PROMOTioN
PROGRESS ON MESHED HVDC OFFSHORE TRANSMISSION NETWORKS

# WP16

# How to avoid converter controller interactions


WindEurope Offshore 2019

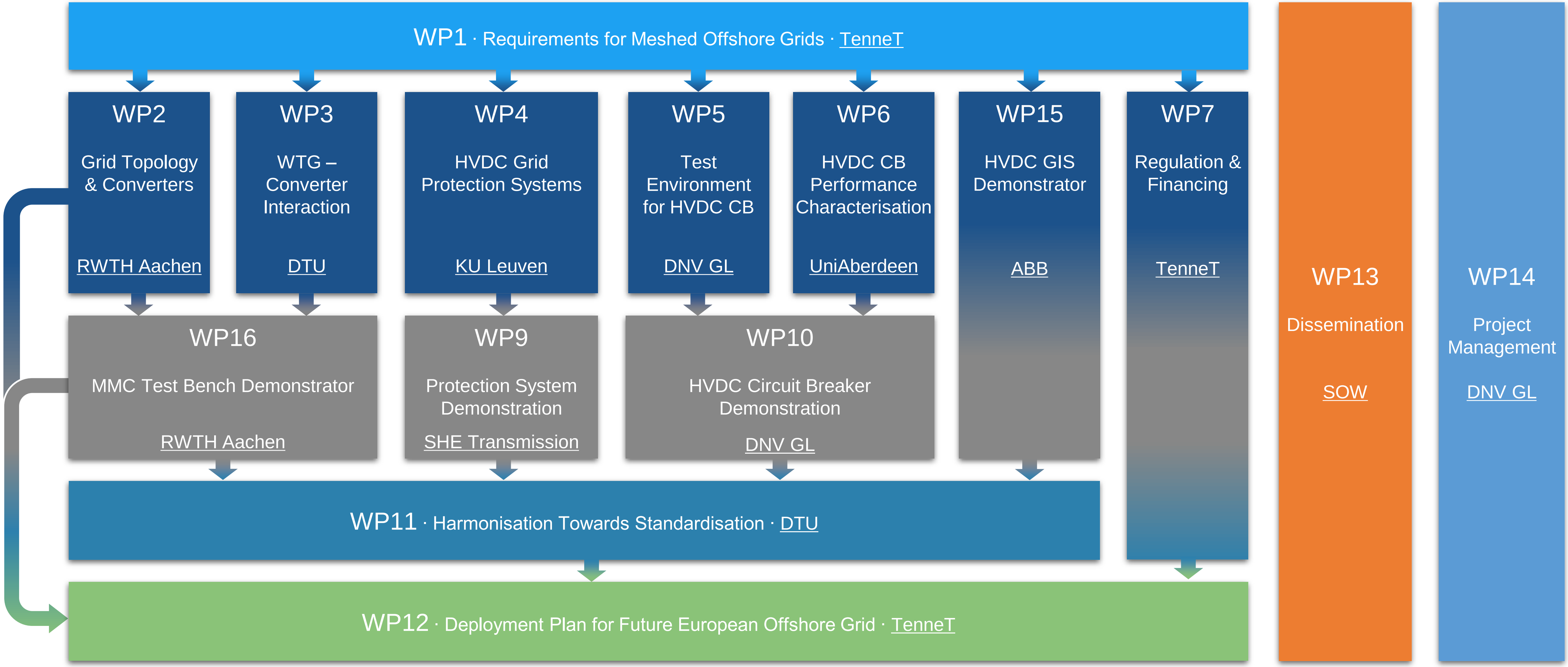
27.11.2019 – Copenhagen

Philipp Ruffing – RWTH Aachen

KTH VETENSKAP OCH KONST | DTU Technical University of Denmark | RWTH AACHEN UNIVERSITY | UNIVERSIDAD POLITECNICA DE VALENCIA | Ørsted | DNV·GL


This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691714.

# Work Packages





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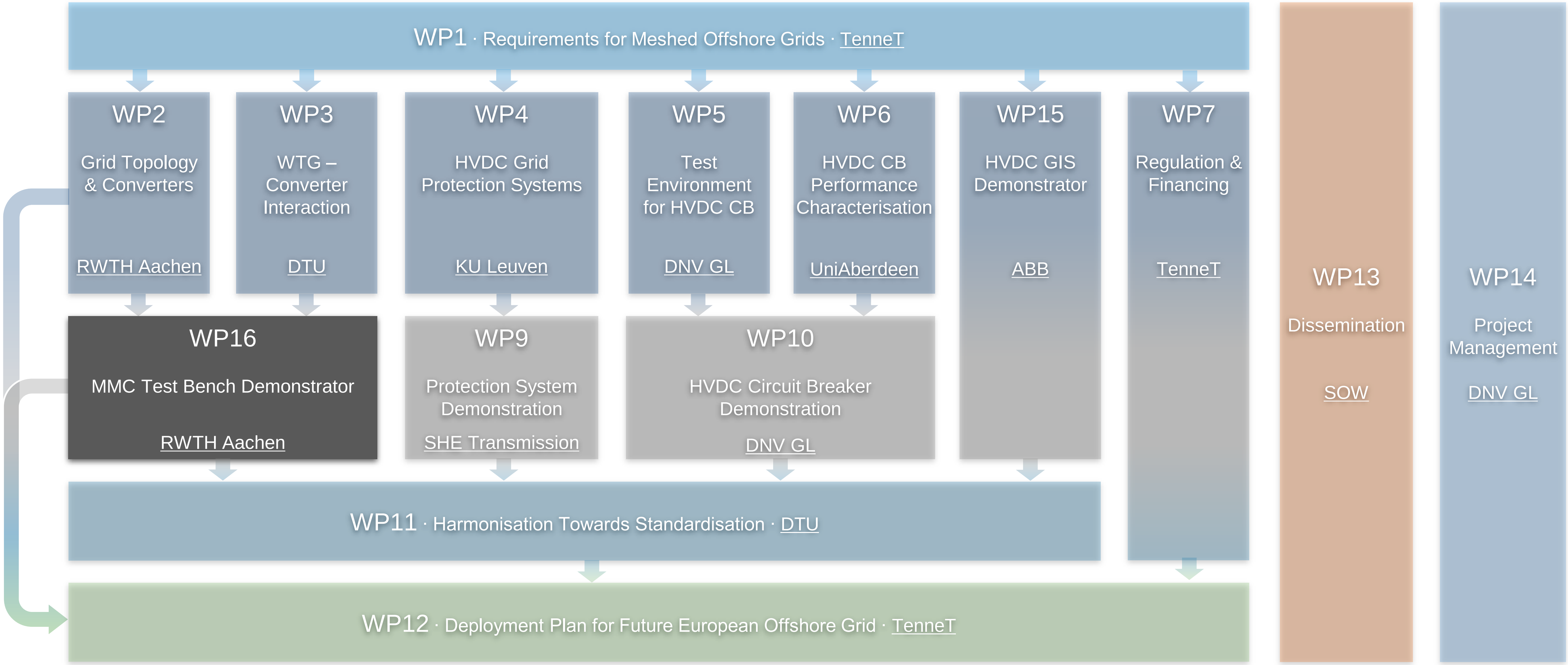



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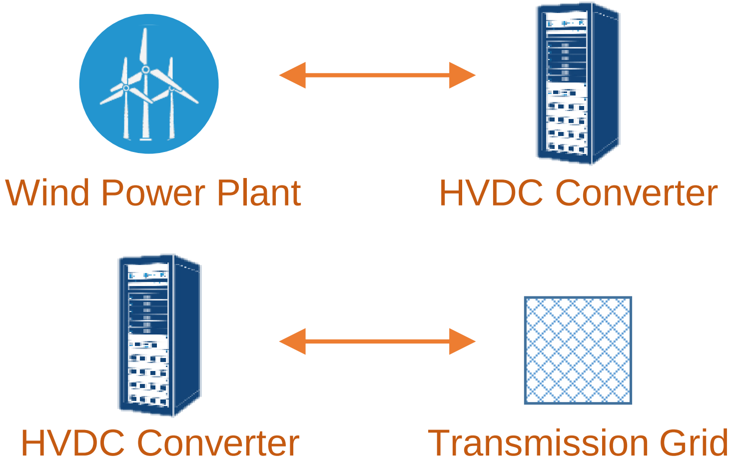
# Stability in Converter-Dominated Networks

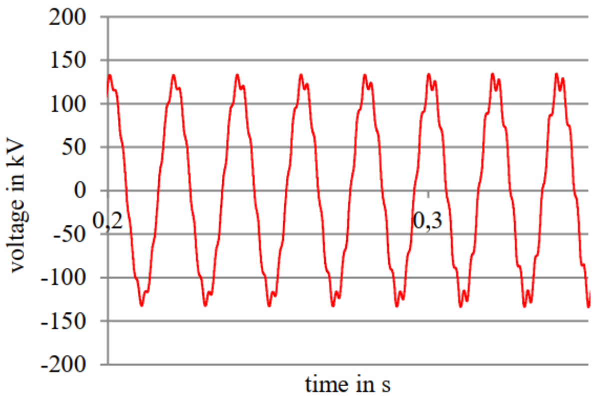


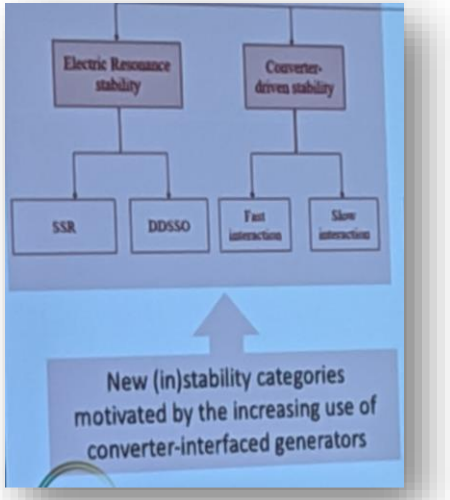

- Sustained oscillations have been observed in converter-dominated networks
  - VSC and AC grid
  - Offshore HVDC link and wind farm

- Related to resonance interactions
  - Interactions of a VSC converters with grid resonance
  - Interactions between different VSC converters

➢ Often referred to as harmonic instability

➢ Or Converter driven stability




Source: PES General Meeting 2019, Atlanta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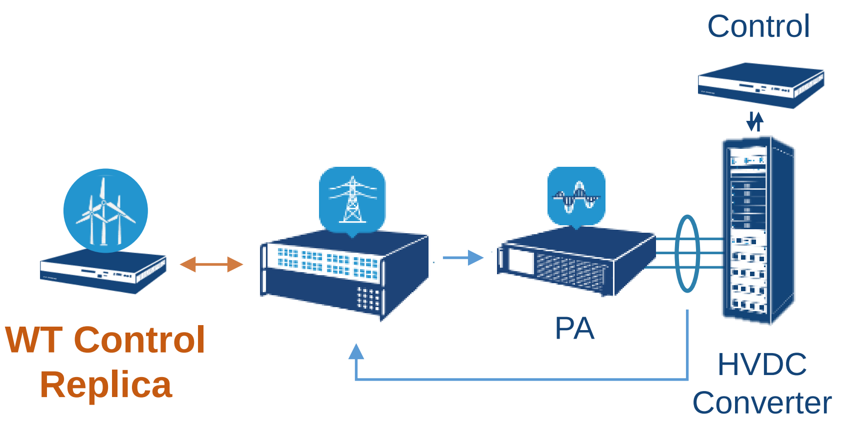
# Methods for the Investigation of Controller Interactions

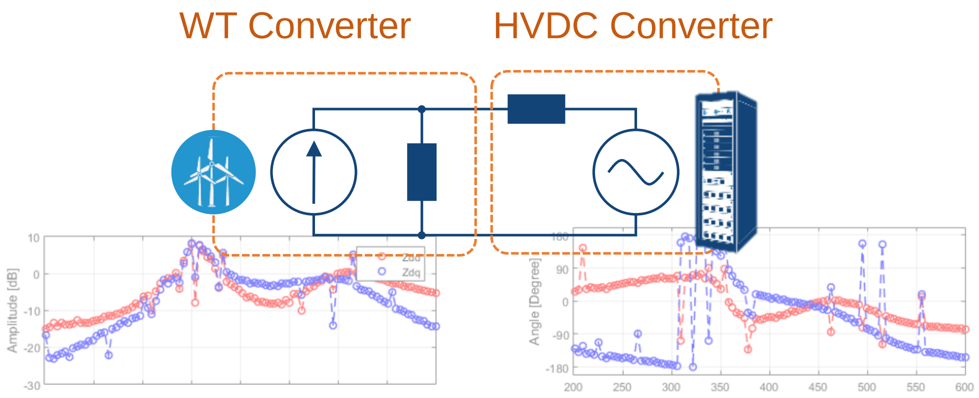
## Hardware-in-the-Loop (HiL)




Operation and control coordination between HVDC networks and Offshore wind power plants

- Grid & converter configurations
- Interaction MTDC network and OWP
- MTDC and OWP fault handling
- AC grid support with meshed offshore grids

## Impedance-based Stability Criterion




Assessment of the “harmonic” stability in offshore collector grids

- Development and validation of impedance models of wind turbine and HVDC converters
- Analysis of harmonic stability and potential interactions of active components and the AC grid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# Impedance-based Stability Criterion

## Stability analysis methods

- State-space modeling
- Time domain
- Frequency domain

➢ No consensus yet which method is applicable

Analytical derivation of the input impedance

Selection/development of a accurate method to measure converter input impedance

Input-impedance measurement of relevant converters

Stability analysis in the frequency domain

Validation of the results in the time-domain


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# Harmonic Resonance Analysis

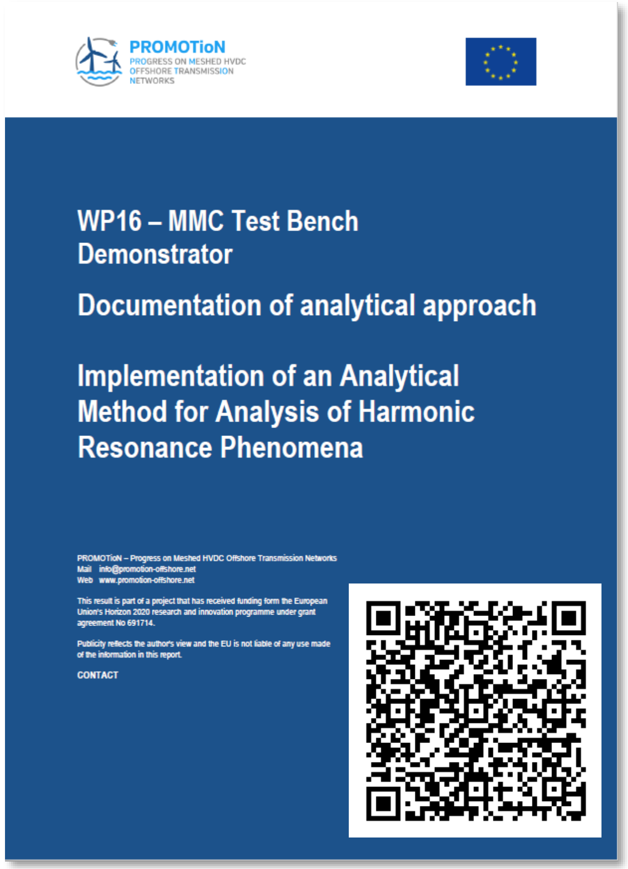
## Analytical derivation of converter impedance models

### Analytical Method (Deliverable 16.5):

Impedance derived via linearized converter models (including controls)

$$Z(s) = \frac{K_m V_{dc}[H_i(s - 2\pi f_1) - jK_d] + sL}{1 - K_m V_{dc}[(H_i(s - 2\pi f_1) - jK_d)I_1 + M_1]T_p(s - 2\pi f_1)}$$

- Insight about root causes of instabilities
- Full knowledge about converter & controllers needed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WP16 – MMC Test Bench Demonstrator

Documentation of analytical approach

Implementation of an Analytical Method for Analysis of Harmonic Resonance Phenomena

PROMOTioN – Progress on Meshed HVDC Offshore Transmission Networks
Mail info@promotion-offshore.net
Web www.promotion-offshore.net

This result is part of a project that has received funding form the European Union's Horizon 2020 research and innovation programme under grant agreement No 691714.

Publicity reflects the author's view and the EU is not liable of any use made of the information in this report.

CONTACT

### Converters under study:

- Wind Turbine Converters
- MMC-HVDC Converters
- DRU-connected Wind Turbines

https://www.promotion-offshore.net/results/deliverables/


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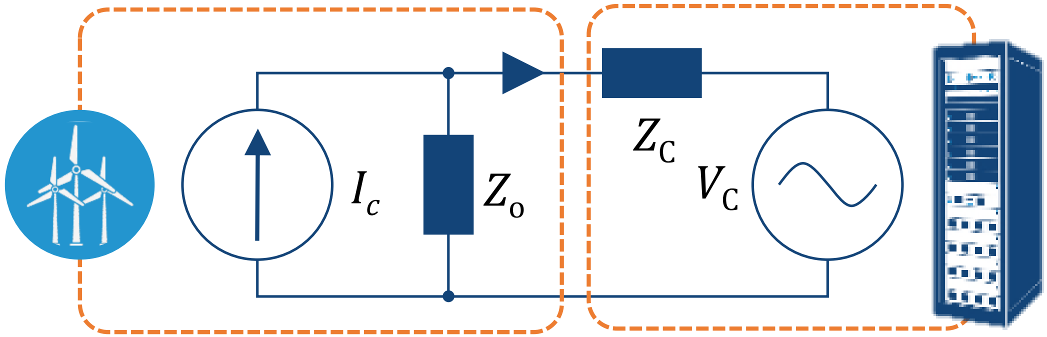
# Harmonic Resonance Analysis

## Impedance-based Stability Criterion

- Harmonic stability is assessed in the frequency domain
- System is modelled as two subsystems having frequency dependent impedances
- Stability is assessed by analyzing the loop gain $G_o(s)$ of the system




$$I(s) = \left[ I_{WTC}(s) - \frac{V_{MMC}(s)}{Z_{WTC}(s)} \right] \frac{1}{1 + \boxed{\frac{Z_{MMC}(s)}{Z_{WTC}(s)}}}$$

Characterisation of real converter behaviour is required

→ **Impedance Measurement**

- System is stable if $G_o(s) = \frac{Z_{MMC}(s)}{Z_{WTC}(s)}$ satisfies Nyquist stability criterion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# Impedance Measurement
## Overview

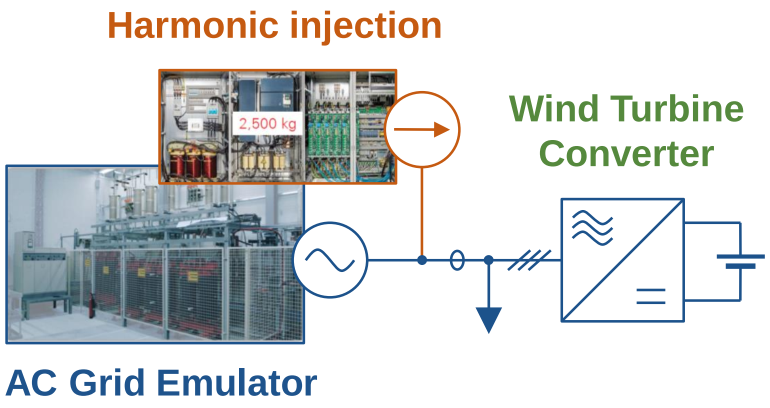
### Objectives:

- Assess characteristic of active components without opening the “blackbox” → OEM IP
- Validation of the methods

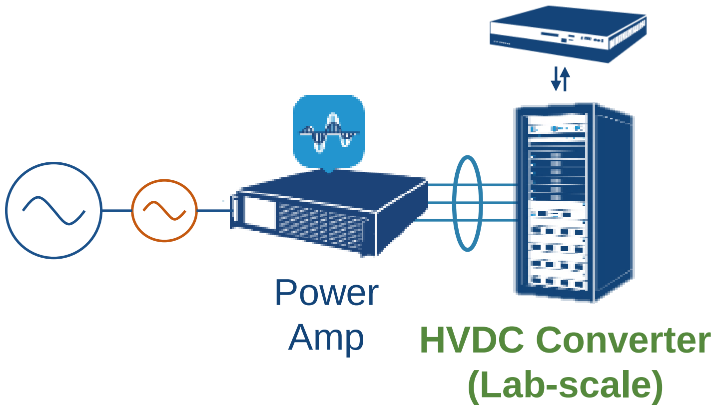
### Method:

- Impedance derived by injecting perturbation voltages or currents (freq. sweep)
- Impedance measurement for:
  - Hardware WTC (full-scale) and MMC (small-scale)
  - Converter Controller + real-time simulation
  - ➢ Comparison

**Flexible Power Grid Lab @ DNV GL**




**MMC Test Bench @ RWTH Aachen**





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# Impedance Measurement
## Wind Turbine Converters/Controllers

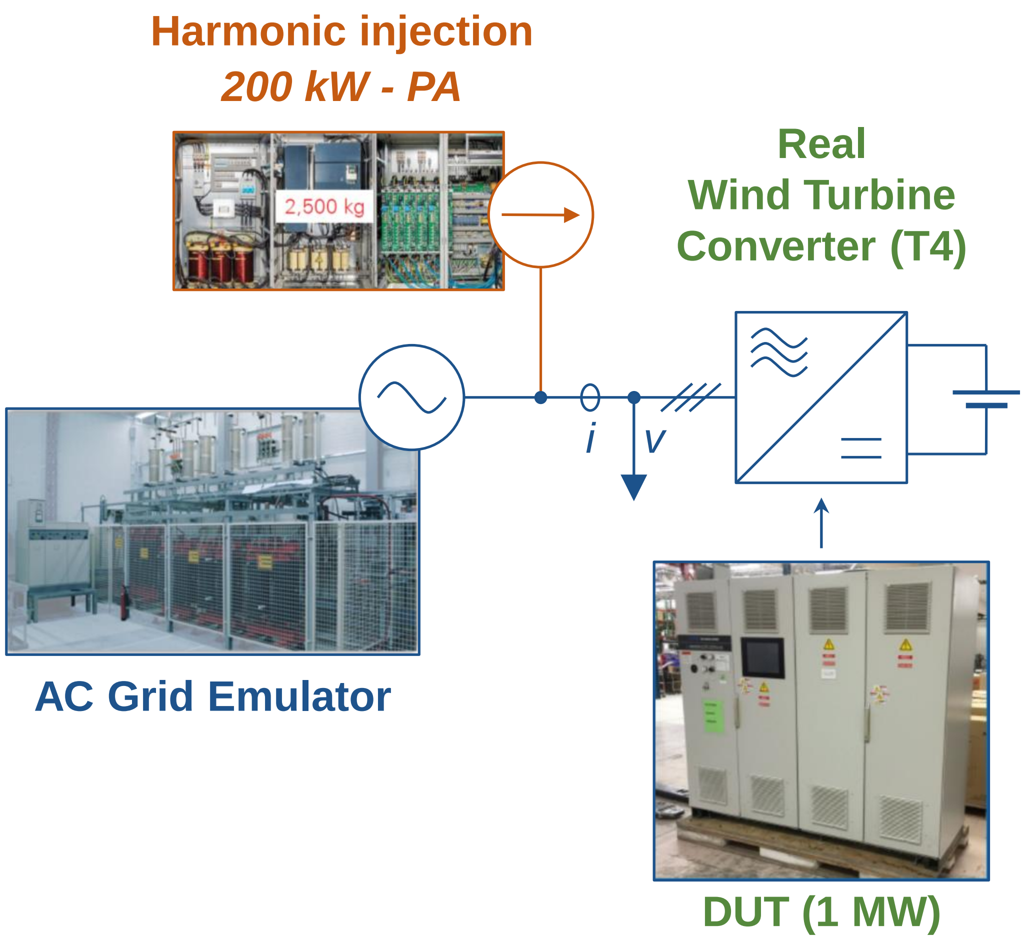
### Achievements:

✓ Development and validation of a impedance measure setup at DNV GL in Arnhem
- MW-scale converter
- Control replicas

✓ Input-impedance measurement of a commercial 1 MW wind turbine converter from Ming Yang Smart Energy, China

✓ Input-impedance measurement of the corresponding control replica

## Flexible Power Grid Lab @ DNV GL





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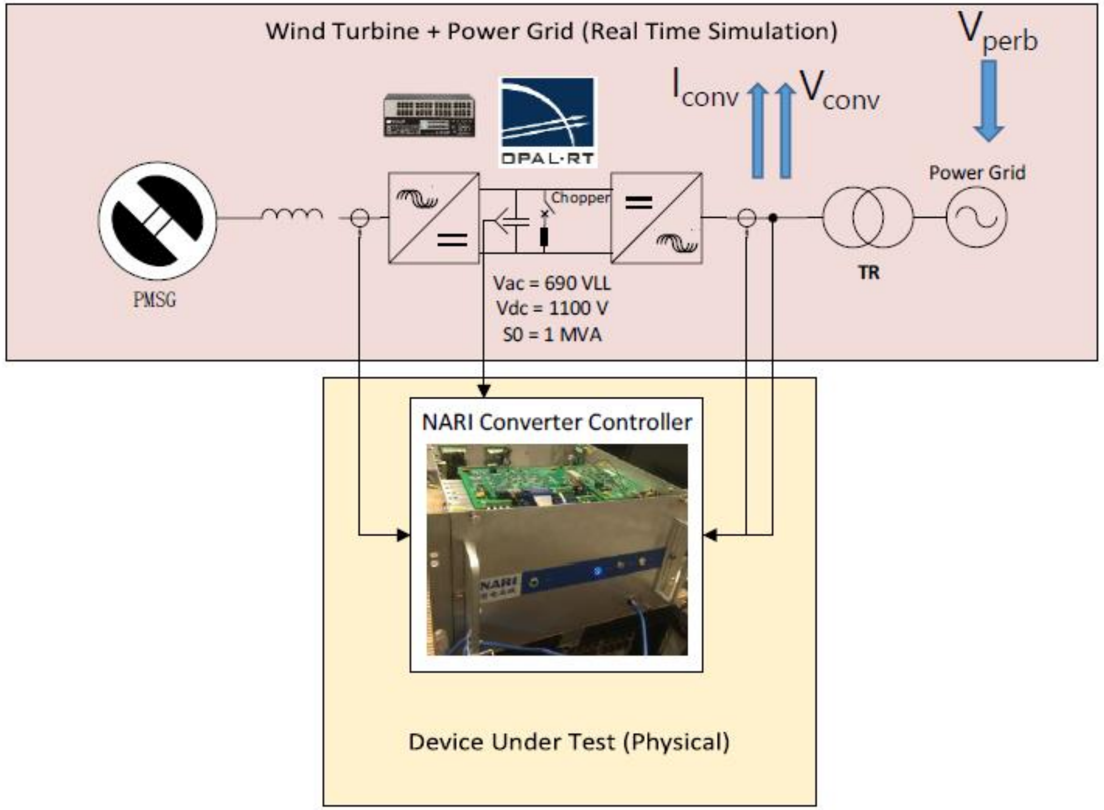



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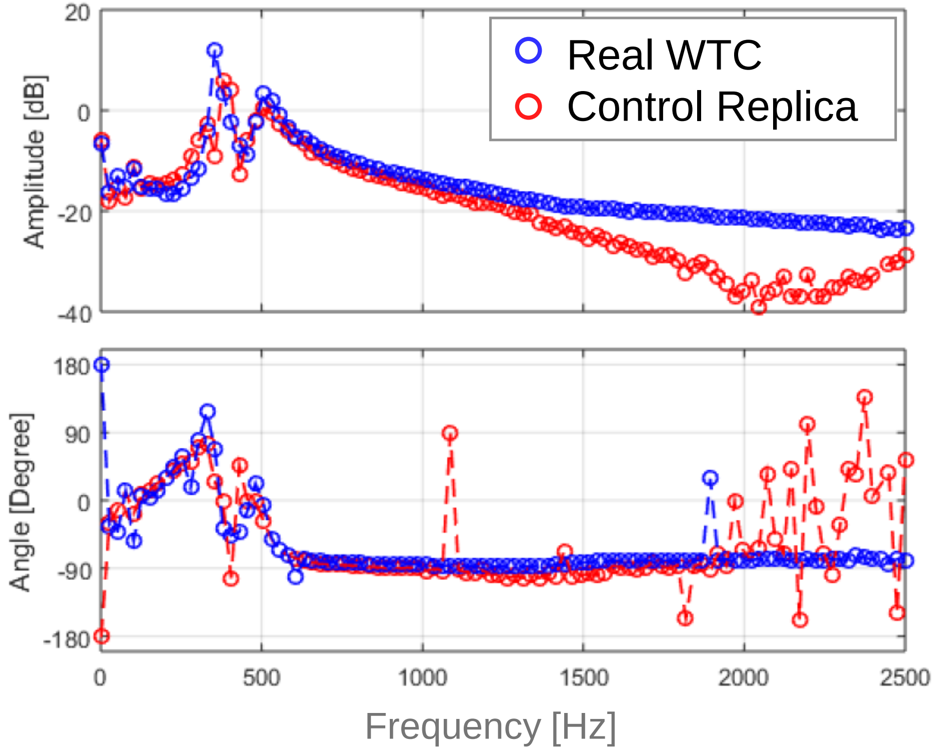
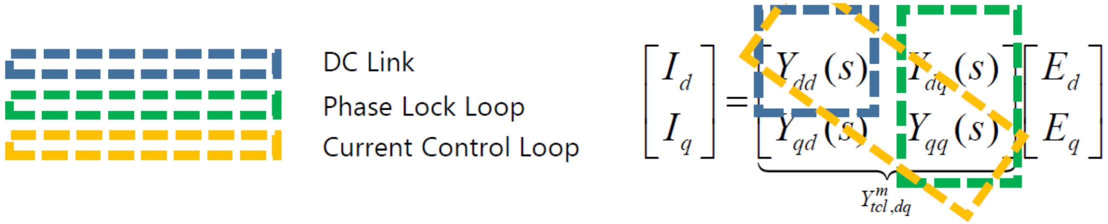
# Impedance Measurement
## Wind Turbine Converters/Controllers

### Results:
- ✓ Current perturbation method is feasible for the input-impedance measurement
- ✓ Input-impedance measurement of a commercial 1 MW converter
- ✓ Good matching between the hardware and control replica approach in the low to medium frequency range

- For frequencies above 1500 Hz:
  - Higher impact of measurement noises
  - Current perturbation through damped by decoupling transformer

### Impedance Measurement of $Z_{dd}$





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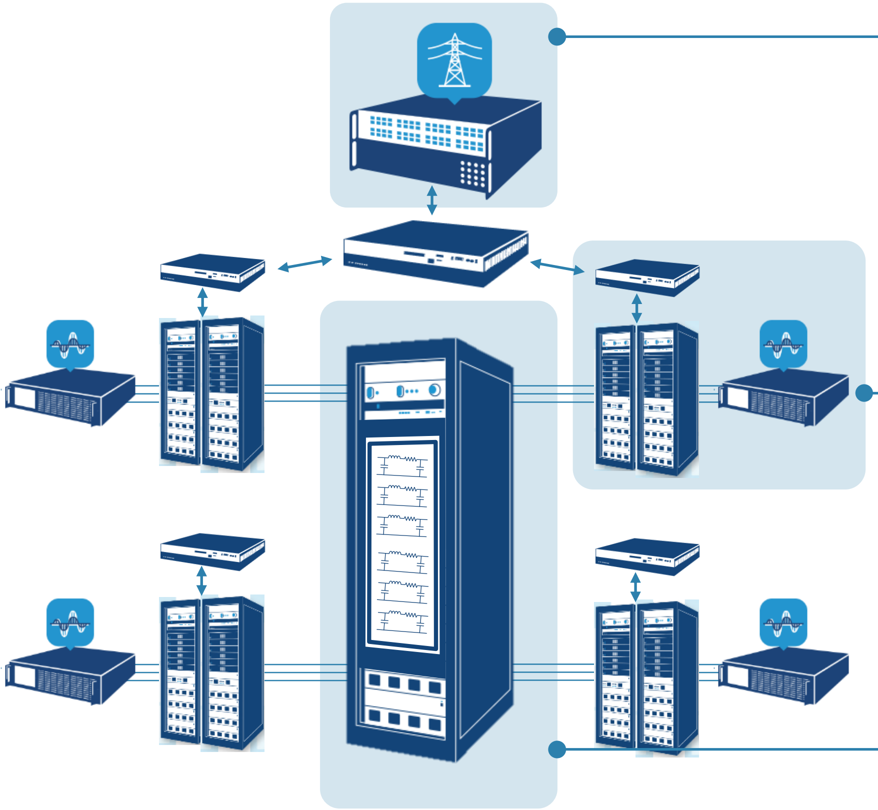
# MMC Test Bench

## Overview



### AC system and component modelling

Source: www.windpoweroffshore.com

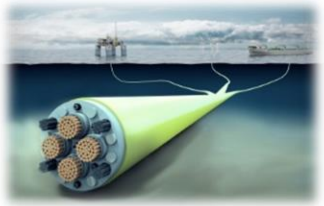
- OP5707 real-time simulator for AC grids (up to 3000 nodes) and wind farms
- OP4510 real-time simulator as DC grid controller
- 4x Puissance Plus power amplifiers (21 kVA, 4-Q operation, -3 dB at 50 kHz)

### MMC converter stations

Source:ABB

- Hardware representation of Modular Multilevel Converters with half-/full-bridge submodules (10 levels per converter arm) at laboratory scale: $V_{dc,r}$ = 400 V, $I_{dc,r}$ = 15 A
- Possibility to investigate DC grids with up to 8 converter stations in sym. monopole or up to 4 converter stations in bipolar configuration

### DC-line models



Source: www.offshore-technology.com

- 32x Pi-Line models
- Up to 800 km in bipolar grid configuration
- Up to 1,600 km in monopolar grid configuration

➢ Different DC topologies can be represented with hardware components at laboratory scale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# MMC Test Bench

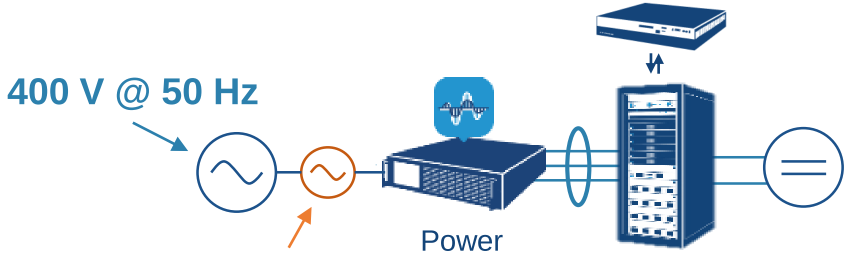
## Status Update

### Achievements:

- ✓ Good matching between MMC Test Bench and Simulations (dynamic studies → Steps and setpoint changes)
- ✓ PHiL with (strong) transmission grids and wind power plant
- ✓ Impedance measurements in grid following operation
- ✓ “Online” impedance evaluation on the FPGAs of the real-time simulator to avoid “heavy” post-processing


### Next Steps:

- Investigation of PHiL operation for wind power plants in grid forming control
- Impedance measurement of the MMCs in grid forming control
- Impact and DC faults on Wind Turbine Controls





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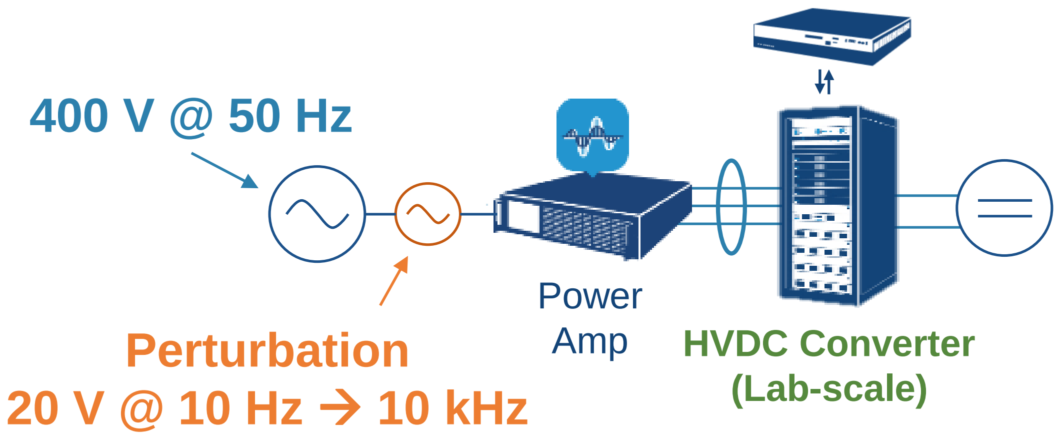
# Impedance Measurement

## MMC Test Bench



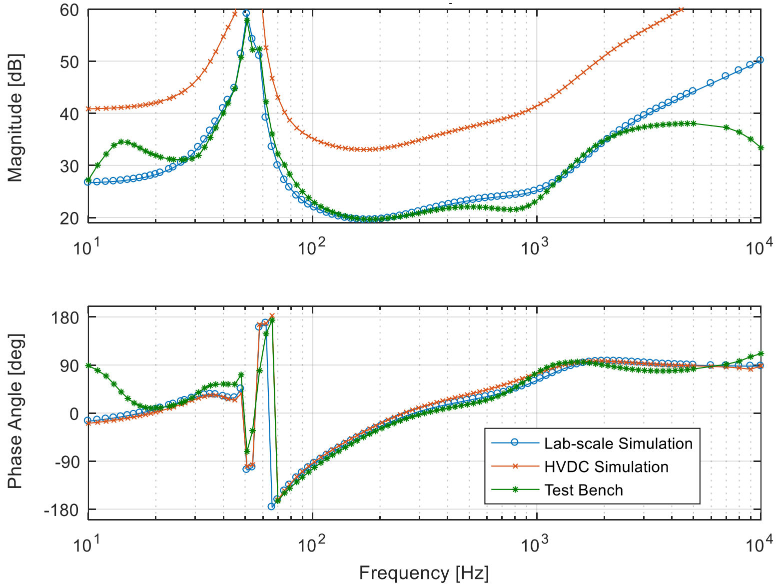

### Comparison between

- Full-scale simulation (1.2 GW – 400 $kV_{RMS,LL}$)
- Lab-scale simulation (6 kW – 400 $V_{RMS,LL}$)
- Lab-scale HVDC Converter (6 kW – 400 $V_{RMS,LL}$)
- *Scaling between full-scale and small-scale is not yet integrated in this figure*

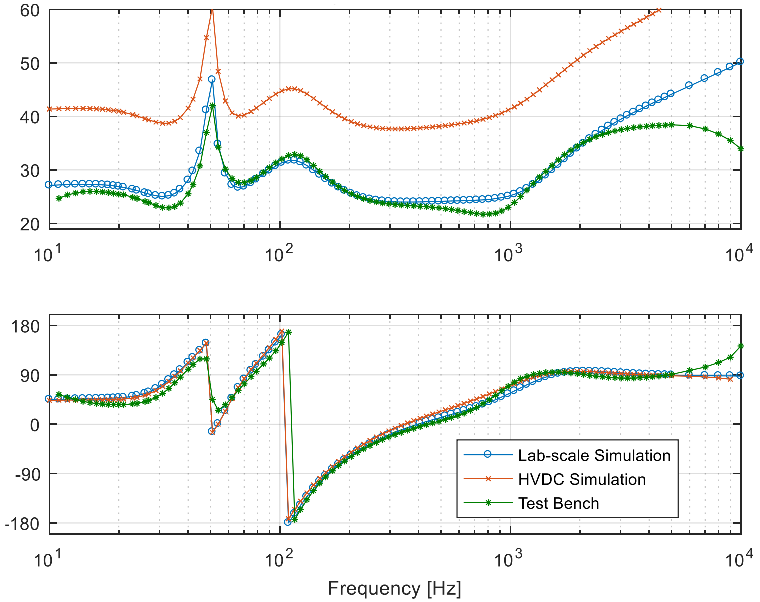
### HVDC Converter Set-point

- P-control mode
- $P_{ac}^{*} = 0.5$ p.u. / $Q_{ac}^{*} = 0.0$ p.u.

### Positive Sequence Impedance




### Negative Sequence Impedance





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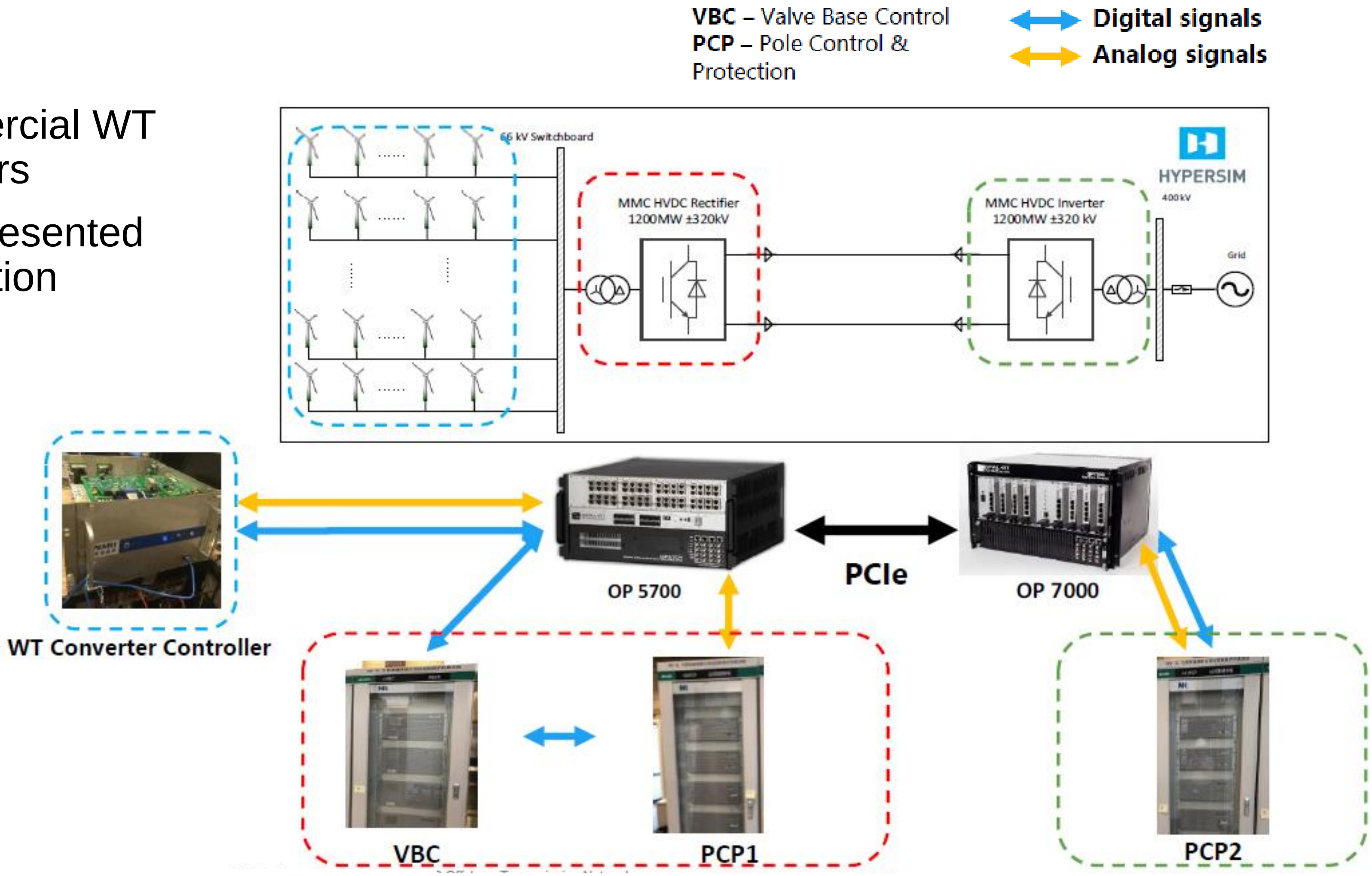
# HVDC / WT Control-Hardware-in-the-Loop

## @ DNV GL, Arnhem

- ✓ Real-time Replica with commercial WT and HVDC converter controllers
- ✓ HVDC and WT Converter represented with detailed real-time simulation

### Harmonic Resonance Analysis:

- Impedance model of a commercial HVDC MMC controller
- Time-domain validation of the results obtained in frequency domain





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# Impedance-based Stability Criterion

## Achievements & Conclusions

✓ Development of test circuits and setups for impedance measurement

✓ Blackbox impedance measurement of WT converters and HVDC MMC

- Comparison of impedance measurements physical converters and their simulation replicas (with real controllers)
  - Good matching for low to medium frequencies
  - Deviations at higher frequencies

Analytical derivation of the input impedance ✓

↓

Selection/development of a accurate method to measurement the input impedance ✓

↓

Input-Impedance measurement of relevant converters

↓

Stability analysis in the frequency domain

↓

Validation of the results in the time domain


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# Any Questions?


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APPENDIX

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