IEEE ENERGY CONVERSION CONGRESS & EXPO | PITTSBURGH, PA, USA | SEPTEMBER 14-18, 2014

Harmonic Stability in Renewable Energy Systems: An Overview

Frede Blaabjerg and Xiongfei Wang
Department of Energy Technology
Aalborg University, Denmark
fbl@et.aau.dk, xwa@et.aau.dk

AALBORG UNIVERSITY
DENMARK

Outline

AALBORG UNIVERSITET

- **Introduction**
  - State-of-the-art
  - Harmonic stability concept
- **Modeling and Analysis of Harmonic Stability**
  - Modeling of power system components
  - Harmonic stability analysis
- **Mitigation of Harmonic Instability**
  - Passive damping of filters
  - Active damper
- **Conclusions**

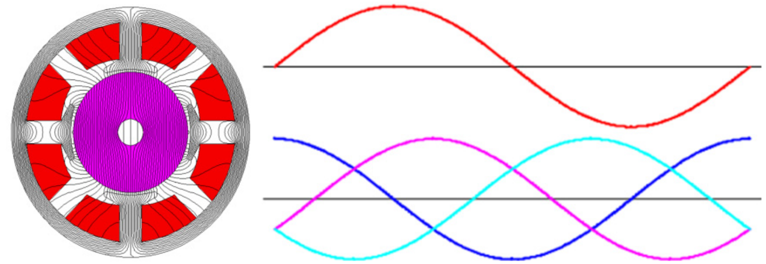
State-of-the-Art

Power Electronics Enabling Sustainable and Flexible Power Grids

State-of-the-Art

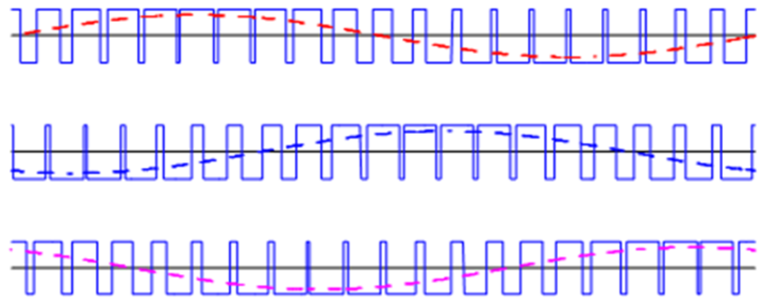
Wideband harmonics will be aggravated

Traditional Generator
- Prime Mover — 0.1Hz
- Excitation Control — 1Hz

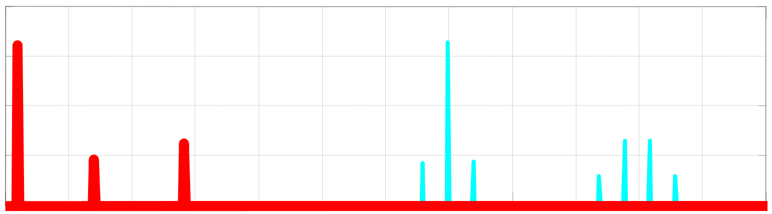


Traditional Generator Output Voltage

Large Wind Generator
- Turbine P & ω Control — 0.1Hz
- Grid Q &V Control
  DC-Link Control — 10Hz
- Grid Synchronization — 100Hz
- Current Control — 500Hz
- Semiconductor Switching — 2500Hz



Wind Generator Output Voltage



Harmonic Spectrum

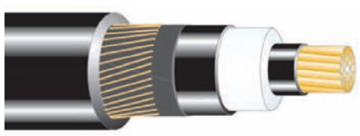
State-of-the-Art

AALBORG UNIVERSITET

Wideband controller interactions of converters – harmonic stability

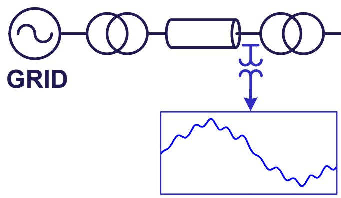
Power Converter

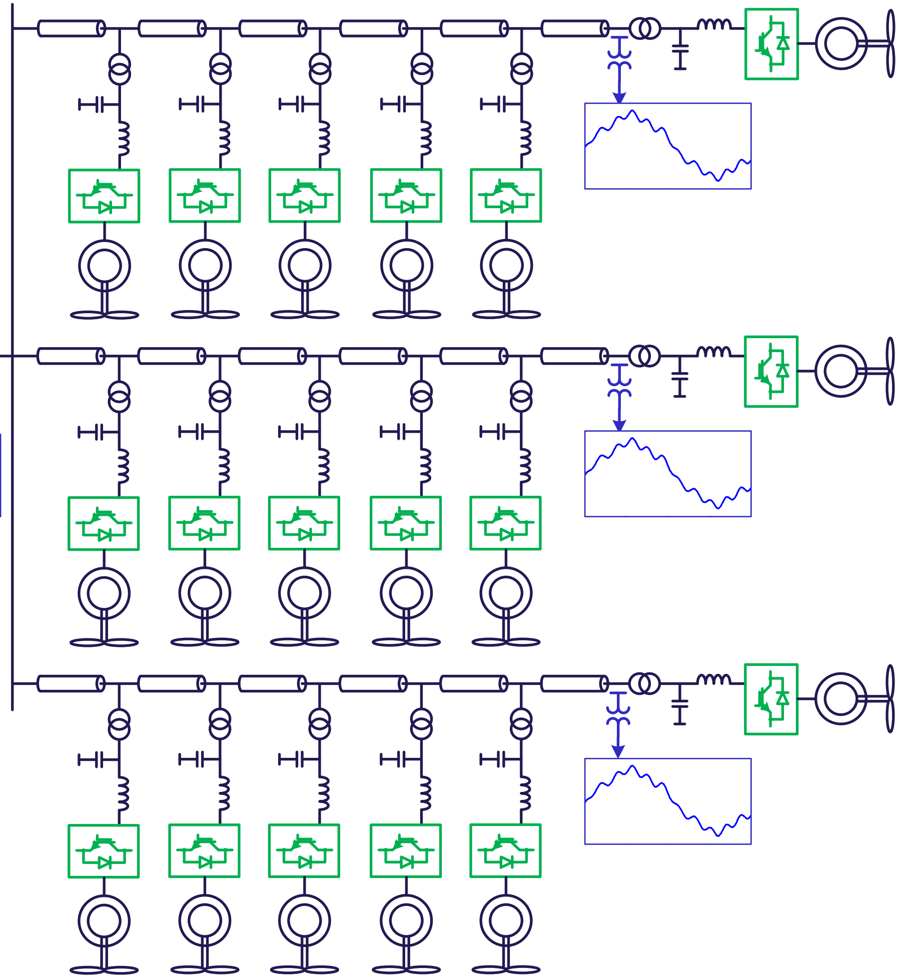
LCL Filter



Power Cable

Power Transformer



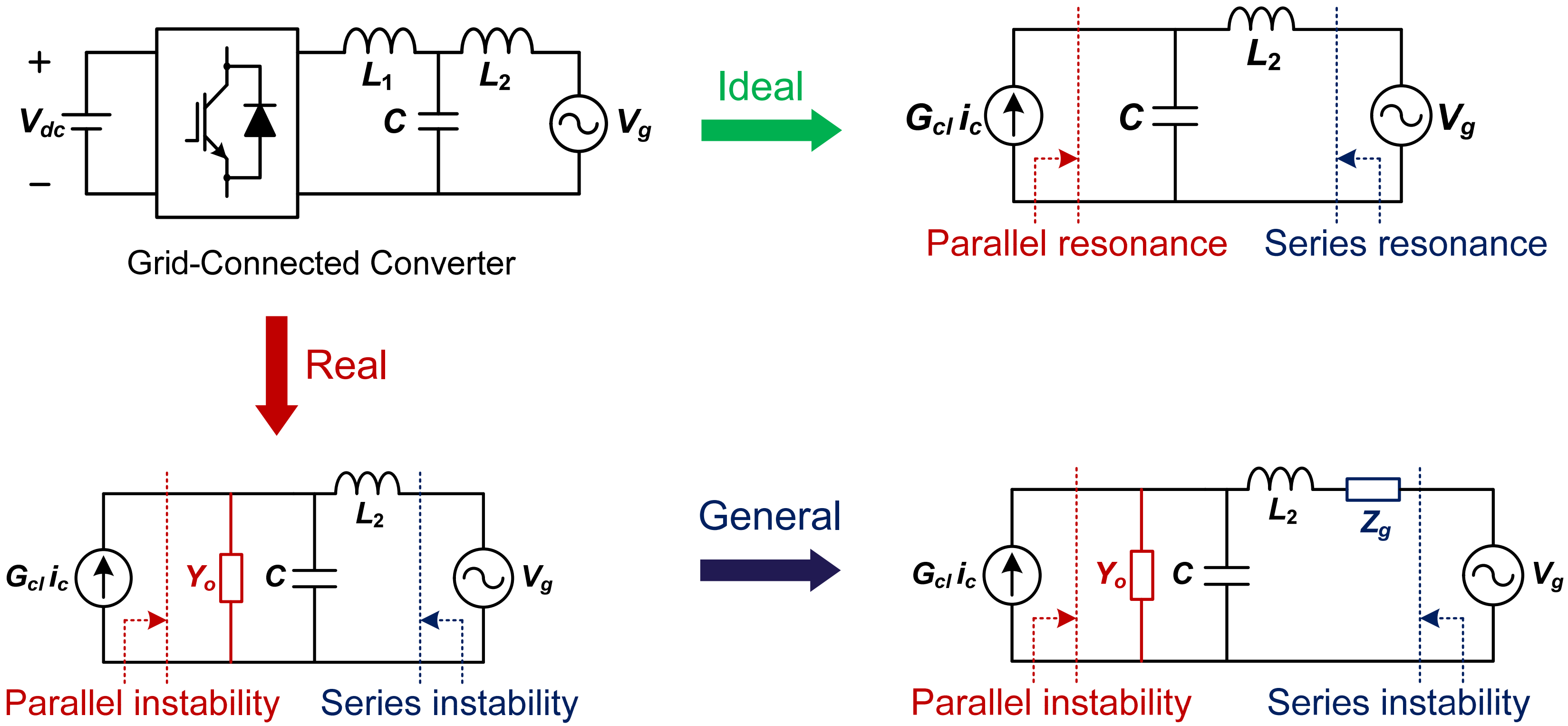


Wind Power Plant

Harmonic Stability Concept

AALBORG UNIVERSITET

Harmonic Instability v.s. Harmonic Resonance



- **Re{Y_o}>0, stable but may be still resonate**
- **Re{Y_o}=0, critically stable (resonance)**
- **Re{Y_o}<0, unstable with amplified resonance**

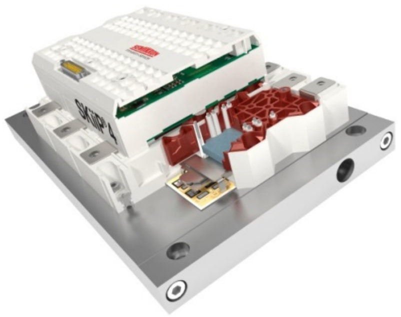
Re{Z_g} + Re{Y_o} ?

- **Modeling and Analysis of Harmonic Stability**
  - Modeling of power system components
  - Harmonic stability analysis

Modeling of Power System Components

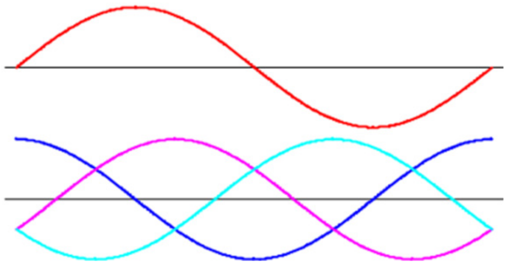
AALBORG UNIVERSITET

Traditionally Sine Wave → Currently Square Wave

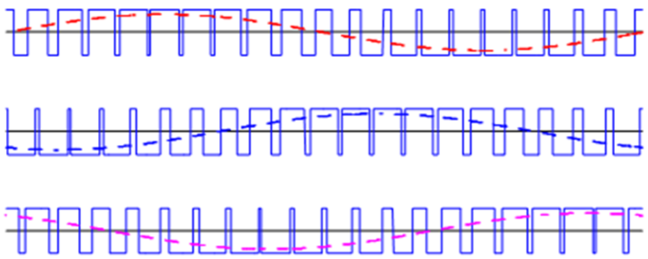


Power Electronics

Passive Filters

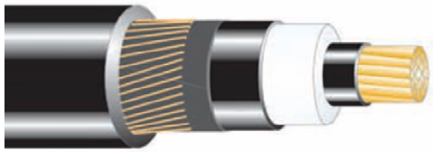


Sinusoidal



Square

Transformers

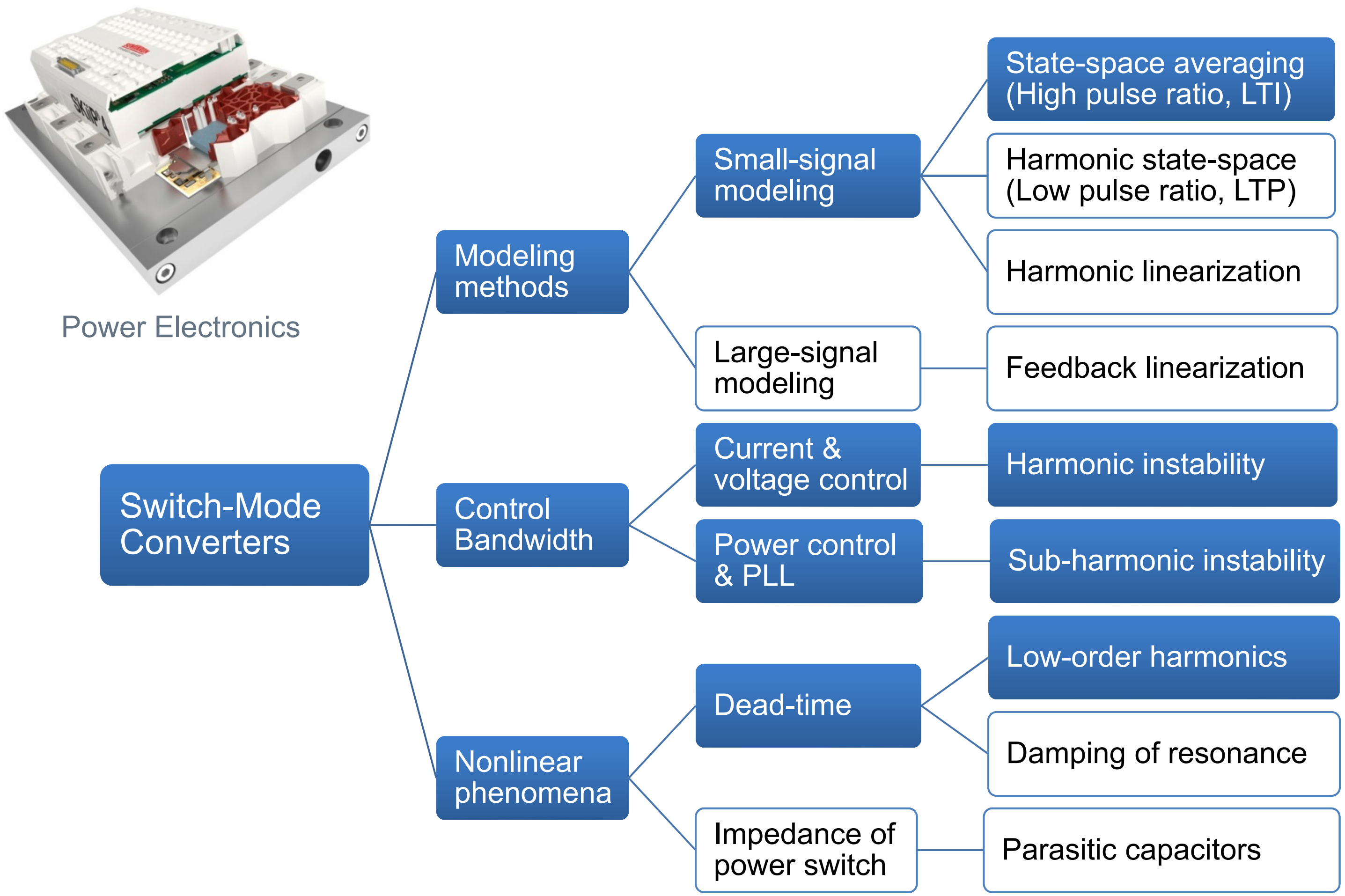


Power Lines & Cables

Modeling of Power System Components

AALBORG UNIVERSITET

Power Electronics Based Sources and Loads



Modeling of Power System Components

AALBORG UNIVERSITET

Small-Signal Modeling of Power Electronics Converters

Linearized model

Harmonic analysis

1. Switching funciton (1984)
2. Harmonic linearizing (1989)
   - simulation derived
3. Harmonic linearizing (2002)
   - analytically derived
4. Iterative admittance matrix (2004)

Control analysis

1. State space averaging (1977)
2. Generalized averaging (1991)
3. Dynamic phasor (1997)
4. Multifrequency averaging (1999)

→ Linear Time-Periodic (LTP)
Harmonic state space model

HARMONY

Modeling of Power System Components

Harmonic State Space Modeling of Converters

Periodical Signals

- *PWM*
- *Grid Voltage*
- *DC Voltage*
- …

→

Harmonic Domain (Steady State)

- Grid Voltage : $\sum_{n=-\infty}^{\infty} X_n e^{jn\omega t}$
- Switching : $\sum_{n=-\infty}^{\infty} S_n e^{jn\omega t}$
- Admittance : $\begin{bmatrix} \ddots & \\ & A_0 \end{bmatrix}$

→ e^{st} →

Harmonic State Space modeling (Transient Performance)

$$\dot{x}(t) = A(t)x(t) + B(t)u(t)$$
$$y(t) = C(t)x(t) + D(t)u(t)$$

$$sX = (A - N)X + BU$$
$$Y = CX + DU$$

↓ *Convolution* (Harmonic Domain)

- Out Current :

$$\mathrm{y(t)} = \sum_{n=-\infty}^{\infty} I_n e^{jn\omega t}$$

↓ *Convolution* (Harmonic State Space)

- Out Current :

$$y(t) = \sum_{n=-\infty}^{\infty} I_n e^{(s+jn\omega)t}$$

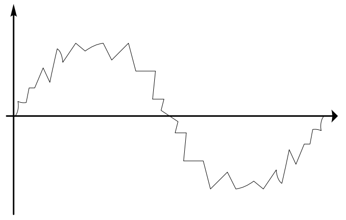
Modeling of Power System Components

AALBORG UNIVERSITET

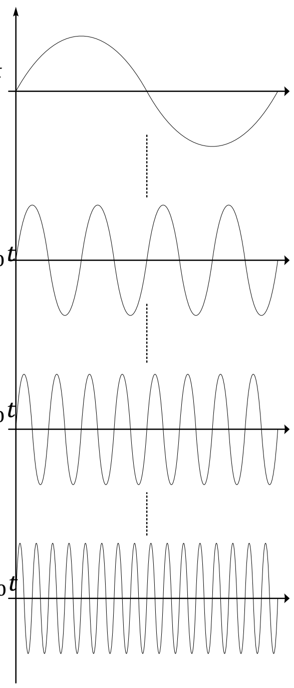
Harmonic Domain

$$f(t) = \sum_{k \in Z} Z_k e^{jk\omega_0 t}$$ *if, s = 0*, fixed periodic signal

$f(t)$ =



$Z_1 e^{\pm j\omega_0 t}$ + $Z_3 e^{\pm j3\omega_0 t}$ + $Z_5 e^{\pm j5\omega_0 t}$ + $Z_k e^{\pm jk\omega_0 t}$

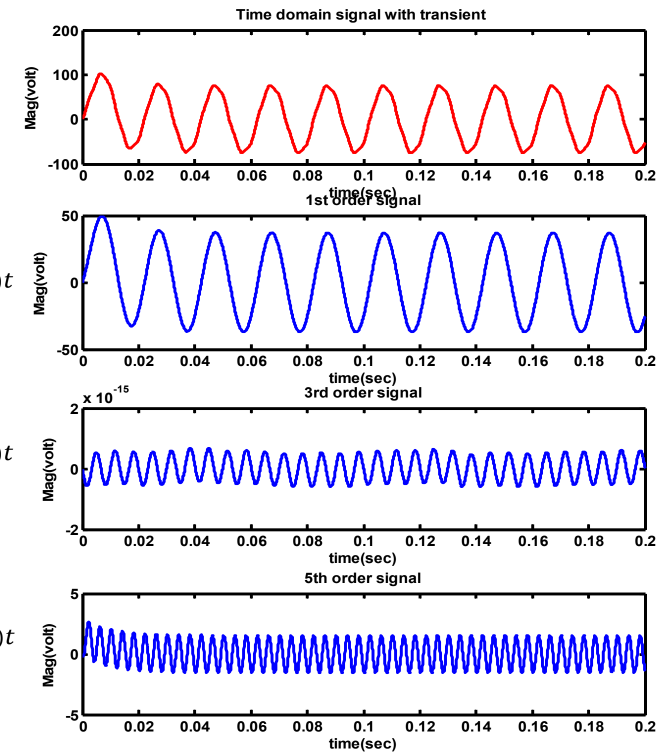


Harmonic State-Space

$$f(t) = e^{st} \sum_{k \in Z} Z_k e^{jk\omega_0 t}$$ *if, s ≠ 0*, dynamically time varying signals

$f(t)$ =

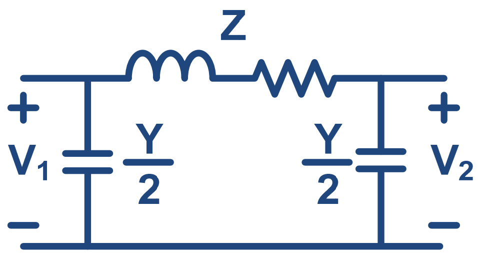
$Z_1 e^{(s \pm j\omega_0)t}$ + $Z_3 e^{(s \pm j3\omega_0)t}$ + $Z_5 e^{(s \pm j5\omega_0)t}$ ⋮ $Z_k e^{(s \pm jk\omega_0)t}$



Modeling of Power System Components

Power Lines and Cables

- **Lumped parameter – Π model (Γ model, T model)**

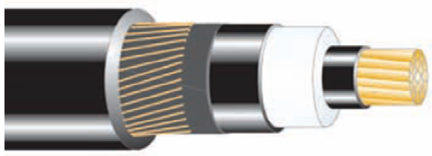


Long line correction →

$$Z_c = Z\frac{\sinh(\gamma\ell)}{\gamma\ell}$$

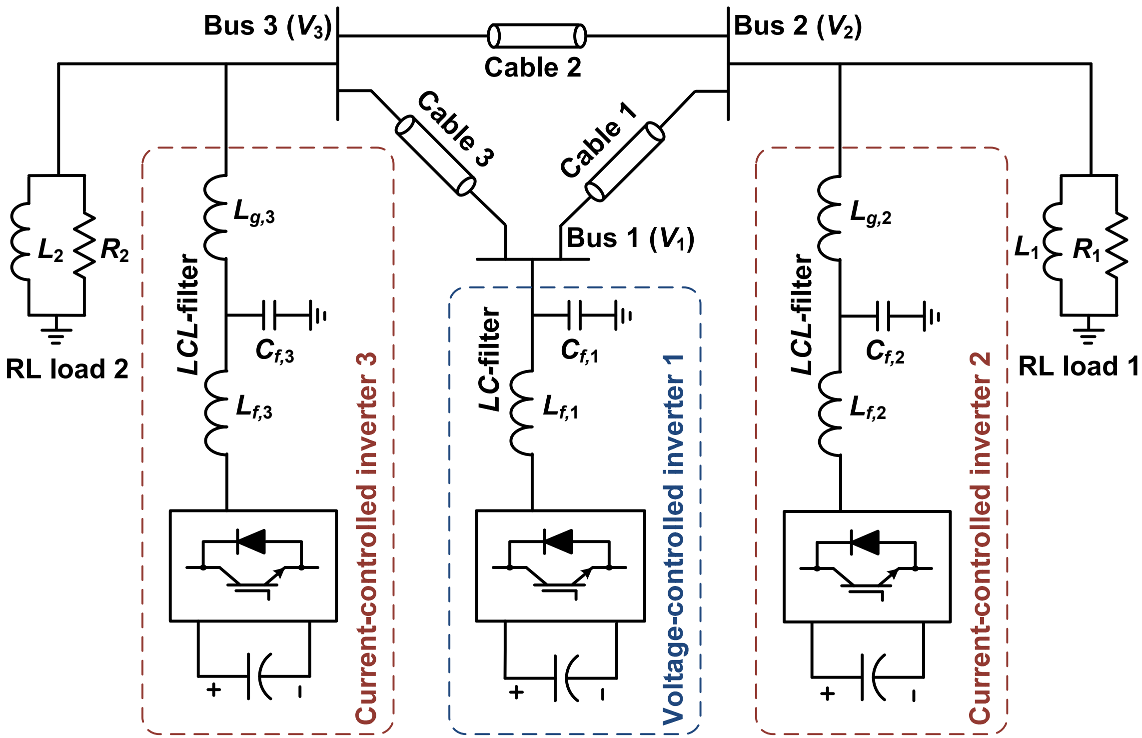
$$Y_c = Y\frac{\tanh(\gamma\ell/2)}{\gamma\ell/2}$$

- **Distributed parameter (traveling wave models)**
  - **Bergeron model – single frequency model**
    - only meaningful at the specified steady-state frequency
  - **Frequency dependent (mode) – distributed resistance**
    - only accurate for modeling balanced systems
  - **Frequency dependent (phase) – most accurate model**



Harmonic Stability Analysis

AC Power-Electronics-Based Power System



- Voltage-controlled inverter – system voltage and frequency regulation
- Current-controlled inverter – unity power factor operation
- Harmonic instability – current/voltage controller interactions of inverters

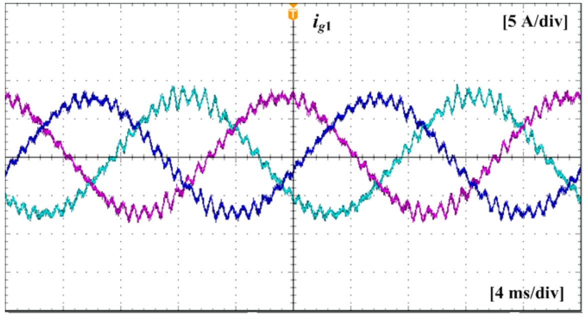
Harmonic Stability of Small-Scale System

AALBORG UNIVERSITET

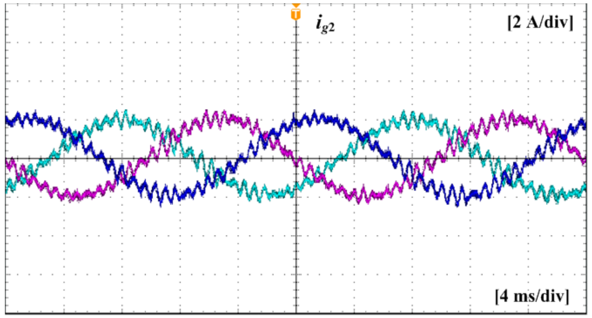
Impedance-Based Analysis and Control

Experimental results – unstable case

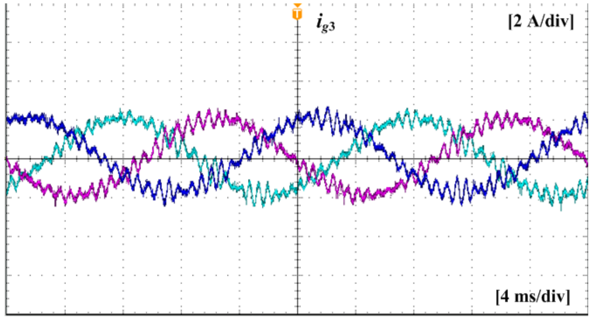
Inverter output currents



Voltage-controlled inverter 1

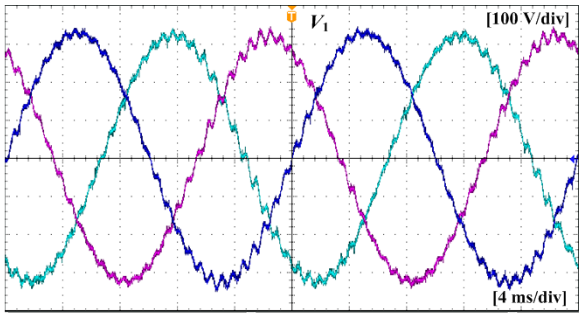


Current-controlled inverter 2

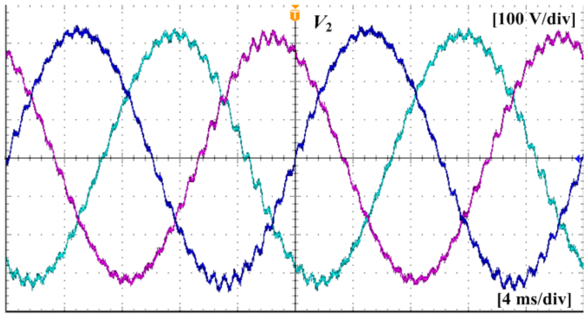


Current-controlled inverter 3

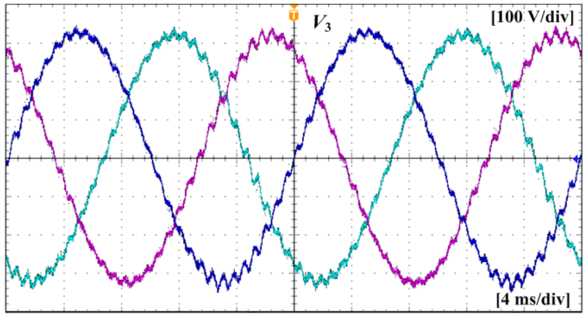
Bus voltages



Bus 1



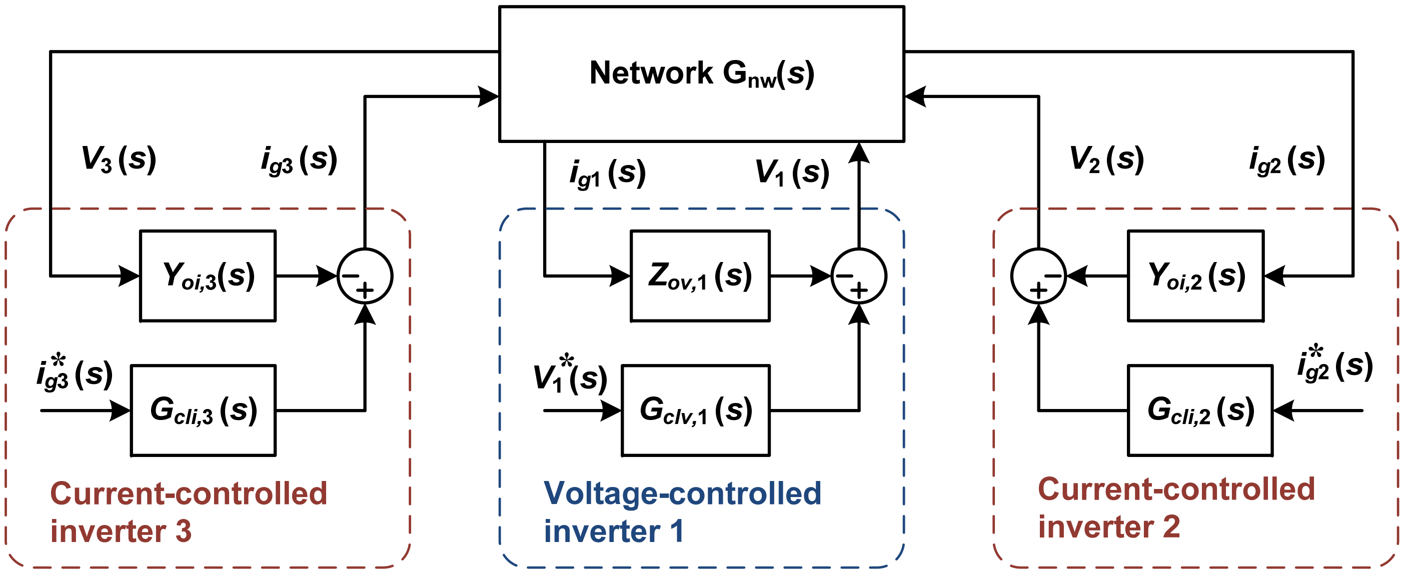
Bus 2



Bus 3

Harmonic Stability Analysis

Harmonic Stability Analysis Tools

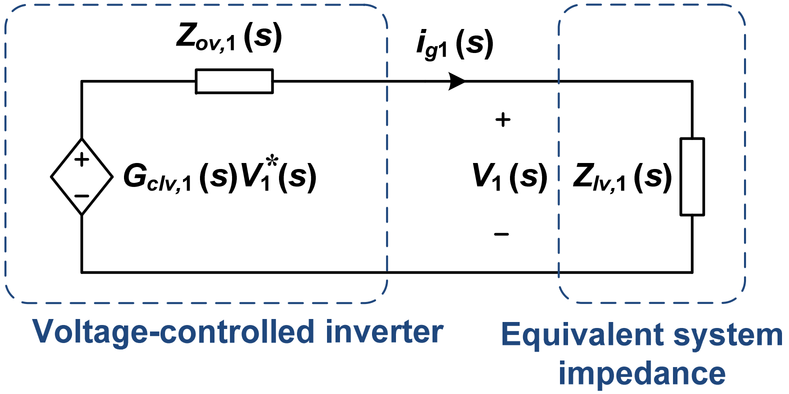


- **Component Connection Method (CCM) – state-space matrix and eigenvalues**
  - ✓ Generalized to multi-bus power system
- **Impedance-based analytical approach – frequency-domain analysis**
  - ✓ Balanced three-phase system – SISO transfer functions
  - ✓ Generalized Nyquist stability criterion is required for MIMO systems

Harmonic Stability Analysis

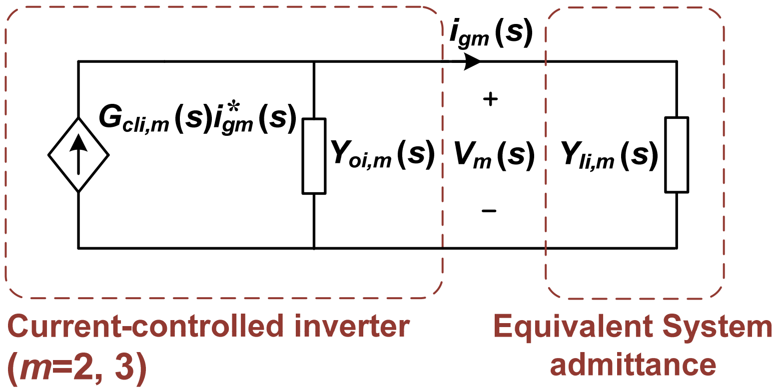
Impedance-Based Analysis and Control

- Identify the effect of each inverter by impedance-based modeling
- Minor-loop gain composed by the impedance ratio



$$V_1(s) = G_{clv,1}(s)V_1^*(s)\frac{1}{1+\underbrace{\frac{Z_{ov,1}(s)}{Z_{lv,1}(s)}}}$$

Minor-loop gain $T_{mv}(s)$



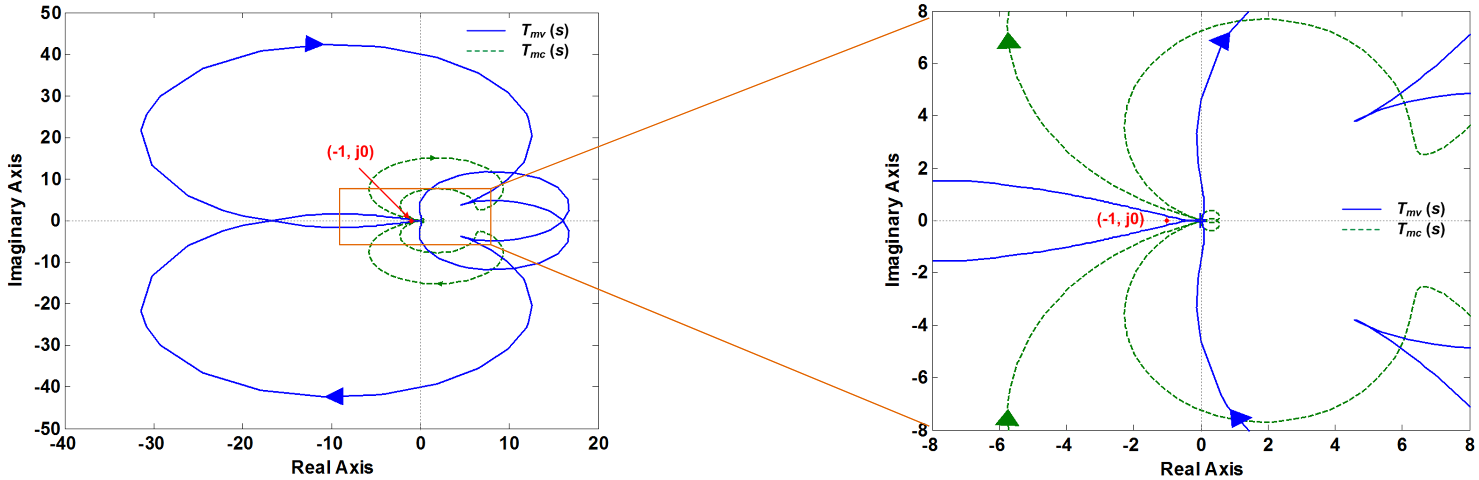
$$i_{gm}(s) = G_{cli,m}(s)i_{gm}^*(s)\frac{1}{1+\underbrace{\frac{Y_{oi,m}(s)}{Y_{li,m}(s)}}}$$

Minor-loop gain $T_{mc}(s)$

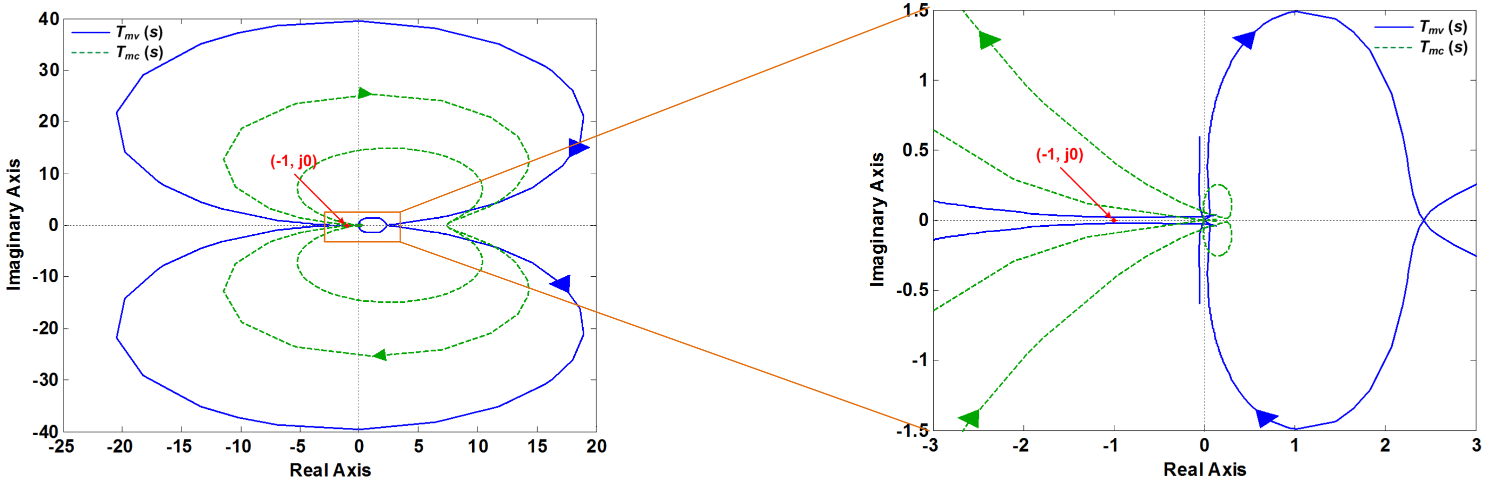
Harmonic Stability Analysis

Impedance-Based Analysis and Control

Unstable closed-loop response caused by voltage-controlled inverter



Stable closed-loop response with the reduced bandwidth of voltage-controlled inverter



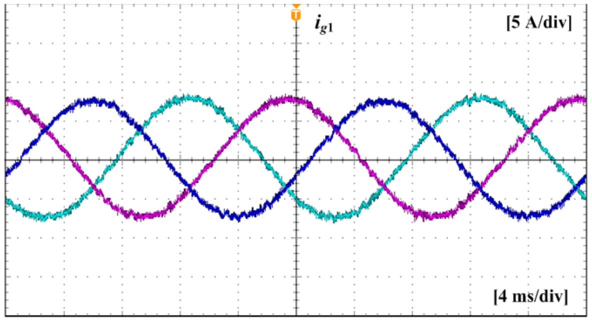
Harmonic Stability Analysis

AALBORG UNIVERSITET

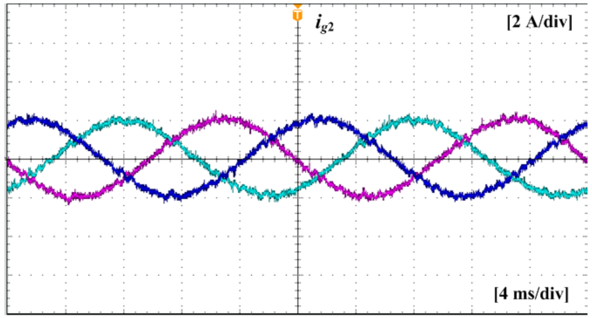
Impedance-Based Analysis and Control

Experimental results – stable case

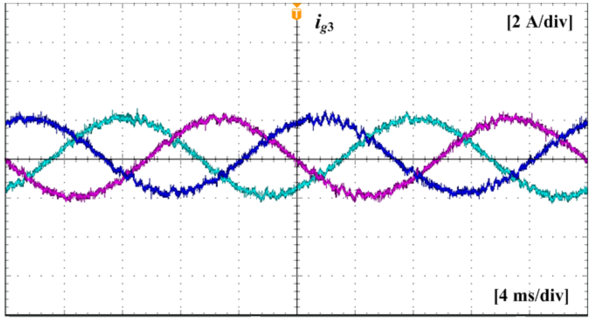
Inverter output currents



Voltage-controlled inverter 1

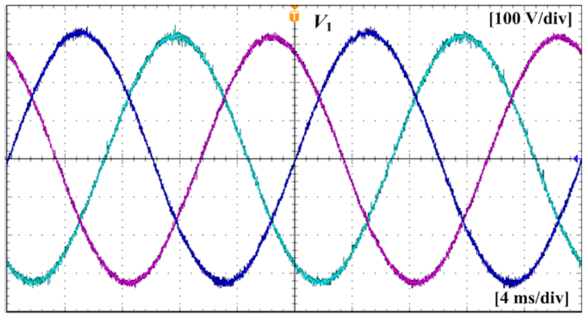


Current-controlled inverter 2

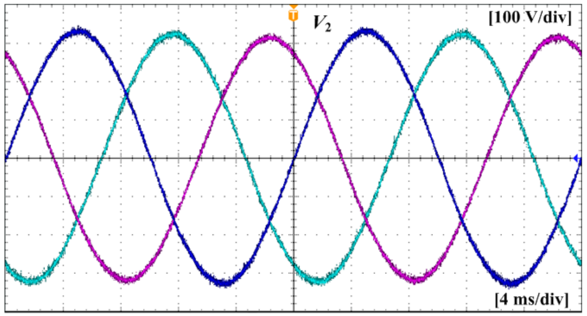


Current-controlled inverter 3

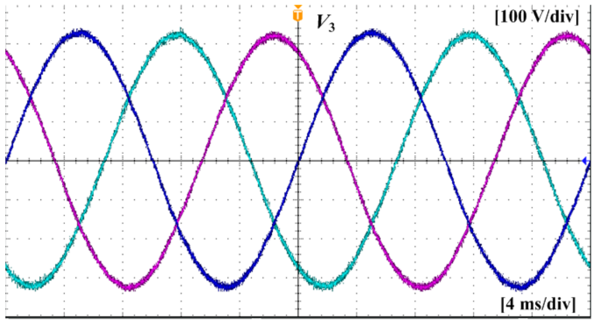
Bus voltages



Bus 1



Bus 2

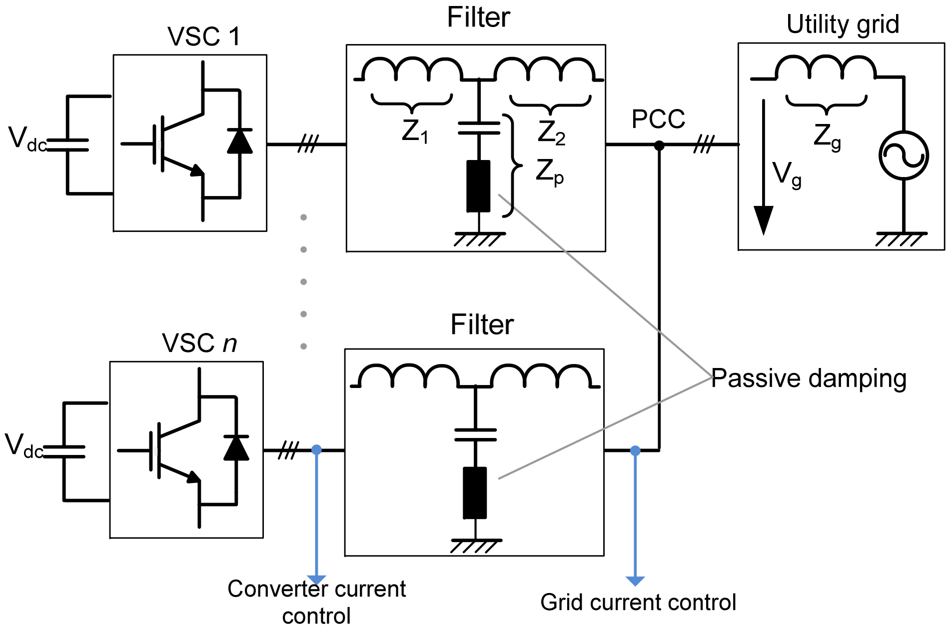


Bus 3

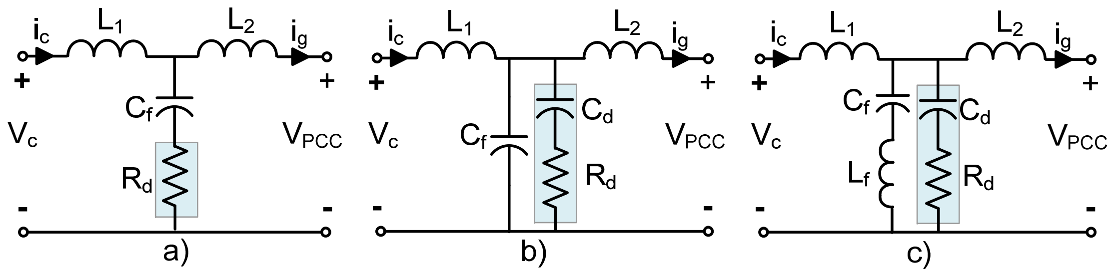
- **Mitigation of Harmonic Instability**
  - Passive damping of filters
  - Active damper

Mitigation of Harmonic Instability

Passive Damping for Output Filters of Converters



10 kW
10 kHz switching/control freq.
2.1kHz resonance freq. LCL
4.5 kHz res. for LCL+trap

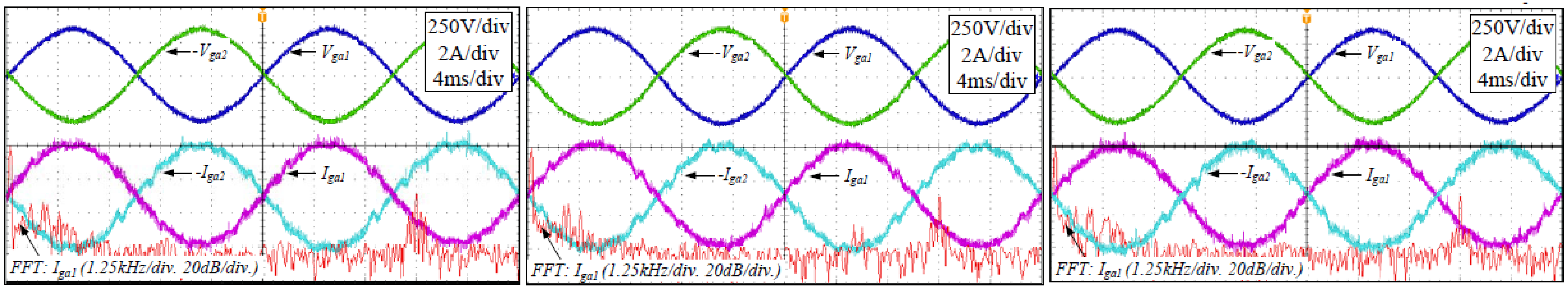


Mitigation of Harmonic Instability

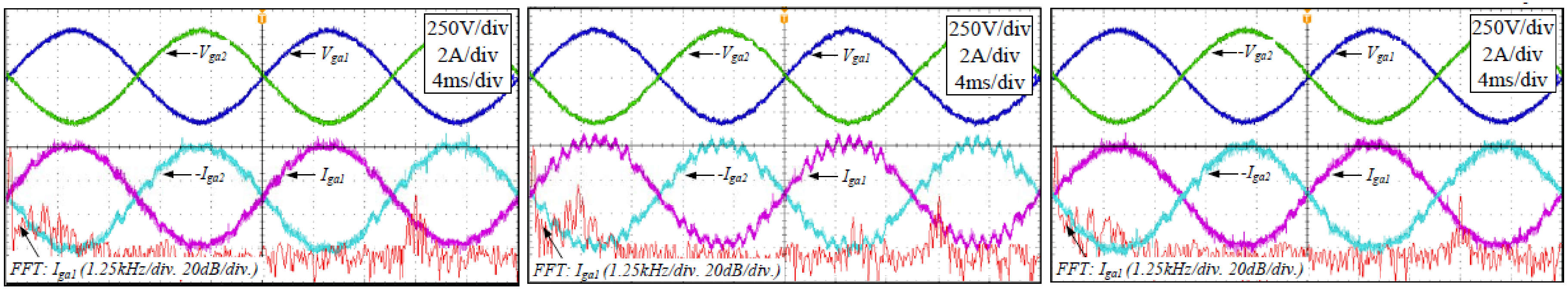
Passive Damping for Output Filters of Converters

Experimental results

Series R | Parallel R-C | LC trap + parallel R-C



Single Converter



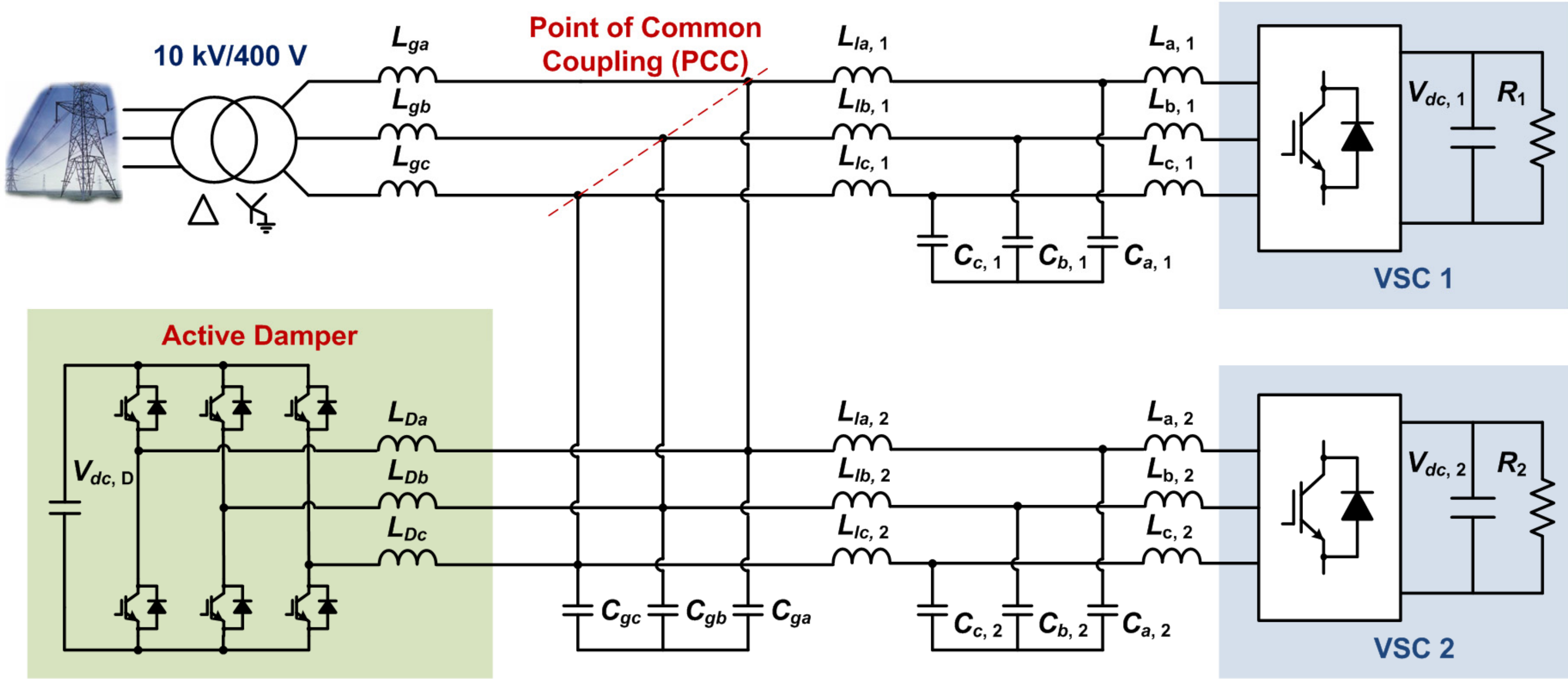
Parallel Converters

Mitigation of Harmonic Instability

AALBORG UNIVERSITET

Active Damper

- Damping of harmonic instability, no low-order harmonic filtering
- Low-power, high-frequency, high-bandwidth, plug-and-play
- ✓ Same hardware topology with APF
- ✓ High-frequency output current needs new design of output filters



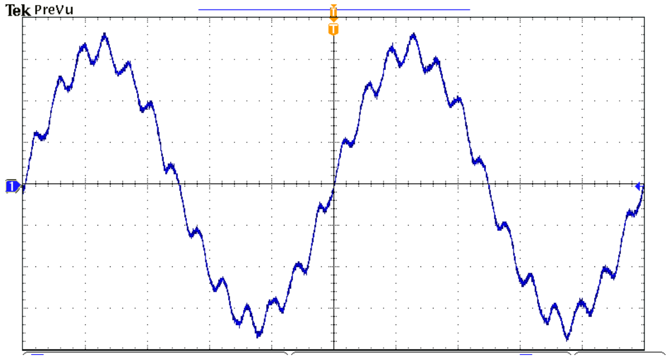
Harmonic Instability Mitigation

AALBORG UNIVERSITET

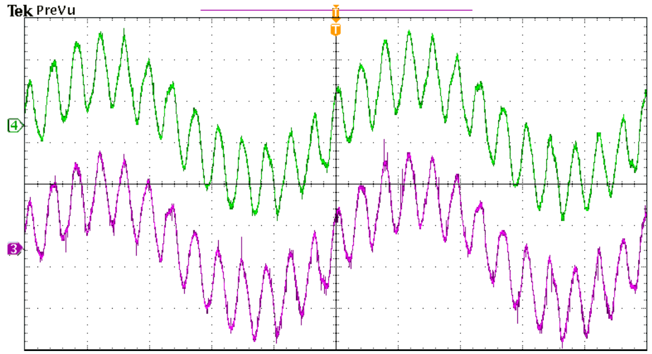
Experimental Results

Stabilizing interactions of harmonic resonant current controllers

Without active damper

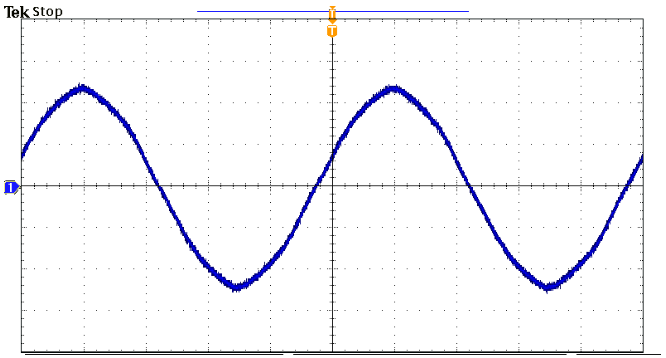


PCC voltage

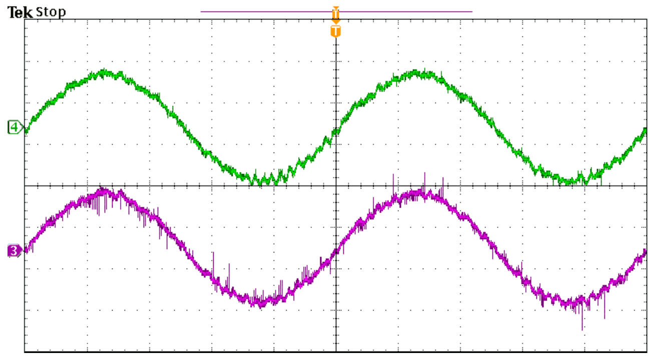


VSC currents

With active damper



PCC voltage



VSC currents

Conclusions

AALBORG UNIVERSITET

- Renewable energy systems – power electronics based power systems
- Pulse width modulation of power converters – high-order harmonics
- Controllers interactions of power converters – harmonic instability
- Impedance-based method – controller-design-oriented analysis tool
- Active damper – a promising power system stabilizer

Future trends

- Advanced modeling of wind power converters – Linear Time-Periodic (LTP) models
- System-level harmonic stability analysis – complex renewable power plants structure
- Resonance detection is the key for active damper

References

AALBORG UNIVERSITET

[1] X. Wang, F. Blaabjerg, and W. Wu, "Modeling and analysis of harmonic stability in an AC power-electronics-based power system," *IEEE Trans. Power Electron.,* vol. 29, no. 12, pp. 6421-6432, Dec. 2014.

[2] X. Wang, F. Blaabjerg, M. Liserre, Z. Chen, J. Li, and Y. W. Li "An active damper for stabilizing power electronics based AC systems," *IEEE Trans. Power Electron.,* vol. 29, no. 7, pp. 3318-3329, Jul. 2014.

[3] X. Wang, F. Blaabjerg, and M. Liserre, "An active damper to suppress multiple resonances with unknown frequencies," in *Proc. APEC* 2014, pp. 2184-2191, 2014.

[4] X. Wang, F. Blaabjerg, and P. C. Loh, "Design-oriented analysis of resonance damping and harmonic compensation for LCL-filtered voltage source converters," in *Proc. IPEC* 2014, 216-223, 2014.

[5] X. Wang, F. Blaabjerg, and P. C. Loh, "An impedance-based stability analysis method for paralleled voltage source converters," in *Proc. IPEC* 2014, 1529-1535, 2014.

[6] X. Wang, F. Blaabjerg, and P. C. Loh, "Analysis and design of grid-current-feedback active damping for *LCL* resonance in grid-connected voltage source converters," in *Proc. ECCE* 2014, 373-380, 2014.

[7] X. Wang, F. Blaabjerg, and P. C. Loh, "Proportional derivative based stabilizing control of paralleled grid converters with cables in renewable power plants," in *Proc. ECCE* 2014, 4917-4924, 2014.

[8] X. Wang, F. Blaabjerg, Z. Chen, and W. Wu, "Resonance analysis in parallel voltage-controlled distributed generation inverters," in *Proc. APEC* 2013, 2977-2983, 2013.

[9] X. Wang, F. Blaabjerg, Z. Chen, and W. Wu, "Modeling and analysis of harmonic resonance in a power electronics based AC power system," in *Proc. ECCE* 2013, 5229-5236, 2013.

[10] R. Beres, X. Wang, F. Blaabjerg, C. L. Bak, and M. Liserre, "A review of passive filters for grid-connected voltage source converters," in *Proc. IEEE APEC* 2014, pp. 2208-2215, 2014

[11] R. Beres, X. Wang, F. Blaabjerg, C. L. Bak, and M. Liserre, "Comparative evaluation of passive damping topologies for parallel grid-connected converters with LCL filters," in *Proc. IPEC* 2014, pp.3320-3327, 2014.

[12] R. Beres, X. Wang, F. Blaabjerg, C. L. Bak, and M. Liserre, "Comparative analysis of the selective resonant LCL and LCL plus trap filters," in *Proc. OPTIM* 2014, pp.740-747, 2014.

[13] R. Beres, X. Wang, F. Blaabjerg, C. L. Bak, and M. Liserre, "New optimal design method for trap damping sections in grid-connected LCL filters," in *Proc. ECCE* 2014, pp. 3620-3627, 2014.

[14] J. Kwong, X. Wang, and F. Blaabjerg, "Impedance-based analysis and design of harmonic resonant controller for a wide range of grid impedance," in *Proc. PEDG* 2014, pp.1-8, 2014.

[15] J. Kwong, X. Wang, C. L. Bak, and F. Blaabjerg, "Modeling and grid impedance variation analysis of parallel connected grid-connected inverter based on impedance-based harmonic analysis ," in *Proc. IECON* 2014, in press, 2014.

Thank You! Questions?

“ THE HIDDEN HARMONY IS BETTER THAN THE OBVIOUS ”

- P. PICASSO

HARMONY

www.harmony.et.aau.dk