Control challenges for grid integration

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• Background
• Diode Rectifier as offshore HVDC
• Grid Forming Wind Turbines
• Offshore AC Grid Start-up
• Black Start by Offshore Wind Turbines

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Offshore wind development

Offshore wind capacity set to reach 520 GW by 2050

- Could raise offshore wind to 4% of global power generation by 2050
- Average new turbine capacity set to reach 8.3 MW by 2022 – up 184% since 2010
- Next-gen turbines offer longer blades and higher output
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Offshore wind development

Figure 1: Global levelised cost of electricity from offshore wind farms by year of commissioning, 2010-2021

Source: IRENA, 2018a.
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Offshore wind development

Main cost components of offshore wind farms:
- turbines (including towers)
- the foundations
- the grid connection to shore
  - AC or DC?

Power flow is in one direction only
Why not use a diode rectifier offshore?

Source: IRENA, Offshore innovation widens renewable energy options, September 2018

Source figure: ABB, [online](http://www.abb.com)
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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

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Voltage [%]

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Deliverable 3.8
List of requirement recommendations to adapt and extend existing grid codes
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Diode Rectifier Units as offshore HVDC

Key features of the Modular Diode Rectifier Unit:
- Encapsulated, rugged equipment
- Bis degradation and flame retardant insulation
- Simple and robust power electronics
- Small platform with easy transport and installation
- High reliability, minimal maintenance
- Via offshore DC converter as single point of failure
- Flexible offshore installation options due to modular rectifier concept

Trondheim 17.01.2019
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**Grid Forming Wind Turbines**

Grid forming wind turbines control
- dq current control based
- voltage/angle control based
  - VSM control
- GPS synchronization based
  - master/slave based
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Offshore AC Grid Start-up Options

- Umbilical AC Cable
- Nearby VSC-HVDC (or AC)
- Local Energy Storage (e.g. battery, diesel)
- Black-startable wind turbines

VSC-MMC onshore

Energy Storage

DRUs

HVDC link

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Onshore AC Grid

DRUs

HVDC link

VSC-MMC onshore
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Some results – AC grid start-up (string connection)
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Some results – Frequency control

Figure 3-12: Case 12 – OWF’s response to an onshore under-frequency event ($t = 0.5s$) at high wind speed – Reserves: 10% – Overloading released at $t = 13s$. CBase: $\dot{P} = P^*$, CP: $\dot{P} = P^* + \Delta P_{FPR}$, CF: $\dot{P} = P^* + \Delta P_{FPR}$, CPFE-MPPT: $\dot{P} = P_{MPPT} + \Delta P_{FPR} + \Delta P_{FPR}$, CPFI: $\dot{P} = P_{MPPT} + \Delta P_{FPR} + \Delta P_{FPR}$, CPFE-Ref: $\dot{P} = P^* + \Delta P_{FPR} + \Delta P_{FPR}$.
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Black-start - Progress Towards Demonstration

Outside PROMOTioN
Energinet performs Black Start field test with Skagerrak 4 (SK4) HVDC interconnector

WP3 Performs Black Start Simulation Test with Offshore WPP

To energize:
- 3 buses
- Overheadline & underground cable
- Shunt reactor & transformer
- Step MW++ load
  - Load changes
  - Frequency & voltage setpoint changes
  - Load disconnection

Results to be compared against HVDC field tests by Energinet

[https://ens.dk/sites/ens.dk/files/Statistik/el_produktion_og_transmission_2017_300dpi.pdf]
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Scenarios – Self-Energization & Black Start

HVAC-connected OWPP

HVDC-connected OWPP(s) with AC collector substation(s)

HVDC-connected OWPP(s) directly (66kV) connected to the HVDC

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Some results – black-start
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Some results – black-start

![Graphs showing voltage and current over time for black-start analysis.](image)
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Models for Control of WT/WPP Connected to DR-HVDC

Confidential - only for members of the consortium

- Aggregated single WT
- Ideal onshore DC voltage
- Ideal WT DC voltage

- Offshore AC start-up
- Voltage & frequency control
- Active power setpoint control
- Offshore AC fault ride-through
- Intentional islanded operation
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**Achievements**

- **Control and Modelling**
  - Novel grid forming wind turbine controls
  - Confidential grid forming WPP simulation models
    - Academic (white-box) & Industrial (black-box)

- **Operation of DRU HVDC Systems**
  - Functional requirements for Diode-Rectifier (DRU) connection of Wind Power Plants
  - Control algorithms and simulation test cases & results
  - Proof of DRU concept via simulations
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Main Findings and Challenges

Operation of DRUs

- Wind turbines can operate with DRU-connection without any degradation compared to VSC
- Wind turbines can operate as islanded (idling, self-sustaining)

Fault Handling in DRU-connected OWPP

- DRU inherent response to DC link voltage eases onshore AC fault ride-through

Ancillary Services by DRU-connected OWPP

- DRU connected OWPP can contribute to frequency support and oscillation damping

OWPP Self-energization and Black Start

- OWPP can energize its AC network and might be able to contribute to black start
Any Questions?