General Information

Please note that this online demonstration event will be recorded and published on the PROMOTioN website

Presentations

• Please make sure that your microphone is muted.

Questions

• Please write your questions down into the chat.
• The questions will be answered during the Q&A-sessions after each demo presentation.

Contact

• Please feel free to contact the speakers by mail after the event, if you have any further questions.
Agenda

Introduction to PROMOTioN – WP16 and the MMC Test Bench

Offshore Wind Farm Integration Using MTDC Networks
Demonstration of the operation of an MTDC network connecting offshore wind farms to shore using a power-hardware-in-the-loop

Fault Clearing in HVDC Networks
Demonstration of DC-side fault clearing using (full-bridge based) fault-blocking converters and fault clearing based on DC circuit breakers and the PROMOTioN protection IED

MMC Impedance Derivation
Demonstration of the MMC Test Bench online impedance measurement and comparison with simulation-based results
PROMOTioN
Progress on Meshed Offshore HVDC Transmission Networks

*Enabling the North Sea power house*

- Develop interoperable & reliable HVDC network protection
- Work towards technology interoperability & standardisation
- Recommendations for EU regulatory & financial framework
- Deployment plan & Roadmap for implementation up to 2050
- Technology demonstrations of:
  - HVDC control & protection systems
  - Converter harmonic model validation
  - HVDC gas insulated switchgear
  - HVDC circuit breakers
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691714.
Work Packages

WP1 - Requirements for Meshed Offshore Grids - TenneT

WP2 - Grid Topology & Converters
   RWTH Aachen

WP3 - WTG – Converter Interaction
   DTU

WP4 - HVDC Grid Protection Systems
   KU Leuven

WP5 - Test Environment for HVDC CB
   DNV GL

WP6 - HVDC CB Performance Characterisation
   UniAberdeen

WP7 - HVDC GIS Demonstrator
   ABB

WP8 - Regulation & Financing
   TenneT

WP9 - Protection System Demonstration
   SHE Transmission

WP10 - HVDC Circuit Breaker Demonstration
   DNV GL

WP11 - Harmonisation Towards Standardisation - DTU

WP12 - Deployment Plan for Future European Offshore Grid - TenneT

WP13 - Dissemination
   SOW

WP14 - Project Management
   DNV GL

WP15 - MMC Test Bench Demonstrator
   RWTH Aachen

WP16 - MMC Test Bench Demo

© PROMOTioN – Progress on Meshed HVDC Offshore Transmission Networks
This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 691714.
Overview and Objectives of WP16

Motivation:
• Meshed offshore DC systems lead to novel challenges for TSOs, manufacturers and grid planners
• Experience missing concerning
  • Multi-terminal operation
  • Interaction with the large AC transmission systems
  • Interaction with offshore wind farms

Objectives:
• Derive appropriate principles and policies to ensure interoperability between different components and technologies in meshed HVDC offshore grids
• Analysis of harmonic resonance phenomena in offshore grids (analysis of the freq. dependent impedance of MMC and WT-VSC)

Work Package 16: Investigation regarding the operation and control of meshed HVDC system
✓ Power Hardware in the Loop (PHiL)
✓ Control Hardware in the Loop (CHiL)
✓ Real-Time Simulation (RTS)
MMC Test Bench – Lab Setup
MMC Test Bench

AC system and component modelling

- 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

- Hardware representation of Modular Multilevel Converters with half-/full-bridge submodules (10 levels per converter arm) at laboratory scale: $V_{dc,r} = 400\,\text{V}$, $I_{dc,r} = 15\,\text{A}$
- 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

- 32x Pi-Line (multi frequency) 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
MMC Test Bench – Lab Setup

Power-Hardware-in-the-Loop
- AC transmission grids
- Offshore wind power plants

Control-Hardware-in-the-Loop
- DC network
- FPGA-based MMC model

MMC Controls
Same controls for different test level
- MMC Test Bench
- Digital twin (lab-scale)
- Full-scale model
Introduction to PROMOTioN – WP16 and the MMC Test Bench

Offshore Wind Farm Integration Using MTDC Networks
Demonstration of the operation of an MTDC network connecting offshore wind farms to shore using a power-hardware-in-the-loop

Fault Clearing in HVDC Networks
Demonstration of DC-side fault clearing using (full-bridge based) fault-blocking converters and fault clearing based on DC circuit breakers and the PROMOTioN protection IED

MMC Impedance Derivation
Demonstration of the MMC Test Bench online impedance measurement and comparison with simulation-based results
Offshore Wind Farm Integration Using MTDC Networks

- Network topology: PROMOTioN Network
- AC-Networks: Simulated as strong grids
- Offshore Wind Farm (OWF): Power Hardware-in-the-Loop (PHIL)
- OWF – Simulated Full-scale Model
- MMC Test Bench: OWF scaled down through the PHIL interface algorithm

### MMC Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Full-scale</th>
<th>Lab-scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal DC voltage</td>
<td>$V_{DC,n}$</td>
<td>640 kV</td>
</tr>
<tr>
<td>Nominal DC current</td>
<td>$I_{DC,n}$</td>
<td>1.875 kA</td>
</tr>
<tr>
<td>Nominal output power</td>
<td>$P_{DC,n}$</td>
<td>1200 MW</td>
</tr>
<tr>
<td>Nominal AC voltage; LL-RMS</td>
<td>$V_{AC,1}$</td>
<td>400 kV</td>
</tr>
<tr>
<td></td>
<td>$V_{AC,2}$</td>
<td>350 kV</td>
</tr>
<tr>
<td>Nominal AC RMS current</td>
<td>$I_{AC}$</td>
<td>2.582 kA</td>
</tr>
<tr>
<td>No. of Submodules</td>
<td>$n_{sub}$</td>
<td>350</td>
</tr>
</tbody>
</table>

© PROMOTioN – Progress on Meshed HVDC Offshore Transmission Networks
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691714.
Offshore Wind Farm Integration Using MTDC Networks

Test Case
- MMC Station 1: \( V_{\text{DC,ref}} = 1 \text{ p.u.}, Q_{\text{ref}} = 0 \text{ p.u.} \)
- MMC Station 2: \( P_{\text{ref}} = -0.3 \text{ p.u.}, Q_{\text{ref}} = 0 \text{ p.u.} \)
- MMC Station 3 and MMC Station 4: Grid forming control
- OWF 1: Wind speed set-point change according to Table 1
- OWF 2: Exposed to a constant wind speed of \( v_{\text{wind}} = 10 \text{ m/s} \).

MMC controls
- Based on Cigre brochure 604 “Guide for the Development of Models for HVDC Converters in a HVDC Grid” WP2 of PROMOTioN

Offshore Wind Warms
- Simulated as a synchronous generator and full-scale converter (Type 4) average model
- \( P_{\text{OWF,nom}} = 400 \text{ MW}, \text{aggregated model} \)
- Sufficient for investigations regarding control system dynamics and system interaction

Table 1 – OWF 1 Wind speed change

<table>
<thead>
<tr>
<th>EXEMPLARY TEST CASE</th>
<th>OWF 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set-point change time</td>
<td>From [m/s]</td>
</tr>
<tr>
<td>( t = 5 \text{ s} )</td>
<td>12</td>
</tr>
</tbody>
</table>
Start-up Sequence of the MMCs

1. Output of PA is activated $\rightarrow$ AC voltage is provided
2. AC Main contactor closes $\rightarrow$ Charging of the SM (via charging R)
3. AC Bypass contactor closes $\rightarrow$ charging R bypassed
4. DC Main and Bypass contactors are closed, respectively $\rightarrow$ DC voltage
5. MMC control activated $\rightarrow$ DC Voltage controlled to 400 V
Start-up Sequence of the MMCs

1. DC voltage is provided by MMC station 1
2. DC Main contactor closes → Charging of the SM (via charging R)
3. DC Bypass contactor closes → charging R bypassed
4. AC Main and Bypass contactors closed, respectively → AC voltage
5. Grid forming control activated → AC Voltage controlled to 400 V
Start-up Sequence of the OWFs

1. Three phase breaker before bus B25 is enabled
2. OWF control is enabled → Wind speed infeed of 10 m/s
3. Automatic wind speed change is applied
Comparison Test Bench vs. Full-scale

- Comparison between Full-scale, Lab-scale and MMC Test Bench
- Dynamic behavior for MMC Test Bench is not completely identical to the simulated models
  - Parasitic impedances, i.e. cable resistance from MMC to the Pi-segments influence the behaviour
Comparison Test Bench vs. Full-scale

- Comparison between Full-scale, Lab-scale and MMC Test Bench
- Dynamic behavior for MMC Test Bench is not completely identical to the simulated models
  - Parasitic impedances, i.e. cable resistance from MMC to the Pi-segments influence the behaviour
  - When the parasitic impedances are considered, then behavior almost identical
Comparison Test Bench vs. Full-scale

- Comparison between Full-scale, Lab-scale and MMC Test Bench
- Difference in DC voltage amplitude is due to calibration error
- Dynamic behavior for MMC Test Bench is not completely identical to the simulated models
  - Parasitic impedances, i.e. cable resistance from MMC to the Pi-segments influence the behaviour
  - When the parasitic impedances are considered, then behavior almost identical
Summary and Conclusion

Summary
• A MTDC network is scaled down and is implemented using the MMC Test Bench
• The MMC controls developed in WP2 and the grid forming control of the MMCs developed in WP3 are demonstrated using the MMC Test Bench
• Results show higher DC line losses for the MMC Test Bench
  • Due to the parasitic resistances
  • They lead to a different dynamic behaviour of the MMC Test Bench compared to the full-scale model
• When the parasitic resistances are considered, the system behaviour shows no significant difference

Conclusion
• The parasitic resistances must be further reduced to improve the accuracy of a full-scale system representation
• The developed controls comply with the real hardware and the independently controlled converters and WPPs.
• The interactions between the MMCs and the OWFs can be demonstrated using real hardware components.
• It is demonstrated that the MMC Test Bench and the developed controls can be used for further investigations:
  • The interactions between HVDC converters and active AC-networks, e.g. OWFs
  • Black start capability of OWFs connected via HVDC,
  • Validation of developed frequency-dependent MMC impedance models
Q&A

Offshore wind farm integration using MTDC networks
Q&A - Offshore wind farm integration using MTDC networks

Not all questions could be answered during the Q&A session. Here the answers to the open questions:

• **Question 1:** What was the SCR of AC grid 1 and 2, and how you managed to make equivalent impedance of the AC system similar to full-scale?
  • **Answer:** AC grid 1 and 2 are implemented as a stiff grids and in the investigated network they are represented as a Thevenin equivalent voltage sources with a very small equivalent grid impedance. To ensure that the impedance of the AC system is similar to full-scale, the AC grids could simply be implemented as full-scale and the reference signals that are provided to the PA then can be scaled down to a lab-scale system specifications.

• **Question 2:** How is the saturation of the converter transformers of MMC 3 modelled? Especially given the fact that you start the AC voltage like a step response, as opposed to a slow ramp up. Wouldn’t you risk saturating the transformers?
  • **Answer:** In the demonstration video it certainly looks like a step response. However, the AC voltage is provided as a ramp up function. This is unfortunately not seen in the respective scope, as the scope shown in the video is from the local console and it is not running at real time. The measurement data taken from the real-time simulators of the MMC stations are sent to the local consoles as a package information and due to the high number of scopes the refreshing rate is not optimal.
Q&A - Offshore wind farm integration using MTDC networks

• **Question 3:** What were/are the major problems you faced when you interfaced both hardware and software? Do you still have problems coupling them (i.e. scaling of the WTGs)?
  
  • **Answer:** Initially, implementing the control algorithms with the hardware components was an issue itself. Having working control algorithms in a simulation model, does not automatically mean that they will work for a hardware system, as several factors, such as parasitic phenomena are usually not considered in a simulated model, which can lead to an unstable behaviour. One of the major issues is the stability of the interface algorithm. A proper interface algorithm has to be found for a respective AC network. This is still an issue when weaker grids are considered. The WTG are simulated as full-scale models for all the cases. For the lab-scaled model and the MMC Test Bench, the Output current from the OWF is scaled down and the output AC voltage from the MMC station is scaled up.

• **Question 4:** On slide 16, the OWF model has been modelled to be equivalent 200*2MW (i.e. by using aggregated model). My question is which approach you have used to model the WTG? i.e. have you made one unit, but you scaled it up from rating point of view to 400 MW or which other approach have you used?
  
  • The OWF is implemented as an aggregated model. Here a single WTG is used and the power rating of the aggregated model is scaled up to represent a 400 MW OWF. The OWF is simulated as a synchronous generator and a Type 4 average model full-scale converter. The OWF average model cannot accurately represent harmonics, however it is sufficient to investigate the dynamics resulting from the control interaction between the MMC controls and the OWF controls. Furthermore, using an average model OWF makes it possible to use the same simulated OWF model for the offline simulation models and the MMC Test Bench, as with the average model a higher simulation time step of some tens of μs can be used.
Agenda

Introduction to PROMOTioN – WP16 and the MMC Test Bench

Offshore Wind Farm Integration Using MTDC Networks
Demonstration of the operation of an MTDC network connecting offshore wind farms to shore using a power-hardware-in-the-loop

Fault Clearing in HVDC Networks
Demonstration of DC-side fault clearing using (full-bridge based) fault-blocking converters and fault clearing based on DC circuit breakers and the PROMOTioN protection IED

MMC Impedance Derivation
Demonstration of the MMC Test Bench online impedance measurement and comparison with simulation-based results
Introduction – HVDC Fault Handling

Fault handling is a key challenge in HVDC networks

- Reliable and fast separation of DC faults
- Limitation of fault propagation and protection of system components
- DC faults must not endanger the AC system stability

**Non-Selective**
- Entire DC grid is one protection zone
- Entire DC grid is temporarily shut down

**Partially Selective**
- DC grid is split into different protection zones
- Faulted line is separated in faulted zone, healthy part in operation

**Fully Selective**
- Every line is a single protection zone
- Only the faulted line is separated
Introduction – Fault Separation Philosophies

Fast DC Circuit Breakers

- Fault separation by fast DC circuit breakers
- High requirements on DC switchgear

Fault Blocking Converters

- Fault separation under near-zero current and voltage conditions
- Reduced requirements on DC switchgear

Faulty Line

Fault Isolation

DC CB Current

Faulted Line

Protection Zones

Fault Feeding Converter (i.e. Half-Bridge MMC)

Fault Blocking Converter (i.e. Full-Bridge MMC)
Introduction – The DC Bypass Concept

The DC Bypass:
➢ DC side interconnection of one (or more) HVDC links

Benefit:
➢ Reduction of transmission losses by avoiding unnecessary DC-to-AC-to-DC power conversions

Possible application cases:
➢ Bypassing AC collector grids (for instance interconnected offshore wind farms)
➢ Interconnection of existing (or future) point-to-point HVDC systems (e.g. NordLink/SuedLink, NorthConnect/Eastern HVDC Link, South-West Link/Hansa PowerBridge, …)
Introduction – Exemplary Study Case: SWL & HPB - Bypass Hurva

The South-West Link:

The Hansa PowerBridge:

Same AC connection point

→ DC Bypass

Pictures: www.svk.se
### Introduction – Overview of the DC Bypass Structure

**Challenge:**
A line fault that is resolved too slowly would lead to both HVDC links being shut down.

**HVDC link 1**
- AC connection point
- DC Bypass Link
- Half-Bridge MMCs
- Line types:
  - 60 km OHL
  - 190 km cable
- Disconnectors

**HVDC link 2**
- AC connection point
- DC Bypass Link
- e.g. Nordic
- e.g. UCTE
- Line type: 300 km submarine cable
- Intelligent Electronic Device (IED)
- Fast DC circuit breakers (DCCB)

**Line types**
- 60 km OHL
- 190 km cable

**Specifications**
- $P_{DC,\text{rated}} = 600 \text{ MW}$
- $V_{DC,\text{rated}} = \pm 300 \text{ kV}$
Introduction – (Simplified) Test Bench Setup

PI section parameters:
(one element represents ~40 km line length)

<table>
<thead>
<tr>
<th></th>
<th>OHL</th>
<th>Cable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance</td>
<td>R</td>
<td>37 mΩ</td>
</tr>
<tr>
<td>Inductance</td>
<td>L</td>
<td>10 mH</td>
</tr>
<tr>
<td>Capacitance</td>
<td>C</td>
<td>25 µF</td>
</tr>
</tbody>
</table>

\[ V_{\text{pole-pole}} = 400 \text{ V} \]
\[ I_{\text{max}} = 15 \text{ A} \]

Fault Detection Unit: KTH Test Bench IED *
* Built by KTH and extensively tested within the PROMOTioN project by „The National HVDC Centre“ in Scotland

Fault Clearing: KTH Test Bench Circuit Breaker

© PROMOTioN – Progress on Meshed HVDC Offshore Transmission Networks
This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 691714.
Introduction – Corresponding Simulink Implementation

1. Line Fault (P-GND)

2. Fault Detection Unit (IED Model) → undervoltage, voltage derivative & overcurrent

3. DC Circuit Breakers (DCCBs)

P_in = 0.3 pu → P_out,new = 0.6 pu

AC 1

Operation shall continue

DC voltage control mode

P_in = 0.3 pu

AC power control mode

AC connection point to be bypassed

P_out = 0.1 pu (P = 0.0 pu)

P_out = 0.5 pu

AC 2

Operation shall stop (fault mode)

AC connection point to be bypassed

P_out,new = 0.6 pu

© PROMOTioN – Progress on Meshed HVDC Offshore Transmission Networks
This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 691714.
Demonstration – Data Recording from the MMC Test Bench (1/3)

- MMC in voltage control mode ($V_{DC} = 400$ V)
- MMC in power control mode ($P_{AC} = 0$ p.u.)

(Video)
Demonstration – Data Recording from the MMC Test Bench (2/3)

**DC voltages**
(at converter terminals)

- Fault occurs at $t = 0$ s & fast DCCBs are tripped by IED

**DC currents**
(at converter terminals)

- MMC (AC power control mode, $P_{in} = 0.3$ pu)
- MMC (AC power control mode, $P_{in} = 0.3$ pu)
- MMC (AC power control mode, $P_{in} = 0$ pu)
- MMC (DC voltage control mode, $V_{DC} = 400$ V)
Demonstration – Data Recording from the MMC Test Bench (3/3)

Algorithms & threshold values used for fault detection

Undervoltage protection triggered
Models show a highly similar transient behaviour

Slight differences presumed to be caused by:

- Different PI models: in the test bench not yet fully upgraded
- Additional components bring additional effects into the laboratory setup
- Different sampling rates for the calculation of the internal converter state
Summary

• Successful demonstration of the DC Bypass concept as a potential future application for fast DC circuit breakers
  ➢ The faultless system can continue to operate without an interruption in power transfer, while the faulty system can be successfully separated by disconnecting the DC bypass
  ➢ The faulty system goes into fault mode until the fault has been safely resolved

• Transients observed in the laboratory environment and in the corresponding offline simulations have a high degree of similarity
  ➢ Differences are likely to be caused by slight differences in the utilised PI line models and due to additionally laboratory components, e.g. connection cables (impedances increased)
Introduction – Protection Based on Fault Blocking Converters

Concept of FB Strategy

- Fault separation under near-zero current and voltage conditions
- Reduced requirements on DC switchgear

DC Fault Detection
Fault Control Mode: Terminal Current Zero

Fault Control Mode: Terminal Voltage Zero

Fault Control Mode: Line Current Zero

Trip FSU

Terminal Voltage Control or Terminal Current Zero

Grid Discharge

Grid Separation

Grid Restoration

Limitation of Fault Current

DC Fault Localisation

Discharged DC Grid

Residual (DC) current

Residual (DC) voltage

DC voltage restoration

$\mathbf{i}_{FSU}$

$\mathbf{u}_{DC,T}$

$t$

$t$
Test Bench Setup

4-Terminal Meshed HVDC Network

- Improved PI-Sections
  - Three parallel R-L strings
  - More accurate transient behavior
- Mechanical Fault Making Switch
- IGBT based residual current breaker

MMC 1
\[ V_{DC} = 1 \text{ p.u.} \]

MMC 2
\[ P = -0.5 \text{ p.u.} \]

MMC 3
\[ P = +0.5 \text{ p.u.} \]

MMC 4
\[ P = +0.5 \text{ p.u.} \]
Demonstration of FB Protection

Before Fault

- 4 terminal meshed grid
- Closed HSS
- DC voltage ± 200 V
- MMC 1 takes $P = -0.5$ p.u.

$V_{DC} = 1$ p.u.
$P = +0.5$ p.u.
$P = -0.5$ p.u.
Demonstration of FB Protection

After Fault

- 3 terminal looped grid
- Opened HSS
- MMC 3 disconnected from DC grid
- DC voltage: ±200 V
- MMC 1 takes P = 0 p.u.

V_{DC} = 1 \text{ p.u.} \quad V_{DC} = 0 \text{ p.u.}

P = -0.5 \text{ p.u.} \quad P = +0.5 \text{ p.u.}
Results

Limitation of Fault Current

Grid Discharge

Grid Separation

Grid Restoration

Normal Operation
Results

Comparison to Simulation
- Simulation runs with the same MMC Control as the Test Bench
- High degree of consistency
- Voltage Restoration Time: 100 ms
- Increased line losses lead to small deviations in current

Successful Demonstration of the FB Protection Strategy

Validation of Simulation Model
Q&A
Fault Clearing in HVDC Networks
Introduction to PROMOTioN – WP16 and the MMC Test Bench

Offshore Wind Farm Integration Using MTDC Networks
Demonstration of the operation of an MTDC network connecting offshore wind farms to shore using a power-hardware-in-the-loop

Fault Clearing in HVDC Networks
Demonstration of DC-side fault clearing using (full-bridge based) fault-blocking converters and fault clearing based on DC circuit breakers and the PROMOTioN protection IED

MMC Impedance Derivation
Demonstration of the MMC Test Bench online impedance measurement and comparison with simulation-based results

Philipp Ruffing
Fisnik Loku
Hendrik Köhler
Matthias Quester
Philipp Wienkamp
Stability in Converter-Dominated Networks

Converter Control Interactions

- Sustained oscillations observed in converter-dominated networks
  - Weak offshore grids connected to VSC converters
  - AC grid HVDC links
- Oscillations are induced by resonances
  - Interactions of converter control systems with AC grid
  - Interactions between different converters

➢ Often referred to as harmonic instability or converter-driven stability
Stability in Converter-Dominated Networks

Frequency Domain Analysis

- Interactions are 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

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

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

Characterization of real converter behavior is required

→ Impedance Measurement
Motivation:

• Perform numerous impedance measurements to determine the converter behavior
  ✓ Influence of control loops and different control systems
  ✓ Effect of controller gain variations
  ✓ Impact of different converter operation points
  ✓ Testing of measurement parameters

Method: Sequential Injections

• Injecting perturbations of a range of frequencies
  • Perturbations are superimposed on AC grid
  • Voltage and current measurements determine converter impedance
  • High accuracy is primary objective → Sequential injections

• Direct impedance calculation in real-time during measurement period
  • No voltage and current data needs to be saved with high sampling rate
  ➢ Numerous measurements can be performed and processed easily due to low file sizes
Measurement Approach

- MMC 1 is perturbed and the response is measured
  - Voltage perturbation for grid following control
  - Current perturbation for grid forming control

- $I_{meas}$ and $U_{meas}$ are evaluated by a discrete Fourier transform (DFT)
  - Moving window with fundamental of 1 Hz
  - 1s of waiting period required for no frequency overlaps
**Impedance Measurement**

**Single Frequencies**

**Settings:**
- MMC 1 is perturbed
- Grid forming control
- Voltage perturbation ➔ Magnitude: 5% of grid voltage
- User-defined frequencies:

<table>
<thead>
<tr>
<th>Frequency [Hz]</th>
<th>Voltage [V]</th>
<th>Current [A]</th>
</tr>
</thead>
<tbody>
<tr>
<td>49</td>
<td>327</td>
<td>6</td>
</tr>
<tr>
<td>40</td>
<td>327</td>
<td>6</td>
</tr>
<tr>
<td>60</td>
<td>327</td>
<td>6</td>
</tr>
<tr>
<td>210</td>
<td>327</td>
<td>6</td>
</tr>
<tr>
<td>900</td>
<td>327</td>
<td>6</td>
</tr>
<tr>
<td>5000</td>
<td>327</td>
<td>6</td>
</tr>
</tbody>
</table>

**GUI Settings:**
- MMC 1 is perturbed
- Grid forming control
- Voltage perturbation ➔ Magnitude: 5% of grid voltage
- User-defined frequencies: 5000 Hz
Impedance Measurement

**Frequency Series**

**Settings:**
- MMC 1 is perturbed
- Grid forming control
- Voltage perturbation ➔ Magnitude: 5% of grid voltage

**Frequency series**
- $f_{\text{start}} = 60 \text{ Hz}$
- $f_{\text{stop}} = 1000 \text{ Hz}$
- 20 steps
- Logarithmic scale
- Results recorded with low sampling rate
Impedance Measurement Results

MMC Test Bench vs. Simulation

Recorded measurements:
- Measurements are plotted with respect to perturbation frequencies
- MMC Test Bench impedance is compared to simulated MMC
- Influence of control system is shown

Conclusion
- Method is able to measure the impedance of active components
- Differences in simulation and test bench can be revealed
- Outer control loops shape the impedance below 100 Hz
  Measured impedances are used for stability assessment
Q&A

MMC Impedance Derivation
Wrap-up

Introduction to PROMOTioN – WP16 and the MMC Test Bench

Offshore Wind Farm Integration Using MTDC Networks
Demonstration of the operation of an MTDC network connecting offshore wind farms to shore using a power-hardware-in-the-loop

Fault Clearing in HVDC Networks
Demonstration of DC-side fault clearing using (full-bridge based) fault-blocking converters and fault clearing based on DC circuit breakers and the PROMOTioN protection IED

MMC Impedance Derivation
Demonstration of the MMC Test Bench online impedance measurement and comparison with simulation-based results

Philipp Ruffing
Fisnik Loku
Hendrik Köhler
Philipp Wienkamp
Matthias Quester
More from PROMOTioN

PROMOTioN Final Conference

Join our final ONLINE PROMOTioN conference
North Sea Grid for the European Green Deal
How to unlock Europe’s Offshore Wind potential - a deployment plan for a resilient HVDC grid

August 24th - September 18th 2020
Pre-Pool September 21st 2020

Registration opens by the end of June 2020

Upcoming Demo Events

WP16 – Demonstration of wind turbine grid forming controller hardware-in-the-loop testing for black-start operation
  • Date: 24.07.2020 – early afternoon
  • Location: Online
  • Invitations will be sent out soon

WP9 – Demonstration of non-selective HVDC protection
  • Date: KW36
  • Location: Online
  • Invitations will be sent out soon

Newsletter
  • https://www.promotion-offshore.net/newsletter/
DISCLAIMER & PARTNERS

PARTNERS

Thank you for your attention!