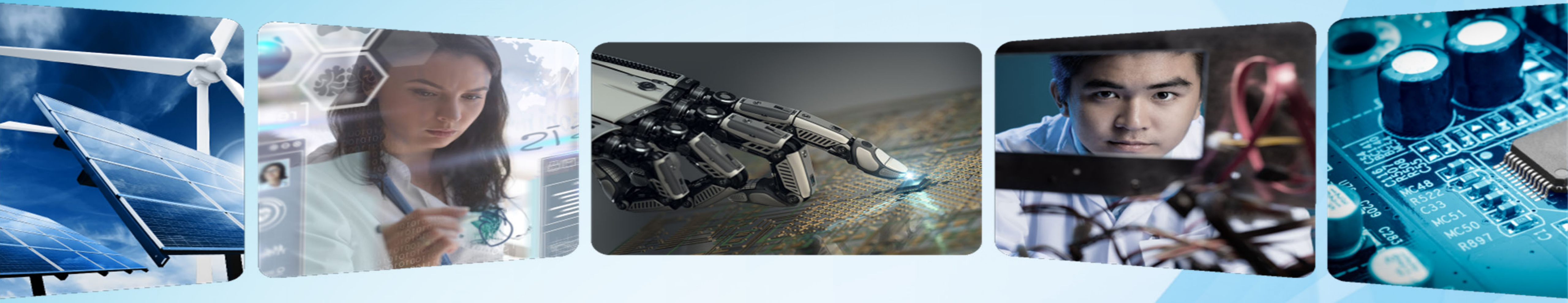

Harmonic Stability in Power Electronic Based Power Systems

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DEPARTMENT OF ENERGY TECHNOLOGY
AALBORG UNIVERSITY

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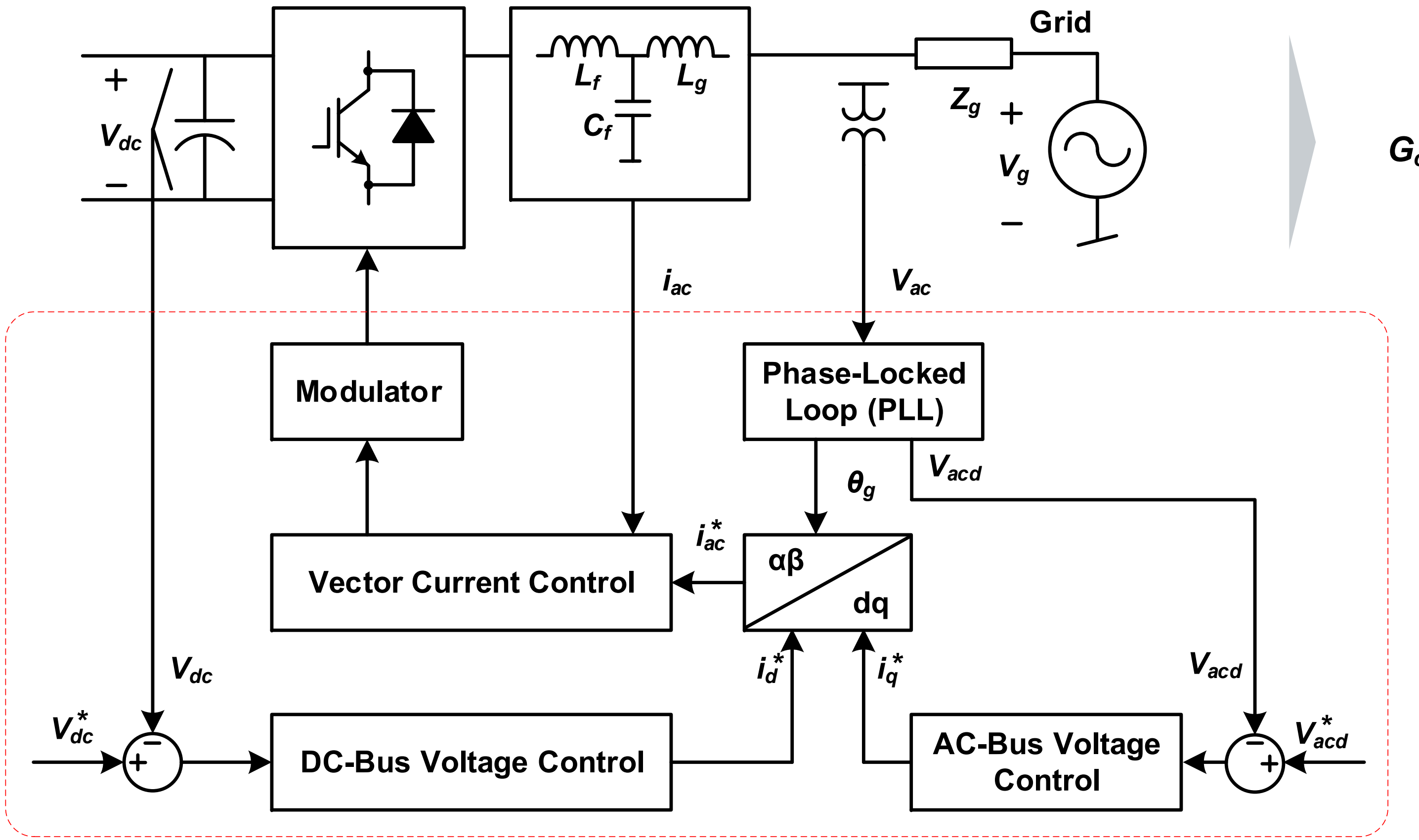
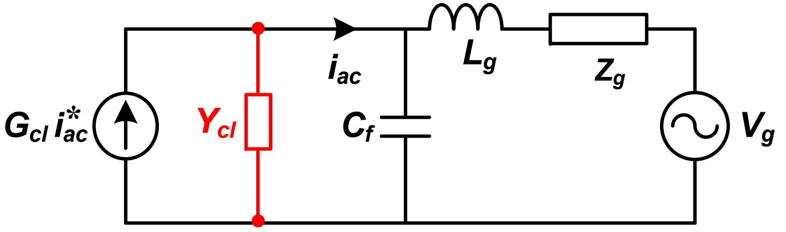
Harmonic Stability - Definitions and Scope

(Inter-) harmonic oscillations induced by control interactions



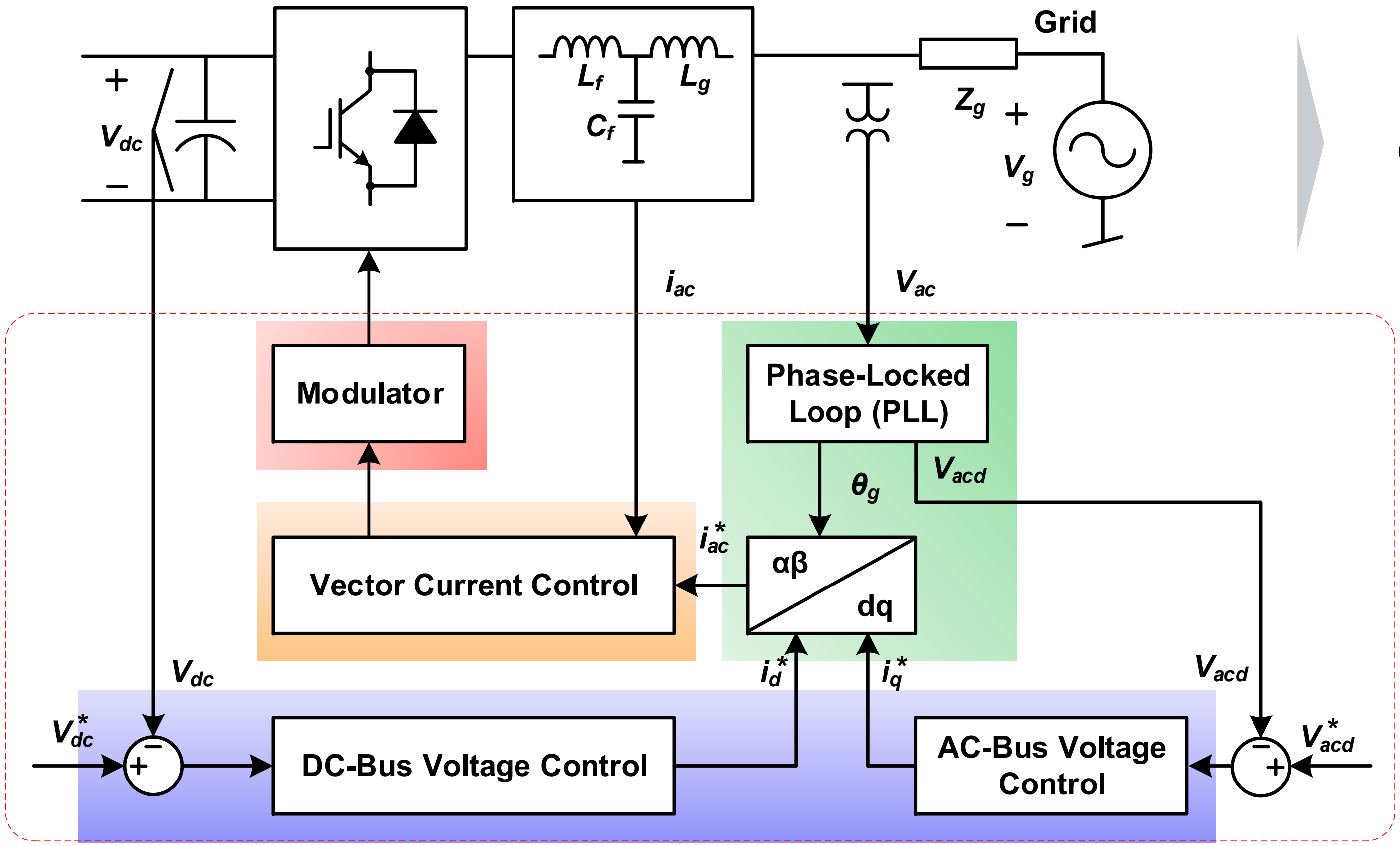


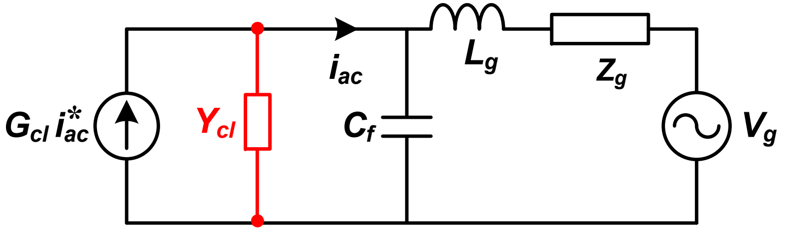
- Re{Y_{cl}}>0: stable, yet underdamped
  Abnormal harmonics
- Re{Y_{cl}}=0: critically stable, zero-damped
  Resonance
- Re{Y_{cl}}<0: unstable, negatively-damped
  Instability

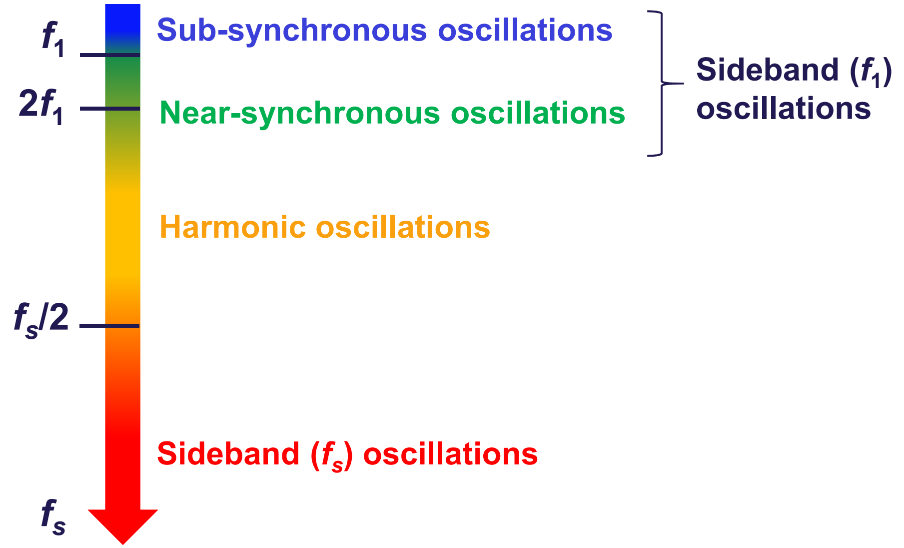
[1] X. Wang and F. Blaabjerg, “Harmonic stability in power electronic based power systems: concept, modeling, and analysis,” IEEE Trans. Smart Grid, Early Access, 2018.

Harmonic Stability - Definitions and Scope

Sideband oscillations and harmonic oscillations[1]





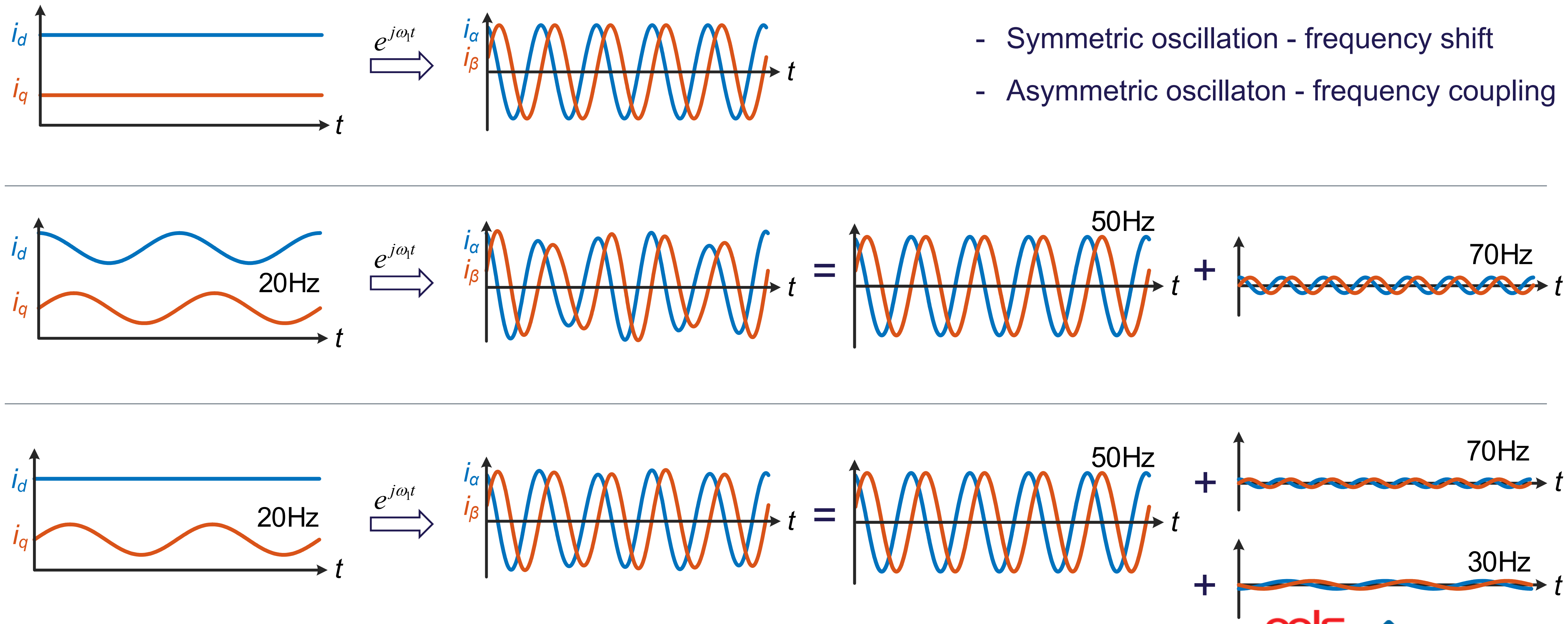


f_1: Grid fundamental frequency, f_s: Switching frequency

Harmonic Stability - Mechanism

Sideband oscillations - frequency coupling nature of DQ-transformation

- Symmetric oscillation - frequency shift
- Asymmetric oscillaton - frequency coupling



Harmonic Stability - Mechanism

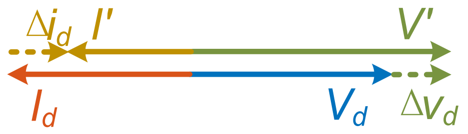
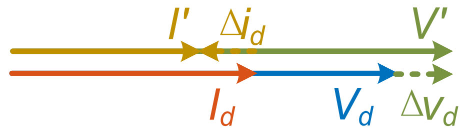
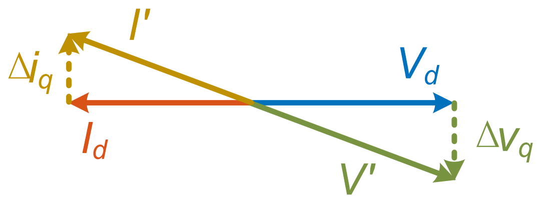
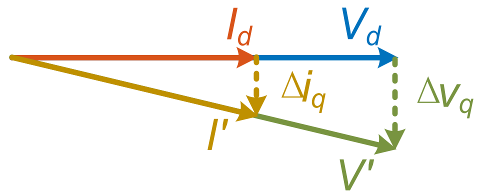
Sideband oscillations - asymmetric control system dynamics

- **Asymmetrical control system dynamics lead to frequency-coupling oscillations!**

	***DQ*-decoupled**	***DQ*-coupled**
Symmetric dynamics	$\begin{matrix} d \Rightarrow \\ q \Rightarrow \end{matrix} \begin{bmatrix} A(s) & 0 \\ 0 & A(s) \end{bmatrix} \begin{matrix} \Rightarrow d \\ \Rightarrow q \end{matrix}$ Symmetric In Symmetric Out	$\begin{matrix} d \Rightarrow \\ q \Rightarrow \end{matrix} \begin{bmatrix} A(s) & B(s) \\ -B(s) & A(s) \end{bmatrix} \begin{matrix} \Rightarrow d \\ \Rightarrow q \end{matrix}$ Symmetric In Symmetric Out
Asymmetric dynamics	$\begin{matrix} d \Rightarrow \\ q \Rightarrow \end{matrix} \begin{bmatrix} A(s) & 0 \\ 0 & D(s) \end{bmatrix} \begin{matrix} \Rightarrow d \\ \Rightarrow q \end{matrix}$ Symmetric In Asymmetric Out	$\begin{matrix} d \Rightarrow \\ q \Rightarrow \end{matrix} \begin{bmatrix} A(s) & B(s) \\ C(s) & D(s) \end{bmatrix} \begin{matrix} \Rightarrow d \\ \Rightarrow q \end{matrix}$ Symmetric In Asymmetric Out

Harmonic Stability - Mechanism

Negative damping at the fundamental frequency (dc in the *dq*-frame)

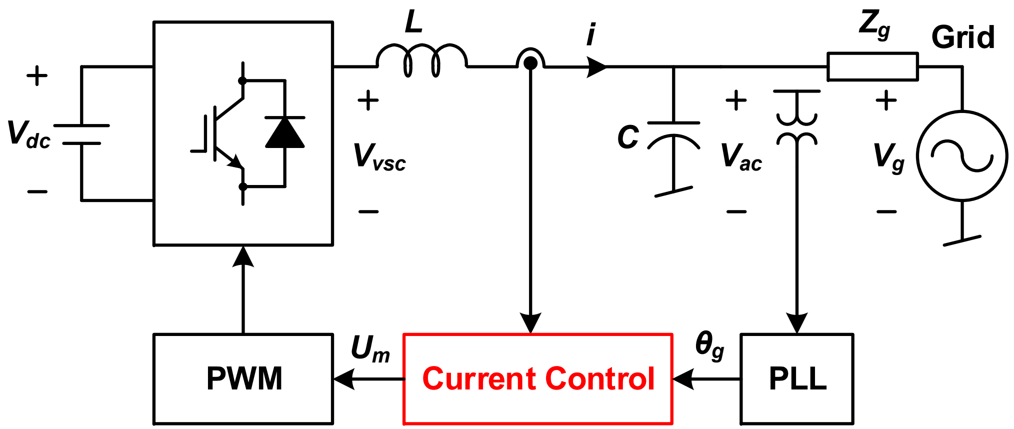
	Inverter	Rectifier
Constant power d-d resistance	 $R_{dd}=\dfrac{\Delta v_d}{\Delta i_d}>0$	 $R_{dd}=\dfrac{\Delta v_d}{\Delta i_d}<0$
Unity power factor q-q resistance	 $R_{qq}=\dfrac{\Delta v_q}{\Delta i_q}<0$	 $R_{qq}=\dfrac{\Delta v_q}{\Delta i_q}>0$

- How about the impedance behavior with **ac perturbations? Frequency range** of negative damping?

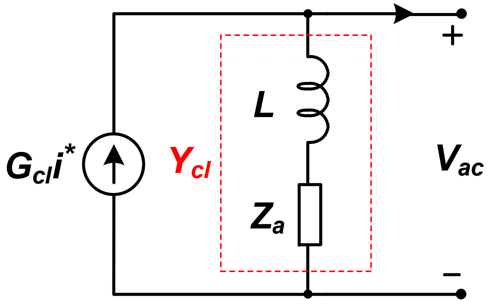
B. Wen, D. Boroyevich, R. Burgos, P. Mattavelli, and Z. Shen, "Analysis of D-Q small-signal impedance of grid-tied inverters," IEEE Trans. Power Electron., vol. 31, no. 1, pp. 675-687, Jan. 2016.

Harmonic Stability - Mechanism

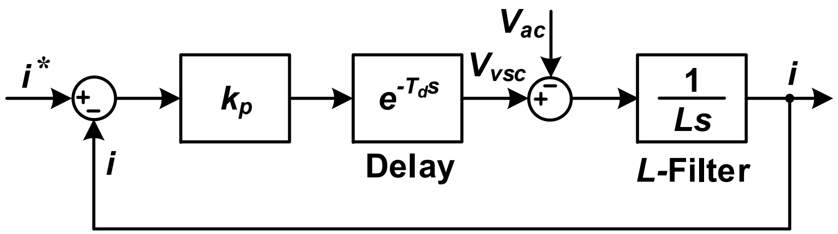
Negative damping with vector current control



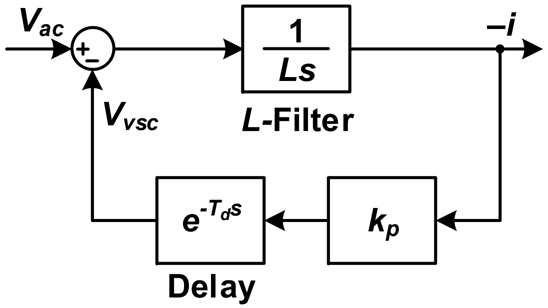
Voltage-Source Converter (VSC) with vector current control



Impedance equivalent



Closed-loop current control with proportional controller



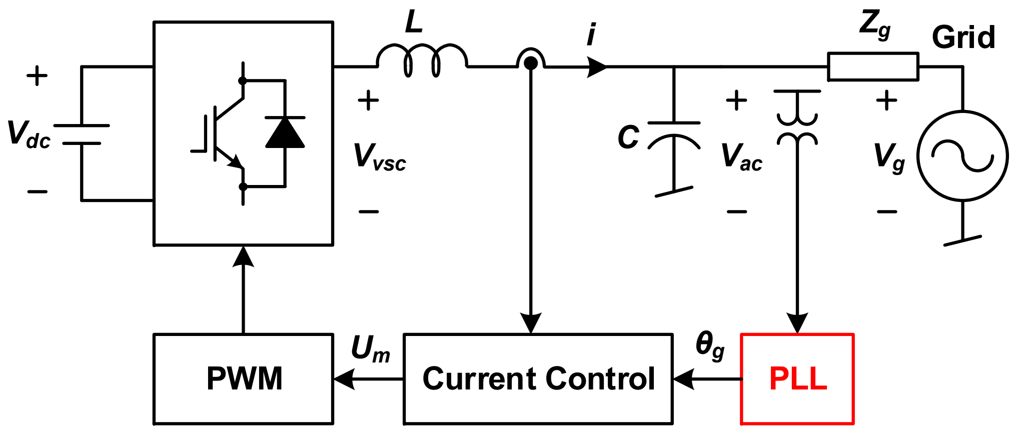
Current control output admittance $Y_{cl}(s)$

$$Z_a(s) = k_p e^{-T_d s}$$

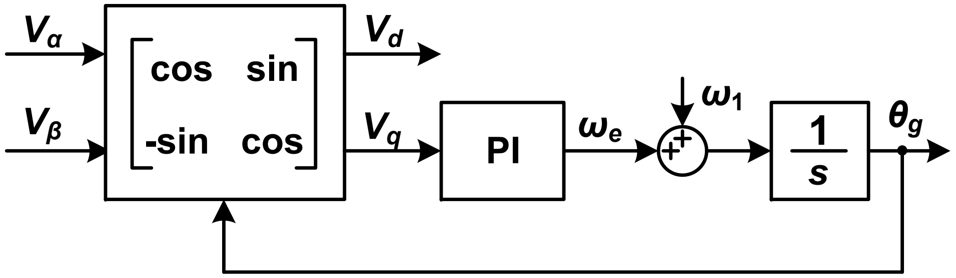
$$Z_a(j\omega) = k_p\left[\cos(\omega T_d) - j\sin(\omega T_d)\right]$$

Harmonic Stability - Mechanism

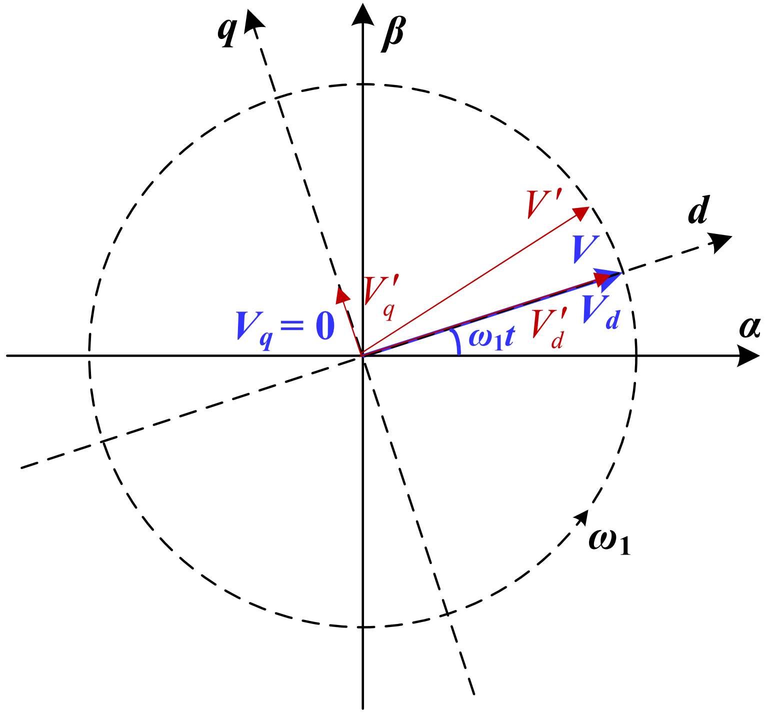
Negative damping with PLL



Voltage-Source Converter (VSC) with vector current control



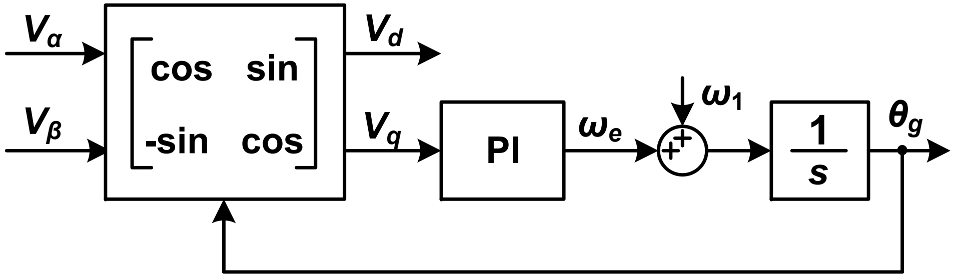
DQ-frame PLL

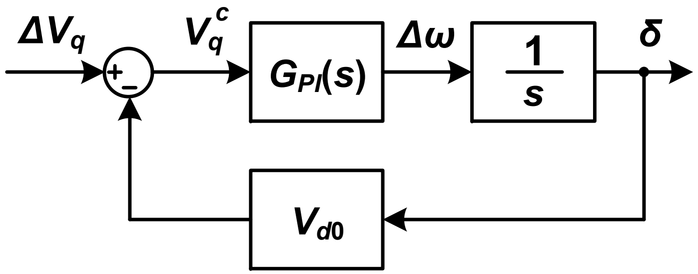


Basic principle of PLL

Harmonic Stability - Mechanism

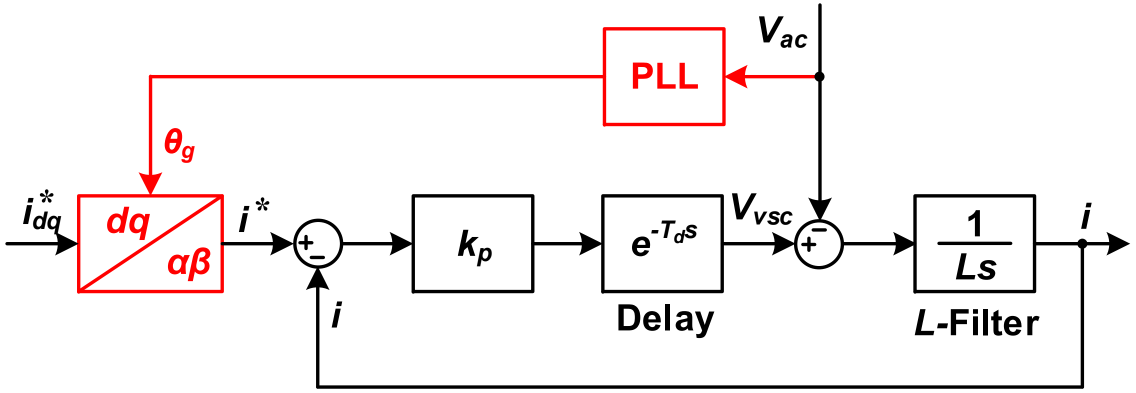
Negative damping with PLL

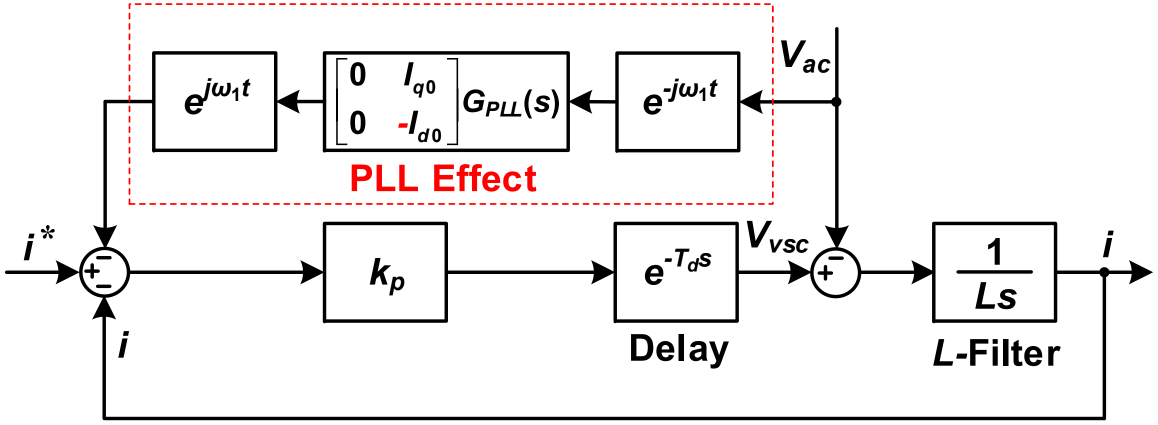




Small-signal model of PLL

$$\delta = G_{PLL}(s)\Delta V_q,\ \ G_{PLL}(s) = \frac{G_{PI}(s)}{s + G_{PI}(s)V_{d0}}$$





Closed-loop current control with PLL effect

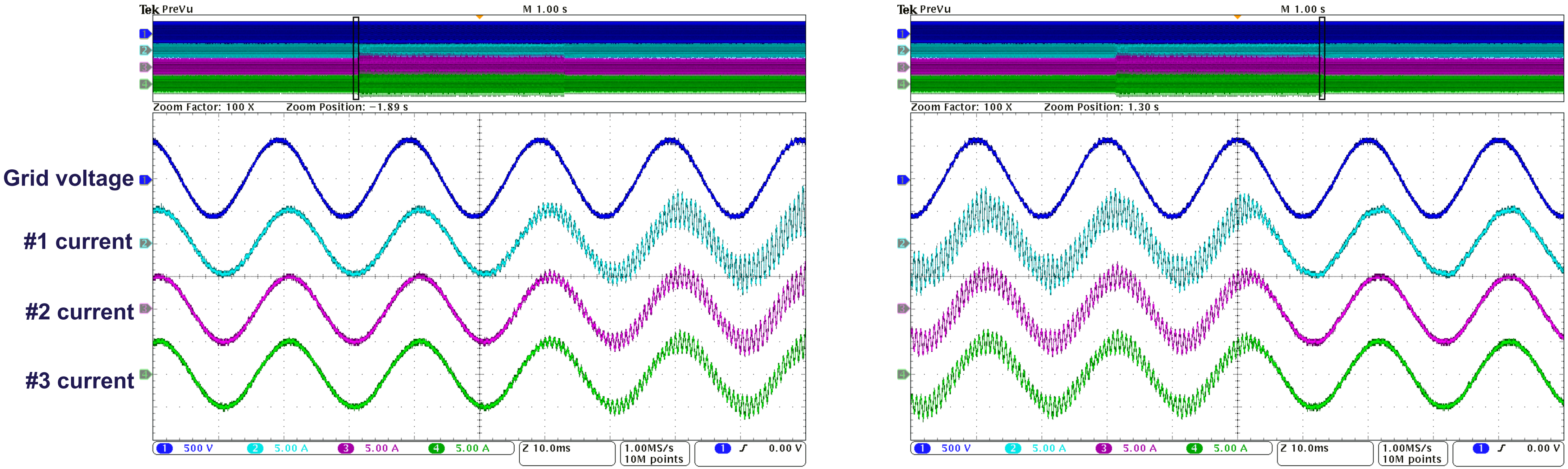
Lab Tests @ AAU

AC (400 V) Distribution Grid

- 6-paralleled three-phase grid converters (50 kVA in total) with LCL-filters
- Rapid control prototyping platform with DS1007 dSPACE systems
- Scalable and reconfigurable for different operating scenarios

Three-Converter Interactions

VCC with LCL-Filters



Three-Converter Interactions

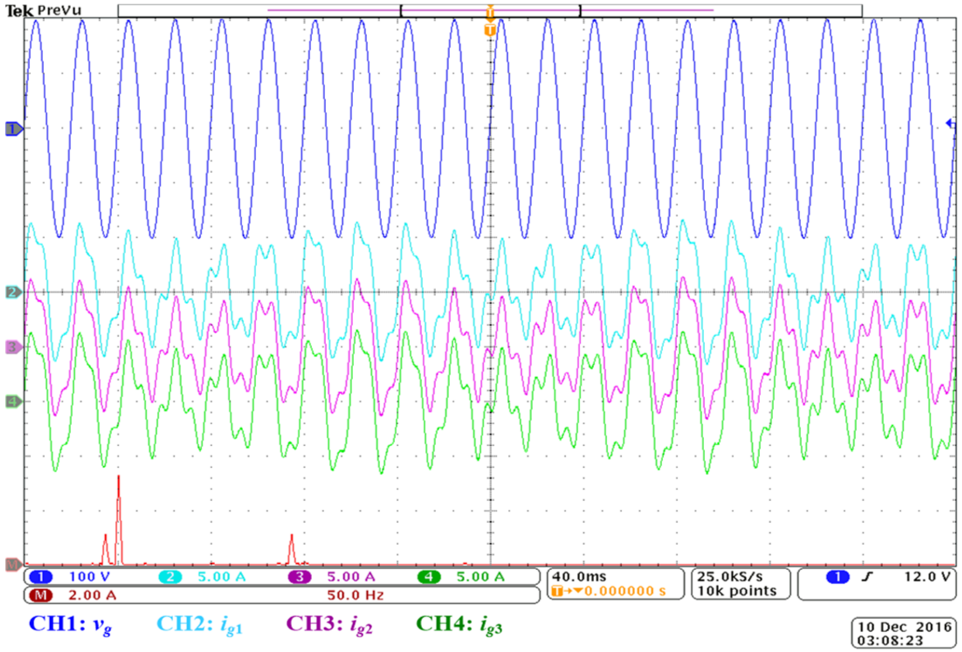
PLL with different Short-Circuit Ratio (SCR) of the grid

Grid voltage

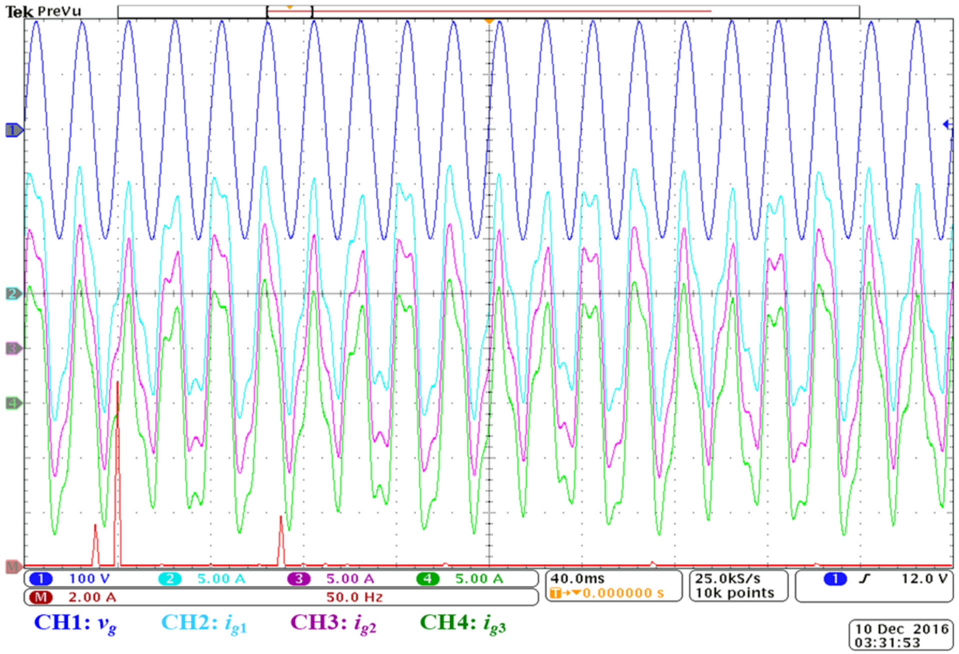
#1 current

#2 current

#3 current



SCR = 8.4



SCR = 4.2

Real-Life Challenges

Control interactions of multiple converters

VSC-HVDC + Offshore Wind

Filter resonance in the offshore HVDC converter station

Electrification of railways

Locomotives is out of control because of abnormal harmonics

©CSG

MMC-HVDC Transmission

Transformer resonance with current control of MMC

Harmonic Stability - Modeling of Power Converters

Small-signal models for harmonic analysis and control design

1970
Persson [7] - thyristor HVDC
Frequency response analysis
Describing Function with single sinusoidal inputs

For control design

1985
Sakui and Fujita [8] - thyristor rectifier, Switching Function model w/o firing angle variation considered

For harmonic analysis

1986
Ngo [9] - PWM converter
State-Space Averaging with Park transformation
DQ-frame linearized model

For control design

1989
Larson, Baker, McIver [10] – thyristor HVDC, numerical simulations derived Harmonic Cross-Coupling Matrix

For harmonic/control analysis

1997
Mattavelli, Verghese, Stankovic [11] - thyristor FACTS devices
Dynamic Phasor with time-variant Fourier coefficients

For control design

2000
Mollerstedt [12] - locomotive inverter, Harmonic State-Space (HSS) modelling, Harmonic Transfer Matrix

For harmonic stability analysis

2003
Rico, Madrigal, Acha [13] - STATCOM with phase angle control, Extended Harmonic Domain (EHD)

For harmonic analysis

2007
Harnefors [14] - DQ-frame model with the phase variation;
Wen, Boroyevich, et, al [15], 2016
Rygg, Molinas, Zhang, [16], 2016

For control design

2014
Cespedes and Sun [17] - stability effect of PLL on PWM converter
Harmonic Balance, Multi-Input Describing Functions

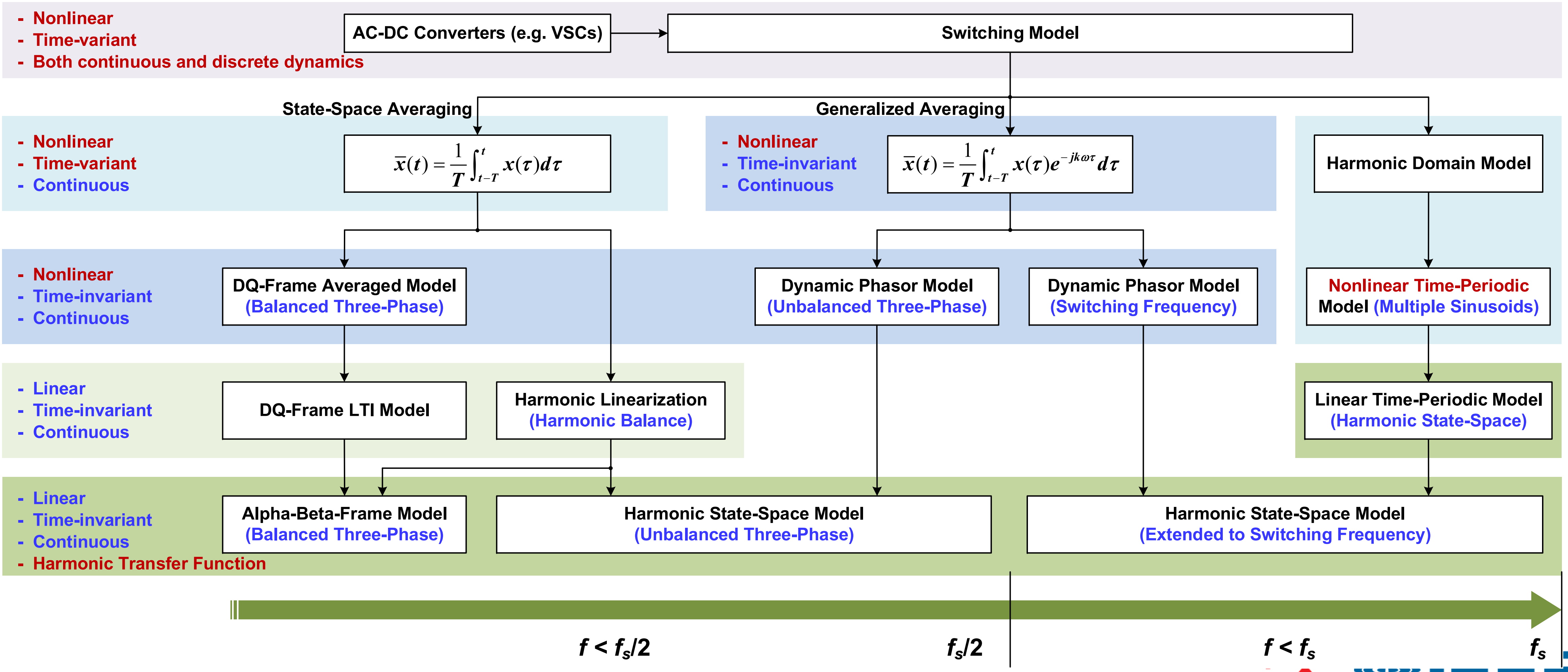
For control design

2016
Wang, Harnefors, Blaabjerg [18] - Unified Impedance Model from *dq*-frame to *αβ*-frame, 2nd-order Harmonic Transfer Matrix

For control design

Harmonic Stability - Modeling of Power Converters

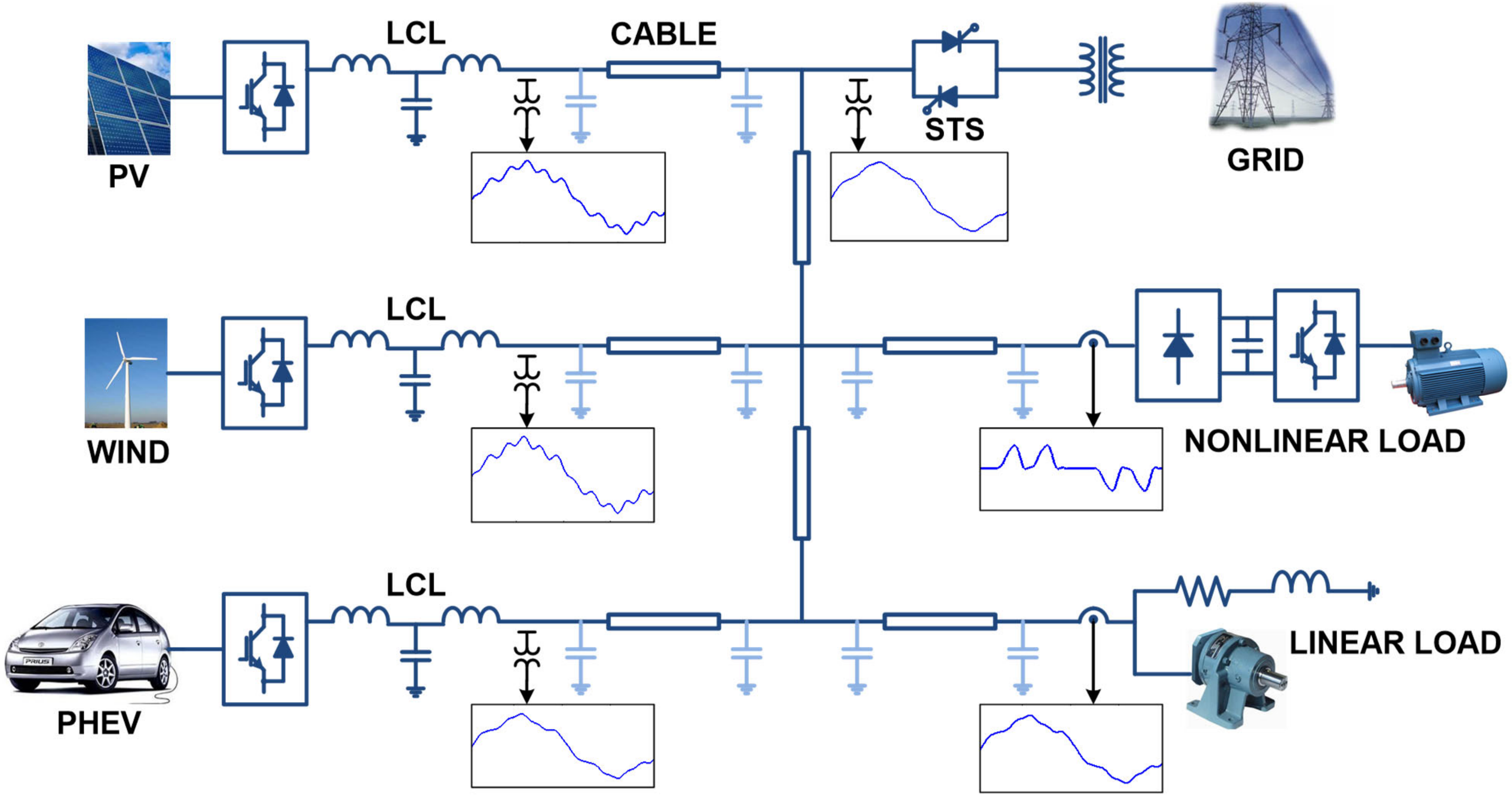
Unified multiple-frequency small-signal model



Future Power Electronic Based Power Systems

Multiple-timescale control interactions with cross-frequency coupling oscillations

- Resonance propagation in renewable clusters, power plants, and power grids
- Abnormal harmonics due to grid-converter interactions
- Cross-frequency coupling and oscillations in multiple converters



Harmonic Stability - System Stability Analysis

Modal analysis based on eigenvalues and eigenvectors (time-domain)

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{u})$$
$$\mathbf{y} = \mathbf{g}(\mathbf{x}, \mathbf{u})$$

$$\dot{\mathbf{x}}_0 = \mathbf{f}(\mathbf{x}_0, \mathbf{u}_0) = \mathbf{0}$$

$$\Delta\dot{\mathbf{x}} = \mathbf{A}\Delta\mathbf{x} + \mathbf{B}\Delta\mathbf{u}$$
$$\Delta\mathbf{y} = \mathbf{C}\Delta\mathbf{x} + \mathbf{D}\Delta\mathbf{u}$$

$$\mathbf{A} = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \cdots & \frac{\partial f_1}{\partial x_n} \\ \vdots & \cdots & \vdots \\ \frac{\partial f_n}{\partial x_1} & \cdots & \frac{\partial f_n}{\partial x_n} \end{bmatrix}$$

$$\det(\mathbf{A} - \lambda\mathbf{I}) = \mathbf{0}$$

- **Eigenvalues λ_i**

  $$\lambda_i = \sigma_i + j\omega_i$$

- **Right eigenvector**

  $$\mathbf{A}\phi_i = \lambda_i\phi_i$$

- **Left eigenvector**

  $$\psi_i\mathbf{A} = \psi_i\lambda_i$$

Pros

- Global overview of oscillation modes
- Controller parameter sensitivity analysis
- Participation factor analysis

Cons

- High computational requirement
- Wide-timescale dynamics of converters
- Very high-order state matrix (A)

Harmonic Stability - System Stability Analysis

Component Connection Method (CCM) - modular, scalable and simple

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{u})$$
$$\mathbf{y} = \mathbf{g}(\mathbf{x}, \mathbf{u})$$

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{a})$$
$$\mathbf{b} = \mathbf{g}(\mathbf{x}, \mathbf{a})$$

Composite component model

$$\Delta\dot{\mathbf{x}} = \mathbf{F}\Delta\mathbf{x} + \mathbf{H}\Delta\mathbf{a}$$
$$\Delta\mathbf{b} = \mathbf{J}\Delta\mathbf{x} + \mathbf{K}\Delta\mathbf{a}$$

Diagonal matrices F, H, J, K

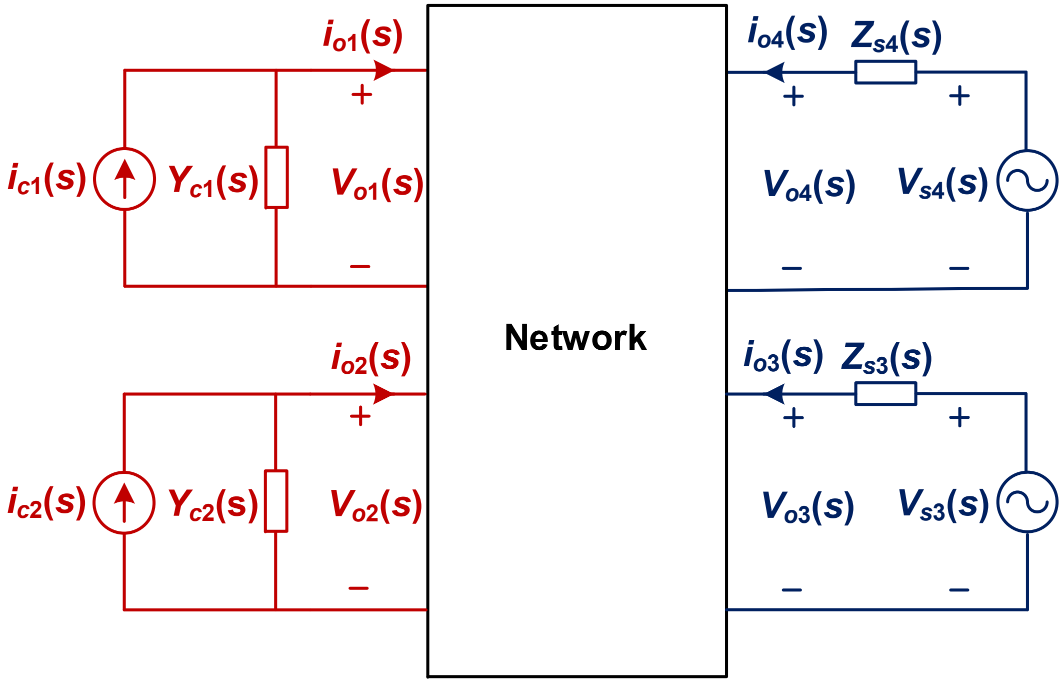
$$\Delta\mathbf{a} = \mathbf{L}_{11}\Delta\mathbf{b} + \mathbf{L12}\Delta\mathbf{u}$$
$$\Delta\mathbf{y} = \mathbf{L21}\Delta\mathbf{b} + \mathbf{L22}\Delta\mathbf{u}$$

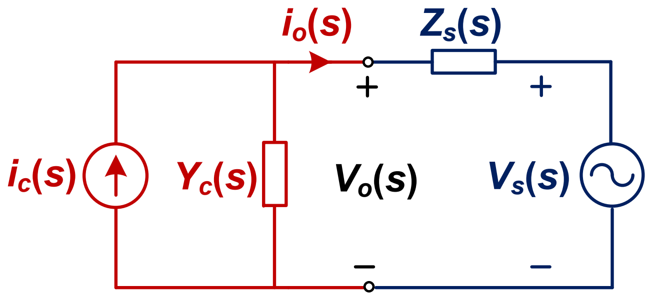
Sparse matrices Lij
Linear algebra

$$\Delta\dot{\mathbf{x}} = \mathbf{A}\Delta\mathbf{x} + \mathbf{B}\Delta\mathbf{u}$$
$$\Delta\mathbf{b} = \mathbf{C}\Delta\mathbf{x} + \mathbf{D}\Delta\mathbf{u}$$

Harmonic Stability - System Stability Analysis

Impedance-based analysis (frequency-domain CCM)





Pros and Cons

- Non-parametric (black-box)
- Local stability prediction
- Input-output, no state information

Harmonic Stability - System Stability Analysis

Comparison of different system stability analysis methods

Conceptual Review of System Stability Analysis Tools

Functionalities	Basic state-space representation	Component-connection method	Impedance-based analysis
Identification of dynamic modes	+	+	–
Impact (participation factor) of state variables	+	+	–
Input-output dynamics	+	+	+
Design-oriented analysis	Moderate	+	+
Black-box modeling (frequency-scanning)	–	+	+
Modularity and scalability	Low	High	High

- Impedance-based analysis: a transfer function approach of CCM, physical insight
- Presence of right half-plane (RHP) zeros/poles imposes constraints on the system partitioning and aggregation in the impedance-based analysis
- Prior knowledge of the system parameters and control structures required for CCM - challenge for multi-vendor power electronics based systems

Conclusions

- **Harmonic stability is a breed of small-signal stability featuring waveform distortions**
  - Either harmonic or inter-harmonic interactions in power-electronic-based power systems
  - Frequency-coupling oscillations both above and below the fundamental frequency
  - Differing from passive electrical resonances in its dependence on converter control dynamics

- **Computationally-efficient stability analysis tools are demanded**
  - Adequate linearized models for capturing frequency-coupling dynamics of converters are missing
  - Large-scale power-electronic-based power systems are of ultra-high order dynamics
  - There is lack of efficient time-domain simulation tools for mapping wide-band oscillations

- **Control methods for stabilizing power electronic based power systems**
  - Stabilization techniques for converters in low-inertia and low-SCR grids are needed

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THANK YOU FOR YOUR ATTENTION

QUESTIONS?

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