault - self-restoration

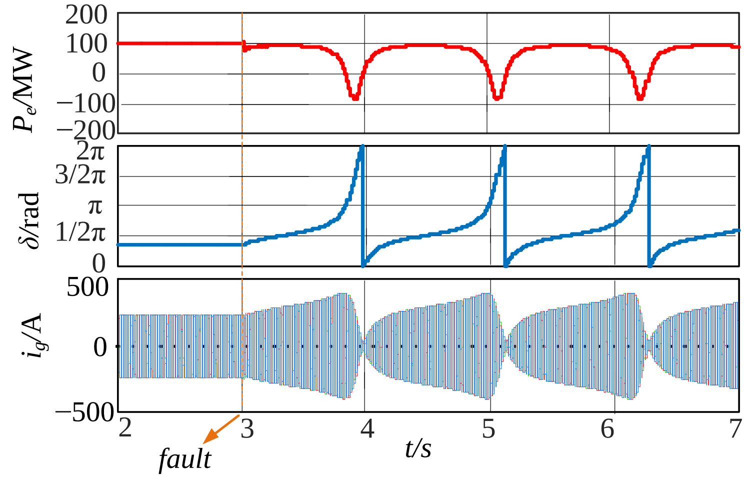


Phase portrait analysis when the fault is cleared beyond the CCA

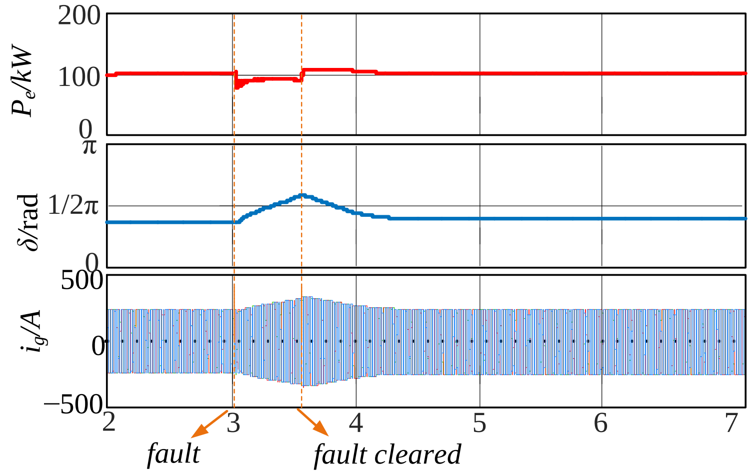
Self-restoration with PSC-VSC

- **The system will be re-synchronized (point c_1) if the fault is cleared beyond the CCA (point *e*)**
- Reduce the risk of the system being collapsed due to the delayed fault clearance

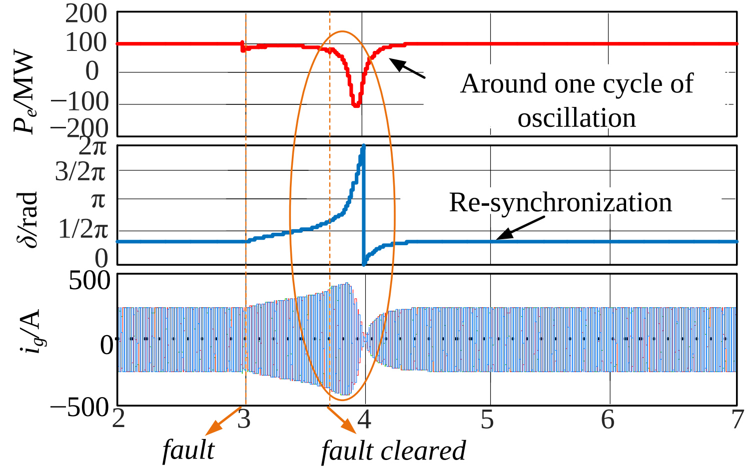
Transient Stability
High impedance fault - simulations



Fault is not cleared - no equilibrium points

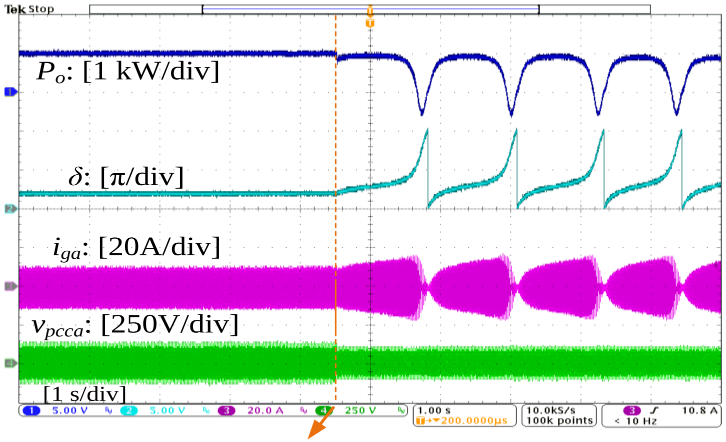


Fault clearing time < CCT



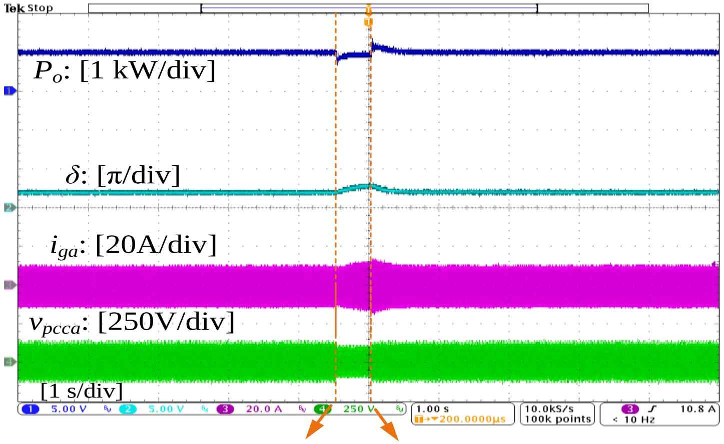
Fault clearing time > CCT

Transient Stability
High impedance fault - experiments



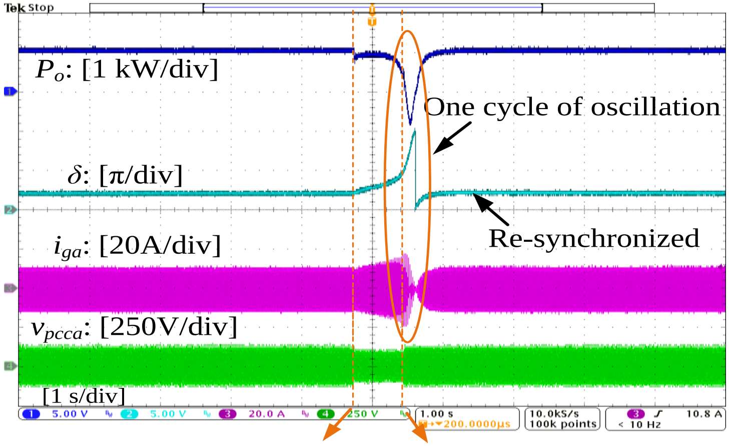
fault

Fault is not cleared - no equilibrium points



fault *fault cleared*

Fault clearing time < CCT

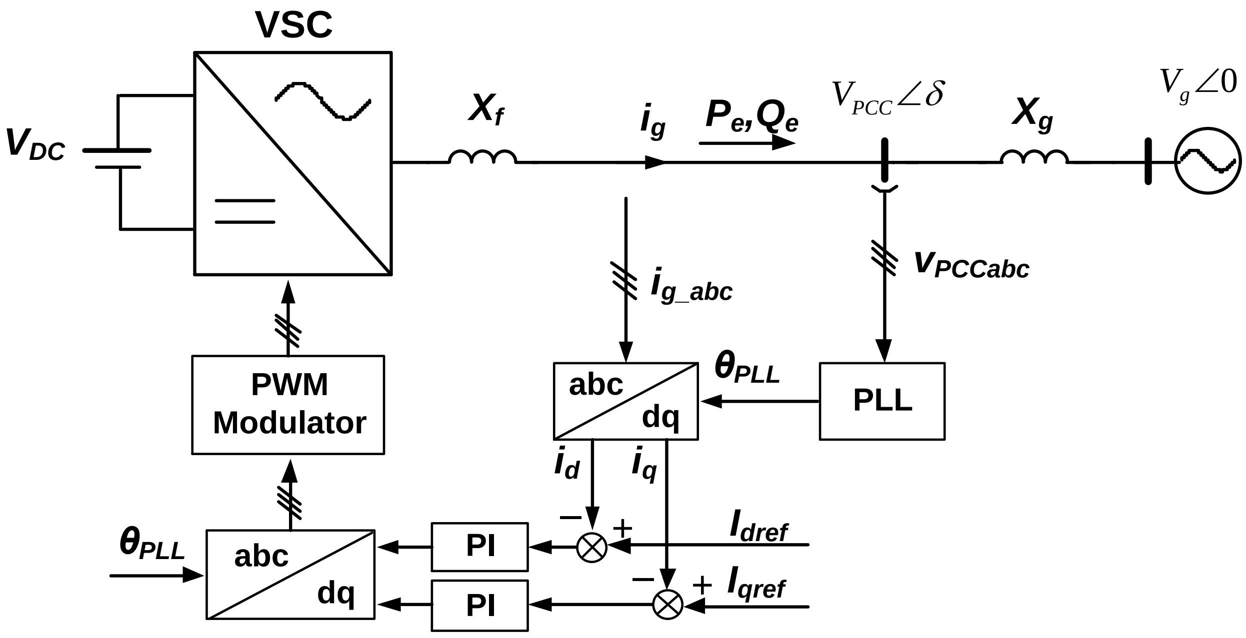


fault *fault cleared*

Fault clearing time > CCT

Transient Stability

PSC-VSC reaching overcurrent limit



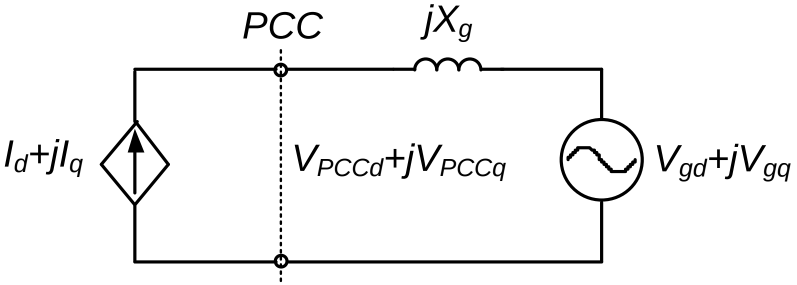
PSC-VSC when $i_g = I_{limit}$

Dynamic representation of PSC-VSC as a Current Source

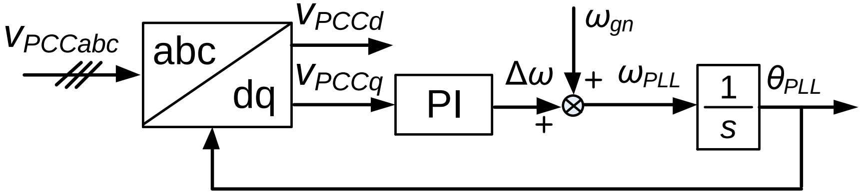
- **Decoupled timescale:** transient stability: 2s ~ 3s, current control: 1ms ~ 10ms[1][3]
- Current control loop can be simplified as a unity gain
- Only the influence of PLL

Transient Stability

Dynamic model of PLL effect



Dynamic equivalent of PSC-VSC when $i_g = I_{limit}$



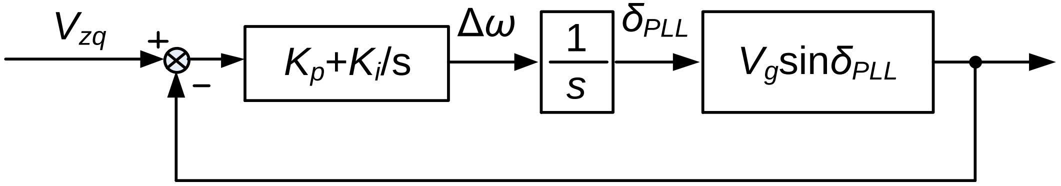
Block diagram of PLL

$$\underbrace{\begin{gathered} V_{zq} = I_d X_g, \quad V_{PCCq} = V_{gq} + V_{zq} \qquad \theta_{PLL} = \int \left[\omega_{gn} + \left(K_p + K_i \int \right) V_{PCCq} \right] \\ V_{gq} = -V_g \sin \delta_{PLL} \qquad \delta_{PLL} = \theta_{PLL} - \theta_g \end{gathered}}$$

$$\delta_{PLL} = \int \left(K_p + K_i \int \right) \left(V_{zq} - V_g \sin \delta_{PLL} \right)$$

Transient Stability

Second-order nonlinear system



Dynamic model of PLL for transient stability analysis

$$\delta_{PLL} = \int \left(K_p + K_i \int\right)\left(V_{zq} - V_g \sin\delta_{PLL}\right)$$

Governing equation of PLL dynamics ⟷ **Swing equation of SG**

$$V_{zq} - V_g \sin\delta_{PLL} - D_{eq} \cdot \dot{\delta}_{PLL} = H_{eq} \ddot{\delta}_{PLL}$$

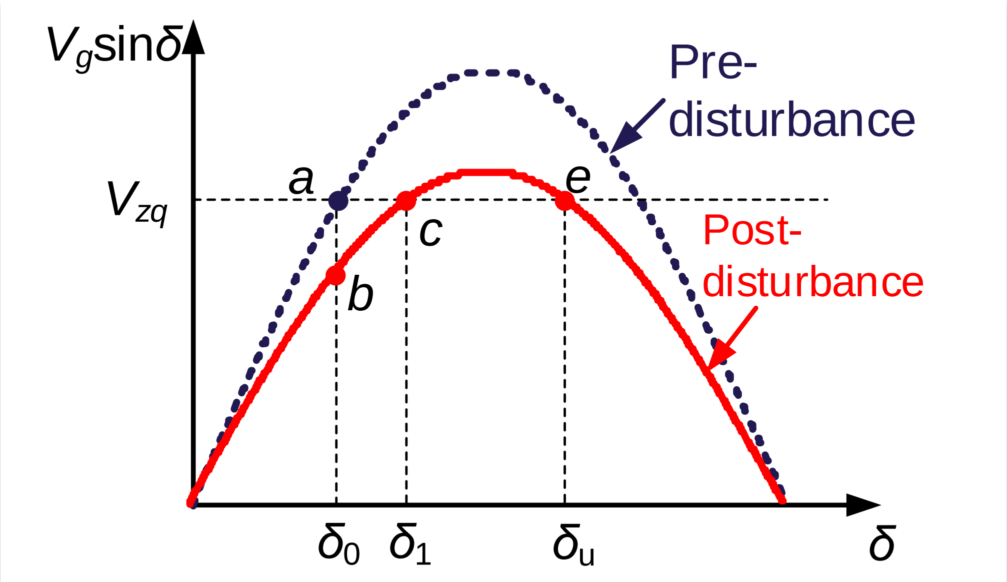
$$P_m - \frac{3 V_{PCC} V_g}{X_g} \sin\delta - D\dot{\delta} = H\ddot{\delta}$$

$$H_{eq} = \frac{\left(1 - K_p I_{gd} L_g\right)}{K_i}$$

$$D_{eq} = \frac{K_p V_g \cos\delta_{PLL}}{K_i}$$

Transient Stability

Voltage-angle curve of PLL



Voltage-angle curve of PLL

Governing equation of PLL

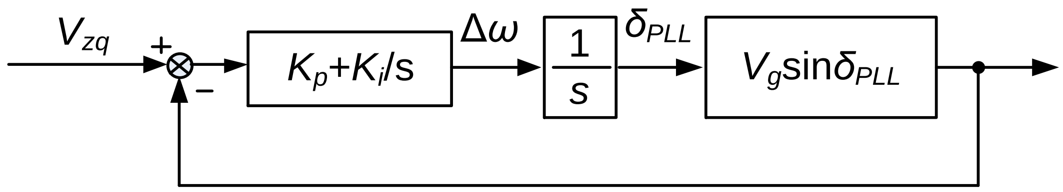
$$V_{zq} - V_g \sin\delta_{PLL} - D_{eq} \cdot \dot{\delta}_{PLL} = H_{eq}\ddot{\delta}_{PLL}$$

Similarly to SG

- Before point *c*, $V_{zq}>V_g\sin\delta$, ω_{PLL} increases
- After point *c*, $V_{zq}<V_g\sin\delta$, ω_{PLL} decreases
- Loss of synchronization if $\omega_{PLL}> \omega_g$ at point *e*

Transient Stability

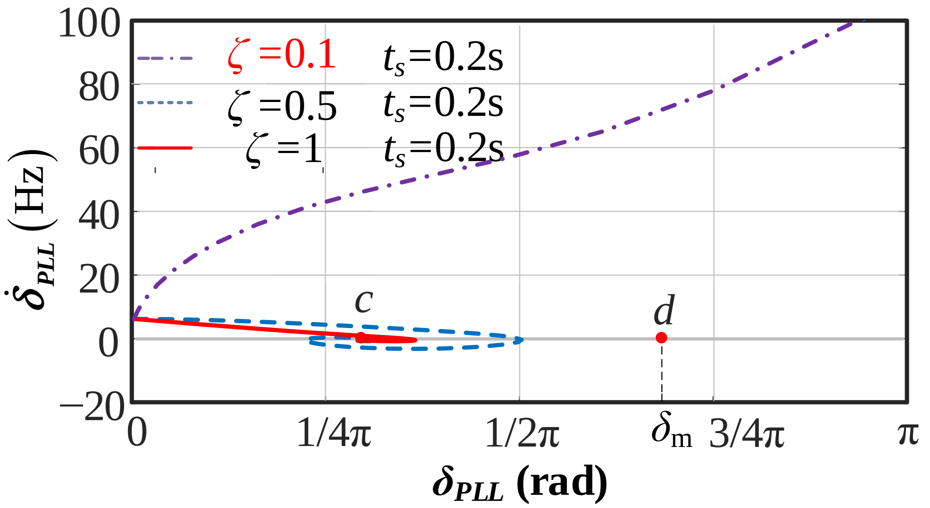
Design-oriented analysis

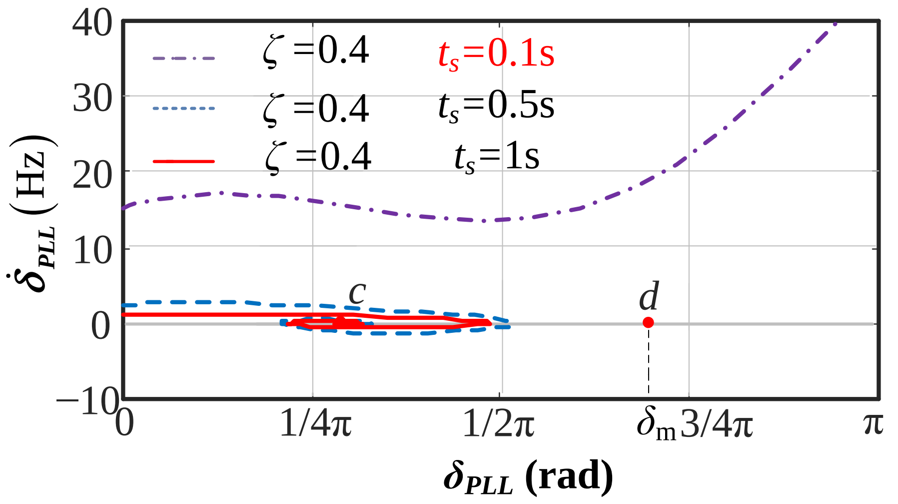


Dynamic model of PLL for transient stability analysis

Damping ratio: $\zeta = \frac{K_p}{2}\sqrt{\frac{V_g}{K_i}}$

Settling time: $t_s = \frac{9.2}{V_g K_p}$

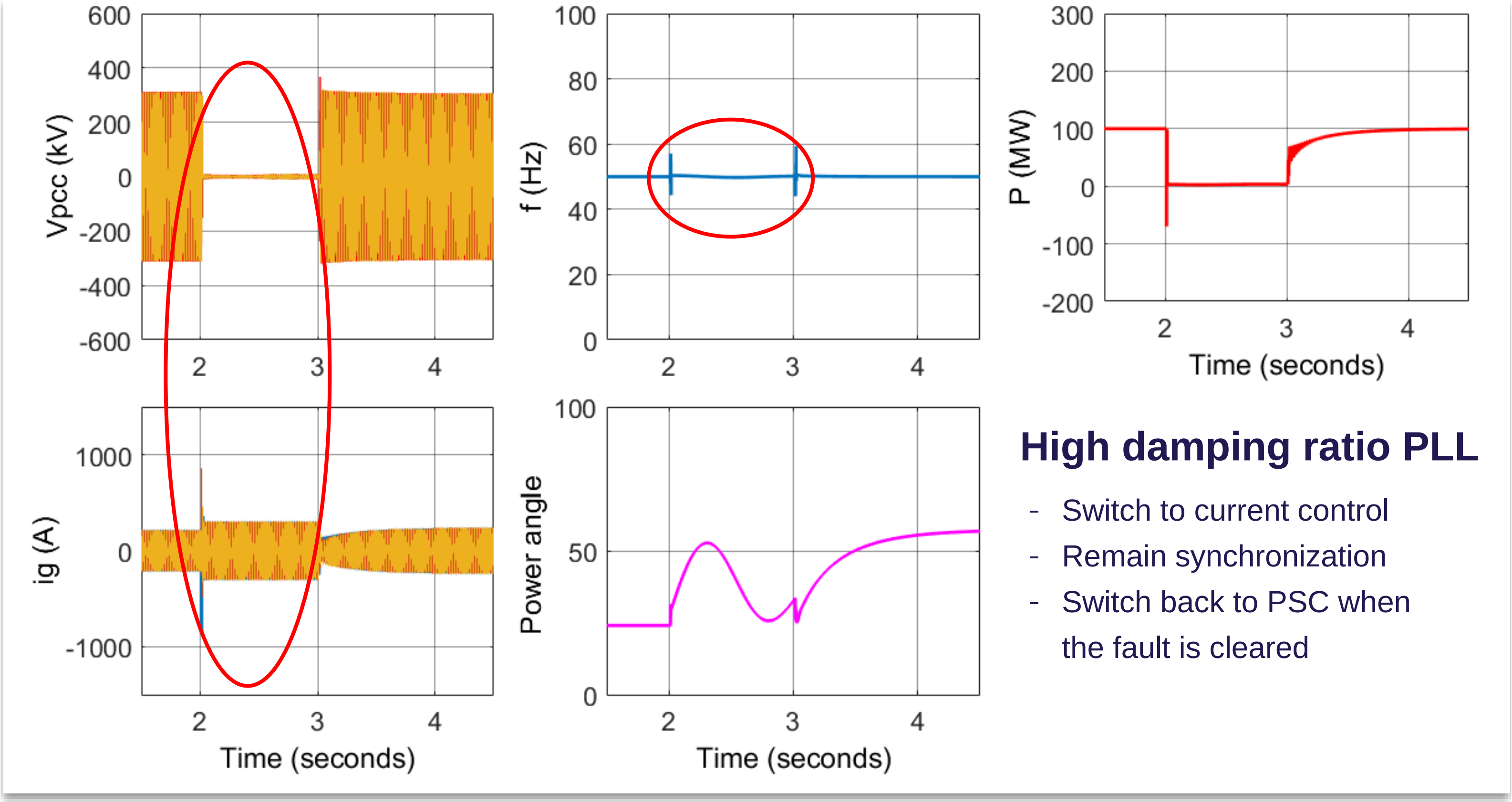




- **Large damping ratio and settling time** lead to better transient behavior.
- With Ki = 0, the PLL is a first-order nonlinear system - small K_i is preferred!

Transient Stability

Simulations - low-impedance fault

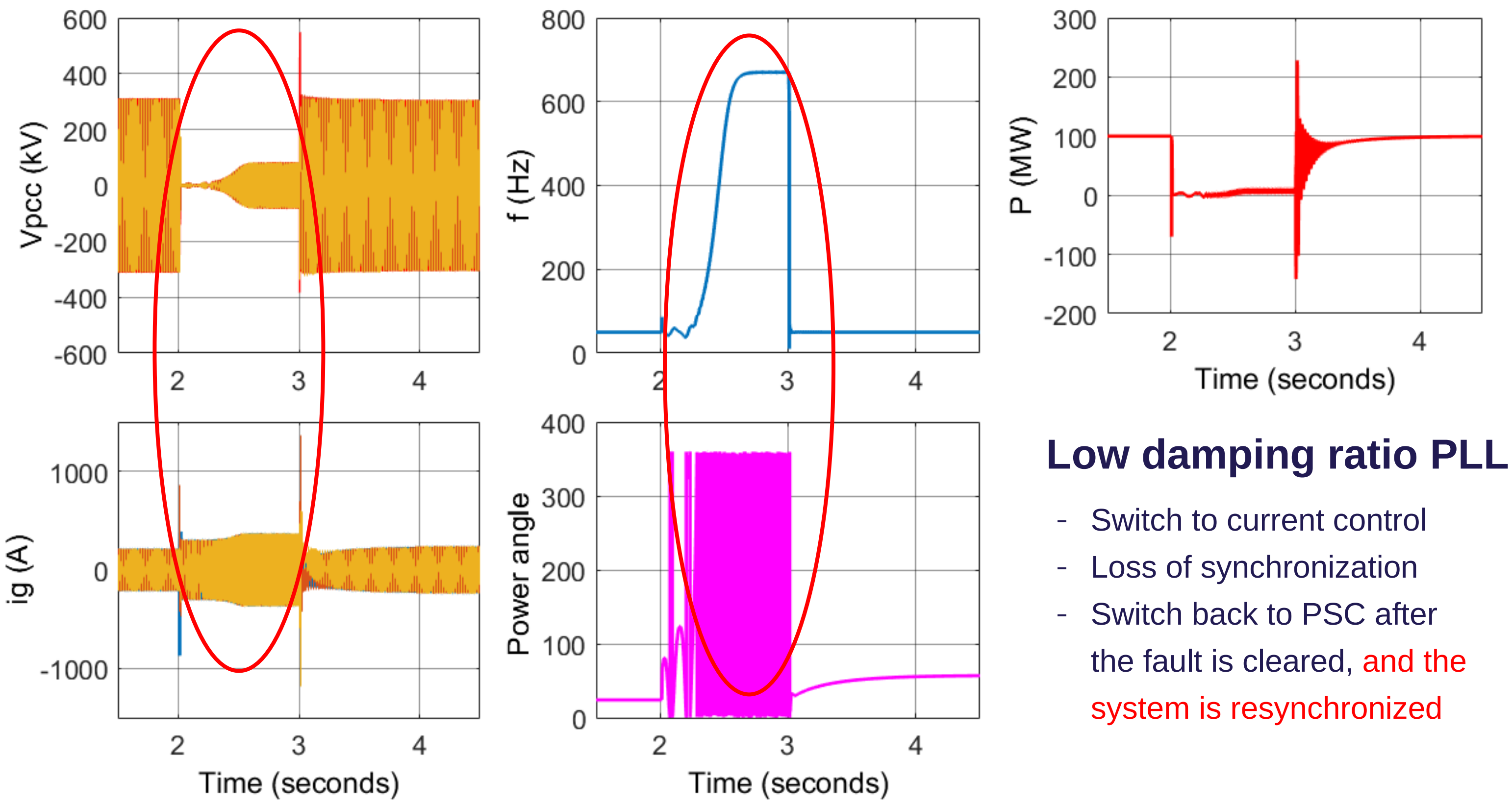


High damping ratio PLL

- Switch to current control
- Remain synchronization
- Switch back to PSC when the fault is cleared

Transient Stability

Simulations - low-impedance fault



Low damping ratio PLL

- Switch to current control
- Loss of synchronization
- Switch back to PSC after the fault is cleared, and the system is resynchronized

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Conclusions

Operating Scenarios		PSC-VSC	SG
With Equilibrium Points		No transient stability problem	May lose synchronization
No Equilibrium Points during the fault	High-impedance fault	- 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	- 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

Thank you! Questions?

[1] P. Kundur, *Power System Stability and Control*. New York, NY, USA: McGraw-Hill, 1994

[2] L. Zhang, L. Harnefors, and H. –P. Nee. “Power-synchronization control of grid-connected voltage-source converters”. *IEEE Trans. Power Syst.,*. 25, no. 2, pp. 809−820, May. 2010.

[3] L. Harnefors, X. Wang, A. G. Yepes, and F. Blaabjerg, “Passivity-based stability assessment of grid-connected VSCs – an overview,” *IEEE J. Emerg. Sel. Topics Power Electron*., vol. 4, no. 1, pp. 116-125, Mar. 2016.

[4] 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.

[5] H. Wu and X. Wang, “Transient stability impact of the phase-locked loop on grid-connected voltage source converters,” *International Power Electronics Conference (IPEC-ECCE Asia*), 2018, accepted.

[6] S. Ma, H. Geng, L. Liu, G. Yang, and B. C. Pal, “Grid-synchronization stability improvement of large scale wind farm during severe grid fault,” IEEE Transactions on Power Systems, vol. 33, pp. 216–226, Jan 2018.

[7] H. Geng, L. Liu, and R. Li, “Synchronization and reactive current support of pmsg based wind farm during severe grid fault,” IEEE Transactions on Sustainable Energy, vol. PP, no. 99, pp. 1–1, 2018.

Transient Stability Analysis of VSC-HVDC Systems

Xiongfei Wang, Aalborg University

Voltage-Source Converters (VSCs) are critical components in modern dc systems. The VSC-grid interactions pose new challenges on the system stability and power quality. Many research efforts have been made to address the small-signal stability of grid-connected VSC systems. Yet, less attention was given to the transient dynamics of VSCs with large grid disturbances. Very few works were reported on the transient stability of grid-connected VSCs, i.e. the ability to maintain synchronism with the power grid under severe transient disturbance. This presentation will give a comprehensive discussion on the transient stability of VSC-HVDC systems. The influences of synchronization control schemes based on active power control and phase-locked loop are analyzed by using the phase portrait. A number of superior features of the VSC over synchronous generators are revealed, and verified by simulations and down-scale experiments.”