# Stability and Control of MMC Interfaced Wind Turbine Systems

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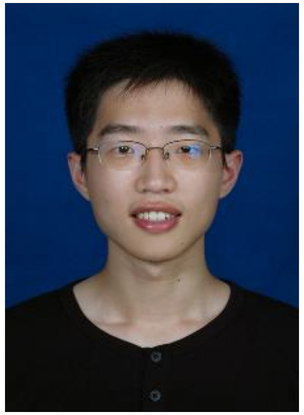
AALBORG UNIVERSITY
DENMARK

# Instructor Bios





Heng Wu received B.S. and M.S. degrees in electrical engineering from Nanjing University of Aeronautics and Astronautics (NUAA), Nanjing, China, in 2012 and 2015, respectively, and the Ph.D. degree in electrical engineering from Aalborg University, Aalborg, Denmark, in 2020. He is now a Postdoctoral researcher with the Department of Energy Technology, Aalborg University.

From 2015 to 2017, He was an Electrical Engineer with NR Electric Co., Ltd, Nanjing, China. He was a guest researcher with Ørsted Wind Power, Fredericia, Denmark, from November to December 2018, and with Bundeswehr University Munich, Germany, from September to December 2019. He is the Co-Chair of IEEE Task Force on Frequency-domain Modeling and Dynamic Analysis of HVDC and FACTS, the member of Cigre working group B4.85, and the Steering Committee Member of Cigre next generation network (NGN), Denmark. His research interests include the modelling and stability analysis of the power electronic based power systems. He is identified as world’s top 2% scientist (single year) by Stanford University. He received the 2019 Outstanding Reviewer Award of the IEEE TRANSACTIONS ON POWER ELECTRONICS.

# Outline



- ❑ Introduction
- ❑ Impedance-based Stability Criterion
- ❑ Impedance Modeling of MMCs
- ❑ Case Studies
- ❑ Impedance Matrix Measurement
- ❑ Conclusion

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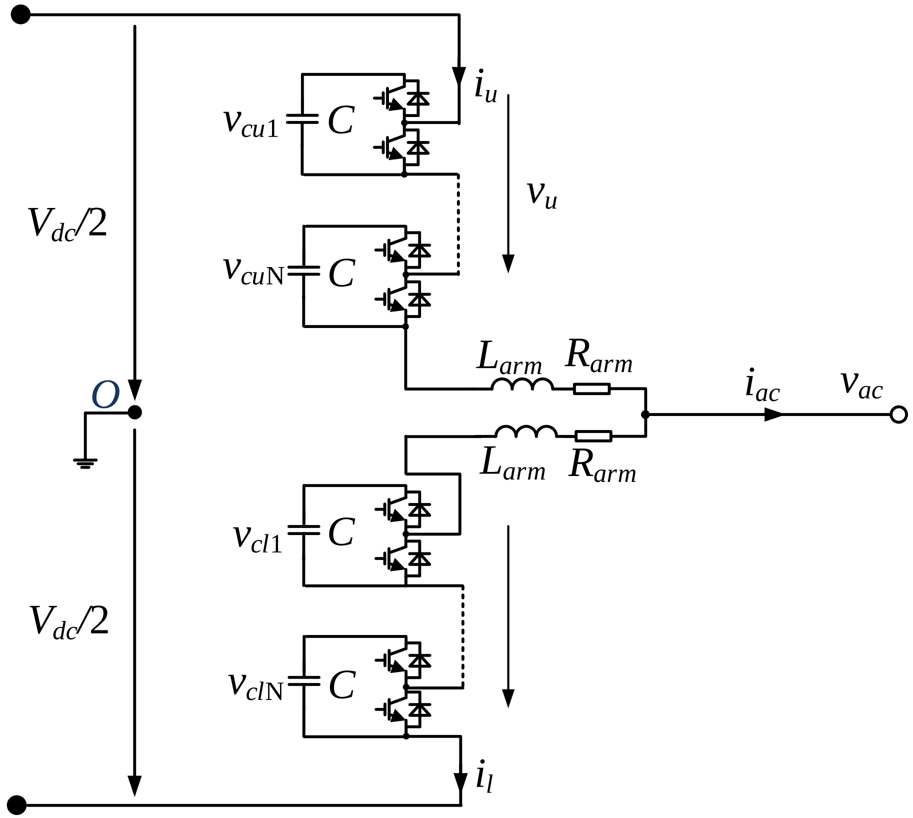
# Modular Multilevel Converters (MMCs)



©Hitachi ABB

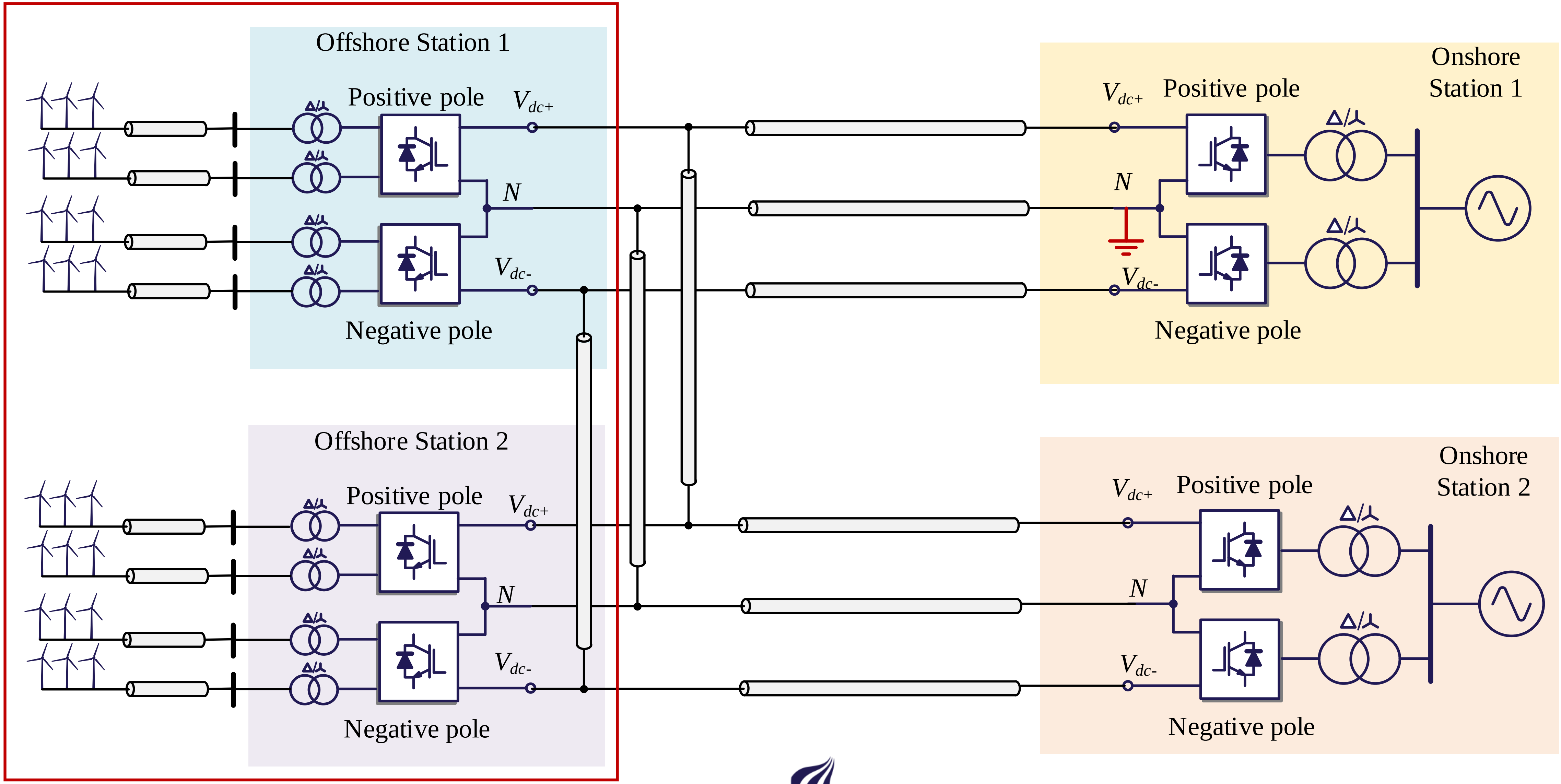



Modular multilevel converters (MMCs)

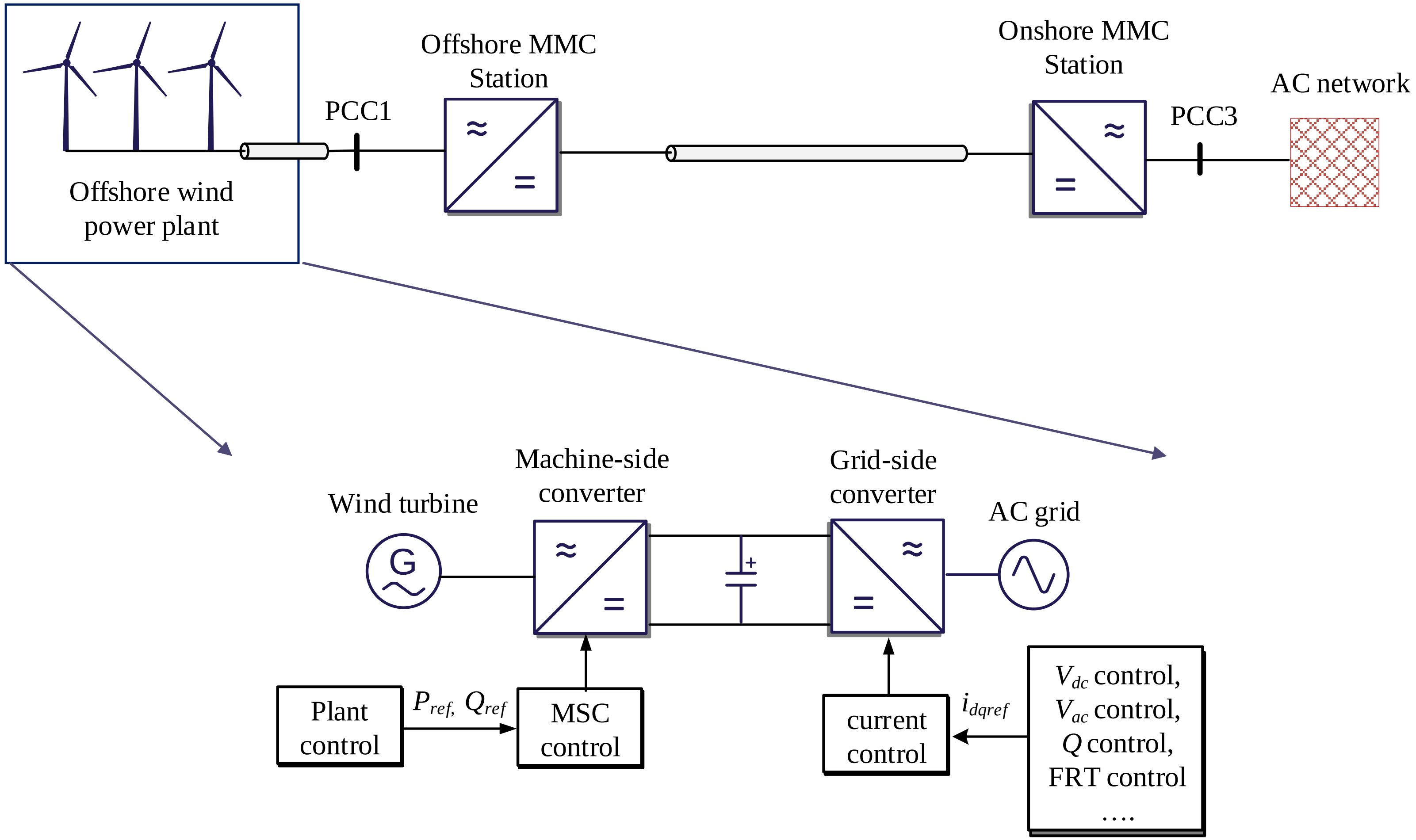
- Modular design, high redundancy
- Low distortion of output voltage
- Black start capability
- Independent control of active and reactive power

# System diagram of MTDC grid

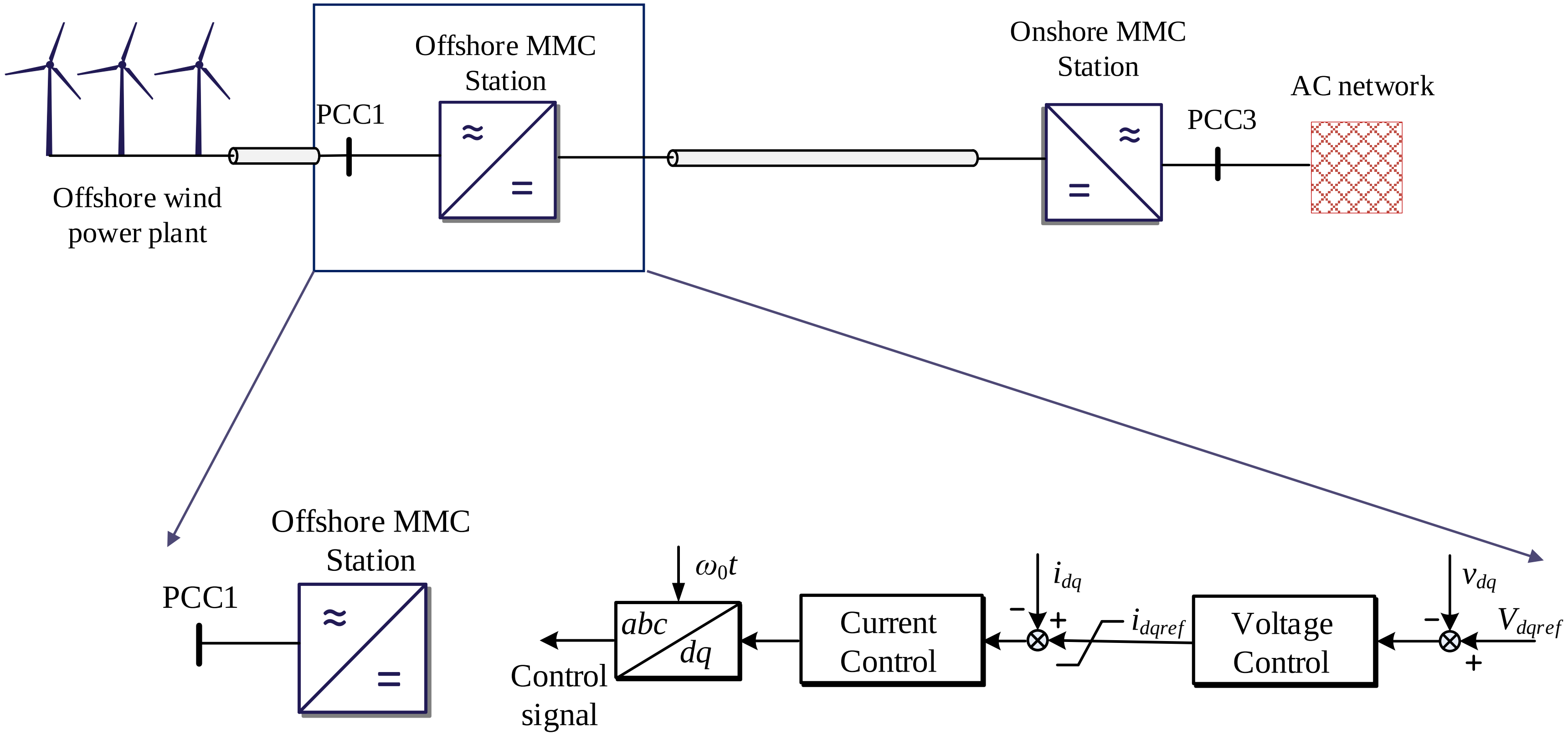




# Preliminary overview of control schemes_WPP

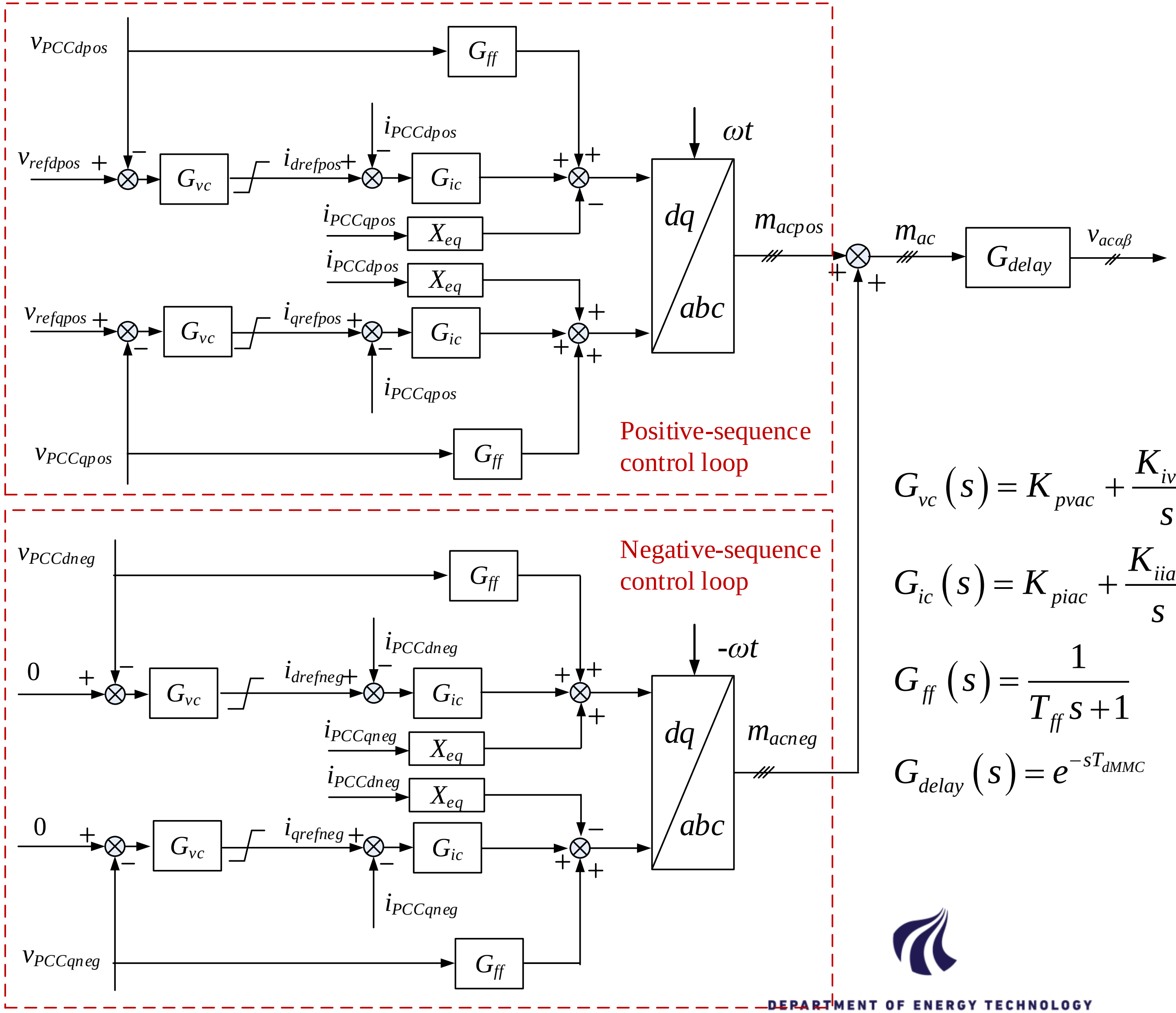


# Control schemes for offshore MMC




- Constant AC voltage control with inner current limitation loop

# Detailed control scheme for offshore MMCs

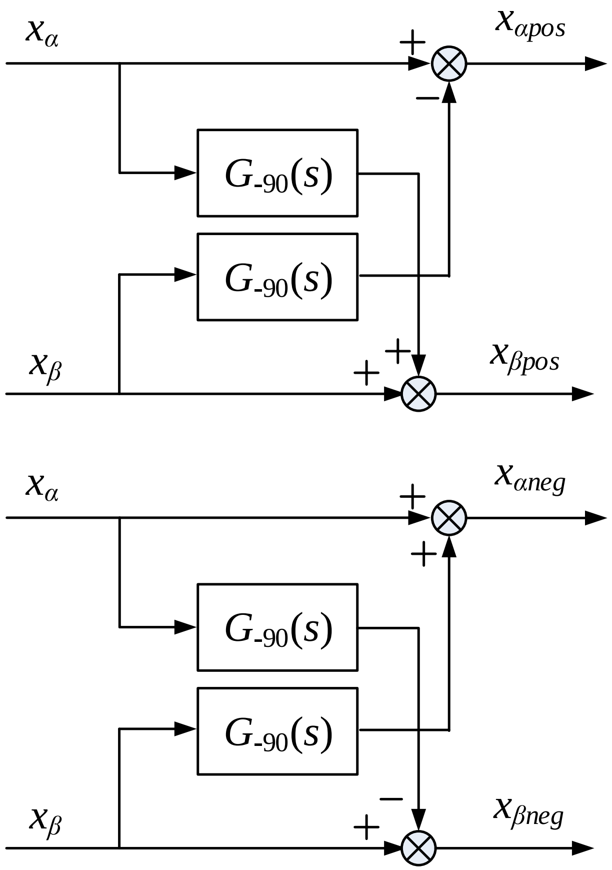



$$G_{vc}(s) = K_{pvac} + \frac{K_{ivac}}{s}$$

$$G_{ic}(s) = K_{piac} + \frac{K_{iiac}}{s}$$

$$G_{ff}(s) = \frac{1}{T_{ff}s + 1}$$

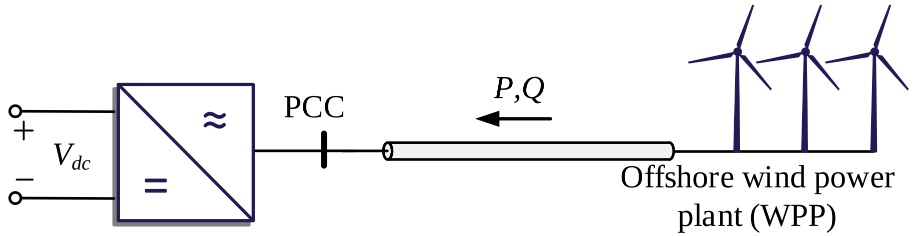
$$G_{delay}(s) = e^{-sT_{dMMC}}$$

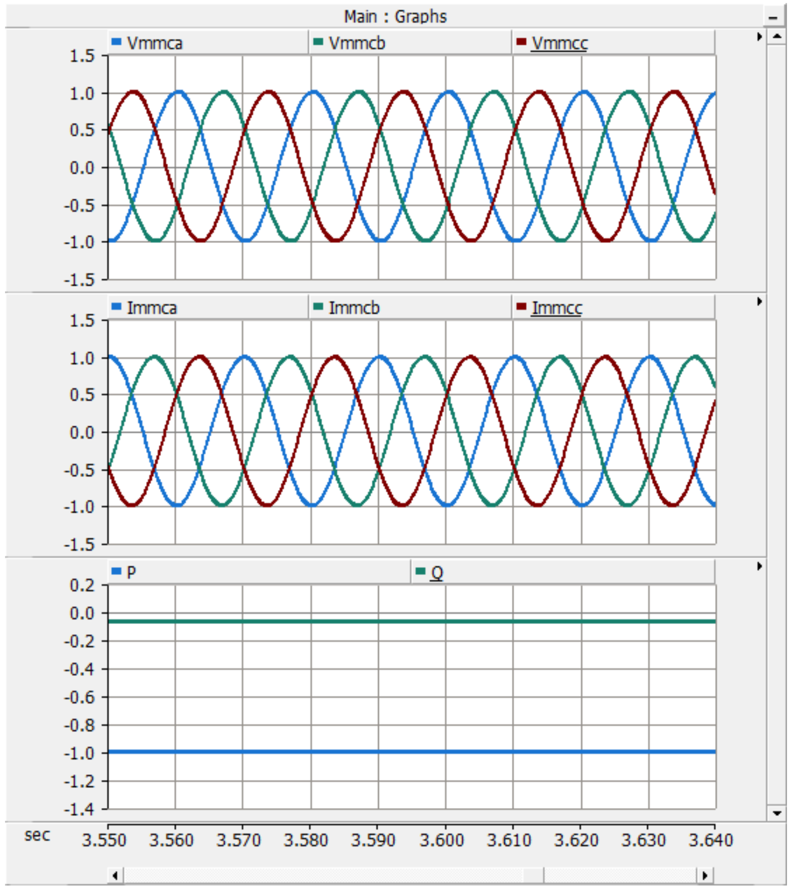



Sequence decomposition

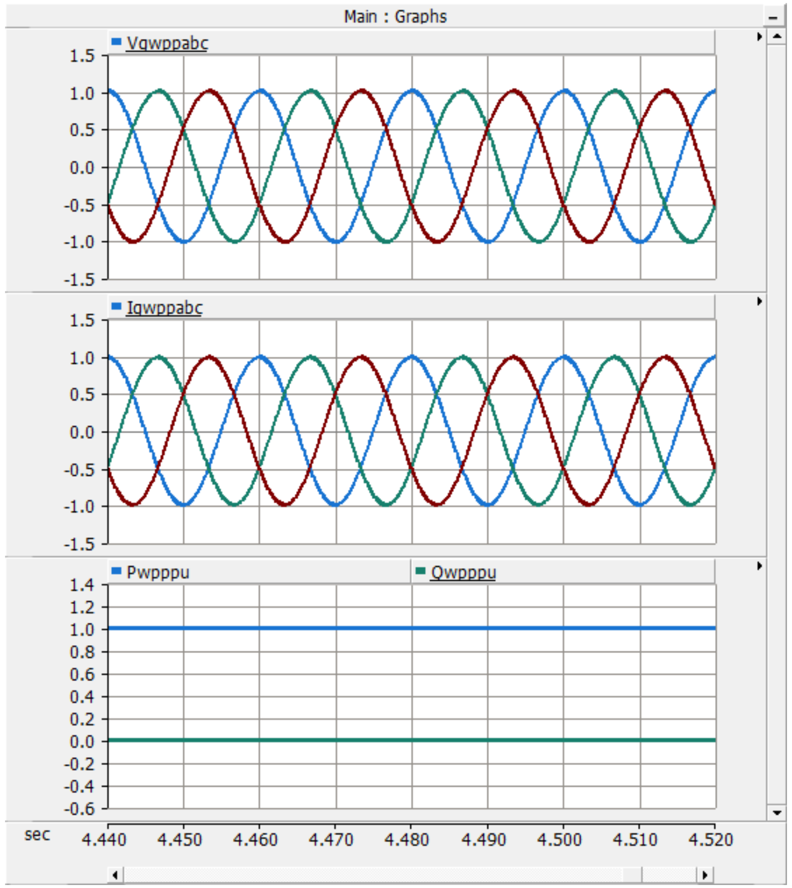
# Normal Operation





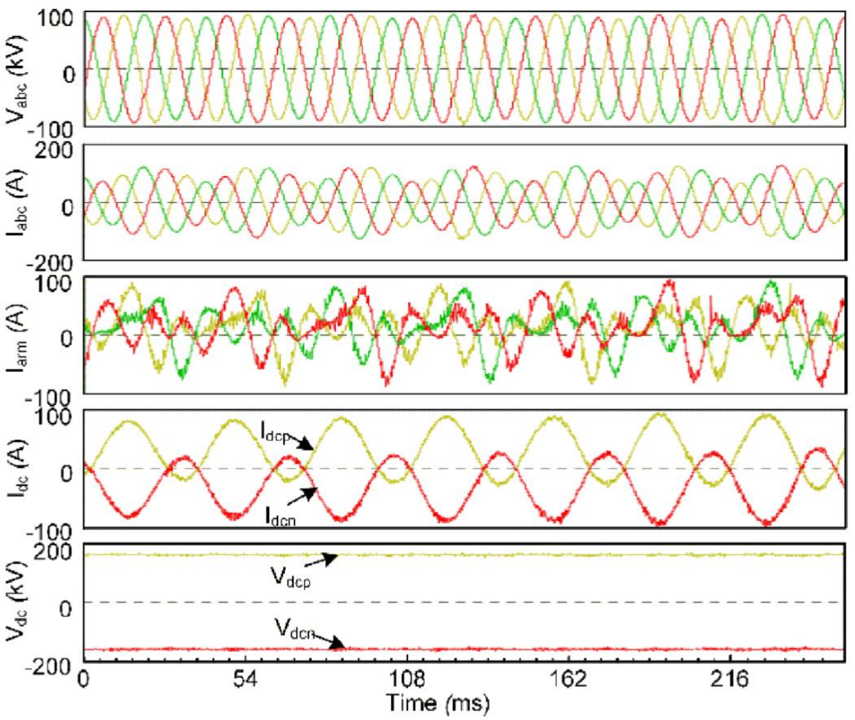




MMC



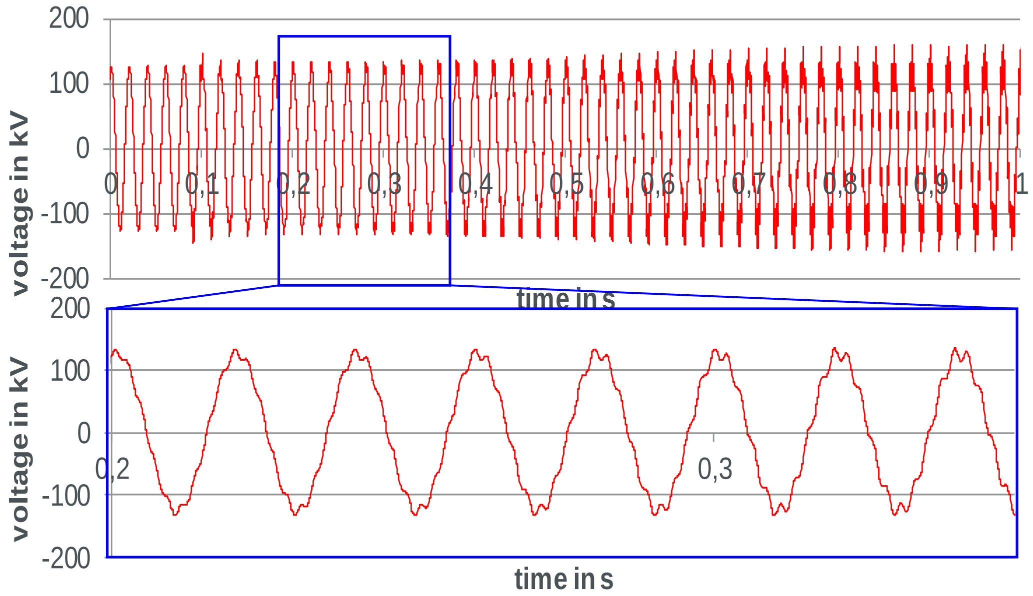

WPP

# Real-world stability challenges




**MMC-HVDC with Type-3 Wind Turbine, China[1]**

- 21 Hz oscillation at wind farm interface




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

- 451 Hz resonance

[1] J. Lv, P. Dong, G. Shi, *et al*.: 'Subsynchronous oscillation and its mitigation of MMC-based HVDC with large doubly-fed induction generator-based windfarm integration', Proc. CSEE, 2015, 35, (19), pp. 4852–4860.

[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.

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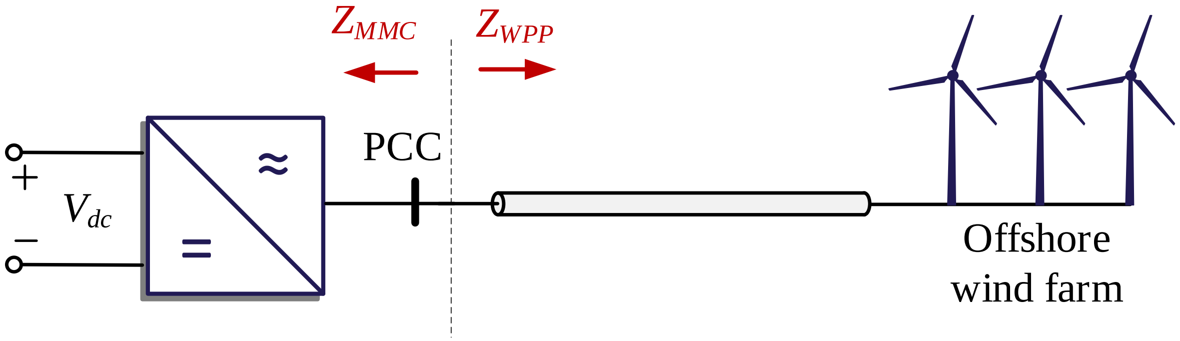
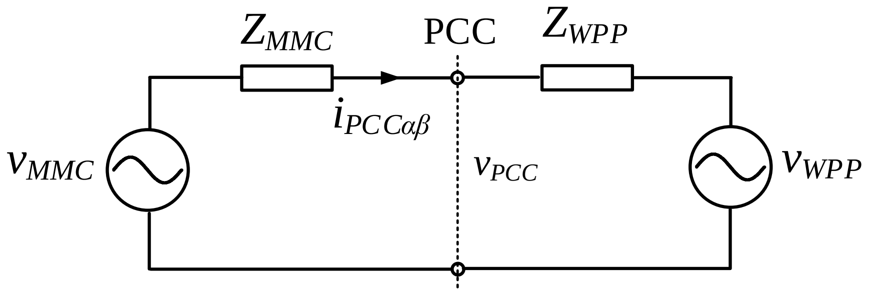
# Stability assessment methdology

## Impedance-based stability analysis




- Time domain simulation
- State-space analysis
- Impedance-based stability analysis

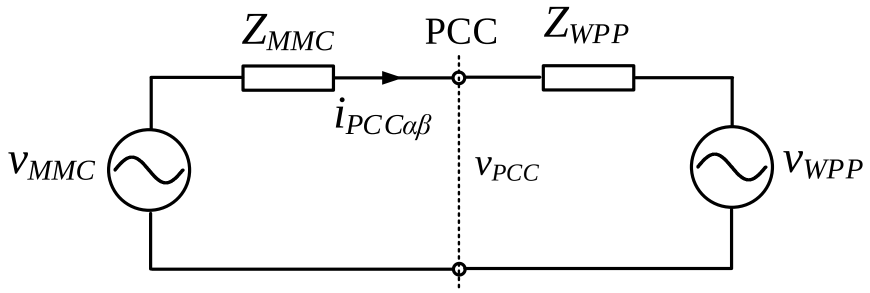
### For TSOs

✓ Impedance can be directly measured from the black-box model

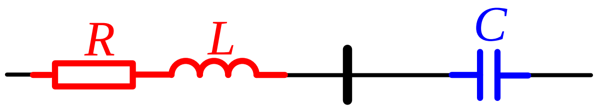
### For manufacturers

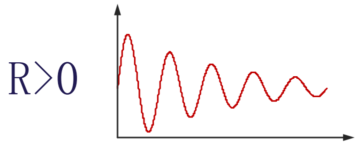
✓ Provide insight for stabilization based on impedance shaping

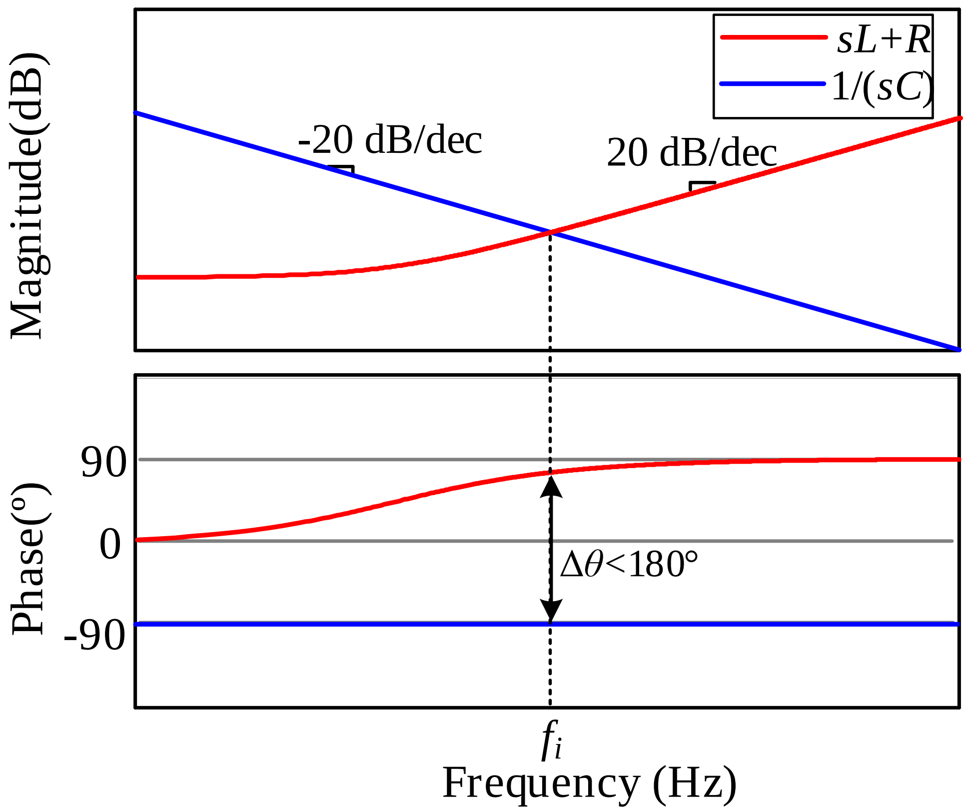
# Impedance-Based Analysis—Concept



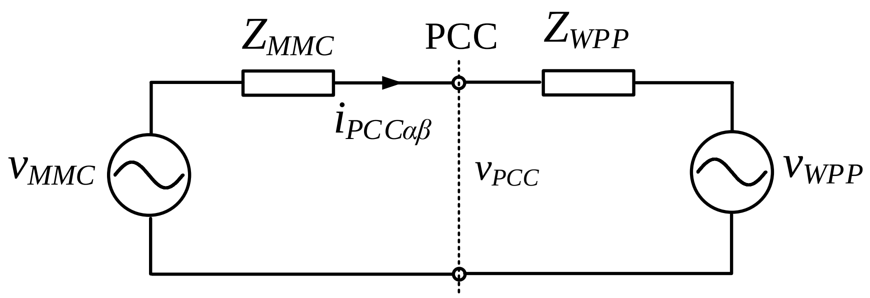

Equivalent circuit of MMC-HVDC and WPP



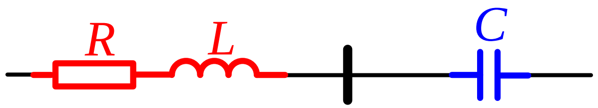



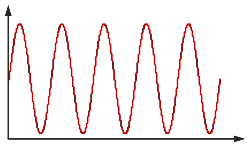
# Impedance-Based Analysis—Concept

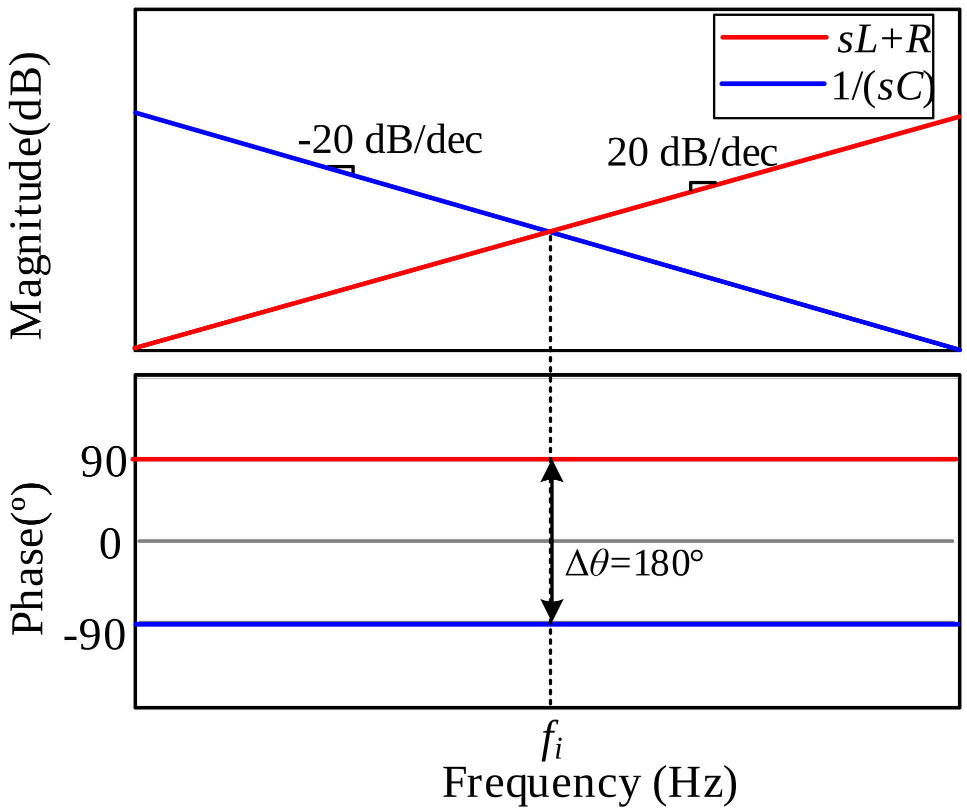



Equivalent circuit of MMC-HVDC and WPP

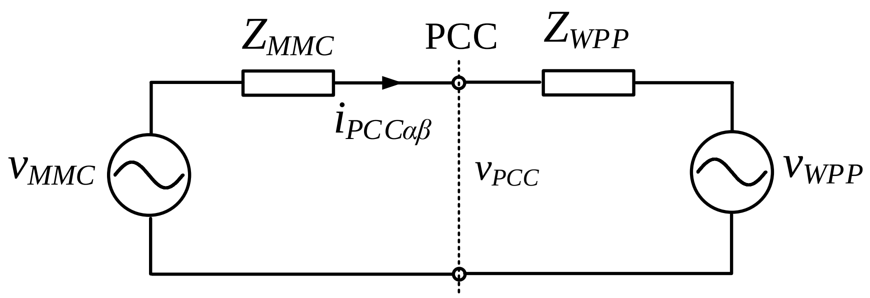



R=0

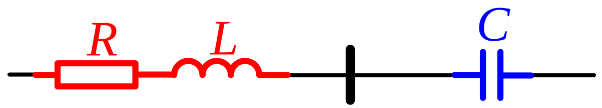


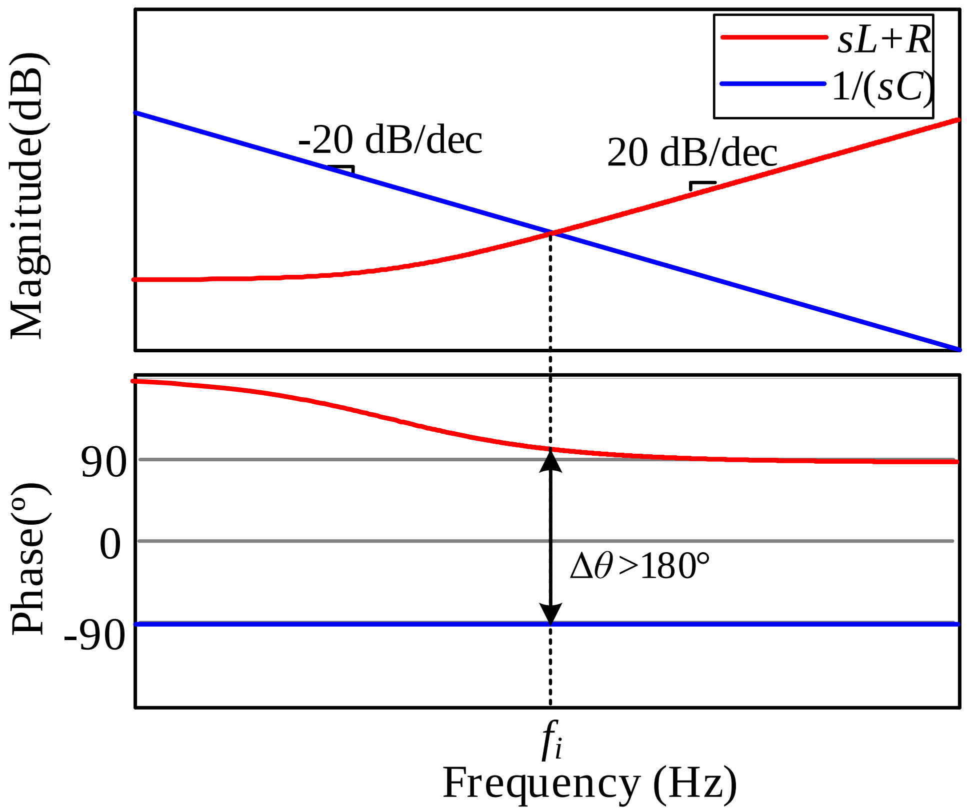


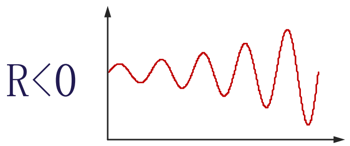
# Impedance-Based Analysis—Concept



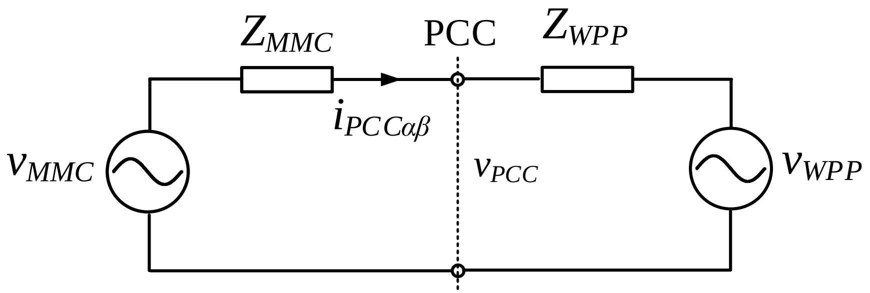

Equivalent circuit of MMC-HVDC and WPP



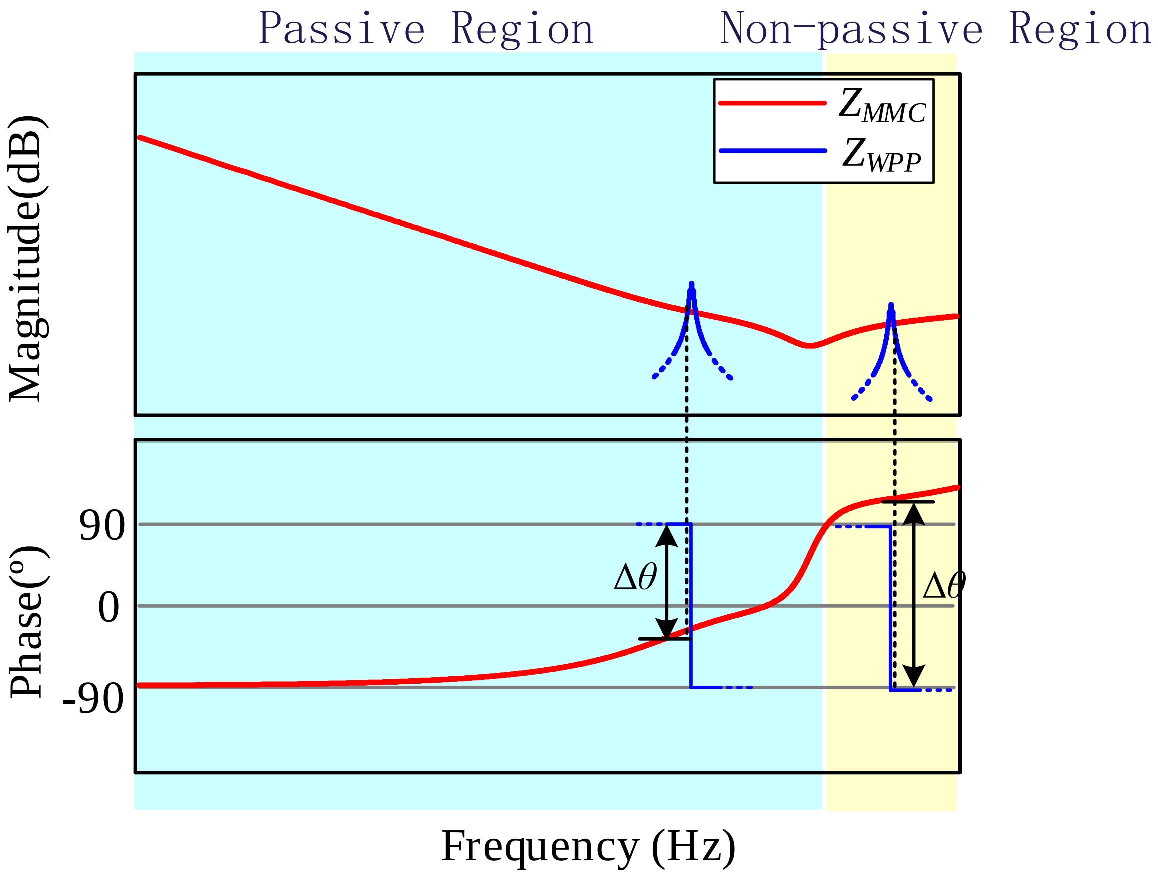



# Impedance-Based Analysis—Concept




Equivalent circuit of MMC-HVDC and WPP




Re{$Z$}>=0 ➔ -90°≤∠$Z$ ≤ 90° ⇔ Passive

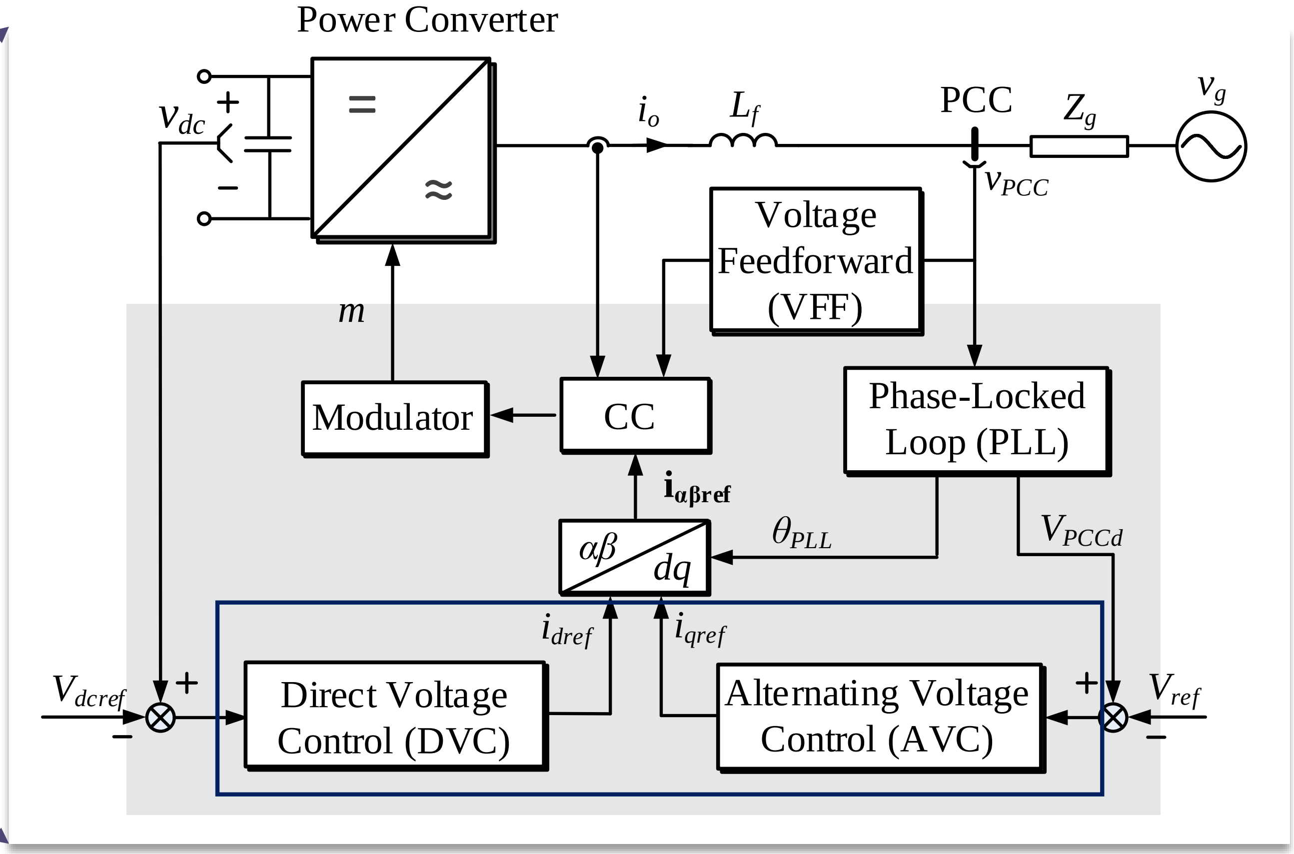
Re{$Z$}<0 ➔ ∠$Z$ > 90° or ∠$Z$ < -90° ⇔ Non-passive

**Good Physical Insight**

- Identify the harmonic instability risk just by **taking a glance** at the converter impedance
- Define the **converter impedance specifications** to manufactures to avoid the risk of the instability

# Impedance representation

## MIMO or SISO




Asymmetrical dq control dynamics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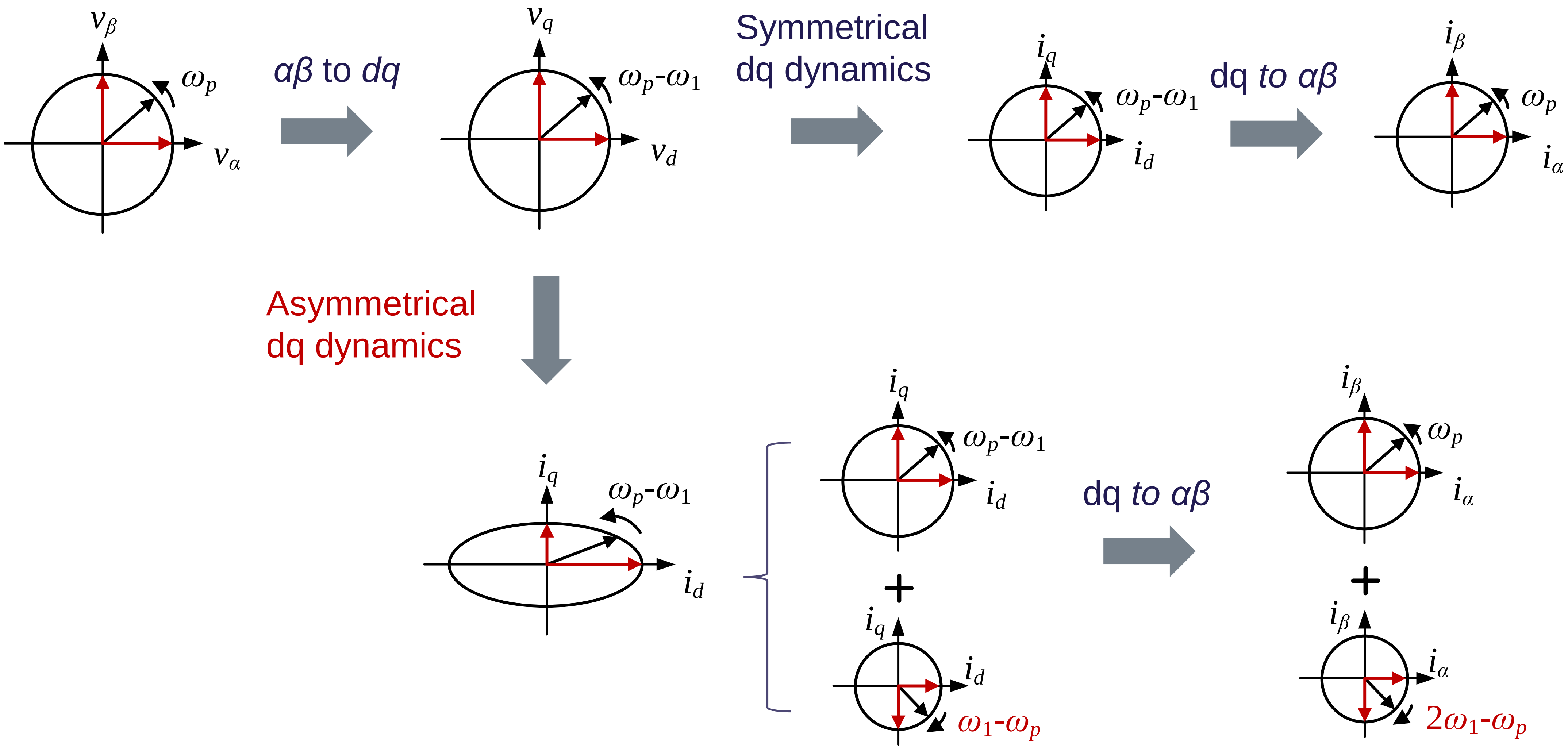
# Graphical illustration of frequency coupling dynamics

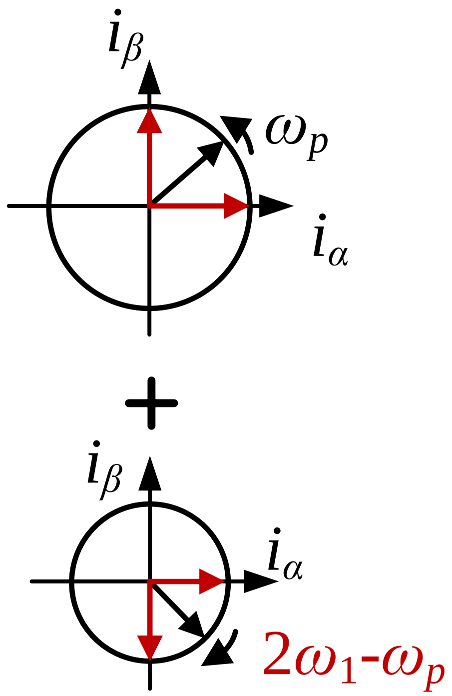



- Coupling between $\omega_p$ and $2\omega_1$-$\omega_p$

# Some Misunderstandings



Stationary frame




$$\begin{bmatrix} i_{ac}(\omega_p) \\ i_{ac}(2\omega_1-\omega_p) \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix} \begin{bmatrix} v_{ac}(\omega_p) \\ v_{ac}(2\omega_1-\omega_p) \end{bmatrix}$$

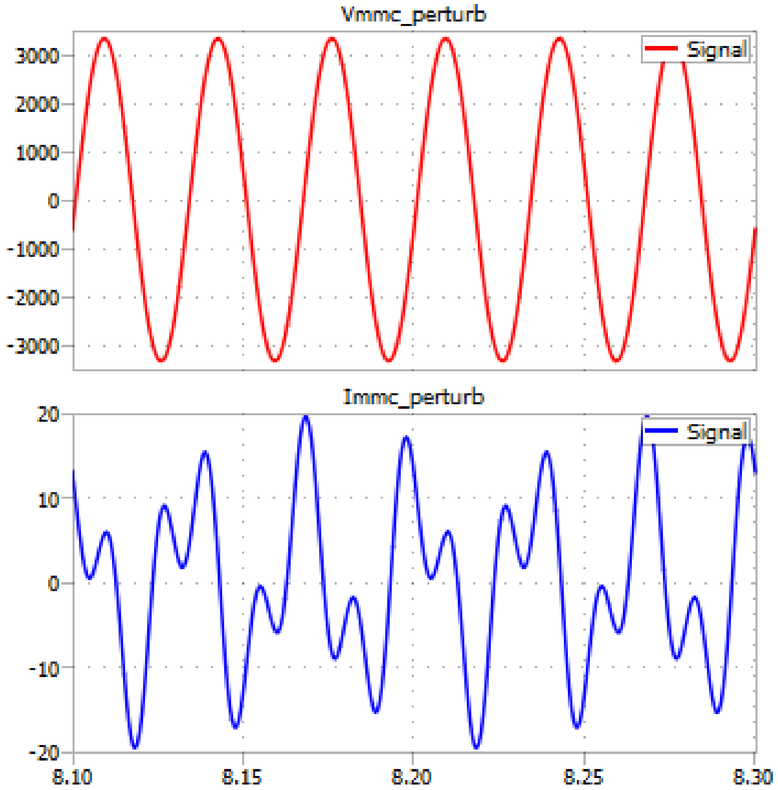
- If $\omega_p > 2\omega_1$, $2\omega_1-\omega_p$ is the negative sequence component, while $\omega_p$ is the positive-sequence component
- If $\omega_p < 2\omega_1$, both $2\omega_1-\omega_p$ and $\omega_p$ are positive-sequence components
- Positive- and negative-sequence impedances are ambiguous terminologies! It is possible that two coupled components are both positive sequence!

# Simulation results

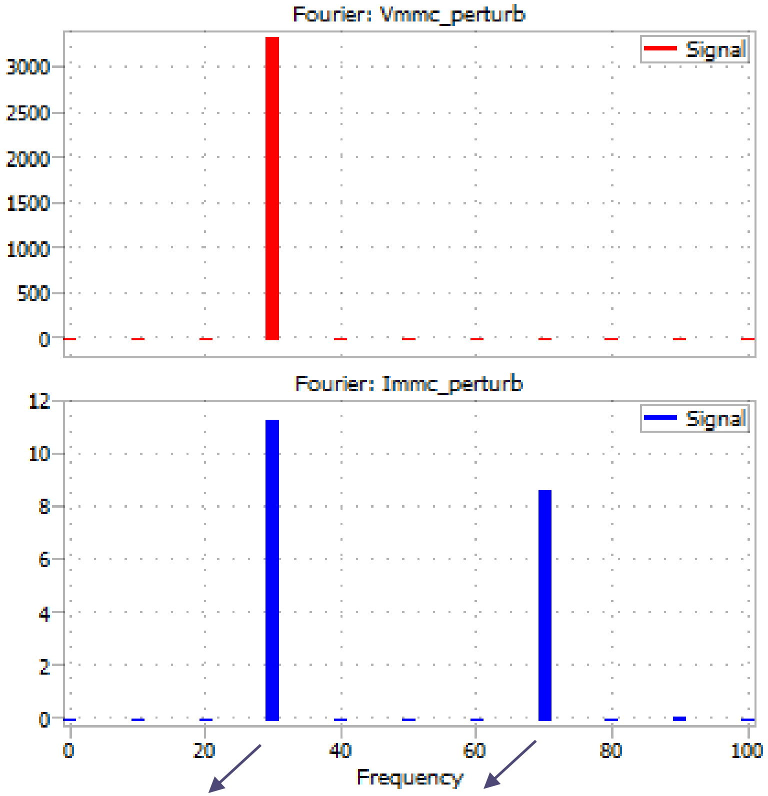


$$\begin{bmatrix} i_{ac}(\omega_p) \\ i_{ac}(2\omega_1-\omega_p) \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix} \begin{bmatrix} v_{ac}(\omega_p) \\ v_{ac}(2\omega_1-\omega_p) \end{bmatrix}$$

Inject 30Hz voltage perturbation



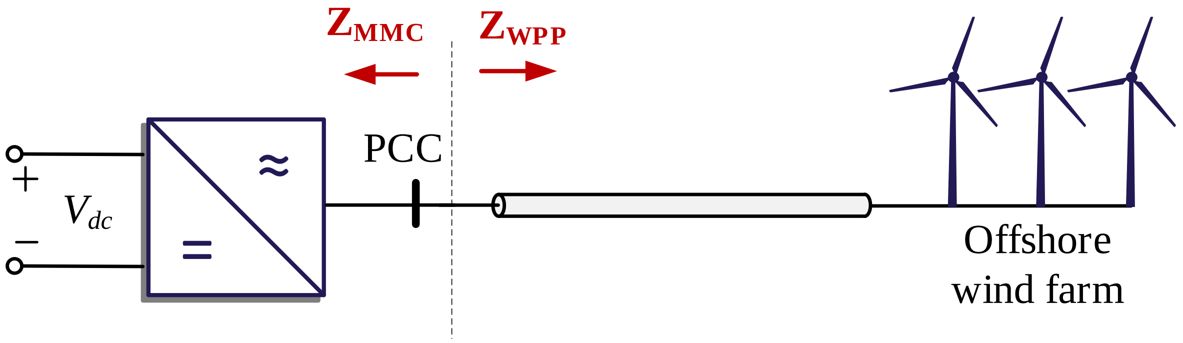

FFT results




30 Hz (Positive seq) 70 Hz (Positive seq)

# MIMO Impedance matrix representation of the system

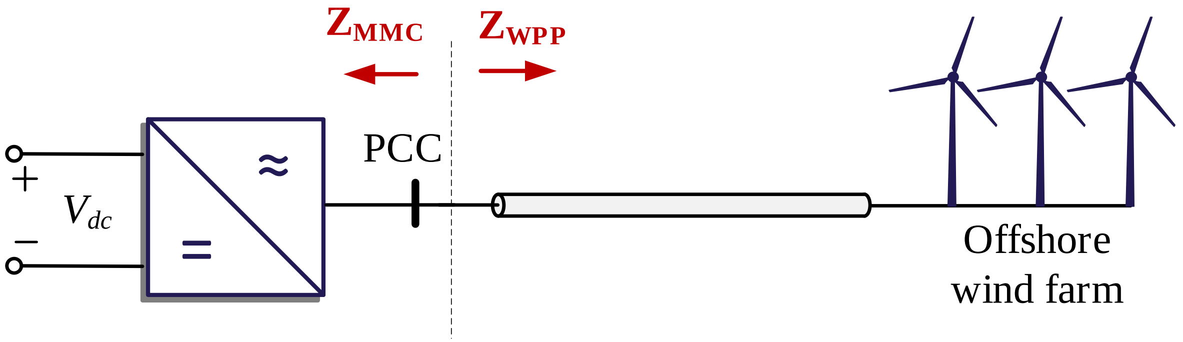


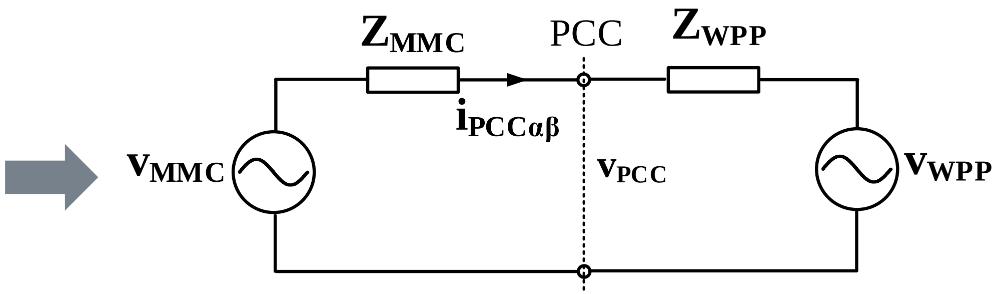


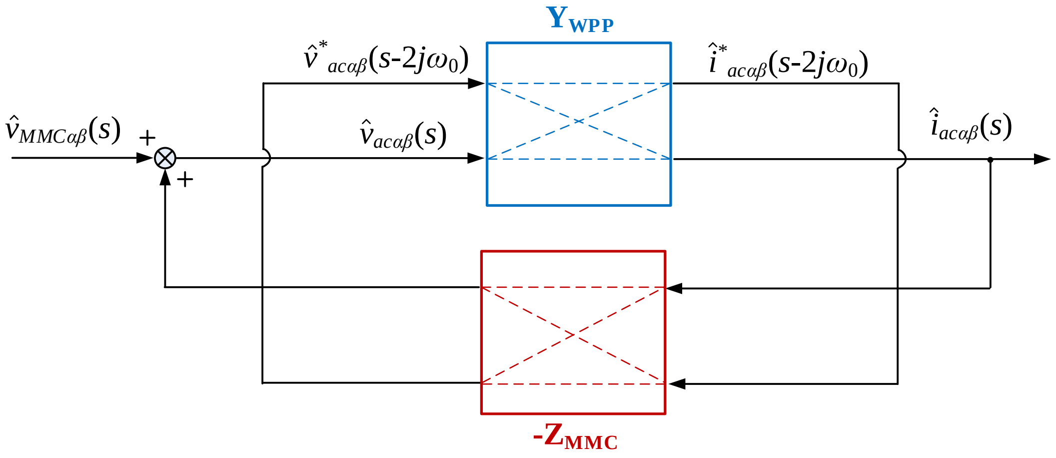

$$\begin{bmatrix} v_{MMC\alpha\beta}(s) \\ v^{*}_{MMC\alpha\beta}(s-2j\omega_0) \end{bmatrix} = \underbrace{\begin{bmatrix} Z_{MMC11} & Z_{MMC12} \\ Z_{MMC21} & Z_{MMC22} \end{bmatrix}}_{\mathbf{Z_{MMC}}} \begin{bmatrix} i_{MMC\alpha\beta}(s) \\ i^{*}_{MMC\alpha\beta}(s-2j\omega_0) \end{bmatrix}$$

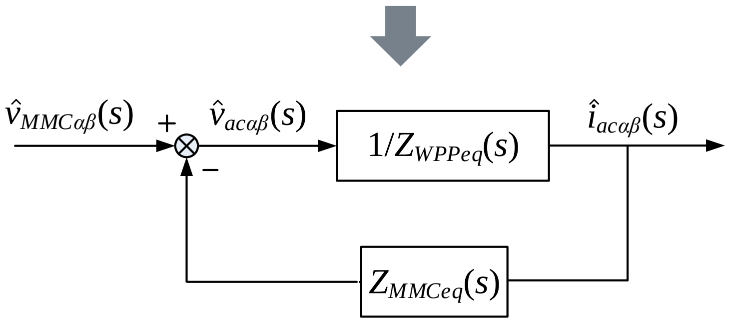
$$\begin{bmatrix} v_{WPP\alpha\beta}(s) \\ v^{*}_{WPP\alpha\beta}(s-2j\omega_0) \end{bmatrix} = \underbrace{\begin{bmatrix} Z_{WPP11} & Z_{WPP12} \\ Z_{WPP21} & Z_{WPP22} \end{bmatrix}}_{\mathbf{Z_{WPP}}} \begin{bmatrix} i_{WPP\alpha\beta}(s) \\ i^{*}_{WPP\alpha\beta}(s-2j\omega_0) \end{bmatrix}$$

# Stability criterion




$$Z_{tot11} = Z_{MMC11} + Z_{WPP11}$$
$$Z_{tot12} = Z_{MMC12} + Z_{WPP12}$$
$$Z_{tot21} = Z_{MMC21} + Z_{WPP21}$$
$$Z_{tot22} = Z_{MMC22} + Z_{WPP22}$$

$$Z_{MMCeq} = Z_{MMC11} - \frac{Z_{tot21}}{Z_{tot22}} Z_{MMC12}$$

$$Z_{WPPeq} = Z_{WPP11} - \frac{Z_{tot21}}{Z_{tot22}} Z_{WPP12}$$

- The frequency coupling terms have no obvious impact in high frequency range (>300 Hz) and can be neglected, where $Z_{MMC}$ and $Z_{WPP}$ become SISO

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.

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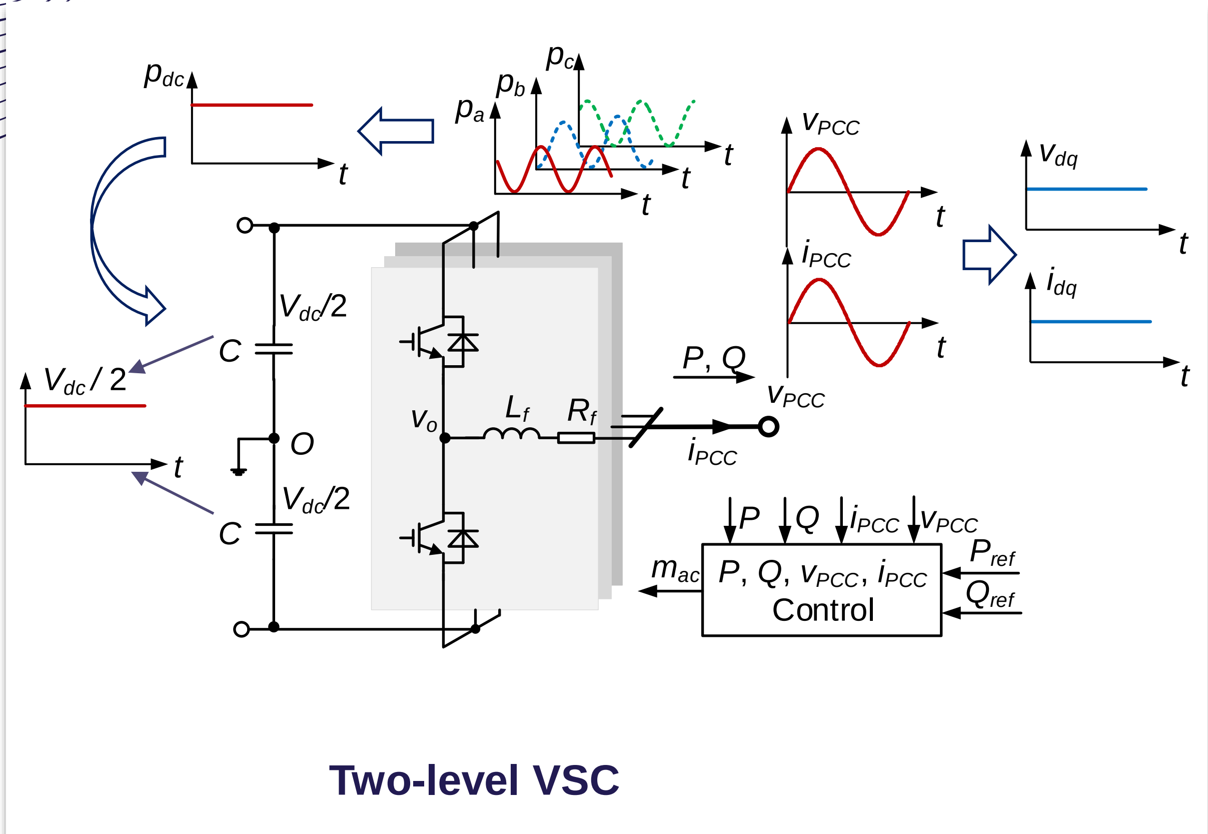
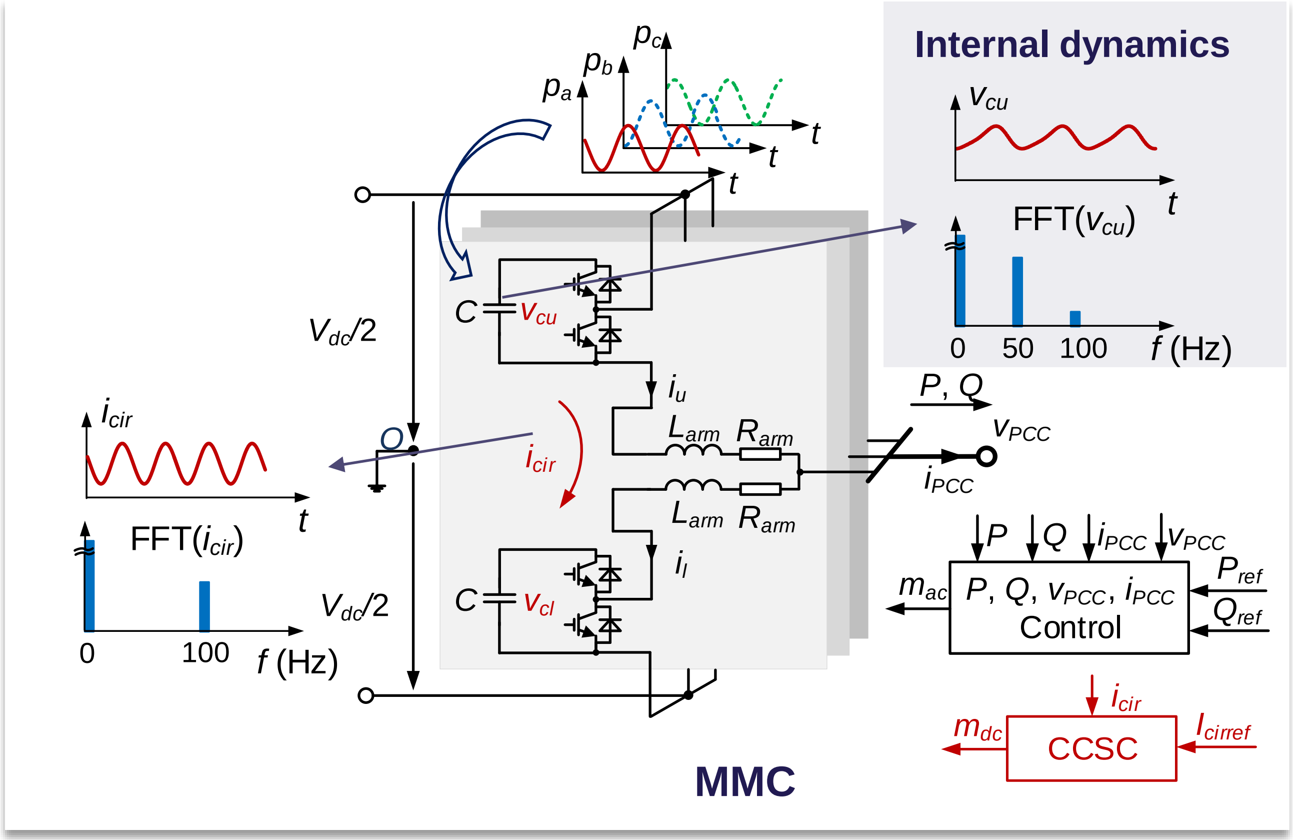
# Challenges in small-signal modeling of MMCs

## Small-signal stability: internal dynamics of MMCs




Time invariant operating point in dq frame —Linearization→ Linear time invariant (LTI) model [1]-[4]

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

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).

# Modeling methodologies

## Harmonic state space(HSS)

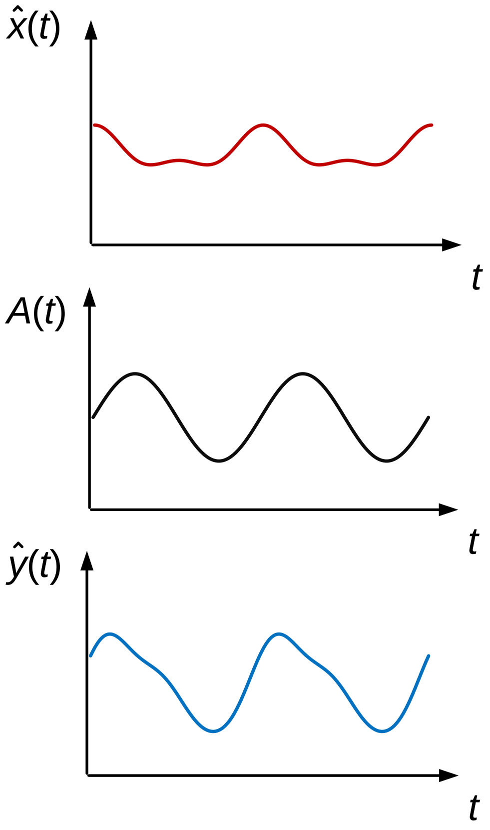


**Time varying system**

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

**LTI representation based on Fourier coefficients**

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

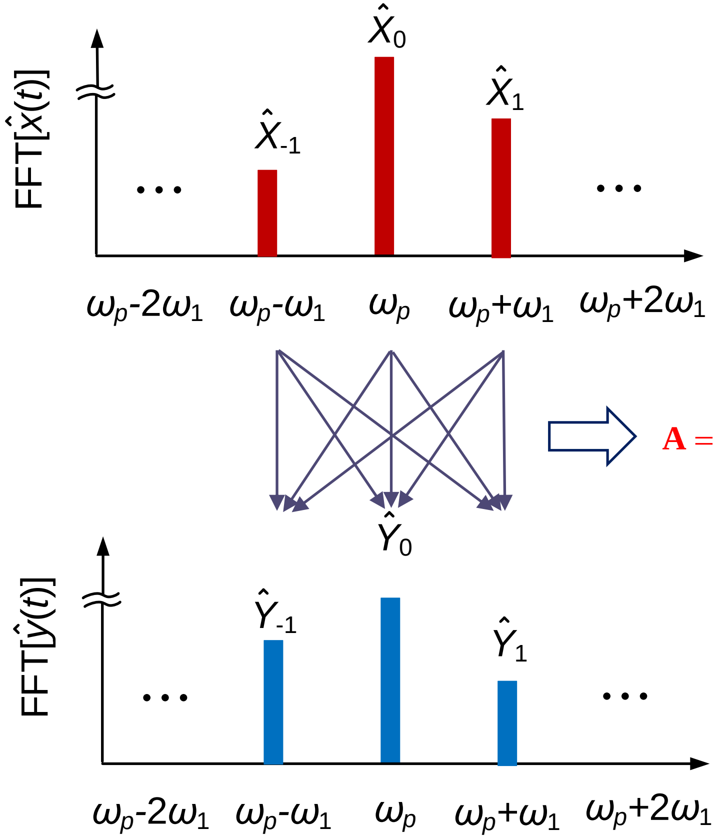



$$\hat{x}(t) = \sum_{k=-\infty}^{+\infty} \hat{X}_k e^{j(\omega_p + k\omega_1)t}$$

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

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

Constant



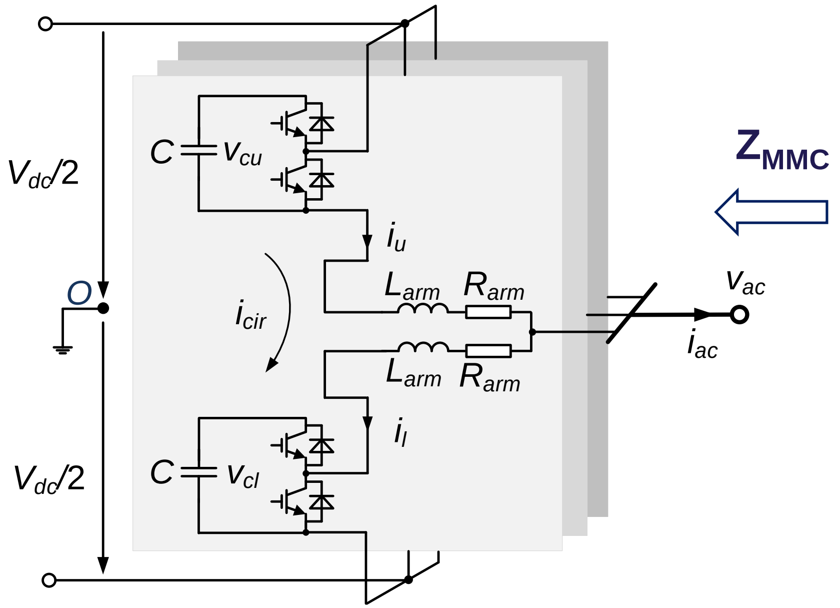

$$\mathbf{A} = \begin{bmatrix} \ddots & & & & \\ & A_0 & A_{-1} & A_{-2} & \\ \cdots & A_1 & A_0 & A_{-1} & \cdots \\ & A_2 & A_1 & A_0 & \\ & & & & \ddots \end{bmatrix}$$

- **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

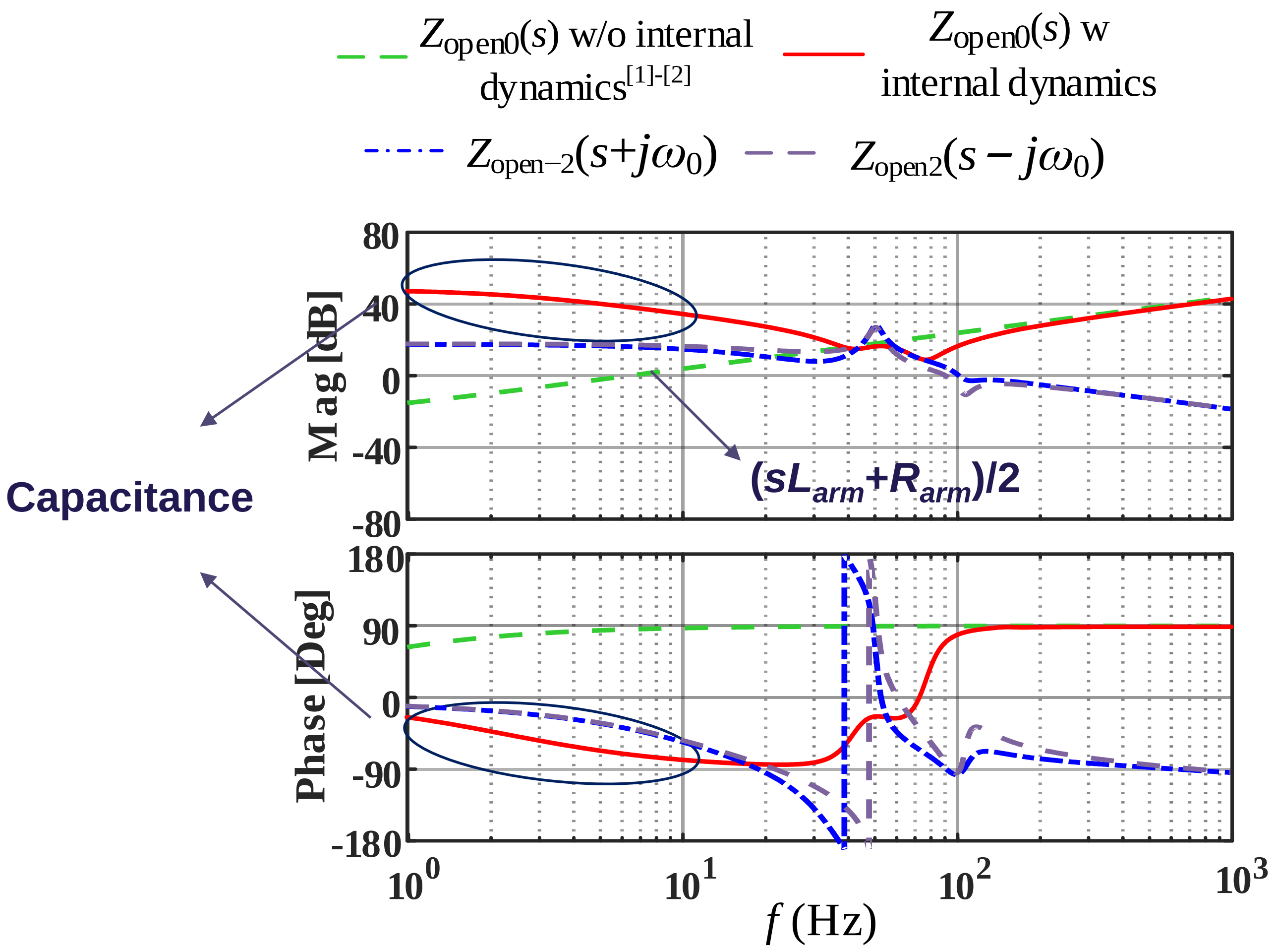
## Open-loop control




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

Centered impedance

Frequency-coupled impedances

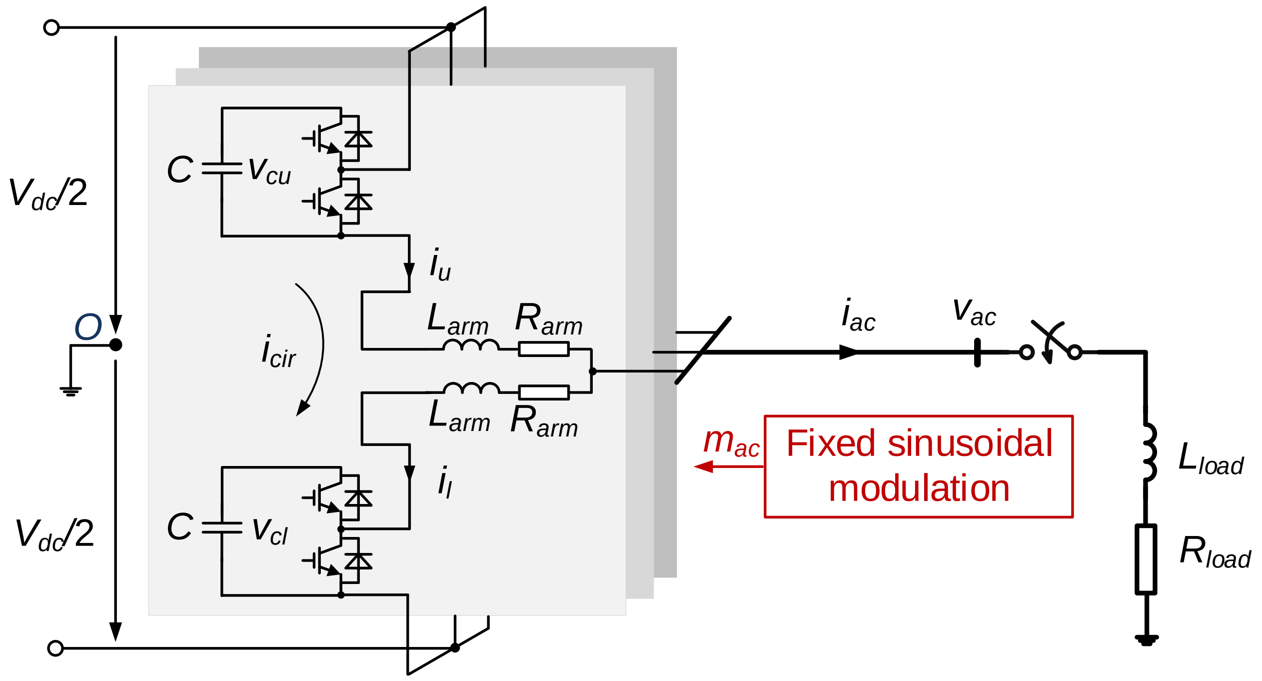


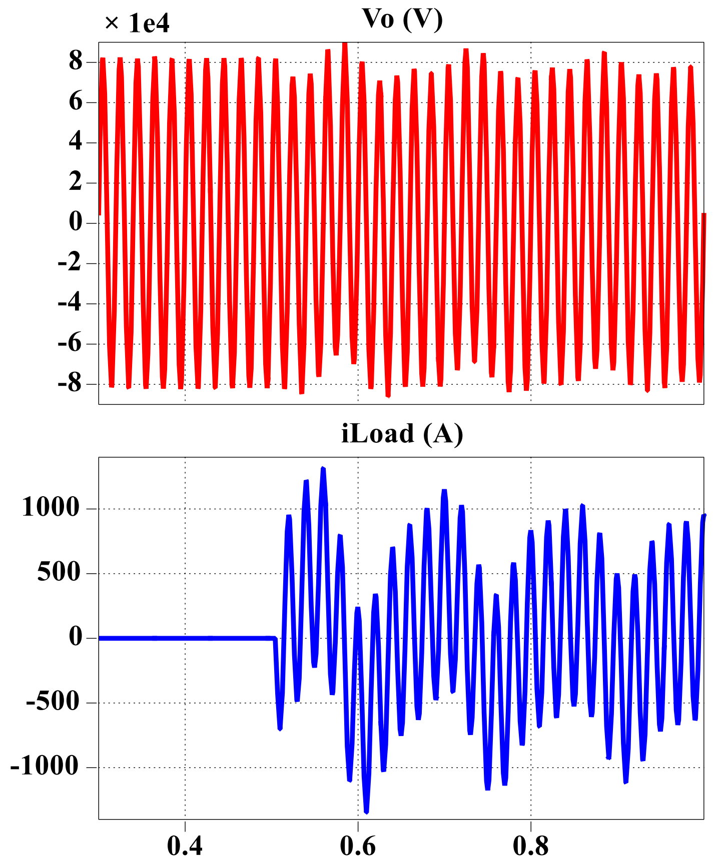

**Significant impact of internal dynamics**

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

# Simulation results

## Open-loop control with inductive load




**Capacitive $Z_{MMC0}(s)$ and inductive load forms an LC resonance**

H. Wu, X. Wang, Ł. 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 Modeling Power Electron. (COMPEL)*, Jun. 2018, pp. 1–8.

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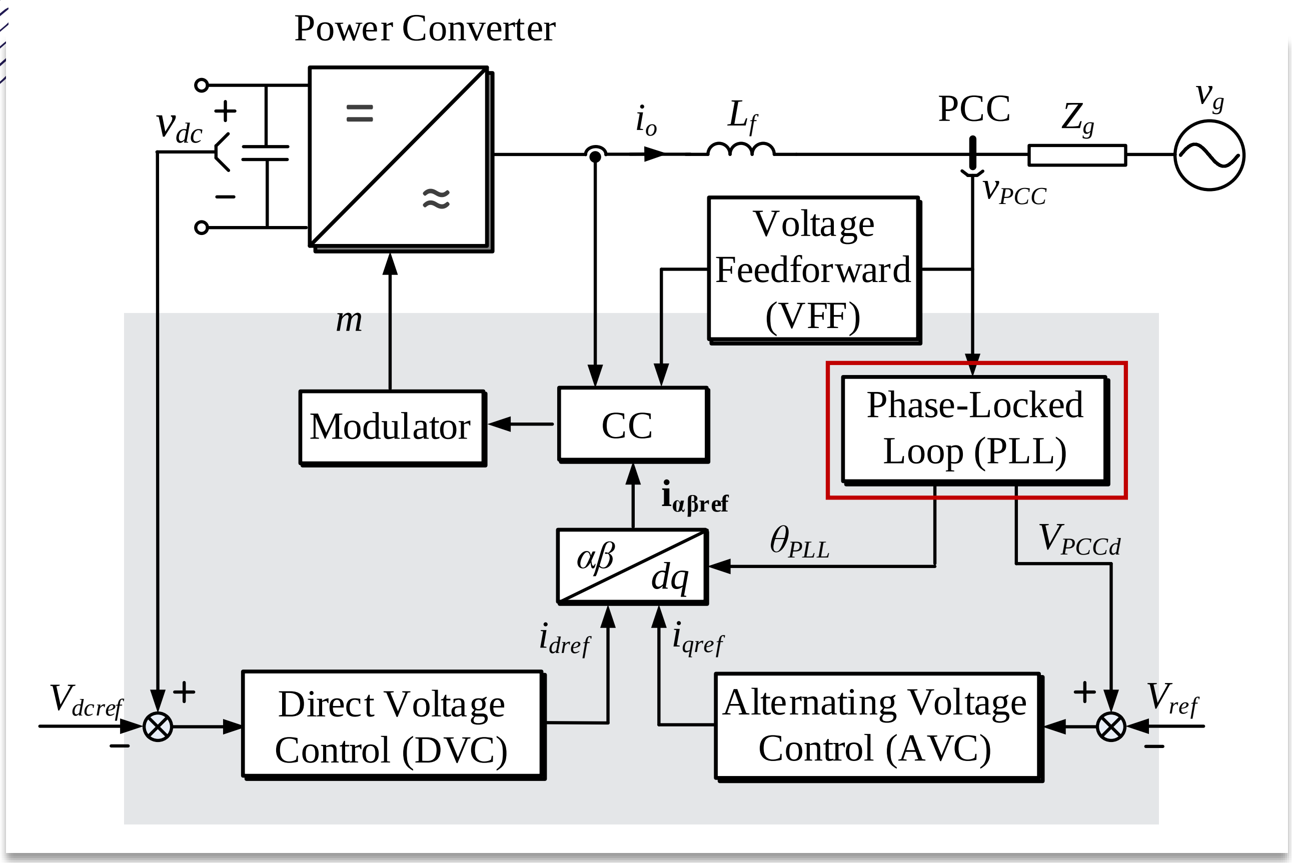
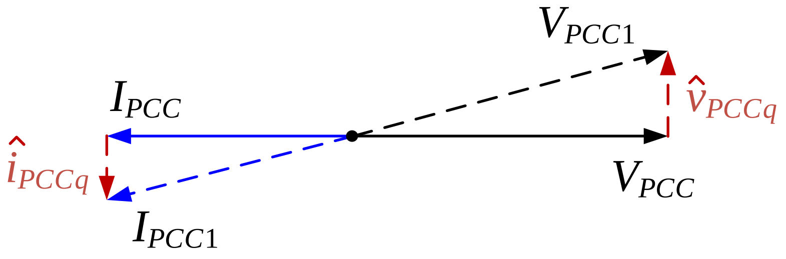
# Case study

## Low frequency oscillaiton caused by PLL

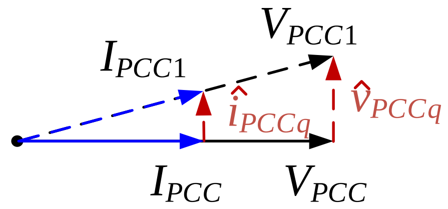



- Inversion mode




$$Z_{qq} = \frac{\hat{v}_{PCCq}}{\hat{i}_{PCCq}} < 0$$

- Rectification mode




$$Z_{qq} = \frac{\hat{v}_{PCCq}}{\hat{i}_{PCCq}} > 0$$

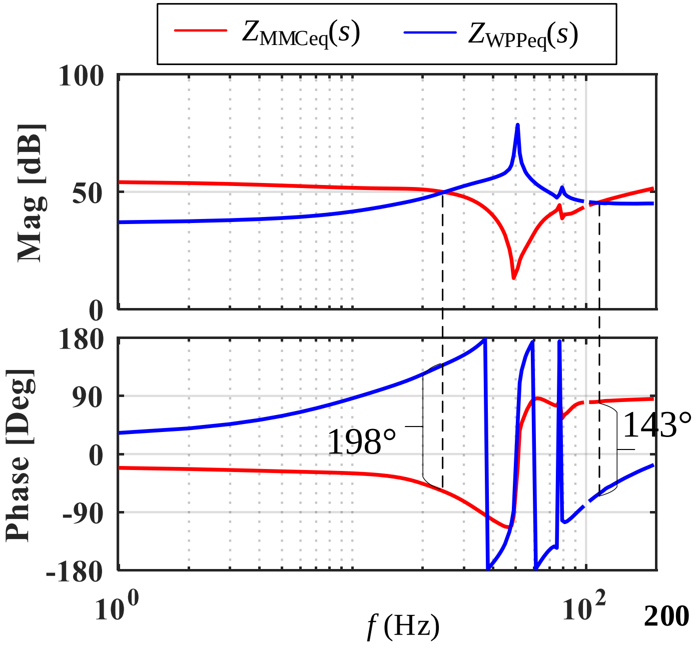
PLL introduces negative damping in the inversion mode but positive damping in the rectification mode

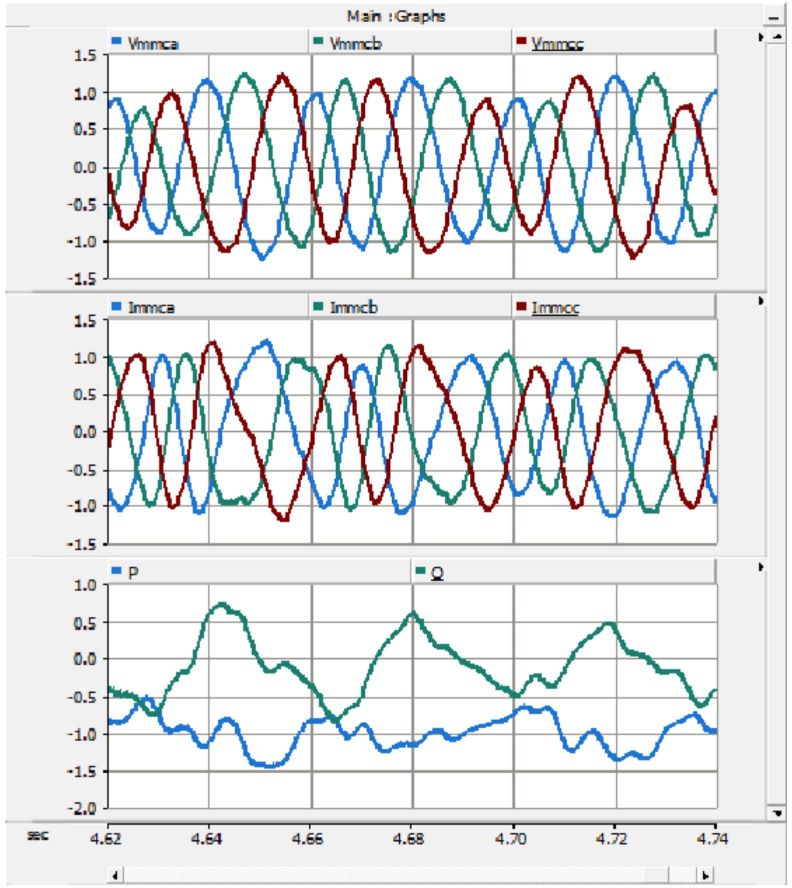
B. Wen, D. Boroyevich, R. Burgos, P. Mattavelli, and Z. Shen, "Analysis of D-Q small-signal impedance of grid-tied inverters," *IEEE Trans. Power Electron.*, vol. 31, no. 1, pp. 675–687, Jan. 2016.

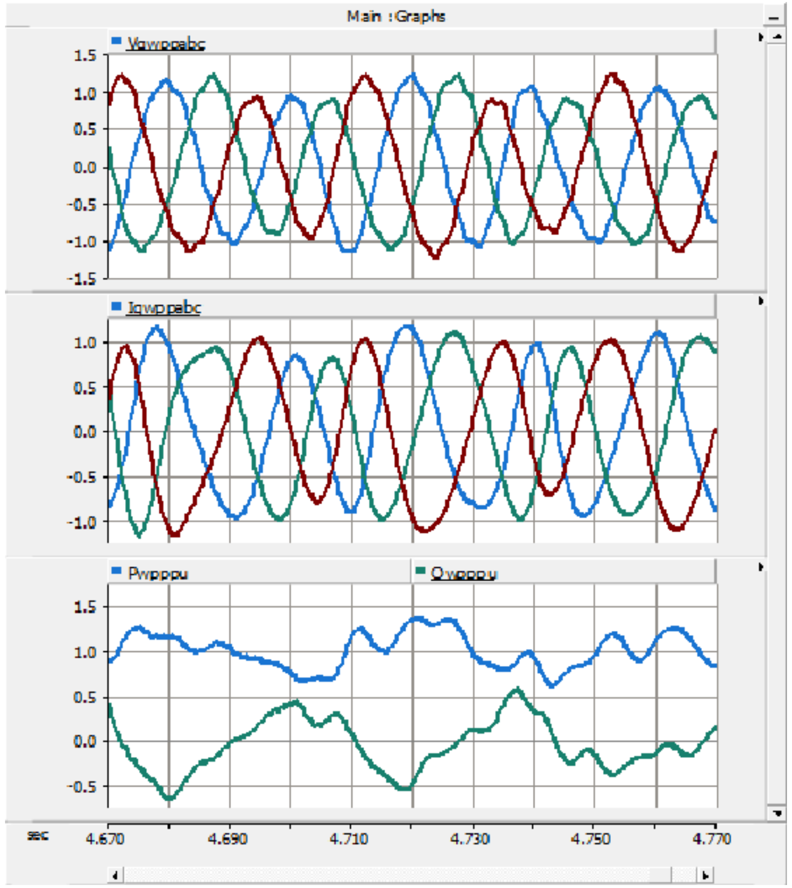
# Case studies (MMC with WPPs)



$f_{PLLWPP}$=30Hz



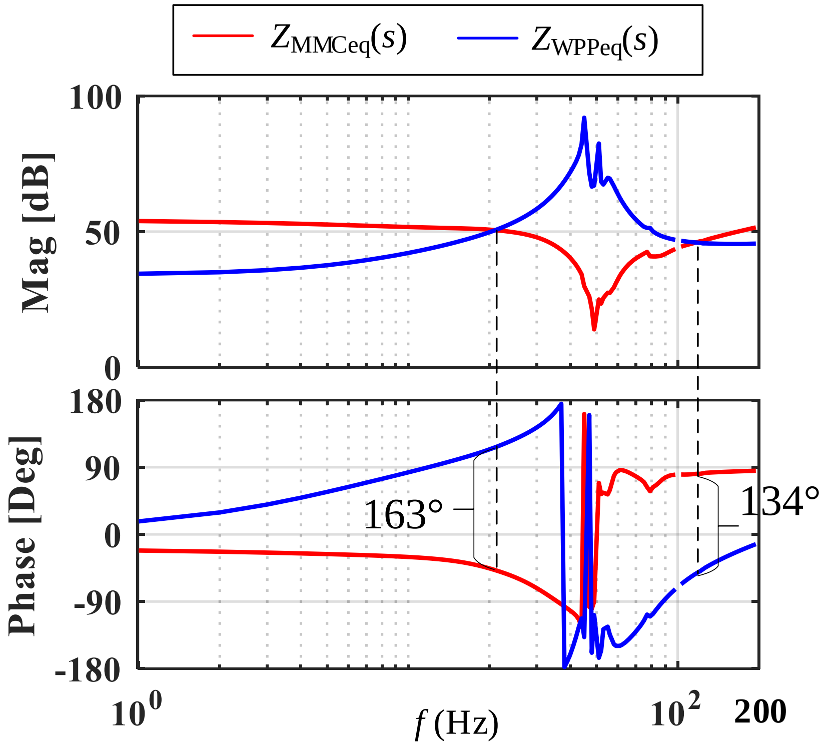

MMC

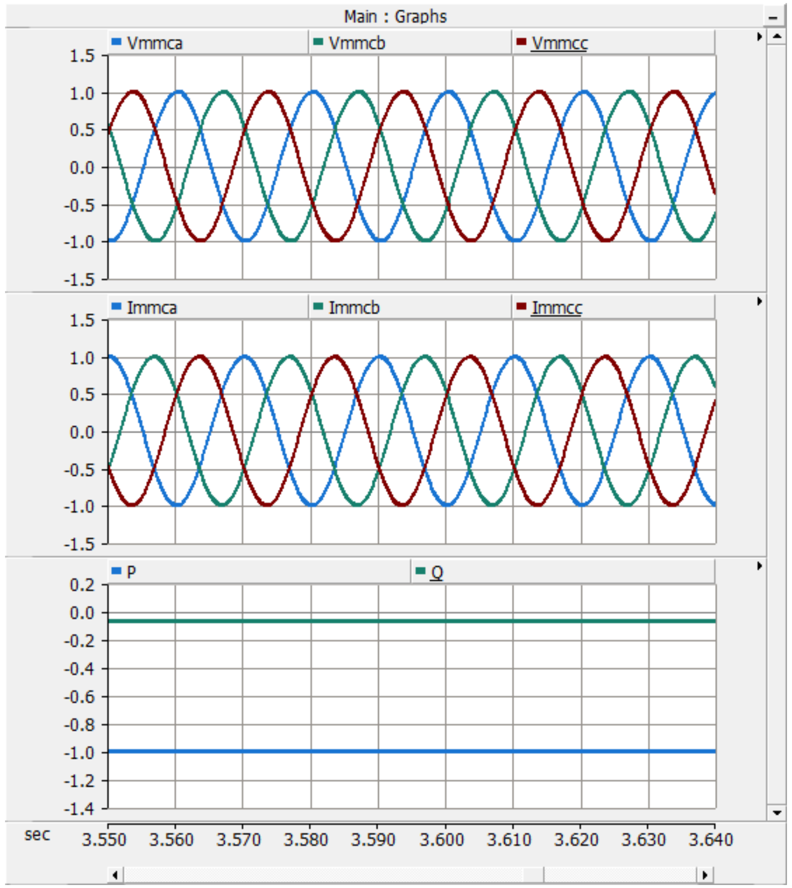
WPP

# Case studies (MMC with WPPs)

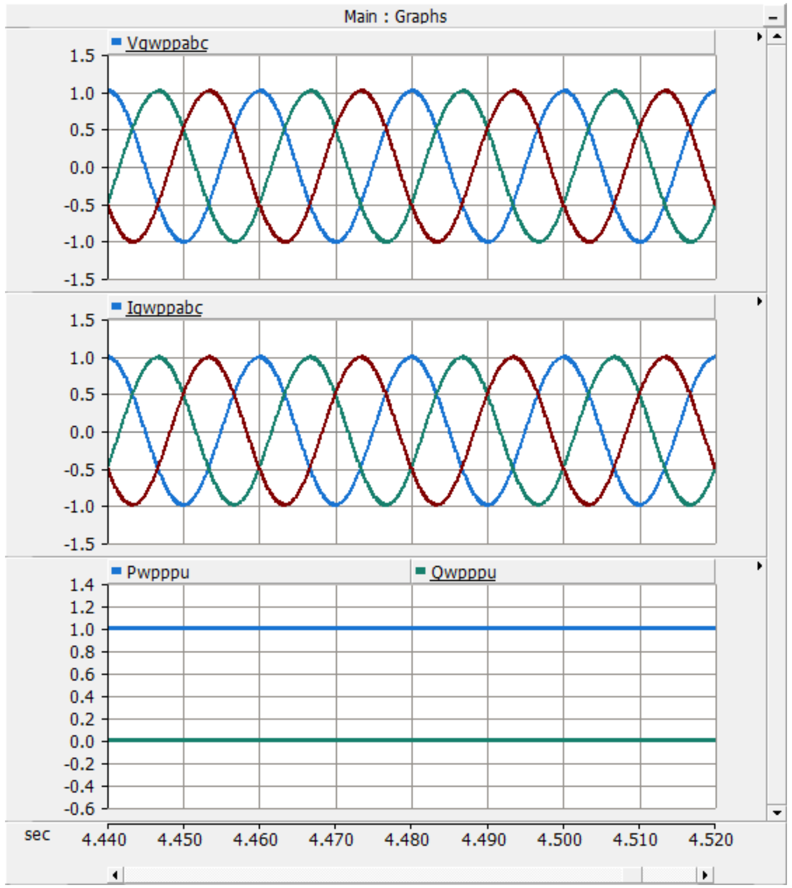


$f_{PLLWPP}$=5Hz




MMC




WPP

# Outline

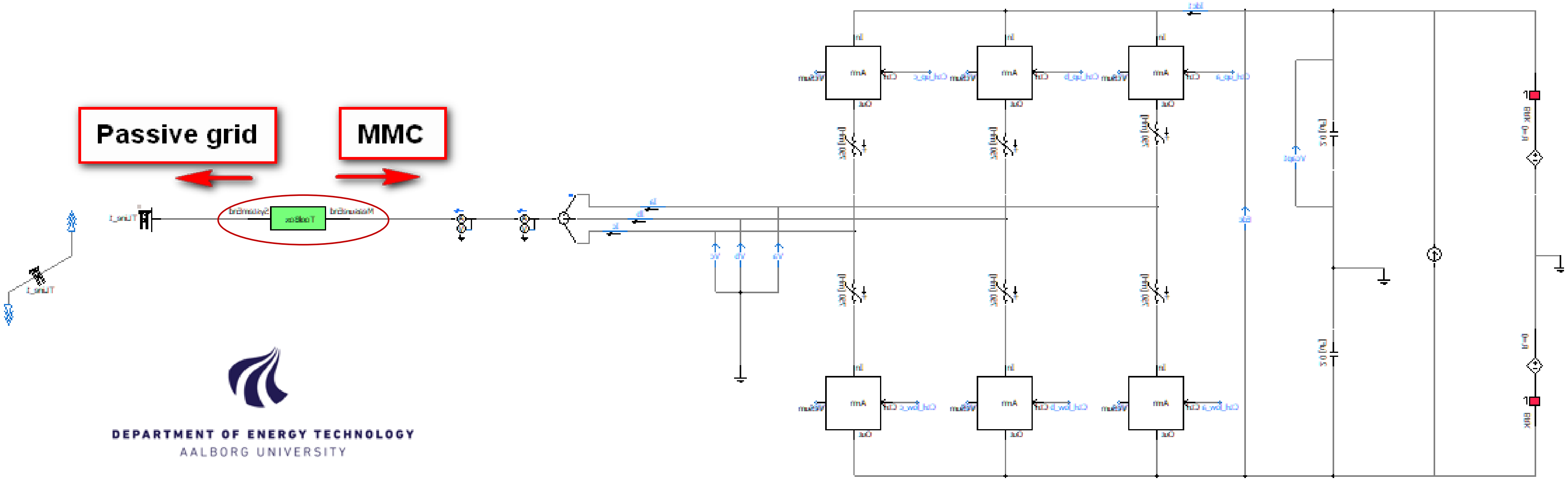



- ❑ Introduction
- ❑ Impedance-based Stability Criterion
- ❑ Impedance Modeling of MMCs
- ❑ Case Studies
- ❑ **Impedance Matrix Measurement**
- ❑ Conclusion

# Introduction of the impedance measurement toolbox

$$\begin{bmatrix} i_{PCC\alpha\beta}(\omega_p) \\ i^*_{PCC\alpha\beta}(\omega_p - 2\omega_0) \end{bmatrix} = \underbrace{\begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix}}_{\mathbf{Y_{MMC}}} \begin{bmatrix} v_{PCC\alpha\beta}(\omega_p) \\ v^*_{PCC\alpha\beta}(\omega_p - 2\omega_0) \end{bmatrix}$$

**We have developed the impedance (admittance) matrix measurement toolbox with European TSO**

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- **This toolbox is under commercialization, you are very welcome to contact us if interested !**


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**Heng Wu [hew@et.aau.dk](mailto:hew@et.aau.dk)**

# Outline



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# Conclusion



Impedance modeling

Internal dynamics of the MMC, nonlinear time periodic (NTP) system

NTP→ LTP → LTI HSS

Impedance based stability criterion

SISO equivalent impedance ratio, frequency coupling terms considered

Case study

- Impedance method is effective in stability prediction
- Destabilization effect of the PLL

Impedance measurement toolbox

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