BEST PATHS Project: Real-Time Demonstrator for the Integration of Offshore Wind Farms using Multi-Terminal HVDC Grids

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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. Real-Time Demonstrator
5. Simulation and Experimental Results
6. Conclusions and Next Steps
• **Wind energy** will be the most widely adopted renewable energy source (RES) by 2050 to contribute towards the **abatement of greenhouse gas emissions**.

• 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**:
  
  o A **higher quality and more reliable** wind resource with higher average wind speeds is farther away from shore, and thus,

  o **Long distances** to shore.
Introduction (2)

- **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 converters and different VSC converter types** in a meshed topology need further investigation.
BEST PATHS Project
BEyond State-of-the-art Technologies for re-Powering Ac corridors & multi-Terminal Hvdc Systems

Key Figures

- **Budget** of €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 – 31/10/2018 (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.
BEST PATHS Demo #1

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.
Offshore Wind Energy 2017

BEST PATHS Demo #1 (2)

HVDC equipment manufacturers provide ‘black boxes’

R&D Centres
Utilities & RES developers
Independent Manufacturers
TSOs

We intend to use ‘open models’

Detailed models Simulation & Validation
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
Network Topologies (3)

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

Six-Terminal HVDC System with Offshore DC Links (Topology C)
Network Topologies (5)

- 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</th>
<th>AC/DC interactions: power and harmonics</th>
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<tbody>
<tr>
<td>Steady state</td>
<td>Power quality</td>
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<tr>
<th>KPI.D1.2</th>
<th>AC/DC Interactions – Transients &amp; Voltage Margins</th>
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<tr>
<td>Normal operation</td>
<td>Extreme operation</td>
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<tr>
<th>KPI.D1.3</th>
<th>DC Protection Performance / Protection &amp; Faults</th>
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<tr>
<td>Protection selectivity</td>
<td>Peak current and clearance time</td>
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<tr>
<th>KPI.D1.4</th>
<th>DC Inter-array Design</th>
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<tr>
<td>Inter-array topology</td>
<td>Power unbalance</td>
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<tr>
<th>KPI.D1.5</th>
<th>Resonances</th>
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<td>AC systems oscillation</td>
<td>Internal DC resonance</td>
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<tr>
<th>KPI.D1.6</th>
<th>Grid Code Compliance</th>
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<tr>
<td>Active and reactive power</td>
<td>Fault ride-through</td>
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</table>
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. These have been published in the BEST PATHS website as a MATLAB ‘Open Access’ Toolbox: http://www.bestpaths-project.eu/.
The ‘Open Access’ Toolbox (2)

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

- Specific blocks in the toolbox include:
  - High level controllers: three modes of operation including ac voltage and frequency, DC voltage and reactive power, and active and reactive power regulation;
  - Converter stations: averaged and switched of modular multilevel converters (MMCs);
  - AC grid: adapted from the classical 9-bus system;
  - DC cables: frequency-dependent, travelling wave model based on the universal line model;
  - Wind farm: a wind turbine generator (WTG) is modelled in detail. The current injection of a WTG is scaled to complete the rated power of the OWF.

- Full details of the models available in Deliverable D3.1 of the BEST PATHS project.
The ‘Open Access’ Toolbox (3)

- Toolbox and user manual uploaded on BEST PATHS website on 14th February.
- Presentation at 13th IET ACDC2017; advertisement via social media and on project website.
- 1,258 new users have been recorded on the website since the toolbox was uploaded.
- The toolbox has been downloaded by 60 different users.

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

- **Research centres** include the 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, Energinet.dk, DNV GL, IBM Research, SP Energy Networks, TenneT Offshore, Nissin, Enstore and SCiBreak.
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)

- 42 modules
- 144 power cell boards
- 1764 capacitors
### KPI Assessment Summary (Simulation Results)

<table>
<thead>
<tr>
<th>KPI</th>
<th>Description</th>
<th>Status</th>
<th>Remarks</th>
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<tbody>
<tr>
<td>1.1</td>
<td>Steady State AC/DC Interactions</td>
<td>✔ Fully Met</td>
<td></td>
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<tr>
<td>1.2</td>
<td>Transient AC/DC Interactions</td>
<td>○ Partially 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>1.3</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></td>
</tr>
<tr>
<td>1.6</td>
<td>Grid Code Compliance</td>
<td>○ Partially 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>
</tbody>
</table>

- Full details of the models available in **Deliverable D3.2** of the BEST PATHS project.
Simulation and Experimental Results

Test System

- Modelled in Simulink using the ‘Open Access’ Toolbox.

- The Grid Emulator creates 380 V AC and 690 V DC voltages in Lab.

- A step change in current references $i_d$ and $i_q$ is applied.

- MMC arm currents and arm voltages are compared.
Simulation and Experimental Results (2)

- 12 Level MMC – Active current reversal from 30 A to \(-30\) A at 1.5 s

Simulation

- Arm Currents

Experiment

- Arm Voltages
Simulation and Experimental Results (3)

- 12 Level MMC – Step in reactive current from 0 A to 10 A at 2.5 s

- **Simulation**
  - Arm Currents

- **Experiment**
  - Arm Currents

- **Arm Voltages**
Simulation and Experimental Results (4)

- 18 Level MMC – Active current reversal from –30 A to 30 A at 1.5 s

**Simulation**

- Arm Currents

- Arm Voltages

**Experiment**

- Arm Currents

- Arm Voltages
18 Level MMC – Reactive current step from 0 A to -10 A at 2.5 s

- Simulation
- Experiment

- Arm Currents

- Arm Voltages
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.

- Preliminary 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

- Conclude commissioning of the demonstrator facilities.

- 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.
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Questions?

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