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Integration of Offshore Wind Farms using HVDC Technologies: Results from the BEST PATHS Project

Additional credit to:
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Outline of the Presentation

1. Introduction

2. The BEST PATHS Project

3. BEST PATHS Demo 1:
   a) Network Topologies
   b) Key Performance Indicators
   c) The ‘Open Access’ Toolbox

4. Simulation Results

5. Real-Time Demonstrator

6. Experimental Results

7. On-Going (Simulation and Experimental) Work

8. Conclusions and Next Steps
Introduction

• **Wind energy** will be the most widely adopted renewable energy source (RES) by 2050 to contribute towards the abatement of greenhouse gas emissions.

• Europe’s installed wind capacity is **168.7 GW** (18% of EU’s total installed power generation capacity). In the **UK**:

  • Operational in 2018:
    - **Onshore**: 12.1 GW (1523 projects, 7057 turbines);
    - **Offshore**: 7.11 GW (33 projects, 1832 turbines).
    - **Total**: 19.214 GW

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Number of operational projects in 2016

- 1182 Onshore
- 27 Offshore

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* ** https://www.renewableuk.com/page/UKWEDhome
HVAC technology is mature and suitable for subsea transmission at typical voltages up to 150 kV and distances up to 100 km.

HVDC has better control capabilities, lower power losses and occupies less space compared with HVAC.

A ‘Business as Usual’ approach to improve infrastructure will not be sufficient to meet policy objectives at reasonable cost.

Operators and manufacturers are now considering HVDC solutions over HVAC for offshore power transmission systems:

- A higher quality and more reliable wind resource with higher average wind speeds is farther away from shore, and thus,

- Long distances to shore.

- Above 150 kV and beyond 100 km HVAC is not practical due to capacitance and hence charging current of submarine cable.
• **Voltage source converter (VSC)** based schemes are becoming the preferred option over **line commutated converter (LCC)** alternatives due to their decoupled power flow control, black-start capability and control flexibility.

• **MTDC grids** will facilitate a cross-border energy exchange between different countries and will enable reliable power transfer from **offshore wind farms (OWFs)**.

• The **interactions between wind turbine (WT) converters and different VSC types** in a meshed topology need further investigation.
Introduction (4)
Introduction (5)
Introduction (6)
The BEST PATHS Project

**Key Figures**

- **Budget**: €62.8M, 56% co-funded by the European Commission under the 7th Framework Programme for Research, Technological Development and Demonstration (EU FP7 Energy).
- **Duration**: 01/10/2014 – 30/09/2018 (*4 years*).
- **Composition**: 5 large-scale demonstrations, 2 replication projects, 1 dissemination project.

**Key Aims**

- Through the contribution of 40 leading research institutions, industry, utilities, and transmission systems operators (8), the project aims to develop novel network technologies to increase the pan-European transmission network capacity and electricity system flexibility.
The BEST PATHS Project (2)

BEyond State-of-the-art Technologies for re-Powering Ac corridors & multi-Terminal Hvdc Systems

WP2: Barriers and KPIs, tools and methodologies for impact assessment (REE)

What are the routes to move from HVDC lines HVDC grids?

- Demo1 - Iberdrola
  - WP3 R&D
  - WP8 Demo
- Demo2 - RTE
  - WP4 R&D
  - WP9 Demo
- Demo3 - Terna
  - WP5 R&D
  - WP10 Demo

What are the new promising capacity upgrading techniques for existing AC parts of the network?

- Demo4 - 50 Hertz
  - WP6 R&D
  - WP11 Demo
- Demo5 - Nexans
  - WP7 R&D
  - WP12 Demo

WP13: Integrated global assessment for future replication in EU 27 (REE)

WP14: Dissemination & Exploitation (Greenovate! Europe)
Objectives:

1. To investigate the electrical interactions between the HVDC link converters and the wind turbine (WT) converters in OWFs.
2. To de-risk multivendor and multi-terminal HVDC (MTDC) schemes.
3. To demonstrate the results in a laboratory environment using scaled models.
4. To use the validated models to simulate a real grid with OWFs connected in HVDC.
HVDC equipment manufacturers provide ‘black boxes’

We intend to use ‘open models’

R&D Centres
Utilities & RES developers
Detailed models
Simulation & Validation
Independent Manufacturers
TSOs
Network Topologies

➢ System configurations have been implemented in Simulink

- A number of *topologies* has been *modelled, simulated and analysed*.
- The topologies considered constitute *likely scenarios* to be adopted for the transmission of offshore wind energy in future years.
- Full details available in *Deliverable D3.1 of the BEST PATHS project*.

➢ Point-to-Point HVDC Link (Topology A)
Network Topologies (2)

➢ Three-Terminal HVDC System
Six-Terminal HVDC System with Offshore AC Links (Topology B)
Network Topologies (4)

➢ Six-Terminal HVDC System with Offshore DC Links (Topology C)

- Offshore Grid #1
  - WFC #1
    - AC Voltage Control
    - \( V_{ac_w1} \), \( \theta_{w1} \), \( f_{w1} \)
  - GSC #1
    - \( V_{dc_g1} \)
    - \( (V_{dc} \text{ vs. } P) \text{ and } Q \text{ Controller} \)
    - \( V_{dc_g1}^{*} \), \( Q_{g1}^{*} \)

- Offshore Grid #2
  - WFC #2
    - AC Voltage Control
    - \( V_{ac_w2} \), \( \theta_{w2} \), \( f_{w2} \)
  - GSC #2
    - \( V_{dc_g2} \)
    - \( (V_{dc} \text{ vs. } P) \text{ and } Q \text{ Controller} \)
    - \( V_{dc_g2}^{*} \), \( Q_{g2}^{*} \)

- Offshore Grid #3
  - WFC #3
    - AC Voltage Control
    - \( V_{ac_w3} \), \( \theta_{w3} \), \( f_{w3} \)
  - GSC #3
    - \( V_{dc_g3} \)
    - \( (V_{dc} \text{ vs. } P) \text{ and } Q \text{ Controller} \)
    - \( V_{dc_g3}^{*} \), \( Q_{g3}^{*} \)

- Onshore AC Grid #1
  - \( P_{g1}, Q_{g1} \)
  - GSC #1
  - DC interlink

- Onshore AC Grid #2
  - \( P_{g2}, Q_{g2} \)
  - GSC #2
  - DC NETWORK

- Onshore AC Grid #3
  - \( P_{g3}, Q_{g3} \)
  - GSC #3
  - DC NETWORK

- Offshore Grid #3
  - \( P_{w3} \)
  - WFC #3
  - AC Voltage Control
  - \( V_{dc_g3} \)
  - \( V_{dc_g3}^{*} \), \( Q_{g3}^{*} \)
Network Topologies (5)

➢ Twelve-Terminal HVDC System with Offshore DC Links (Topology D)

![Diagram of Twelve-Terminal HVDC System with Offshore DC Links (Topology D)]
Key Performance Indicators

- To assess the suitability of the models and proposed HVDC network topologies, converter configurations and control algorithms, a set of KPIs have been defined.
- Full details available in Deliverable D2.1 of the BEST PATHS project.

<table>
<thead>
<tr>
<th>KPI.D1.1 – AC/DC interactions: power and harmonics</th>
<th>KPI.D1.4 – DC Inter-array Design</th>
</tr>
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<tbody>
<tr>
<td>Steady state</td>
<td>Power quality</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>KPI.D1.2 – AC/DC Interactions – Transients &amp; Voltage Margins</th>
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<tr>
<td>Normal operation</td>
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<table>
<thead>
<tr>
<th>KPI.D1.3 – DC Protection Performance / Protection &amp; Faults</th>
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<tbody>
<tr>
<td>Protection selectivity</td>
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<tr>
<th>KPI.D1.5 – Resonances</th>
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<tr>
<td>AC systems oscillation</td>
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<table>
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<tr>
<th>KPI.D1.6 – Grid Code Compliance</th>
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</thead>
<tbody>
<tr>
<td>Active and reactive power</td>
</tr>
</tbody>
</table>
The ‘Open Access’ Toolbox

- A set of models and control algorithms has been developed, simulated and assessed.

- Their portability as basic building blocks will enable researchers and designers to study and simulate any system configuration of choice.
The ‘Open Access’ Toolbox (2)

- The models and control algorithms have been published in the BEST PATHS website as a **MATLAB ‘Open Access’ Toolbox: [http://www.bestpaths-project.eu/](http://www.bestpaths-project.eu/)**.

- The toolbox was originally presented last year in the **13th IET Conference on AC and DC Power Transmission (ACDC2017)**:
The ‘Open Access’ Toolbox (3)

- A user manual is also provided, together with the published models and accompanying examples.

- Full details of the models available in Deliverable D3.1 of the BEST PATHS project.
The ‘Open Access’ Toolbox (4)

➢ Converter Stations

- **Averaged** and **switched** models for an **MMC**.

- The combined **averaged-switched** model consists of two blocks:
  
  o *Power electronics block*,
  
  o *Low level controller block*: circulating current reference generation, circulating current controller, nearest level control modulation strategy & sub-module voltage regulator.

➢ AC Grid

- AC network adapted from the classical **nine-bus power system**.

➢ DC Cable

- The **DC cable section** has been modelled as a one-phase, frequency-dependent, **travelling wave model**.

- It is based on the **universal line model (ULM)**, which takes into account the frequency dependence of parameters.
Wind Farm

- It accurately represents the behaviour of an aggregated OWF.

- To avoid large simulation times and undesirable computer burden, simplifications have been carried out in the electrical system:
  - The converter of the a wind turbine generator (WTG) is modelled with averaged-model based voltage sources.
  - A current source represents the remaining WTGs of the OWF. The current injection of the first WTG is properly scaled to complete the rated power of the whole OWF.

- The detailed WTG contains
  - a permanent magnet synchronous generator model;
  - Averaged models: machine- and grid-side converters, including filters and DC link;
  - An LV/MV transformer and internal control algorithms.
The ‘Open Access’ Toolbox (6)

➢ High Level Controller

- It considers converter operation in **three control modes**.

- The aim is to cover the main control needs for different system configurations.
High Level Controller

- **Mode 0: $V_{ac}$ voltage control:** The converter sets the voltage and frequency.

\[
\omega = 2\pi f
\]

\[
V_{wf,a} = M\sin(\omega t + \theta)
\]

\[
V_{wf,b} = M\sin(\omega t + \theta + 2\pi/3)
\]

\[
V_{wf,c} = M\sin(\omega t + \theta - 2\pi/3)
\]
The ‘Open Access’ Toolbox (8)

➢ High Level Controller

Mode 1: $V_{dc} - Q$ control scheme with a $P - V_{dc}$ droop
The ‘Open Access’ Toolbox (9)

➢ High Level Controller

Mode 2: $P - Q$ control scheme with a $V_{dc} - P$ droop
The ‘Open Access’ Toolbox (10)

- Toolbox and user manual uploaded on BEST PATHS website on 14th February 2017.

- Presentation at 13th IET ACDC2017; advertisement via social media and on project website.

- 5,076 new users have been recorded on the website since the toolbox was uploaded.

- The toolbox has been downloaded by 119 different users (until 23rd May 2018).

- **Universities** include Aalborg University, KU Leuven, Fukui University of Technology, Imperial College London, Technical University of Denmark, University College of Dublin, Ensam, Technical University of Darmstadt, Technical University of Eindhoven, University College London, Pontifical Comillas University, King Fahd University of Petroleum and Minerals, Shanghai Jiao Tong University, Huazhong university, Florida State University, and Technical University Kaiserslautern.

- **Research centres** include KTH Royal Institute of Technology, the SuperGrid Institute, GridLab, IREC (Institut de Recerca en Energia de Catalunya) and L2EP (Laboratoire d'Electrotechnique et Electronique de Puissance, Lille).

- **Companies** include Siemens, Tractebel, Sarawak Energy, DNV GL, IBM Research, SP Energy Networks, TenneT Offshore, Nissin, Enstore, SCiBreak, and General Electric.
Simulation Results

Example: KPI Assessment

- Simulation results for **three topologies** are presented.
- A subset of the **KPIs** is shown.

**Topology 1**

**Topology 2**

**Topology 3**

- Full details of KPI assessment for all defined topologies available in **Deliverable D3.2 of the BEST PATHS project**.

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- Full details of KPI assessment for all defined topologies available in **Deliverable D3.2 of the BEST PATHS project**.
Example: KPI Assessment (continued…)

- Assessment of KPI.D1.1 – Steady state error (SSE)

  The converter control performance is assessed when references for **DC voltage and reactive power** are changed to **onshore converter** GSC in Topologies 1 and 2 and GSC2 in topology 3.

  - Reactive power changed from 330 MVAr to 165 MVAr at 1.5 s;
  - DC voltage changed from 640 kV to 576 kV at 1.8 s.
Example: KPI Assessment (continued...)

➢ Assessment of KPI.D1.6 – Grid Code Compliance
  • The **AC fault ride-through capability** of the systems is evaluated.
    - A voltage dip at an onshore grid converter is applied at 1.5 s during 300 ms, reducing the AC voltage from 1 p.u. to 0.15 p.u.
Simulation Results (4)

Example: KPI Assessment (continued...)

➢ Assessment of KPI.D1.1 – Harmonics and SSE

- The THD of the AC voltage and the converter performance are evaluated during AC voltage regulation (offshore converter).
  - The offshore AC voltage (rms) is changed from 1 p.u. (380 kV) to 0.9 p.u. (342 kV) at 1.5 s.

![Topologies](image-url)
## Simulation Results (5)

### KPI Assessment Summary

<table>
<thead>
<tr>
<th>KPI</th>
<th>Description</th>
<th>Status</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Steady State AC/DC Interactions</td>
<td>✓ Fully Met</td>
<td>Due to converter overloading and DC overvoltage during extreme conditions (e.g. AC faults). Overloading sustained for a very short time &lt;300ms and braking resistor prevents overvoltage.</td>
</tr>
<tr>
<td>1.2</td>
<td>Transient AC/DC Interactions</td>
<td>o Partially met</td>
<td></td>
</tr>
<tr>
<td>1.3</td>
<td>Protection Performance</td>
<td>✓ Fully Met</td>
<td></td>
</tr>
<tr>
<td>1.4</td>
<td>DC Inter-array Design</td>
<td>✓ Fully Met</td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>Resonances</td>
<td>✓ Fully Met</td>
<td>Due to steady-state error between actual and reference active power during frequency oscillations on the AC grid of Topology A &amp; B.</td>
</tr>
<tr>
<td>1.6</td>
<td>Grid Code Compliance</td>
<td>o Partially met</td>
<td></td>
</tr>
</tbody>
</table>

- Full details of the models available in **Deliverable D3.2 of the BEST PATHS project.**
Real-Time Demonstrator

➢ Built in the premises of SINTEF (Trondheim, Norway), it aims to:

- **Provide experimental validation** to the results obtained from simulations:
  - Establish a correspondence between simulation and experimental setup on single components and at system level;
  - Identify relevant scenarios to test in the laboratory;
  - Perform experiments.

- **Reduce** risks of HVDC link connecting OWFs.
- **Validate** meshed HVDC grids with different VSC technologies.
- **Foster** new suppliers and sub-suppliers of HVDC technology.

➢ Facilities include:

- a **four-terminal 50 kW HVDC grid** with 3 VSC-based MMCs and 1 two-level VSC;
- a **20 kW synchronous generator**;
- **DC circuit breakers**;
- a **wind emulator**;
- a **real-time simulator system** and **control unit** (OPAL-RT).
Real-Time Demonstrator (2)

- Further detail on the demonstrator available in Deliverable D8.1 of the BEST PATHS project.
Real-Time Demonstrator (3)

- National SmartGrid Laboratory (SINTEF)
Real-Time Demonstrator (4)

- MMC Power Cells Boards
Real-Time Demonstrator (5)

- MMC Assembling Stages
Real-Time Demonstrator (6)

- MMC Assembling Stages (2)
Experimental Results

➢ Matching converter parameters of demonstrator with those of simulation models

- The matching process was based on experimental results from the demonstrator running in open loop connected to a resistive load.

- This way, the MMC arm current and submodule voltages would depend only on converter parameters and not on the control action.

- MMC parameters were iteratively matched, including arm inductance, arm resistance, and submodule capacitance.

- With component parameters matched, the delay between measurements of arm current and submodule voltage could be determined from experimental results.

- The main aim of this iterative exercise was to:
  - Increase the accuracy of the simulation models.
  - Obtain a highly reliable representation to perform offline tests.
  - Help ensure adequate performance of test configurations.
  - Identify adverse operating conditions via software.
Experimental Results (2)

- Matching converter parameters of demonstrator with those of simulation models (continued...)

- **MMC with AC voltage control** connected to a load resistance.
  - The control schemes creates an AC voltage with a reference amplitude of 330 V and 50 Hz.

- **MMC with inner current control** connected to an islanded AC grid.
Experimental Results (3)

➢ Matching converter parameters of demonstrator with those of simulation models (continued…)

MMC with AC voltage control connected to load resistance

<table>
<thead>
<tr>
<th></th>
<th>18-level</th>
<th>12-level</th>
<th>6-level</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Voltage [V]</td>
<td><img src="image1" alt="AC Voltage" /></td>
<td><img src="image2" alt="AC Voltage" /></td>
<td><img src="image3" alt="AC Voltage" /></td>
</tr>
<tr>
<td>AC Current [A]</td>
<td><img src="image4" alt="AC Current" /></td>
<td><img src="image5" alt="AC Current" /></td>
<td><img src="image6" alt="AC Current" /></td>
</tr>
<tr>
<td>Arm Current [A]</td>
<td><img src="image7" alt="Arm Current" /></td>
<td><img src="image8" alt="Arm Current" /></td>
<td><img src="image9" alt="Arm Current" /></td>
</tr>
</tbody>
</table>
Experimental Results (4)

- Matching converter parameters of demonstrator with those of simulation models (continued...)

MMC with inner current control connected to islanded AC grid

- Reference of $d$-axis current increased from 20 to 30 A at $t = 2.5$ s.

<table>
<thead>
<tr>
<th>18-level</th>
<th>12-level</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMS AC Current [A]</td>
<td>RMS AC Current [A]</td>
</tr>
<tr>
<td><img src="image1.png" alt="Graph" /></td>
<td><img src="image2.png" alt="Graph" /></td>
</tr>
</tbody>
</table>

**6-level**

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>2.4</th>
<th>2.9</th>
<th>3.4</th>
<th>3.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMS AC Current [A]</td>
<td>14</td>
<td>18</td>
<td>22</td>
<td>26</td>
</tr>
</tbody>
</table>

**18-level**

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>2.5</th>
<th>3.0</th>
<th>3.5</th>
<th>4.0</th>
<th>4.5</th>
<th>5.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMS AC Current [A]</td>
<td>14</td>
<td>18</td>
<td>22</td>
<td>26</td>
<td>26</td>
<td>26</td>
</tr>
</tbody>
</table>

**12-level**

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>2.4</th>
<th>2.6</th>
<th>2.8</th>
<th>3.0</th>
<th>3.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMS AC Current [A]</td>
<td>14</td>
<td>18</td>
<td>22</td>
<td>26</td>
<td>26</td>
</tr>
</tbody>
</table>
Experimental Results (5)

- **Experimental Validation for Topology A**

  - **Sending converter** (18-level half-bridge) uses a nearest level modulation (NLM) and operates in a $P/Q$ mode.
  
  - **Receiving converter** (6-level half-bridge) uses a phase disposition PWM (PD-PWM) and operates in a $V_{dc}/Q$ mode.

  - Both converters make use of a **circulating current regulator** and **voltage balancing algorithms**.
Experimental Results (6)

- Experimental Validation for Topology A (continued...)

- **Reference currents at the sending end:**

![Graphs showing reference currents](image)
Experimental Results (7)

- **Experimental Validation for Topology A (continued...)**

  • **DC voltage.** Performance upon changes in current reference $i_d$ and changes in the DC voltage reference:

![Graphs showing DC voltage performance](image)
Experimental Results (8)

➢ Experimental Validation for Topology A (continued…)

- **Upper and lower arm currents and voltages** at the receiving end converter in steady-state.
Objective:
Evaluate the operation of the point-to-point link when the WF power varies.

Procedure:
Change active power of the WF from 0 to 1 p.u. with ramp rate limitation of 10 p.u./s.
On-Going Work (2)

Point-to-Point System (continued...)

19-Level AC current

DC-bus Voltage Vdc

7-Level AC current

DC-bus Current Idc
On-Going Work (3)

Point-to-Point System (continued…)

19-Level Arm current

0.9 1 1.1 1.2 1.3 1.4 1.5

19-Level Arm voltage

0.9 1 1.1 1.2 1.3 1.4 1.5

7-Level Arm current

0.9 1 1.1 1.2 1.3 1.4 1.5

7-Level Arm voltage

0.9 1 1.1 1.2 1.3 1.4 1.5
On-Going Work (4)

Three-Terminal System

Objective:
Evaluate the operation of a three-terminal system when the WF power varies.

Procedure:
- Set the power of the PQ node to $-0.5 \text{ p.u.}$ (injecting power into the grid).
- Change active power of the WF from 0 to 1 p.u. with ramp rate limitation 10 p.u./s
On-Going Work (5)

Three-Terminal System (continued…)

- 7-Level Id
- 19-Level Id
- 13-Level Id
- DC-bus voltage Vdc
- 7-Level DC current
- 19-Level DC current
- 13-Level DC current
On-Going Work (6)

Three-Terminal System (continued…)

7-Level Arm current

19-Level Arm current

13-Level Arm current

7-Level Arm voltage

19-Level Arm voltage

13-Level Arm voltage
Three-Terminal System – TEST TWO

Objective:
Evaluate the operation of a three-terminal system when the power flow of the PQ node is reversed.

Procedure:
- Set the power of the WF to 0.5 p.u.
- Change the active power of the PQ node from –0.5 p.u to 0.5 p.u. with ramp rate limitation 10 p.u./s.
On-Going Work (8)

Three-Terminal System – TEST TWO (continued...)

- 7-Level ld
- 19-Level ld
- 13-Level ld
- DC-bus voltage Vdc
- 7-Level DC current
- 19-Level DC current
- 13-Level DC current
On-Going Work (9)

Three-Terminal System – TEST TWO (continued…)

![7-Level Arm current](image)

![7-Level Arm voltage](image)

![19-Level Arm current](image)

![19-Level Arm voltage](image)

![13-Level Arm current](image)

![13-Level Arm voltage](image)
Interactions of droop and power control characteristics

- Different droop and power control strategies could have adverse interactions from multiple crossings of the control characteristics.
  - **Conv1 (in black):** an exporting converter (inverter).
  - **Conv2 (in blue):** an importing converter (rectifier), voltage reference is given as 1 p.u. and the droop gain is 1.25 p.u.
  - **Conv3 (in red):** an exporting converter (inverter).

- Bases are 650 V, 32500 W and 50 A.
Interactions of droop and power control characteristics

- The **green power curve** is an equivalent curve of adding those of Conv1 (black line) and **Conv3 (red line)**.

- The **droop curve** is intersected by the **power curve**. This results in three different operation points.
On-Going Work (12)

Interactions of droop and power control characteristics

- Initial power references for all converters are 0 p.u.

- From 1.5 to 1.7 s, ramp changes are applied to the power references. The power reference of Conv1 is changed to -1 p.u. and the power references of Conv2 and Conv3 are changed to 0.69 p.u. and 0.31 p.u., respectively.

- DC voltage in steady-state shifted.
- The current cannot be regulated effectively.
On-Going Work (13)

Interactions of droop and power control characteristics

- An additional test is performed, where the sign of all power references in the previous test is reversed.

- The **multiple-crossing** problem is **avoided**.
Interactions of droop and power control characteristics

- I-V trajectory for Conv 2’s voltage and current.

The voltage for the characteristic without multiple crossings (green curve) stays around 650 V (from $V_{opt}$ to $V_{opt\_new}$). Following the transient regime, the current stays at 50 A (1 p.u.) at one end and hence it is well regulated.

- The voltage for the characteristic with multiple crossings (yellow curve) shifts from 650 to 610 V ($V_{opt2}$) in steady-state and also there are significant oscillations. The current settles at $-54.2$ A ($-1.084$ p.u.) and hence not accurately regulated at $-50$ A.
Conclusions and Next Steps

Main Contributions of this Work

• A set of **models** and **control algorithms** has been developed, simulated and assessed. These have been published as an ‘Open Access’ Toolbox.

• **Network topologies** constituting likely scenarios for the transmission of offshore wind energy have been proposed.

• To assess the suitability of the models, topologies and control algorithms, **a set of KPIs** have been defined.

• An **experimental demonstrator** for the integration of grid-connected OWFs using HVDC grids has been presented.

• Results demonstrating the capabilities of the demonstrator have been compared against simulation results. **These show good agreement.**
Main Contributions of this Work (continued)

- The main contribution of this work is the provision to TSOs, utilities, manufacturers and academic institutions with simulation and experimental tools to generate the necessary knowledge for the development, construction and connection of MTDC systems – aiming to help de-risking the use of MTDC grids for the connection of OWFs.

On-Going and Future Work

- Using the real-time experimental demonstrator, conduct tests for different system topologies representing future scenarios to validate simulation results obtained using computational tools.
- Make the demonstrator available to interested parties for R&D activities.
Conclusions and Next Steps (3)

Some papers linked to this presentation


The authors gratefully acknowledge the financial support provided by the EU FP7 Programme through the project “BEyond State of the art Technologies for re-Powering AC corridors & multi-Terminal HVDC Systems” (BEST PATHS), grant agreement number 612748.

Questions?

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