HALF YEARLY MEETING DTU, ROSKILDE, DENMARK

2 - 5 December 2019
HALF-YEARLY CONSORTIUM MEETING ROSKILDE

Date: 2 – 5 December 2019

ACCESS TO THE DTU RISØ CAMPUS
1. At the gate at Risø: mention your name and that you come for the PROMOTION CONSORTIUM MEETING
2. Go to BLDG 112, foyer: pick up your name badge (MANDATORY AT THE DTU RISØ CAMPUS)

Schedule:

<table>
<thead>
<tr>
<th>Time</th>
<th>Monday, 2 December</th>
<th>Tuesday, 3 December</th>
<th>Wednesday, 4 December</th>
<th>Thursday, 5 December</th>
</tr>
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<tbody>
<tr>
<td>Morning</td>
<td>WP Meetings I</td>
<td>Plenary Session</td>
<td>General Assembly</td>
<td>Exploitation Plan II</td>
</tr>
<tr>
<td>Afternoon</td>
<td>WP Meetings II</td>
<td>Plenary Session &amp; General Assembly</td>
<td>a. Exploitation Plan</td>
<td>b. PMG Meeting</td>
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<tr>
<td>Evening</td>
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Place: DTU Risø Campus
Department of Wind Energy
Frederiksborgvej 399, Roskilde, Denmark
# AGENDA

Monday 2 December

## Work Package Meetings

<table>
<thead>
<tr>
<th>Time</th>
<th>Description</th>
<th>Where</th>
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<tbody>
<tr>
<td>Work Package</td>
<td>Time</td>
<td>Room</td>
</tr>
<tr>
<td>WP2</td>
<td>10:00 – 12:00</td>
<td>Bldg. 116, Lille Kantine</td>
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<tr>
<td>WP3</td>
<td>09:00 – 12:00</td>
<td>Bldg. 116, VIP Kantine</td>
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<tr>
<td>WP7</td>
<td>09:00 – 10:00</td>
<td>Bldg. 112, HH Koch</td>
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<tr>
<td>WP4</td>
<td>09:00 – 10:00</td>
<td>Bldg. 109, Room 202</td>
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<tr>
<td>WP6</td>
<td>09:00 – 12:00</td>
<td>Bldg. 116, Pejestue</td>
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<tr>
<td>WP15</td>
<td>11:00 – 17:00</td>
<td>Bldg. 118, Tycho Brahe/Ole Rømer</td>
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<tr>
<td>Coffee/Tea</td>
<td>10:00 – 10:30</td>
<td>Bldg. 112, Foyer</td>
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<tr>
<td>Lunch</td>
<td>12:00 – 13:00</td>
<td>Bldg. 112, Foyer</td>
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<tr>
<td>WP9</td>
<td>10:30 – 17:00</td>
<td>Bldg. 109, Room 202</td>
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<tr>
<td>WP10</td>
<td>13:00 – 17:00</td>
<td>Bldg. 116, Pejestue</td>
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<td>WP11</td>
<td>13:00 – 17:00</td>
<td>Bldg. 116, Lille Kantine</td>
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<td>WP12</td>
<td>10:30 – 17:00</td>
<td>Bldg. 112, HH Koch</td>
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<tr>
<td>WP16</td>
<td>13:00 – 17:00</td>
<td>Bldg. 116, VIP Kantine</td>
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<tr>
<td>Coffee/Tea</td>
<td>15:00 – 15:30</td>
<td>Bldg. 112, Foyer</td>
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<tr>
<td>Time</td>
<td>Description</td>
<td>Where</td>
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<tr>
<td>08:30 – 09:00</td>
<td>WP13</td>
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<tr>
<td>09:00 – 09:30</td>
<td>WP11</td>
<td>Bldg. 112, Niels Bohr Auditorium</td>
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<tr>
<td>09:30 – 10:00</td>
<td>WP15</td>
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<tr>
<td>10:00 – 10:30</td>
<td>Coffee break</td>
<td>Bldg. 112, Foyer</td>
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<tr>
<td>10:30 – 11:00</td>
<td>WP2</td>
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<td>11:00 – 11:30</td>
<td>WP3</td>
<td>Bldg. 112, Niels Bohr Auditorium</td>
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<td>11:30 – 12:00</td>
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<tr>
<td>12:00 – 13:00</td>
<td>Lunch</td>
<td>Bldg. 112, Foyer</td>
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<tr>
<td>13:00 – 13:30</td>
<td>WP6</td>
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<tr>
<td>13:30 – 14:00</td>
<td>WP10</td>
<td>Bldg. 112, Niels Bohr Auditorium</td>
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<tr>
<td>14:00 – 14:30</td>
<td>WP4</td>
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<tr>
<td>14:30 – 15:00</td>
<td>WP9</td>
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<tr>
<td>15:00 – 15:30</td>
<td>Coffee break</td>
<td>Bldg. 112, Foyer</td>
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<tr>
<td>15:30 – 17:00</td>
<td>General Assembly, WP12</td>
<td>Bldg. 112, Niels Bohr Auditorium</td>
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<tr>
<td>19:00 – Late</td>
<td>Dinner</td>
<td>Restaurant Ilden</td>
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<td>Algade 62, 4000 Roskilde</td>
</tr>
</tbody>
</table>
Wednesday 4 December

General Assembly
09:00 – 12:00 Bldg. 112, Niels Bohr Auditorium

- Amendment 8 [vote to agree with changes: more detailed information will be sent]
  o Tractebel Engineering leaves consortium and Tractebel Impact is added as full partner
  o KU Leuven and University of Strathclyde are added to WP9
  o Budget transfers
- Announce amendment 9
- D7.9 Regulatory and Financing principles for a Meshed HVDC Offshore Grid
  [Vote to approve the WP7 recommendations to be taken forward into WP12 - please prepare by reading the recommendations of D7.9 (https://service.projectplace.com/pp/pp.cgi/r278548619, chapter 15, pp72-78). A more detailed preparation document will be shared before the meeting and explained during the meeting]
- Reporting
- Demos

12:00 – 13:00 Lunch Bldg. 112, Foyer

a. Exploitation workshop | PMG
13:00 – 17:00 Bldg. 112, HH Koch

b. PMG
13:00 – 17:00 Bldg. 116, VIP Kantine

Thursday 5 December

Exploitation workshop
09:00 – 12:00 Bldg. 112, HH Koch

12:00 Lunch Bldg. 112, Foyer
WP13 Dissemination

Stiftung OFFSHORE-WINDENERGIE • Sebastian Menze
Progress Task 13.2 – Development and production of a newsletter

- **Steady increase in subscribers** for newsletter since project start
- Regular cooperation & exchange with PMG
- **Newsletter #7 for Q4/2019, topics amongst others:**
  - Mitsubishi DC Circuit Breaker test
  - Demonstration of HVDC Protection Systems
  - Impedance Characterisation of Wind Turbine Converters using PHiL & CHiL
  - MMC CHiL Test
  - Regulatory principles for meshed offshore grids
  - Summary Copenhagen activities PROMOTioN
  - Further demonstration activities
Progress Task 13.3 - Content management for website and intranet

• **Main Objective**: maintenance and constant improvement of the PROMOTioN website

• **Regular updates of news, calendar and download-sections**

• **Satisfactory numbers of visitors and page impressions** – increasing tendency

• **People stay roughly 2 minutes** on our website

• **Visitors look at ~ 2 different pages per visit** (average **bounce rate ~ 60%**)

**Visits**: Number of overall visits

**Unique Visitors**: Distinct individuals

**Page Impressions**: Number of different pages
Progress Task 13.4 - Development of a targeted mailing list

1,152 Stakeholders

- European Bodies
- Policy institutions
- Industry Stakeholders
- Financing Bodies
- Academia & Consulting
- Others

Stakeholder Categories (as of 01.12.2019)

- European Bodies: 393
- Policy institutions: 235
- Industry Stakeholders: 93
- Financing Bodies: 287
- Academia & Consulting: 124
- Others: 20
Progress Task 13.6 - Production of public reports, papers/articles, presentations

Thank you! We are right on track!

- Objectives:
  → 50 conference papers
  → 25 journal articles
  → Revision until the end of this year
  → Numbers look very promising
Progress Task 13.6. – Publications

1. Include one of the disclaimers

→ “This work has been supported by the PROMOTioN project through the European Union’s [...]”

2. Inform the related WP’s all partners

3. Upload the paper/presentation/poster to the “Publications” folder in projectplace
   (https://service.projectplace.com/pp/pp.cgi/0/1474230898)

   → Follow the naming manual (https://service.projectplace.com/pp/pp.cgi/r1474238139) and add info to the file.

4. Inform the WP leader or PC (project coordinator, Cornelis Plet, DNV GL) 45 days prior to the publication date!

5. When the paper is published, send the open access version to WP13 (Sebastian Menze s.menze@offshore-stiftung.de) to be published on the PROMOTioN website.
Progress Task 13.7. – Stakeholder Interaction Review Q3 & Q4 2019

• Support of PROMOTioN Demonstration activities

→ Converter harmonic model and black start validation, 15 August, Arnhem

→ Protection System Demonstration, 22 August, Cumbernauld

→ MMC CHiL Test, 21 November, Arnhem

• HVDC Circuit Breaker & HVDC Protection Workshop, 27 September, Brussels

• WindEurope Offshore 2019 conference & exhibition, 26-28 November, Copenhagen

• Joint dissemination activities AURES II and PROMOTioN policy study
Progress Task 13.7. – Stakeholder Interaction Review
Q3 & Q4 2019 - Converter harmonic model and black start validation

- 15 August, Arnhem
- Around 25 attendees
- Presentations by consortium partners and Chinese manufacturer „Ming Yang Smart Energy“
- Link to press release
Progress Task 13.7 – Stakeholder Interaction Review Q3 & Q4 2019 - Demonstration of protection of multi-terminal HVDC grids

• 22 August, Cumbernauld
• Around 20 attendees
• Real-time simulation test of both PROMOTioN IED as well as MEU IED
• Link to press release
Progress Task 13.7. – Stakeholder Interaction Review Q3 & Q4 2019 - MMC CHiL Test

- 21 November, Arnhem

- 25 attendees

- Press release „under construction“
Progress Task 13.7. – Stakeholder Interaction Review Q3 & Q4 2019 - HVDC Circuit Breaker & HVDC Protection Workshop

• 27 September, Brussels
• 40 attendees from TSO, Developers, manufacturers academia, consultancy and associations
• Full-day workshop format
Progress Task 13.7. – Stakeholder Interaction Review
Q3 & Q4 2019 – Regulatory & Financing Side Event

- 26 November, during the WindEurope Offshore 2019 conference & exhibition
- Between 30 and 40 attendees
- Presentation and discussion of regulatory & financing principles for MOG
- Discussion of consideration for a deployment plan for MOG

<table>
<thead>
<tr>
<th>Time</th>
<th>Title</th>
<th>Speaker</th>
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<tbody>
<tr>
<td>14:00</td>
<td>Introduction PROMOTioN &amp; overview</td>
<td>Marc Schmidt, TenneT TSO GmbH</td>
</tr>
<tr>
<td>14:15</td>
<td>Recommendations for a legal regulatory framework</td>
<td>Ceciel Nieuwenhout, Groningen Centre of Energy Law</td>
</tr>
<tr>
<td>15:00</td>
<td>Recommendations for an economic regulatory framework</td>
<td>Pradyumna Bhagwat, Florence School of Regulation</td>
</tr>
<tr>
<td>15:45</td>
<td>Recommendations for a financial regulatory framework</td>
<td>Alexandra Armeni, Deutsche WindGuard</td>
</tr>
<tr>
<td>16:30</td>
<td>Outlook and next steps in PROMOTioN towards meshed offshore grids</td>
<td>John Moore, TenneT TSO B.V.</td>
</tr>
<tr>
<td>17:00</td>
<td>End of the side event</td>
<td></td>
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</tbody>
</table>
Progress Task 13.7. – Stakeholder Interaction Review Q3 & Q4 2019 – Technical Side Event

- 27 November, during the WindEurope Offshore 2019 conference & exhibition
- Between 30 and 40 attendees
- Presentation and discussion of various technical challenges and solutions for MOG, e.g. HVDC Circuit Breakers, HVDC GIS, Network Control & Protection, standardization

<table>
<thead>
<tr>
<th>Time</th>
<th>Title</th>
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<tbody>
<tr>
<td>14:30</td>
<td>Welcome and opening</td>
<td>Mark van Stiphout, DG ENER</td>
</tr>
<tr>
<td>14:40</td>
<td>Introduction PROMOTioN &amp; overview</td>
<td>Cornelis Plet, DNV GL</td>
</tr>
<tr>
<td>14:50</td>
<td>How to export offshore wind using DC grids?</td>
<td>Christina Brandt, RWTH Aachen</td>
</tr>
<tr>
<td>15:00</td>
<td>How offshore wind can provide black start?</td>
<td>Ramon Blasco-Gimenez, UPV</td>
</tr>
<tr>
<td>15:10</td>
<td>How to protect a DC grid?</td>
<td>Geraint Chaffey, KU Leuven</td>
</tr>
<tr>
<td>15:30</td>
<td>How to apply DC Circuit Breakers?</td>
<td>Cornelis Plet, DNV GL</td>
</tr>
<tr>
<td>15:50</td>
<td>How to reduce the size of platforms with HVDC GIS?</td>
<td>Michael Gatzsche, ABB</td>
</tr>
<tr>
<td>16:10</td>
<td>How to avoid converter controller interaction?</td>
<td>Philipp Ruffing, RWTH Aachen</td>
</tr>
<tr>
<td>16:30</td>
<td>What’s the progress towards standardization and grid codes?</td>
<td>Poul Sørensen, DTU</td>
</tr>
<tr>
<td>16:50</td>
<td>Final Q&amp;A</td>
<td>Moderator: Cornelis Plet, DNV GL</td>
</tr>
<tr>
<td>17:00</td>
<td>End of the side event</td>
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</tbody>
</table>
Progress Task 13.7. – Stakeholder Interaction Review Q3 & Q4 2019 – PROMOTioN during conference programme

- 28 November, 10:45 – 12:15
- Session A11: Offshore wind, balancing, inertia and other ancillary services
- Ramon Blasco-Gimenez presented on “Grid forming wind turbine and wind power plant control for black start operation”
Progress Task 13.7. – Stakeholder Interaction Review
Q3 & Q4 2019 – Innovation Park [I]
Progress Task 13.7. – Stakeholder Interaction Review
Q3 & Q4 2019 – Innovation Park [II]
Progress Task 13.7. – Stakeholder Interaction Review
Q3 & Q4 2019 - AURES II and PROMOTioN policy study

- Different PROMOTioN partners take part in a joint policy study together with the AURES II project
- Objective: explore challenges and benefits for cross-border auctions at energy islands connecting offshore wind from different EU member states
- SOW supports joint dissemination activities
Progress Task 13.8 – External Communication activities

• Includes press and media work (e.g. press briefings, social media)

• Press briefings & background talks as well as press releases (WP7, WP9, WP16)

• All press releases created significant media attention, e.g. from Renew, Recharge and other media corporations

• Communication of news-items on Twitter channel (206 Followers) & LinkedIn
Examples of social media activity

PROMOTioN Project @PROMOTioN_HVDC - 17. Sep.
@PROMOTioN_HVDC PROMOTioN has successfully demonstrated, how multi-terminal HVDC grids can be protected - great job done at the @HVDC_CENTRE_GBI Find out more in our news- and press release: promotion-offshore.net/news_events/ne...

Du hast retweeted
reNEWS @reNEWS_ - 9. Sep.
Technology to monitor and detect faults in DC multi-terminal grids is being put through its paces at the National HVDC Centre in the UK renews.biz /55206/

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

Roskilde, 03.12.2019
Save the Date!
MIGRATE Final Conference – 4 December 2019, Brussels

https://lamapoll.de/MigrateFinalConference/
Save the Date!
PROMOTioN Final Conference - 26 & 27 May 2020

• Royal Museum of Fine Arts of Belgium, Rue de la Régence 3, Brussels
• Lunch-To-Lunch event
• High-level panels and speakers
• Presentation of PROMOTioN results
• Parallel break-out sessions
• Poster Session
• Our expectation:
  → Up to 250 attendees
Save the Date!

• PROMOTioN will be represented with a dedicated half-day session in the conference programme
• Additionally, PROMOTioN plans a separate room for dedicated PROMOTioN side events
Any Questions?
WP11 – Harmonization towards standardization

Poul Sørensen – Technical University of Denmark
Presentation at Plenary meeting, Aachen 13 July 2019
Overall Objectives:
• To support harmonization of the industry’s best practices, standards and requirements.
• To ensure that the PROMOTioN experience is utilised in harmonization work.
• To support harmonization of the work between existing and future working groups.
• To ensure that different manufacturer concepts are considered.

Expected outputs:
• Functional specifications / requirements.
• Test and measurement procedures.
• Modelling.
• Procedures for compliance validation.
WP11 Main Workflow

Harmonization Catalogue
- To provide common overview of relevant harmonization activities and potential PROMOTioN contributions

Initial Workshops
- To discuss possible new harmonization initiatives with external harmonization groups

Writing Contributions
- PROMOTioN WP11 deliverables
- Contributions to existing WGs
- Potential new work proposals
- Other

Final Workshop
- Disseminate PROMOTioN contributions
- Discuss future work
Deliverables and milestones

- Deliverables and milestones
  - D11.1 Harmonization catalogue (DTU M38)
  - D11.2 Report on harmonization of HVDC systems (RWTH M52)
  - D11.3 Report on harmonization of WPPs connected to HVDC systems (DTU M51)
  - D11.4 Report on justified recommendations to grid codes (FGH M51)
  - D11.5 Report with recommendations to best practice for compliance evaluation (FGH M42>M45)
  - D11.6 Report with summary of findings from PROMOTioN final harmonization workshop (DTU M54)

- Milestones
  - MS50 Recommended functional requirements to HVDC systems and WPPs (DTU M52)
  - MS51 Recommendations received from WP2 to 6 (DTU M38)
Harmonization Catalogue – Relevant Harmonization Activities

- CIGRE
  - SC B4
  - SC D1
  - SC C2
  - SC C4
- IEC
  - TC88 MT21 / WG27
  - TC8A
  - TC115
  - TC17
- China GB/T
- CENELEC
- IEEE-SA
- Grid codes
  - Commission Regulation – HVDC
  - Commission Regulation – Requirements for generators
  - Commission Regulation – Demand connection Code

IEA

CIGRE

IEEE

IEC

CENELEC

Grid codes

RD&D

Best practice

Standard

Requirement
Harmonization factsheets

HVDC system (to D11.2)

- Terminology and Functional Specification
- HVDC converter controls
- Controller HIL testing of MMC HVDC and STATCOM
- MMC Impedance Derivation
- Design of protection
- Classification of protection systems
- Performance evaluation of HVDC protection systems
- Cable overvoltages
- Communication protocols
- Communication interfaces
- Testing of protection devices (IEDs)
- Approach to modelling of HVDC circuit breakers
- Application and specification of HVDC circuit breakers
- Testing of HVDC circuit breakers
- GIS

HVDC connected WPPs (to D11.3)

- Harmonic impedance measurement wind turbine converter
- Black Start study (test) of offshore wind turbine
- Requirements for black-start capability
- Compliance evaluation procedure of (self-start and) black-start operation
- Generic Characterization of Electrical Test Benches for AC- and HVDC-Connected Wind Power Plants
HVDC systems
Test procedure for HVDC protection IED

• Test procedures have been developed to assess the functional performance of an HVDC protection IED (Intelligent Electronic Device)
• Test demonstrated on IEC prototype
• The tests use synthesised waveforms to examine the accuracy of the algorithm characteristic
  • Example: du/dt algorithm
• Output of test is accuracy of algorithm
• Standardization groups:
  • Interest from IEC TC95. Measuring relays and protection equipment (so far AC)
HVDC connected wind power plants
IEC standards for grid connection of wind power

• PROMOTioN contributions:
  • Test bench – Component and subsystem tests
  • Harmonic impedance test (model validation)

Wind turbine test bench

- Generic structure of wind turbine test bench:
Harmonic model validation – classes and costs

IEC TC88 MT21: Validation
CLASS 1. SIMULATED/CALCULATED BASED ON WT DESIGN
CLASS 2. VERIFIED IN THE LAB
CLASS 3. VALIDATED BY FIELD MEASUREMENTS
Test of wind turbine converter (PHIL)

- Power hardware in the loop test
  - DUT is wind turbine inverter (type 4)
  - Wind turbine rectifier inactive (controls power)
  - Controllable harmonic current injection
  - Controllable WT power from DC supply
  - Losses supplied from grid emulator
- Harmonic impedance from changes in FFT of $v_{abc}$ and $i_{abc}$
Test of wind turbine converter controller (CHIL only)

- Controller hardware in the loop test
- Real time simulation of generator, converter, filter, transformer and grid

Fig. 5. CHIL setup for the WTG controller replica input-impedance measurement
Harmonic impedance – comparison of results

- Different levels of validation (IEC 61400-21-3 classes):
  - PSCAD simulation (Class 1)
  - CHIL (Class 2)
  - PHIL (Class 3)

- Purpose to study which level is required

- CHIL test and PSCAD simulation replicate PHIL test in low to medium frequency range (up to ~1200 Hz)

- In higher frequency range, it is reported that PHIL tests suffers from measurement uncertainty and inability to inject sufficient perturbation
HVDC grid codes

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 691714.
Commission regulation – National implementation

- Commission Regulation – National implementation
  - Requirements for generators (RfG)
  - HVDC
  - Demand connection Code (DCC)

- Danish implementation also approved
  - Should be dark green

- PROMOTioN (WP2 – D2.4):
  - Comparison of implementations in Germany, Spain, Denmark and UK
  - Recommendations

https://docs.entsoe.eu/cnc-al/#implementation-maps
accessed 26 Nov. 2019
Comparison of European Network Codes

• According to Energinet, the Commission Regulation HVDC
  • Is intended as regulation for connecting HVDC components and HVDC connected PPM to the AC system
  • Was never intended to cover (multiterminal) DC grids
  • Therefore, there are only a very few requirements to the DC side.

• Some observations from NC review:
  • Voltage ranges
  • LVRT comparison of SG – WPP – HVSC-VSC
Summary and questions

• PROMOTioN has (/ will) in particular contribute to the development and demonstration of several test procedures – supporting standardization:
  • Harmonic impedance measurement of converter based systems (WTs and HVDC MMC)
  • Functional test of HVDC protection IED
  • Circuit breaker test
  • Black start capability of WPP

• Future HVDC grid code requirements will need to take into account multiterminal (and meshed) HVDC grids – requirements to DC side (from WP2 D2.4)

• Final harmonization workshop: back-to-back with PROMOTioN final conference?

• Questions?
APPENDIX

DISCLAIMER & PARTNERS

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MAIL info@promotion-offshore.net WEB www.promotion-offshore.net

The opinions in this presentation are those of the author and do not commit in any way the European Commission

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Tel +31 26 3 56 9111
Web www.dnvgl.com/energy

CONTACT
WP11: Poul Sørensen – DTU

PARTNERS

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This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 691714.
WP15

HVDC Gas Insulated Systems Demonstrator

ABB ● Uwe Riechert

Half-yearly meeting Roskilde, 2019, Tuesday, 3rd December
Milestones & Deliverables (2)

MS71 Provided DC GIS systems are tested according to the test program (54)

MS72 Test experience shared with WP11 (48) – PPT prepared

D15.4 Anonymized test reports on tests carried out (54) – first draft in 50

D15.5 Report of diagnostic analysis and condition assessment (54) – first draft in 50

D15.6 White- and position papers on pre-standardization of DC GIS testing (54) – first draft in 50

D15.8 Report on long term monitoring of DC GIS with defects (54) – first draft in 50
WP15 – HVDC GIS technology demonstrator

Task 15.1: SHE Transmission
Defining specifications and long term testing requirements

Task 15.3: DNV-GL
Long term testing of the DC GIS equipment

Task 15.2: TU Delft
Develop monitoring and diagnostic method and applicability of SF₆ alternatives

Task 15.4: ABB
Initiation of standardization activities for HVDC GIS design, testing and application

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691714.
PROMOTioN – Task 15.2. To develop monitoring and diagnostic methods for HVDC GIS equipment.

HVDC monitoring and diagnostic methods

- **Fundamental Questions**
  - Type of sensors (HFCT, Antennas)?
  - Correlation AC and DC?
  - Number and where to install sensors?
  - Which other parameters can be monitored?
### D15.5: Report of diagnostic analysis and condition assessment.
This document is the final report of the diagnostic analysis and suitability to assess the condition of DC GIS by partial discharge measurements.

<table>
<thead>
<tr>
<th>Task</th>
<th>Description</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Processing techniques</td>
<td>Discrimination of PD signals from background noise and external disturbances: Crosswavelet transform technique.</td>
<td>Abstract conference paper submitted (IEEE DEIS)</td>
</tr>
</tbody>
</table>
| - Charge estimation               | The charge estimation has been studied on small scale test bench and preliminary results have been obtained from actual size GIS. | Journal paper 1: A Novel Antenna for Partial Discharge Measurements in GIS Based on Magnetic Field Detection, *Sensors*.  
PROMOTioN – Task 15.2. To develop monitoring and diagnostic methods for HVDC GIS equipment.

From the HFCT based measuring system to the Magnetic Antenna

<table>
<thead>
<tr>
<th>Task</th>
<th>Description</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Localization</td>
<td>Feasibility study of PD source compartment location in GIS</td>
<td>Pending</td>
</tr>
<tr>
<td>- Software</td>
<td>Integration of signal post-processing techniques and visualization of data.</td>
<td>All the techniques tested and considered in the development of the project are coded in our software tool PDflex and they will be open to public.</td>
</tr>
</tbody>
</table>

D15.5: Report of diagnostic analysis and condition assessment. This document is the final report of the diagnostic analysis and suitability to assess the condition of DC GIS by partial discharge measurements.

![Graph showing amplitude over time](image-url)
### PROMOTioN WP15.2

#### Subtask WP15.2.4

<table>
<thead>
<tr>
<th>Mediums</th>
<th>SF₆</th>
<th>C₀₂</th>
<th>Fluoroketone (FK)</th>
<th>Fluoronitrile (FN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAS number</td>
<td>2551-62-4</td>
<td>124-38-9</td>
<td>756-12-7</td>
<td>42532-60-5</td>
</tr>
<tr>
<td>Boiling point (°C)</td>
<td>-64</td>
<td>-78.5</td>
<td>26.5</td>
<td>-4.7</td>
</tr>
<tr>
<td>GWP</td>
<td>23900</td>
<td>1</td>
<td>&lt;1</td>
<td>2100</td>
</tr>
<tr>
<td>Flammability</td>
<td>none</td>
<td>none</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td>Dielectric strength (relative to SF₆)</td>
<td>1</td>
<td>0.3</td>
<td>≈2</td>
<td>≈2</td>
</tr>
<tr>
<td>Toxicity TWA (ppmv)</td>
<td>1000</td>
<td>5000</td>
<td>225</td>
<td>65</td>
</tr>
<tr>
<td>Potential insulator</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Potential interrupter</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

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This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 691714.
PROMOTioN WP15.2

Long term test

- Conventional measuring system
- Non conventional measuring systems:
  - UHF antenna
  - Magnetic sensor (adapted from TUD magnetic sensor)
  - Direct current measurement
- Two defect and three type of filling gas:
  - SF$_6$ at 5 bar abs
  - 10% Fluoronitrile – CO$_2$ mixture at 6.5 bar abs
  - 6.6% Fluoroketones – Dry air mixture at 7.5 bar abs
### Long term test

<table>
<thead>
<tr>
<th>Defect</th>
<th>SF6 equivalent dielectric</th>
<th>Gas</th>
<th>2019</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>protrusion on HV conductor</td>
<td>5 bar abs</td>
<td>SF6 5 bar abs</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10%FN-CO2 6.5 bar abs</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>FK-Air 7.5 bar abs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metallic particle on solid insulator</td>
<td>5 bar abs</td>
<td>SF6 5 bar abs</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10%FN-CO2 6.5 bar abs</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>FK-Air 7.5 bar abs</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Note:**
- **we are here** indicates the position where the defect was observed.
- **1\textsuperscript{st} draft** and **final draft** refer to the drafts mentioned in the document.

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691714.
Higher amplitude of FN mixture respect to SF$_6$ under positive polarity coherent with observation in phase 1

Higher repetition frequency for FN mixture respect to SF6 coherent with observation in phase 1
WP15 – HVDC GIS technology demonstrator

Task 15.1: SHE Transmission
Defining specifications and long term testing requirements

Task 15.2: TU Delft
Develop monitoring and diagnostic method and applicability of SF$_6$ alternatives

Task 15.3: DNV-GL
Long term testing of the DC GIS equipment

Task 15.4: ABB
Initiation of standardization activities for HVDC GIS design, testing and application

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

- Bus-ducts and high voltage DC conductors
- Disconnect- and earthing switches
- Bushings
- Current- and voltage measurement sensors
Prototype installation test

<table>
<thead>
<tr>
<th>Pre-Tests</th>
<th>BLOCK 1</th>
<th>60 days -DC ZL SIM LI/SI 10 C/O</th>
<th>2 -DC HL SIM C/O</th>
<th>3 +DC ZL SIM C/O</th>
<th>4 +DC HL SIM C/O</th>
<th>BL 5 -DC HL SIM C/O</th>
<th>BLOCK 6</th>
<th>60 days +DC HL SIM LI/SI 10 C/O</th>
<th>BLOCK 7</th>
<th>30 days LC (+ and -) SIM LI/SI</th>
<th>add. Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan. 2019</td>
<td>14 month</td>
<td>April. 2020</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ZL = zero load (zero heating)</td>
<td>HL = high load (continuous heating)</td>
<td>LC = load cycle</td>
<td>SIM = Superimposed switching and lighting impulse voltage test</td>
<td>ACPD = AC partial discharge measurement at $U_{ac}$</td>
</tr>
</tbody>
</table>

Monitoring
- Gas density
- PD: UHF/Optical/HFCT
- Arc Detection
- Enclosure Temperature

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

**Block 1**
- 60 days -DC
- ZL
- SIM LI/SI
- 10 C/O

**Block 2**
- 2
- -DC
- HL
- SIM
- C/O
- 3
- +DC
- ZL
- SIM
- C/O
- 4
- +DC
- HL
- SIM
- C/O

**Block 5**
- 5
- -DC
- HL
- SIM
- C/O

**Block 6**
- 60 days +DC
- HL
- SIM LI/SI
- 10 C/O

**Block 7**
- 30 days
- LC (+ and -)
- SIM LI/SI

**Pre-Tests**
- Jan. 2019
- 14 month
- April. 2020

**Monitoring**
- Gas density
- PD: UHF/Optical/HFCT
- Arc Detection
- Enclosure Temperature

** Tests**
- ZL = zero load (zero heating)
- HL = high load (continuous heating)
- LC = load cycle
- SIM = Superimposed switching and lighting impulse voltage test
- ACPD = AC partial discharge measurement at $U_{ac}$
Additional Tests

• Additional tests
  ➢ Testing across the disconnectors
  ➢ PD measurements with real defects
  ➢ Artificial defects from TU Delft

• Extra cost till 2019 expected 124 kEUR
### Additional Tests (NON – SF6)

#### DC Insulation System Test

<table>
<thead>
<tr>
<th>Test</th>
<th>Conditions</th>
<th>Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-tests</td>
<td>Heating Dielectric Pretests</td>
<td></td>
</tr>
<tr>
<td>Long duration continuous DC voltage test</td>
<td>Maximum continuous operating DC voltage (-)</td>
<td>HL</td>
</tr>
<tr>
<td>Superimposed LIWV tests (bipolar and unipolar superposition)</td>
<td>Rated values</td>
<td>HL</td>
</tr>
<tr>
<td>Superimposed SIWV tests (bipolar and unipolar superposition)</td>
<td>Rated values</td>
<td>HL</td>
</tr>
<tr>
<td>Polarity reversal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Long duration continuous DC voltage test</td>
<td>Maximum continuous operating DC voltage (+)</td>
<td>HL</td>
</tr>
<tr>
<td>Superimposed LIWV tests (bipolar and unipolar superposition)</td>
<td>Rated values</td>
<td>HL</td>
</tr>
<tr>
<td>Superimposed SIWV tests (bipolar and unipolar superposition)</td>
<td>Rated values</td>
<td>HL</td>
</tr>
</tbody>
</table>

**JWG D1/B3.57:**
Dielectric Testing of Gas-Insulated HVDC Systems

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Additional Tests (NON – SF6)

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### Additional Tests (NON – SF6)

**Table: Test Conditions**

<table>
<thead>
<tr>
<th>Test</th>
<th>Conditions</th>
<th>Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-tests</td>
<td>Heating Dielectric Pretests</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maximum continuous operating DC voltage</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rated values</td>
<td>HL</td>
</tr>
<tr>
<td>Double polarity superposition</td>
<td>d ≥ 30 days</td>
<td></td>
</tr>
<tr>
<td>Superimposed SIWV tests (bipolar and unipolar superposition)</td>
<td>d ≥ 30 days</td>
<td></td>
</tr>
<tr>
<td>Polarity reversal</td>
<td>Rated values</td>
<td>HL</td>
</tr>
<tr>
<td>Long duration continuous DC voltage</td>
<td>Maximum continuous operating DC voltage</td>
<td>Time</td>
</tr>
<tr>
<td></td>
<td>Rated values</td>
<td>HL</td>
</tr>
</tbody>
</table>

- **U = 320/350 kV**
- **d ≥ 30 days**
Task Structure

WP15 – HVDC GIS technology demonstrator

Task 15.1: SHE Transmission
Defining specifications and long term testing requirements

Task 15.2: TU Delft
Develop monitoring and diagnostic method and applicability of SF$_6$ alternatives

Task 15.3: DNV-GL
Long term testing of the DC GIS equipment

Task 15.4: ABB
Initiation of standardization activities for HVDC GIS design, testing and application
Publications / Demonstrations

• HVDC GIS and HHB demonstration, 27th February, Arnhem
• CIGRE Session 2020: 2 paper, see ProjectPlace
• Demo – HVDC GIS, Final tests, 2020
Standardization – WP11

- Integration/addition of DC specific standardization into existing AC GIS standardization - Results from IEC SC 17 C – AHG37:
  - It is recommended to establish a new DC GIS standard
    → IEC 62271-317 DC GIS “DC gas-insulated switchgear assemblies”
    - First NWIP draft rejected due to lack of participation, second proposal with more participation
    - Start expected 2020, Uwe Riechert possible convener
  - It is recommended to establish a new DC GIL standard
    → IEC 62271-3XX DC GIL - start later
  - It is recommended to establish a new DC Common Specification standard
    → IEC 62271-5 DC Common Specification for direct current switchgear
    - This document shall cover all requirements which are common to DC GIS and DC GIL as well as air insulated DC switchgear
    - start 2020
    - Convener Motoharu Shiiki (Toshiba)

- Parallel DC GIS standardization activities
  - CIGRE SC B3 / B1: proposal for the creation of a new working group “Recommendations for dielectric testing of HVDC gas insulated system cable sealing ends”
    - Cees Plet will be convener
    - Planned start Jan 2020, final report 2021
    - Further members wanted
Any Questions?
WP2

Grid Topology & Converters

RWTH Aachen University • Christina Brantl
Objectives

Trade-off analysis of different topologies

Interconnection of VSC and DRC systems

Control concepts to ensure interoperability

To define recommendations on onshore and offshore power systems for existing grid codes
Partners - Start
Original Timeline

- Divided into four tasks:
  1. Definition of model parameters, control objectives and operational assumptions for the meshed HVDC offshore topologies
     → D 2.1: Grid topology and model specification
  2. Adaption of simulation models for the meshed HVDC offshore topologies
     → D 2.2: Scenario and test case specification
  3. Simulative investigation and functionality demonstration of the meshed HVDC offshore topology system interoperability
     → D 2.3: Simulation results and benchmark
  4. Define recommendations for minimum requirements on onshore and offshore power systems
     → D 2.4: Requirements for grid code extension
**Final Timeline**

**Month**

- **Task 2.1**: Definition of model parameters, control objectives and operational assumptions for the meshed HVDC offshore topologies
  - First discussions on grid topologies
  - Siemens NoGo decision
  - WP16 confirmation

- **Task 2.2**: Adaption of simulation models for the meshed HVDC offshore topologies

- **Task 2.3**: Simulative investigation and functionality demonstration of the meshed HVDC offshore topology system interoperability

- **Task 2.4**: Define recommendations for minimum requirements on onshore and offshore power systems
Task 2.1 Grid topology and model specification

1. Analysis of existing and planned systems
   - Input from WP 1 (D1.3)
   - Ten Year Network Development Plan (TYNDP)
   - Cigré compendium of all HVDC projects

2. Deduction of topology and component specifications
   - Comparison of different topologies
   - Representation of different technologies

3. Definition of model and control structure
   - Based on Cigré definitions
   - Different simulation time frames and scopes
   - Modelling expertise of beneficiaries
Idea: One topology for the investigations of different converter types and studies

Main parameters

- Symmetric monopole
- $U_{DC} = 640$ kV
- $P = 1200$ MW
Different topologies for different converter types
Different topologies for different system studies
Task 2.2 Implementation of converter and network models

EMT Models in PSCAD
- Mainly for AC and DC fault studies
- Variety of converter types and configurations
- Suitable for system studies according to vendors’ check
- Benchmark for other models

RMS Models
- In Eurostag, MatPat and Siemens internally
- Interaction of the DC and the AC grid
- Focus: Frequency support

Quasi-stationary in Integral
- Investigation of operational strategies
- Mainly basis for WP12 studies
Task 2.3: Simulative investigation and functionality demonstration of the meshed HVDC offshore topology

Grant Agreement description

a) Steady-state analysis
b) Investigation on operational strategies
c) Offshore DC grid operation
d) RMS dynamic analysis
e) Transient fault analysis
f) Transient analysis during AC and DC faults
g) FRT, fault handling
h) Performance evaluation during AC and DC faults
i) Combination of HVDC VSC and DRC solution
j) Simulations on combined AC-DC systems

• D2.3: Report on the simulation results (confidential)
• Considering 7 topologies for the different aspects
• Variety of test cases

➢ Extensive document > 250 pages
Publication of content of confidential deliverable via papers

DRU
- DC voltage control in off-shore wind farms with distributed diode rectifier units
- Hybrid Full Bridge-Half Bridge MML Power Converter for HVDC Diode Rectifier Connection of Large Off-Shore Wind Farms
- Hierarchical control of offshore wind farm connected by parallel diode-rectifier based HVDC and HVAC links
- Offshore AC Fault Protection of Diode Rectifier Unit-Based HVdc System for Wind Energy Transmission
- Coordinated Control of Parallel Connected DR-HVDC and MMC-HVDC Systems for Offshore Wind Energy Transmission
- Interoperability Assessment of MMC and DRU based offshore windfarms in meshed multi-terminal DC grids

AC & DC fault studies
- A Novel DC Fault Blocking Concept for Full-Bridge Based MMC Systems with Uninterrupted Reactive Power Supply to the AC Grid
- Impact of the HVDC system configuration on DC line protection
- Post-Fault Recovery for Multiterminal HVDC Networks based on Fault Blocking Converters
- Fault current control methods for multiterminal DC systems based on fault blocking converters
- Control of Offshore AC Collection Network of HVDC Connected Wind Farms during Asymmetric Offshore AC Faults
- DC Fault Control and High-Speed Switch Design for an HVDC Networks Protection Based on Fault Blocking Converters
- Impact factors on the power flow recovery in multi-terminal HVDC systems after fault clearance

Frequency support
- Droop-Based Frequency Support from Offshore HVDC Grids
- Primary Frequency Support from Offshore Wind Power Plants Connected to HVDC Grids
- On Feasibility of Autonomous Frequency-Support Provision from Offshore HVDC Grids

To be continued...
Task 2.4 Define recommendations for minimum requirements on onshore and offshore power systems

Basis

- ENTSO-E / EC network codes
- Selected national implementations of grid codes
- ENTSO-E NC gives a broad range of values, several requirements are left open to be specified by the TSO
- Not intended for multi-terminal HVDC systems

(https://docs.entsoe.eu/cnc-all#implementation-maps, accessed 6 November 2019)
Task 2.4 Define recommendations for minimum requirements on onshore and offshore power systems

National implementations

- Some aspects are specified in a similar fashion, e.g. AC FRT levels and the requirement of reactive power support
- Some aspects are specified with different timings, e.g. fast fault current contribution
- Some requirements are imposed for some countries for others not (inertia provision)
- Some national implementations exhibit more detailed requirements than others
- Some implementations specify requirements on the converter, some on the system

➢ Alignment still needed on the AC side

Task 2.4 Define recommendations for minimum requirements on onshore and offshore power systems

**DC side recommendations**

- DC voltage levels → Agreement should be achieved on voltage levels
- DC FRT → Not possible to specify without a dedicated
- General comment from TSOs: The requirements should be specified at the connection point

![Diagram of pole-to-ground voltage](image-url)

- $U_{\text{DC,max}}$ at time $t$ ($\sim$ DCCB opening time)
- $U_{\text{DC, max}}$ recovery via the converters
- Fault control + switch opening

$U_{\text{nominal}} \pm x\%$?
Thank you for your attention!
WP3

Wind Turbine Generator – Converter Interaction

DTU ● Nicolaos A. Cutululis
3 December 2019, Roskilde, Denmark
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
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

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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 - HVDC GIS Demonstrator - ABB

WP16 - MMC Test Bench Demonstrator - RWTH Aachen

03.12.2019
Objectives

Objective 1
Define functional requirements to OWFs

Objective 2
Develop test cases & control algorithms

Objective 3
Define & apply compliance evaluation

Objective 4
Recommend grid code requirements

- Diode Rectifier Unit (DRU)
- Grid forming WPP
- HVDC link
- VSC
- Onshore

Deliverable 3.8: List of requirement recommendations to adapt and extend existing grid codes
WP3 Partners
WP3

3.1 Functional requirements to WPPs

3.2 General control algorithms

3.3 Compliance evaluation procedure

3.4 Compliance evaluations based on detailed numerical simulations

WP1

WP2

WP16

WP11
Ongoing Work

- **Task 3.4**
  - **MS20** Recommendations on requirements to existing grid codes provided to WP11
    - An internal deliverable with the recommendations
  - **MS80** WP16 Test cases regarding WP3 successfully completed
    - Test reports received from WP16
  - **D3.8** List of requirement recommendations to adapt and extent existing grid codes
    - Requirements for DRU connected OWPPs
  - **D3.7** Report with the compliance evaluation results using simulations
    - Compliance test procedures for DRU connection
    - Self-Energization & Black Start
      - Requirements and Test Scenarios – HVAC and HVDC connected OWPP
      - Simulations results
      - Black start capability assessment
    - Paradigm shift from grid following wind turbines to grid forming

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D3.8 Recommendations for Requirements

Some general remarks:

• **D3.8 is providing “recommendations”, rather than specific grid code requirements.** The objective of D3.8 is to give insight and a reference when the DRU or a similar concept is being deployed in the future.

• **The set of grid code recommendations given in D3.8 are the outcome of the studies performed in WP3 and should not be considered as a complete set of requirements for DRU connection.**

• **Some of the requirements might be based on the specific structure(s) studied in WP3 (for instance the WTs are assumed as Type 4 – Full converter interfaced WTs).** Hence, the requirements should be studied together with the previous Deliverables of WP3, especially D3.1 and D3.2. For the sake of brevity, the detailed structures are not provided here.

• **The quantitative requirements in D3.8 are valid for the studied case(s) in WP3.** Hence the values (e.g. voltage range) can change depending on the case/project.

• **This document does not include a study on existing codes to identify existing requirements which indirectly assume grid following WTGs connected to VSC-HVDC rectifiers and might be incompatible with DRU use.**

• **The grid code recommendations and conclusions expressed in D3.8 are those of the authors and do not necessarily reflect those of the PROMOTioN partnering organizations.**
### D3.8 Recommendations for Requirements

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Existing grid codes</th>
<th>DRU OWPP specific</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1 Dynamic Active Power Control</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>2.2 Island Support (No HVDC or AC Connection)</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>2.3 Minimum Production Limit</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>2.4 Steady State Frequency Control</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>2.5 Optimized (narrow) frequency range</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>2.6 Dynamic Frequency Control</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>2.7 Rate of Change of Frequency (ROCOF) Limits</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>2.8 Steady State Voltage/Reactive power Control</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>2.9 Dynamic Voltage Control</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>2.10 Offshore Fault-Ride-Through</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>2.11 DC Fault Ride Through Requirements</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>2.12 Onshore AC Fault Ride Through</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>2.13 Onshore Frequency Support Requirements</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>2.14 Synthetic Inertia</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>2.15 Onshore Oscillation Damping Requirements</td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>
Example - 2.10 Offshore Fault-Ride-Through

OWPP shall be capable of staying connected to the network and continuing to operate stably after the (offshore) power system has been disturbed by faults on the offshore ac network. That capability shall be in accordance with the voltage-against-time profile at the connection point […]

Added:
After offshore AC fault isolation, the OWPP should restore the offshore AC voltage and frequency to the pre-fault condition, without significant overvoltage or overcurrent.

Figure 2.1 Example voltage-time profile for offshore AC faults [ENTSO-E NC RfG Article 16 (3) (a) (i)].
D3.7 Report with the compliance evaluation results using simulations (ongoing)

- DRU-connected WTs
  - Fundamental Operation
  - Fault response
  - Ancillary Services
- Self-Energization & Black Start
  - AC-connected offshore WPP
  - VSC-HVDC-connected offshore WPP
  - Identify gaps with respect to TSO requirements
  - Requirements recommendations
  - Comparison with industry results (MVOW and Energinet)
DRU-HVDC – Technical compliance testing via simulations

Normal operation
- HVDC link and off-shore AC grid start-up operation
- HVDC link and off-shore AC grid disconnection operation
- Intentional islanding
- Dynamic voltage control
- Wind farm power control and power tracking
- Response to changes in reactive power sharing command
- Response to active power reference commands when connected to external AC
- Disconnection / reconnection of filters

Fault ride-through and protection
- Unintended transmission capability limitation
- Umbilical AC cable faults
- Offshore AC faults

Ancillary services
- Onshore Frequency support
- Onshore power oscillation damping
## DRU-HVDC – Technical compliance testing via simulations

### Example of results

<table>
<thead>
<tr>
<th>Test case</th>
<th>4.2.11.a. DISCONNECTION OF DRU FILTERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation detail</td>
<td>WT</td>
</tr>
<tr>
<td>Level</td>
<td>Level 4: Perfect DC link control is assumed</td>
</tr>
<tr>
<td>Configuration (connected strings)</td>
<td>Compliance</td>
</tr>
<tr>
<td>6 Strings + 6 Strings + 6 Strings</td>
<td>pass</td>
</tr>
<tr>
<td>6 Strings + 3 Strings + 1 String</td>
<td>pass</td>
</tr>
<tr>
<td>6 Strings + 1 String + 1 String</td>
<td>pass</td>
</tr>
<tr>
<td>3 Strings + 3 Strings + 3 Strings</td>
<td>pass</td>
</tr>
<tr>
<td>3 Strings + 3 Strings + 1 String</td>
<td>pass</td>
</tr>
<tr>
<td>3 Strings + 1 String + 1 String</td>
<td>pass</td>
</tr>
<tr>
<td>1 String + 1 String + 1 String</td>
<td>pass</td>
</tr>
</tbody>
</table>
The connection of the DRU filters reduce the required reactive power of the off-shore ac grid. It reduces the losses of the grid. The result shows the active and the reactive power of the WTGs within a string. It shows that the active power remains at its reference value (power drop lower than 0.5%). Initially, the system has all filters connected and hence, it is over-compensated. As the filters are disconnected, the reactive power absorbed by the WTGs decreases. The opposite is true when the filters are connected.

(a) Active power (pu) of WTGs in string 1 of OWF1; (b) Reactive power (pu) of WTGs in string 1 of OWF1
Self start and black start

Off-shore wind farm Self start
Operational and stability requirements
  Frequency ranges
  Voltage ranges
  Block load size
  Reactive power capacity
  Dynamic voltage control
  Frequency control capability
  Harmonic distortion
  Low Voltage Ride-Through
  Over-Voltage Ride Through
  Power Sharing between Wind Turbines
  Synchronisation capability
  Inertia Response

Considered Scenarios
  HVAC connected WPP
  VSC Connected WPP

Simulation test cases
  Normal operation
    Off-shore AC grid start-up operation (Self-Start to Houseload Operation)
    Response to changes in reactive power sharing command (ISL operation)
    Response to Changes in Frequency Set-point
    Dynamic voltage control
    Harmonic compliance
    Off-shore hvac substation energisation
    HVAC export cable ENERGISATION
    Off-shore HVDC station energisation
    On-shore HVDC station energisation
    On-shore hvac substation energisation
    Synchronisation to on shore grid
    Power block delivery
    Soft energisation (from Houseload to Power block)

Fault ride-through and protection
  Unintended transmission capability limitation
  HVAC cable faults
  Offshore AC faults
## Self start and black start

### Example results

<table>
<thead>
<tr>
<th>2.4.15. HARD SWITCHING</th>
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</thead>
<tbody>
<tr>
<td><strong>System Configuration</strong></td>
</tr>
<tr>
<td><strong>Control hierarchy levels affected</strong></td>
</tr>
<tr>
<td><strong>Related functional requirements</strong></td>
</tr>
<tr>
<td><strong>Methodology</strong></td>
</tr>
<tr>
<td><strong>Minimum simulation detail (maximum level of aggregation)</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Case description</strong></td>
</tr>
<tr>
<td><strong>Sensitivity analysis</strong></td>
</tr>
<tr>
<td><strong>Result assessment</strong></td>
</tr>
</tbody>
</table>
Self start and black start
Example results
Progress Towards Demonstration in WP16

WP3 controls → WP16 setups

- Grid forming OWPP cluster
- Offshore AC and DC faults
- Fault Handling with Grid-Forming WTGs
- Black start capability of HVAC and DRU-connected offshore wind farms
- Harmonic impedance analysis for DC grids with DRU
WP3 Wind Turbine – Converter Interaction

Objectives

The main objective of this work package is to identify and specify appropriate analyses and tests to demonstrate the interoperability of the wind turbine (WT) and wind power plant (WPP) controls with two different types of HVDC systems: diode rectifiers (DR) and VSC converters respectively to connect the wind power plants to the DC network.

The focus will mainly be on the novel DR-HVDC link. The tests will be formulated such, that they serve as a basis for type technical compliance testing of both WT and WPP. The goals are:

• to analyse the functional requirements to WPPs connected to DR- and VSC-HVDC
• to identify and specify general control algorithms
• to define and demonstrate compliance evaluation procedures by simulations and tests
Main messages from WP3

➢ DRU-HVDC connection concept is technically feasible

➢ A very large body of simulations (and scientific publications) has been performed and analysed, increasing the level of knowledge and confidence in the DRU-HVDC connection concept

➢ Technical requirements and compliance evaluation procedures have been developed and tested for:
  ➢ Fundamental operation
  ➢ Fault response
  ➢ Ancillary services
Main messages from WP3

➢ Self-energization of the WTs and black start – feasible & achievable

➢ Lessons learnt:
  ➢ Hard-switching of large transformers and long AC export cables might be a challenge for the WT converters
  ➢ Soft-start (voltage ramp-up) by the WTs very useful and recommended:
    ➢ Eliminates inrush effects on transformers
    ➢ Avoids over-voltages
    ➢ Allows for fast energization of onshore AC network
  ➢ Aspects related to transients during the ramping period need further investigation, including protection behaviour
Any Questions?
WP16
MMC Test Bench Demonstrator

Plenary Session 03.12.2019
Philipp Ruffing – RWTH Aachen

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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)
- Demonstrate the operation of DRU

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

**Task Structure of WP16**

- **T16.1** Definition and specification of test cases for the new test bench
- **T16.2** Preparatory measures for the MMC test bench set up
- **T16.3** MMC test bench lab setup and commissioning
- **T16.4** Basic testing of the MMC test bench system
- **T16.5** Implementation of an analytical method for analysis of harmonic resonance phenomena
- **T16.6** Demonstration of defined test cases regarding interoperability, control schemes and protection
- **T16.7** Analysis of the impact on requirements for meshed off-shore HVDC grids

**WP2, 3, 4**

**WP11, 12**
## Progress

### Milestones & Deliverables

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<th>Due</th>
<th>Topic</th>
<th>Status</th>
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<tr>
<td>D16.1</td>
<td>28 (Apr 18)</td>
<td>Test case overview</td>
<td>✓</td>
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<tr>
<td>MS73</td>
<td>28 (Apr 18)</td>
<td>All test cases defined</td>
<td>✓</td>
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<tr>
<td>D16.2</td>
<td>32 (Aug 18)</td>
<td>Lab documentation</td>
<td>✓</td>
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<tr>
<td>D16.5</td>
<td>38 (Feb 19)</td>
<td>Analytical converter impedance modelling</td>
<td>✓</td>
</tr>
<tr>
<td>MS74</td>
<td>38 (Feb 19)</td>
<td>Set up completed</td>
<td>✓</td>
</tr>
<tr>
<td>D16.7</td>
<td>38 (Feb 19)</td>
<td>Updated Lab documentation</td>
<td>✓</td>
</tr>
<tr>
<td>MS75</td>
<td>39 (Mar 19)</td>
<td>First tests completed</td>
<td>✓</td>
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<tr>
<td>MS79</td>
<td>46 (Oct 19)</td>
<td>WT-CHIL Lab Documentation</td>
<td>✓</td>
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<tr>
<td>D16.3</td>
<td>49 (Jan 20)</td>
<td>Test case analysis for WP3</td>
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<tr>
<td>D16.6</td>
<td>51 (Mar 20)</td>
<td>WT Control + Protection HIL</td>
<td></td>
</tr>
<tr>
<td>D16.4</td>
<td>53 (Mai 20)</td>
<td>Test case analysis WP3</td>
<td></td>
</tr>
</tbody>
</table>

- **Task 16.6**
  - Dec 2019 - Aachen
  - August 2019 – Arnhem
    - WTC Demo & Imp. Meas
  - Nov 2019 – Lehrte
    - Exch. with Cigre WG C4.48
    - Nov. 2019 – Arnhem
    - MMC CHIL Demo

- **Task 16.7**
  - Dec 2019 - Roskilde
  - MS79
  - MS76
  - MS77

- **MS79**
  - August 2019 – Arnhem
    - WTC Demo & Imp. Meas
  - Nov 2019 – Lehrte
    - Exch. with Cigre WG C4.48
    - Nov. 2019 – Arnhem
    - MMC CHIL Demo

- **Task 16.8**
  - Contribution to WP11
  - May 2020 - Brussels FC

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Agenda

• MMC Test Bench Demonstrator

• WT Control-Hardware-in-the-Loop

• Resonant Phenomena Studies
MMC Test Bench Demonstrator

Status Update

Achievements:

✓ Comparison between MMC Test Bench and Simulations
✓ Controller optimisation for similar dynamics of the demonstrator and full-scale simulations
   ➢ Per-unitized controls
   ➢ Parameter dependent “optimum” control
✓ PHiL with (strong) transmission grids and wind power plant

Ongoing Work:

• Implementation of the protection strategy for MTDC grids with full-bridge MMCs
• Improvement of the PI sections towards freq. behavior
• PHiL with weak transmission grids and wind power plant
• PHiL with OWPs in grid forming control
  ➢ Black-Start, DC-FRT, …
MMC Test Bench Demonstrator
Status Update

Next Steps:

- Integration of KTH small-scale HVDC Breaker
  - Build & tested at KTH
  - Computable with KTH protection IED

- Investigation of PHiL methods for OWP in grid forming control

- Implementation of the protection strategy for MTDC grids with full-bridge MMCs
  - Small-scale HSS under construction
Resonant Phenomena Studies
WP16 Approach
Resonant Phenomena Studies

Stability analysis methods
- State-space modeling
- Time domain
- Frequency domain

➢ No consensus yet which method is applicable

➢ Close collaboration with CIGRE WG C4.49
  Multi-frequency Stability Of Converter-based Modern Power Systems

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
Impedance-based Stability Criterion

Resonant Phenomena Studies

- 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

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

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

Characterisation of real converter behaviour is required

→ Impedance Measurement
Impedance Measurement – WT Converter
Resonant Phenomena Studies

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
**Impedance Measurement – WT Converter Controller**

**Resonant Phenomena Studies**

**Achievements:**

- Development and validation of an 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
Impedance Measurement – WT Converter
Resonant Phenomena Studies

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 $Z_{dd}$
Impedance Measurement – MMC Test Bench

Resonant Phenomena Studies

Investigated Control Modes

✓ DC Voltage Control
✓ P/Q Control
  • Grid Forming Control

Method

• Impedance measurement is carried out in real time
• Real-time simulation part has the AC grid signals and measurement method
  • Small-signal perturbations are superimposed on grid voltage or current
  • Impedance measured online
  • Part of the measurement model is implemented on the FPGA to enable smaller time steps

400 V @ 50 Hz

Perturbation
20 V @ 10 Hz → 10 kHz

Power Amp

HVDC Converter (Lab-scale)

CPU

FPGA
Impedance Measurement – MMC Test Bench
Resonant Phenomena Studies

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})

MMC set-point
- P-control mode
- \( P_{ac}^* = 0.5 \) p.u.
- \( Q_{ac}^* = 0.0 \) p.u.
Impedance Measurement – MMC Test Bench
Resonant Phenomena Studies

Comparison between

• Full-scale simulation (1.2 GW – 400 kV\(_{\text{RMS,LL}}\))
• Lab-scale simulation (6 kW – 400 V\(_{\text{RMS,LL}}\))
• Lab-scale HVDC Converter (6 kW – 400 V\(_{\text{RMS,LL}}\))

Scaling

\[ |Z_{\text{scaled}}| = |Z| \cdot |k| \]
\[ \varphi_{Z_{\text{scaled}}} = \varphi_{Z} - k_\varphi \]

\[ |k| = \sqrt{\frac{r_{FS}^2 + (\omega \cdot l_{FS})^2}{r_{SS,TB}^2 + (\omega \cdot l_{SS,TB})^2}} \]
\[ k_\varphi = \arctan \frac{r_{FS}}{\omega \cdot l_{FS}} - \arctan \frac{r_{SS,TB}}{\omega \cdot l_{SS,TB}} \]

Positive Sequence Impedance
Negative Sequence Impedance
**MMC / WT CHiL**

Resonant Phenomena Studies

- 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
DRU connected OWP – CHiL
DRU connected OWP – CHiL

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PROMOTioN WP16 • MMC Test Bench Demo
Achievements:

✓ Implementation of DRU models and wind turbine controls from WP3 on real-time simulators (RTS)
✓ Integration of commercial protection IEDs into CHiL system

Next Steps

• Implementation of ~ 20 independent WT controllers (DSP)

➢ Investigation of the Black Start Capability of HVAC and DRU-Connected OWP
➢ Fault handling (detection) in collector grid with grid forming WTG
Dissemination
Dissemination

Demonstrations Events:

- WT Impedance Measurement and Testing (DNV GL) → August 2019
  - WT Impedance Measurement → WT converter and control replica
  - WT Black-Start Capability
- MMC Impedance Measurement and Testing (DNV GL) → November 2019
  - MMC CHiL
  - MMC control replica impedance measurement
  - DRU-WT CHiL (UPV) → Beginning 2020
  - MMC Test Bench (RWTH) – Interactions between DC grids and OWPPs → Mai 2020
  - MMC Test Bench (RWTH) – Full-bridge based Protection & SWL/HPB → March 2020
  - CIGRE 2020 (Demo and Paper) → September 2020

Working Groups:

- CIGRE WG C4.49 – Multi-frequency Stability Of Converter-based Modern Power Systems
Past Conferences/Events:

- WESC Wind Energy Science Conference 2019 (Cork) → Presentation
- IEEE PES General Meeting 2019 (Atlanta) → Presentation
- WindEurope 2019 (Copenhagen) → Presentation

- IEEE PES PowerTech Conference 2019 (Milan)
  RWTH – Quester - Impact of Offshore Wind Farm Grid Configuration on Harmonic Stability
  DTU – Arasteh - On the Methods of Resonance Identification in Power Systems

- ISGT Conference (Bucharest)
  RWTH – Quester - Online Impedance Measurement of a Modular Multilevel Converter

- Wind Integration Workshop 2019 (Dublin)
  DTU – Arasteh - Coordinated Control of Wind Turbines in Diode-Rectifier-connected Offshore Wind
  DNV GL – Sun – Harmonic Resonance Demonstrator: Wind Turbine Generator Input-Impedance Measurement in DQ Frame
  DNV GL – Pérez – Co-Simulation Hardware in the Loop Test Bench for a Wind Turbine: Validation of a Wind Turbine Black Start Capability

- IECN 2019 (Lisabon)
  UPV - Añó-Villalba - Impedance-based Stability Analysis for HVDC Diode-Rectifier Connected Off-shore Wind Farms
Any Questions?
APPENDIX

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PARTNERS
Power-Hardware-in-the-Loop

What is the challenge?

- Interface algorithm to transmit signals between the digital and the physical system
- Instabilities with PHiL
  - Caused by delay times and sensor inaccuracies
  - These do **not** occur in reality
- PHiL with weak and converter dominated grids
  - Island & small countries
  - Offshore WPPs
  - Future transmission grids

![Graph showing AC Voltage over time with two impedances and their corresponding SCR values: Z_{\text{grid}} = 1.57 \Omega \rightarrow \text{SCR} = 17 and Z_{\text{grid}} = 1.26 \Omega \rightarrow \text{SCR} = 21.](image-url)
WP6 Characterisation of DC Circuit Breakers

December 2019
Dragan Jovcic, University of Aberdeen

PROgress on Meshed HVDC Offshore Transmission Networks

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CONTENT

- WP6 overview,
- WP6 work completed and conclusions,
- WP6 contribution towards objectives and outputs to be taken by WP11 and WP12,
<table>
<thead>
<tr>
<th>Tasks</th>
<th>Lead</th>
<th>partners</th>
<th>status</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1 Develop system-level model for hybrid DC CB</td>
<td>UAbdn</td>
<td>ABB, SGI, DNV-GL</td>
<td>Submitted M11</td>
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<tr>
<td>6.2 Develop system-level model for mechanical DC CB</td>
<td>DELFT</td>
<td>MEU, DNV-GL</td>
<td>Submitted M11</td>
</tr>
<tr>
<td>6.3 Develop component-level and real-time model for hybrid DC CB</td>
<td>UAbdn</td>
<td>DELFT, ABB, DNV-GL</td>
<td>Submitted M30</td>
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<tr>
<td>6.4 Develop component-level and real-time model for mechanical DC CB</td>
<td>DELFT</td>
<td>MEU, DNV-GL, UAbdn</td>
<td>Submitted M30</td>
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<tr>
<td>6.5 Develop kW-size hardware prototypes for hybrid and mechanical DC CBs</td>
<td>UAbdn</td>
<td>ABB, DELFT, DNV-GL</td>
<td>Submitted M31</td>
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<tr>
<td>6.6 Demonstrate DC CB failure modes on kw-size hardware prototypes</td>
<td>UAbdn</td>
<td>DELFT</td>
<td>Outline submitted, Due M48</td>
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<tr>
<td>6.7 Analyse hybrid DC CB integration into EHV DC grid</td>
<td>UAbdn</td>
<td>DELFT, TenneT</td>
<td>Outline submitted, Due M48</td>
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<tr>
<td>6.8 Develop roadmap for VARC DC CB scaling to EHV DC voltage</td>
<td>DELFT</td>
<td>SciBreak, TenneT</td>
<td>Outline submitted, Due M48</td>
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<tr>
<td>6.9 Develop standard DC CB verification plan and RTDS models</td>
<td>UAbdn</td>
<td>ABB, DELFT, MEU, DNV-GL, SGI, SciBreak</td>
<td>Submitted M36</td>
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<td>6.10 Develop roadmap for mechanical DC CB scaling to EHV DC voltage</td>
<td>MEU</td>
<td>DNV-GL, TenneT, UAbdn</td>
<td>Outline submitted, Due M48</td>
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1) WP6 Characterisation of DC CBs, overview

**Meetings**

1. Meeting 1: Arnhem, January 2016, 9 participants in person and 3 over phone
2. Meeting 2: Aberdeen, 03 June 2016, 15 Participants
3. Meeting 3: Teleconference, 24 November 2016, 8 Participants
4. Meeting 4: Berlin, 29 November 2016, 17 Participants
5. Meeting 5: DELFT, 23rd February 2017, 15 participants
6. Meeting 6: Aberdeen, 31st May 2017, 10 participants,
7. Meeting 7: Vasteras, 21st September 2017, 18 participants,
8. Meeting 8: Valencia, 20th November 2017, 15 participants,
9. Meeting 9: Arnhem, 10th April, 2018, 16 participants,
10. Meeting 10: Groningen, 07th June 2018, 10 participants,
11. Meeting 11: Croydon, 20th September 2018, 7 participants,
12. Meeting 12: Lyon, 11th December 2018, 8 participants,
13. Meeting 13: Stockholm, 03 April 2019, 11 participants,
14. Meeting 14: Aachen, 12 June 2019, 7 participants,
15. Meeting 15: DELFT, 26th September 2019, 10 participants,
16. Meeting 16: Roskilde, 02 December 2019, 9 participants,
2) WP6 Characterisation of DC CBs, contribution and conclusions, deliverables and journals

Deliverables:
- 6 submitted
- 4 in final stages

journals published:

1. A. Jamshidifar and D Jovicic “Design, Modeling and Control of Hybrid DC Circuit Breaker Based on Fast Thyristors”, IEEE Transactions on power Delivery, October 2017, DOI: 10.1109/TPWRD.2017.2761022
2. M. Hedayati and D Jovicic “Reducing Peak Current and energy in HVDC CB using disconnector voltage control”, IEEE Transactions on power Delivery, February 2018, DOI: 10.1109/TPWRD.2018.2812713
5. D. Jovicic, M. Zaja and M. Hedayati, “Bidirectional Hybrid HVDC CB with a single HV Valve“ IEEE Transactions on Power Delivery, early access, 2019,
6. D. Jovicic “ Series LC DC Circuit Breaker” IET High Voltage, early access, 2019

2 further papers in review statege.
2) WP6 Characterisation of DC CBs, contribution and conclusions, deliverables and journals

conferences published:
4.  M.H. Hedayati and D Jovcic “Low Voltage Prototype Design and Testing of Ultra-Fast Disconnector (UFD) for Hybrid HV DC CB” CIGRE B4 colloquium, Winnipeg 2017,
7.  M.H. Hedayati and D Jovcic “500A, 900V, Mechanical DC CB Demonstrator for HVDC applications”, ISGT, Sarajevo, October 2018
8.  D Jovcic “1200V, 200A Laboratory prototype for series LC DC Circuit Breaker“ CIGRE Alborg, June 2019,

Panels:
1.  WP6, Characterisation and testing of DC CBs for future DC grids, IEEE PES GM, Portland, August 2018,
2.  WP6 and WP4, DC Grid protection, IEEE ISGT, Sarajevo, October 2018,
3.  WP6 and WP4, DC grid protection equipment and methodologies, IEEE PES GM, Montreal, August 2020,

Workshops:
1.  WP6 and WP4, DC Circuit breakers and DC protection, Brussels, September 2019,

Promotion newsarticle:
1.  Two newsarticles from WP6

1 patent.
2) WP6 Characterisation of DC CBs, contribution and conclusions,

Task 6.1 Develop system-level model for hybrid DC CB

1. DC Circuit breakers in DC grids,
2. Modelling IGBT based hybrid DC Circuit Breaker
3. Modelling Thyristor based hybrid DC Circuit Breaker

Models include:
- All key components,
- Detailed controls including self-protection
- Thermal models,

Modelling IGBT based Hybrid DC CB:
- Load Branch (Load switch and Ultrafast disconnector),
- Breaker Branch (Commutation switch),
- Energy Absorption Branch (Surge arresters),
- Residual current breaker,
- Series inductor,

Figure 1. Structure of IGBT based hybrid DCCB
2) WP6 Characterisation of DC CBs, contribution and conclusions,

Task 6.1 Develop system-level model for hybrid DC CB

Figure 2. IGBT based Hybrid DC CB Simulation results for reclosing in fault
Modelling thyristor based hybrid DC CB:
- Load Branch (Load switch and Ultrafast disconnector),
- Breaker Branch (Time delaying branches with thyristors),
- Energy Absorption Branch (Surge arresters),
- Residual current breaker,
- Series inductor,

Figure 3. Structure of Thyristor based Hybrid DC CB
2) WP6 Characterisation of DC CBs, contribution and conclusions, Task 6.1

Task 6.1 Develop system-level model for hybrid DC CB

Figure 4. Thyristor based Hybrid DC CB Simulation results for opening
2) WP6 Characterisation of DC CBs, contribution and conclusions,

Task 6.2 Develop system-level model for mechanical DC CB

1. Mechanical DC Circuit Breakers,
2. Modelling mechanical DC Circuit Breakers
3. Simulation results

• Ideal switches
• Modelling of 3kHz resonant circuit
  • As Lc circuit
  • As series capacitor
• Detailed controller model,

Modelling mechanical DC CB:
• Main branch (main interrupter),
• Current injection branch (high speed making switch, capacitor, inductor),
• Energy Absorption Branch (Surge arresters),
• Residual current interrupter,
• Series inductor,

Figure 5. Structure of mechanical DCCB with active resonance.
2) WP6 Characterisation of DC CBs, contribution and conclusions,

Task 6.2 Develop system-level model for mechanical DC CB

Modelling mechanical DC CB

Figure 6. Simulation comparison of model 1 and model 2 for mechanical DC CB.
2) WP6 Characterisation of DC CBs, contribution and conclusions, Task 6.3

Task 6.3 Develop component-level model for hybrid DC CB

1. DC CB Thermal stress,
2. Hybrid DC CB Electrical Stress,
3. Failure mode analysis of hybrid DC CB,
4. Fault current limiting and proactive breaking,
5. Ultrafast disconnector detailed model,
6. Voltage control of Ultrafast disconnector

Figure 7. IGBT-based hybrid DC CB model with 4 modules.
Task 6.3 Develop component-level and real-time model for hybrid DC CB

Figure 8. Simulation of fault current limiting mode.
2) WP6 Characterisation of DC CBs, contribution and conclusions, Task 6.3

Task 6.3 Develop component-level and real-time model for hybrid DC CB

Figure 8. Failure tree diagram for hybrid DCCB in closed state.

DCCB: DC circuit breaker  
EA: Energy absorber  
LCS: Load commutation switch  
MB: Main breaker  
RCB: Residual circuit breaker  
UFD: Ultrafast disconnector
2) WP6 Characterisation of DC CBs, contribution and conclusions, Task 6.4

Task 6.4: Develop component-level and real-time model for mechanical DC CB

1. Thermal modelling of Surge Arresters,
2. Determination of suitable parameters of an active current injection DCCB,
3. Injection switches, time control and related stress on components,
4. Investigation on DCCB performance during a current interruption failure at first current zero,

Figure 10. Typical configuration of mechanical DC CB.
2) WP6 Characterisation of DC CBs, contribution and conclusions, Task 6.4

Task 6.4 Develop component-level and real-time model for mechanical DC CB

1. Finite element Thermal modelling of Surge Arresters,

Figure 11. Temperature profiles on the border of SA housing and gas.
2) WP6 Characterisation of DC CBs, contribution and conclusions,

Task 6.5 Develop kW-size hardware prototypes for hybrid and mechanical DC CBs

1. Test Circuit design and implementation,
   • 900V, 500A
   • Upgraded to 5kV, 2kA,
2. IGBT based Hybrid DC CB, 500A, 900V
3. Mechanical DCCB Demonstrator, 500A, 900V

Figure 12. Hardware DC CB and test circuit.
2) WP6 Characterisation of DC CBs, contribution and conclusions,

Task 6.5 Develop kW-size hardware prototypes for hybrid and mechanical DC CBs

Voltage control of Ultrafast disconnector in Hybrid DC CB

![Figure 13. Voltage and current with UFD voltage control.](image1)

![Figure 14. Energy with UFD voltage control.](image2)

![Figure 15. 3mm, 2ms Ultrafast Disconnector.](image3)
2) WP6 Characterisation of DC CBs, contribution and conclusions,

Task 6.5 Develop kW-size hardware prototypes for hybrid and mechanical DC CBs

Figure 16. Successful interruption with mechanical DCCB (Vdc=750V)
2) WP6 Characterisation of DC CBs, contribution and conclusions, Task 6.6

Task 6.6 Demonstrate DC CB failure modes on kw-size hardware prototypes

1. Failure mode analysis of hybrid DC CB,
   1. Failure tree diagram
   2. Failure of Load commutation switch,
   3. Failure of ultrafast disconnector,
   4. Failure of main breaker
   5. Failure of energy absorber
   6. Failure of Residual current breaker

2. Failure mode analysis of hybrid DC CB,
   1. Failure tree diagram
   2. Failure of main breaker
   3. Failure of injection circuit,
   4. Failure of energy absorber,
   5. Failure of Residual current breaker
2) WP6 Characterisation of DC CBs, contribution and conclusions, Task 6.6

Task 6.6 Demonstrate DC CB failure modes on kw-size hardware prototypes

Figure 17 – Fitted arc models versus experimental data for high current

Figure 18 – Fitted arc models versus experimental data for low current
Component-level failure of surge arresters:

- Healthy arrester has variable resistance between 100 and 20k ohm in the observed range
- Failed arrester has constant resistance of around 2 ohms

**Figure 19** – Test circuit schematic for SA failure study.

**Figure 20** – Healthy and failed arrester’s I-V characteristic
Cascaded failure of the main arrester bank

- One arrester in 2x2 bank failed,
- In the next interruption the second arrester in the same branch fails – cascaded failure.
- Faulted branch takes the full DC current with very little counter voltage – breaker remains a closed circuit

Figure 21 – Arrester bank after failure (bottom)

Figure 22 – Arrester bank failure during breaker opening
2) WP6 Characterisation of DC CBs, contribution and conclusions, Task 6.6

Task 6.6 Demonstrate DC CB failure modes on kw-size hardware prototypes

Failure of arrester at Load Commutation Switch

- UFD fails to open.
- LCS arrester takes full line current because of its low voltage rating. The arrester overloads and ruptures.
- An arc ignites between the arrester’s ruptured contacts which maintains low voltage across T1.
- The breaker remains a closed circuit but T1 survives.

Figure 23 – T1 with arrester after failure

Figure 24 – Test results for LCS arrester failure

Failure of arrester at Load Commutation Switch

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This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 691714.
2) WP6 Characterisation of DC CBs, contribution and conclusions,

Task 6.7 Analyse hybrid DC CB integration into EHV DC grid

1. Scaling the hybrid DC circuit breaker to extra high voltage
2. Integration of a hybrid DCCB in a DC grid
3. Simplified hybrid DC CB modelling for grid-level studies
4. Advanced DC CB topologies

<table>
<thead>
<tr>
<th>Topology</th>
<th>Detailed</th>
<th>Simplified</th>
<th>Generic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hybrid DC CB</td>
<td>690 min ~ 11.5 h</td>
<td>25 min</td>
<td>2.5 min</td>
</tr>
<tr>
<td>Active-resonant</td>
<td>6.0 min</td>
<td>2.5 min</td>
<td>2.5 min</td>
</tr>
<tr>
<td>VARC</td>
<td>197 min ~ 3.3 h</td>
<td>2.5 min</td>
<td>2.5 min</td>
</tr>
</tbody>
</table>
2) WP6 Characterisation of DC CBs, contribution and conclusions,

Task 6.7 Analyse hybrid DC CB integration into EHV DC grid

DC grid integration of hybrid DCCB
a) DC grid model from WP4,
b) Common test plan (T6.7, T6.8 and T6.10),
c) Common variables of interest (T6.7, T6.8 and T6.10),

Figure 27 – Four terminal DC grid employed in T6.7, T6.8 and T6.10,
2) WP6 Characterisation of DC CBs, contribution and conclusions,

Task 6.7 Analyse hybrid DC CB integration into EHV DC grid

Advanced topologies:
   a) Bidirectional breaker with unidirectional valve,
   b) LC DC Circuit Breaker,

Figure 28 – Bidirectional DC CB with unidirectional valve and two double-throw disconnectors,
2) WP6 Characterisation of DC CBs, contribution and conclusions,

Task 6.8 Develop roadmap for VARC DC CB scaling to EHV DC voltage

1. Modelling and Experimental Verification of VARC HVDC Circuit Breakers

2. Scaling of VARC DC CB to EHV

3. The Implementation of VARC DC CB in TenneT grid

4. Implementation of VARC DC CB in a 4-terminal MTDC grid (as developed in wp4)

Figure 29 – Detailed and simplified VARC DCCB model,
2) WP6 Characterisation of DC CBs, contribution and conclusions,

Task 6.9 Develop standard DC CB verification plan and RTDS models

1. General DC CB model verification plan (including self protection)

2. Verification of IGBT-BASED Hybrid DC CB model

3. Verification of Thyristor based Hybrid DC CB model

4. Verification of mechanical DC CB model

5. Verification of VSC assisted mechanical DC CB model

6. RTDS modelling and verification of IGBT based hybrid DCCB

7. RTDS modelling and verification of mechanical DCCB

Models will be verified against WP10 test measurements

---

Figure 30. Test circuit for DC CB model verification.
2) WP6 Characterisation of DC CBs, contribution and conclusions,

Task 6.9 Develop standard DC CB verification plan and RTDS models

![Graphs and charts showing current, voltage, temperature, and energy over time.](image-url)

Figure 31. High current interruption IGBT DC CB model testing.
2) WP6 Characterisation of DC CBs, contribution and conclusions,

Task 6.10 Develop roadmap for mechanical DC CB scaling to EHV DC voltage

1) STUDY OF SCALING TO EHV ON DETAILED MODEL
2) MECHANICAL DCCB INTERACTION WITH GRID
3) VERIFICATION OF SYSTEM-LEVEL MODEL

<table>
<thead>
<tr>
<th>MODEL</th>
<th>TIV RISING POINT</th>
<th>MMC RESTARTING POINT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detailed</td>
<td>308.7 kV (100%)</td>
<td>267.6 kV (100%)</td>
</tr>
<tr>
<td>MOSA</td>
<td>312.1 kV (101%)</td>
<td>223.3 kV (33.5%)</td>
</tr>
<tr>
<td>Simplified</td>
<td>311.1 kV (101%)</td>
<td>260.4 kV (97.3%)</td>
</tr>
</tbody>
</table>

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This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 691714.
2) WP6 Characterisation of DC CBs, contribution and conclusions,

Task 6.10 Develop roadmap for mechanical DC CB scaling to EHV DC voltage

Figure 32. The simulation results show examples of waveforms at the DC BUS 1 current/voltage close to the operated DCCB.
3) WP6 Characterisation of DC CBs, Contribution towards objectives, WP12 and WP11,

1 ‘To establish interoperability between different technologies and concepts by providing specific technical and operational requirements, behaviour patterns and standardization methods for different technologies’ – WP12

3 Different DC CB technologies are considered and for all technologies:

- Models (detailed, simplified) delivered on common platform (PSCAD),
- Real time modes delivered on common platform (RTDS),
- Demonstrated on scaled hardware 900V, 500A DC CB demonstrator (except VARC DC CB),
- Common simplified and generic DC CB model developed,
- Common verification plan for DC CB models,
- Generic input/output DC CB interface developed (jointly with WP4),
2. ‘To develop interoperable, reliable and cost-effective technology of protection for meshed HVDC offshore grids and the new type of offshore converter for wind power integration’ – WP12

- Multiple studies on improved and advanced DC CB technologies (Lower costs, smaller/simpler, faster DC CB),
- Evaluated and demonstrated failure modes for DC CB and components, (understanding and improving reliability),
- Proposed interface between DC CB and protection system (jointly with WP4), (enhancing interoperability),
3) WP6 Characterisation of DC CBs, Contribution towards objectives, WP12 and WP11,

5. To facilitating the harmonization of ongoing initiatives, common system interfaces and future standards by actively engaging with working groups and standardization bodies and actively using experience from the demonstrations’ - WP11

- Models (detailed, simplified) for 3 DC CB technologies delivered on common platform (PSCAD),
- Real time modes for 3 DC CB technologies delivered on common platform (RTDS),
- 2 DC CB technologies demonstrated on scaled hardware 900V, 500A DC CB in Universiy laboratory,
- Common simplified and generic model developed applicable to all 3 DC CB topologies,
- Common verification plan for DC CB models,
- Generic input/output DC CB interface developed (jointly with WP4),
- DC CB model common verification plan,
- Engagement in professional community:
  - Dissemination at professional conferences and in journals (9 conferences and 9 journals),
  - 3 panels at professional events (IEEE conferences),
  - Participation in CIGRE JWG A3/B4.80,
  - (Small) contribution to CENELEC.
Conclusions

1. WP6 status
   a. 6 deliverables completed
   b. 4 deliverables in final stages
   c. 16 meetings,

2. WP6 Outputs
   a. PSCAD models for 3 DC CB topologies – publicly available
   b. Generic/simplified DC CB model and model verification method, - publicly available,
   c. RTDS models for 3 DC CB topologies,
   d. DC CB low power demonstrators and DCCB test circuit,
   e. 9 journal articles,
   f. 9 conference articles,
   g. 3 panels,
   h. 1 workshop,
   i. 2 newsletter articles,

3. Proposed improvements to DC CB and new topologies,
   a. UFD voltage control,
      a) Bidircetional DC CB with unidiercational valve,
      b) DC CB with parallel capacitor,

4. Contribution to project objectives,

5. Contribtion to WP11,

6. Contribution to WP12,
WP10: HVDC CIRCUIT BREAKER PERFORMANCE DEMONSTRATION

PROMOTioN Half-Yearly Consortium Meeting, Roskilde, Dec. 2, 2019
René Smeets / Nadew Belda / Roy Nijman, KEMA Labs, DNV GL
• Document status
• MEU’s 160 - 200 kV breaker testing + demo
• Results and lessons learnt
• Evaluation of component stresses
• Standards development
• 2020 HVDC breaker demos
Deliverables to come

- D10.1 – D10.4 Submitted
- D10.5 Failure modes of HVDC breakers - final draft confidential
- D10.6 Testing of HVDC circuit breakers (details, incl. all tests) confidential
- D10.7 Demonstration of HVDC circuit breakers (performance) public
- D10.8 Initialization of standardization public
- D10.9 Reporting public

- Deadline: June 30, 2020
Nadew Belda wins *Wang Jimei Young Investigators Award* at ICEPE-ST conference in Japan, Oct.16, 2019

High-Frequency Current Interruption in an Experimental DC Circuit Breaker

- 40 papers on DC switching
- One invited lecture
- One panel session with PROMOTioN and Chinese manufacturers
The critical stresses on HVDC circuit breakers

Tests shall cover all stresses

- fault current rise
- internal commutation
- current zero creation
- steady state
- fault current
- fault current suppression
- interruption
- CB open
- counter voltage
- overvoltage withstand
- energy absorption
- di/dt
- UMOSA
- US
- Ipk
- ICon
- US

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

27.11.19
# Proposed breaking test requirements – Test program agreed WP10

<table>
<thead>
<tr>
<th>Name</th>
<th>Current</th>
<th>Breaking test</th>
<th>#</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC10+</td>
<td>10% of rated continuous current</td>
<td>2 tests in positive current direction</td>
<td>2</td>
</tr>
<tr>
<td>TC10-</td>
<td>10% of rated continuous current</td>
<td>2 tests in negative current direction</td>
<td>2</td>
</tr>
<tr>
<td>TC100+</td>
<td>100% of rated continuous current</td>
<td>2 tests in positive current direction</td>
<td>2</td>
</tr>
<tr>
<td>TC100-</td>
<td>100% of rated continuous current</td>
<td>2 tests in negative current direction</td>
<td>2</td>
</tr>
<tr>
<td>TF100+</td>
<td>100% of peak fault current</td>
<td>2 test at specified energy absorption*, positive current direction</td>
<td>2</td>
</tr>
<tr>
<td>TF100-</td>
<td>100% of peak fault current</td>
<td>2 test at specified energy absorption*, negative current direction</td>
<td>2</td>
</tr>
<tr>
<td>TDT+</td>
<td>TBD</td>
<td>2 test at rated fault current suppression time**, positive current direction</td>
<td>2</td>
</tr>
<tr>
<td>TDT-</td>
<td>TBD</td>
<td>2 test at rated fault current suppression time**, negative current direction</td>
<td>2</td>
</tr>
</tbody>
</table>

*: Specified energy absorption based on specified value of energy absorption (MJ) of the test-object delivered

**: Rated fault current suppression time based on $Us$, $UMOSA$, $\Delta Tic$, $Ipk$, as would be present in service condition

All tests are single opening operations

In all tests, $Us$ (considering 10-15 % overvoltage) will be supplied during 300 ms after main current interruption
### MEU demo test June 20

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>11:30</td>
<td>Registration</td>
</tr>
<tr>
<td>12:00 – 13:00</td>
<td>Lunch</td>
</tr>
<tr>
<td>12:40 – 13:00</td>
<td>Welcome (starts during lunch)</td>
</tr>
<tr>
<td></td>
<td>Shankkar Subramany</td>
</tr>
<tr>
<td></td>
<td>DNV GL – KEMA High Power Laboratory</td>
</tr>
<tr>
<td>13:00 – 13:30</td>
<td>Progress on Meshed Offshore HVDC Transmission Networks</td>
</tr>
<tr>
<td></td>
<td>Cornelis Piet</td>
</tr>
<tr>
<td></td>
<td>DNV GL – PROMOTIoN Coordinator</td>
</tr>
<tr>
<td>13:30 – 14:00</td>
<td>Mechanical HVDC Circuit Breaker with Active Current Injection</td>
</tr>
<tr>
<td></td>
<td>Ito Hiroki</td>
</tr>
<tr>
<td></td>
<td>Mitsubishi Electric Co.</td>
</tr>
<tr>
<td>14:00 – 14:30</td>
<td>Testing Methods for HVDC Circuit Breakers</td>
</tr>
<tr>
<td></td>
<td>Nadew Belda</td>
</tr>
<tr>
<td></td>
<td>DNV GL – KEMA High Power Laboratory</td>
</tr>
<tr>
<td>14:30 – 15:00</td>
<td>Transport to laboratory (incl. safety briefing)</td>
</tr>
<tr>
<td>15:00 – 16:00</td>
<td>Demonstration of DC fault current interruption</td>
</tr>
<tr>
<td>16:00 – 17:00</td>
<td>Tour through high power and high voltage laboratory</td>
</tr>
<tr>
<td>17:00 – 17:30</td>
<td>Transport to Haarhuis hotel and Central station</td>
</tr>
</tbody>
</table>
MEU 160 - 200 kV / 16 kA HVDC breaker under test
Full-power testing of 160-200 kV active current injection breaker
Combination of different sources

AC power generators

Test laboratory and DC sources
Application of adequate stresses in tests with limited MOSA

Fault current interruption with energy limitation

Load current interruption incl. TIV overvoltage stress

1.2 ms overvoltage duration

> 6 ms overvoltage duration
Six stresses applied

- Fault current rise
- Internal commutation
- Energy absorption
- Counter voltage
- Overvoltage withstand
- DC voltage withstand

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 691714.
Getting to know the internal critical stresses by power experiments
Standard components used in a non-standard application

- switching gaps and drives
- semiconductor switches
- metal oxide surge arresters
## Risk mitigation by defining proper verification methods

<table>
<thead>
<tr>
<th>subcomponent</th>
<th>normal operation</th>
<th>HVDC CB application</th>
<th>potential issue?</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Multiple) electrodynamic actuator(s) for mechanical switching device</td>
<td>Speed 1 – few m/s</td>
<td>Ultra-high speed, high impact force Electronics onboard</td>
<td>Mechanical reliability Compatibility with equipment attached (bellows of vacuum interrupters) EMI sensitivity</td>
</tr>
<tr>
<td>Power supply to actuator(s)</td>
<td>On earth potential</td>
<td>On high potential</td>
<td>Non-galvanic power supply</td>
</tr>
<tr>
<td>Vacuum interrupters for interruption</td>
<td>Power frequency AC current interruption</td>
<td>HF current and / or interruption, isolation at small gap length</td>
<td>HF current interruption</td>
</tr>
<tr>
<td>Vacuum interrupters for insulation</td>
<td>AC voltage insulation</td>
<td>DC voltage applied</td>
<td>DC voltage withstand capability</td>
</tr>
<tr>
<td>High-speed (vacuum, PE) making switches</td>
<td>Capacitor bank inrush current making</td>
<td>Injection current making above highest IEC standardized value</td>
<td>Contact welding</td>
</tr>
<tr>
<td>Multiple vacuum breakers in series</td>
<td>Not applied; vast majority of VCB is single break</td>
<td>Several / many in series</td>
<td>Grading for transients and DC Redundancy Mechanical synchronicity</td>
</tr>
<tr>
<td>SF6 gap(s) for insulation (ultra-fast disconnector)</td>
<td>Very low opening speed in GIS AC application</td>
<td>Ultra-high contact separation speed</td>
<td>Shall not switch any current Dynamic DC voltage withstand capability Mechanical consistency over time</td>
</tr>
<tr>
<td>Semiconductors in continuous current path (load commutation switch function)</td>
<td>Semiconductors switch with high frequency</td>
<td>Conduct continuously and switch only occasionally</td>
<td>Thermal stability</td>
</tr>
<tr>
<td>Semiconductors in commutation path (main breaker function)</td>
<td>Semiconductors switch with high frequency</td>
<td>Never conduct and switch only occasionally</td>
<td>Reliability after long idle time</td>
</tr>
<tr>
<td>MOSA consisting of multiple columns</td>
<td>Overvoltage protection</td>
<td>Significant energy absorption</td>
<td>Thermal overload Current sharing between columns</td>
</tr>
<tr>
<td>MOSA columns</td>
<td>Always under (AC) voltage</td>
<td>Occasionally stressed by voltage</td>
<td>Conditioning</td>
</tr>
</tbody>
</table>
Standardization initiatives 2019

With WP10 participation:

• CIGRE WG A3.40: MVDC circuit breakers and systems (Heinrich, DE)
  Meeting Xi’an, Oct. 2019; Darmstadt, Feb. 2020

• CIGRE JWG B4A3.80: HVDC circuit breakers (Cao, CN)
  Meeting Lyon, Nov. 2019; Ningbo, Apr. 2020 -> draft technical brochure

• IEC HVDC Transfer switches (Ren, CN) - meeting Xi’an, Feb. 2020
• IEC HVDC Circuit breakers (Jia, CN) - meeting Xi’an, Feb. 2020

Other:

• IEC HVDC Bypass switches
• IEC HVDC Earthing and disconnecting switches
• IEC HVDC General clauses
• IEC HVDC GIS assemblies
Demo tests 2020

- **February 2020**
  - Thursday, Feb 27th 2020
    - ABB 320 kV 16 kA breaker
    - 320 kV GIS

- **April 2020**
  - Thursday 30th Apr 2020
    - SciBreak 80 kV 16 kA

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This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 691714.
WP4 status report

Dirk Van Hertem (KU Leuven)
Serge Poullain (Supergrid Institute)
• WP4, where we are
• D4.5 status
• Preparation of cost- benefit analysis from a protection point of view
  • D4.7 status
  • Reminder on key performances indicators
  • Reminder on implemented case studies
  • Key takeaways from case studies
  • Some recommendation proposals
• Final message
WP 4: DC Grid protection system development

**Objectives:**
- Develop a set of functional requirements for a set of representative DC grids
- Analyse a wide range of DC grid protection philosophies on a common set of metrics
- Identify the best performing methods for each identified DC grid
- Develop detailed protection methodologies for the selected methods
- Develop configurable multi-purpose HVDC protection IEDs to allow testing of the methodologies
- Investigate the key influencing parameters of protection systems on the cost-benefit evaluation

**Partners:** KU Leuven (WP Leader), DNV GL, ABB, KTH, EIRGRID, SGI, MEU, SvK, RTE, Statoil, TenneT, Siemens, RWTH, Tractebel, Iberdrola, SHE Trans
WP 4: DC Grid protection system development

Partners: KU Leuven (WP Leader), DNV GL, ABB, KTH, EIRGRID, SGI, MEU, SvK, RTE, Statoil, TenneT, Siemens, RWTH, Tractebel, Iberdrola, SHE Trans

Deliverables and Milestones:

• Reports:
  • D4.1: Definition of test cases and functional requirements for DC grid protection methodologies
  • D4.2: Broad comparison of protection methodologies for identified grid topologies
  • D4.3 Performance, interoperability and failure modes of implementation of selected methodologies
  • D4.5: Requirements for DC switchgear (joint deliverable with WP 5) (M48)
  • D4.6: Functional HVDC protection IED
  • D4.7: Impact of protection system design factors on CBA of a system (M47)
PROMOTioN - The Work Packages

WP 4: DC Grid protection system development

- Start of WP 4
- List of top candidate protection philosophies (report)
- Preparation for testing of methodologies in MTTE
- Real time model of DC grid communication architecture
- Protection system performance (report)
- Requirements for DC switchgear (Report with WP5)
- Performance, interoperability and failure modes of selected methods
- CBA analysis summarized
- Protection IED with algorithms to WP9
- Comparison of protection philosophies (report)
Requirements for DC switchgear

D 4.5

02 December 2019
Objectives of D4.5

- Classify DCCBs into different types based on results obtained in WP4, WP5 and WP6
- Specify general requirements of DCCBs with the intention of contributing to standardization and interoperability
- Focus is on breakers, not switches
- What are the
- Bringing work together rather than new ideas
- Executive summary
### DCCB Types (or Classes) based on application scenarios

<table>
<thead>
<tr>
<th>Application scenarios</th>
<th>DCCB types</th>
<th>Parameter ranges</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td><strong>Operation speed</strong> $(t_{br,o})$</td>
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<tr>
<td>Fully selective protection strategy</td>
<td>Type-I</td>
<td><strong>Dealing with pole-to-pole and pole-to-ground faults</strong></td>
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<tr>
<td>Fully selective strategy (Cable-based symmetrical monopolar HVDC grids)</td>
<td>Type-II</td>
<td>Only dealing with pole-to-ground faults</td>
</tr>
<tr>
<td>Non-selective protection strategy (Converter + DCCB)</td>
<td>Type-III</td>
<td>Line/Converter DCCB</td>
</tr>
</tbody>
</table>
General requirements of Type-I DCCBs in a fully selective protection strategy

Constraints or requirements from HVDC grid system and components

- **Converter DC fault-ride-through (DCFRT) requirements** [1]
- Selectivity requirements
  - Inductors are used for separating protection zones, and have to be large enough to allow for discrimination of internal and external faults [2][3]
- **Protection coordination requirements** [4]:
  - Hybrid DCCB auxiliary functions: DCCB-level protection and internal failure detection
  - System-level (IEDs) protection should act before triggering DCCB-level protection
    - Breaker opening time
    - Inductor size
- **HVDC grid stability requirements:**
  - The choice of main circuit parameters has to result in a stable system [5].
- **Multivendor interoperability requirements:**
  - DCCB sizing should consider a range of parameters as they differ from one vendor from another.
Converter DCFRT requirements

HVDC Grid Fault Ride Through Scenarios:

- **DC-FRTS1** leads to high values of line inductors for the given HVDC grid test system, which may be impractical towards real applications.

- **DC-FRTS2** reduces the requirements for the line inductors in the grid for all DCCB operating times. However, it shows higher line inductor values for longer DCCB operating times in combinations with low converter ratings.

- **DC-FRTS3** can be used for any HVDC grid with any DCCB technology, and the DCCB operating time and line inductor value can be determined depending on the allowable fault level in the grid.

Protection coordination requirements in case of hybrid DCCBs

**Self-protection**: trip DCCB on internal command without receiving a trip order from the IED(s).

**Driver-level protection**: block semiconductor switches at the gate driver unit without receiving an order from the DCCB controller.

**Without DCCB-level protection**:

\[
\begin{align*}
\begin{cases}
    i_{MMC} < I_{diode,MAX} \quad (DCFRTS3) \\
    \tau_{eq,i} (t_{IED,p} + t_{br,o}) + I_{DC,n} \leq I_{br,pk}
\end{cases}
\]

Protection coordination:

- Primary IED operates before self-protection:

- Breaker failure backup IEDs operates before driver-level protection (of the failed DCCB):

\[
\begin{align*}
\begin{cases}
    \tau_{eq,i} (t_{IED,p} + t_{br,o} + t_{mgn.sp}) + I_{DC,n} \leq I_{br,pk} \\
    \tau_{eq,i} (t_{BF2} + t_{br,o} + t_{mgn.dp}) + I_{DC,n} \leq I_{MB,dp}
\end{cases}
\end{align*}
\]
General requirements of Type-II DCCBs in a fully selective protection strategy for cable-based symmetrical monopolar system

DCCB requirements [6]:

- Opening time: slow ~ 20 ms
- Breaking current: few kA
- Energy: few MJ
Status of D4.5 (Due M48)

Submission to reviewers: this week
Final submission, not after M49

<table>
<thead>
<tr>
<th>Chapters</th>
<th>Responsible partner</th>
<th>Completion percentage (writing)</th>
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<tbody>
<tr>
<td>1. Executive summary</td>
<td>KUL</td>
<td>95%</td>
</tr>
<tr>
<td>2. Introduction</td>
<td>KUL</td>
<td>100%</td>
</tr>
<tr>
<td>3. DC circuit breaker</td>
<td>KUL</td>
<td>100%</td>
</tr>
<tr>
<td>4. Fully selective strategy</td>
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<td></td>
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<tr>
<td>4.1 Type-I DCCB</td>
<td>KUL</td>
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<tr>
<td>4.2 Type-II DCCB</td>
<td>KUL</td>
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<tr>
<td>5 Non-selective strategy (Type-III DCCB)</td>
<td>SGI</td>
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</tr>
<tr>
<td>6 Summary</td>
<td>KUL</td>
<td>100%</td>
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</table>
Preparation of cost-benefit analysis from a protection point of view

WP 4.5

02 December 2019
Deliverable D4.7

WP 4.7 Deliverable: Preparation of cost-benefit analysis from a protection point of view

Sent to Reviewers by 30 November

John Moore (TenneT)
Nicoloas Cutululis (DTU)

Due date M47
Considered Key Performance Indicators within WP4.5

**Economic KPIs**
- Capital Expenditures (CAPEX)
- Operational expenditures (OPEX)
  - Losses
  - Maintenance
  - Expected Energy Non Transmitted (EENT)

**Technical KPIs: Efficiency & reliability (from works of WP4.2 and WP4.3)**
- Efficiency Indicators
  - Voltage restoration time
  - Active power restoration time
  - Reactive power restoration time
  - Transient energy unbalance
- Reliability Indicators
  - Backup Probability
  - Non-cleared fault probability

**Technical KPIs: AC grid impact indicators**
- Frequency deviation
- Frequency Reserve Requirement
- ROCOF
- Generation dispatch costs

---

© PROMOTiN – 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.
Case studies

Small 4 terminal meshed DC grid

(WP 4.2, WP4.3)

Four protection strategies

A full selective with fast DC CB
A full selective with slow DC CB
A non-selective with DC CB at converter output
A non-selective with fault blocking capability converter
Grid splitting with non-selective with DC CB at converter output

Large 35 terminal radial DC grid (WP 12)
Key Takeaways: Methodology and tools

Methodologies and tools for supporting a CBA assessment relative to protection systems of DC grids have been proposed and developed.

Indicators have been demonstrated as relevant to discriminate protection systems from both costs and performances analysis.
Dominated by DC circuit breakers costs

Lower CAPEX is associated to non-selective protection strategy using DC CB at converter output, whereas higher CAPEX is related to full selective protection strategy with fast DC CB (ratio of two)

CAPEX relative to non-selective fault blocking converter based protection strategy needs to consider additional costs incurred by such converters

Protection system CAPEX lies between 4% and 8% of DC grid total CAPEX
Contributions of protection system to total losses are observed as less that 6%. Fault blocking converters additional losses needs to be considered.

Contributions of protection system to total maintenance costs is between 4% and 8% (modeled as a coefficient of CAPEX).

Key Takeaways: OPEX

- Observed maximal EENT due to protection systems does not exceed 10% of total EENT.
- EENT due to non-selective protection strategy using DC CB at converter output is slightly higher than for other protection strategies.
WP12 case study: Used ENTSO-e model of frequency response for the Nordic grid

Assuming hydro power plants as the main frequency containment reserves (FCR)

With no additional reserves, the load shedding duration is 20 hr/annum and 54 hr/annum for selective and nonselective strategies respectively

Nonselective strategy needs faster and higher amount of reserves

There is no difference in load shedding/reserve requirement among selective and nonselective groups of strategies

**Key Takeaways: OPEX: Frequency reserves**

Transient frequency constraint violations incurred during DC fault clearing and DC grid restoration processes can be counterbalanced by using fast frequency reserves (FFR)

Slower protection strategies could require more FFR and would then incurred some additional OPEX
Key Takeaways: Total Costs

Considering CAPEX and OPEX: The range of protection system cost contribution to total grid cost varies from approximatively 4% to approximatively 8%.

While not negligible, protection system cost is not seen as determining in respect to total grid cost.
Key Takeaways: Technical Efficiency KPIs

- **Non selective with converter breaker protection strategy**

- **Full selective with fast DCCBs protection strategy**

- **Grid splitting with non selective with converter breaker protection strategy**
**Key Takeaways : Technical KPIs**

<table>
<thead>
<tr>
<th>Not affected converters (%)</th>
<th>Strategy</th>
<th>Active power restoration time</th>
<th>Energy Imbalance</th>
</tr>
</thead>
<tbody>
<tr>
<td>NS-CB</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>FS-FDCCB</td>
<td>75</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>FS-SDCCB</td>
<td>55</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td>NS-CB</td>
<td>[120,200]</td>
<td>[10,150]</td>
</tr>
<tr>
<td>(lowest/highest values)</td>
<td>FS-FDCCB</td>
<td>[0,100]</td>
<td>[0,30]</td>
</tr>
<tr>
<td>(ms or MJ)</td>
<td>FS-SDCCB</td>
<td>[0,150]</td>
<td>[0,40]</td>
</tr>
<tr>
<td>Grid splitting</td>
<td>NS-CB</td>
<td>[120,200]</td>
<td>[10,150]</td>
</tr>
<tr>
<td></td>
<td>Grid splitting</td>
<td>[0,220]</td>
<td>[0,150]</td>
</tr>
</tbody>
</table>

Computation of technical KPIs has demonstrated that impacts on both DC and AC grids are dependent on protection strategies. As such, computation of technical KPIs is fundamental when assessing the performances of protection systems.

In the case of the large size radial backbone DC grid, it is shown that, if well-adapted converter controls are implemented, full selective protection strategies will have less grid impact (DC and AC grids).

For large DC grids, grid splitting design has been shown as an applicable and efficient solution to reduce grid impact when implementing non-selective protection strategies.
Some recommendation proposals

A large set of protection strategies are technically applicable to small size and large size DC grids

The performances of protection system do not only depend on DC circuit breakers and protection equipment performances but also highly rely on converter control behavior. With low control performances, significant increase of time to restore the grid can be observed.

There are no preferred protection strategies suitable for all DC grid systems

There is not a unique way to protect DC grids and the selection of protection system will depend on many parameters. First objective of protection system is to ensure system security as well as allow system stable operation during and after fault clearing process. Cost considerations are then addressed.

From case studies, it seems that full selective or non-selective strategies based on grid splitting would be preferable for large size DC grids. As such, grid splitting design is a good way to use non-selective protection strategies for large grids.

Although not investigated in detail in the deliverable, the authors do not see a reason why a mix of protection systems cannot exist (potentially requiring some additional engineering).
Some recommendation proposals

Protection system design needs a full assessment and no short cut to design a protection system can be applied.

Both technical performances and costs have to be addressed and relevant key performance indicators need to be defined and used to perform a full assessment of protection system.

Designing protection systems will then result in protection system components specification. Specification of DC circuit breakers will play a central role regarding cost of protection systems as it has been shown that costs are mainly DC CB driven.

Cost of DC circuit breakers can vary in a large range

It has been observed that the cost of DC CBs vary approximately with a factor of two, depending on breaker requirements.

Additional costs due to installation of DC CB on offshore platform are not negligible.

From cost considerations, the general transmission system (DC grid) layout is not so much affected by the selection of protection system. As a consequence, it seems that no protection system is impossible due to excessive cost.
The end of WP4

02 December 2019
Output of WP4

- Regular invitation to participate in workshops and conferences
- Organized a workshop in Brussels with WP6 on 30/9
- Developed testing protocols for DC IEDs:
  - Applied to both Promotion and Melco IED (successfully)
- Interfacing with WP9 and transferring ideas from WP4 to WP9
  - First outcomes confirm our work
- Scientific output:
  - 14 conference papers (more to come)
  - 5 papers (more to come)
High level conclusions of WP4

- HVDC grid protection is realistic: from academic to (near) industry grade implementation
- Different approaches are possible, with different advantages and disadvantages
- HVDC grid protection equipment (IEDs) are available: academic and industrial
- IEDs are tested
- Interfaced with WP9 for validation at higher TRL
- HVDC grid protection is not blocking technically nor economically
Thank you to all WP4 contributors!
WP9 Plenary
2019-12-03
Ian Cowan – SHE Transmission
This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 691714.
WP9 Scope

HIL demonstration of fault clearing strategies (real system)

- Partially selective
  Symmetrical monopole configuration

- Fully selective
  Symmetrical monopole configuration

HIL demonstration of **Non-selective** fault clearing strategies (IEC61850)

- Converter-breaker strategy
  HB-MMC: Bipole configuration

- Full-Bridge based converter strategy
  FB-MMC: Symmetrical monopole configuration
Progress Update
Progress Update – Task 9.1 through 9.6

- **Deliverables**
  - D9.1 Real-time models for benchmark DC grid systems (KUL M38)
  - D9.2 DC grid protection testing guidelines (TU Delft M36) – Delivered M36
  - D9.3 Protection system demonstration (SHET M42[44]) – Delivered M44
  - D9.4 Demonstration of protection system interoperability and primary and back-up protection (SHET M46[51-TBC])
  - D9.5 Hardware-in-the-loop test environment and guidelines for non-selective protection systems demonstrations (SGI M48[49])
  - D9.6 Demonstration of non-selective protection systems interoperability and primary and back-up protection (SGI M54)

- **Milestones**
  - MS42 DC grid and CB models are delivered (SHET M30) - ?Completed
  - MS43 Relays and grid models successfully integrated in RTDS, and project moves to testing (SHET M38[40])
  - MS44 Protection system successfully demonstrated (SHET M42[44])
  - MS45 Interoperability successfully demonstrated (SHET M46[51])
  - MS81 Full bridge converter models are developed (SGI M38)
  - MS82 Relays and grid models successfully integrated in real-time simulation environment, and project moves to testing(SGI M41[49])
  - MS83 Supervisor prototype for HVDC system restoration ready (SGI M48[49])
  - MS84 Non-selective protection systems successfully demonstrated (open-loop system restoration) (SGI M48[49])
  - MS85 Non-selective protection systems successfully demonstrated (closed-loop system restoration) (SGI M54)
D9.3 Protection System Demonstration
Summary
D9.3 Overview

- **Purpose of D9.3:**
  Demonstration of protection system

- Protection systems will be tested using hardware in the loop real-time approach

- Integration of:
  - WP6 DCCBs
  - WP4 IED
  - MELCO IED
  - detailed ‘realistic’ real time models

---

**Demonstration of HVDC protection system - Agenda**

**Location & Registration:** The National HVDC Centre, Cumbernauld, G68 0FQ, UK

**Agenda, 22nd August 2019**

<table>
<thead>
<tr>
<th>Time</th>
<th>Activity</th>
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<tbody>
<tr>
<td>09:00 – 09:30</td>
<td>Registration &amp; Welcome</td>
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<tr>
<td>09:30 – 09:50</td>
<td>Safety Induction and Introduction – Ian Cowan (SHET)</td>
</tr>
<tr>
<td>09:50 – 10:20</td>
<td>DC Grid Protection philosophy – Geraint Chaffey (KUL)</td>
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<tr>
<td>10:20 – 10:50</td>
<td>DC circuit breakers - tbc</td>
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<tr>
<td>10:50 – 11:20</td>
<td>Break</td>
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<tr>
<td>11:20 – 11:45</td>
<td>Technical description of IED-1 - PROMOTioN IED – Ilka Jahn (KTH)</td>
</tr>
<tr>
<td>11:45 – 12:10</td>
<td>Technical description of IED-2 - MELCO IED – Frederick Page (MELCO)</td>
</tr>
<tr>
<td>12:10 – 12:50</td>
<td>Description of test set up and walking tour – Various WP9 Members</td>
</tr>
<tr>
<td>12:50 – 13:50</td>
<td>Lunch</td>
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<tr>
<td>13:50 – 15:20</td>
<td>Demonstration of selected fault cases – Various WP9 Members</td>
</tr>
<tr>
<td>15:20 – 15:45</td>
<td>Presentation of past test results and discussions – Various WP9 Members</td>
</tr>
<tr>
<td>15:45 – 16:10</td>
<td>WP9 future test plans - Ian Cowan (SHET) and William Leon Garcia (SGI)</td>
</tr>
<tr>
<td>16:10 – 16:30</td>
<td>Close out session including Q&amp;A - Ian Cowan (SHET)</td>
</tr>
</tbody>
</table>

**End of Event**
### D9.3 Attendees

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<tr>
<th>Nr.</th>
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<tr>
<td>1</td>
<td>Bhavinh Formanagian</td>
<td>The National HVDC Centre (SHE Transmission)</td>
<td></td>
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<tr>
<td>2</td>
<td>Daniil Olavde</td>
<td>The National HVDC Centre (SHE Transmission)</td>
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<tr>
<td>3</td>
<td>Dirk Van Hemel</td>
<td>KU Leuven</td>
<td></td>
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<tr>
<td>4</td>
<td>Dragan Jovick</td>
<td>University of Aberdeen</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Frederick Page</td>
<td>Mitsubishi Electric Europe</td>
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<td>6</td>
<td>Gerhard Ch OFF</td>
<td>KU Leuven</td>
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<td>7</td>
<td>Ian Cowan</td>
<td>The National HVDC Centre (SHE Transmission)</td>
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<td>8</td>
<td>Ibra John</td>
<td>KTH Royal Institute of Technology</td>
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<td>9</td>
<td>Kamran Shafiparasti</td>
<td>Equinor ASA</td>
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<td>10</td>
<td>Lei Xu</td>
<td>University of Strathclyde</td>
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<td>Linship Kunjuhammed</td>
<td>Mitsubishi Electric Europe</td>
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<td>Nicolas A. Cutululis</td>
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<td>13</td>
<td>Rory Stanshine</td>
<td>The Carbon Trust</td>
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<td>14</td>
<td>Rui Lü</td>
<td>University of Strathclyde</td>
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<td>15</td>
<td>Sertan Kabul</td>
<td>Tennet TSO B.V.</td>
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<td>16</td>
<td>Simon Marshall</td>
<td>The National HVDC Centre (SHE Transmission)</td>
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<td>17</td>
<td>Willem Letemee</td>
<td>KU Leuven</td>
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<tr>
<td>18</td>
<td>William Leon Garcia</td>
<td>SuperGrid Institute</td>
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</tbody>
</table>
Partially and Fully Selective Testing
Real time Simulation test setup.
HVDC grid protection IEDs – hardware prototypes

**KTH IED**
- Off-the-shelf System-on-Chip development platform (Zedboard)
- Six independent function unit
  - Inputs: line voltage(1) and current (1)
  - Outputs: trip out
- Implemented protection functions:
  - Primary protection: travelling wave, $\frac{dv}{dt}$
  - Breaker failure backup: breaker failure bit
  - Busbar protection

**MELCO IED**
- State-of-the-art, industrial-grade hardware
- High speed input measurement sampling and computation
- Outputs: flexible applicable in variety of network topologies
- Implemented protection functions [1][2]
System model
# System Parameters

<table>
<thead>
<tr>
<th>Table 1: Parameters of 3-Terminal HVDC System</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Converter</strong></td>
</tr>
<tr>
<td>Station 1</td>
</tr>
<tr>
<td>Topology</td>
</tr>
<tr>
<td>Arm inductance</td>
</tr>
<tr>
<td>No. of cells per arm</td>
</tr>
<tr>
<td>Cell capacitance</td>
</tr>
<tr>
<td>Av. cell capacitance</td>
</tr>
<tr>
<td>Rated power</td>
</tr>
<tr>
<td>Rated active power</td>
</tr>
<tr>
<td>DC voltage</td>
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<table>
<thead>
<tr>
<th>Transformer</th>
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<tbody>
<tr>
<td>Rating</td>
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<td>Voltage ratio</td>
</tr>
<tr>
<td>Reactance</td>
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<table>
<thead>
<tr>
<th>AC Grid</th>
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<tbody>
<tr>
<td>Voltage</td>
</tr>
<tr>
<td>Nominal frequency</td>
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<tr>
<td>SCR</td>
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<td>X/R ratio</td>
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<td>Local load</td>
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<tr>
<th>Wind Farm</th>
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<tbody>
<tr>
<td>Rated power</td>
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<tr>
<td>Rated active power</td>
</tr>
<tr>
<td>VSC DC Voltage</td>
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<tr>
<td>VSC AC Voltage</td>
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<tr>
<td>Trans. rated power</td>
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<tr>
<td>Trans. voltage ratio</td>
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<tr>
<td>Trans. reactance</td>
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<table>
<thead>
<tr>
<th>Table 2: Cable Parameters of 3-Terminal HVDC System</th>
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</thead>
<tbody>
<tr>
<td><strong>Item</strong></td>
</tr>
<tr>
<td>Type</td>
</tr>
<tr>
<td>Conductor</td>
</tr>
<tr>
<td>Insulation</td>
</tr>
<tr>
<td>Length</td>
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</table>

<table>
<thead>
<tr>
<th>Table 3: Additional inductance required to meet specified fault ride through scenario for each circuit breaker topology</th>
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</thead>
<tbody>
<tr>
<td><strong>DCCB topology 1</strong></td>
</tr>
<tr>
<td>FRTS3</td>
</tr>
</tbody>
</table>
**Test conditions**

- Pole-to-pole faults every 5 km
- Three repetitions at each fault location
- IED operating time (mean time of 3 repetitions):
  - Primary protection: from fault arrival to the IED issues a trip outputs
  - Backup protection: from fault arrival to the backup protection IED issues a trip outputs
Performance and Results for Hybrid Breaker

Fig. 5: IED Operating Time for PROMOTioN IED when Utilising Hybrid DCCB

Fig. 6: IED Operating Time for MELCO IED when Utilising Hybrid DCCB

Fig. 7: DC Current Measured at the IED Location when Utilising Hybrid DCCB for Mid-Cable Pole-to-Pole Fault (MELCO IED Under Test)

Fig. 8: DC Voltage Measured at the IED Location when Utilising Hybrid DCCB for Mid-Cable Pole-to-Pole Fault (MELCO IED Under Test)
Performance and Results

Fig. 9: IED Operating Time for PROMOTioN IED when Utilising Mechanical DCCB

Fig. 10: IED Operating Time for MELCO IED when Utilising Mechanical DCCB

Fig. 11: DC Current Measured at the IED Location when Utilising Mechanical DCCB for Mid-Cable Pole-to-Pole Fault (PROMOTioN IED Under Test)

Fig. 12: DC Voltage Measured at the IED Location when Utilising Mechanical DCCB for Mid-Cable Pole-to-Pole Fault (PROMOTioN IED Under Test)
Multi-vendor interoperability of IEDs

• Interoperability of IEDs from multiple vendors is one of the essential aspects to achieve a successful fault clearing.

• How to evaluate multi-vendor interoperability
  • Step 1: evaluate IED performance in a **single-vendor** setup
  • Step 2: evaluate IED performance in a **multi-vendor** setup
  • Step 3: comparison
Multi-vendor interoperability test setup

- Fully selective strategy
  - IEDs are placed at both ends of a cable
  - DCCBs are placed at the DC switching station: inductors are chosen to allow breaking current to fall within the capability of hybrid DCCBs (2 ms/16 kA)
  - ACCBs at the converter side
### Test Cases

<table>
<thead>
<tr>
<th>Case No</th>
<th>Vendor</th>
<th>Type</th>
<th>IED</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>41</td>
</tr>
<tr>
<td>C1</td>
<td>Single-vendor</td>
<td>Primary</td>
<td>SW</td>
</tr>
<tr>
<td>C2</td>
<td>Single-vendor</td>
<td>Primary</td>
<td>SW</td>
</tr>
<tr>
<td>C3</td>
<td></td>
<td>Breaker failure</td>
<td>MELCO</td>
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<tr>
<td>C4</td>
<td>Multi-vendor</td>
<td>Primary</td>
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<tr>
<td>C5</td>
<td>Multi-vendor</td>
<td>IED failure</td>
<td>SW</td>
</tr>
<tr>
<td>C6</td>
<td></td>
<td>Breaker failure</td>
<td>KTH</td>
</tr>
</tbody>
</table>

**IED types:**
- **KTH** and **MELCO**: Hardware IEDs; **SW**: Software IEDs modeled in RTDS
Primary protection

👩‍💻 IED configuration:
   👩‍💻 Single-vendor setup:
       👫 C1: KTH IED functional units connected to IED$_{42}$ and IED$_{24}$
       👫 C2: MELCO IED functional units connected to IED$_{42}$ and IED$_{24}$

👩‍💻 Multi-vendor setup:
   👫 C4: KTH IED: IED$_{42}$, MELCO IED: IED$_{24}$

👩‍💻 Example results (KTH IED):
   👫 Mean operating time: less than 200 $\mu s$
   👫 Single-vendor and multi-vendor cases:
       👫 Comparable operating time (Multi-vendor case is slightly higher $\rightarrow$ needs further investigation)
       👫 100% dependable along the 136 km cable
IED failure backup protection in a dual redundant setup

 نيوز
IED configuration (multi-vendor setup (C5)):

- KTH IED as IED\textsubscript{42a}, MELCO IED as IED\textsubscript{42b} with separate measurement inputs, and independent trip outputs
- One of the hardware IEDs is disabled to simulate a failure
IED failure “backup” protection in a dual redundant setup

→ IED performance:
  → Operating time: few hundreds $\mu s$
  → 100% dependable
Breaker failure backup protection

**IED configuration:**

- **Single-vendor setup (C3):**
  - MELCO IED functional units are connected to IED$_{42}$, IED$_{41}$ and IED$_{43}$.

- **Multi-vendor setup (C6):**
  - MELCO IED: IED$_{42}$
  - KTH IED: IED$_{41}$ and IED$_{43}$
  - MELCO and KTH IED: directly connected with a wire

**Tests:**

- DCCB$_{42}$ is disabled
- IED$_{42}$ detects a fault and issues a trip order
- IED$_{42}$ detects a breaker failure and send a trip order to IED$_{41}$ and IED$_{43}$
- IED$_{41}$ and IED$_{43}$ trip the backup DCCBs
**Breaker failure backup protection**

- **IED performance:**
  - BF delay setting: 10.42 ms
  - Single-vendor and multi-vendor cases:
    - BF backup IED time: comparable
    - BF decision time: few hundreds $\mu$s
    - 100% dependable
Use of CMS Control and Protection Replcias
Replica Setup

Real Time Simulator Rack
- Measured Node Voltages & Currents
- Analogue Output
- Modelled in RTS Software
- Digital Input
- Firing Pulses

HVDC Control Replica Cubicle
- Signal Processing at Interface Cubicles
- VSC Station Computer
- Valve Control Unit
- Firing Pulses

Real-Time Simulator
- RTM HMI
- RTS HMI

Measured Voltage and Current
Analogue signals
Firing Pulses (Digital Signal)

Replica HVDC Control
Operator Work Station
- Start up / shut down
- Change control mode
- Change set points
- etc

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This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 691714.
• Two subsystems
• Not frequency dependant cable models
• Only the convertors in small time step
• New subsystem
• Moved to small time step
• Frequency dependant line used
• Many interfaces…
• Also had to move the DCSS
Partially and Fully Selective Testing Summary
SUMMARY

PROGRESS

• Two hardware IEDs are tested in a realistic three-terminal network for primary, IED failure backup and breaker failure backup protection. The test results demonstrate
  • Single-vendor and multi-vendor cases: comparable performance
  • Multi-vendor HVDC grid protection system: feasible and a viable option
• Initial steps to test with CMS Control and Protection Replicas undertaken

NEXT STEPS

• Further testing with different combinations of DCCB models and IED locations
• Extend model to 4T system
• Add in pole rebalancing to allow move to system level testing
• Further testing including the CMS Control and Protection Replicas
• Prepare for the next Demonstation
  • (Probably the second week in May)
Non-selective Testing
This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 691714.
Bipole HVDC

- System and IEDs from SuperGrid Institute

In simulation (25µs):
- Ground return
- AC side (Thevenin equivalent)
- HB-MMC average model
- Wideband cable model

HIL:
- IEDs (1 pole)
- Relays x11 (11 IEDs)
- Station supervisor (4 IEDs)
- Grid supervisor (1 IEDs)

**16 IEDs**
Monopole HVDC

- System provided by RWTH Aachen
- IEDs from SuperGrid Institute

In simulation (40µs):
- Star point reactor
- FB-MMC average model
- Wideband cable model
- AC side (Thevenin equivalent)

HIL:
- IEDs (2 poles because monopole)
  - Relays x16
  - No station supervisor (FB-MMC restoring given)
  - No grid supervisor
Protection and supervision architecture

Vision from SuperGrid Institute

Interoperable
Central supervisors
Station supervisors

Modes:
- Start-up
- Short-circuit fault
- Voltage recovery
- Power recovery
Non Selective Testing Summary
**PROGRESS**

- Hypersim models
  - MMC-HB
  - MMC-FB
  - Mechanical DC CB
- Pre-validation tests of a 4T
  - Start-up
  - DC fault (open-loop)
- Validation tests of the FB-MMC model in a 3T grid (symm. Monopole).
  - Start-up
  - DC fault (closed-loop with simulated IEDs)
- Improvement of IED prototypes
  - Developpment (C code)

**NEXT STEPS**

- Pre-validation tests of the 4T including SuperGrid IEDs (bipole).
- Pre-validation tests of the 4T including SuperGrid IEDs (symm. monopole).
- Validation tests of the FB-MMC model in the 4T grid (bipole) using simulated relays.
- First version of supervisor for the 4T grid in Hypersim.
- Prepare for the Demonstration
  - Aligned with SuperGrid Institute TO event May/June
Thank you!
Minutes of Meeting

Event: PROMOTioN Half-yearly meeting
Location: Roskilde
Date: 3rd of December 2019
Session: Plenary session

WP13 – Sebastian Menze (SOW)
Cees Plet: DG RTD mentioned during visit to the booth that in the Horizon Europe program he will put particular focus on ensuring the results of research projects are exploited. Hence please participate with intent in the exploitation of results initiative led by DNV GL.

WP11 – Poul Sørensen (DTU)
Lorenzo Zeni: The cost axes on the figure refers to the cost of a test. It is not easy to compute the cost of a bad model.

Cees Plet: What are you doing to ensure active uptake of our recommendations such as writing CIGRE WG ToR proposals?

Poul Sørensen: We are carefully looking at where this is of value, as starting a new WG is not always addressing the issue in the most effective way and can even cause confusion. It is therefore also important to make sure existing initiatives are strengthened by ensuring PROMOTioN results are transferred to them.

Cees Plet: The creation of a grid code on the DC side was seen as a key requirement for the development of a DC grid during the WP12 meeting. What is WP11 doing to kick-start the formation of such a grid code?

Poul Sørensen: This is the task of TSOs. As PROMOTioN we can provide the input and a first draft but we cannot start the activity.

WP15 – Uwe Riechert (ABB)
Rene Smeets: With regards to the presented additional test (SF6 alternative AirPlus long term test) are you planning to also include alternative gases from other manufacturers, as is done with other technologies in PROMOTioN?

Uwe Riechert: In principle open to do so, but it requires more time which is no longer possible within the project.

Cees Plet: Are there any other OEMs that are interested in showcasing there are alternative gases in a similar way?
- No response

WP2 – Christina Brantl (RWTH Aachen)
Dragan Jovcic: Why are deliverables confidential if no vendor-specific models were used?

Kanstantsin Fadzeyeu: Models in WP2 were all derived from publicly available CIGRE models. WP2 models were benchmarked by OEMs and the dynamic response was...
deemed reasonable. The enhanced models of WP2 have been delivered back to the public domain (e.g. CIGRE).

Christina Brantl: PSCAD model will be available on ProjectPlace. Other university internal models will also be made available. Commercial software e.g. Eurostag will not be made available.

Cees Plet: supports making all deliverables in WP2 publicly available as not OEM specific info was used. Should be discussed in WP2 and PMG, also to make library of models of all HVDC grid components available publicly as a project.

Ramon Blasco: supports making it open, but we need to think about what to publish as some material in deliverables is probably not of interest for general public.

Karim Karoui: Can we recommend values for the limits on our CG requirement recommendations?

Christina Brantl: can be done, but it should be done by ENTSO-E.

Cees Plet: We should provide numbers based on state of art and PROMOTioN understanding, including argumentation and disclaimer that of course final values should be determined by ENTSO-E.

Niklas Svensson: How much of the WP2 results are applicable to point-point HVDC links?

Christina Brantl: in principle everything, as point-point can be regarded as a special case of HVDC grids, so even though all requirements are applicable, they may not be relevant.

WP3 – Nikolaos Cutululis

Kanstantsin: Were models Matlab or PSCAD?

Nikos: Models were provided in PSCAD.

Kanstantsin Fadzeyeu: How do industry and academia see perspective of self-energisation and black start and how does this translate to requirements of customers and when do you think this might happen?

Nikolaos Cutululis: Industry was not very much involved in that part, so can’t comment on that. OEMs have provided vendor specific models with black-start functionality. There is a lot of interest, but a lot of engineering and details still need to be defined.

PROMOTioN has developed basics and fundamentals. Push is coming from TSOs.

Ramon Blasco: depends on when technology is available, e.g. Siemens Gamesa has been working on it. Need to convince TSO’s that black start from offshore wind can work, as there is a drive to close down coal plants who often have black start duty. This drive is happening, and in latest bidding for black start by national grid, wind farms were included. It looks like it might happen in medium term.

Philipp Ruffing: do we ave any actions like the STP planned for DRUs to demonstrate that it can be done.

Nikolaos Cutululis: do what promotion originally set out to do.
Dirk van Hertem: It seems that DRU is dead, even though technically feasible there are no next steps in industry. A STP should be included in WP12 to create this push.

Cees Plet: WP3 output should include requirement for validation of models used for grid code compliance evaluation. WP3 and WP16 should create joint message on this topic.

WP16 – Philipp Ruffing
Dragan Jovcic: Will results from WP16 demo using Chinese OEM equipment be shared? Will deliverable be reviewed by Chinese partner? Will they be available for questions?

Cees Plet: Other OEMs in the project were contacted but were not willing to rent out control & protection replicas for this purpose. Hence the equipment was rented from Chinese OEMs where it was possible. The Chinese vendors are only suppliers to the work package and are not partners of the project. As such they do not review deliverables for example. If there are specific questions, then these can be forwarded to the OEM.

WP6 – Dragan Jovcic
Cees Plet: As a suggestion to add to the failure mode analysis is to create reliability block diagrams which relate the failure rates (mean time between failure) of individual components to the overall failure rate, or reliability, of a DCCB as a system. This figure is typically used in grid planning and availability studies. Even though MTBFs for new components in DCCBs are not yet known, the logical relationship between the failure rates can already be derived.

Dragan Jovcic: WP6 will look into this.

WP10 – Rene Smeets
Dirk van Hertem: How many people will be able to attend the demo test?
Rene Smeets: Lab is limit of about 30 people, tests are open to anyone in the consortium, date is fixed, invitation will come soon

Cees Plet: will multi-part testing in which different stresses are tested in separate tests be sufficient for qualifying HVDC circuit breaker technology?

Rene Smeets: Yes, it has to be, since other commercial labs will not be able to carry out one-stop-shops in the way KEMA Labs can. This is the topic of the Cigre B4.80 WG on HVDC circuit breakers.

WP4 – Dirk van Hertem (KU Leuven) & Serge Poullain (Super Grid Institute)
John Moore: in contrary to claim, protection design must be thought of a priori to reserve space on platforms etc. So how to choose between different protection strategies
Dirk van Hertem: not necessary during basic grid design, but later, before platform FEED, tool provided by promotion can provide insight in which method is best

Cees Plet: how do we select what is best strategy in a specific project?

Dirk van Hertem: Prob fully selective but this cannot be said without exact information on costs and reserve benefits

Christina Brantl: What are EENT pie charts based on? Should be clear if this is used to support external message.
Serge Poullain: only part of cost. Includes cables, transformers and protection contribution to total EENT. This is topology specific

Karim Karoui: At the beginning of PROMOTioN the question was if fully or non-selective protection strategies would be best, now it emerges that the conclusion is that probably a mix of both will be best.

**WP9 – Ian Cowan (SHE Transmission)**
Philiipp Ruffing: It seems supergrid topology is not the same as the one used in Aachen, can we align?

SGI: Yes

Cees Plet: Are the real ABB control & protection replicas going to be used?

Ian Cowan: Yes
Deployment considerations for HVDC Meshed Offshore Grids in the Northern Seas

TenneT ● John Moore
What is the challenge for transmission operators?

- To hit 2050 Carbon targets we need to accelerate the build of Offshore Wind
- Distance to shore increases as near shore locations filled and resistance increases: 55km today to >100km
- Preparation time increases
- Uncertainty as to technological change and need
- A consistent Legal & Regulatory environment is required to facilitate more efficient evacuation and anticipatory investment
- The infrastructure requires to adopt and provide flexibility options at scale and interact with the onshore grid
PROMOTioN researches into technology and broader issues

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
WP10 · HVDC Circuit Breaker Demonstration · DNV GL
WP16 · MMC Test Bench Demonstrator · RWTH Aachen
WP11 · Harmonisation Towards Standardisation · DTU
WP12 · Deployment Plan for Future European Offshore Grid · TenneT

WP9 · Protection System Demonstration · SHE Transmission
WP15 · HVDC GIS Demonstrator · ABB
WP14 · Project Management · DNV GL
WP13 · Dissemination · SOW

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Copenhagen 28.11.2019
To produce a Deployment Plan for European future offshore grid development.

- Technical
- Governmental
- Financial

- Economic
- Market
- Legal & Regulatory

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691714.
Two parallel paths to a Deployment plan:

- Offshore Wind Generation Scenarios
- Topologies
- Technological Choice
- Cost Benefit Analysis
- Economic Analysis (CBA methods & CBCA Proposals)
- Financing & Potential legal structures
- Legal & Regulatory
- Governmental
- Market Structures
1. Top down market
2. GIS mapping studies
3. Country Allocation
PROMOTioN recommendations

- PROMOTioN High scenario projects higher growth than current ENTSO-e scenarios in order to reach 2050 Carbon reduction targets,
  - Our high scenario is not the highest we have seen in parallel studies.
  - Be aware of space constraints and ability to deliver.

- Optimising offshore wind potential is subject to political influences and does change, e.g. new governing trends shift towards an increased emphasis on RES
  - Positive increase in Wind potential (e.g. DK – greater ambition) can lead to use of better locations for generation. EU Clean Energy Package encourages cooperation.
  - Use local powers for more rational allocation of spatial planning (e.g. NL rationalises spatial planning).

- High development of offshore wind leads to some utilisation of Nature 2000 areas
  - Prioritise and coordinate spatial planning for offshore wind
  - We fixed wind development, but could be optimised more per concept.
1. Concepts
2. Temporal development
3. Optimisation
PROMOTioN recommendations

• Islands planned and built early on in the period (2025 – 2030)
  • PROMOTioN assumes a current status quo that concentrates energy into (small) hubs as Business as Usual
  • For maximum Cost-Benefit, the optimiser suggests a benefit in the use of islands.
  • This is a theoretical model, and requires feasibility and further optimisation.

• Meshing and multi-terminal connections are important and should be used where appropriate
  • Technical choice of bipole architecture and N-1 security criterion reduces benefit of redundant paths
  • Cable maximum power is matched to onshore infeed constraints.
  • The optimisation does not have large amounts of meshing, but it does provide material cost savings in some cases.

• Early planning facilitates meshing later in the period (2040 onward)
  • As distance to shore increases, meshing of offshore wind clusters becomes more cost effective

• Adopt standards to facilitate meshing, but we anticipate ‘stacked’ meshed systems rather than an entire meshed offshore grid

• Interconnection between windfarms of different countries in order to save on cable costs and increase cable utilisation
1. Cost data / inputs
2. Clustering
3. Hub design: bare bones and Protection
4. Costing the network

Standard voltages, e.g. 525 KV
Standard configuration: Bipole with fixed return
Standard cable sizes – current Max 2 GW
No onshore load shedding – N-1

Different Hub structures per Concept with different components (standard architectures depend on distance/power flows)

Protection Strategies determined by WP4

Costs Analysis
Investments
- AC equipment & cables
- DC Hub Equipment & cables
Protection Costs (where required)
Operating Costs

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Copenhagen 28.11.2019
PROMOTioN recommendations

- Design standard Platforms that can be either modular or built out for multi-terminal use.
  - Protection equipment requires increased space on platforms such that costs increase quickly
- Plan early and anticipate future capacity needs to minimise cable costs.
  - Small changes to the topology can have major costs impact
  - Direct connection of AC inter-array cables saves high AC platform costs
- Shorter distance connections will still be in AC, and therefore utilise (cheaper) AC meshing where large power concentrations (Hub model)
- HVDC protection costs dependent on choice of fault clearing strategy
  - Protection may be done fully selective which requires many expensive DC Circuit Breakers
  - Smart protection using grid splitting may significantly reduce protection costs
### Offshore Wind Generation Scenarios

- Topologies
- Technological Choice
- Cost Benefit Analysis

---

#### Costs Analysis

<table>
<thead>
<tr>
<th>Investments</th>
<th>Protection Costs (where required)</th>
<th>Operating Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>- AC equipment &amp; cables</td>
<td>- DC Hub Equipment &amp; cables</td>
<td></td>
</tr>
</tbody>
</table>

#### Cost Analysis

<table>
<thead>
<tr>
<th>#</th>
<th>NAME</th>
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<tbody>
<tr>
<td>B1</td>
<td>Socio Economic Welfare</td>
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<tr>
<td>B2</td>
<td>RES Integration</td>
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<tr>
<td>B3</td>
<td>CO2 Variations</td>
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</tr>
<tr>
<td>B4</td>
<td>Societal Well-being</td>
<td>Qualitative</td>
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<tr>
<td>B5</td>
<td>Grid losses</td>
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<td>B6</td>
<td>Security of Supply – Adequacy</td>
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<td>B7</td>
<td>Security of Supply – Flexibility</td>
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<td>B8</td>
<td>Security of Supply – Security</td>
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<tr>
<td>B9</td>
<td>Security of Supply – Resilience</td>
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<tr>
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<td>Social</td>
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</tr>
<tr>
<td>S3</td>
<td>Other</td>
<td></td>
</tr>
</tbody>
</table>

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1. Network Costs
2. Benefits Analysis
3. Non Quantitative analysis
4. KPIs - LCoT

---

Cost-Benefit Report per Concept-Scenario
PROMOTioN recommendations

• Where sufficient generation concentration use European Hub concept to deliver significant savings in costs for support structures

• Multi-terminal connections depend on anticipatory investment, therefore steer deployment through organised and structured planning.

• Cooperate across Europe to build grid infrastructure (connect hubs in country A to country B if shorter distance)

• Mesh where appropriate not for meshing’s sake
  • Meshing leads to lower curtailment and higher security of supply, but at high costs for additional infrastructure

• Different grid goals may lead to additional benefits of the different topologies per region – but overall quite similar. Optimise on grid elements
  • PROMOTioN constraints on onshore load shedding result in retaining 2GW cables. This results in partial redundancy and therefore lower benefits compared to BAU.

• Environmental and social impact of concepts different but none more impactful than the others
1. Application of improved and standardised (ENTSO-E) CBA techniques
2. Formal and standard Cross Border Cost Allocation

D7.2 analyses how to best allocate cross border costs

D7.11 Cost Benefit Analysis - Method

1. Application of improved and standardised (ENTSO-E) CBA techniques
2. Formal and standard Cross Border Cost Allocation

D7.2 analyses how to best allocate cross border costs
1. **Financing Investments**

2. **Potential structures for transmission owners/operators**

<table>
<thead>
<tr>
<th>NSG TSO</th>
<th>Co-operation of national TSOs/third parties</th>
<th>Tenders before construction</th>
<th>Tenders post construction</th>
</tr>
</thead>
</table>
| • System operation, asset operation (O&M), ownership, construction  
• Owned by National TSOs or national TSOs & private investors, or private investors | • Extension of the current national structures  
• Each actor applies their current approach within its own EEZ | • Asset operation (O&M), ownership and construction  
• Private or public investors/ national or international/ public-private consortia | • Construction carried out by national TOs or a single TO  
• Assets tendered to third parties (private investors) for ownership, maintenance and asset operation |

1. A clear definition of responsibilities and liabilities of investors, constructors and managers of the meshed HVDC offshore grid is advisable, to allow institutional investors, debt and equity providers the clarity needed to make an assessment of the investment risk. Offshore grid asset ownership should be designed to ensure the participation of multiple funding sources to support the challenging volume of required investments.

2. Grid ownership when meshed is likely to become more “blurred”:
   1. e.g. with North Sea Wind Power Hub, we already see a consortium ownership. Incumbents are likely to see a dilution in ownership, and need similar controls/management to cross border interconnectors.
   2. PROMOTioN recommends clear rules for Cross Border Cost Allocation, in order to clarify the discussion, but we also accept pragmatism in the eventual finance of new grid infrastructure.
1. Cooperation – Develop a mixed partial agreement

North Sea coastal states should work to develop a multilateral mixed partial agreement (a North Sea Treaty) which can serve as a framework for formalising the rules of a meshed offshore grid.
1. Cooperation – Develop a mixed partial agreement
2. A robust Legal definition of an Offshore Hybrid Asset

North Sea coastal states should adopt a common interpretation of the law of the sea regarding hybrid assets within the MOG, by taking a broad interpretation of UNCLOS terminology. This definition of hybrid assets should be set out in a multilateral (mixed partial) agreement that is used for the governance of the MOG.
1. Cooperation – Develop a mixed partial agreement
2. A robust Legal definition of a Hybrid Asset
3. Agreement on approach to regulating the grid (who and how)
   - 1. Finance of Anticipatory assets
   - 2. Transmission owner income regulation
   - 3. Coordinated offshore wind support schemes

- The internal market regulation should be amended to include a definition and a substantive provision on how offshore hybrid assets should be regulated. The amendments should be designed to support a long-term, stable and predictable regulatory framework, so to reduce the risk exposure on capital in relation to investments in the meshed offshore grid.
- It is recommended that NRAs organise themselves in a specific regulatory coordination group to oversee grid development and operations through strong, mutual cooperation.
1. Cooperation – Develop a mixed partial agreement
2. A robust Legal definition of a Hybrid Asset
3. Agreement on approach to regulating the grid (who and how)
   1. Finance of Anticipatory assets
   2. Transmission owner income regulation
   3. Coordinated offshore wind support schemes
4. Decommissioning regulation

The internal market regulation should be amended to include a definition and a substantive provision on how offshore hybrid assets should be regulated. The amendments should be designed to support a long-term, stable and predictable regulatory framework, so to reduce the risk exposure on capital in relation to investments in the meshed offshore grid.
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691714.

1. Planning & permit Processes alignment/simplification
2. Stakeholder participation and Consultation

- Streamline the permitting process to reduce the risk of legislative change during the permitting phase. Legislative changes should not retroactively impact projects already approved. Once granted, permits/licenses will remain valid for the duration of the construction and operation phase.
- A central approach for grid planning and strong coordination of grid development plans in terms of timing and location is recommended to increase the transparency of future network investments requirements and their cross-border impact.
1. Market structures from extension of country bidding zone into EEZ to small zones models
2. Market models where meshing exists

- In the short term, current practice of extending the National Bidding zones to the country EEZ is sufficient
- With an increase in development and meshing, then a small zones approach may be more appropriate.
- Market management and organisation has not been studied, but new trading tools could be implemented to support this proposal.
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691714.
Deployment plan gives direction and says what is needed – we suggest ground rules for potential development and interoperability

**Legal & Regulatory**
- Hybrid Asset
- Mixed partial agreement
- Coordinated planning
- Supply chain
- DC Grid Code
- Decommissioning

**Market Models**
- Small Zones Bidding Zone

**Technology**
- Anticipatory investments
- Interoperability
- Island solution
- (Multivendor) pilot projects
- Application of DCCBs/GIS etc.

As alternative to hybrid assets
Boundaries of the deployment plan - what we propose as the best solution will never be built

Primary Goal: Efficient, secure evacuation of offshore generated wind energy to shore

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

Copenhagen 28.11.2019
APPENDIX

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MAIL info@promotion-offshore.net WEB www.promotion-offshore.net

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About PROMOTioN
PROMOTioN is a European Union funded Horizon 2020 project consortium, formed to address the technical, regulatory, financial and legal challenges for offshore HVDC transmission networks. It consists of 33 organizations including European HVDC manufacturers, Transmission System Operators (TSO), academic institutions, testing institutions and consultants. This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 691714.

For more information please visit www.promotion-offshore.net
Any Questions?
Results benefit analysis

Felix Rudolph (FGH), 03.12.2019
CONTENT

• Introduction to benefit analysis
• Results B1: Socio-economic welfare
• Results B2: RES integration
• Results B3: CO₂ variation
• Results B6: Adequacy - Loss Of Load Expectation
• Conclusion
Introduction benefit analysis

• Operational dispatch simulation with hourly resolution
  • BAU / NAT / EUR / HUB concepts
  • Scenario years 2025 – 2050
  • Including most ENTSO-E bidding zones as node model
  • Offshore topologies in detail
  • Time-coupling simulation (hydro)
  • Input data mostly from TYNDP2018 and ENTSO-E Transparency Platform (extrapolated to 2050)
• Output as KPIs (D7.11)
Results B1: Socio-economic welfare of all simulated bidding zones

- Generation Costs:
  - Includes only fuel type specific marginal costs
  - No distinction between markets
- Increase in costs in 2030:
  - High CO₂ price results in a sharp rise of marginal costs
  - Not offset by RES
- Small differences between concepts with less than 2%

- EUR concept with best socio-economic welfare in 2050
Results B2: RES integration of all simulated bidding zones

- Curtailment of PV and Wind (onshore / offshore / OWF)
- Missing flexibility leads to curtailment in times of low load – high RES generation
- OWFs are only source of curtailment until 2035

- Additional IC could improve RES integration
- Flexibility (e.g. storage units, DSM, P2X) could improve RES integration
- Not always cost-effective
Results B2: RES integration of North Seas countries

→ Flexibility needed to fully integrate the high amount of offshore generation
Results B3: CO₂ variation of all simulated bidding zones

- CO₂ emissions in all four concepts similar
- 2040-2050: dispatch of thermal generation (mostly gas turbines) when low wind and solar radiation
- Additional IC could improve hydro integration
- Flexibility (e.g. storage units, DSM, P2X) could improve CO₂ emissions
- Not always cost-effective
Results B3: CO₂ variation of North Seas countries

Variations of CO2 emissions between the concepts in bidding zones
Results B6: Security of Supply - Adequacy of North Seas countries

- Loss Of Load Expectation (LOLE): Expectation that the available generation capacity cannot meet the load
- Expected Energy Not Supplied (EENS): Expected amount of electricity that cannot be delivered per year
- Markets: DE, DK, NL
Results B6: Security of Supply - Adequacy of North Seas bidding zones

- LOLE only in Winter
  - Low solar radiation
  - Low wind capacity factors
- Interconnector capacity and generation capacity of available flexibilities not sufficient to fully avoid LOLE
Conclusion

• All results quite close to each other with marginal differences
• EUR concept always slightly the best, followed by BAU and HUB
  ➔ Recommendation for EUR concept from operational benefits standpoint

• Installing interconnections earlier could benefit RES integration
• Increasing NTCs would increase RES integration
  • Onshore between (continental) Western ⇔ Eastern Europe, Western ⇔ South Europe
  • For hydro pump-storage integration: NO ⇔ DE/DK, DE ⇔ AT/CH

• Flexibility needed to integrate these amounts of offshore generation
• Further research and simulations with flexibility necessary, especially for horizon 2035 and beyond
  • Not scope of the project PROMOTioN, as battery storage, DSM and P2X are researched within other European projects
  • Flexibility should be developed in parallel with offshore topologies
Deployment considerations for HVDC Meshed Offshore Grids in the Northern Seas

TenneT ● John Moore
## Overview of costs

<table>
<thead>
<tr>
<th>CAPEX (bn€)</th>
<th>2025</th>
<th>2030</th>
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<th>2040</th>
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<th>2050</th>
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<tr>
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<td>NAT</td>
<td>28.1</td>
<td>59.1</td>
<td>84.5</td>
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<td>HUB</td>
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<td>133.2</td>
<td>178.5</td>
<td>221.5</td>
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## Where is the difference? - NAT

Figures in billion

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<th>BAU</th>
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<th>NAT - BAU</th>
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<tbody>
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<td>Offshore converters, transformers and platforms (AC, DC, sub-total)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Offshore converters</td>
<td>€ 37.96</td>
<td>€ 33.82</td>
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<td>Transformers and platforms</td>
<td>€ 80.79</td>
<td>€ 93.69</td>
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<td>Platforms (AC, DC, sub-total)</td>
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<td>Cabling</td>
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<td>€ 0.00</td>
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<td>Onshore stations</td>
<td>€ 27.65</td>
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<td>Total</td>
<td>€ 208.7</td>
<td>€ 223.4</td>
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Where is the difference? - HUB

Figures in billion

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<th>BAU</th>
<th>HUB</th>
<th>HUB - BAU</th>
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<td>Offshore converters, transformers and platforms (AC, DC, sub-total)</td>
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<tr>
<td></td>
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<td>Protection equipment</td>
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<td>€ 0.40</td>
<td>€ 0.40</td>
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<tr>
<td>Cabling</td>
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<td>€ 15.12</td>
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<td>Point-to-point interconnection</td>
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<td>Onshore stations</td>
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<tr>
<td>Total</td>
<td>€ 208.7</td>
<td>€ 216.0</td>
<td>€ 7.36</td>
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## Where is the difference? - EUR

Figures in billion

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<th>BAU</th>
<th>EUR</th>
<th>EUR - BAU</th>
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<tr>
<td>Offshore converters, transformers and platforms (AC, DC, sub-total)</td>
<td>€ 37.96</td>
<td>€ 33.49</td>
<td>-€ 4.48</td>
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<td>€ 80.79</td>
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<td>€ 118.76</td>
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<td>€ 11.32</td>
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<td>Protection equipment</td>
<td>€ 0.00</td>
<td>€ 5.28</td>
<td>€ 5.28</td>
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<tr>
<td>Cabling</td>
<td>€ 58.95</td>
<td>€ 55.57</td>
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<tr>
<td>Point-to-point interconnection</td>
<td>€ 3.33</td>
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<tr>
<td>Onshore stations</td>
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<td>€ 1.18</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>€ 208.7</strong></td>
<td><strong>€ 221.5</strong></td>
<td><strong>€ 12.78</strong></td>
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</tbody>
</table>
Conclusions that we may tie to these figures

• Meshing will increase the need for DC technologies
• These DC technologies drive costs upwards through replacement of AC components
• Decrease in cable length is minimal but present, but does not offset this cost increase
• Large hubs replace costs made for DC platforms to a large extent
• Cabling largely offsets this cost decrease, due to rerouting of cables
Deployment plan gives direction and says what is needed – we suggest ground rules for potential development and interoperability

**Legal & Regulatory**
- Hybrid Asset
- Mixed partial agreement
- Coordinated planning
- Supply chain
- DC Grid Code
- Decommissioning

**Market Models**
- Small Zones Bidding Zone

**Technology**
- Anticipatory investments
- Interoperability
- Island solution
- (Multivendor) pilot projects
- Application of DCCBs/GIS etc.

As alternative to hybrid assets
APPENDIX

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EirGrid plc, SuperGrid Institute, Deutsche WindGuard GmbH, Mitsubishi Electric
Europe B.V., Affärsverket Svenska kraftnät, Alstom Grid UK Ltd (Trading as GE Grid
Solutions), University of Aberdeen, Réseau de Transport d'Électricité, Technische
Universiteit Delft, Statoil ASA, TenneT TSO B.V., Stiftung OFFSHORE-
WINDENERGIE, Siemens AG, Danmarks Tekniske Universitet, Rheinisch-
Westfälische Technische Hochschule Aachen, Universitat Politècnica de València,
SCiBreak AB, Forschungsgemeinschaft für. Elektrische Anlagen und
Stromwirtschaft e.V., Ørsted Wind Power A/S, The Carbon Trust, Tractebel
Engineering S.A., European University Institute, European Association of the
Electricity Transmission & Distribution Equipment and Services Industry,
University of Strathclyde, S.L., Prysmian, Rijksuniversiteit Groningen, MHI Vestas
Offshore Wind AS, Energinet.dk, Scottish Hydro Electric Transmission plc

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WP12 – John Moore (TenneT), Felix Rudolph (FGH) & Jelle van Uden (TenneT)
Wei He: analysis shows meshing after 2035, but Doggerbank is already in full development will be ready before 2022. Unlikely to be 525 kV. Offshore loads may be connected (storage and capacity) and also floating solar might be connected.
Dirk van Hertem: Optimisation model looks at optimizing offshore wind efficiently to onshore system, and not necessarily the overall system flow. Dirk suggests that due to large wind resource, markets will change increasing the need for interconnection. Also, protection devices are not significant cost contributor as shown by WP4 and thus not stopping grid development. This should also be indicated as such in the end conclusion.
Olivier Antoine: estimation done in two steps, first offshore wind export and reducing cable length, second step TYNDP price scenarios and interconnector model candidates are selected based on market study.
Poul Sorensen: Did similar project that also came to conclusion for meshing. Hence results are credible from a markets optimization point of view. It seems national and European concepts they are very similar, and national concept is much easier to regulate.
Dirk van Hertem: are redispatch costs included in the model as this is a common complaint of TSOs?
Felix Rudolph: No, this may come in the flexibility analysis
John Moore: base assumptions of bipole gives natural redundancy which means availability benefit of meshing is not as obvious.
Paul Neilson: Maps are not showing existing interconnectors and windfarms or the ones under construction. We need to be careful not to play in the hands of parties that are looking to avoid building grid, and continue radial build out.
John Moore: it is important to show that significant benefits can be realized if: basic technological harmonization can be achieved, planning of different projects can be coordinated. This requires political will in addition to pilots which show that benefit is real.
Dirk van Hertem: if you look at cost of grid per person, then it is very low. This is what to tell the regulator
Karim Karoui: investment looks big, but it is not very large compared to figures relating to other energy systems such as gas.

Staffan Norrøa: Was it considered to have hub interconnection on DC side?

Jelle van Uden: no, earlier feedback from PROMOTioN suggested that this was impossible.

Cees Plet: we need to include the benefit of avoided losses (and avoided converter capex) for DC side connection of HUB conception.

Everyone agrees that connection on DC side should be considered as this will significantly reduce costs.

Ramon Blasco: HUB solutions show benefit over other solutions, but TenneT is also promoter of HUB concept. How to avoid that this looks like a TenneT push for the hub?

John/Jelle: TenneT concept is actually different and includes storage or conversion on island too. The approach in PROMOTioN assumes complete power export.

Dragan Jovcic: Top down planning is not the way to go about grid build-out, it should grow organically and all pre-requisites should be in place to allow that to happen. E.g. Ijmuiden Ver platform offshore should have open connection on DC bus, allowing the market to determine the connections.

Ceciel van Nieuwenhout: coordinated planning does not necessarily refer to technical grid planning, but very much to spatial planning and permitting.
General Assembly

4th of December 2019 | Roskilde
Roskilde – General Assembly

Agenda

• Amendment 8

• Announce amendment 9

• Reporting

• D7.9 Regulatory and Financing principles for a Meshed HVDC Offshore Grid
  • Vote to approve the WP7 recommendations to be taken forward into WP12 - please prepare by reading the recommendations of D7.9
Amendment 8
Name change Tractebel

• As result of spin off TRACTEBEL ENGINEERING has requested to terminate the PROMOTioN contract and to add TRACTEBEL IMPACT in a new Partner in the project.

• With this amendment we effectuate the termination of TRACTEBEL ENGINEERING and want to add TRACTEBEL IMPACT as a new partner.

• The remaining budget of TRACTEBEL ENGINEERING is transferred to TRACTEBEL IMPACT.
Budget transfer SHE Transmission

• We noticed a risk with the available resourcing in SHE Transmission to complete their task in WP9. As mitigation action KU Leuven and the University of Strathclyde will support SHE Transmission.

• 12 MM will go to KU Leuven, including the corresponding budget and some travel cost, in total a subsidy budget of €100,750 will go to KU Leuven.

• The University of Strathclyde will support SHE Transmission with 4 MM. There is budget available in the own budget of the University for this.
Budget transfer DNV GL

- DNV GL Netherlands BV has transferred an amount of €220,537.50 from budget to the third party DNV GL Norway. On request of DNV GL NL, DNV GL Norway assisted in far more topics than originally foreseen.
On request of SuperGrid Institute their acronym SGI will not be used anymore as they prefer to be addressed as SuperGrid Institute. Only the acronym is changed in SuperGrid Institute, but the work packages descriptions are not changed.
In support of the objective of achieving technology interoperability, in work package 6 two more HVDC circuit breaker topologies will be recreated in scaled versions in the laboratory to carry out characterisation tests which are not possible in the full scale demonstrations tests in WP10.

The additional work is a collaboration of University of Aberdeen, KU Leuven and the tests will be held at RWTH Aachen’s DC laboratory.

To enable this meaningful extension, 30k of personal cost budget is transferred from RWTH Aachen to KU Leuven. Furthermore, RWTH Aachen needs to shift 27k from Other direct costs to Personnel costs budget.
General Assembly – Amendment 8

Vote

• Tractebel name change
Amendment 9
KEMA Laboratories

• KEMA Laboratories was a linked 3rd party of DNV GL but has been sold to CESI

• Actual transfer still subject to regulatory approval

• All WP10 and WP15 and WP16 tests will go ahead as planned

• OEMs have already confirmed their continued commitment for the demonstrators

• KEMA Laboratories or CESI (depends on actual transfer date and type) will become full partner in PROMOTioN
Reporting
CONTENT

• Financial reporting January 2020

• Final reporting October 2020
Financial Reporting January 2020

• Reporting to the EC, but different format.

• Original for January 2020 the final reporting was planned, due to prolongation of the project the final reporting is postponed until October 2020

• Reporting period became > 18 months → interim financial reporting according art. 20.5

• Reporting is not in ECAS, but a table in a report

• Only Financial Reporting, but no payment will follow.
### Reporting format

**Report on cumulative expenditure incurred**

(Art 20.5 of the Grant Agreement)

<table>
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- Only Total need to be reported, including 25% overhead
- First 2 columns filled in on basis of ECAS
- Please check
- Cumulative expenditure
- Now to report: period 01 Jan 2016 – 31 Dec 2019
- Calculate the period 01 Jul 2018 – 31 Dec 2019 and add that amounts earlier reported
- Format will be sent by e-mail next week
- Deadline for the reporting is 31 Jan 2020
- Send the reporting to marga.vandeelen@dnvgl.com
Final reporting October 2020

• The financial figures reported in Jan 2020 need to be reported again in October 2020

• The period will then be: July 2018 – Sept 2020

• Reporting in ECAS

• Financial reporting and Technical reporting

• Quite similar to the 2 earlier reporting to the EU, in Jan 2017 and Jul 2018

• Detailed instructions will come by e-mail next year
Certificates on the financial statements (CFS)

• A certificate is needed as the requested contribution from the EU is 325,000 EUR or more

• Start early with it, at least inform your accountant/auditor in time, so the audit can be planned for October
Cost for reporting at the end of the project

• In principle only cost made during the project are eligible cost
• One exception: costs for reporting at the end of the action, especially Certificate on the financial statement

• Explanation given by the EU

Costs for reporting at end of the action — Costs related to drafting and submitting the periodic report for the last reporting period and the final report are eligible even if they are incurred after the action duration. Those costs include the cost of certificates on the financial statements (CFS) required by the GA and the cost of participating in a final review carried out by the Commission/Agency before the submission of the final reports. They may also include the cost of personnel necessary to prepare the periodic report for the last reporting period and the final report. However, they do NOT include research or innovation activities undertaken after the end date of the action.
QUESTIONS?
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CONTACT

APPENDIX
WP7

Regulation & Financing principles for a Meshed HVDC grid
Scope of the report D7.9 “regulatory and financial framework”

- Summarise the findings from Deliverables:
  - D7.2 “Legal Framework”
  - D7.4 “Economic Framework”
  - D7.6 “Financing Framework”

- Analyse and make recommendations on additional cross-disciplinary aspects, not addressed in the three deliverables.

- Deliver a set of recommendations to define the Regulatory and Financing Framework for the project lifecycle of a meshed HVDC offshore grid

- Provide a high level indication of the parties responsible for implementing the recommendations
Content of the report

1. Defining Offshore Hybrid Assets
2. Legal and Governance Framework
3. Operation of the MOG
4. Planning: Organization, CBA, Grid tariffs
5. Electricity Market
6. Transmission Owner Revenue
7. Financing Investment
8. Cross-Border Cost Allocation (CBCA)
9. Decommissioning

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 691714.
## 1. Defining Offshore Hybrid Assets

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<th>Problem</th>
<th>Recommendation</th>
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<td><strong>Short-term recommendation</strong>: Adjustment of the Electricity Regulation to include Hybrid asset definition</td>
</tr>
<tr>
<td>Uncertain regulatory framework hindering attractiveness of investments</td>
<td><strong>Long-term recommendation</strong>: common interpretation of UNCLOS by a multilateral agreement.</td>
</tr>
<tr>
<td></td>
<td>Obstacle: long implementation time</td>
</tr>
</tbody>
</table>
## 2. Legal and Governance Framework

<table>
<thead>
<tr>
<th>Problem</th>
<th>Recommendation</th>
</tr>
</thead>
<tbody>
<tr>
<td>States currently coordinate their plans bilaterally and most coastal states cooperate with each other in the context of the EU.</td>
<td>Adopt a ‘mixed partial agreement’ (signatories: states participating in the MOG, EU) to set out the objectives and high-level principles of the MOG</td>
</tr>
</tbody>
</table>
| No international agreement (signatories: coastal states, EU) for the cooperation of the North Sea about MOG | National Regulatory Authorities (NRAs) to organize regulatory coordination group to:  
  - oversee grid development and  
  - grid operations. |
### 3. Operation of the MOG

<table>
<thead>
<tr>
<th>Problem</th>
<th>Recommendation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Significantly increase in complexity for operating a multi-connection</td>
<td>North Sea Regional Coordination Centre for system operation governance.</td>
</tr>
<tr>
<td>meshed system connecting offshore windfarms to several countries in</td>
<td>Staged approach to create operational knowledge base to master MOG operation</td>
</tr>
<tr>
<td>line with SOGL</td>
<td>and interface with onshore grids</td>
</tr>
<tr>
<td></td>
<td>Balancing Mechanism design to remove barriers to entry for OWFs as BRPs/BSPs</td>
</tr>
</tbody>
</table>
### 4. Planning: Organization / 1

<table>
<thead>
<tr>
<th>Content addressed by the principles</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Problem</strong></td>
</tr>
<tr>
<td>Planning and permitting procedures are perceived as a key risk in large infrastructure projects. Permitting issues become increasingly burdensome when the projects concerned span more than one jurisdiction, with the possibility of these risks materializing in two (or more) countries. Permitting can cause offshore infrastructure projects to be delayed by several years.</td>
</tr>
<tr>
<td><strong>Recommendation</strong></td>
</tr>
<tr>
<td>Streamlined permitting process.</td>
</tr>
<tr>
<td>Permits/licenses to remain valid for the duration of the construction and operation phase.</td>
</tr>
<tr>
<td>Separate the process for the wind farm and cables but coordinate to align the projected commissioning dates</td>
</tr>
<tr>
<td>Coordinated approach for grid planning, strong coordination of grid development plans (timing, location) to increase the transparency</td>
</tr>
<tr>
<td>Simplify them in number and interdependency</td>
</tr>
</tbody>
</table>
### 4. Planning: Organization / 2

<table>
<thead>
<tr>
<th>Problem</th>
<th>Recommendation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stakeholder objections to new OWF or transmission asset development could delay or prevent the deployment of the MOG</td>
<td>Wind farm developers should use the evidence and tools presented in the literature, to develop strategies for understanding public opinion and broadening active public participation.</td>
</tr>
</tbody>
</table>
### 4. Planning: Cost Benefit Analysis (CBA)

<table>
<thead>
<tr>
<th>Problem</th>
<th>Recommendation</th>
</tr>
</thead>
</table>
| **Dealing with interactions between (offshore) PCIs:** Assessed CBA methodologies don't fully account for the interdependencies of meshed grid projects | • **Clustering projects:** Introducing clearer criteria on to consider projects part of a cluster for CBA  
• **Baseline definition:** compare a project against two baselines (TOOT and PINT) to identify potential synergies between new projects |
| **Gaining trust and public acceptance:** Lack of transparency about costs in decision making process for PCIs | • **Harmonize and disaggregate cost and benefits** reporting  
• **Open source CBA model** as target model |
| **Reducing the politics in the valuation of PCIs:** Decisions about PCI investments not always based on complete CBAs | • **Fully monetized CBA** of the value of project needed.  
• **Eligibility criteria** to be agreed upfront by all parties. |
### 4. Planning: grid tariffs

<table>
<thead>
<tr>
<th>Problem</th>
<th>Recommendation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Different regulatory handling of the grid connection costs of OWF between the North Sea countries</td>
<td>Develop <strong>consistent approaches</strong> about selecting • wind farm locations, • onshore grid access responsibility and • grid connection charges</td>
</tr>
<tr>
<td>The transmission charges paid by generators for access to the transmission network are not harmonized across Europe.</td>
<td><strong>Alignment of transmission</strong> tariffs across North Sea countries (solution for OWF connected to multiple countries)</td>
</tr>
<tr>
<td>For assets connected to more than one country there is no mechanism for calculating their transmission charges.</td>
<td></td>
</tr>
</tbody>
</table>
## 5. Electricity Market

<table>
<thead>
<tr>
<th>Problem</th>
<th>Recommendation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subsidies paid to RES are recognized only when electricity generation is effectively delivered from the EEZ into the respective country, thus preventing RES generation to move freely.</td>
<td>In the short term, decouple physical electricity flows from market flows when it comes to support for RES.</td>
</tr>
<tr>
<td>►►►</td>
<td>►►►</td>
</tr>
<tr>
<td>In the longer term, establish a joint fund (or joint support scheme) and calculate each country’s contribution ex-post, based on the principle &quot;beneficiary pays&quot;.</td>
<td></td>
</tr>
</tbody>
</table>
### 6. Transmission Owner Revenue

<table>
<thead>
<tr>
<th>Problem</th>
<th>Recommendation</th>
</tr>
</thead>
</table>
| **Regulatory framework undefined** (undefined risk of the investment) | • **Long term stable regulatory framework** to increase assets ‘bankability’  
  • **Roles, responsibilities and liabilities** of investors, constructors and managers to support investment risk assessment |
| **TSO restrictions** on legal ownership and on balance sheet hindering  
  • private equity provision  
  • leverage on debt. | • **Multiple funding sources** via design of offshore grid asset ownership  
  • **Flexible access to private equity** to:  
    • overcome the TSOs’ balance sheet constraints and  
    • optimize allocation of capital available from global investors. |
| **Congestion rent as only investor income** in case of MOG as merchant not viable for a long-term business model | • **Regulated income for OS hybrid assets**  
  • Possible **regulatory grant of dedicated investment** for the additional risk (if offshore assets part of a RAB).  
  • **Fixed revenue for Individually owned assets** depending on assets availability, performance and on market indicators |
## 7. Financing Investment

### Content addressed by the principles

<table>
<thead>
<tr>
<th>Problem</th>
<th>Recommendation</th>
</tr>
</thead>
<tbody>
<tr>
<td>National regulation with no incentives for cross-border anticipatory investments regarding hybrid assets</td>
<td>EU public financing support (CEF/EEPR funding) to remunerate cross-border anticipatory investments for the early phase of the MOG.</td>
</tr>
<tr>
<td>No risk mitigations in construction phase for:</td>
<td>Regulated revenues grant during construction</td>
</tr>
<tr>
<td>• technical problems and</td>
<td></td>
</tr>
<tr>
<td>• delays from permitting/public consultation processes.</td>
<td></td>
</tr>
<tr>
<td>Not common adoption of funding for innovation in the price controls across.</td>
<td>• Support for technological innovation through EU funding at the early stage of the infrastructure development</td>
</tr>
<tr>
<td>Transmission networks legislation can hinder deployment of innovation in grid</td>
<td>• Regular review of the future developments in the energy sector and its associated technologies</td>
</tr>
</tbody>
</table>
8. Cross-Border Cost Allocation (CBCA)

<table>
<thead>
<tr>
<th>Problem</th>
<th>Recommendation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBCA application for offshore to be improved.</td>
<td>Ensuring complete CBCA decisions, costs allocation to national systems, with and without CEF contribution</td>
</tr>
<tr>
<td>Key areas to be considered:</td>
<td>Single, coordinated CBCA agreement for a group of complementary projects (again: clustered approach):</td>
</tr>
<tr>
<td>- Use of significance threshold for CEF</td>
<td>Binding, formal cooperation contract between the involved parties with specification of non-compliance penalties (commissioning dates, reduction stranded assets)</td>
</tr>
<tr>
<td>- Conducting Market tests</td>
<td>Revisit the interaction between the significance threshold and EU funding, for more effective;</td>
</tr>
<tr>
<td>- Incorporate binding contracts</td>
<td>- Cost allocation</td>
</tr>
<tr>
<td>- Consider project interactions</td>
<td>- CEF funding</td>
</tr>
<tr>
<td>- Innovative approach to CBCA</td>
<td>- Reach complete CBCA decisions</td>
</tr>
</tbody>
</table>
## 9. Decommissioning

<table>
<thead>
<tr>
<th>Problem</th>
<th>Recommendation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rules for decommissioning offshore assets vary</strong> by country</td>
<td>General process: <em>transmission cables left in place at the end of life of a wind farm</em>, unless otherwise needed</td>
</tr>
<tr>
<td><strong>Limited accounting of different technical lifespan</strong> of offshore wind elements (e.g. lines technical life longer than OWF)</td>
<td>Case-by-case assessment of decommissioning requirements by the relevant permitting agency.</td>
</tr>
<tr>
<td></td>
<td>• Complete removal or</td>
</tr>
<tr>
<td></td>
<td>• Foundation left in place</td>
</tr>
<tr>
<td>There are no guidelines supporting decommissioning of offshore assets</td>
<td><strong>State takeover of responsibility of any assets in situ</strong> after their useful life, with compensation for potential future costs (e.g. ring-fenced fund).</td>
</tr>
<tr>
<td></td>
<td>Guidelines for decommissioning should be agreed upon at an international level such as International Maritime Organization (IMO) or OSPAR.</td>
</tr>
</tbody>
</table>
Conclusions

• The legal framework shall be integrated by the definition of hybrid assets, by the drafting of a mixed-partial agreement, by the creation of a joint fund for OWF support and by the framework for decommission of offshore assets

• The governance of all traditional roles for the design, permitting, planning, construction, operation, maintenance and decommissioning of the offshore assets must be defined and must be founded on a strong cooperation of involved nations

• From the economic point of view, processes and methodologies (permitting, CBA, CBCA…) should be more aligned and applied consistently to all projects, considering their costs interdependencies, so to increase the overall economic efficiency

• From financing perspective, key driver for investments in a MOG is a stable, long-term legal and regulatory framework with clear assignment of roles and responsibilities among involved parties, provides adequate remuneration to transmission owners, considers technology innovation risk and provides remuneration for agreed anticipatory investments.
### 1. Defining Offshore Hybrid Assets

<table>
<thead>
<tr>
<th>Number</th>
<th>Principle</th>
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<tbody>
<tr>
<td>2</td>
<td>North Sea coastal states should adopt a common interpretation of the law of the sea regarding hybrid assets within the MOG, by taking a broad interpretation of UNCLOS terminology. This definition of hybrid assets should be set out in a multilateral (mixed partial) agreement that is used for the governance of the MOG.</td>
</tr>
<tr>
<td>3</td>
<td>The internal market regulation should be amended to include a definition and a substantive provision on how offshore hybrid assets should be regulated. The amendments should be designed to support a long-term, stable and predictable regulatory framework, so to reduce the risk exposure on capital in relation to investments in the meshed offshore grid.</td>
</tr>
</tbody>
</table>
2. Legal and Governance Framework

<table>
<thead>
<tr>
<th>Number</th>
<th>Principle</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>North Sea coastal states should work to develop a multilateral mixed partial agreement (a North Sea Treaty) which can serve as a framework for formalizing the rules of a meshed offshore grid.</td>
</tr>
<tr>
<td>4</td>
<td>Grid governance should be designed to recognise the central role of states surrounding the North Sea in the decision making process: ministries should coordinate their actions with National Regulatory Authorities (NRAs) for long-term decisions in regular meetings, while favouring the centralisation of planning, technical and operational processes so to support a timely project delivery and a secure and reliable system operations.</td>
</tr>
<tr>
<td>5</td>
<td>It is recommended that NRAs organise themselves in a specific regulatory coordination group to oversee grid development and operations through strong, mutual cooperation.</td>
</tr>
<tr>
<td>29</td>
<td>Establish an offshore liability regime as part of the regulatory regime for the MOG. Clearly define and allocate the liabilities regarding asset operation and maintenance and liabilities related to the late delivery of transmission assets among the transmission owners.</td>
</tr>
</tbody>
</table>
3. Operation of the MOG

<table>
<thead>
<tr>
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<th>Principle</th>
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<tbody>
<tr>
<td>7</td>
<td>The governance of system operation should evolve towards a North Sea Regional Coordination Centre. A staged approach shall be followed to create an adequate knowledge base for any operator involved in the dispatching and operation of the MOG and its interfaces with onshore systems.</td>
</tr>
<tr>
<td>25</td>
<td>Changes to the Balancing Mechanism should remove barriers to entry for OWFs and should be cost-effective from an energy system perspective. Introducing a single price settlement rule, 15-minute settlement periods, scarcity pricing for capacity, and a liquid intraday market with gate closure as close to real time as possible would help to deliver a cost-effective balancing mechanism.</td>
</tr>
</tbody>
</table>
4. Planning: Organization

<table>
<thead>
<tr>
<th>Number</th>
<th>Principle</th>
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</thead>
<tbody>
<tr>
<td>8</td>
<td>Streamline the permitting process to reduce the risk of legislative change during the permitting phase. Legislative changes should not retroactively impact projects already approved. Once granted, permits/licenses will remain valid for the duration of the construction and operation phase.</td>
</tr>
<tr>
<td>9</td>
<td>A central approach for grid planning and strong coordination of grid development plans in terms of timing and location is recommended to increase the transparency of future network investments requirements and their cross-border impact.</td>
</tr>
<tr>
<td>10</td>
<td>National planning and permitting procedures should separate the process for the wind farm and cables but coordinate to align the projected commissioning dates.</td>
</tr>
<tr>
<td>11</td>
<td>National planning and permitting procedures should be simplified in terms of number and interdependency: this action can be supported by the creation of a one stop shop for key project permits.</td>
</tr>
<tr>
<td>15</td>
<td>A high level of public participation can have a positive impact on the public acceptability of offshore wind projects. Wind farm developers should use the evidence and tools presented in the literature, to develop strategies for understanding public opinion and broadening active public participation</td>
</tr>
</tbody>
</table>
### 4. Planning: Cost Benefit Analysis (CBA)

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>12</td>
<td>Interactions between offshore PCIs should be taken into consideration in CBAs. Improvements can be made to the clustering of projects and the baseline definition in the common CBA method. A project can be compared against two baselines (TOOT and PINT) in order to identify potential synergies between new projects.</td>
</tr>
<tr>
<td>13</td>
<td>It is recommended to harmonize and disaggregate cost and benefits reporting to gain trust and public acceptance, with an ambition to move towards an open source CBA model.</td>
</tr>
<tr>
<td>14</td>
<td>To reduce the politics in the valuation of PCIs, it is important to carry out a fully monetized CBA of the value of project. To increase transparency of the process, the Regional Groups could express their policy priorities at the start of the process via the eligibility criteria.</td>
</tr>
</tbody>
</table>
4. Planning: grid tariffs

<p>| | |</p>
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</thead>
<tbody>
<tr>
<td>16</td>
<td>Develop consistent approaches across North Sea countries to selecting wind farm locations (preferably zoned or single site), onshore grid access responsibility and grid connection charges (preferably super-shallow). Coordinating on these three aspects should enable stakeholders to successfully implement an integrated approach to offshore grid development in the North Sea</td>
</tr>
<tr>
<td>17</td>
<td>Work to align transmission tariffs across North Sea countries to prevent any negative impact on OWF development.</td>
</tr>
</tbody>
</table>
5. Electricity Market

<table>
<thead>
<tr>
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<th>Principle</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>In the short term, decouple physical electricity flows from market flows when it comes to support for RES. In the longer term, establish a joint fund (or joint support scheme) and calculate each country’s contribution ex-post, based on the principle “beneficiary pays”.</td>
</tr>
</tbody>
</table>
## 6. Transmission Owner Revenue

<table>
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<tr>
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<th>Principle</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>A clear definition of responsibilities and liabilities of investors, constructors and managers of the meshed HVDC offshore grid is advisable, to allow institutional investors, debt and equity providers the clarity needed to assess the investment risk. Offshore grid asset ownership should be designed to ensure the participation of multiple funding sources to support the challenging volume of required investments.</td>
</tr>
<tr>
<td>19</td>
<td>Offshore hybrid asset income should be based on regulated income (with appropriate incentives and adjustments to encourage good performance) rather than on congestion rent.</td>
</tr>
<tr>
<td>20</td>
<td>A long term and stable regulatory framework will increase the ‘bankability’ of offshore transmission assets. Where offshore assets are remunerated as part of a wider portfolio (RAB) additional dedicated investment incentives should be granted by the regulator where necessary. Where assets are owned individually, they should receive a fixed revenue subject to the availability and performance of the assets as well as market indicators (e.g. UK OFTO-regime).</td>
</tr>
</tbody>
</table>
## 7. Financing Investment

<table>
<thead>
<tr>
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<th>Principle</th>
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<tbody>
<tr>
<td>26</td>
<td>There should be flexibility regarding access to private equity in order to overcome the TSOs’ balance sheet constraints and optimise allocation of capital available from global investors. Apply existing financing structures to the MOG that have proven to be successful in raising sufficient finance for other capital-intensive transmission infrastructures.</td>
</tr>
<tr>
<td>27</td>
<td>Given the importance of creating the MOG, it is essential to ensure public financial support by the EU for the remuneration of the necessary cross-border anticipatory investments. Using EU financial support (CEF/ EEPR funding) to fund anticipatory investment would reduce the risk of stranded assets for investors and bridge any financing gaps.</td>
</tr>
<tr>
<td>28</td>
<td>Support for technological innovation through EU funding at the early stage of the infrastructure development is a key enabler. It should be accompanied by a regular review of the future developments in the energy sector and its associated technologies.</td>
</tr>
<tr>
<td>30</td>
<td>Provide revenue during construction to reduce the risk to investors. This could make finance more readily available at lower interest rates during these riskier periods and reduce the interest accrued during construction</td>
</tr>
</tbody>
</table>
## 8. Cross-Border Cost Allocation (CBCA)

<table>
<thead>
<tr>
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<th>Principle</th>
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<tbody>
<tr>
<td>21</td>
<td>Coordination of CBCA decisions for complementary projects. This could be achieved by taking a clustered approach in which a CBCA agreement is reached for a group of projects. This would enable robust consideration of project complementarities and mitigate any distortions in the development of the projects.</td>
</tr>
<tr>
<td>22</td>
<td>Formalization of the CBCA as a binding contract between the involved parties with clear specification of non-compliance penalties, especially with respect to commissioning dates. In a multi-stakeholder environment, such a step can ensure greater commitment towards the project by all parties, thereby avoiding the construction of “bridges to nowhere”, also called stranded assets.</td>
</tr>
<tr>
<td>23</td>
<td>Revisit the interaction between the significance threshold and EU funding. This step would aid in more effective cost allocation by encouraging complete CBCA decisions as well as enable effective EU funding allocation.</td>
</tr>
<tr>
<td>24</td>
<td>Ensuring complete CBCA decisions. A complete CBCA is one which considers how costs would be allocated between nation states, both with and without a contribution from the EU’s Connecting Europe Facility (CEF). This is necessary as CBCAs are often carried out prior to a decision on whether CEF funding will be provided to a project. Having to revisit a decision in light of such funding being declined, can result in project delays.</td>
</tr>
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</table>
## 9. Decommissioning

<table>
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<tr>
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</tr>
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</table>
| 31     | The decommissioning requirements for OWFs should be based on a case-by-case assessment by the relevant permitting agency, during the planning process. However, in general the standard process should be:  
- At the end of life of a wind farm, the transmission cables may be left in place unless in a sensitive area with high shipping or fishing activity, changeable sea bottom or areas such as the beach. Depending on the grid topology, these transmission assets could continue to be used as interconnectors or to connect a new wind farm built in the same place.  
- For wind farms, the permitting agency should decide whether removal of all wind farm assets are required, or whether the foundations can be left in place. This should be decided as early as possible to provide greater cost certainty to developers.  
- Any assets which remain in situ after their useful life (and after the owner has discharged their decommissioning responsibilities) should fall under the responsibility of the state provided that the state is compensated for potential future costs, for example through a ring fenced fund. |
| 32     | To provide consistency on guidelines for decommissioning of offshore wind assets (turbines and transmission assets), guidelines should be agreed upon at an international level such as International Maritime Organisation (IMO) or OSPAR. To inform this, further research into the environmental impact of decommissioning OWFs and offshore electricity cables is necessary. |
Content of the report
Minutes of Meeting
Event: PROMOTioN Half-yearly meeting
Location: Roskilde
Date: 4th of December 2019
Session: General Assembly
Present Refer to attendance register

27 partners present out of 33 → quorum reached

Minutes:

Amendment 8
[VOTE] → All in favour of Tractebel namechange

Amendment 9
The change of KEMA Laboratories from linked third party from DNV GL to full partner will mean that the PMG will also have an additional industrial partner.

It is announced that Amendment 9 will also include a namechange of ABB.

Reporting
Ramon: do you need some financial certificate from the administration?
Marga: No, just the number, in order to get an overview

John: TenneT changed auditor, new auditor will start next year (2020). Might have to get certificate for end of year.
Marga will look into it

Cees: will there be another review meeting?
Marga: not sure, but we will check it. In principle EC can request a meeting for 5 years after project meeting
AP Cees to check with Mariana

Final payment (10%) is done after final reporting October 2020, payment in principle 90 days after but can be postponed for several reasons
Financial certificate period is whole project

WP7

Vote 1 – 1 Hybrid asset classification
Antje: Why is definition needed? If we create separate bidding zones, everything should work without the need of new legislation.

Ceciel: This is right, and is a simple solution if all countries work together. However, bidding zone configuration offshore is a tricky point, so hence this is a work around which avoids bilateral difficulties

Dirk: This changes the responsibilities of the developers significantly. So it is a choice, not necessarily the best

Dragan: Hybrid implies dual purpose of export and interconnection, does this also allow for different uses such as offshore loads?
Ceciel: Yes, the definition of hybrid should be sufficiently broad to cover this.

Antje: With bidding zones the link from the offshore wind farm to shore would also be interconnector. Also, word hybrid is not specific enough, we should consider different wording.

Paul: Offshore transmission is regardless of purpose. Perhaps the point is to more broadly define offshore transmission.

Ceciel: Should be careful to make broad definition that affects legal certainty of existing infrastructure. Separate definition of hybrid class avoids this issue. Term ‘hybrid asset’ has already been included as recital in clean energy package. Not recommended to change name.

John: The 70% rule on interconnector is causing problems for hybrid projects. Definition of hybrid asset should follow lines in clean energy package to open markets and reduce restrictions.

Ceciel: This rule is contradictory to offshore wind development as it would mean curtailing windfarms and why would these OWFs be build in the first place?

Antje: Summarizing the above, perhaps our message should be that a bidding zone configuration is the best and most simple solution but that - given the recital that already exists, - applying a definition of a hybrid asset class might be the second best, but more cumbersome solution to move forward for countries that have an aversion against bidding zones.

**Vote 2 – 2 Mixed partial agreement**

Karim: How does framework deal with disagreement, and what is the role of the EU in this?

Ceciel: Intl agreement is mainly based on ensuring UK and Norway is included as EU law does not apply to them. EC is included in agreement, so necessary EU law principles will also be included in agreement. Conflict resolution clauses need to be put in the agreement, like it is currently described by NRAs, ACER, EC sequence in EU, but this may not be acceptable to UK after Brexit. Agreements like CETA can provide examples on how to do this.

Dirk: to what does the agreement apply? To all offshore assets or only multi-lateral projects? What should be the grand-fathering approach?

Ceciel: depends on agreement and the amount of trust one wants to build in.

Niklas: Can you explain offshore liability regime?

Alexandra: Refers to multi-actor grid to define how liabilities due to eg project delays are assigned, and to make it part of regulatory framework. This must be clearly defined, but we do not yet have specific details as this is part of the roadmap. Timing should be discussed in WP12, by when does framework need to be in place?

**Vote 3 – 3 Operation of MOG**

Dirk: This can be rewritten by integrating this in future grid codes, however, 15 min should not be specified by PROMOTioN, it could be less too.

Prad: This is taken from EBGL.

Dragan: The last recommendation is too restrictive as it should not be limited only to OWFs.
John: This will be amended in WP12

Vote 4 – 4 Planning / organization
John: please remove word central and replace by coordinated.
Dirk: One-stop shop approach should be build up starting at national level. Hard to achieve on European level

Vote 5 – 4 CBA
Antje: this is describing usual project risk which is also valid for every other project. Unlikely that more and deeper calculations will help, it might even further complicate and slow down processes
Prad: need to make sure it is made simplified as possible to reduce adverse impact. The CBA analysis needs to be seen from a system perspective, especially when considering an offshore grid, as any project will affect surrounding projects.
Antje: look at the ENTSO-E TYNP’s online project map: Everything which is requested by PROMOTioN is already published for each single project on ENTSO-E’s homepage. You can find about 13 market- and network indicators per project, many of them monetized. Seems that the recommendation is outdated.
Dirk: what will be actual recommendation if these are already being done?
John: difference in PROMOTioN is that a system social economic welfare CBA is done for European consumer, rather social benefits for projects and developers. WP12 will take into account global perspective, but will not prescribe a method.
Antje: That’s no difference – ENTSO-E’s analysis is from a global system perspective analyzing benefits from a European perspective.

Vote 6 – 4 Grid tariffs
Dirk: change the word ‘any’ to something less restrictive.
Accepted

Vote 7 – 5 Electricity market
Ceciel: only applies to wind farms connected to hybrid grids
Paul: Should this not be covered by mixed partial agreement?
Ceciel: could be, but is not preferred as it may be more subject to change, so in terms of time required for changes it should be decoupled from the governance framework. This is only relevant whilst offshore wind is subsidized.
Dirk: we should not write anything that suggests subsidies will be required. Hence rewrite to include ‘as long as required’ and remove 2nd part.
Ceciel: 2nd part is required to increase political acceptance to ensure fair distribution of support

Vote 8 – 6 Transmission Owner Revenue
John: change wording to make sure third party investors are ‘facilitated’, and regulatory income ‘may’ be a source of income.
Alexandra: in large meshed grid, merchant income may be hard to estimate increasing risk for investors, hence income should be regulated

Dirk: allow for small exceptions such as individual links to say offshore O&G platforms
John: it should not be definitive

Maksym: last statement needs to be changed as fixed revenue and market indicators are conflicting.

Alexandra: agreed, it will be reworded accordingly

Paul: cannot see how entrepreneurial or merchant initiatives are enabled by this.
Alexandra: can be for example through equity partnerships with TSOs
John: early links will be merchant, so this needs to be facilitated

**Vote 9 – 7 Financing investment**
Alexandra: Correction to slide: the 2nd point should be extended to meshed offshore grids
Paul: post Brexit EU members may not want to support UK investments. How can this be done?
Alexandra: this concerns cross-border investments, so EU will have a say on it.
Paul how to deal with UK getting social welfare benefit
Prad could be done in same way as east west link, where UK also contributes, based on negotiation
Dirk: change ‘TSO’s balance sheet’ to ‘investors’ balance sheet’, because also developers may wish to build links
Alexandra: here really TSO’s are meant due to the specific rules which may cause some TSO’s to not be able to attract private financing. Wording will be adapted accordingly

**Vote 10 – 8 CBCA**
No questions

**Vote 11 – 9 Decommissioning**
Dirk: What does state responsibility take over mean in international environment?

Ceciel: This includes international waters on continental shelf
John: This may be part of commercial assets from a non-TSO country
Ceciel: situations could arise were assets are left if removing them causes more damage than leaving it. This can change with changing seabed for example, so should be monitored, and removed if necessary