# Small-Signal and Transient Stability Analysis of Voltage-Source Converters

## Heng Wu

Supervisor: Prof. Xiongfei Wang
Department of Energy Technology
Aalborg University, Denmark

AALBORG UNIVERSITY
DENMARK

# Outline

- ❑ **Introduction**

- ❑ **Small-Signal Stability Analysis of MMCs**
  - ➢ Grid-Forming MMCs
  - ➢ Grid-Following MMCs

- ❑ **Transient Stability Analysis of VSCs**
  - ➢ Grid-Forming VSCs
  - ➢ Grid-Following VSCs

- ❑ **Conclusion**

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- ❑ **Conclusion**

# Grid-connected voltage-source converters (VSCs)

**Generation**

©ABB

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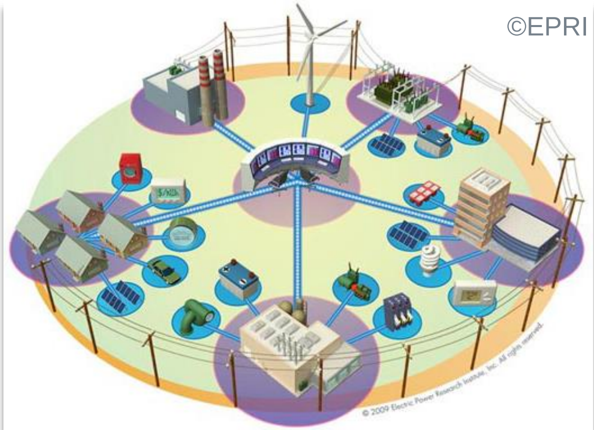

**Transmission/Distribution**

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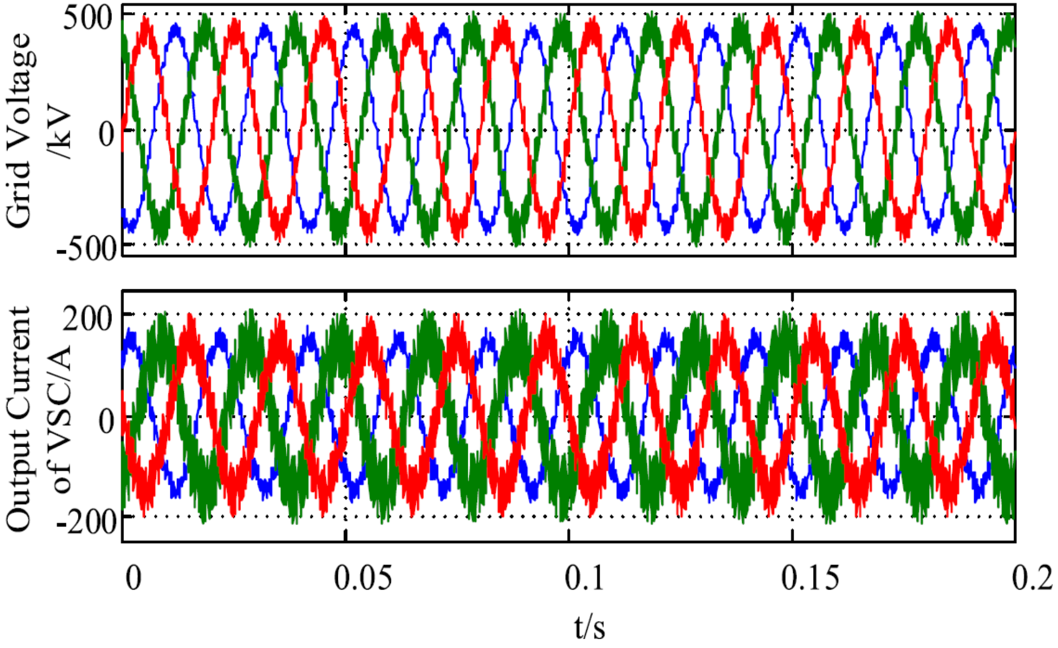
**Consumption**

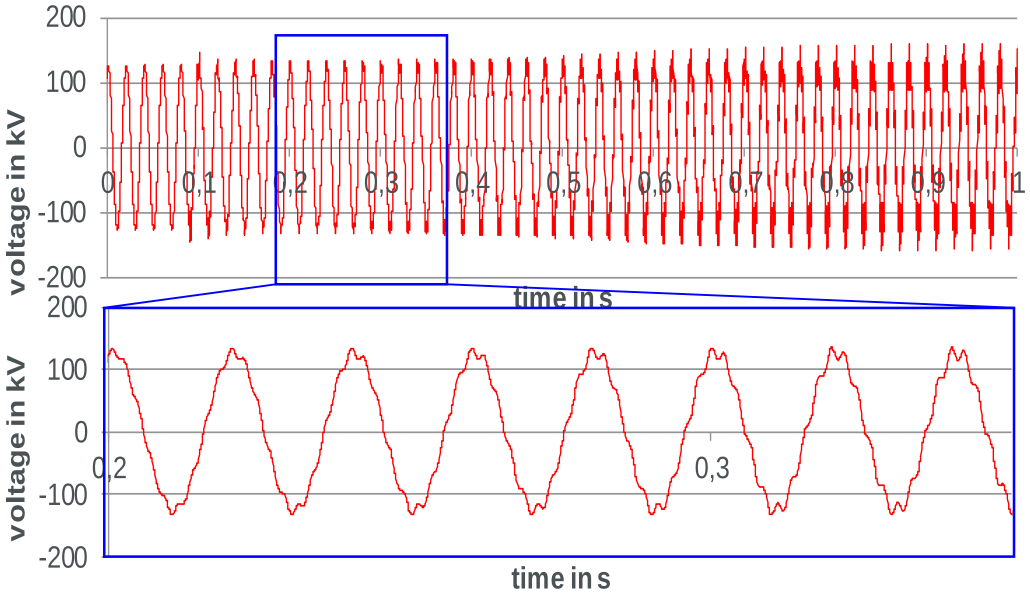
# Real-world challenges

## Small-signal stability



**MMC-HVDC in AC Grid, Luxi, Yunnan, China**[1]

- 1270 Hz resonance



**MMC-HVDC in Offshore Wind Farm, Germany**[2]

- 451 Hz resonance

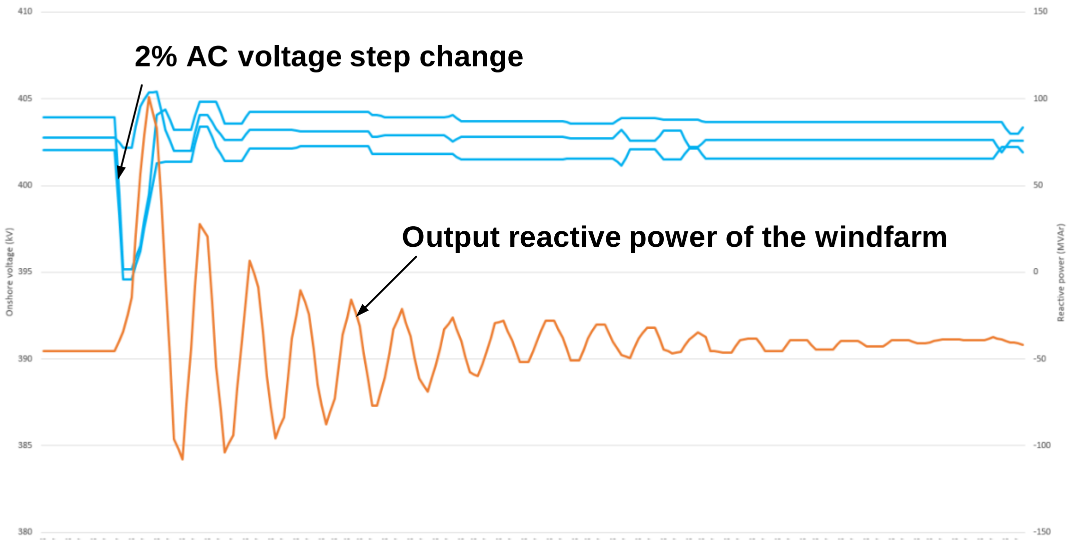
[1] C. Zou, H. Rao, S. Xu, et al., ”Analysis of resonance between a VSC-HVDC converter and the ac grid,” *IEEE Trans. Power Electron.*, vol. 33, no. 12, pp. 10157–10168, 2018.

[2] C. Buchhagen, M. Greve, A. Menze, and J. Jung, “Harmonic stability-practical experience of a TSO,” *Proc. 15th Wind Integration Workshop*, pp. 1–6, 2016.

# Real-world challenges

## Transient stability

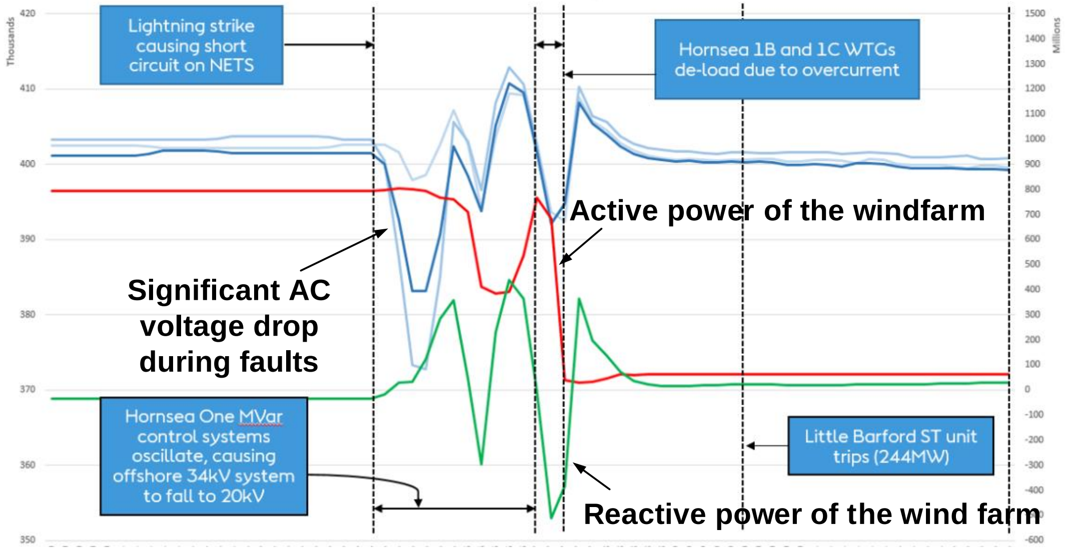
**In 2019, the Trip of an offshore wind power plant during grid faults lead to the blackout in London [1]-[2]**



2% AC voltage step change

Output reactive power of the windfarm

Stable after small-signal disturbance[2]



Lightning strike causing short circuit on NETS

Hornsea 1B and 1C WTGs de-load due to overcurrent

Active power of the windfarm

Significant AC voltage drop during faults

Hornsea One MVar control systems oscillate, causing offshore 34kV system to fall to 20kV

Little Barford ST unit trips (244MW)

Reactive power of the wind farm

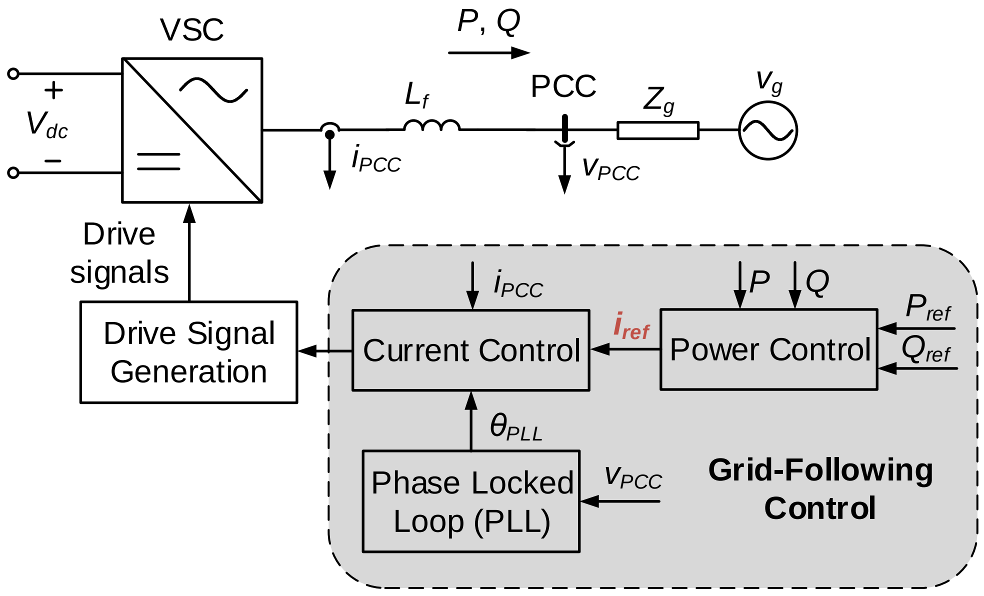
Unstable during the fault [2]

[1] National Grid, "Technical Report on the events of 9 August 2019," UK, Sep. 2019, [Online]. Available: https://www.nationalgrideso.com/document/152346/download
[2] National Grid, "Appendices to the Technical Report on the events of 9 August 2019." UK, Sep. 2019, [Online]. Available: https://www.ofgem.gov.uk/system/files/docs/2019/09/eso_technical_report_-_appendices_-_final.pdf

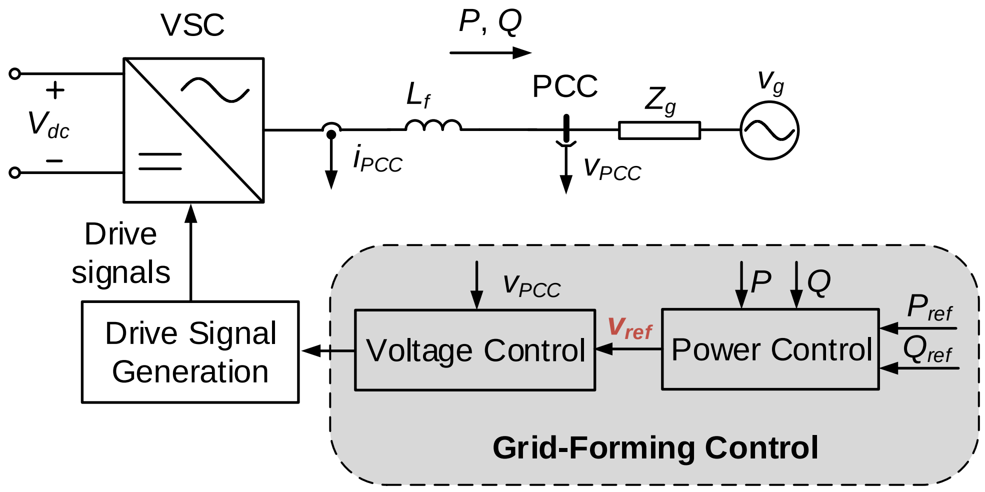
# Motivations

## Grid-Forming and Grid-Following VSCs

**Small-signal and large-signal synchronization stability (transient stability) of VSCs**



**Grid-Following (GFL) VSCs**

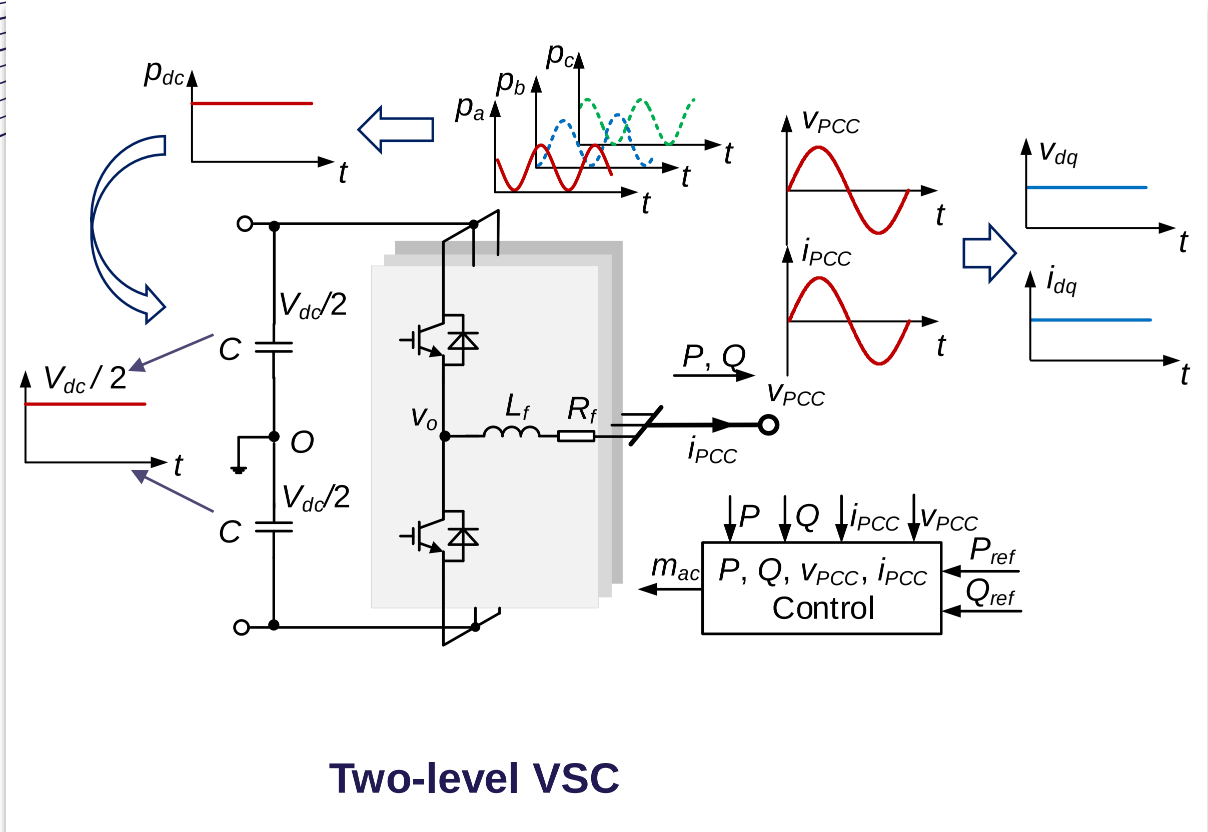


**Grid-Forming (GFM) VSCs**

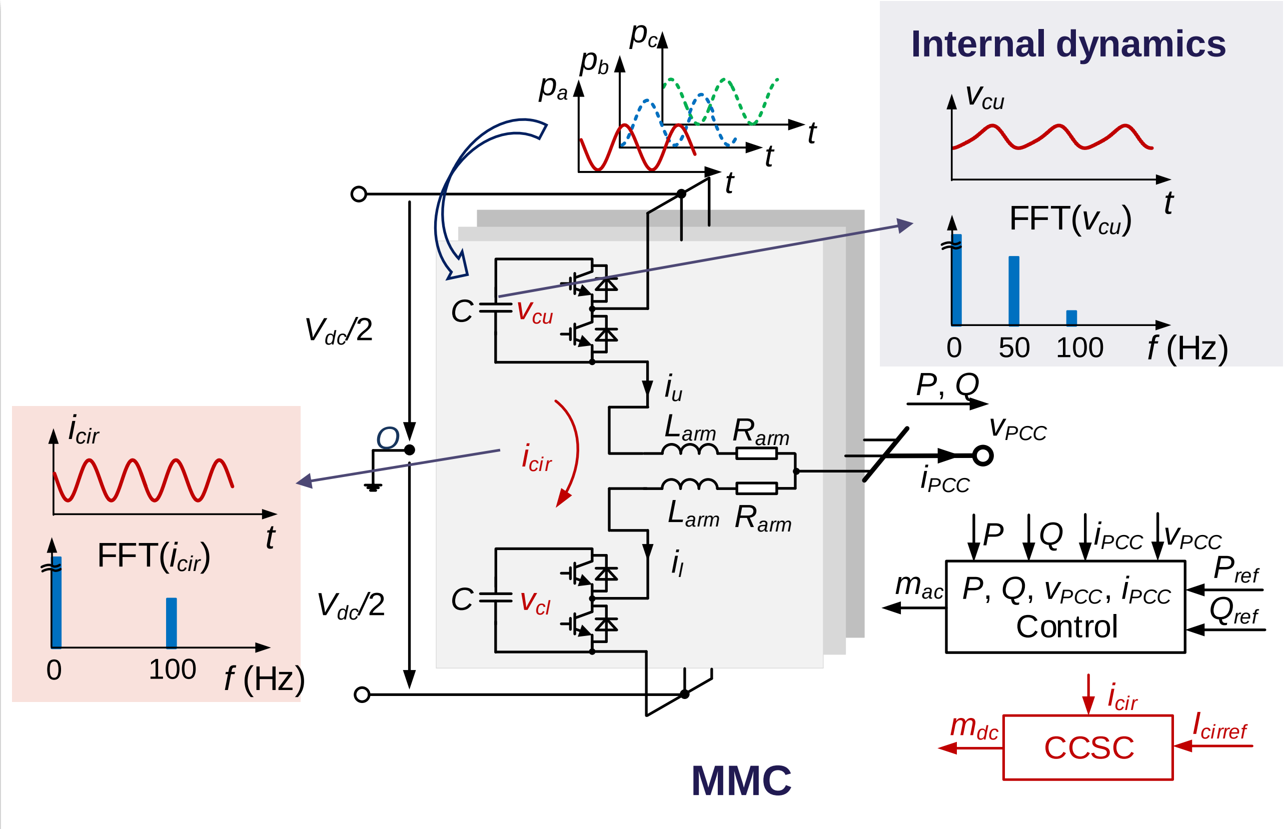
J. Matevosyan *et al*., "GFM inverters," *IEEE Power & Energy Magazine*, vol. 17, no. 6, pp. 89–98, November/December 2019.

# Scientific challenges and research questions

## Small-signal stability: internal dynamics of MMCs



**Two-level VSC**



**MMC**

Constant operating point in dq frame

Linearization ⇒

Linear time invariant (LTI) model [1]-[4]

Time varying operating point ⇢ **Q1: LTI ?**

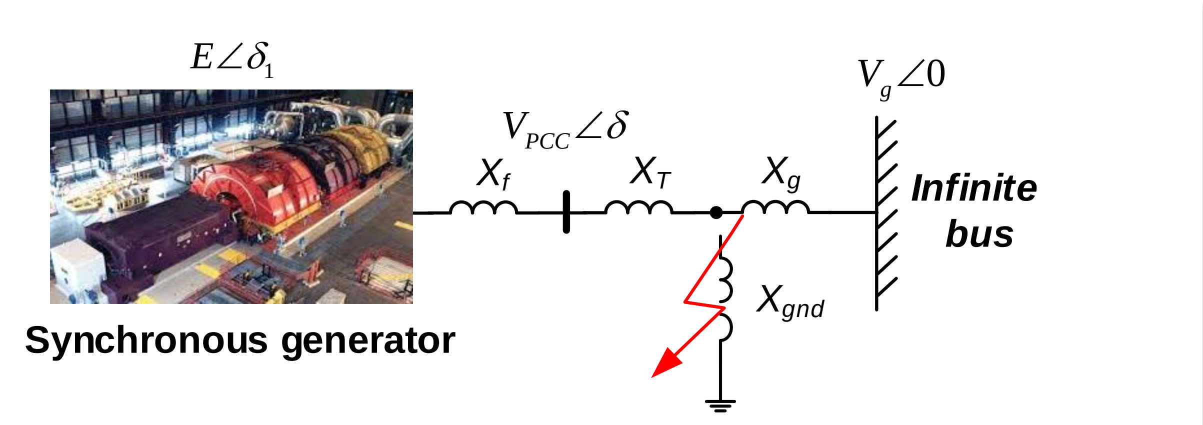
**Q2: Stability impact of the CCSC ?**

Source: [1] K. Ngo (1986). [2] L. Harnefors (2007). [3] B. Wen (2015). [4] X. Wang (2016)

Source: [1] E. Rakhshani (2013). [2] Hani Saad (2017).

# Scientific challenges and research questions

## Transient stability basics of synchronous generators (SGs)



**Swing equation**

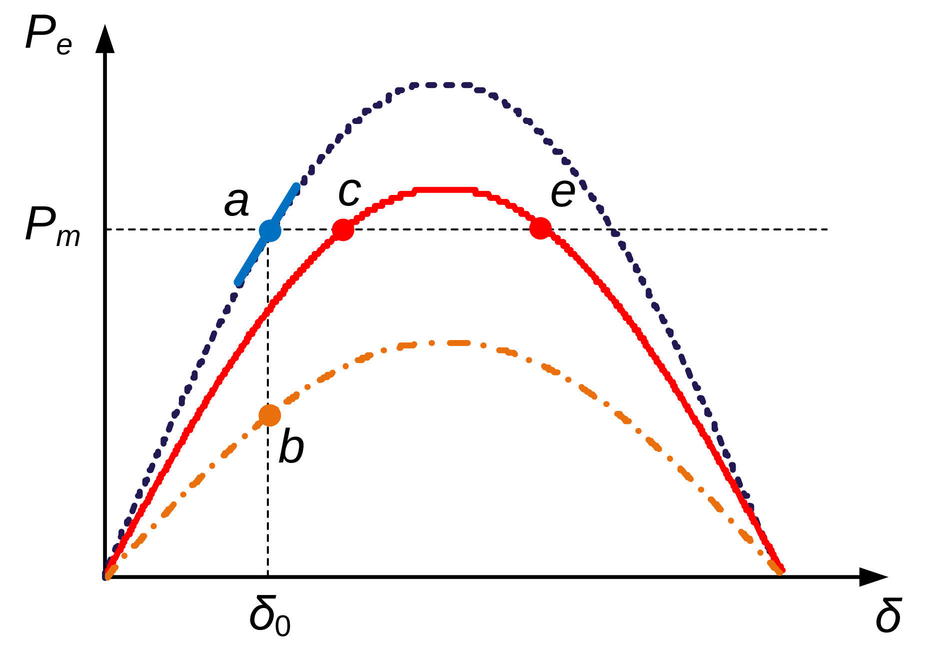
$$P_e = \frac{3V_{PCC}V_g}{2X_g}\sin\delta$$

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

⇒ Converge to the stable equilibrium point

**Transient Stability**

Existence of the stable equilibrium point



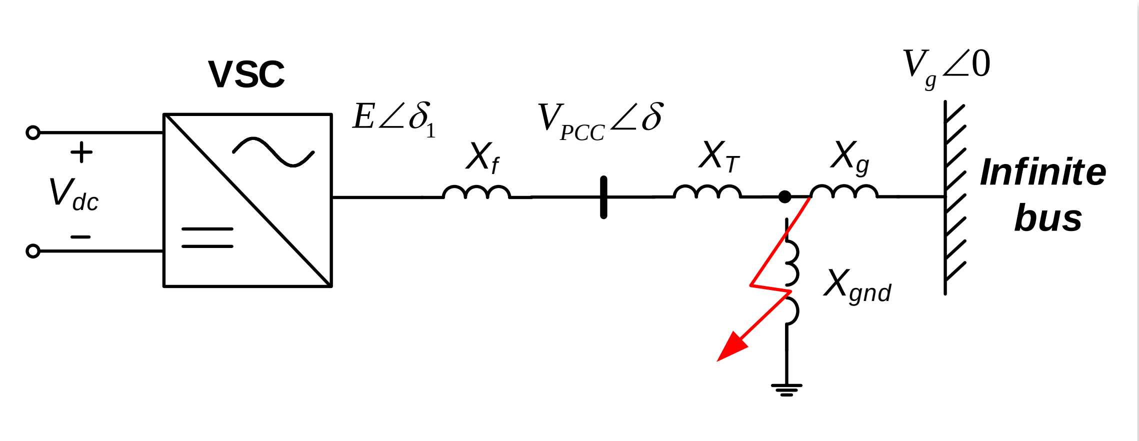
Critical clearing angle (CCA)

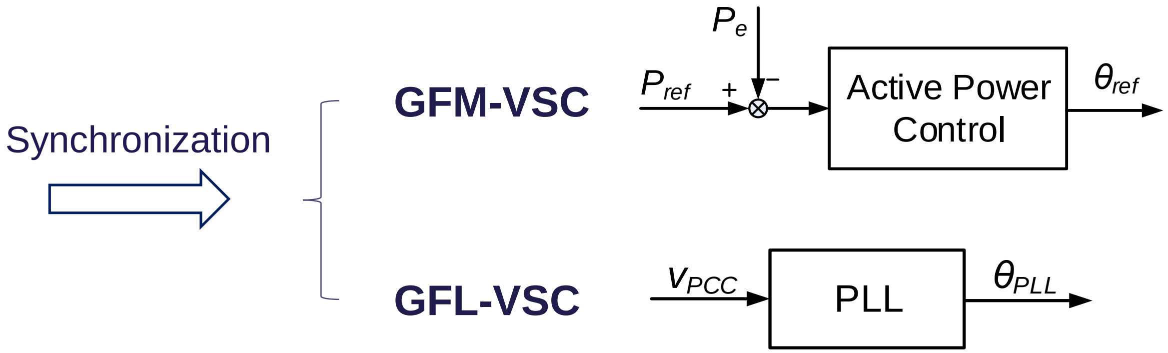
Critical clearing time (CCT)

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

# Scientific challenges and research questions

## Transient stability of VSCs





- Results of SGs cannot be directly borrowed
- Difficult to obtain analytical solution for nonlinear systems

**EMT simulation-based transient stability analysis [1]-[2]**

× Case-specific results

× Limited analytical insight

**Q3 and Q4: Design-oriented transient stability analysis considering different synchronization dynamics?**

Source: [1] E. Vittal (2012). [2] M. Edrah (2015).

# Thesis structure

### Small-signal stability of MMCs

**Q1:** LTI model

**Q2:** Stability impact of the CCSC

### Small-signal stability of MMCs

- Small-signal modeling and stability analysis of GFM-MMC
- Small-signal modeling and stability analysis of GFL-MMC

**Impact of internal dynamics**

### Transient stability of VSCs

**Q3:** Transient stability impact of the active power control

**Q4:** Transient stability impact of the PLL

### Transient stability of VSCs

- Large-signal modeling and transient stability analysis of GFM-VSC
- Large-signal modeling and transient stability analysis of GFL-VSC

**Impact of synchronization dynamics**

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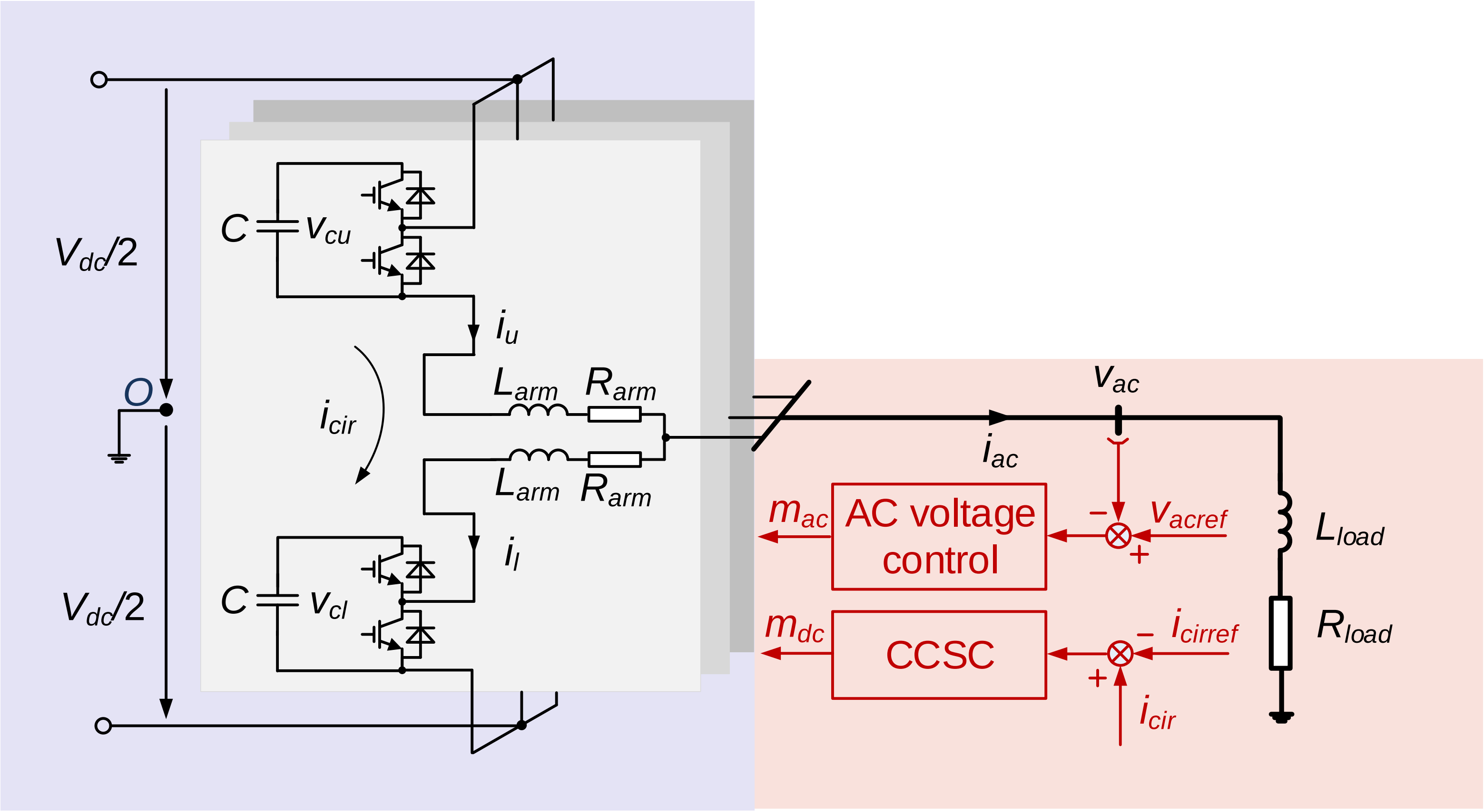
# GFM-MMC with the inductive load



Time-varying power stage

Linear control loops

# Modeling methodologies

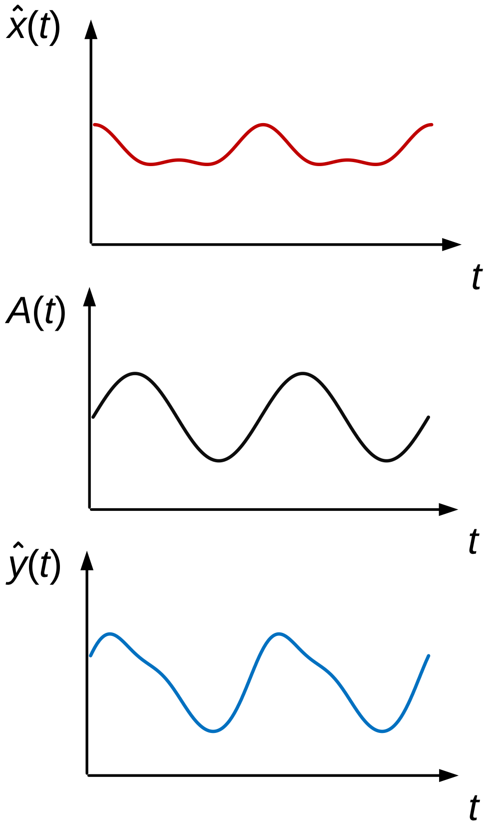
## Harmonic state space(HSS)

**Time varying system**

$$\hat{y}(t) = A(t)\cdot\hat{x}(t)$$

**LTI representation based on Fourier coefficients**

$$\hat{\mathbf{Y}} = \mathbf{A}\hat{\mathbf{X}}$$

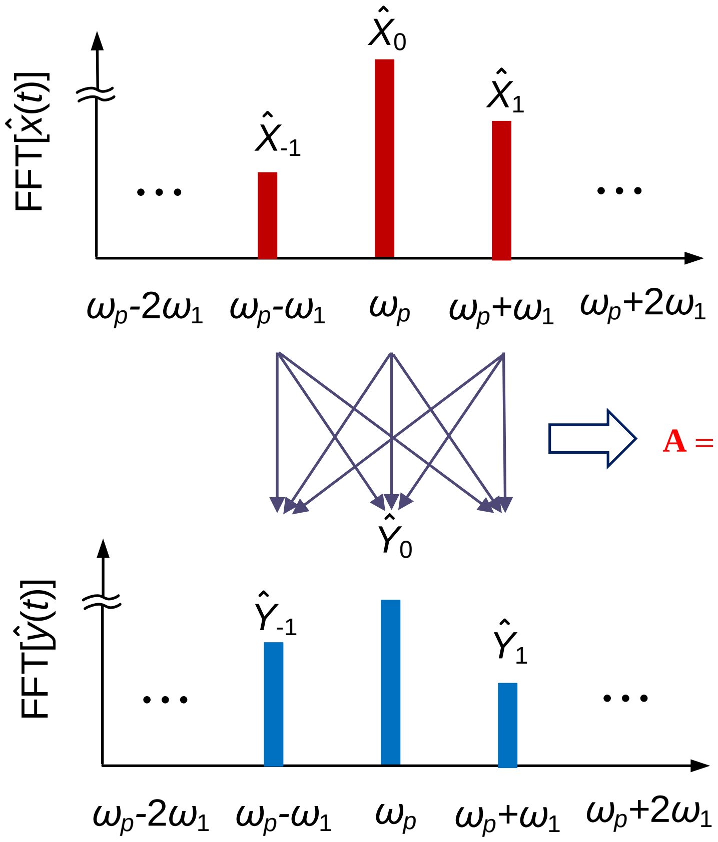


$$\hat{x}(t) = \sum_{k=-\infty}^{+\infty} \hat{X}_k e^{j(\omega_p + k\omega_1)t}$$

$$A(t) = \sum_{k=-\infty}^{+\infty} A_k e^{jk\omega_1 t}$$

$$\hat{y}(t) = \sum_{k=-\infty}^{+\infty} \hat{Y}_k e^{j(\omega_p + k\omega_1)t}$$

Constant



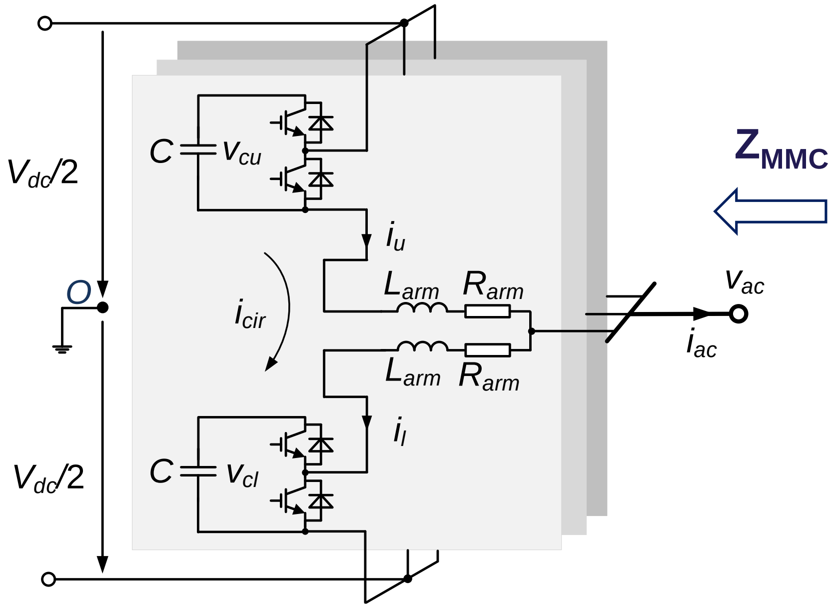
$$\mathbf{A} = \begin{bmatrix} \ddots & & & & \iddots \\ & A_0 & A_{-1} & A_{-2} & \\ \cdots & A_1 & A_0 & A_{-1} & \cdots \\ & A_2 & A_1 & A_0 & \\ \iddots & & & & \ddots \end{bmatrix}$$

- **Frequency coupling dynamics is captured**

N. M. Wereley, “Analysis and control of linear periodically time varying systems,” Ph.D. dissertation, Dept. Aeronaut. Astronaut., Massachusetts, Inst. Technol., Cambridge, MA, USA, 1991.

# Impedance matrix of the MMC

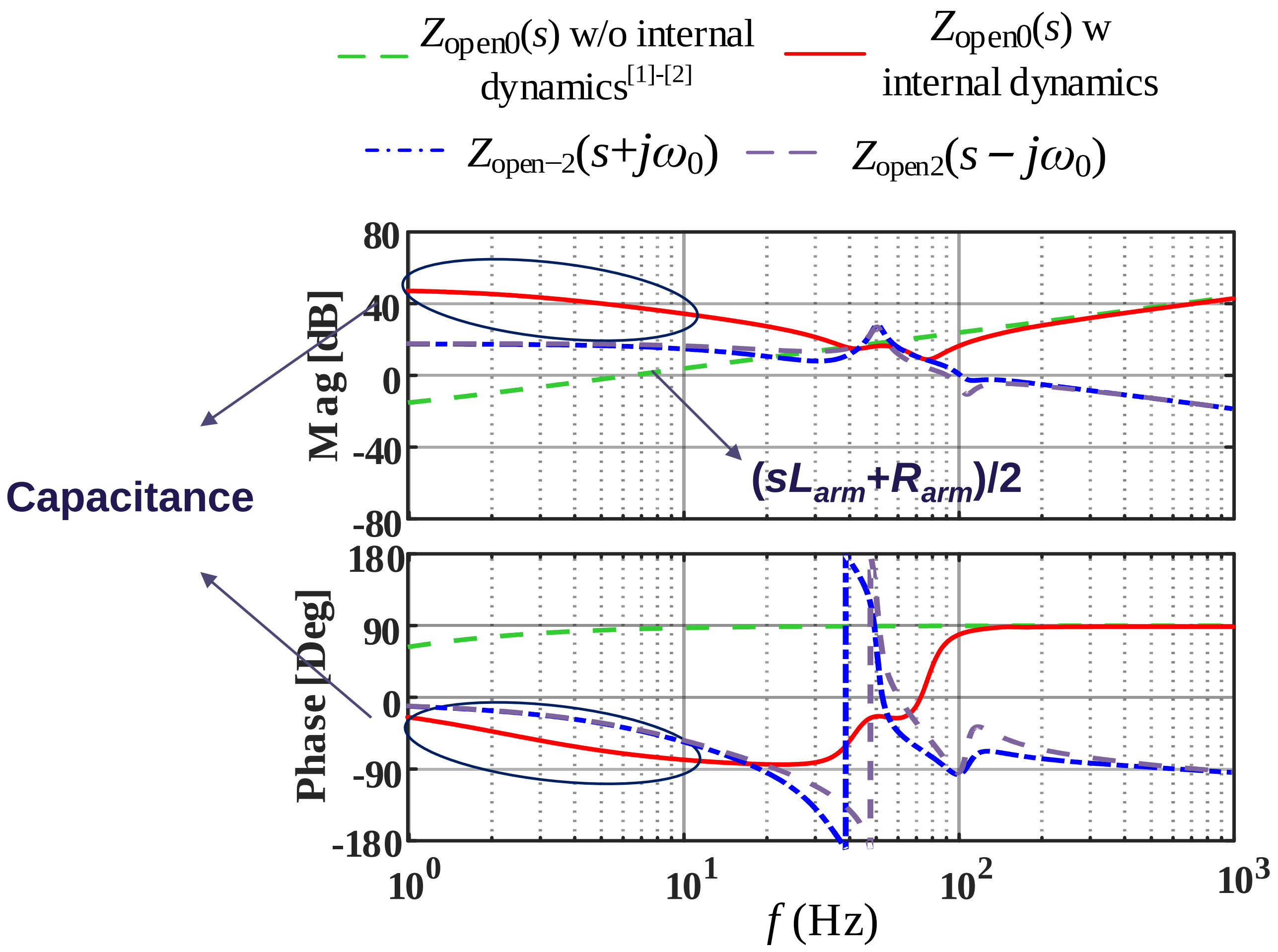
## Open-loop control



$$\mathbf{Z}_{\mathrm{MMC}} = \begin{bmatrix} \ddots & & \vdots & & \iddots \\ & Z_0(s-j\omega_0) & 0 & Z_{-2}(s+j\omega_0) & \\ \cdots & 0 & Z_0(s) & 0 & \cdots \\ & Z_2(s-j\omega_0) & 0 & Z_0(s+j\omega_0) & \\ \iddots & & \vdots & & \ddots \end{bmatrix}$$

⬜ Centered impedance

🟪 Frequency-coupled impedances

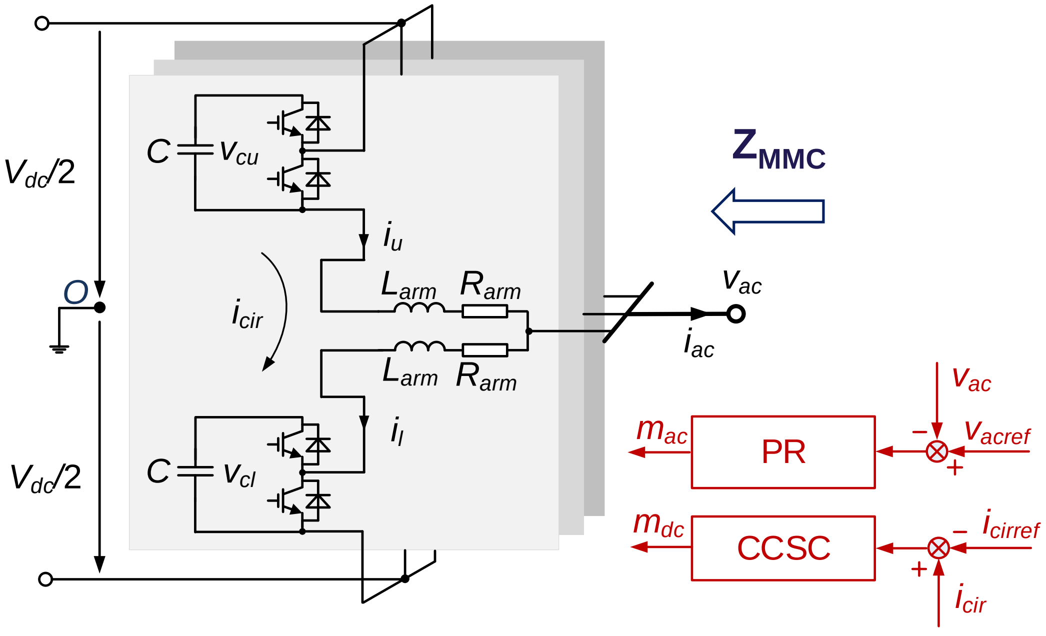


**Significant impact of internal dynamics**

Source: [1] E. Rakhshani (2013). [2] Hani Saad (2017).

# Impedance matrix of the MMC

## GFM control with PR voltage regulator

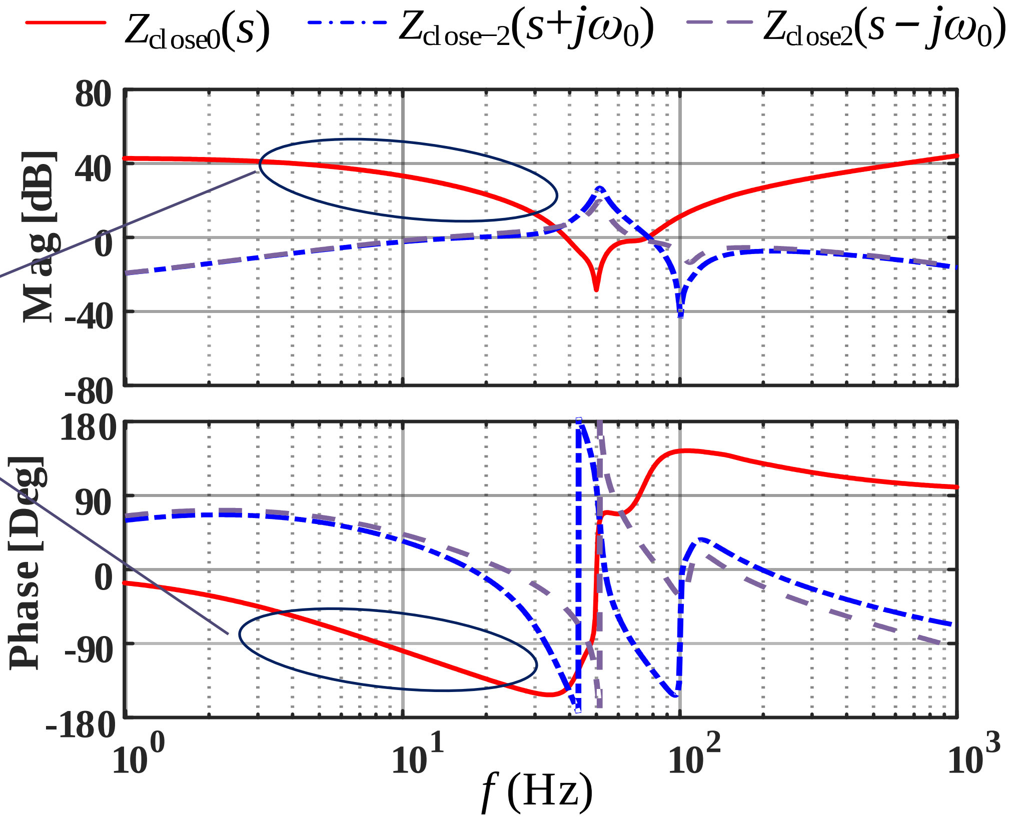


$$\mathbf{Z}_{\mathrm{MMC}} = \begin{bmatrix} \ddots & & \vdots & & \iddots \\ & Z_0(s-j\omega_0) & 0 & Z_{-2}(s+j\omega_0) & \\ \cdots & 0 & Z_0(s) & 0 & \cdots \\ & Z_2(s-j\omega_0) & 0 & Z_0(s+j\omega_0) & \\ \iddots & & \vdots & & \ddots \end{bmatrix}$$

⬜ Centered impedance

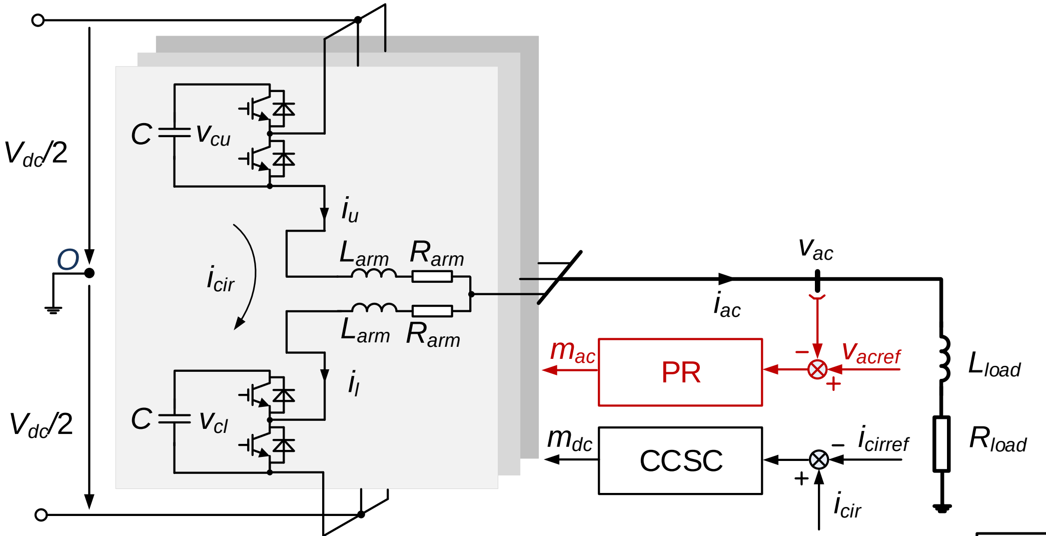
🟪 Frequency-coupled impedances

**Capacitance + negative resistance**

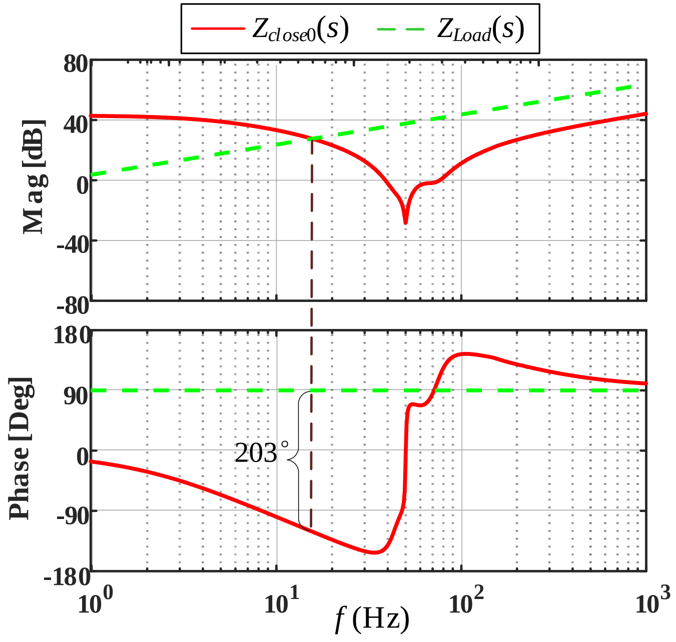


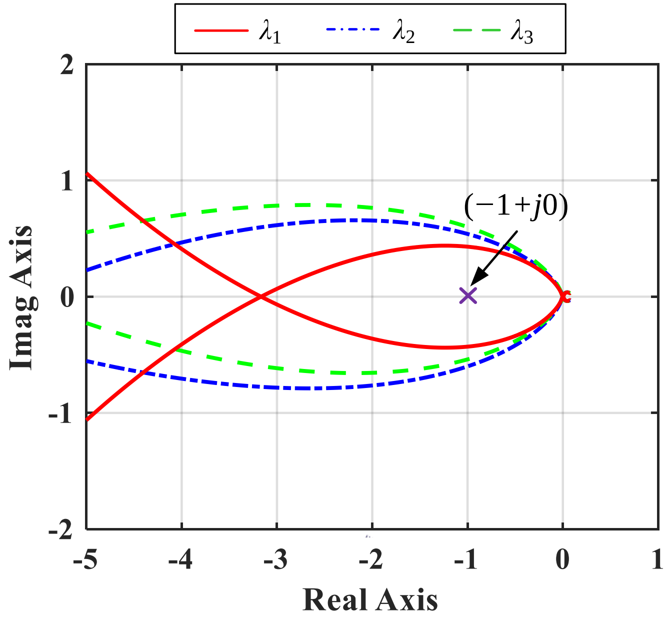
# Case studies with inductive load

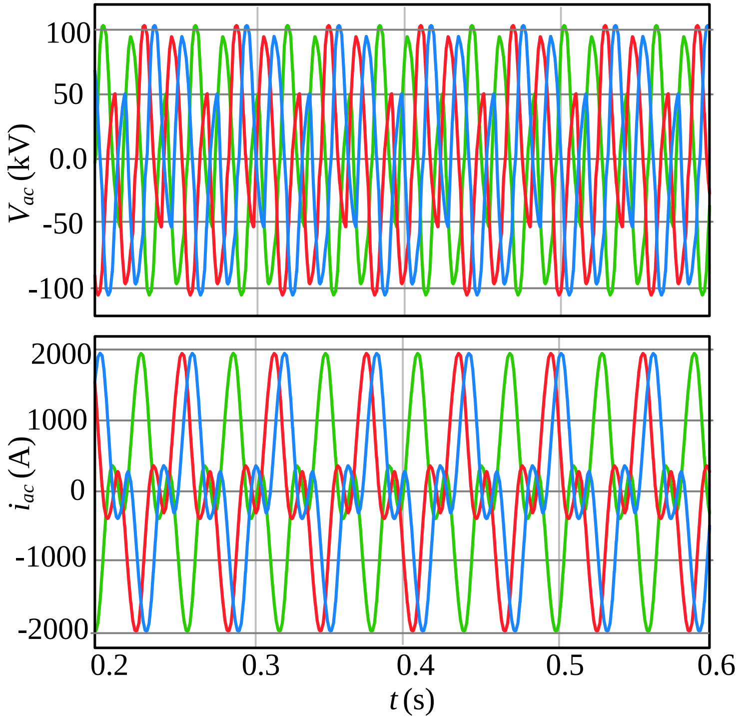
## PR voltage regulator



**Capacitance and negative resistance in $Z_{close0}$ interacts with inductive load**



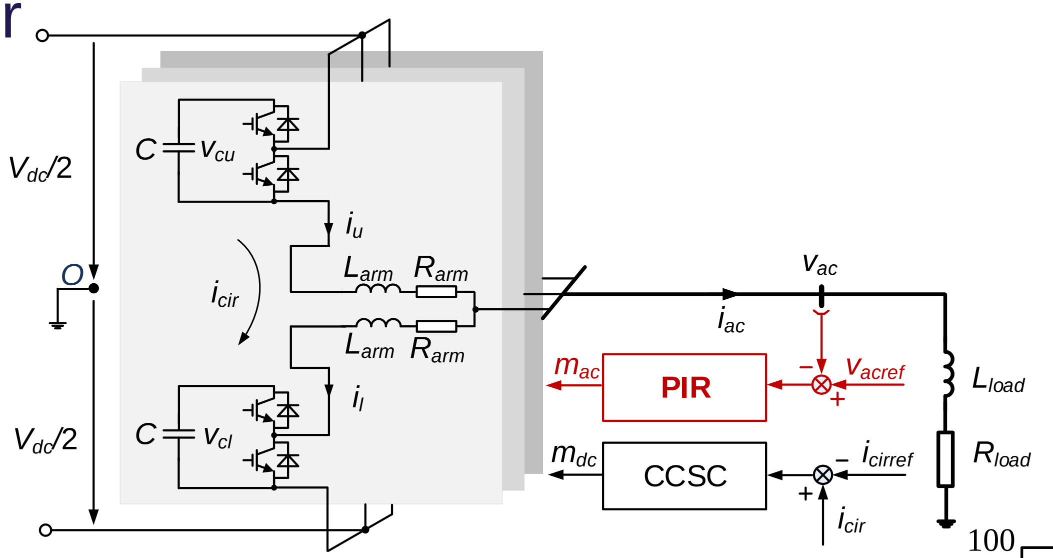


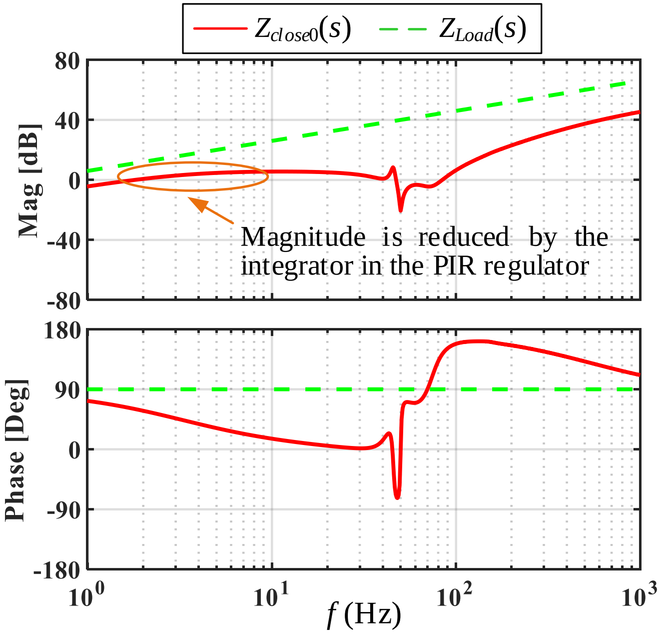


# Case studies with inductive load

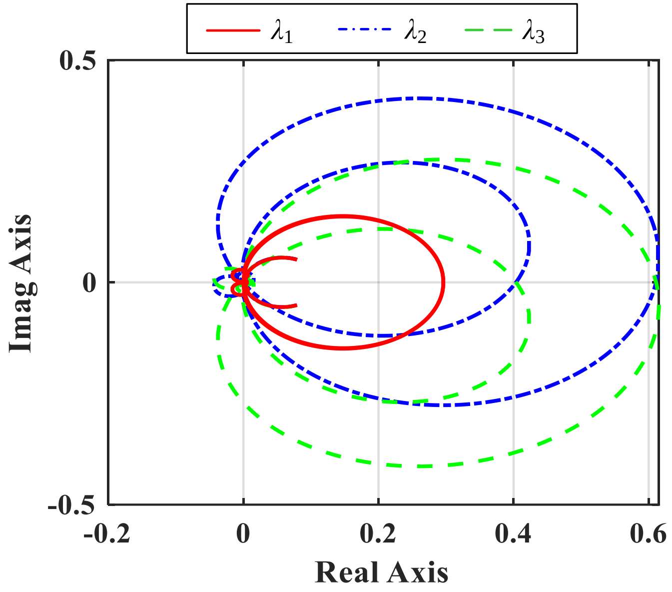
## PIR voltage regulator

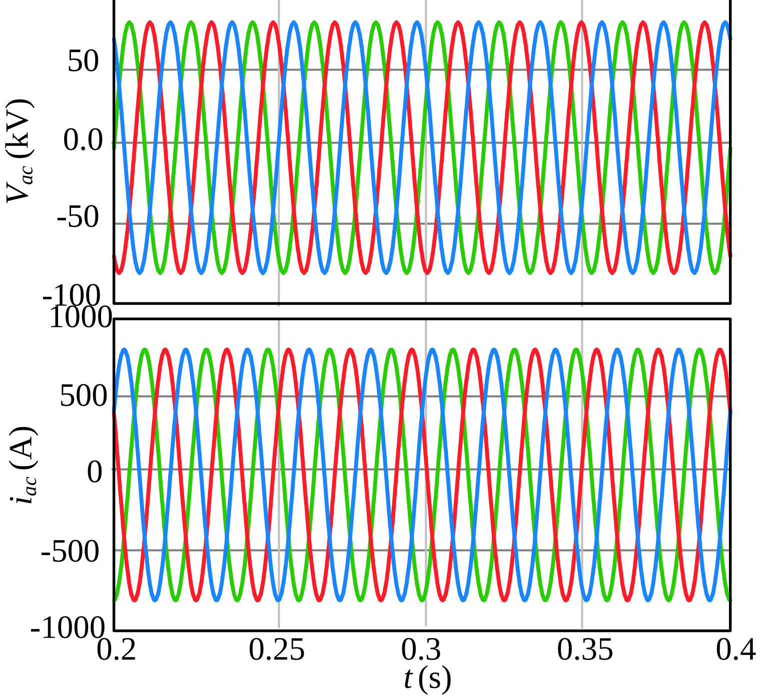
**Reduce magnitude of $Z_{close0}$ to avoid the intersection**





Magnitude is reduced by the integrator in the PIR regulator





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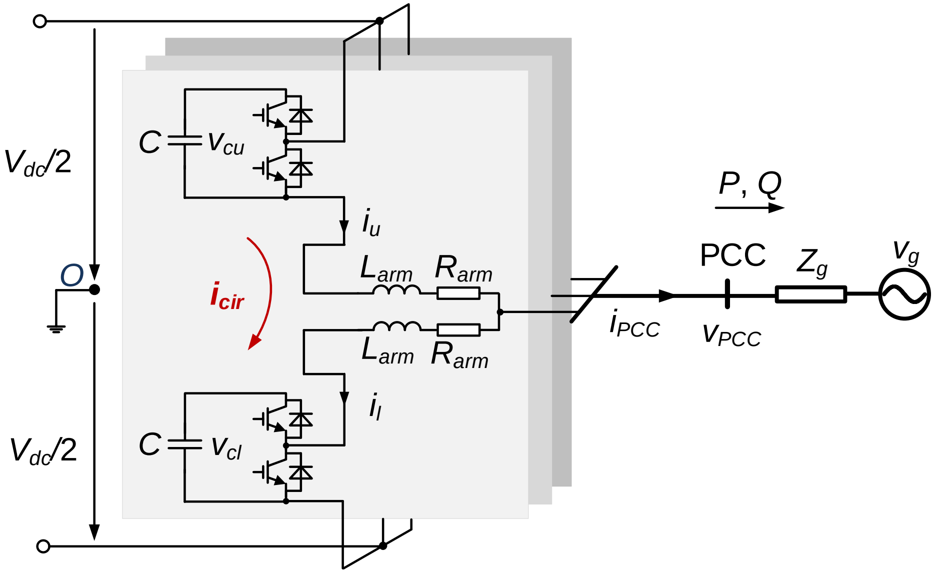
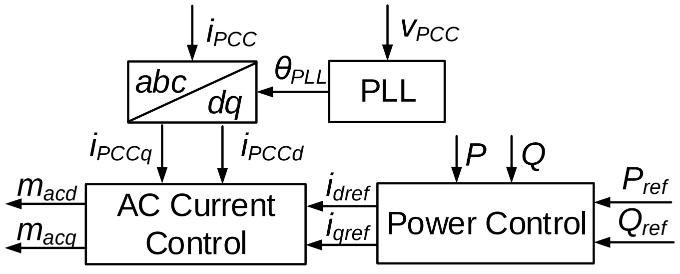
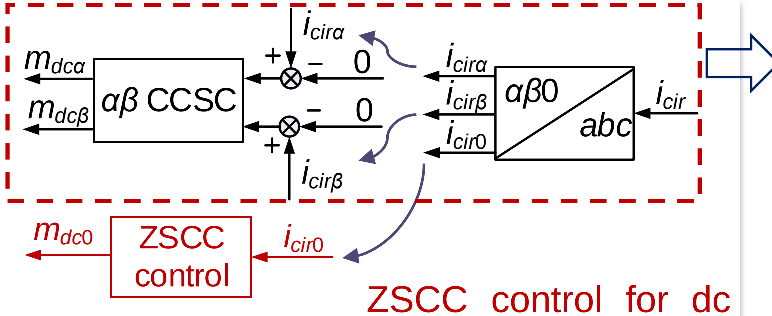
- ❑ **Conclusion**

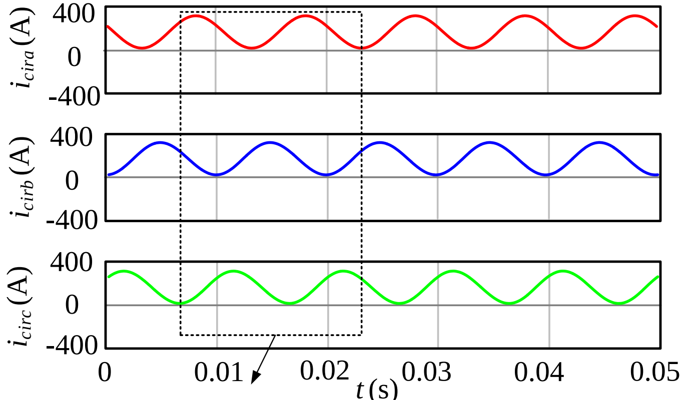
# GFL-MMC



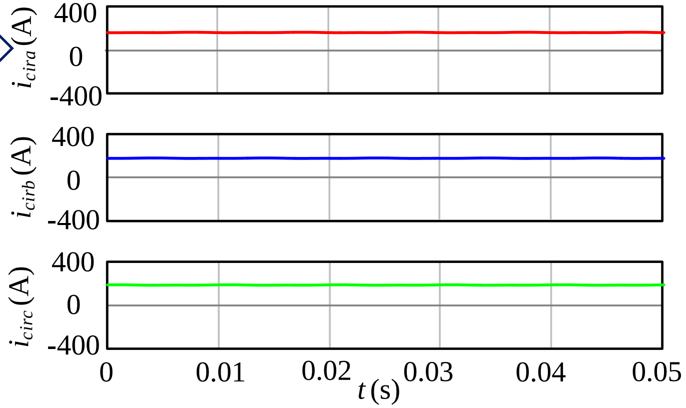




ZSCC control for dc oscillation damping [1]



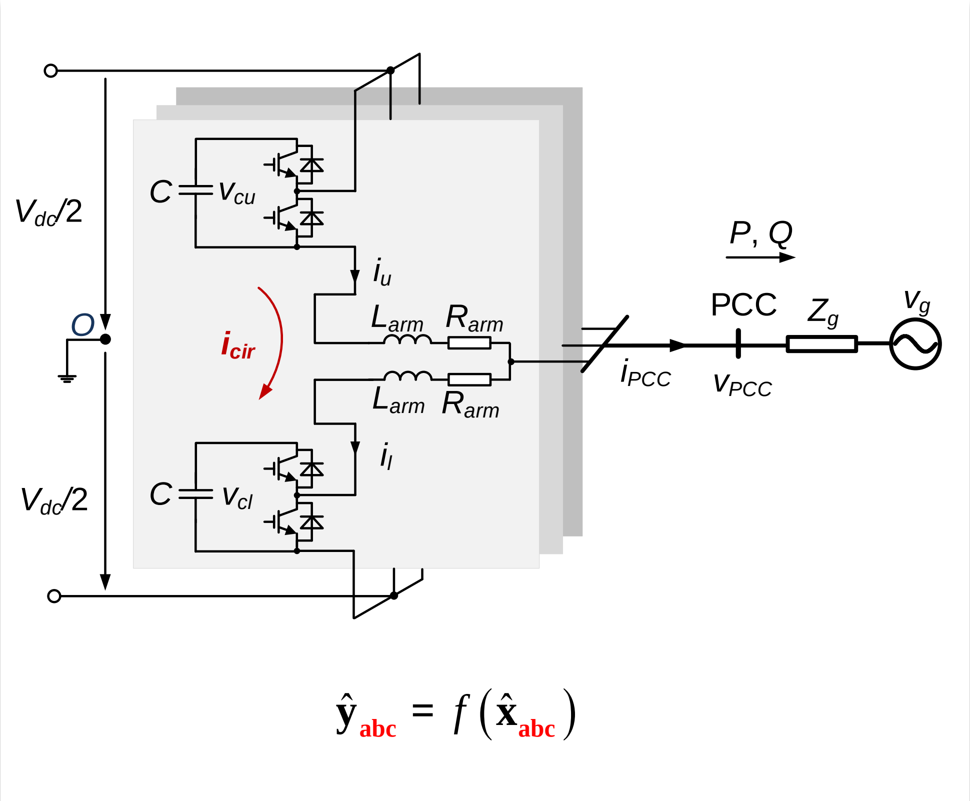
Negative-sequence 2nd -order harmonics



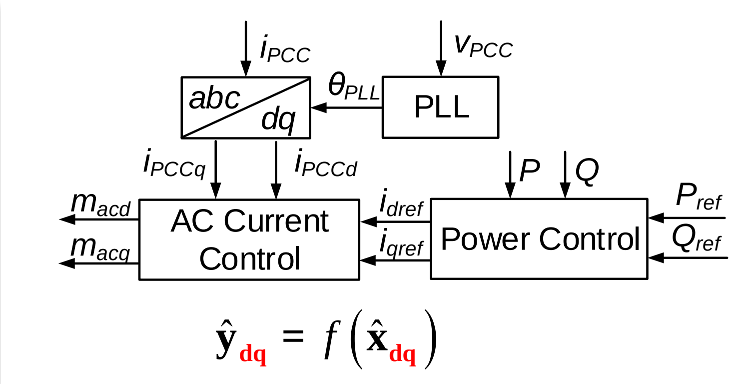
**AC dynamic impact of the ZSCC control**

[1] J. Freytes et al., “Improving small-signal stability of an MMC with CCSC by control of the internally stored energy,” *IEEE Trans. Power Del.*, vol. 33, no. 1, pp. 429–439, Feb. 2018.

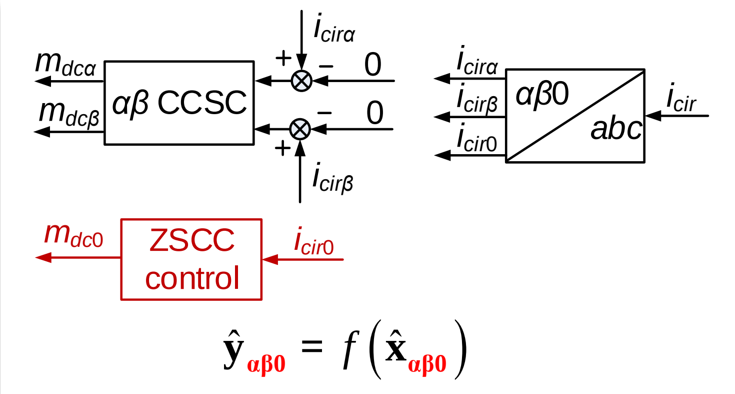
# Modal integration



$$\hat{\mathbf{y}}_{\mathbf{abc}} = f\left(\hat{\mathbf{x}}_{\mathbf{abc}}\right)$$



$$\hat{\mathbf{y}}_{\mathbf{dq}} = f\left(\hat{\mathbf{x}}_{\mathbf{dq}}\right)$$



$$\hat{\mathbf{y}}_{\boldsymbol{\alpha\beta0}} = f\left(\hat{\mathbf{x}}_{\boldsymbol{\alpha\beta0}}\right)$$

$x_a, x_b, x_c \longleftrightarrow x_\alpha, x_\beta, x_0 \longleftrightarrow x_d, x_q, x_0$

$\updownarrow$

$x_{\alpha\beta} = x_\alpha + jx_\beta$

**d, q real vector model, MIMO [1]**

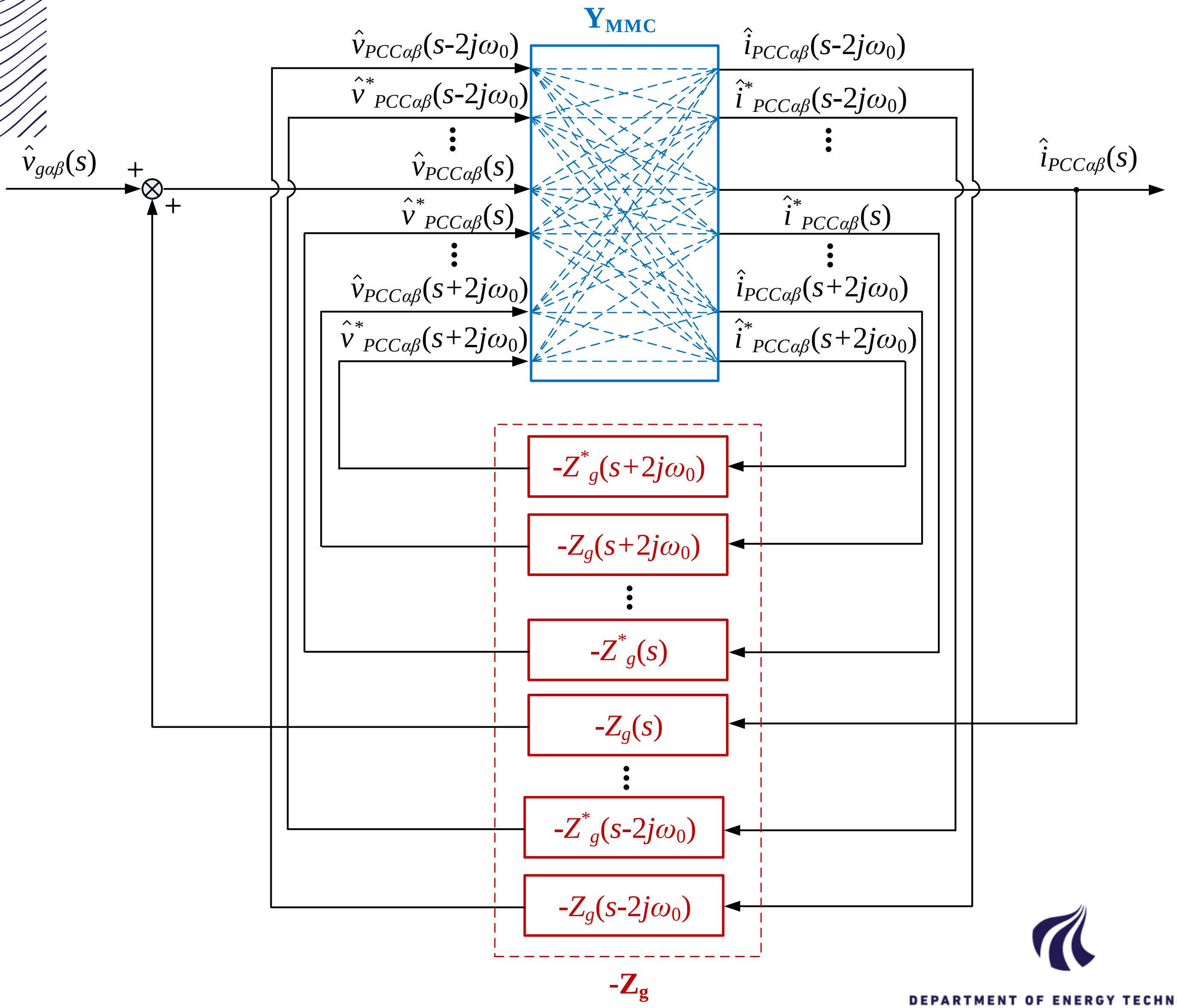
**× Not convenient for stability analysis**

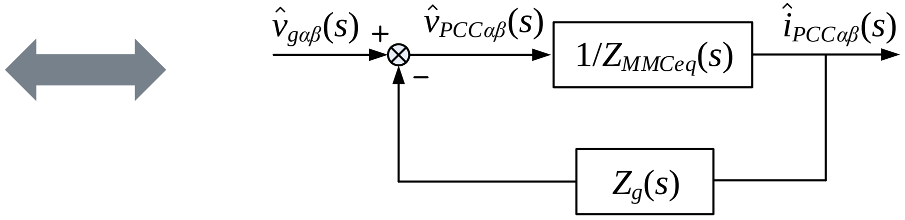
***αβ* complex vector model, SISO equivalent [2]**

[1] J. Freytes et al., “Improving small-signal stability of an MMC with CCSC by control of the internally stored energy,” *IEEE Trans. Power Del.*, vol. 33, no. 1, pp. 429–439, Feb. 2018.

[2] **H. Wu** and X. Wang, “Dynamic impact of zero-sequence circulating current on modular multilevel converters: complex valued AC impedance modeling and analysis,” *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 8, no. 2, pp. 1947-1963, June 2020.

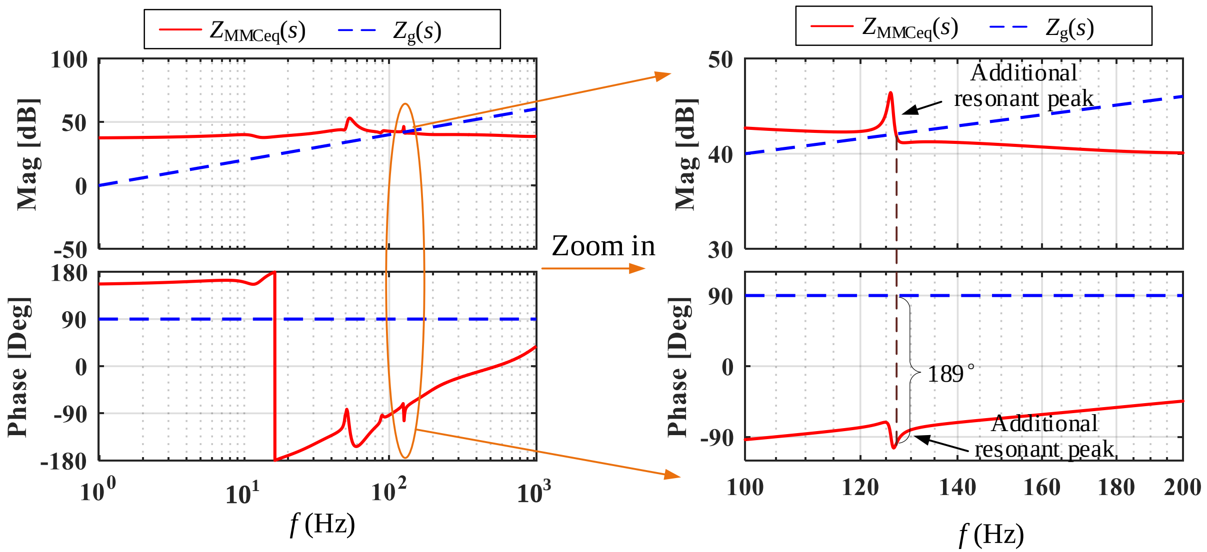
# Stability assessment methodology



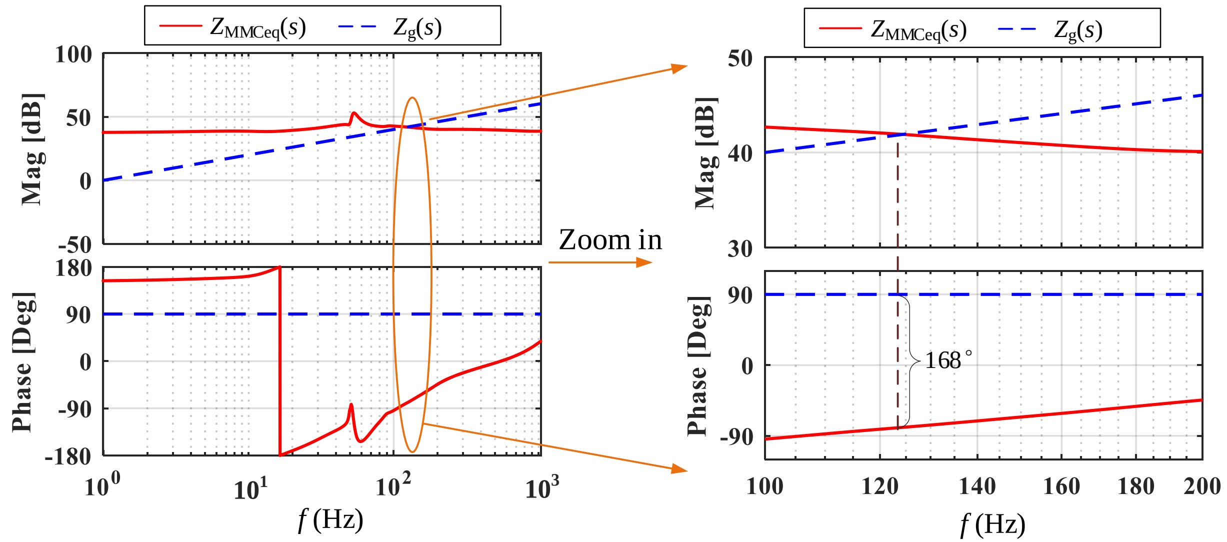


- **SISO Impedance-based stability criterion can still be used**

# Impact of ZSCC control ($Z_g$=0.5pu)



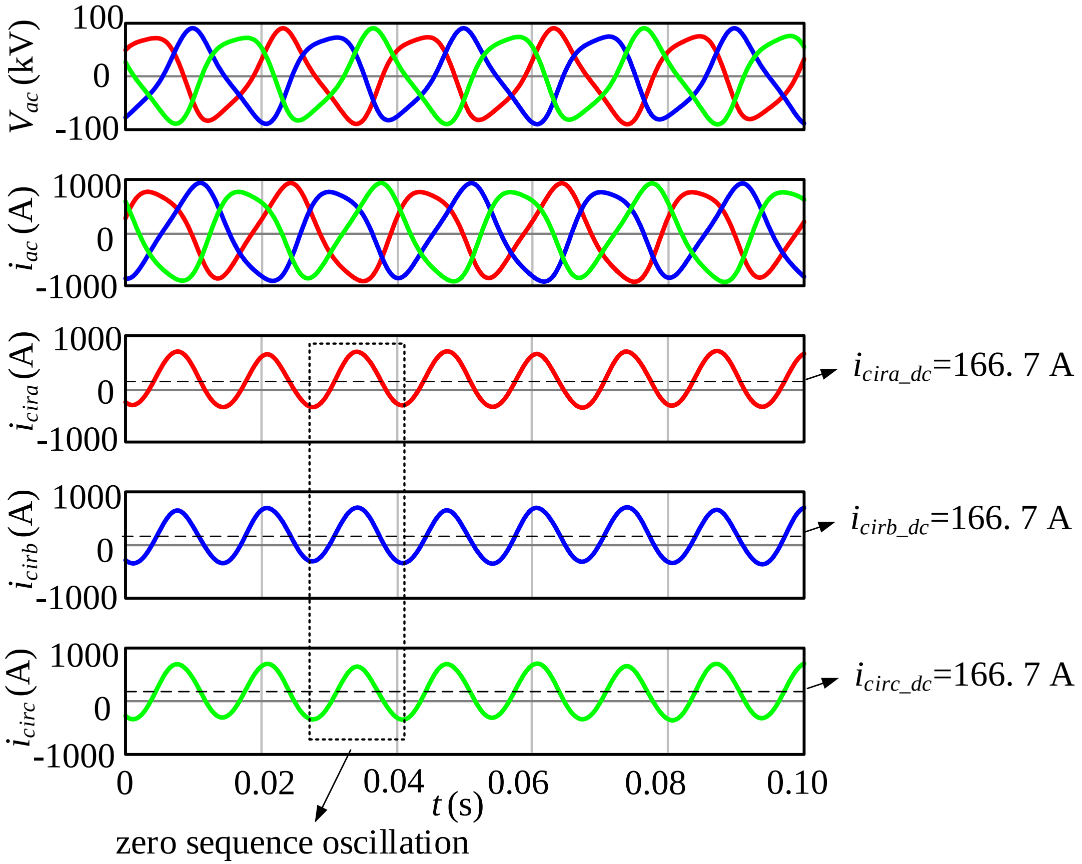
Without ZSCC control



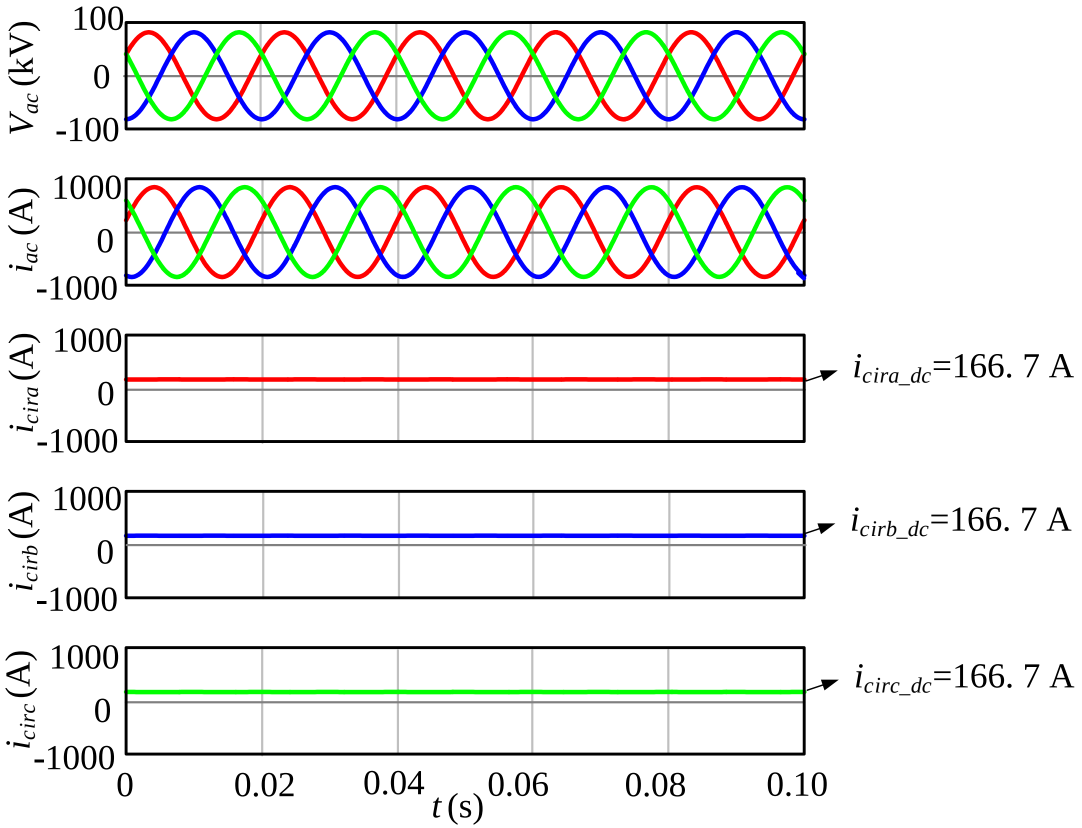
With ZSCC control

**Resonant peak appears in $Z_{mmceq}$ without the ZSCC control, destabilize the system under the weak grid**

# Impact of ZSCC control ($Z_g$=0.5pu)



Without ZSCC control



With ZSCC control

**ZSCC control is recommended to stabilize the system**

# Summary

## General modeling framework: complex-valued harmonic state space method

- LTI representation
- SISO equivalent, facilitate stability analysis

## Power stage (open-loop) model of the MMC

- Capacitance in $Z_0(s)$
- Non-negligible frequency-coupled impedances

### Grid-forming control

- Capacitance + negative resistance in $Z_0(s)$ with PR regulator
- Unstable with inductive load
- Stabilization by PIR regulator

### Grid-following control

- Stabilization effect of ZSCC control under the weak ac grid

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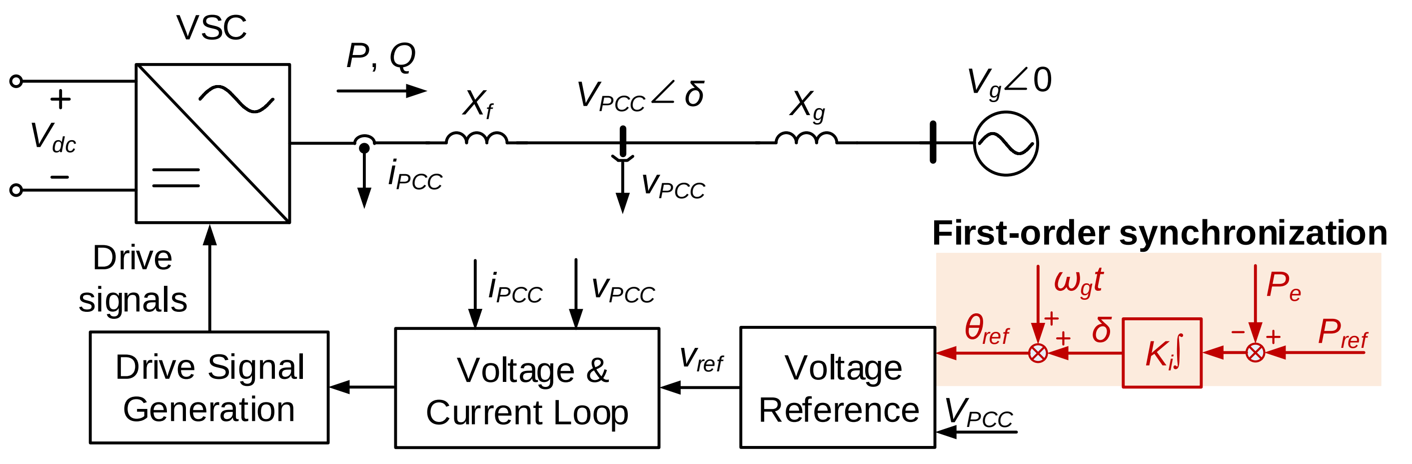
- ❑ Conclusion

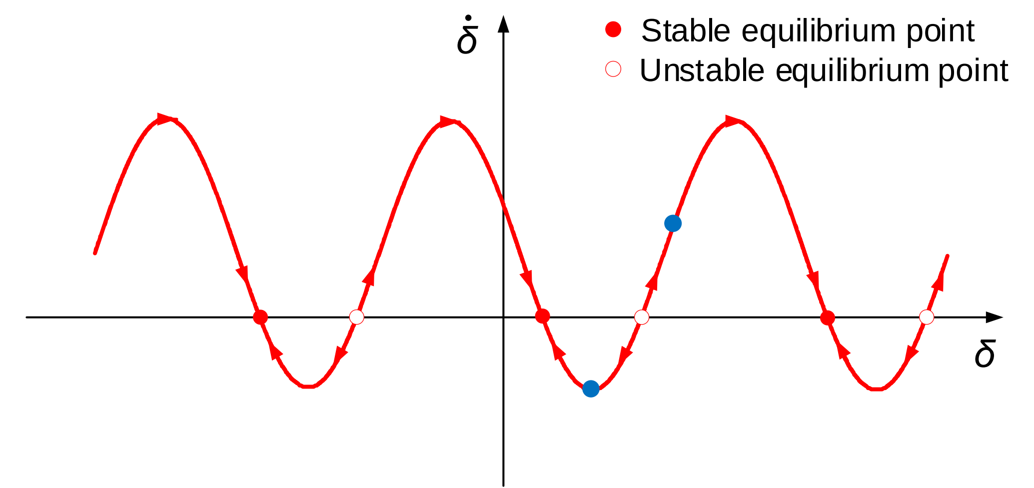
# GFM-VSCs with the first-order active power control loop



GFM-VSC with power synchronization control (PSC) [1]

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

**Solving $\delta(t)$**



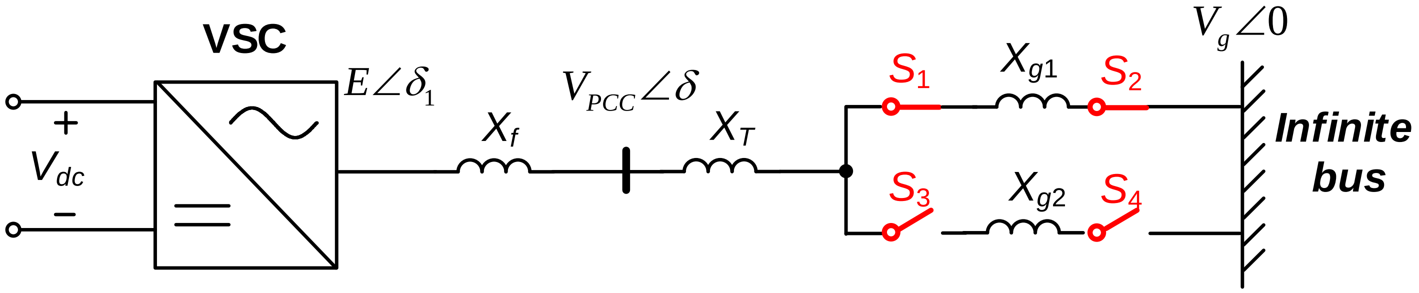
**First-order nonlinear system with equilibrium points**

- Always converge to the closest stable equilibrium point without overshoot

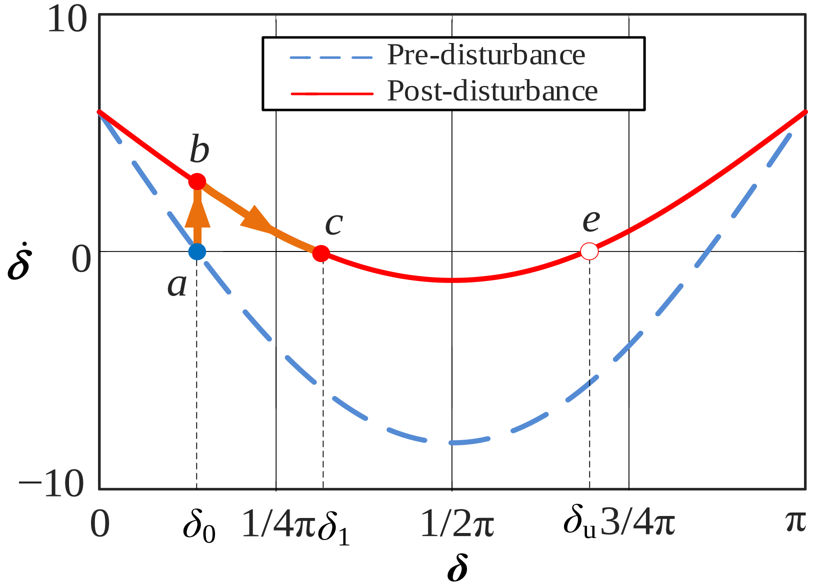
[1] L. Zhang, L. Harnefors, and H. –P. Nee. "Power-synchronization control of grid-connected voltage-source converters". *IEEE Trans. Power Syst*., vol. 25, no. 2, pp. 809−820, May. 2010.

# Transient stability of PSC-VSC w/o triggering current limit

## Case I - presence of equilibrium points after disturbances



**Abrupt disconnection of transmission line $X_{g2}$**



**Phase portrait analysis**

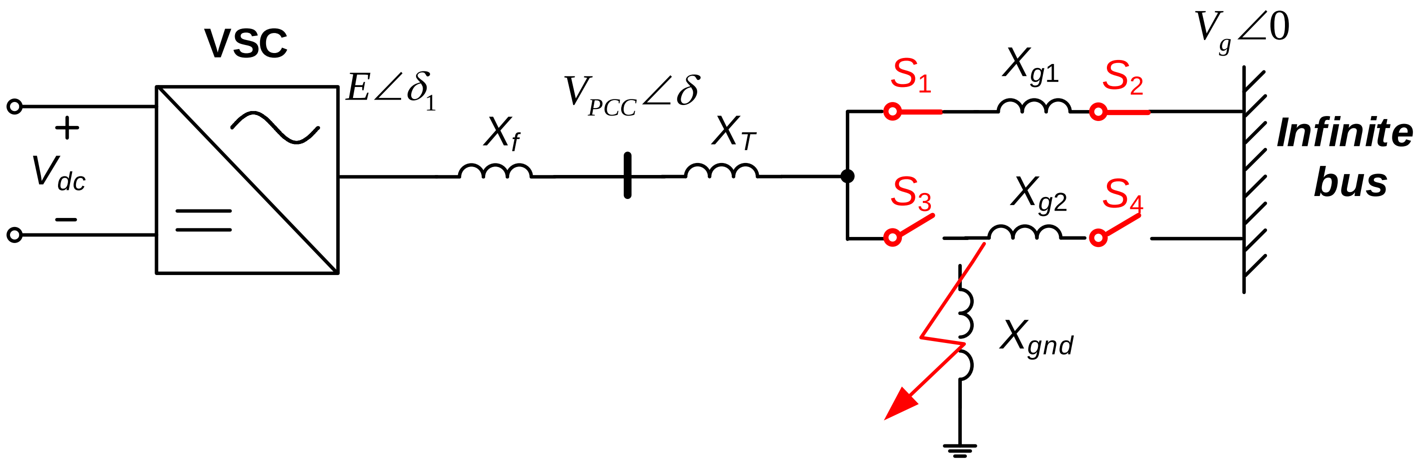
### With equilibrium points after disturbance

- PSC-VSC has no transient stability problem
- Better performance than SG

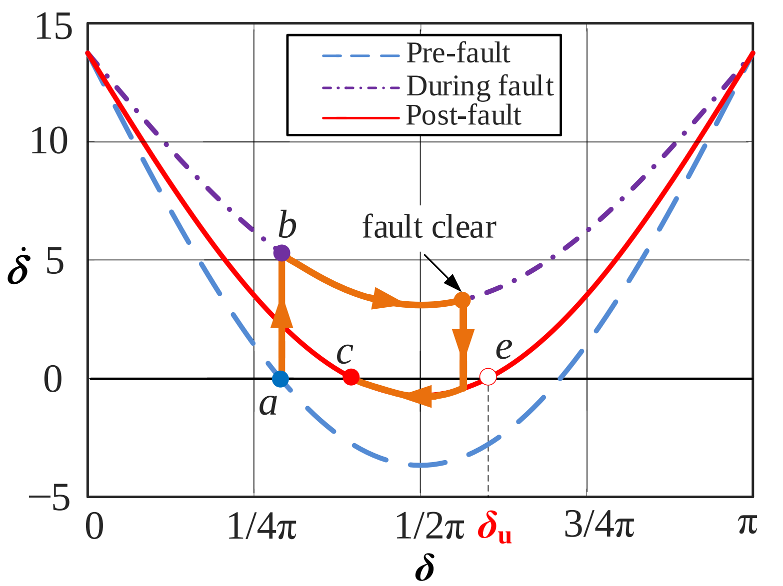
**H. Wu** and X. Wang, “Design-oriented transient stability analysis of grid-connected converters with power synchronization control,” *IEEE Trans. Ind. Electron.*, vol. 66, no. 8, pp. 6473–6482, Aug. 2019.

# Transient stability of PSC-VSC w/o triggering current limit

## Case II - No equilibrium points after disturbances



Grid fault with high short-circuit impedance $X_{gnd}$



**Phase portrait analysis**

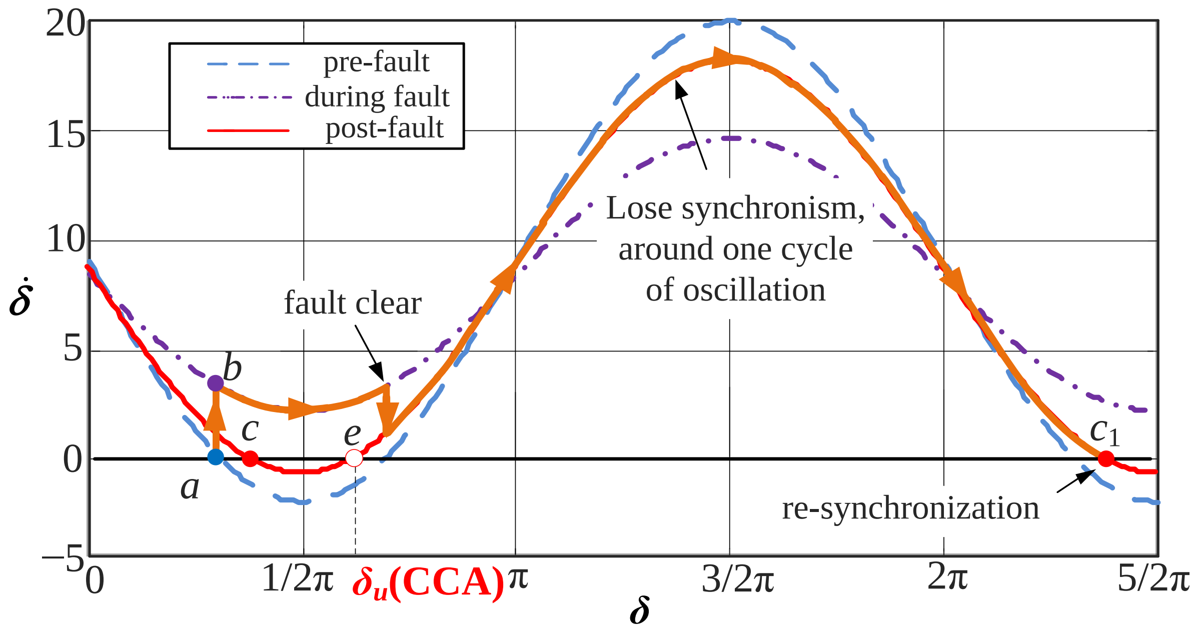
**Constant Critical Clearing Angle (CCA)**

$$CCA = \delta_u$$

**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.

# Transient stability of PSC-VSC w/o triggering current limit

## Case II - No equilibrium points after disturbances



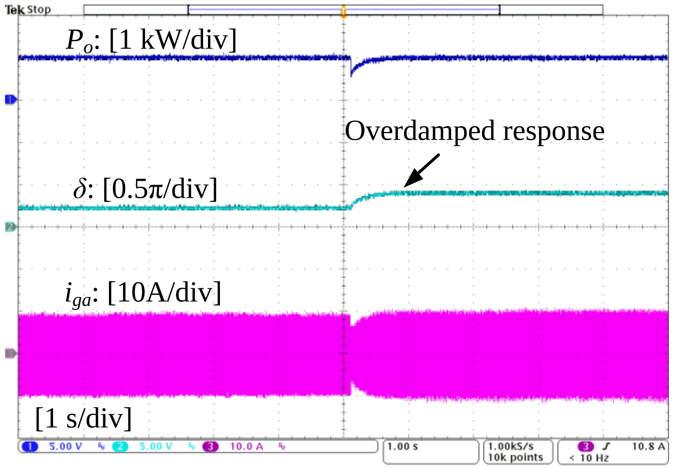
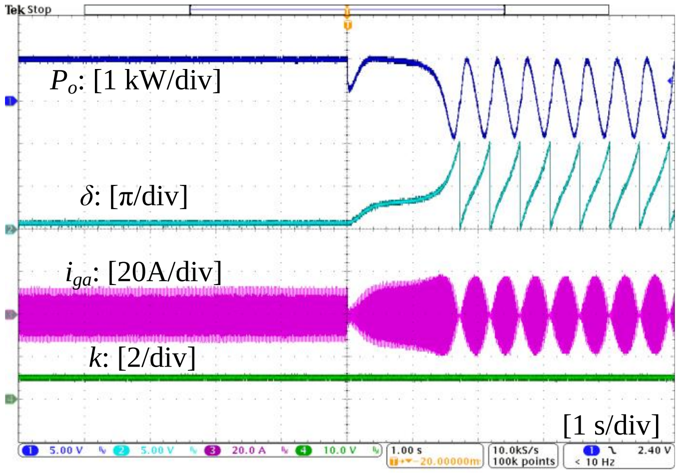
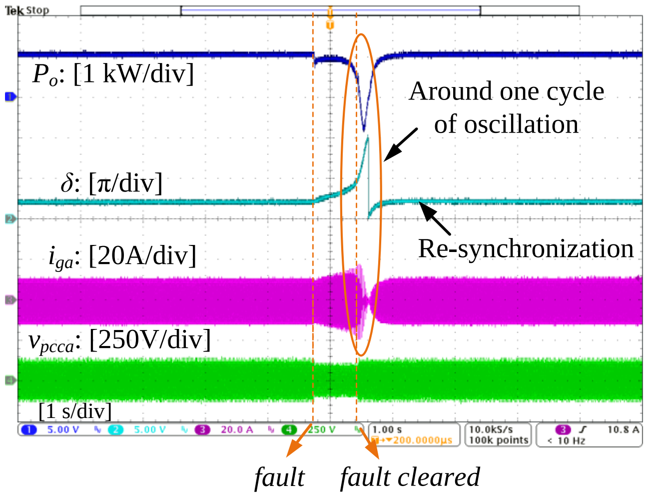
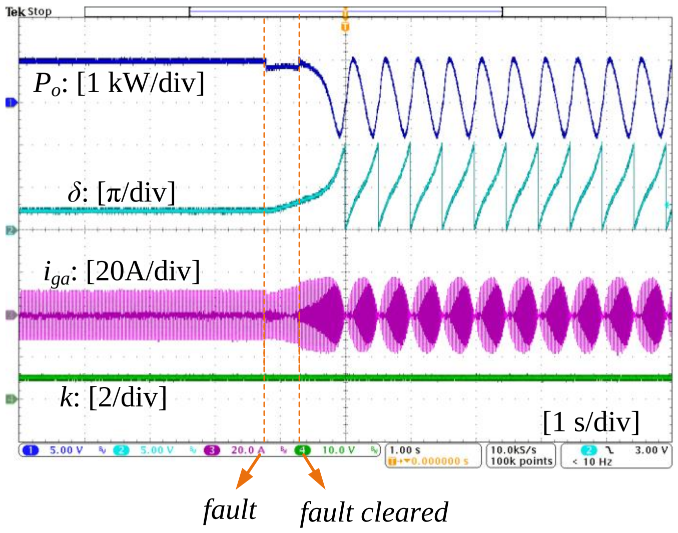
Phase portrait analysis when the fault is cleared beyond the CCA

- **Resynchronization Capability**
- **Reduce the risk of system collapse due to the delayed fault clearance**

**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.

# Experimental Results

## Comparaison with VSG

| Operating Scenarios | PSC-VSC | Virtual synchronous generator (VSG) |
|---|---|---|
| With Equilibrium Points |  |  |
| No Equilibrium Points<br>(FCT>CCT) |  |  |

# Outline

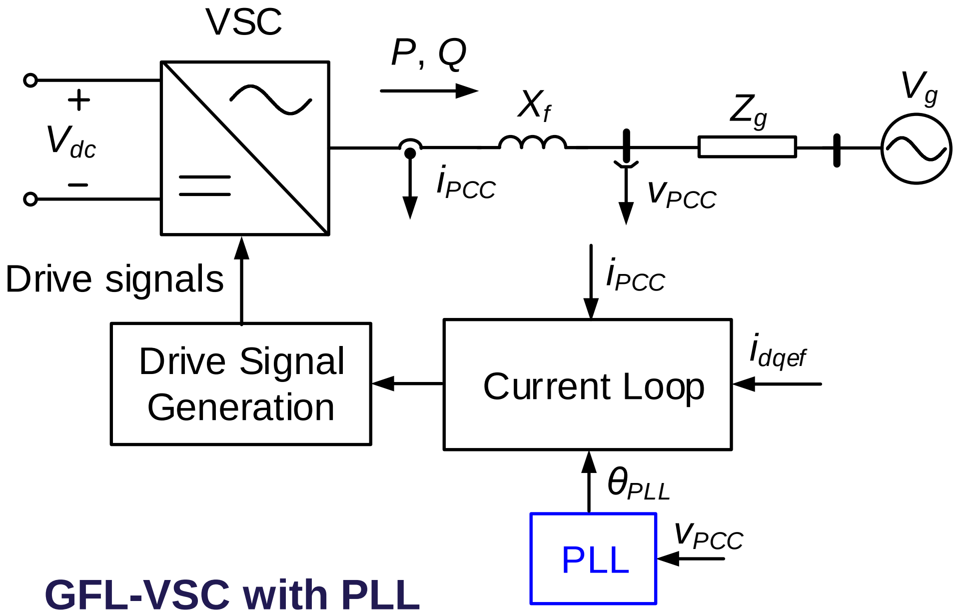
- ☐ **Introduction**

- ☐ **Small-Signal Stability Analysis of MMCs**
  - ➢ Grid-Forming MMCs
  - ➢ Grid-Following MMCs

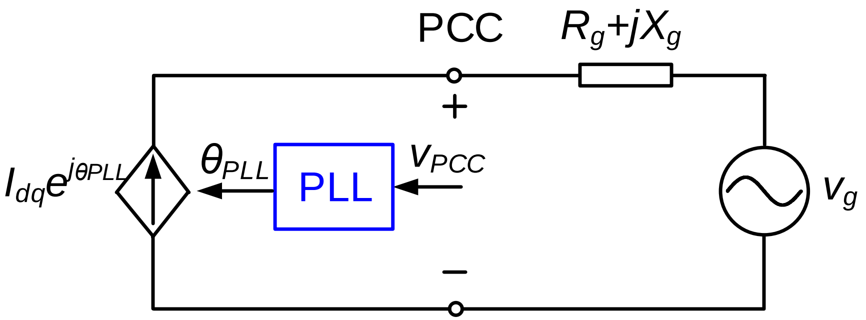
- ☐ **Transient Stability Analysis of VSCs**
  - ➢ Grid-Forming VSCs
  - ➢ Grid-Following VSCs

- ☐ **Conclusion**

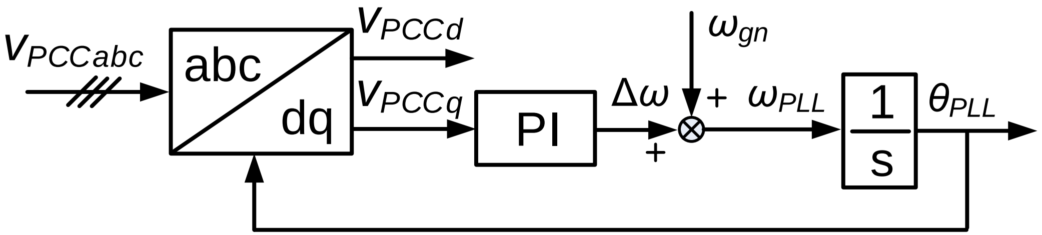
# GFL-VSCs with PLL



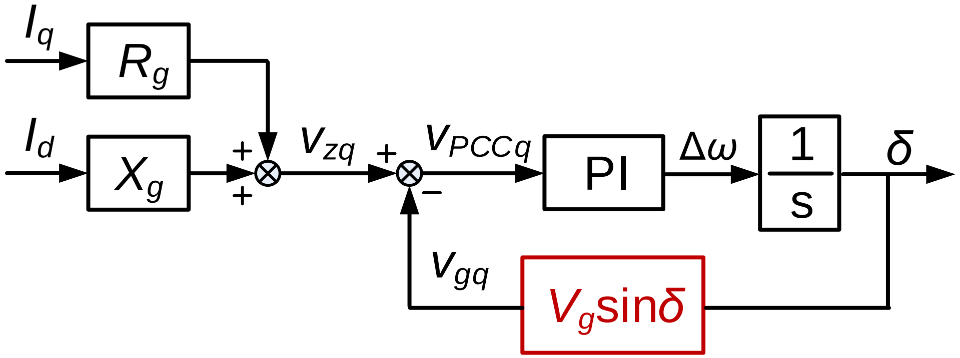
**GFL-VSC with PLL**



**Norton Equivalent circuit**

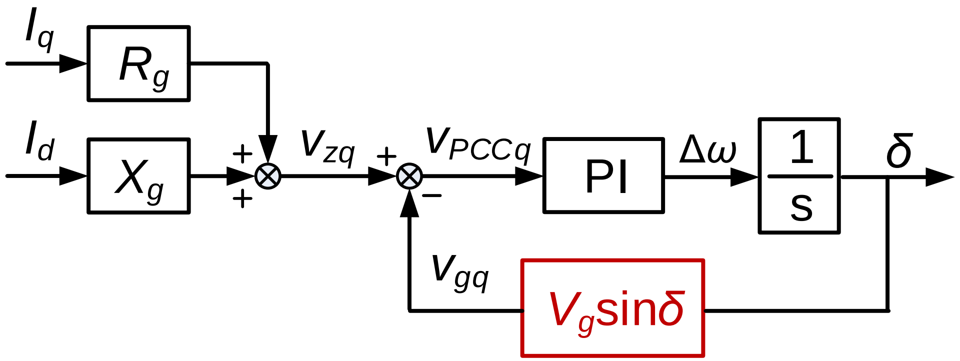


**SRF-PLL**

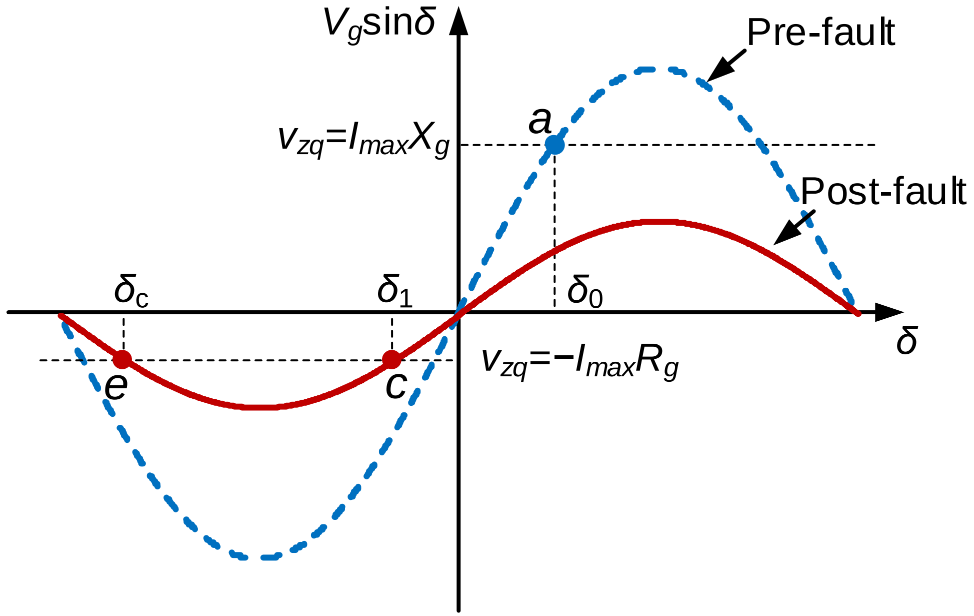


**Large-signal model of the SRF-PLL**

# Second-order nonlinear synchronization dynamics



**Large-signal model of the SRF-PLL**

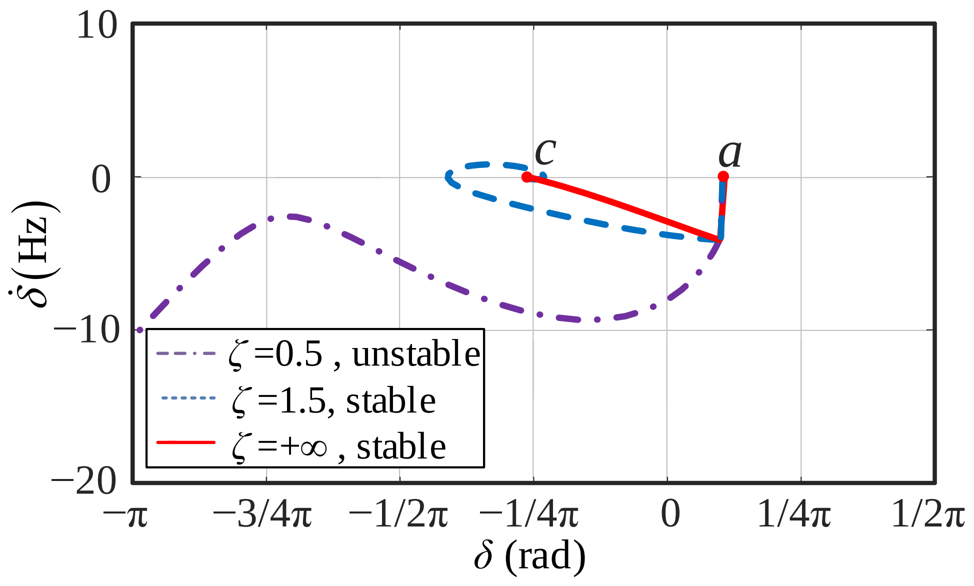


***V*-δ curve**

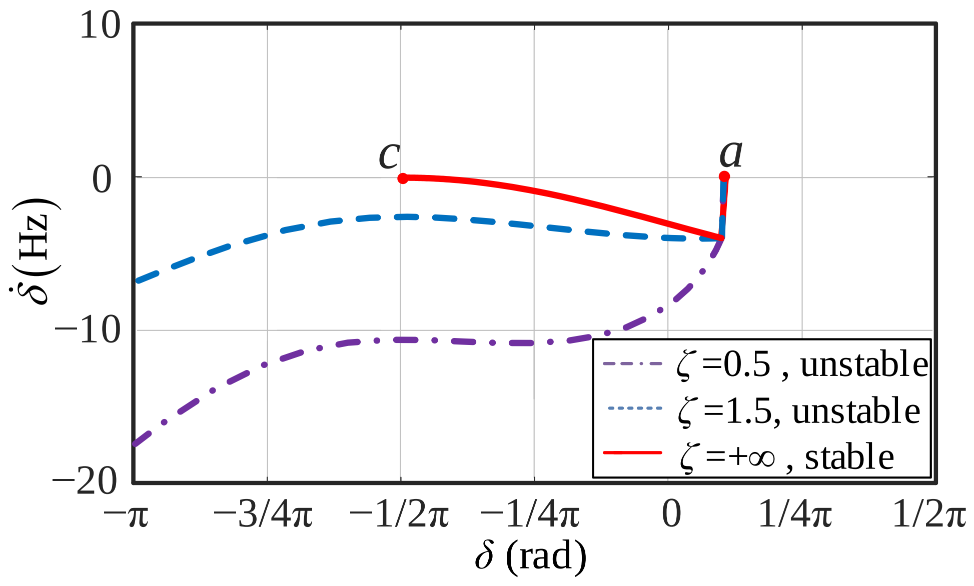
| PLL: *V-δ* swing equation | SG: *P-δ* swing equation |
|---|---|
| $v_{zq} - V_g \sin\delta - D_{eq}\dot{\delta} = H_{eq}\ddot{\delta}$ | $P_m - \dfrac{3V_{PCC}V_g}{2X_g}\sin\delta - D\dot{\delta} = H\ddot{\delta}$ |

- **Pre-fault: $I_d=I_{max}$, $I_q=0$**
- **Post-fault: $I_d=0$, $I_q=-I_{max}$**

# Phase portrait analysis



$V_g$ **drops to 0.14 pu**



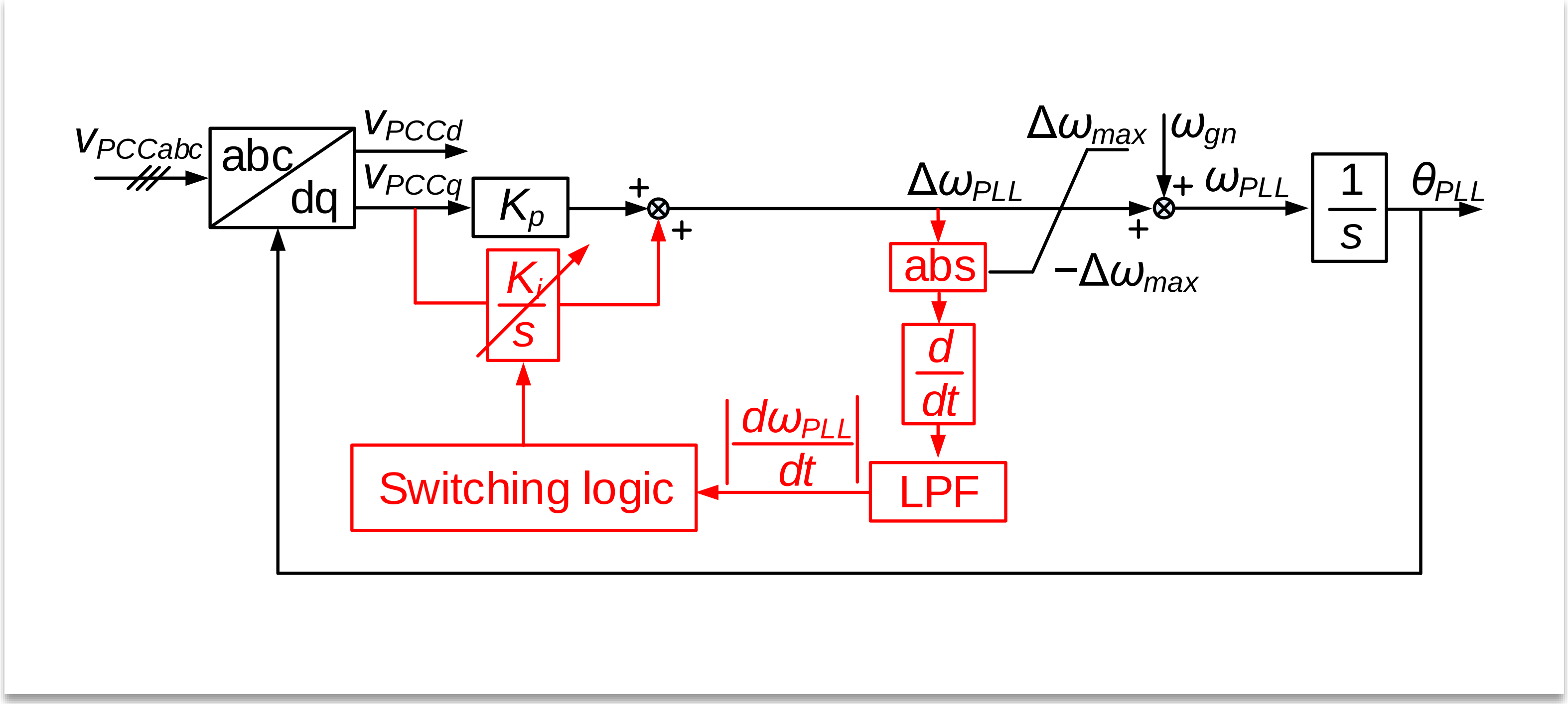
$V_g$ **drops to 0.10 pu**

$$\zeta = \frac{K_p}{2}\sqrt{\frac{V_{gn}}{K_i}}$$

- **Better transient stability with increased ζ**
- **Always stable with infinite ζ ($K_i$=0, first-order PLL)**

**H. Wu** and X. Wang, “Design-oriented transient stability analysis of PLL-synchronized voltage-source converters,” *IEEE Trans. Power Electron.*, vol. 35, no. 4, pp. 3573 - 3589, Apr. 2020

# Adaptive PLL

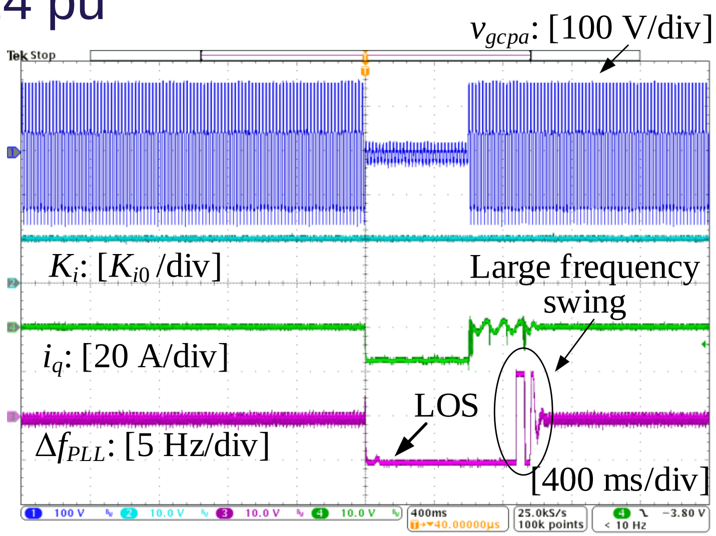


- **Steady-state: second-order ($K_i$=$K_{i0}$)**
- **Transient: first-order PLL ($K_i$=0)**

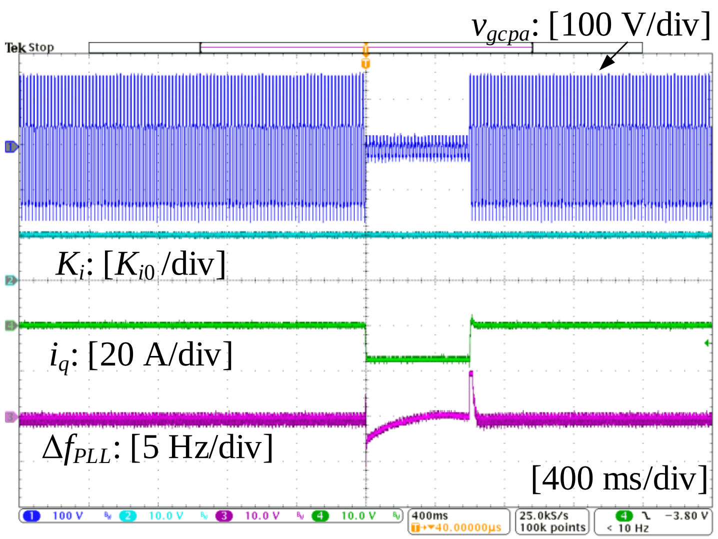
**H. Wu** and X. Wang, "Design-oriented transient stability analysis of PLL-synchronized voltage-source converters," *IEEE Trans. Power Electron.*, vol. 35, no. 4, pp. 3573 - 3589, Apr. 2020

# Experimental Results

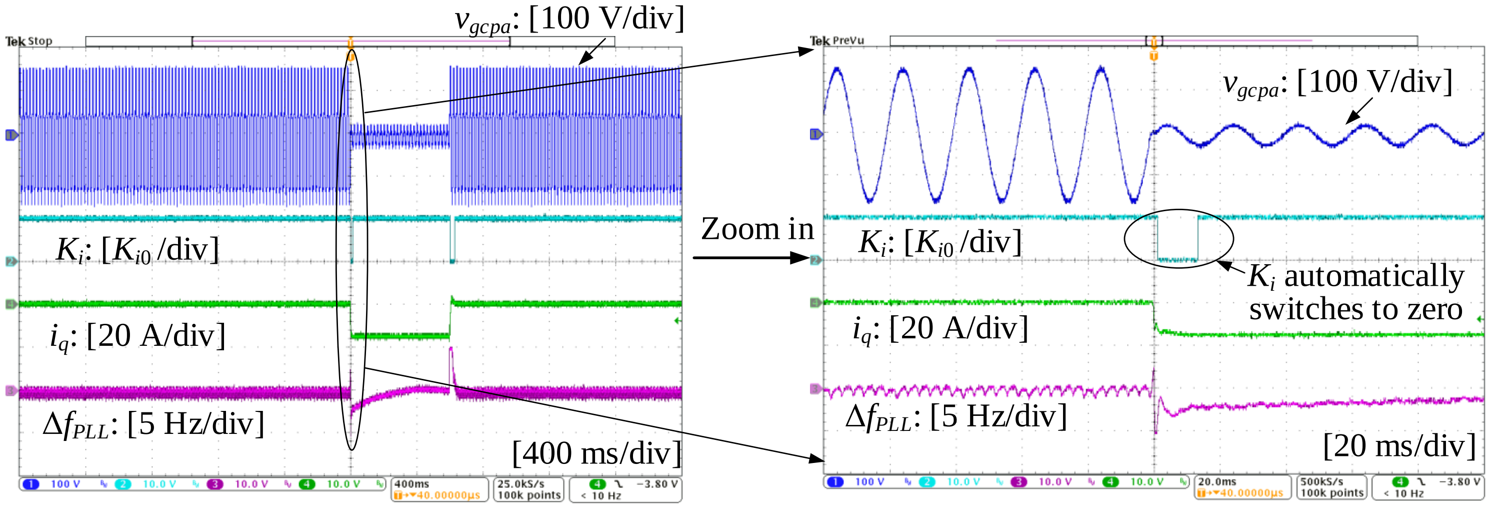
## $V_g$ drops to 0.14 pu



**ζ = 0.5, unstable**



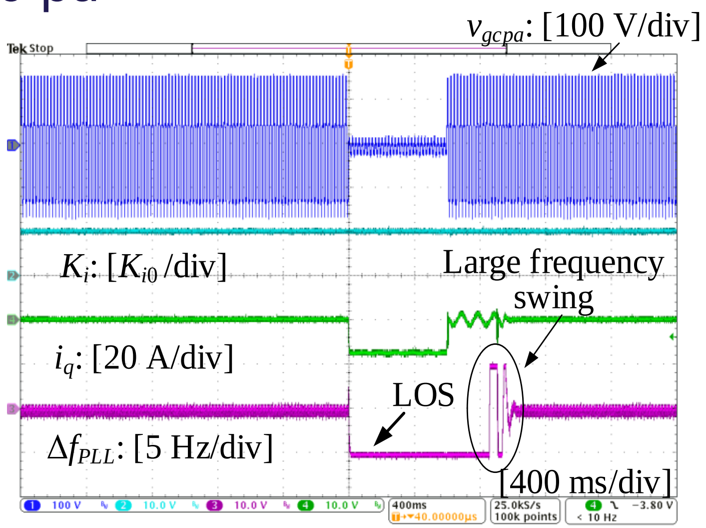
**ζ = 1.5, stable**



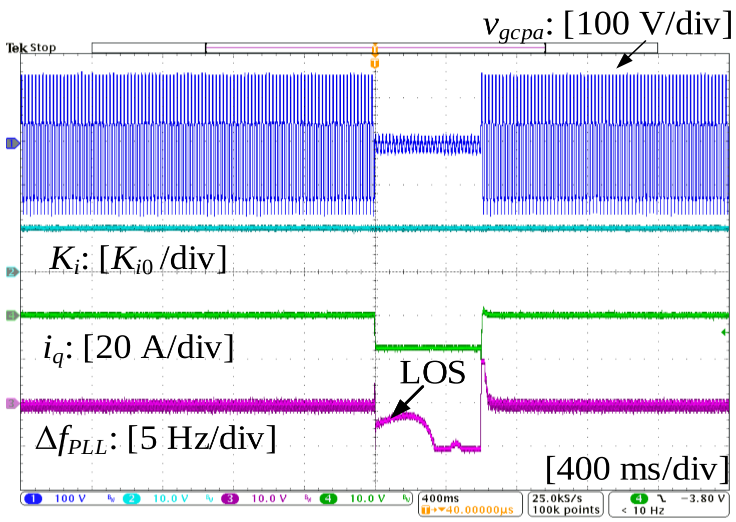
**Adaptive PLL, stable**

# Experimental Results

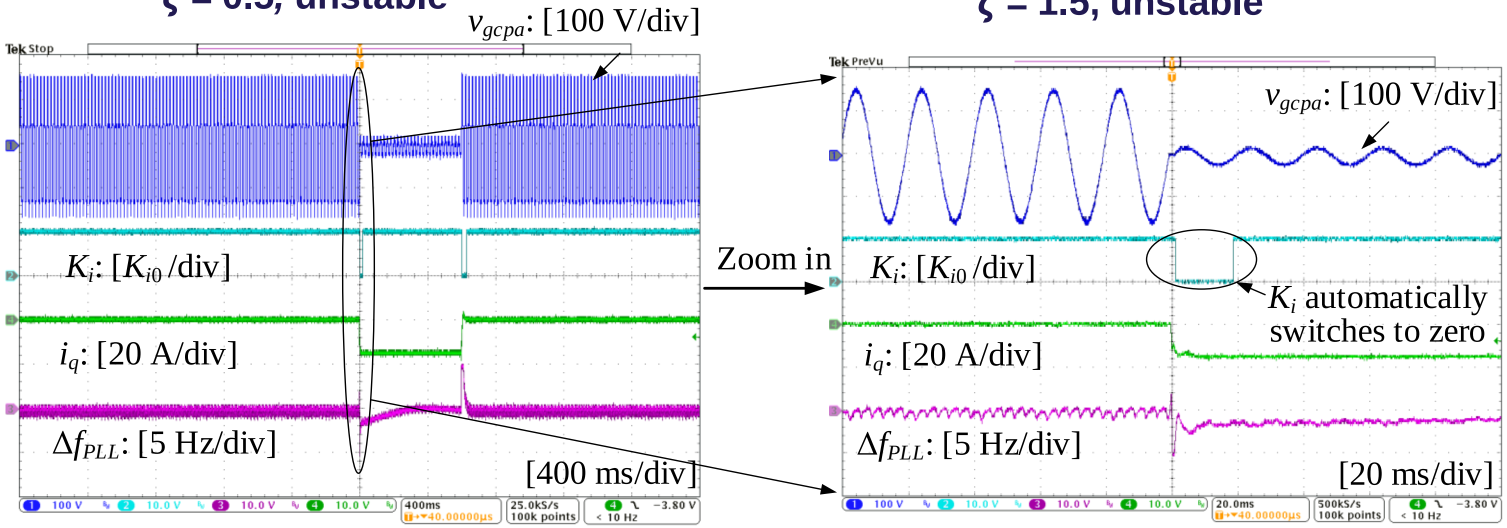
## $V_g$ drops to 0.10 pu



**$\zeta$ = 0.5, unstable**



**$\zeta$ = 1.5, unstable**



**Adaptive PLL, stable**

# Summary

**Phase portrait**

**Superior transient stability performance of the first-order synchronization loop**

## Grid-forming control

- **No transient stability problem with equilibrium points**
- **Fixed CCA/CCT**
- **Resynchronization capability even if FCT > CCT**

## Grid-following control

- **Adaptive PLL**

# Outline

- ☐ **Introduction**

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  - ➢ Grid-Forming VSCs
  - ➢ Grid-Following VSCs

- ☐ **Conclusion**

# Conclusion

| | Modeling methodologies | Stability assessment | Stabilization |
|---|---|---|---|
| **Small-signal stability of MMCs** | Complex-valued HSS method | Multi-variable frequency domain theory | • PIR control for GFM-MMC<br>• ZSCC control for GFL-MMC |
| **Transient stability of VSCs** | Differential equations | Phase portrait | • First-order power control for GFM-VSC<br>• Adaptive PLL for GFL-VSC |

# Publication List

## Journal Papers

1. **H. Wu** and X. Wang, “Virtual-flux-based passivation of current control for grid-connected VSCs”, *IEEE Trans. Power Electron.*, early access, 2020.
2. **H. Wu** and X. Wang, “Dynamic impact of zero-sequence circulating current on modular multilevel converters: complex valued AC impedance modeling and analysis,” *IEEE J. Emerg. Sel. Topics Power Electron*., vol. 8, no. 2, pp. 1947-1963, June 2020.
3. **H. Wu** and X. Wang, "A mode-adaptive power-angle control method for transient stability enhancement of virtual synchronous generators," *IEEE J. Emerg. Sel. Topics Power Electron*., vol. 8, no. 2, pp. 1034-1049, June 2020.
4. **H. Wu** and X. Wang, “Design-oriented transient stability analysis of PLL-synchronized voltage-source converters,” *IEEE Trans. Power Electron.*, vol. 35, no. 4, pp. 3573 - 3589, Apr. 2020.
5. **H. Wu**, X. Wang, and Ł. Kocewiak, “Impedance-based stability analysis of voltage-controlled MMCs feeding linear AC systems,” *IEEE J. Emerg. Sel. Topics Power Electron.*, early access, 2019.
6. **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.

## Conference Papers

1. **H. Wu** and X. Wang, “An adaptive phase-locked loop for the transient stability enhancement of grid-connected voltage source converters,” in *Proc. IEEE Energy Convers. Congr. Expo.*, 2018, pp. 5892–5898.
2. **H. Wu** and X. Wang, “Transient stability impact of the phase-locked loop on grid-connected voltage source converters,” in *Proc. IEEE Int. Power Electron. Conf. (IPEC-ECCE Asia)*, 2018, pp. 2673–2680.
3. **H. Wu**, X. Wang, L. Kocewiak, and L. Harnefors, “AC impedance modeling of modular multilevel converters and two-level voltage-source converters: Similarities and differences,” in *Proc. IEEE 19th Workshop Control. Model. Power Electron. (COMPEL)*, Jun. 2018, pp. 1–8.
4. **H. Wu** and X. Wang, “Transient angle stability analysis of grid-connected converters with the first-order active power loop,” in *Proc. IEEE Appl. Power Electron. Conf. Expo.*, Mar. 2018, pp. 3011–3016.

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**My family**

DEPARTMENT OF ENERGY TECHNOLOGY
AALBORG UNIVERSITY

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Universität der Bundeswehr München

TenneT
Taking power further

# Small-Signal and Transient Stability Analysis of Voltage-Source Converters

**Contact: Heng Wu**

**Email: hew@et.aau.dk**

**egrid.et.aau.dk**

DEPARTMENT OF ENERGY TECHNOLOGY
AALBORG UNIVERSITY