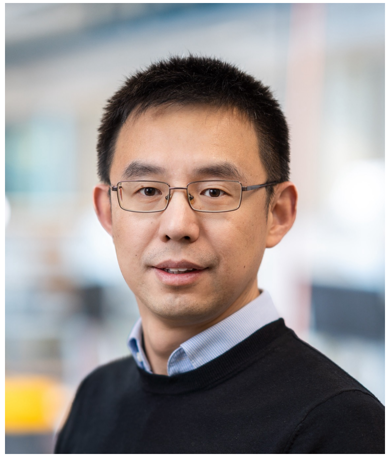
Harmonic Stability in Power Electronic Based Power Systems

Xiongfei Wang, Professor, IEEE Fellow

KTH Royal Institute of Technology

Speaker - Introduction



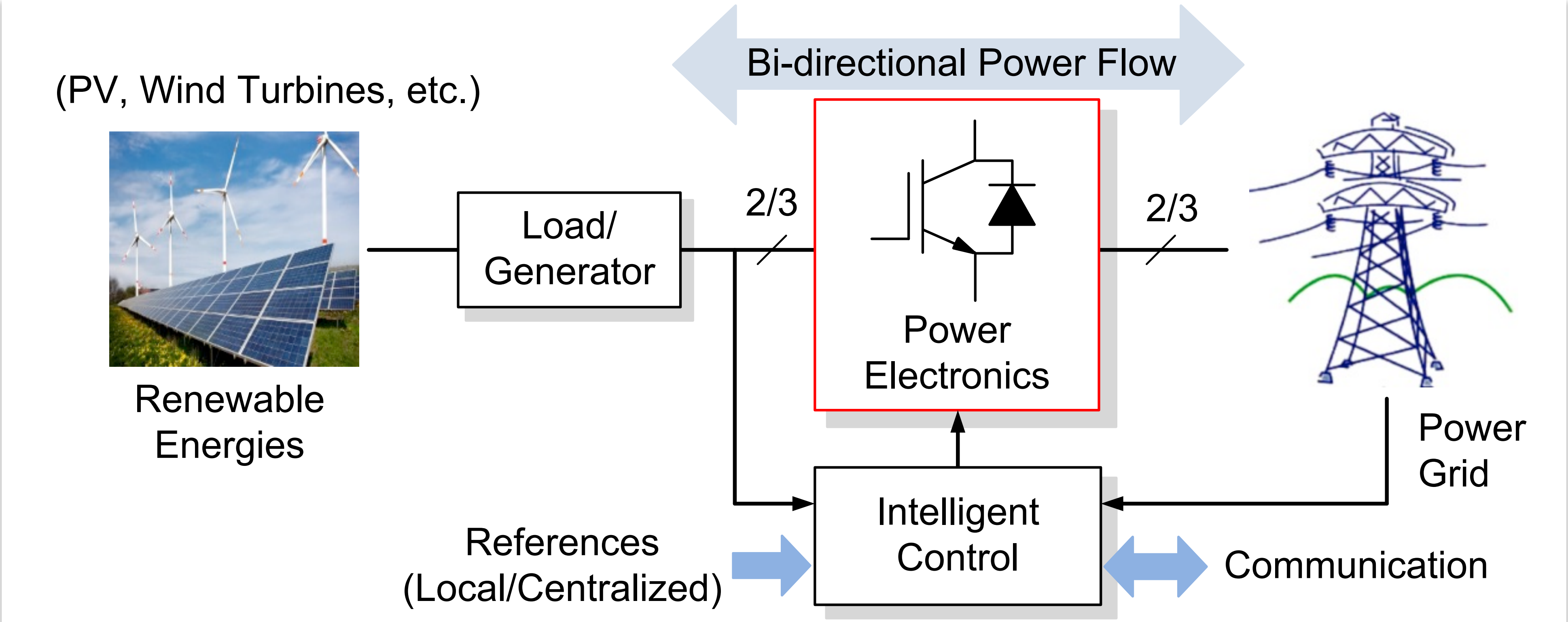
Xiongfei Wang

- **Full Professor**, KTH Royal Institute of Technology, Sweden
- **Professor (part-time)**, AAU Energy, Aalborg University, Denmark
- **Visiting Professor**, Hitachi Energy Research Center, Sweden
- **Executive Editor (EiC)**, IEEE Transactions on Power Electronics Letters
- **10 IEEE Prize Papers** in Transactions and Conferences
- **IEEE Fellow** for contributions to “power electronic based power systems”
- 2019 IEEE PELS Sustainable Energy Systems Technical Achievement Award
- 2022 The Isao Takahashi Power Electronics Award

Xiongfei Wang received the B.S. degree from Yanshan University, China, in 2006, the M.S. degree from Harbin Institute of Technology, China, in 2008, both in electrical engineering, and the Ph.D. degree in energy technology from Aalborg University, Denmark, in 2013. From 2009 to 2022, he was with Aalborg University where he became an Assistant Professor in 2014, an Associate Professor in 2016, a Professor and the founding Leader of Electronic Power Grid (eGRID) Research Group in 2018. From 2022, he has been a Full Professor with KTH Royal Institute of Technology, Stockholm, Sweden, and a part-time Professor with Aalborg University, Denmark. From 2023, he has also been a visiting professor at Hitachi Energy Research Center, Vasteras, Sweden.

His current research interests include modeling and control of power electronic converters and systems, stability and power quality of power-electronic-based power systems, and high-power converters.

Power Electronics - Key Technology for Modern Grids



Switched-Mode Power Semiconductor Devices: higher efficiency and lower levelized cost of energy

Digital Control: fully programmable, wide-timescale control dynamics

Power Electronic Based Power Systems

Generation

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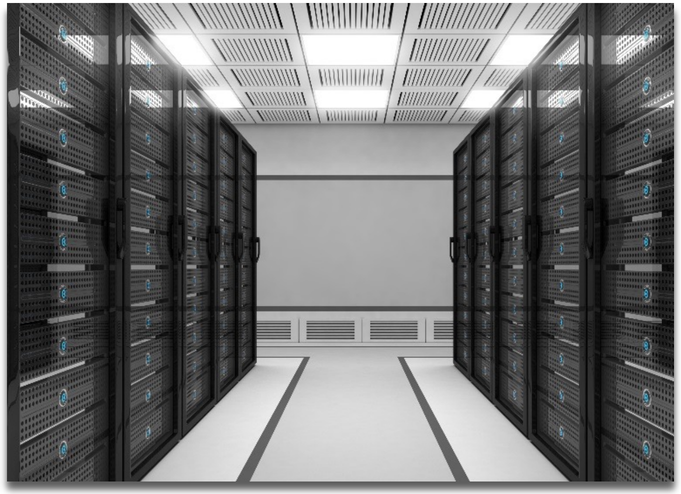
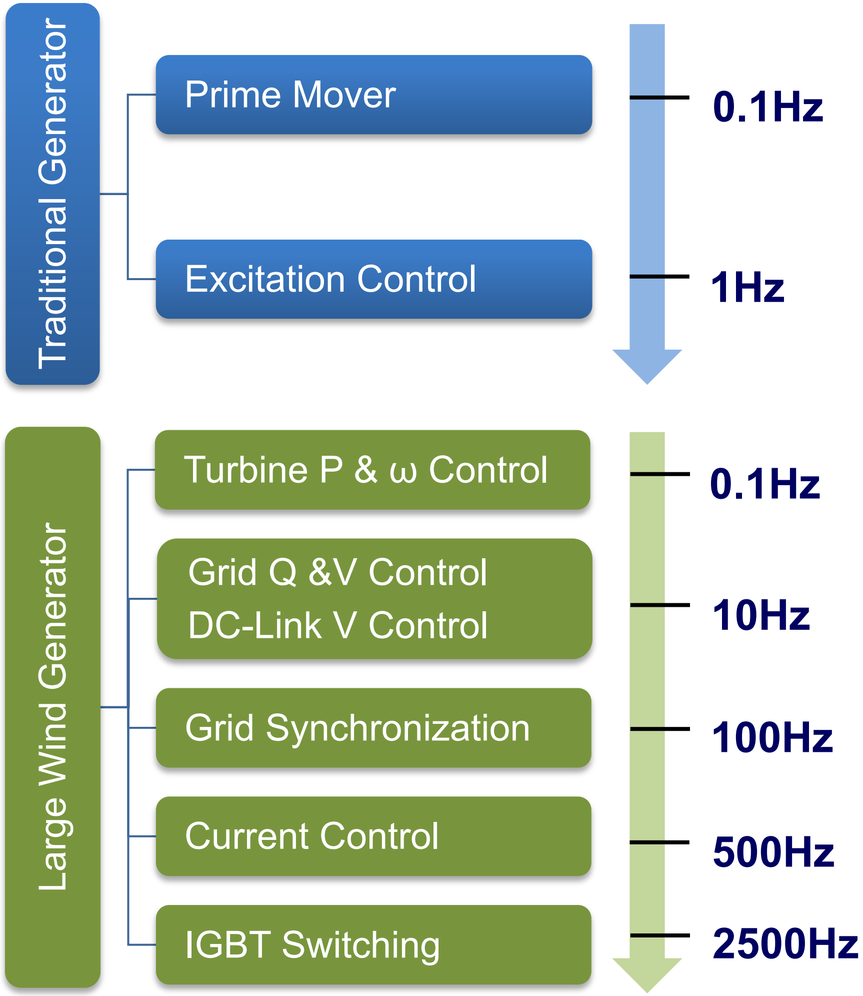
Transmission/Distribution



Consumption

Harmonics and Wideband Control of Power Electronics

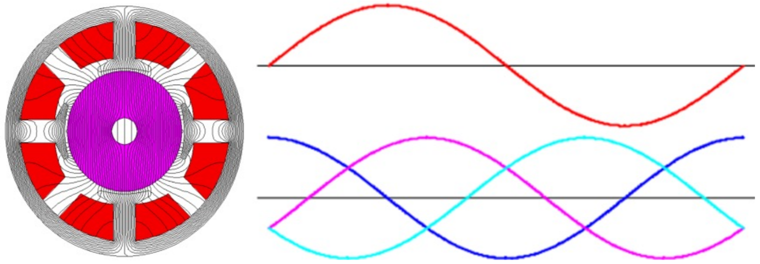


Traditional Generator

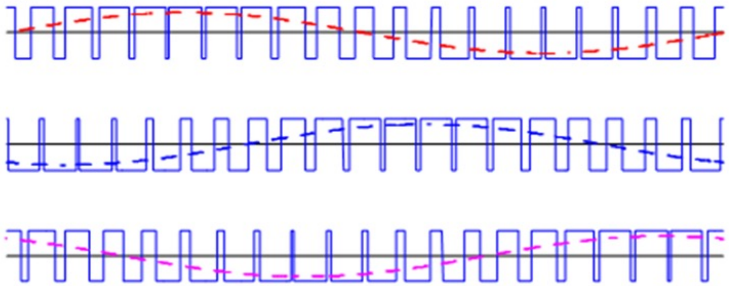
- Prime Mover — 0.1Hz
- Excitation Control — 1Hz

Large Wind Generator

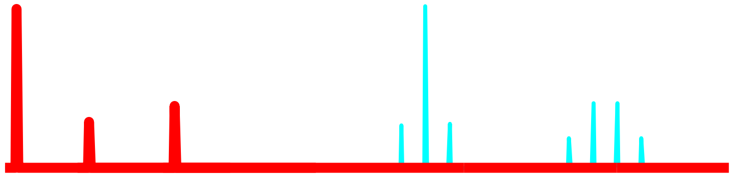
- Turbine P & ω Control — 0.1Hz
- Grid Q &V Control
  DC-Link V Control — 10Hz
- Grid Synchronization — 100Hz
- Current Control — 500Hz
- IGBT Switching — 2500Hz



Traditional Generator Output Voltage



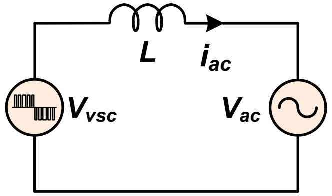
Wind Generator Output Voltage



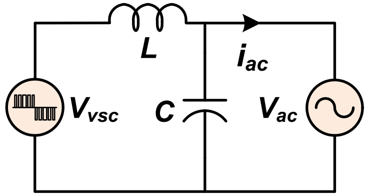
Harmonic Spectrum

LC Resonances of Converter Filters and Power Cables

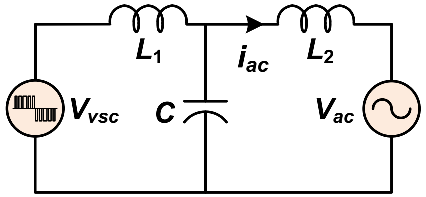
➢ Use of high-order passive filters for switching harmonics attenuation



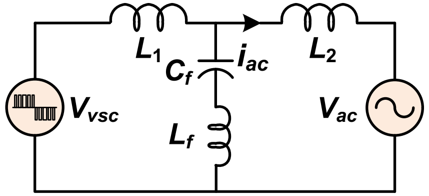
L-filter



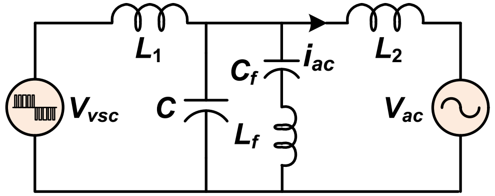
LC-filter



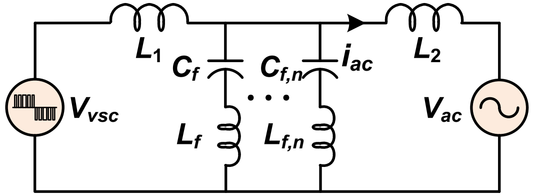
LCL-filter



LLCL-filter

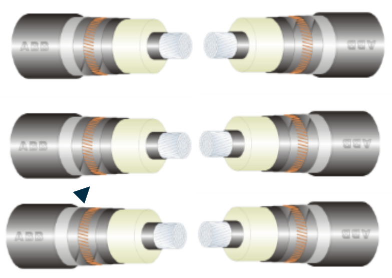


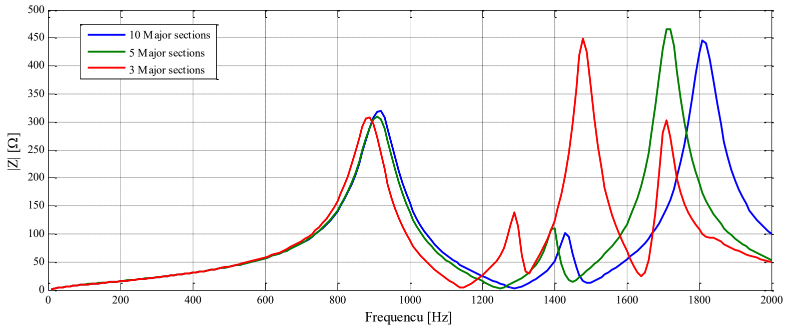
LCL + trap filter



Mutli-trap filter

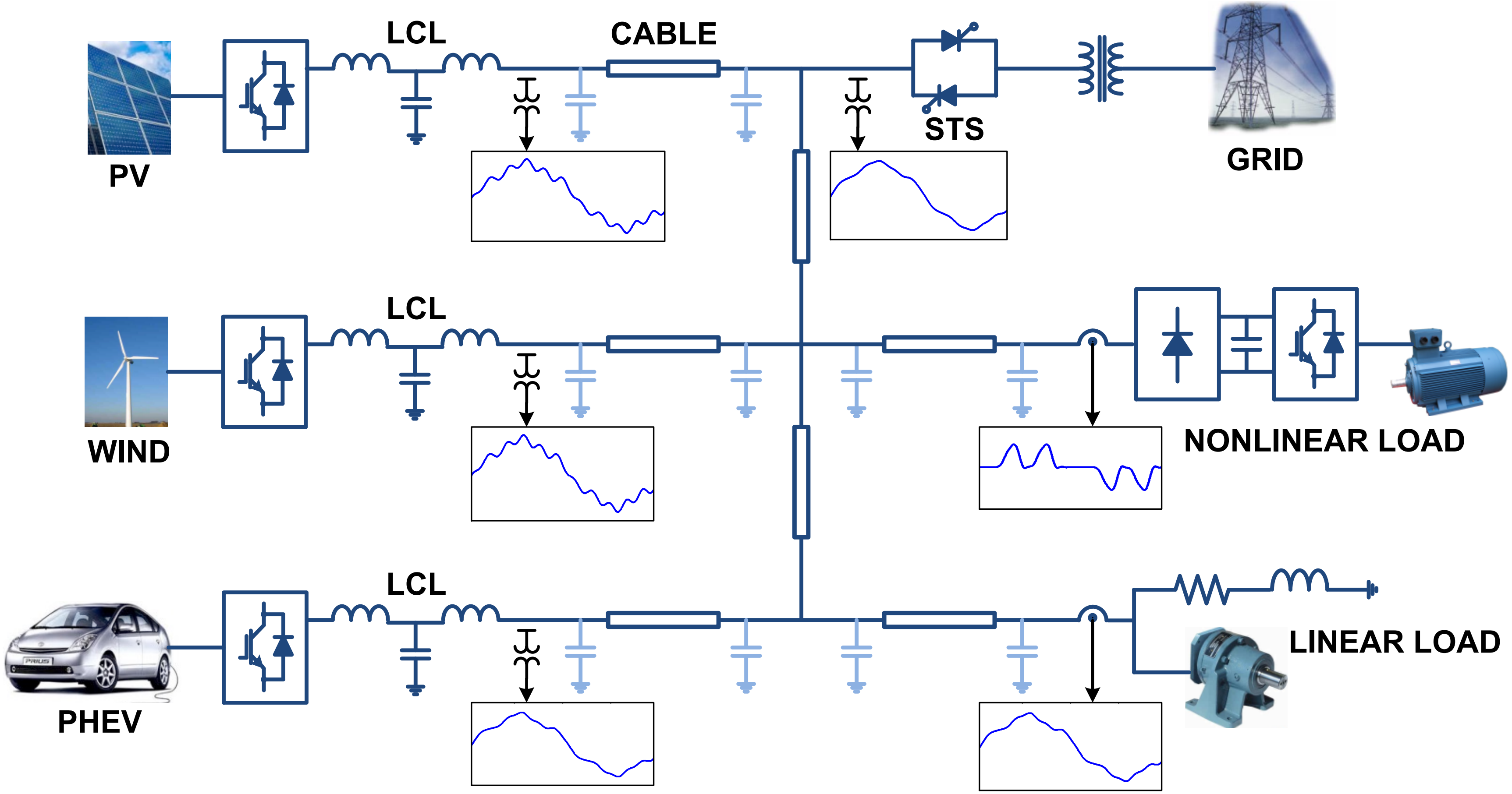
➢ Power cables





Harmonic Stability in Future Electronic Power Systems

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

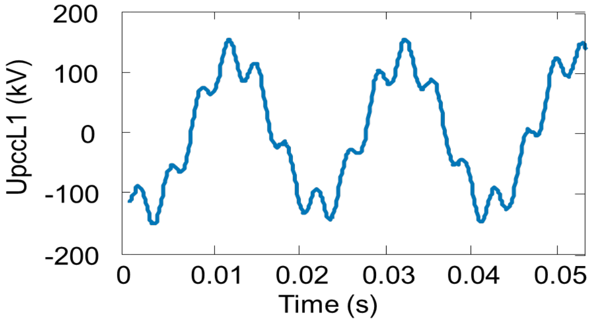


Real-World Harmonic Instability Phenomena

VSC-HVDC + Offshore Wind

Two-Level VSC filter resonance

Type-3 (DFIG) wind turbine



Rätselhafter Defekt legt größten Windpark lahm

DER SPIEGEL 35/2014

Ökostrom

Knall auf hoher See

Störung legt Windpark BARD Offshore 1 weiter lahm

Seit März liefert der Windpark BARD Offshore 1 keinen Strom mehr. (Archivbild)

Beim Windpark BARD Offshore 1 vor der Nordseeinsel Borkum gibt es eine Panne nach der anderen. Seit März steht der Windpark still. "Die Störungen zu beheben, zieht sich länger hin, als es allen Beteiligten lieb ist", sagte Mathias Fischer, Sprecher des Netzbetreibers Tennet. Noch immer suchen Experten des Windparkbetreibers Ocean Breeze Energy, des Elektronikkonzerns ABB und von Tennet nach der Störungsursache. Erst im September können die 80 Anlagen von BARD 1 voraussichtlich wieder Strom liefern.

Schutzabschaltungen wegen "schmutzigem Strom"

- World's first High-Voltage Direct Current (HVDC) connecting offshore wind farm
- **Harmonic instability** tripped the offshore wind farm [1]
- **3 years** behind schedule at a cost of **€3 billion** [2]

[1] M. Larsson, "Harmonic resonance and control interoperability analysis of HVDC connected wind farms," IEEE eT&D, Aalborg, 2017.

[2] https://en.wikipedia.org/wiki/BARD_Offshore_1

Real-World Harmonic Instability Phenomena

VSC-HVDC + Offshore Wind

Two-Level VSC filter resonance
Type-3 (DFIG) wind turbine

©CSG

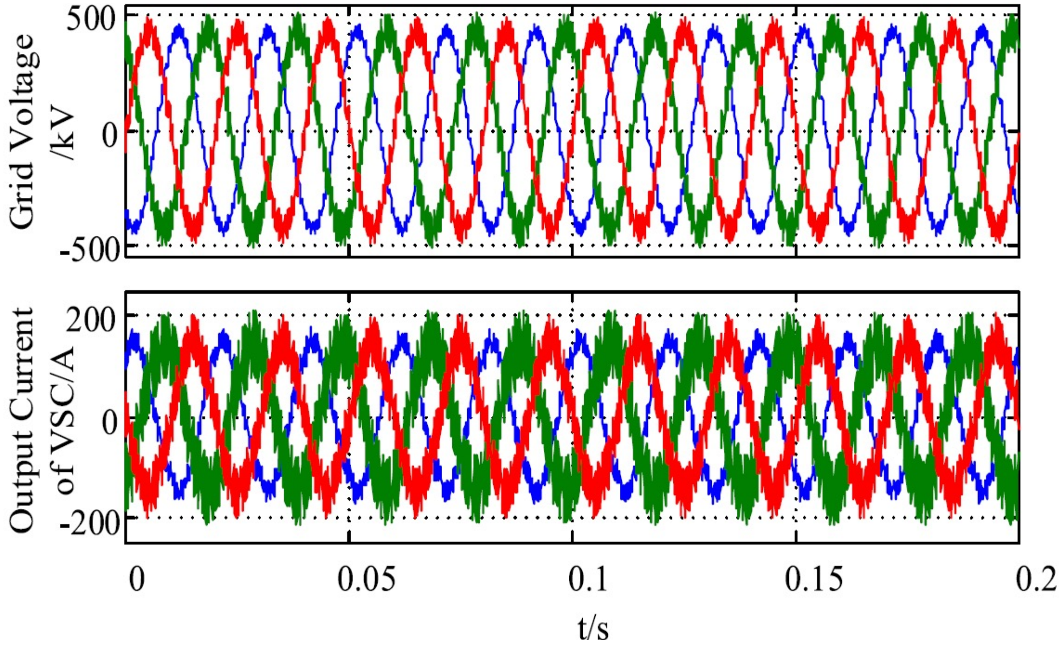
MMC-HVDC Transmission

Instability of current control in weak ac grid

Electrification of Railways

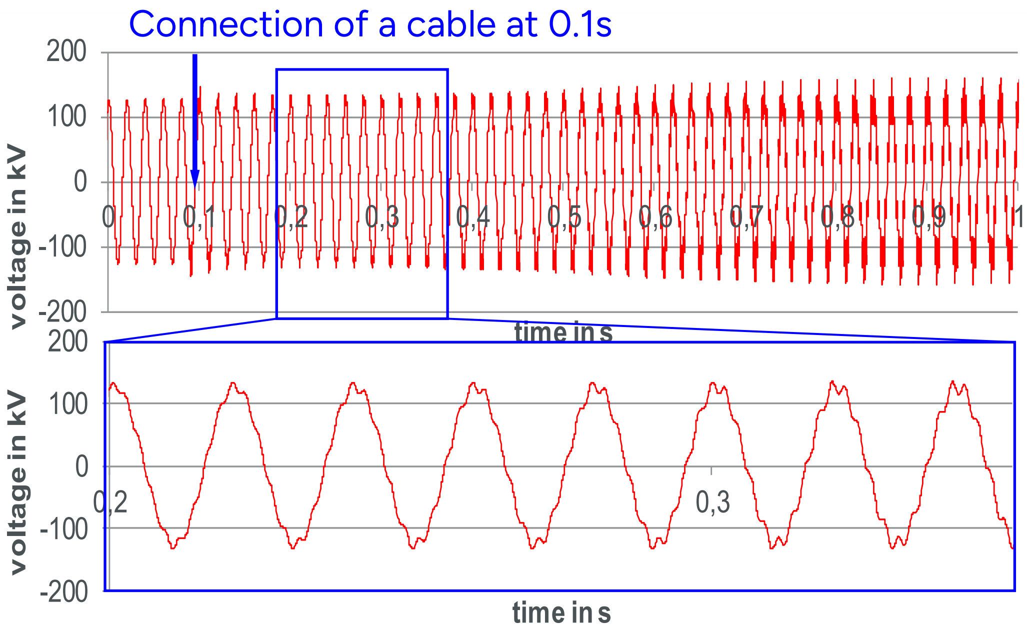
Locomotives is out of control because of abnormal harmonics

Real-World Harmonic Instability Phenomena



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

- 1270 Hz resonance induced by current control
- Negative damping caused by time delay



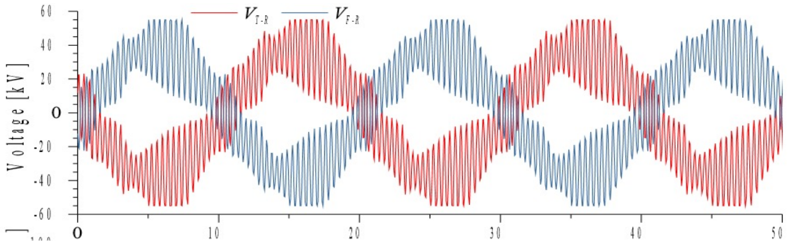
MMC-HVDC in Offshore Wind Farm, Germany [2]

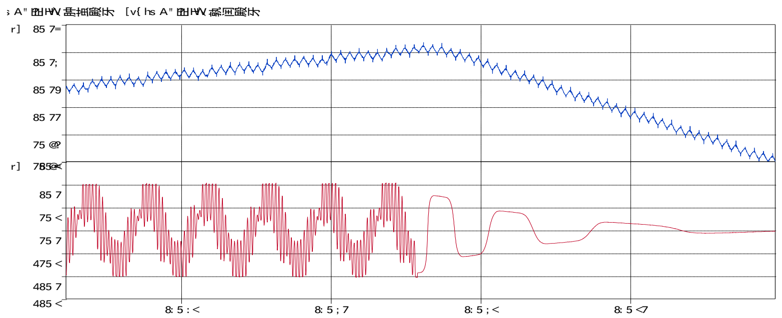
- 451 Hz resonance in the North Sea wind farm
- Connection of a cable at 0.1 s

[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 Harmonic Instability Phenomena



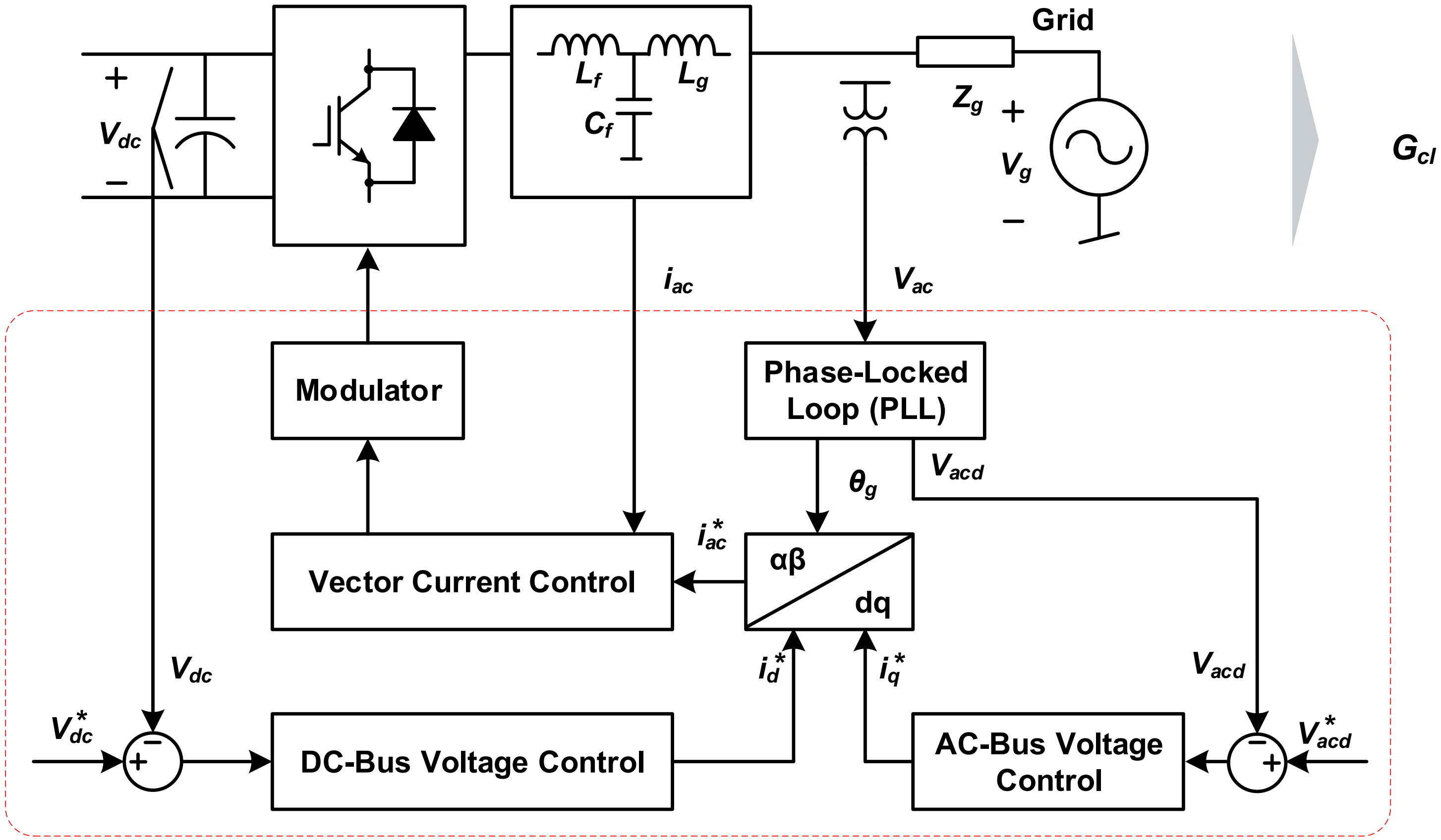


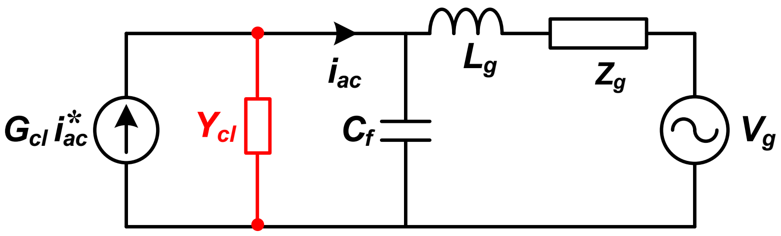
Harmonic instability in railway traction power supply system - 15-75 times fundamental frequency [1]

- Derating surge arrester due to harmonic resonances - short-circuit fault

[1] K. Song, M. Wu, S. Yang, Q. Liu, V. G. Agelidis, and G. Konstantinou, “High-order harmonic resonances in traction power supplies: a review based on railway operational data, measurements and experience,” *IEEE Trans. Power Electron.*, vol. 35, no. 3, Mar. 2020.

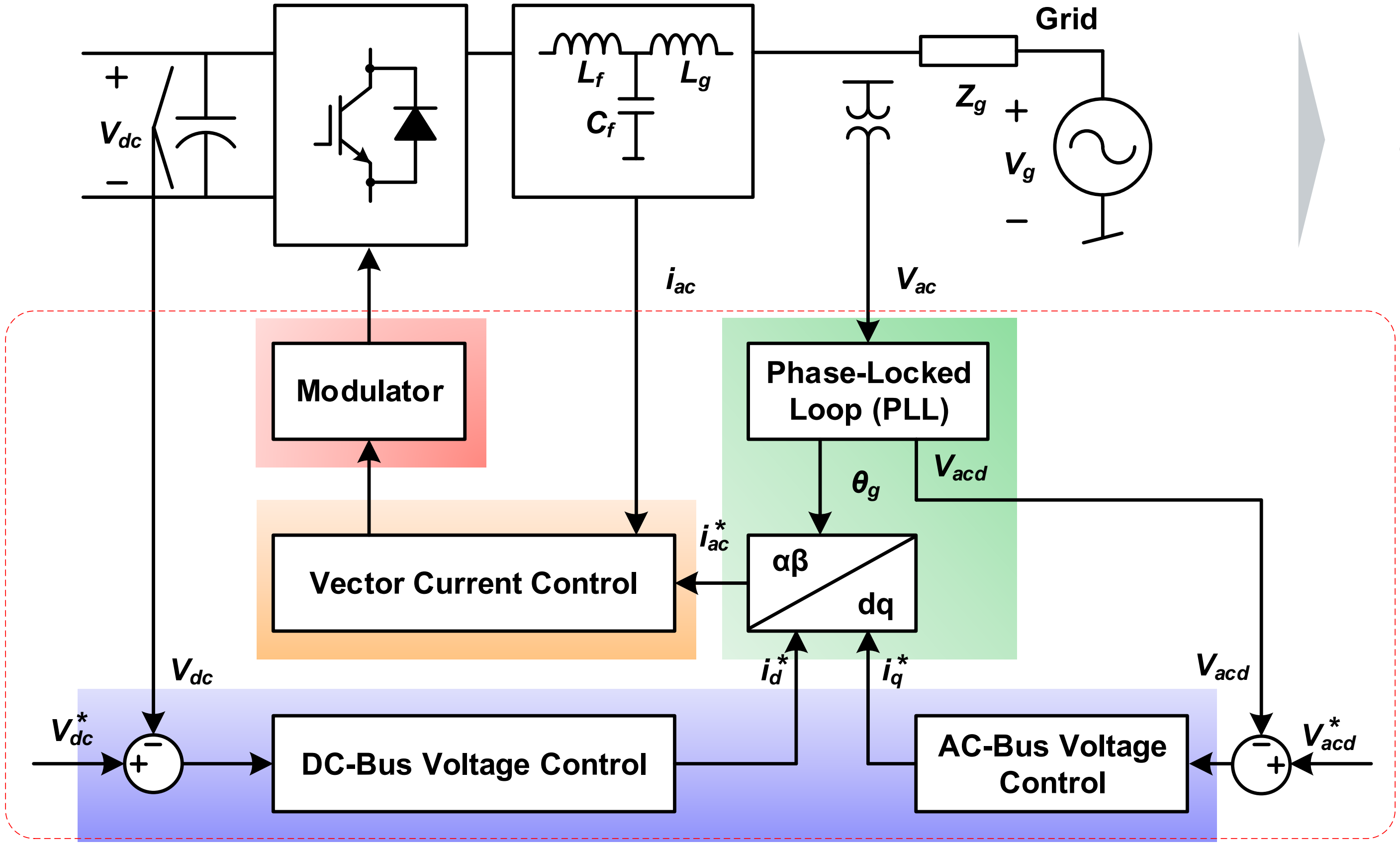
Harmonic, Resonance, and Instability

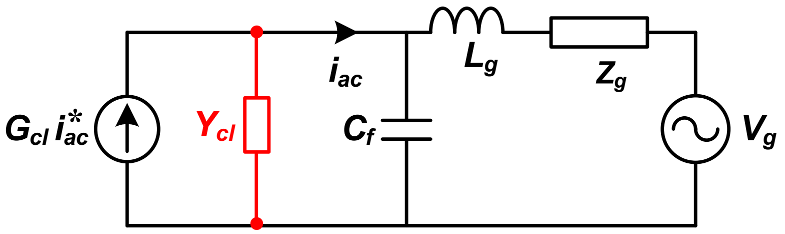


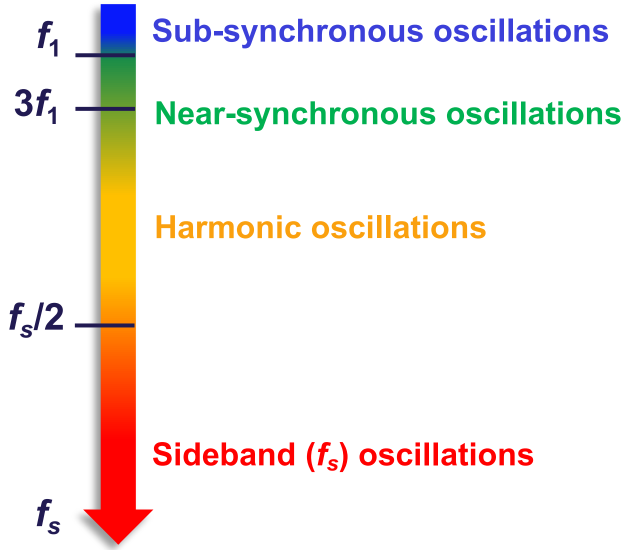


- Re{Y_{cl}}>0: stable, yet underdamped
  Harmonic
- Re{Y_{cl}}=0: critically stable, zero-damped
  Resonance
- Re{Y_{cl}}<0: unstable, negatively-damped
  Instability

Harmonic, Resonance, and Instability



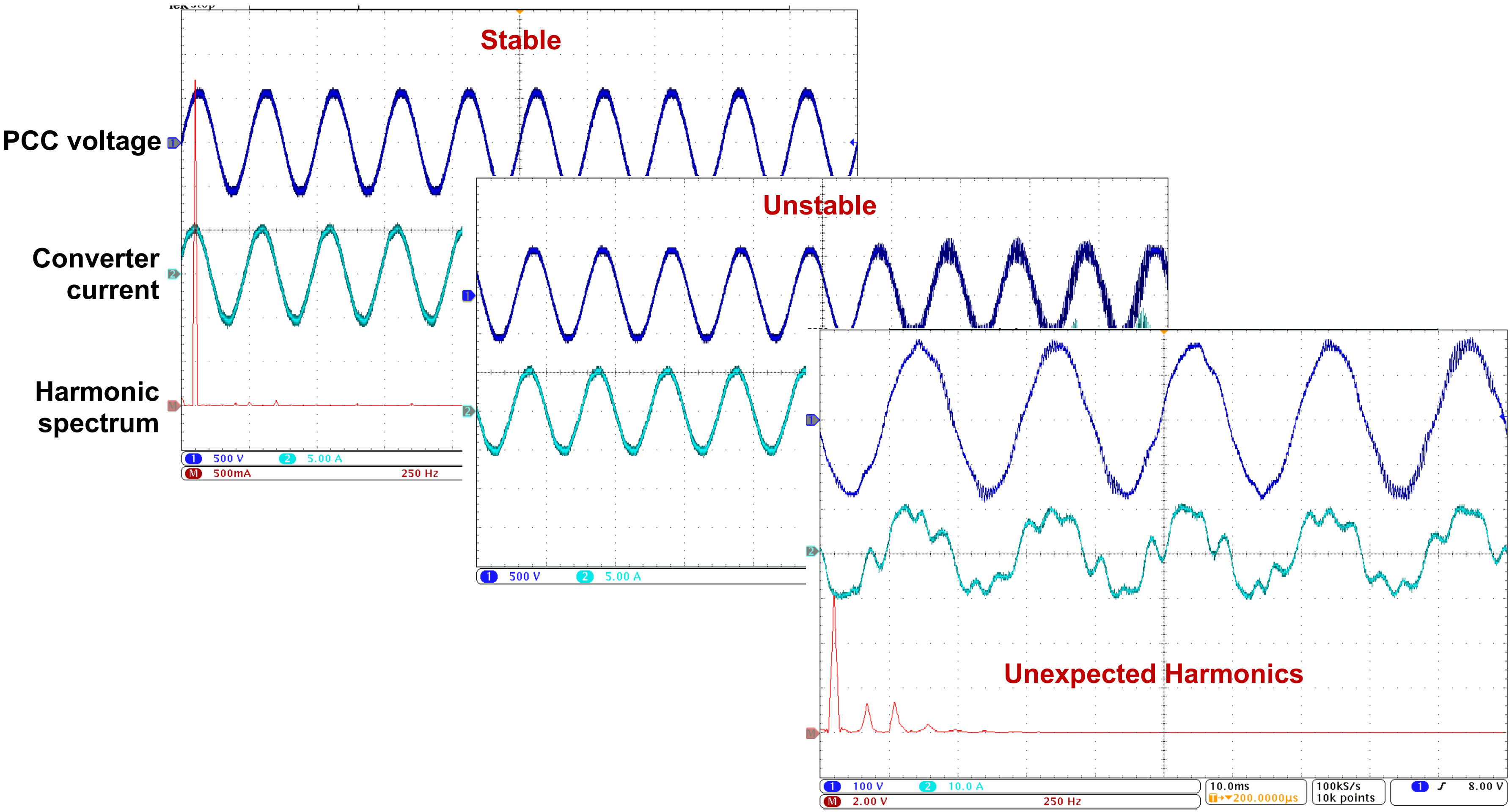




f_1: Grid fundamental frequency, f_s: Switching frequency

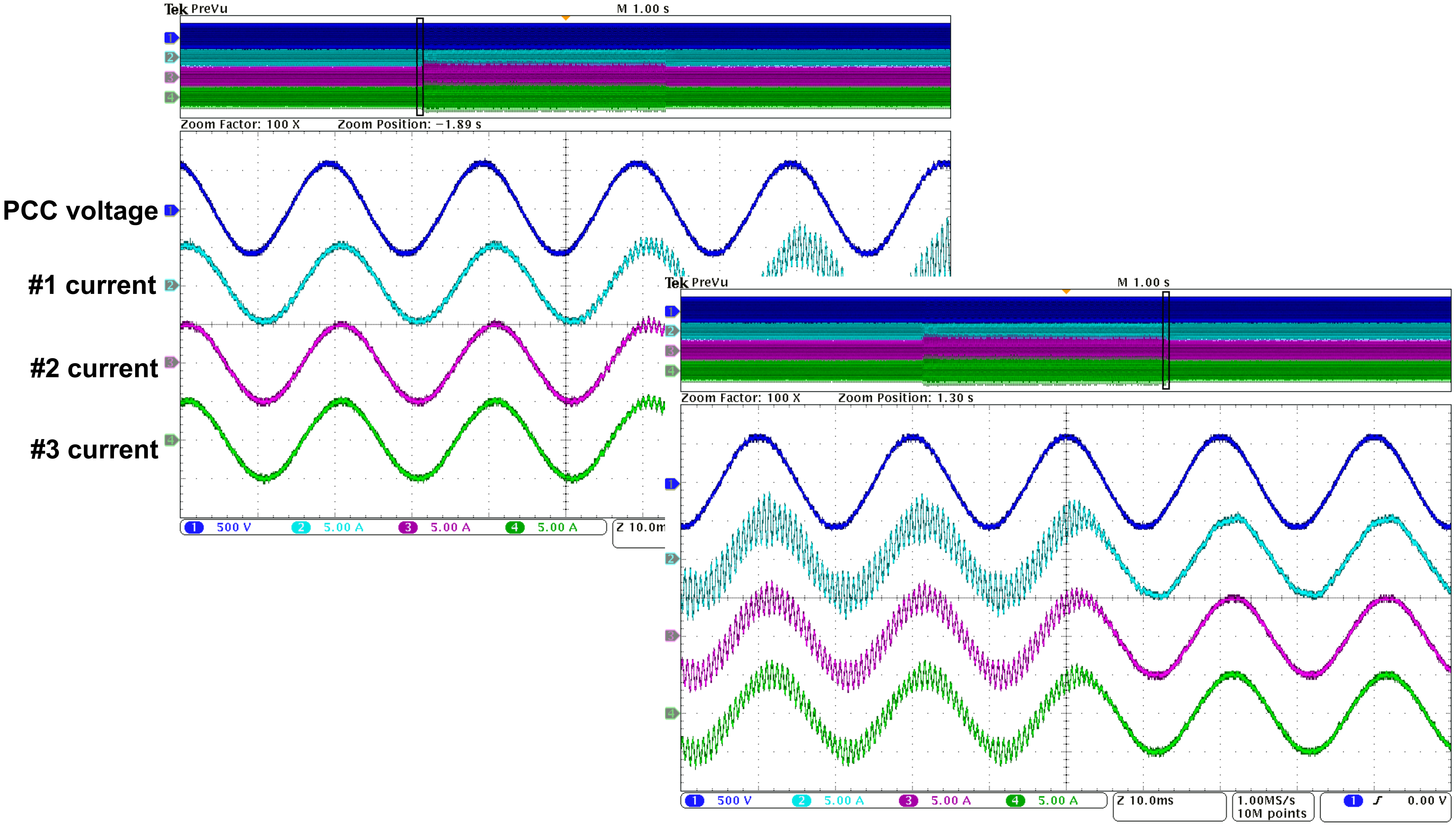
[1] X. Wang and F. Blaabjerg, “Harmonic stability in power electronic based power systems: concept, modeling and analysis,” *IEEE Trans. Smart Grid*, vol. 10, no. 3, pp. 2858-2870, May 2019.

Harmonic, Resonance, and Instability



[1] X. Wang and F. Blaabjerg, “Harmonic stability in power electronic based power systems: concept, modeling and analysis,” *IEEE Trans. Smart Grid*, vol. 10, no. 3, pp. 2858-2870, May 2019.

Harmonic, Resonance, and Instability



[1] X. Wang and F. Blaabjerg, "Harmonic stability in power electronic based power systems: concept, modeling and analysis," *IEEE Trans. Smart Grid*, vol. 10, no. 3, pp. 2858-2870, May 2019.

Converter Modeling for Harmonic Stability Analysis

1970

Persson [1] - thyristor HVDC
Frequency response analysis
Describing Function with single sinusoidal inputs

For control design

1985

Sakui and Fujita [2] - thyristor rectifier, Switching Function model w/o firing angle variation considered

For harmonic analysis

1986

Ngo [3] - PWM converter
State-Space Averaging with Park transformation
DQ-frame linearized model

For control design

1989

Larson, Baker, McIver [4] - thyristor HVDC, numerical simulations derived Harmonic Cross-Coupling Matrix

For harmonic/control analysis

1997

Mattavelli, Verghese, Stankovic [5] - thyristor FACTS devices
Dynamic Phasor with time-variant Fourier coefficients

For control design

2000

Mollerstedt [6] - locomotive inverter, Harmonic State-Space (HSS) modelling, Harmonic Transfer Matrix

For harmonic stability analysis

2003

Rico, Madrigal, Acha [7] - STATCOM with phase angle control, Extended Harmonic Domain (EHD)

For harmonic analysis

2007

Harnefors [8] - DQ-frame model with the phase variation;
Wen, Boroyevich, et, al [9], 2016
Rygg, Molinas, Zhang, [10], 2016

For control design

2014

Cespedes and Sun [11] - stability effect of PLL on PWM converter
Harmonic Balance, Multi-Input Describing Functions

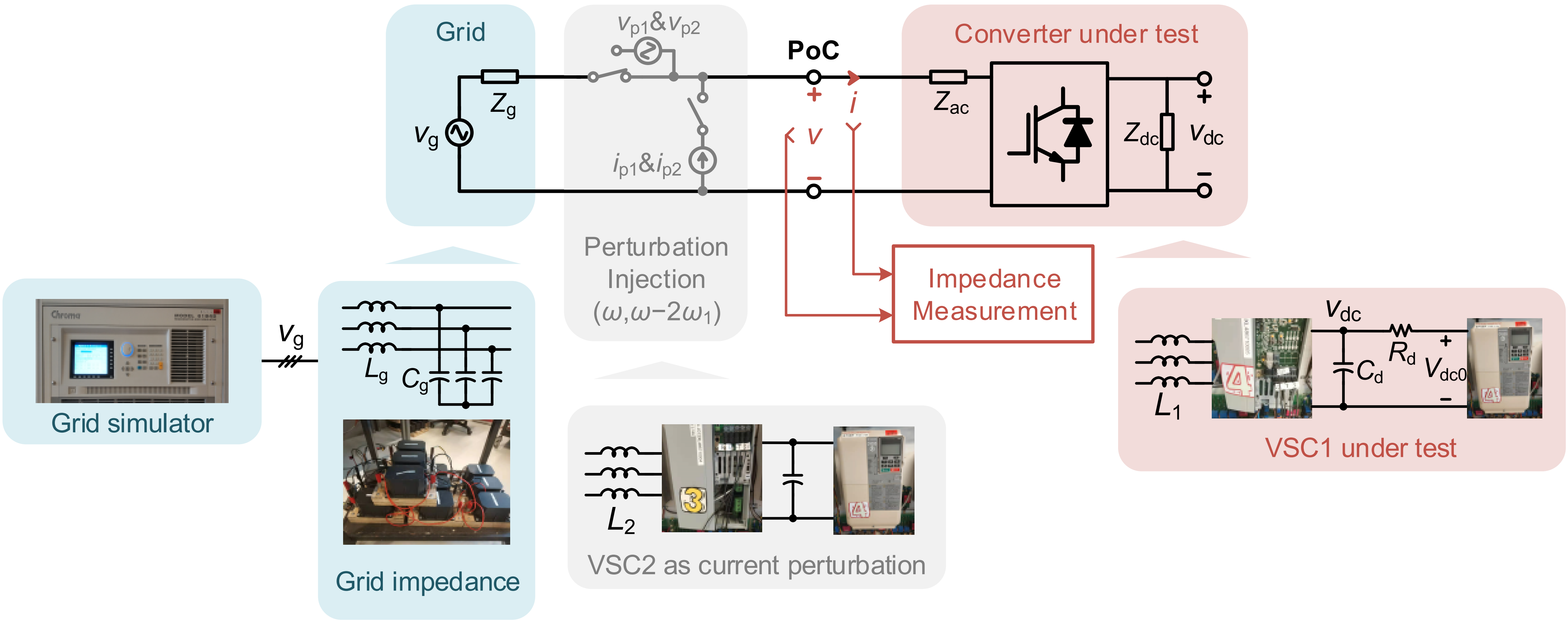
For control design

2016

Wang, Harnefors, Blaabjerg [12] - Unified Impedance Model from *dq*-frame to *αβ*-frame, 2^nd^-order Harmonic Transfer Matrix

For control design

Converter Model Validation - Frequency Scan



Grid

Perturbation Injection (ω,ω−2ω_1)

Converter under test

Impedance Measurement

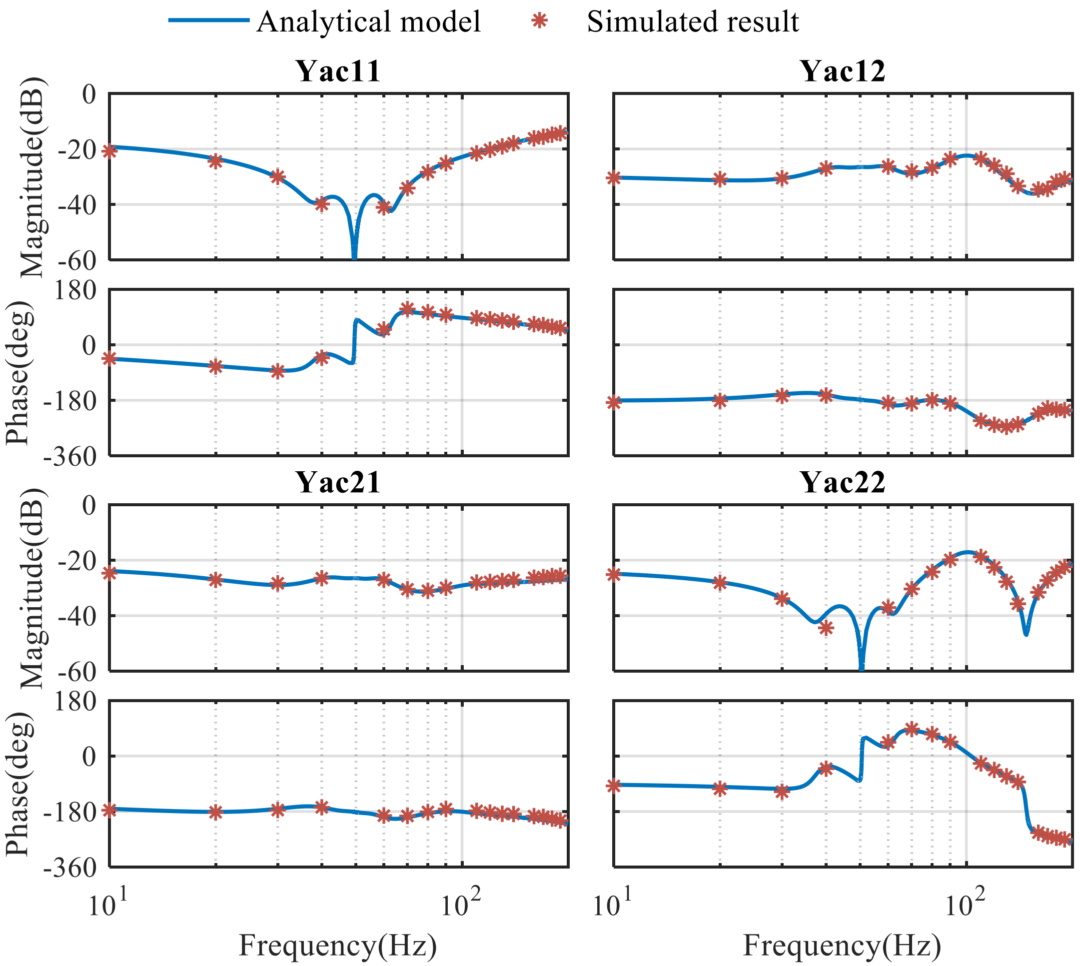
Grid simulator

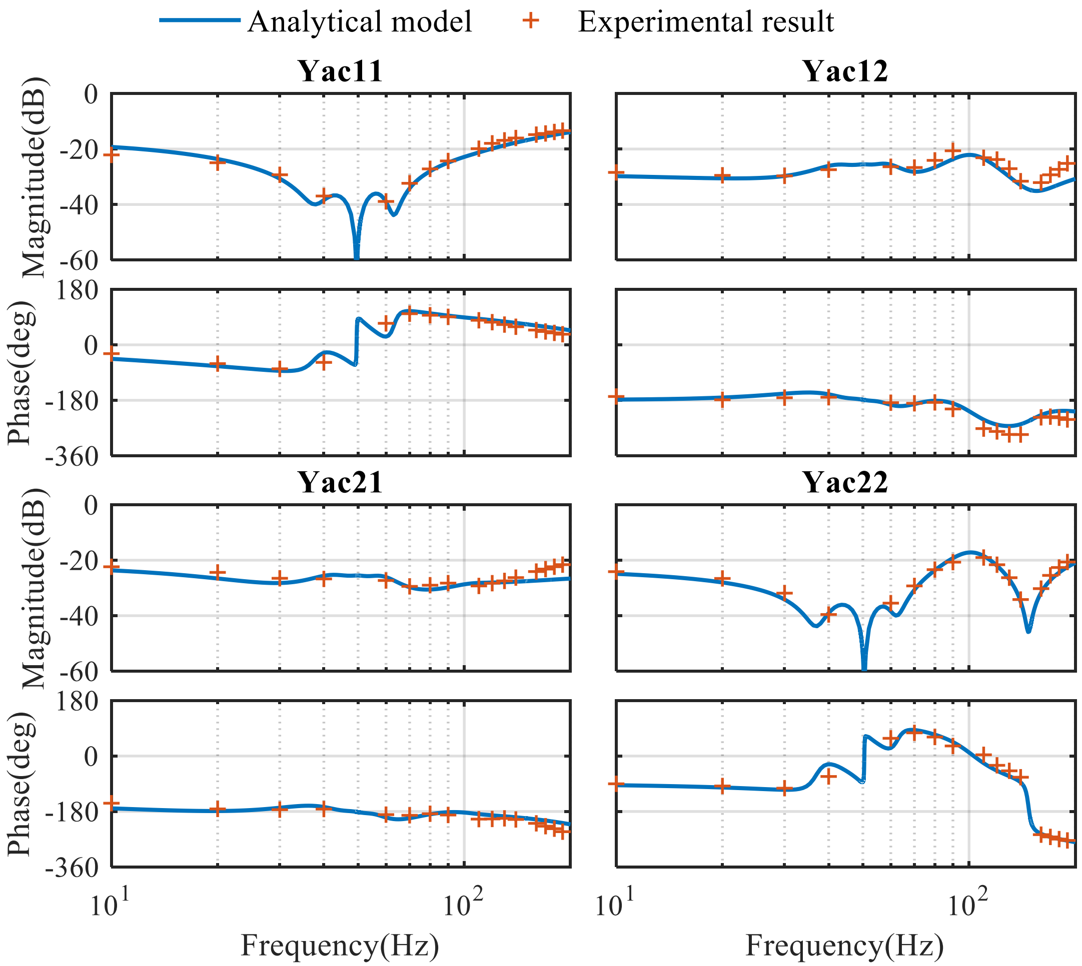
Grid impedance

VSC2 as current perturbation

VSC1 under test

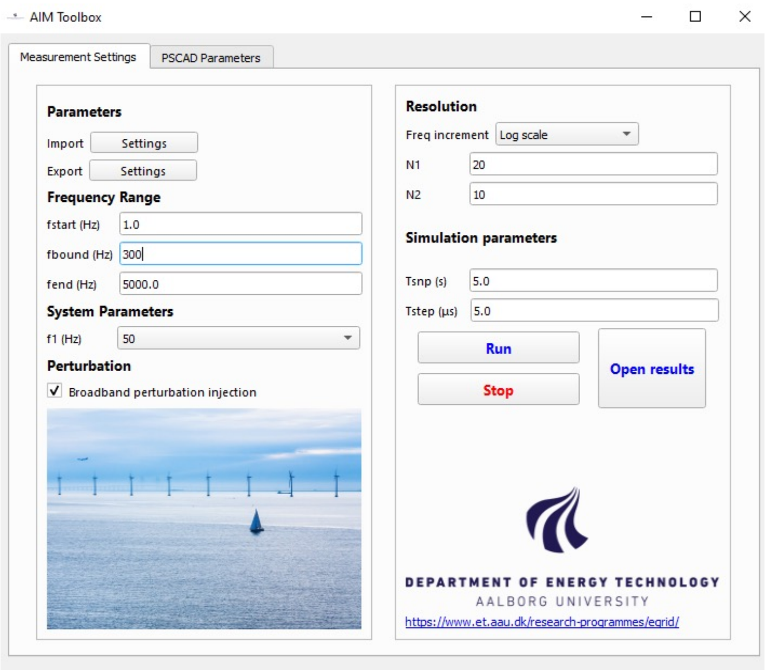
Converter Model Validation - Frequency Scan





Converter Model Validation - Frequency Scan

Impedance measurement software – commercialized



Parameters

Import: Settings

Export: Settings

Frequency Range

fstart (Hz): 1.0

fbound (Hz): 300

fend (Hz): 5000.0

System Parameters

f1 (Hz): 50

Perturbation

☑ Broadband perturbation injection

Resolution

Freq increment: Log scale

N1: 20

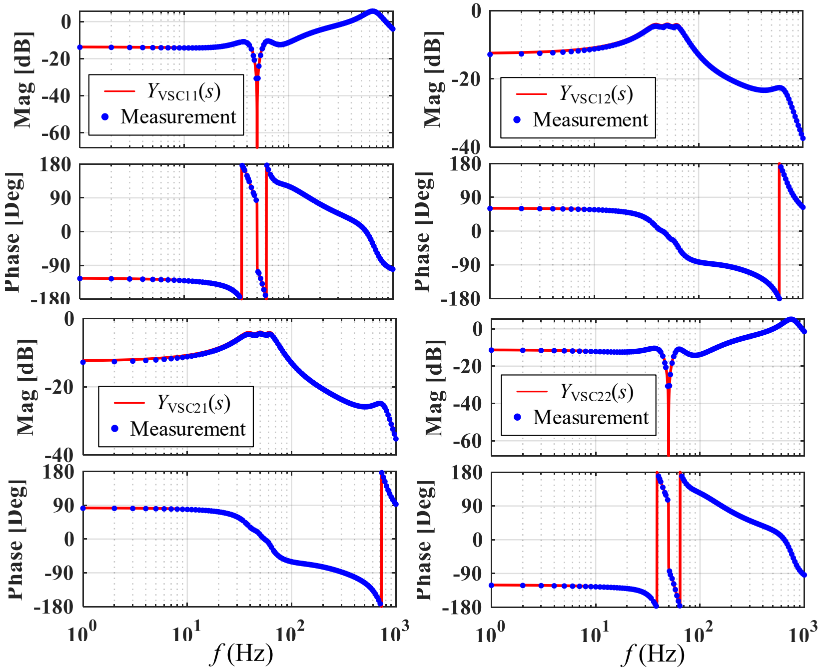
N2: 10

Simulation parameters

Tsnp (s): 5.0

Tstep (µs): 5.0

https://www.et.aau.dk/research-programmes/egrid/



Software users

TRANSNET BW

TenneT
Taking power further

YONSEI UNIVERSITY

상명대학교
SANGMYUNG UNIVERSITY

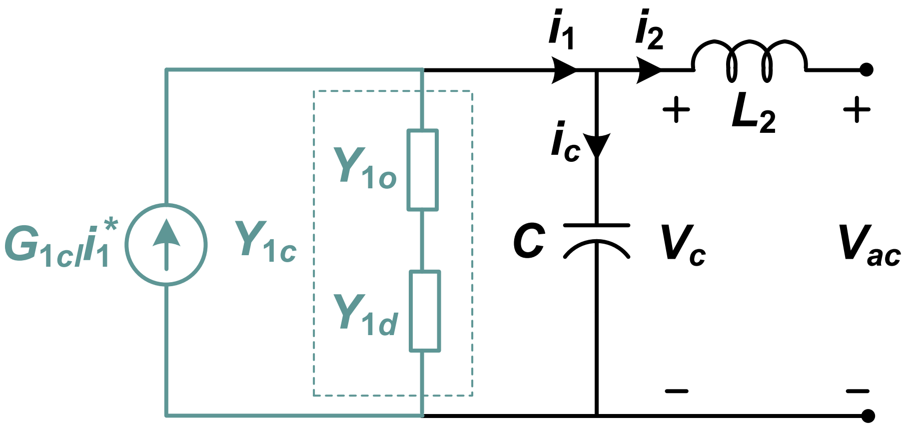
- Fully automated, PSCAD/EMT compatible
- Impedance matrix in different reference (dq or αβ) frame
- Used by Europe's leading TSOs in multiple commercial projects

- For more information, visit our spinoff www.aistability.dk

AI STABILITY

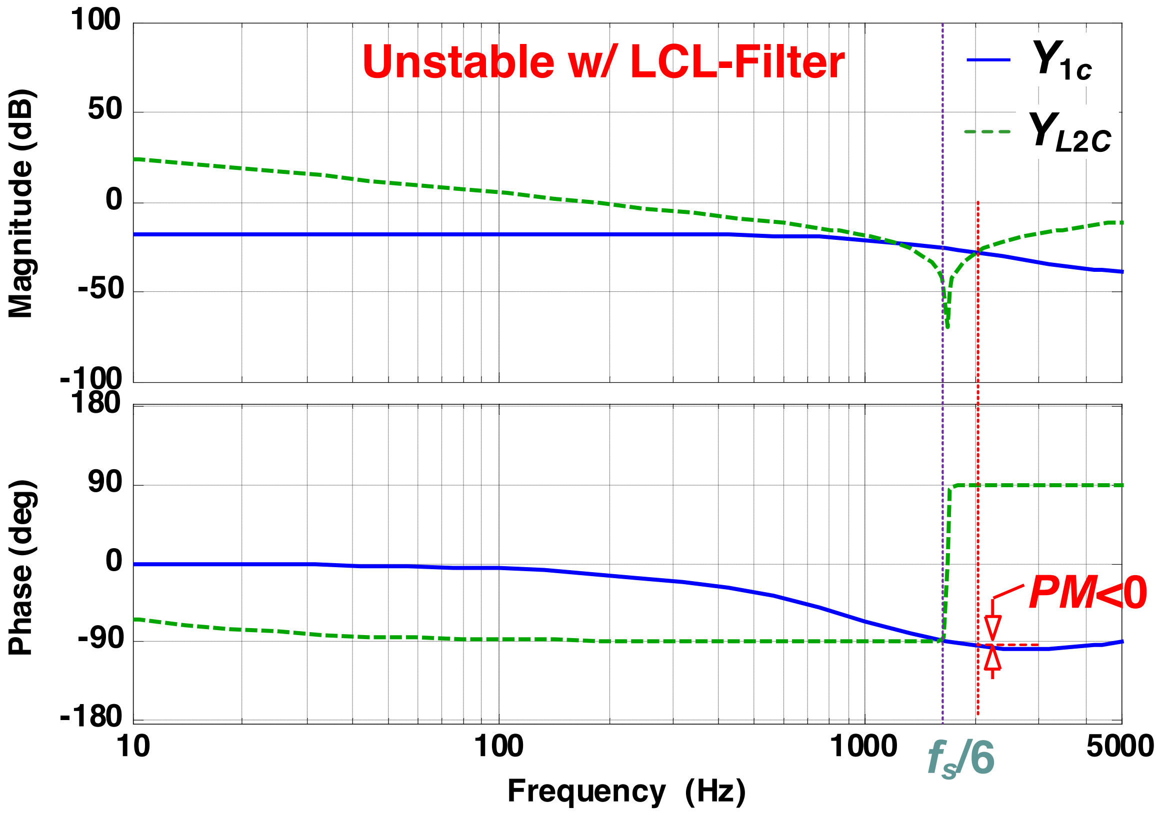
Origin of Negative Resistance

Digital current control of grid-connected converter – Proportional controller + L-filter



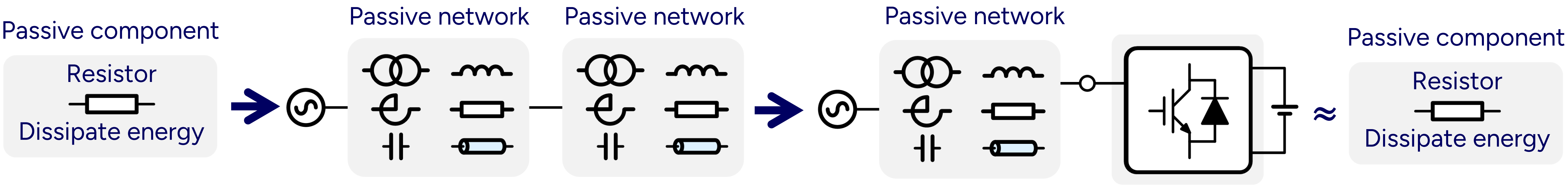
$$Y_{1o}=\frac{1}{L_1 s}\quad Y_{1d}\approx\frac{1}{k_p}e^{j\omega T_d}=\frac{1}{k_p}\left[\cos(T_d\omega)+j\sin(T_d\omega)\right]$$

- Ideal inductor with zero parasitic resistance
- Re{Y_{1d}}<0 introduced by digital control delay T_d



Methods for Mitigation of Harmonic Instability

Frequency-Domain Impedance Passivity Control



Passive component

Resistor

Dissipate energy

Passive network

Passive network

Passive network

≈

Passive component

Resistor

Dissipate energy

Grid-forming (GFM) battery energy storage systems shall present a non-negative resistance within 0-300 Hz [1]

- In low frequency range, grid-connected converter is inherently non-passive at 0 Hz (*dq*-frame), or 50 Hz ($\alpha\beta$-frame)
- Nature of constant power operation, e.g., $P = ui$
- Impedance matrix is required for the frequency range below 100 Hz ($\alpha\beta$-frame)
- Insufficient, unnecessary stability criterion

GFM battery energy storage system shall present a non-negative resistance within 0-47 Hz and 53-250 Hz [2]

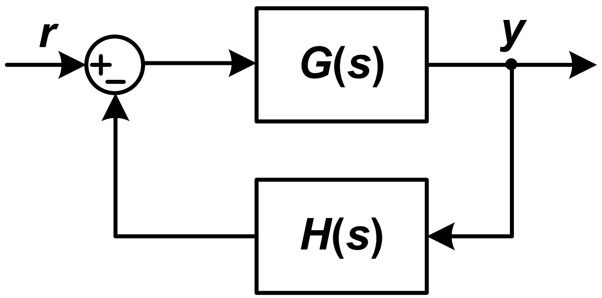
[1] NERC, "Grid forming functional specifications for BPS-connected battery energy storage systems," Sept. 2023.

[2] FINGRID, "Specific study requirements for grid energy storage systems," Jun. 2023.

Methods for Mitigation of Harmonic Instability

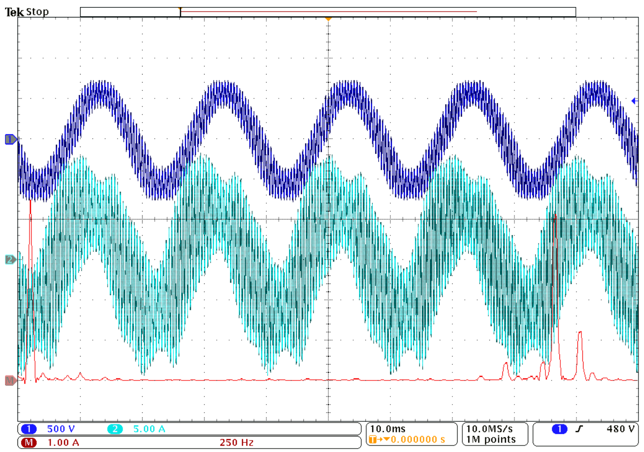
Frequency-Domain Impedance Passivity Control

- A linear, continuous system *G*(*s*) is **passive** if
  - *G*(*s*) is stable, no right half-plane poles
  - Re{*G*(*jω*)} ≥ 0, -90° ≤ arg{*G*(*jω*)} ≤ 90°
- A cascaded dynamic system is **stable** if
  - All subsystems *G*(*s*), *H*(*s*) are passive
  - Sufficient, but not necessary, condition
  - Increasingly adopted by industry



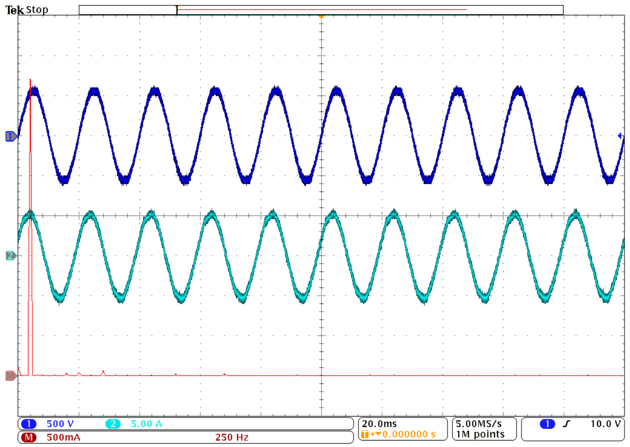
-180° ≤ arg{*G*(*jω*)*H*(*jω*))} ≤ 180°

- Minimization of control delay
  - Multi-sampling control
  - Hysteresis current control



$$G_d(s) = e^{-1.5T_s s} \Rightarrow \omega \in (\omega_s/6, \omega_s/2]$$

T_s: computation; $0.5T_s$: PWM



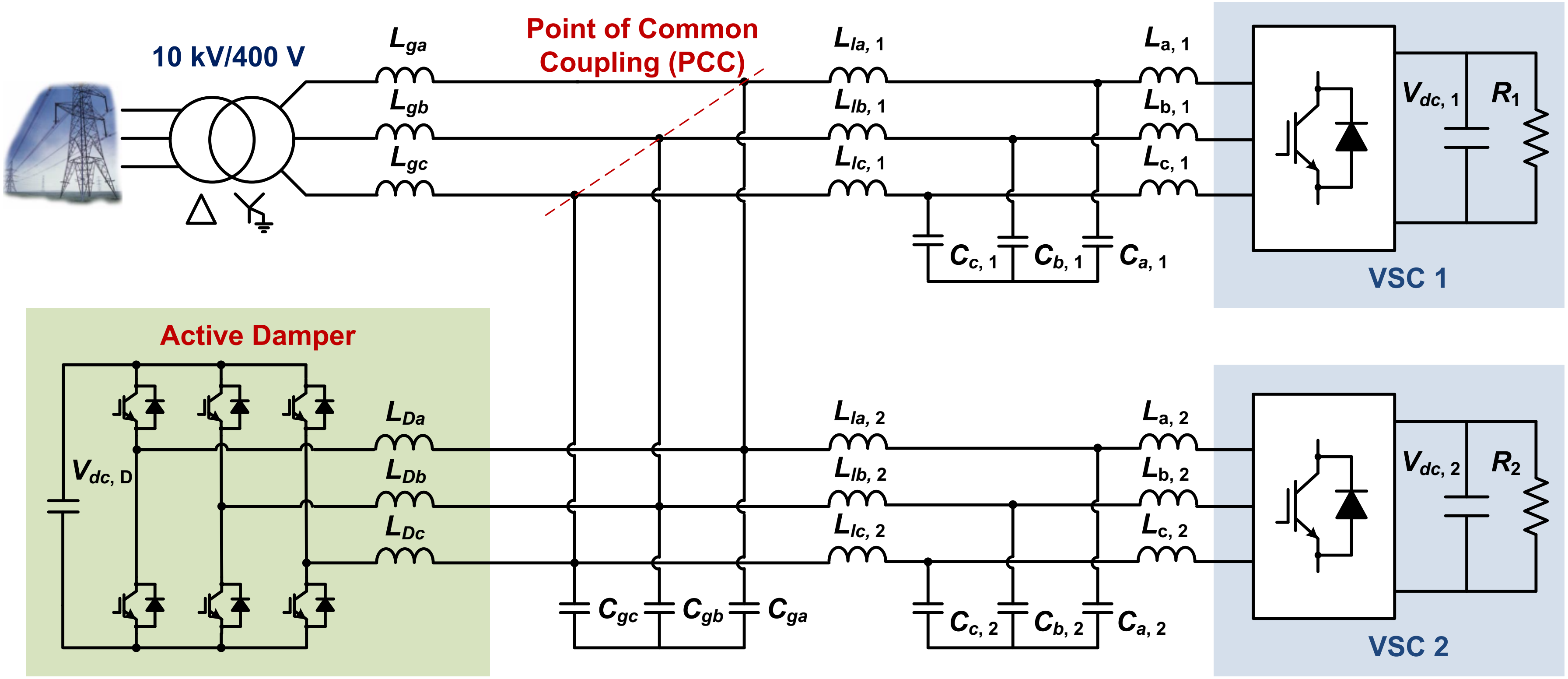
$$G_d(s) = e^{-T_s s} \Rightarrow \omega \in (\omega_s/4, \omega_s/2]$$

$0.5T_s$: computation; $0.5T_s$: PWM

Sampling instant shift with $0.5T_s$

Methods for Mitigation of Harmonic Instability

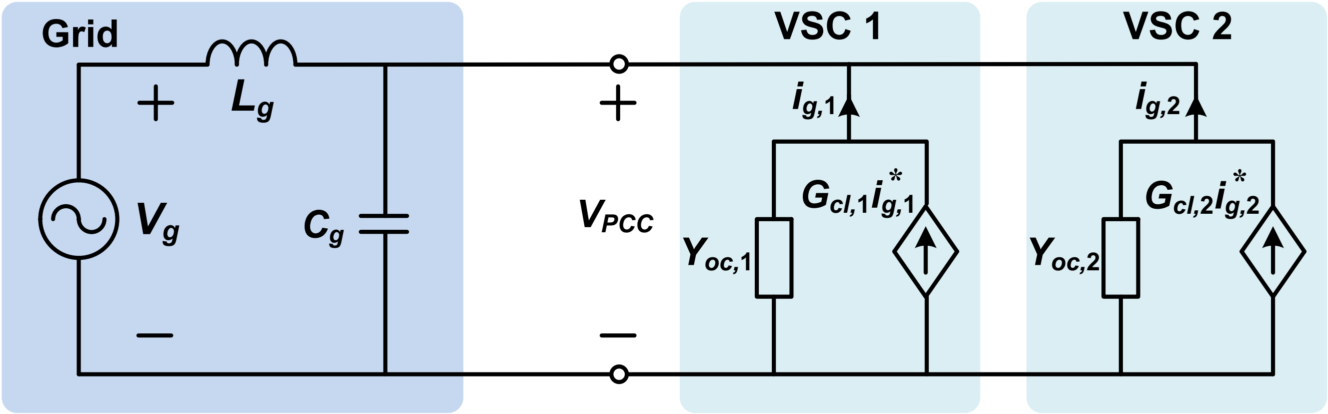
Hardware solution – active damper based on high-frequency switching power converter



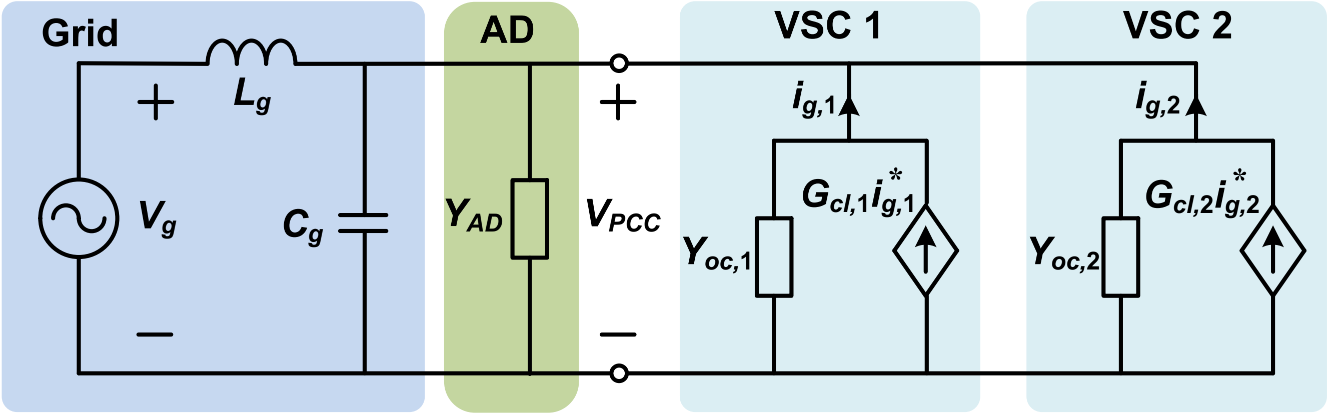
Methods for Mitigation of Harmonic Instability

Hardware solution – active damper based on high-frequency switching power converter

- Paralleled VSCs w/o AD



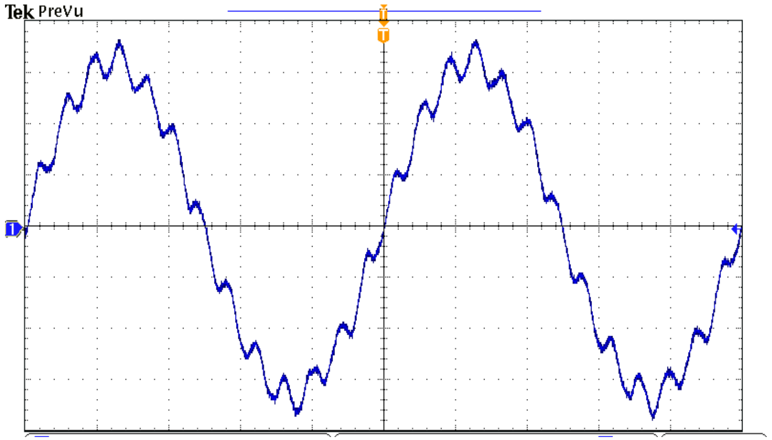
- Paralleled VSCs w/ AD



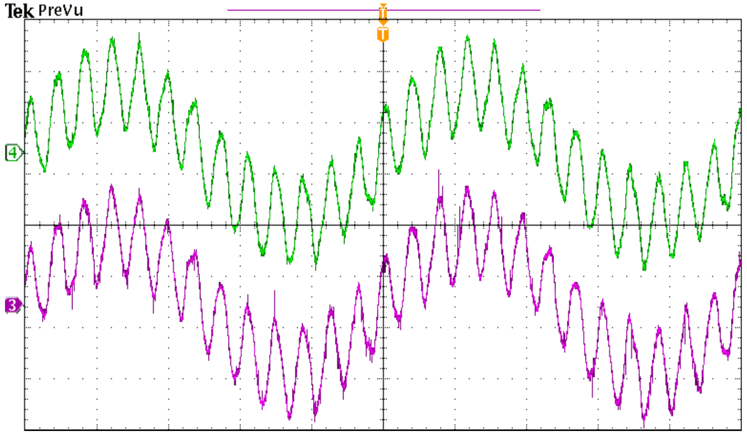
Methods for Mitigation of Harmonic Instability

Hardware solution – active damper based on high-frequency switching power converter

w/o active damper

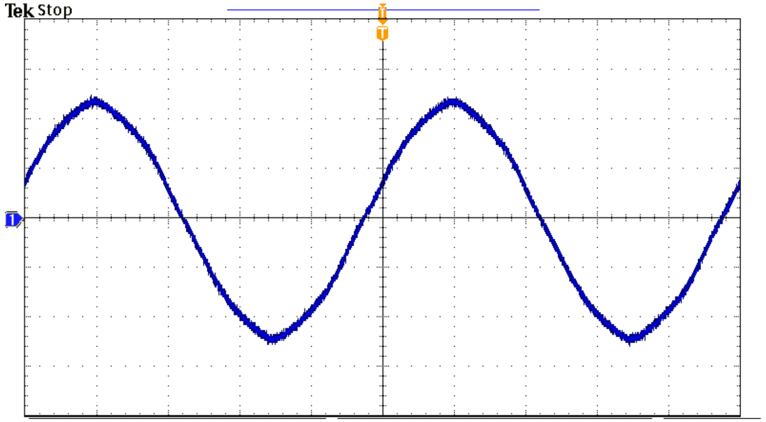


PCC voltage

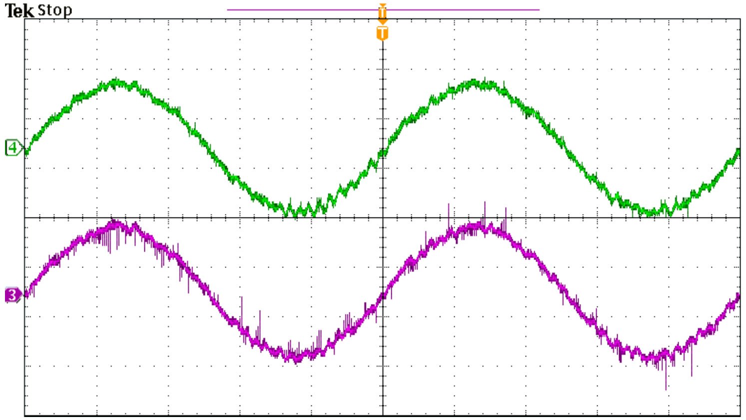


Converter currents

w/ active damper



PCC voltage

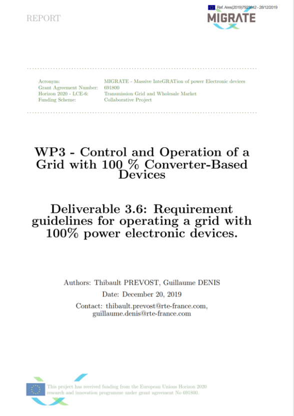


Converter currents

Methods for Mitigation of Harmonic Instability

Grid-Forming Control Driven by Transmission System Operators (TSOs)

- 2020


REPORT

Ref. Ares(2019)7923842 - 28/12/2019

MIGRATE

Acronym: MIGRATE - Massive InteGRATion of power Electronic devices
Grant Agreement Number: 691800
Horizon 2020 - LCE-6: Transmission Grid and Wholesale Market
Funding Scheme: Collaborative Project

WP3 - Control and Operation of a Grid with 100 % Converter-Based Devices

Deliverable 3.6: Requirement guidelines for operating a grid with 100% power electronic devices.

Authors: Thibault PREVOST, Guillaume DENIS
Date: December 20, 2019
Contact: thibault.prevost@rte-france.com, guillaume.denis@rte-france.com

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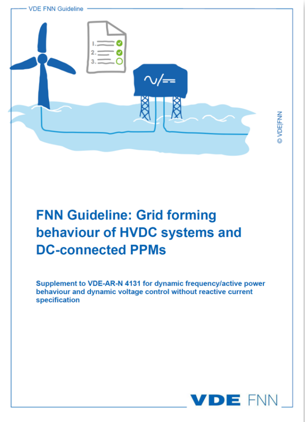
High Penetration of Power Electronic Interfaced Power Sources and the Potential Contribution of Grid Forming Converters

Technical Report

ENTSO-E Technical Group on High Penetration of Power Electronic Interfaced Power Sources

SolarPower Europe T&D europe Wind EUROPE entsoe

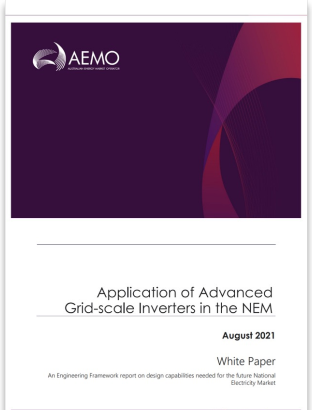

VDE FNN Guideline

FNN Guideline: Grid forming behaviour of HVDC systems and DC-connected PPMs

Supplement to VDE-AR-N 4131 for dynamic frequency/active power behaviour and dynamic voltage control without reactive current specification

VDE FNN

2021

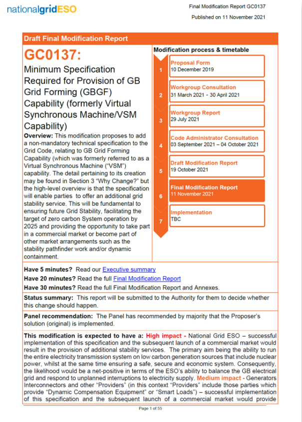

AEMO

Application of Advanced Grid-scale Inverters in the NEM

August 2021

White Paper

An Engineering Framework report on design capabilities needed for the future National Electricity Market


nationalgridESO

Final Modification Report GC0137
Published on 11 November 2021

Draft Final Modification Report

GC0137: Minimum Specification Required for Provision of GB Grid Forming (GBGF) Capability (formerly Virtual Synchronous Machine/VSM Capability)

Overview: This modification proposes to add a non-mandatory technical specification to the Grid Code, relating to GB Grid Forming Capability (which was formerly referred to as a Virtual Synchronous Machine ("VSM") capability. The detail pertaining to its creation may be found in Section 3 "Why Change?" but the high-level overview is that the specification will enable parties to offer an additional grid stability service. This will be fundamental to ensuring future Grid Stability, facilitating the target of zero carbon System operation by 2025 and providing the opportunity to take part in a commercial market or become part of other market arrangements such as the stability pathfinder work and/or dynamic containment.

Modification process & timetable

1 Proposal Form
10 December 2019

2 Workgroup Consultation
31 March 2021 - 30 April 2021

3 Workgroup Report
29 July 2021

4 Code Administrator Consultation
03 September 2021 – 04 October 2021

5 Draft Modification Report
19 October 2021

6 Final Modification Report
11 November 2021

7 Implementation
TBC

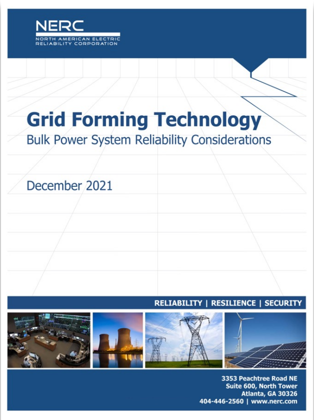
Have 5 minutes? Read our Executive summary
Have 20 minutes? Read the full Final Modification Report
Have 30 minutes? Read the full Final Modification Report and Annexes.

Status summary: This report will be submitted to the Authority for them to decide whether this change should happen.

Panel recommendation: The Panel has recommended by majority that the Proposer's solution (original) is implemented.

This modification is expected to have a: High impact - National Grid ESO – successful implementation of this specification and the subsequent launch of a commercial market would result in the provision of additional stability services. The primary aim being the ability to run the entire electricity transmission system on low carbon generation sources that include nuclear power, whilst at the same time ensuring a safe, secure and economic system. Consequently, the likelihood would be a net-positive in terms of the ESO's ability to balance the GB electrical grid and respond to unplanned interruptions to electricity supply. Medium impact - Generators Interconnectors and other "Providers" (in this context "Providers" include those parties which provide "Dynamic Compensation Equipment" or "Smart Loads") – successful implementation of this specification and the subsequent launch of a commercial market would provide

Page 1 of 55


NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

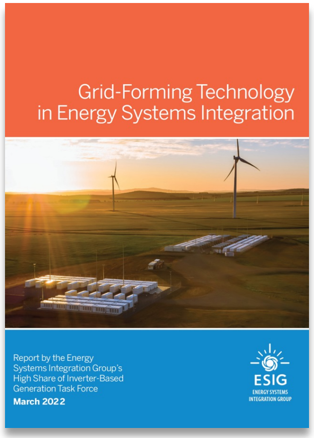
Grid Forming Technology
Bulk Power System Reliability Considerations

December 2021

RELIABILITY | RESILIENCE | SECURITY

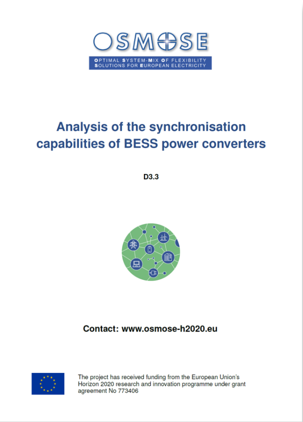
3353 Peachtree Road NE
Suite 600, North Tower
Atlanta, GA 30326
404-446-2560 | www.nerc.com

2022


Grid-Forming Technology in Energy Systems Integration

Report by the Energy Systems Integration Group's High Share of Inverter-Based Generation Task Force
March 2022

ESIG
ENERGY SYSTEMS INTEGRATION GROUP

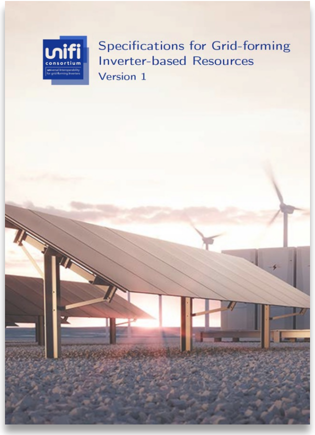

OSMOSE
OPTIMAL SYSTEM MIX OF FLEXIBILITY SOLUTIONS FOR EUROPEAN ELECTRICITY

Analysis of the synchronisation capabilities of BESS power converters

D3.3

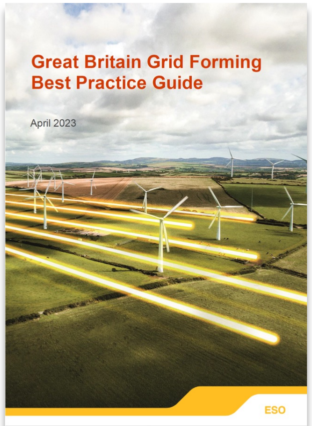
Contact: www.osmose-h2020.eu

The project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 773406


unifi consortium

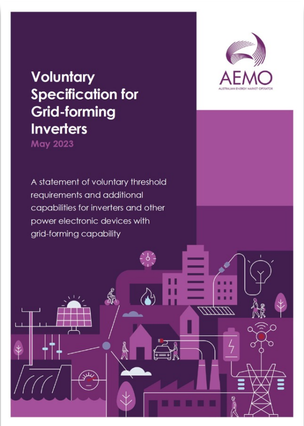
Specifications for Grid-forming Inverter-based Resources
Version 1

2023


Great Britain Grid Forming Best Practice Guide

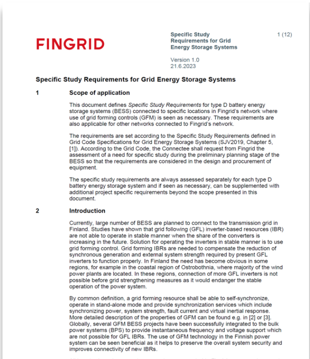
April 2023

ESO


Voluntary Specification for Grid-forming Inverters
May 2023

AEMO

A statement of voluntary threshold requirements and additional capabilities for inverters and other power electronic devices with grid-forming capability


FINGRID

Specific Study Requirements for Grid Energy Storage Systems

1 (12)

Version 1.0
21.6.2023

Specific Study Requirements for Grid Energy Storage Systems

1 Scope of application

This document defines *Specific Study Requirements* for type D battery energy storage systems (BESS) connected to specific locations in Fingrid's network where use of grid forming controls (GFM) is seen as necessary. These requirements are also applicable for other networks connected to Fingrid's network.

The requirements are set according to the Specific Study Requirements defined in Grid Code Specifications for Grid Energy Storage Systems (SJV2019, Chapter 5, [1]). According to the Grid Code, the Connectee shall request from Fingrid the assessment of a need for specific study during the preliminary planning stage of the BESS so that the requirements are considered in the design and procurement of equipment.

The specific study requirements are always assessed separately for each type D battery energy storage system and if seen as necessary, can be supplemented with additional project specific requirements beyond the scope presented in this document.

2 Introduction

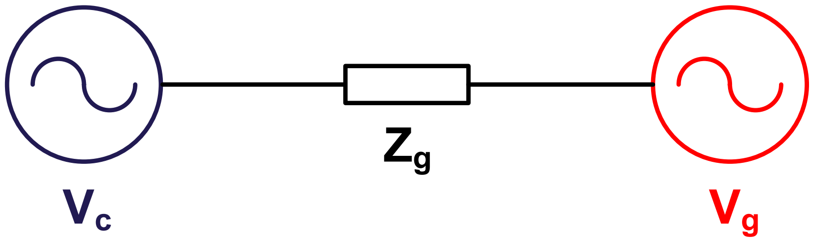
Currently, large number of BESS are planned to connect to the transmission grid in Finland. Studies have shown that grid following (GFL) inverter-based resources (IBR) are not able to operate in stable manner when the share of the converters is increasing in the future. Solution for operating the inverters in stable manner is to use grid forming control. Grid forming IBRs are needed to compensate the reduction of synchronous generation and external system strength required by present GFL inverters to function properly. In Finland the need has become obvious in some regions, for example in the coastal region of Ostrobothnia, where majority of the wind power plants are located. In these regions, connection of more GFL inverters is not possible before grid strengthening measures as it would endanger the stable operation of the power system.

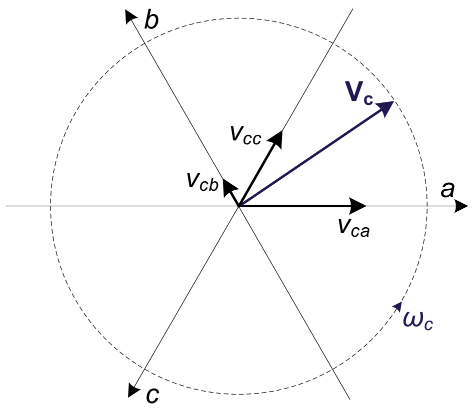
By common definition, a grid forming resource shall be able to self-synchronize, operate in stand-alone mode and provide synchronization services which include synchronizing power, system strength, fault current and virtual inertial response. More detailed description of the properties of GFM can be found e.g. in [2] or [3]. Globally, several GFM BESS projects have been successfully integrated to the bulk power systems (BPS) to provide instantaneous frequency and voltage support which are not possible for GFL IBRs. The use of GFM technology in the Finnish power system can be seen beneficial as it helps to preserve the overall system security and improves connectivity of new IBRs.

All inverter-based energy storage systems connected to Finnish power system must comply with The Grid Code Specifications for Grid Energy Storage Systems SJV2019 [1]. The grid code SJV2019 has been originally created to set the requirements for GFL inverters and consequently the requirements for emerging grid forming (GFM) technology are not addressed in the grid code. This document

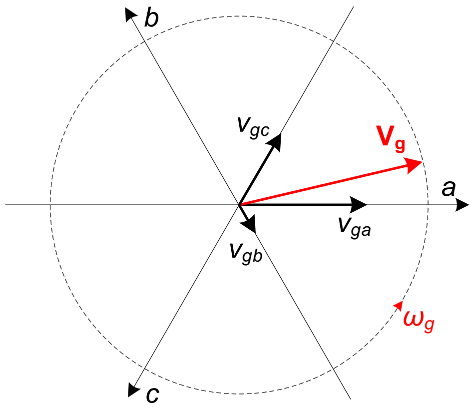
Methods for Mitigation of Harmonic Instability

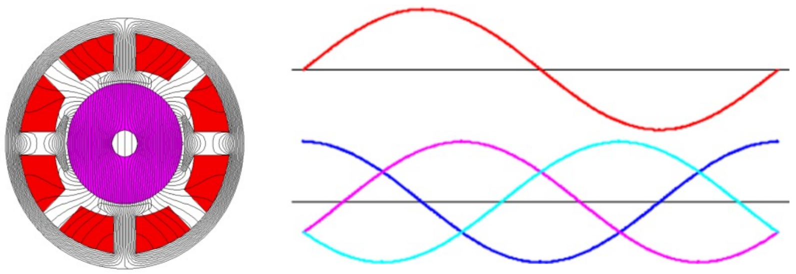
Initial Idea behind Grid-Forming Control – A voltage source in synchronism with other power sources



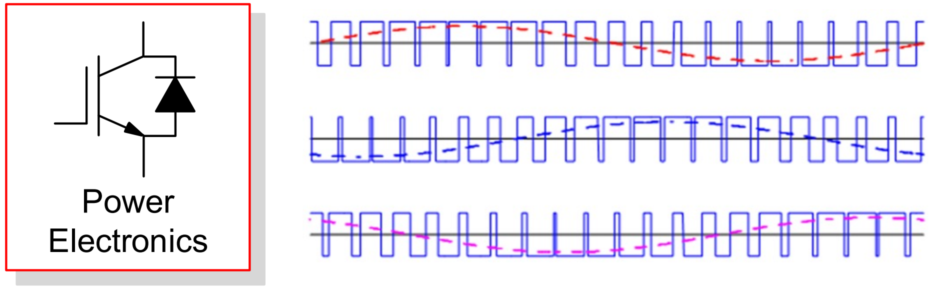


$\omega_c = \omega_g$





Synchronous machines



Power electronic converters

Methods for Mitigation of Harmonic Instability

A deeper dive into difference between legacy grid-following control and grid-forming control

Control Principle	Grid-Following Converter	Grid-Forming Converter
Synchronization	- Reliance on external voltage - Voltage-based synchronization - Phased-Locked Loop (PLL) or equivalent	- Self-synchronization - Power-/current-based synchronization - PLL may be used [1], [2]
Operation mode	- Current source in the <u>sub-transient</u> timeframe	- Voltage source in the <u>sub-transient</u> timeframe
Active power (P) control	- P-ω droop by measuring ω; constant P	- P-ω droop without measuring ω; constant P
Voltage and Reactive Power (Q) control	- Voltage magnitude (V) control - Q-V droop, constant V, constant Q	- Voltage vector control, critical to voltage stiffness - Q-V droop + P-ω droop
Current control	- Fast current control with limited response speed - Reference tracking and disturbance rejection	- Fast (natural) response speed within current limit - Overcurrent limiting + impedance shaping [3]

Takeaways

- **Harmonic stability differs from harmonic resonance in its dependence on converter control dynamics**
- **Impedance modeling of converter for harmonic stability analysis**
  - Negative real part of converter impedance causes harmonic instability
  - Origin of negative real part of converter impedance – time delay of current control, constant power operation
- **Advancements in mitigating harmonic instability are demanded**
  - Impedance passivity control – sufficient, but not necessary, condition for harmonic stability
  - Active damper based on high-frequency, high-bandwidth converter – more flexible than passive dampers
  - Grid-forming capability being required soon by power system operators

Thank You

Xiongfei Wang

xiongfei@kth.se