PROMOTioN
PROGRESS ON MESHED HVDC OFFSHORE TRANSMISSION NETWORKS

Control challenges for grid integration

Nicolaos A. Cutululis, DTU Wind Energy

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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.

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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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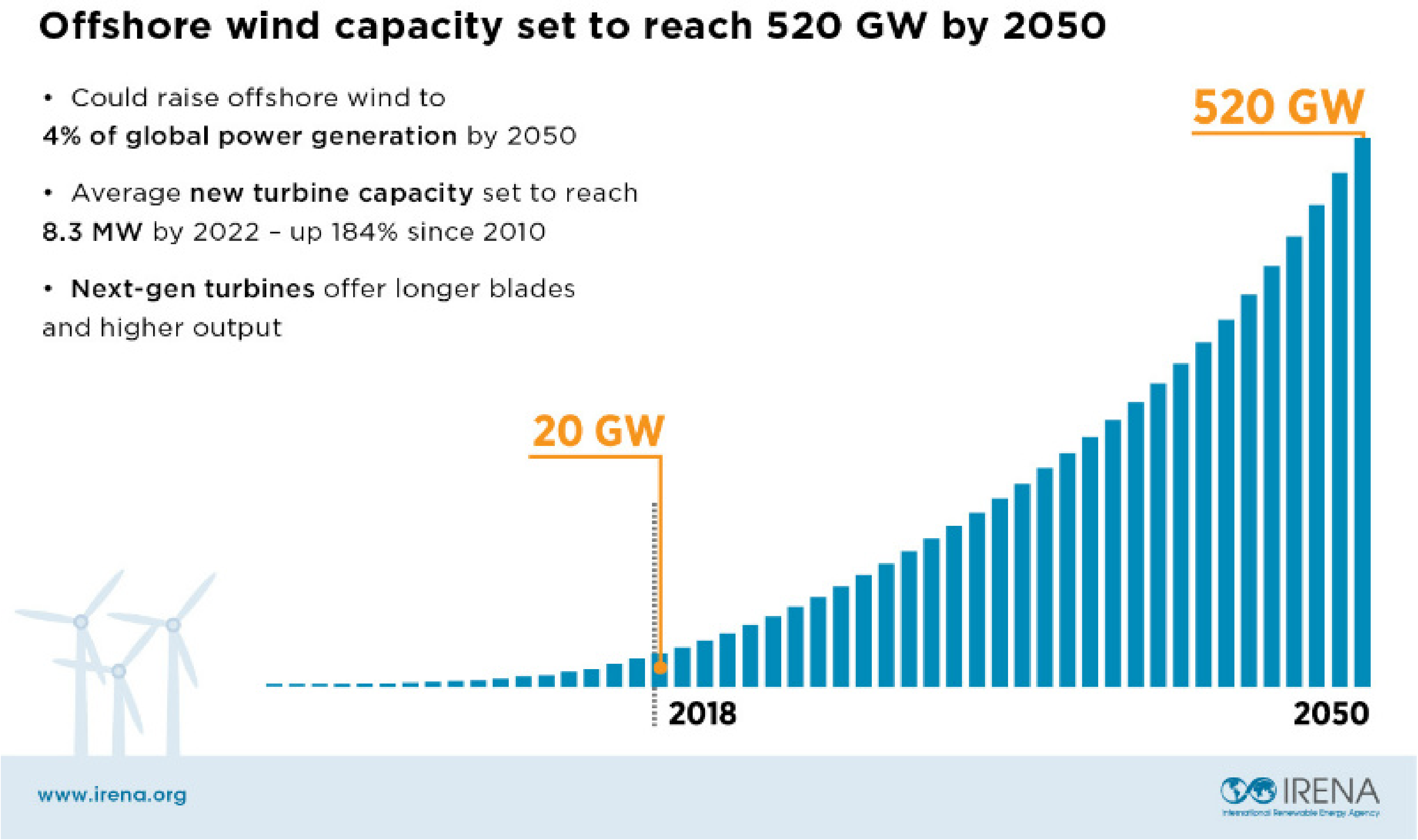
Offshore wind development



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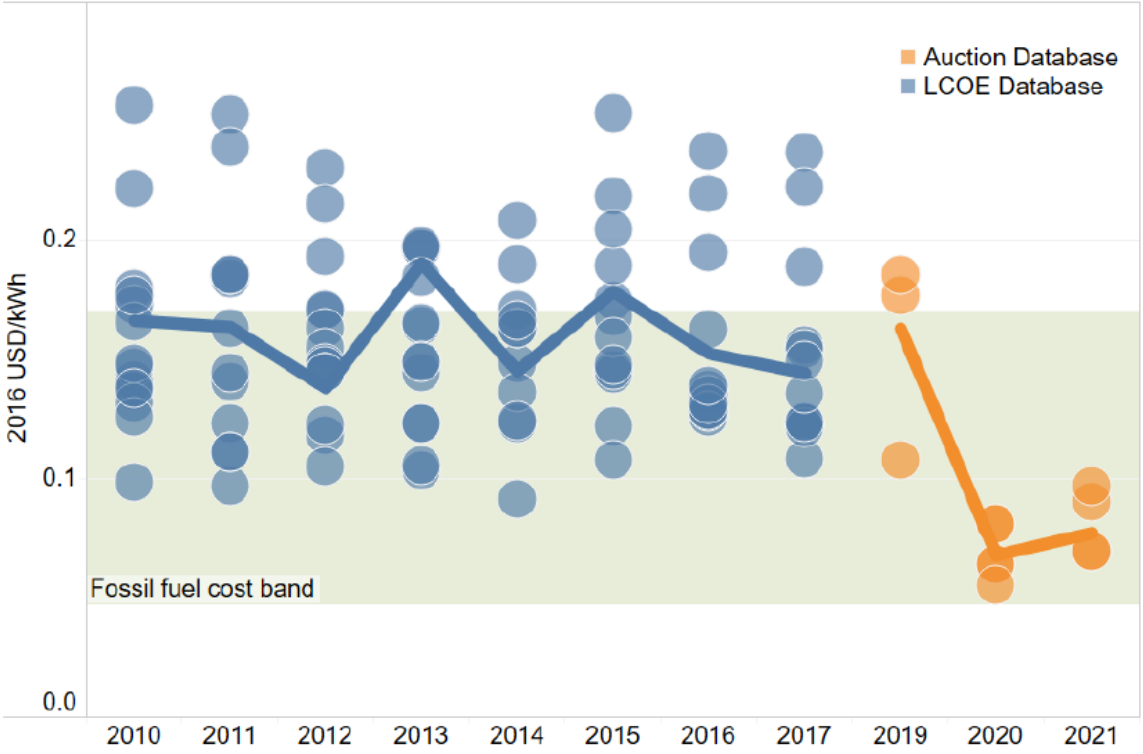
Offshore wind development

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



Source: IRENA, 2018a.

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

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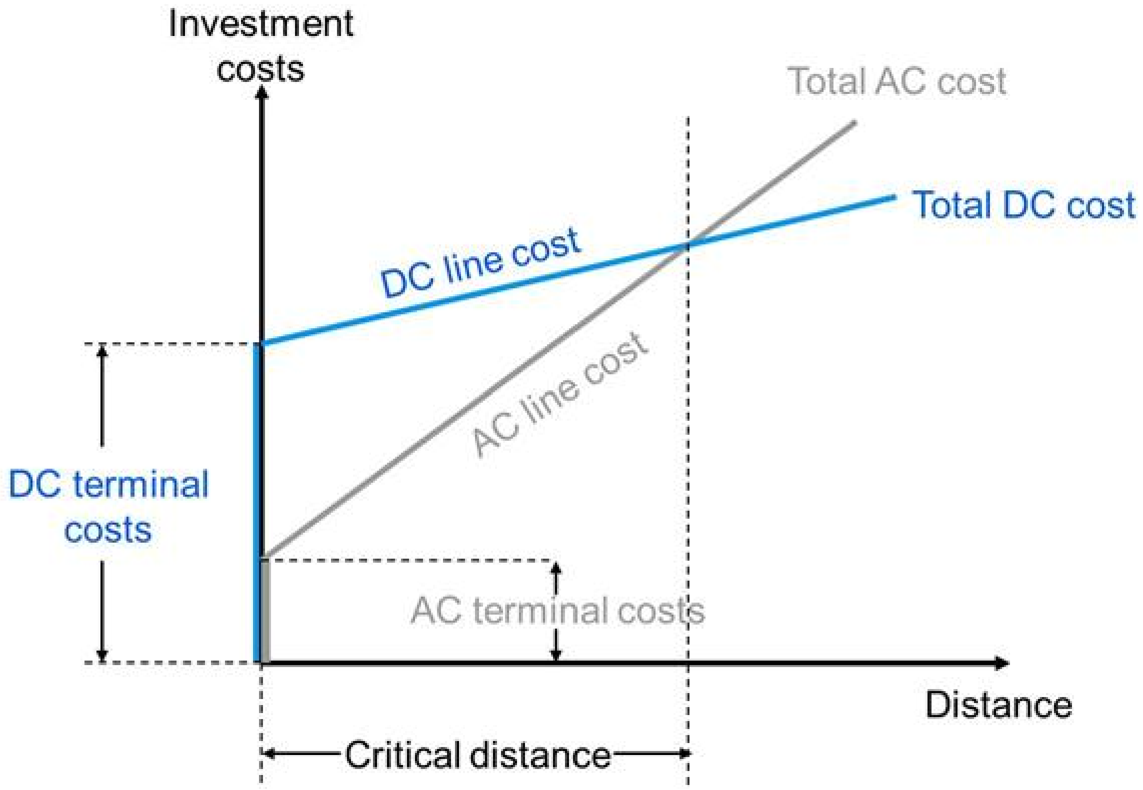
Offshore wind development

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

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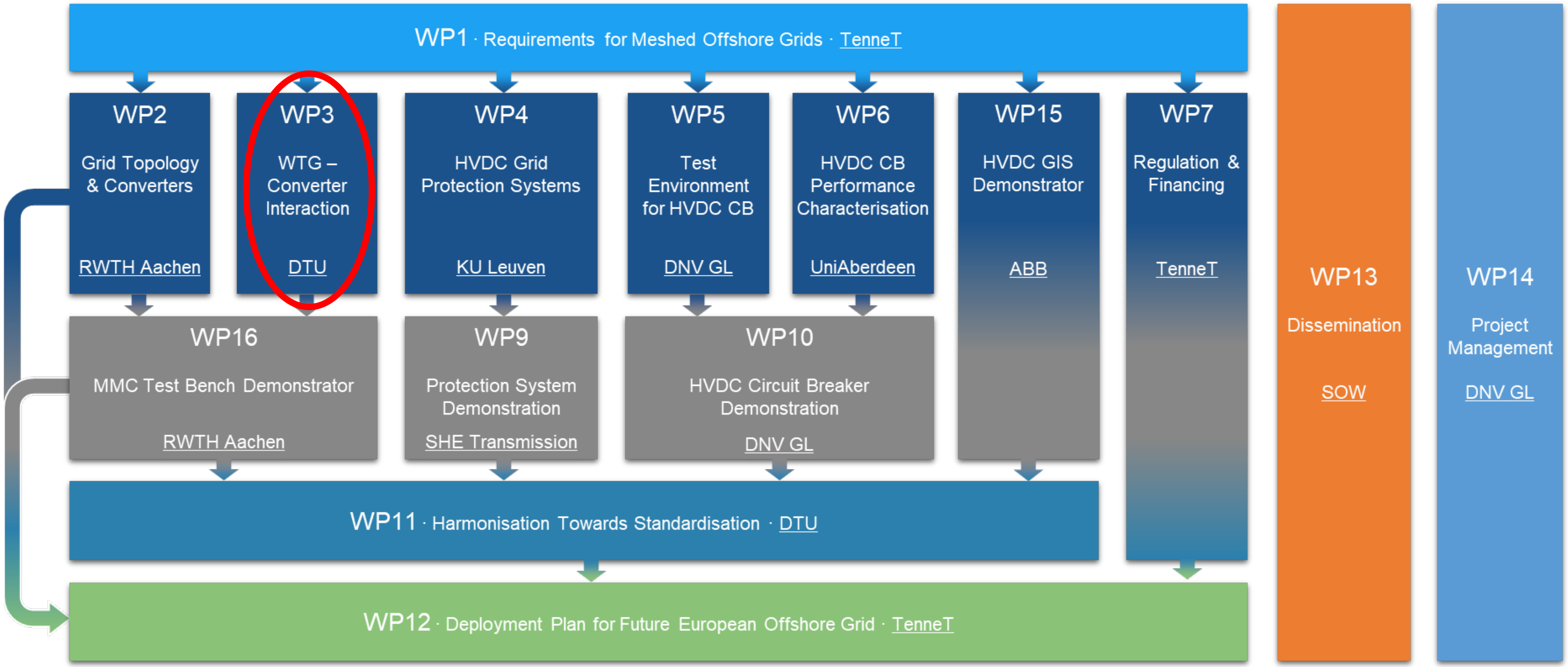
PROMOTioN project

Progress on Meshed HVDC Offshore Transmission Networks



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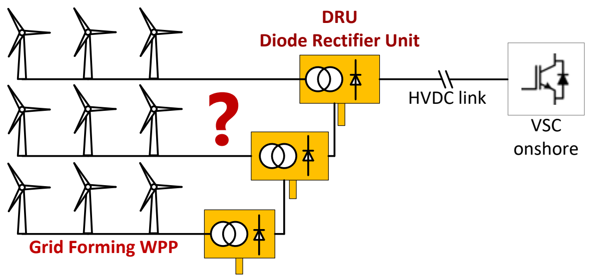
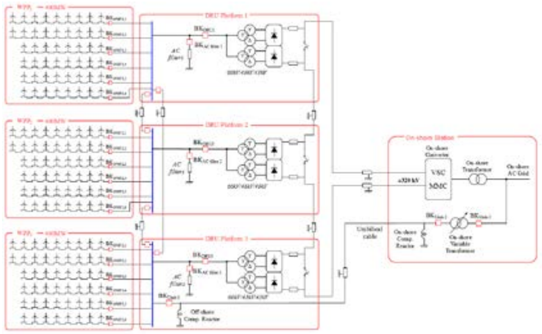
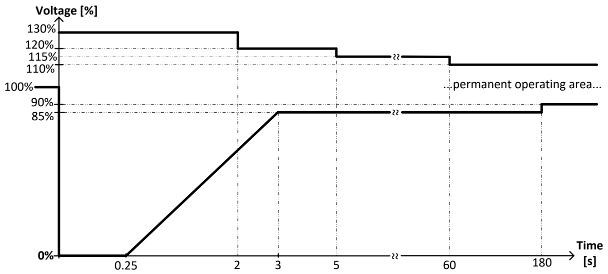
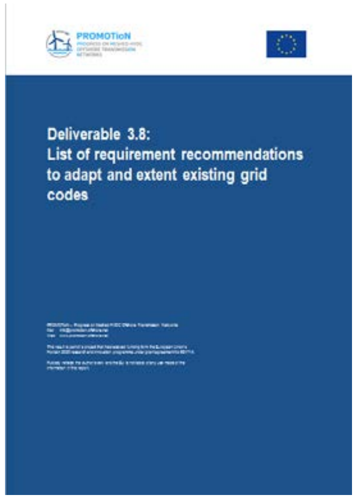
Objectives

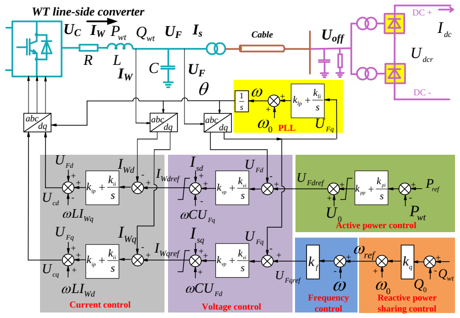
Objective 1	Objective 2	Objective 3	Objective 4
Define functional requirements to OWFs	Develop test cases & control algorithms	Define & apply compliance evaluation	Recommend grid code requirements

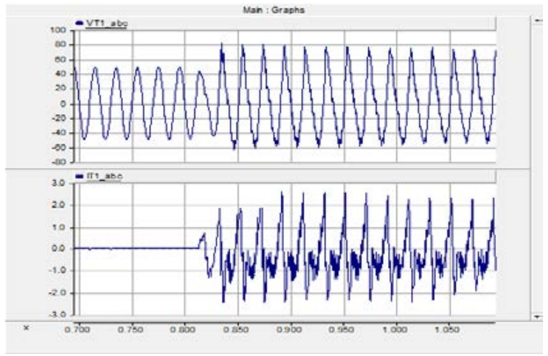






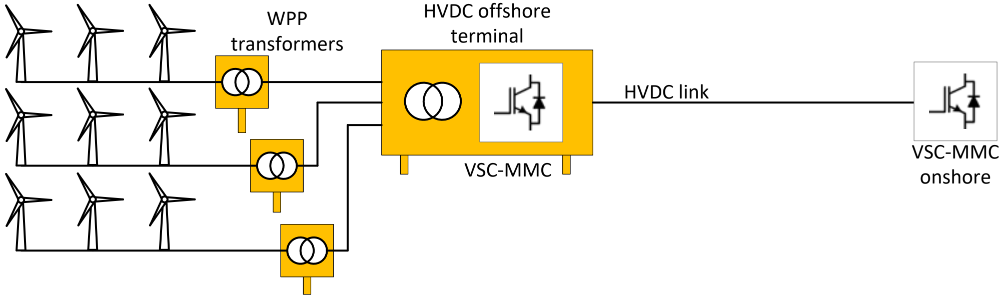




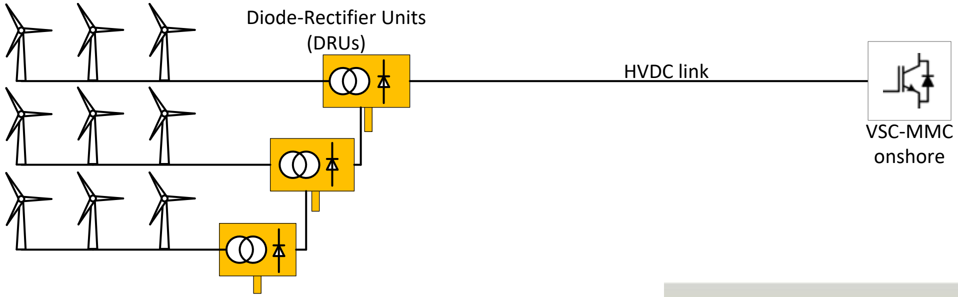


Diode Rectifier Units as offshore HVDC

current VSC solution

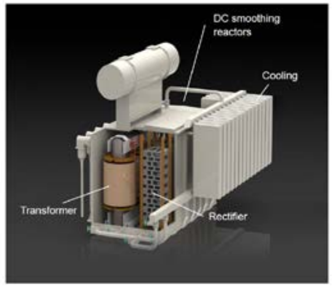


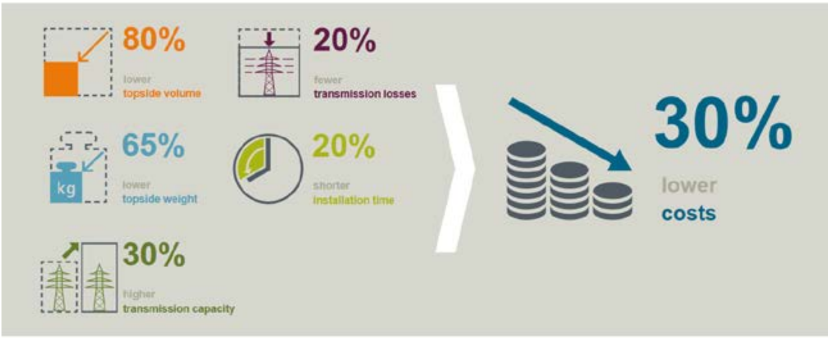
new DRU solution



Key features of the Modular Diode Rectifier Unit

- Encapsulated, rugged equipment
- Bio degradable and flame retardant insulation
- Simple and robust power electronics
- Small platform with easy transport and installation
- High reliability, minimal maintenance
- No offshore DC converter as single point of failure
- Flexible offshore installation options due to modular rectifier concept





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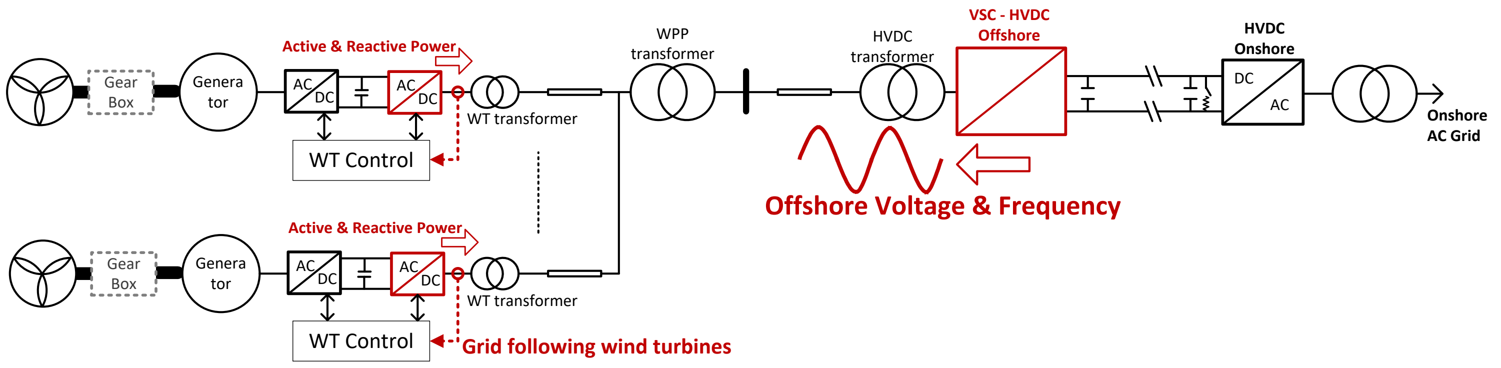
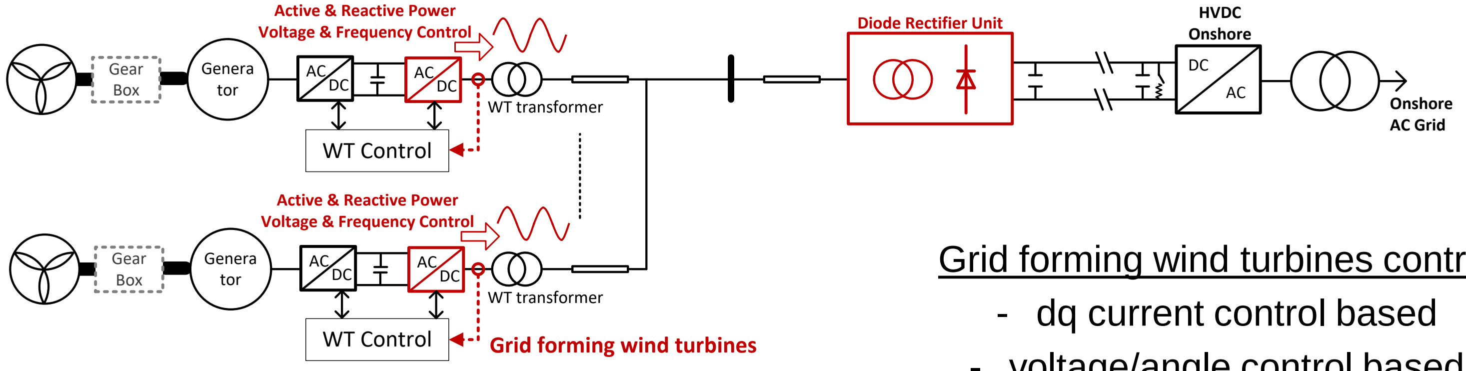
Grid Forming Wind Turbines





<u>Grid forming wind turbines control</u>

- dq current control based
- voltage/angle control based
  - VSM control
- GPS synchronization based
- master/slave based

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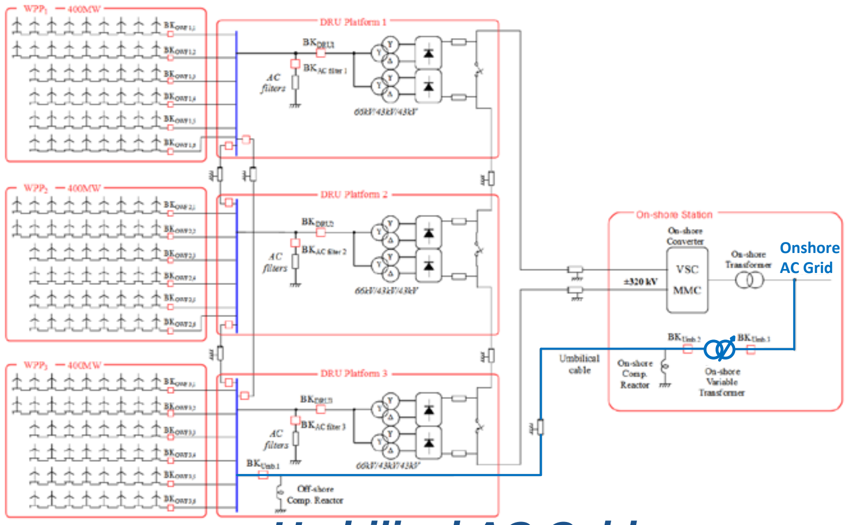
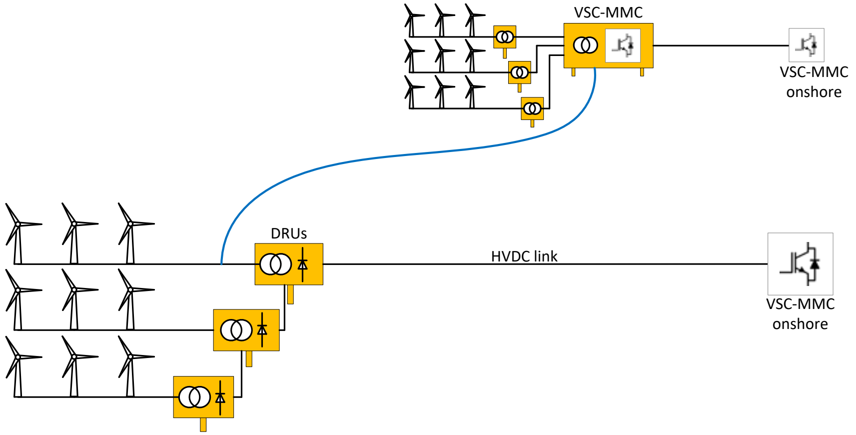
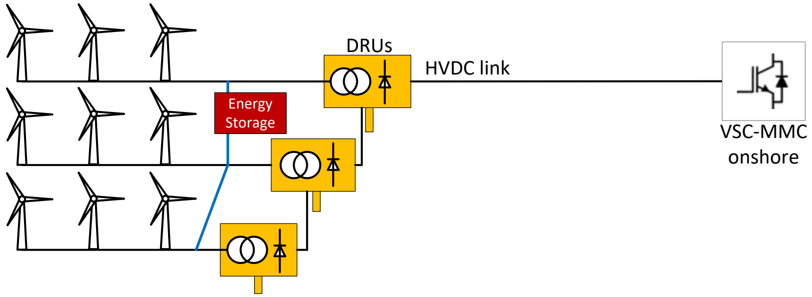
Offshore AC Grid Start-up Options



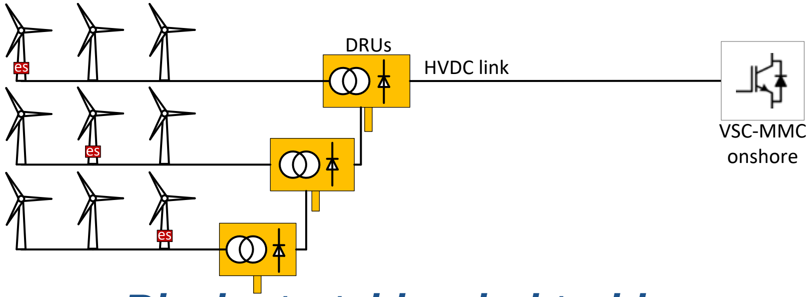
Umbilical AC Cable



Nearby VSC-HVDC (or AC)



Local Energy Storage (e.g. battery, diesel)



Black-startable wind turbines

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Some results – AC grid start-up (string connection)

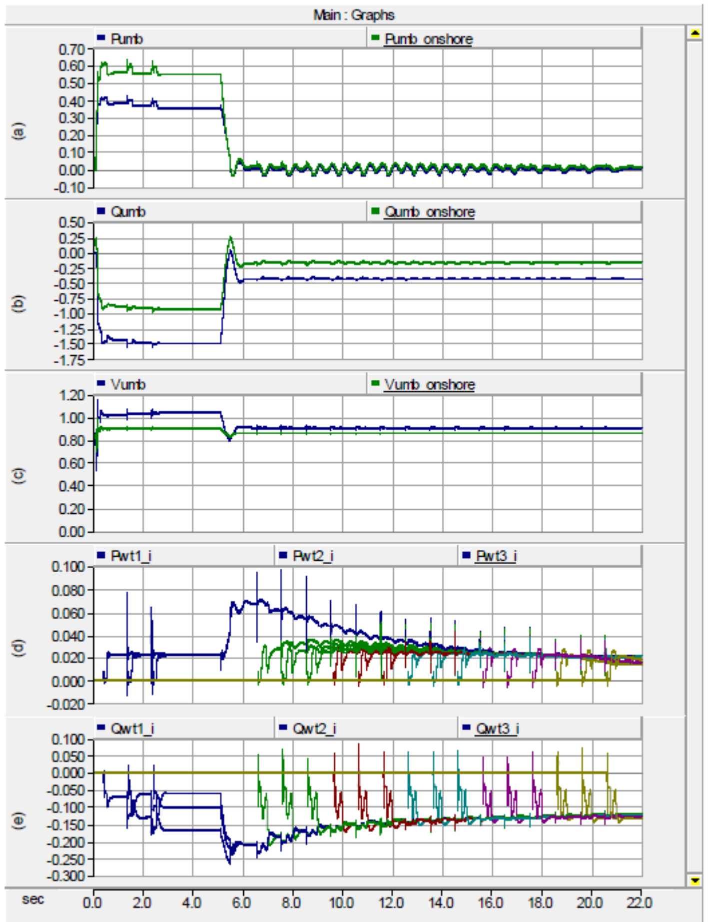
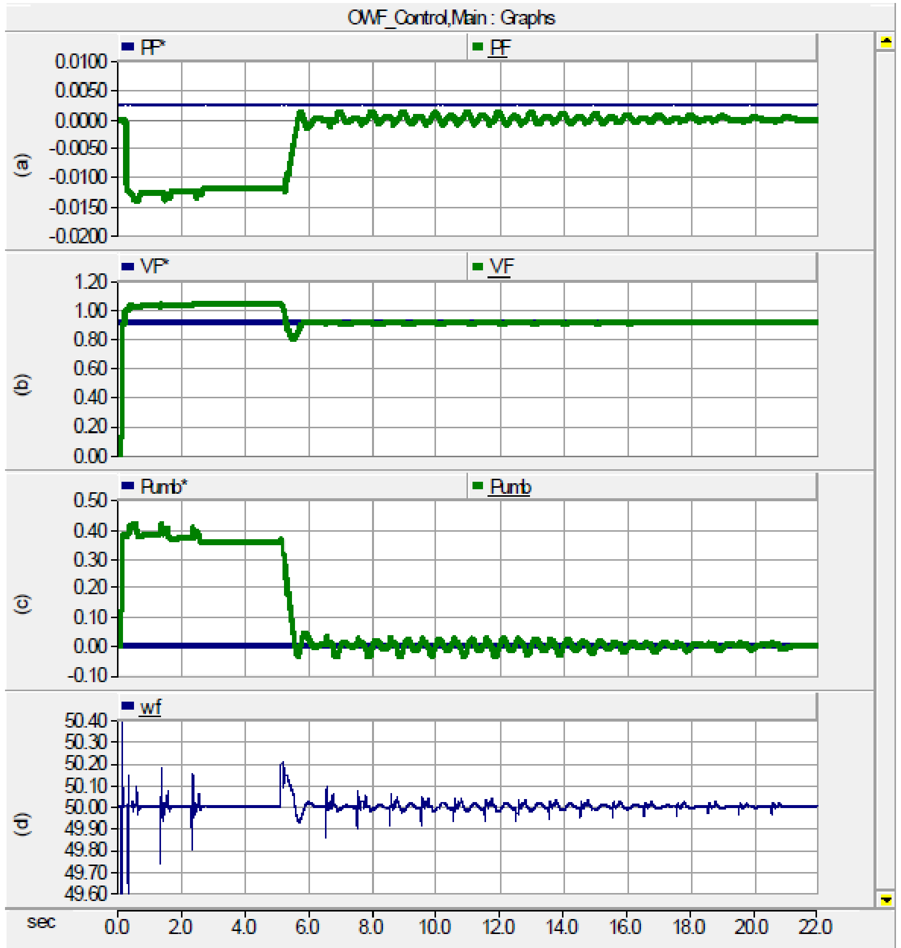
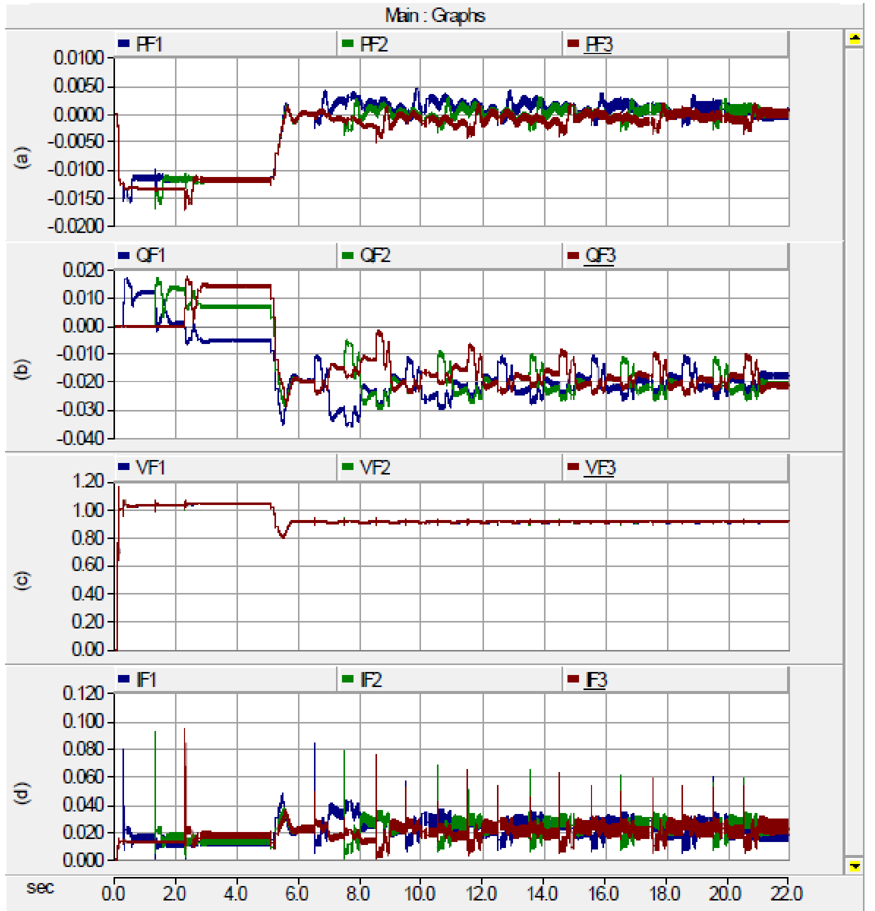


Figure 2-6: Simulation results during offshore AC grid start-up (string connection): (a) active power through umbilical cable measured at umbilical offshore and on-shore ends; (b) reactive power through umbilical cable measured at offshore and on-shore ends; (c) offshore and on-shore AC voltages; (d) WTG active power $P_{WT-i,j}$; (e) WTG reactive power $Q_{WT-i,j}$.



gure 2-7: Simulation results during offshore AC grid start-up (string connection): (a) total OWF active power; (b) offshore voltage V_{F1}; (c) active power through the umbilical cable; (d) frequency of the offshore AC grid.



igure 2-8: (d) Simulation results during offshore AC grid start-up (string connection): (a) active power delivered by each /F-i; (b) reactive power generated by each OWF-i, (c) voltage at terminals of each DRU platform; (d) current through ea OWF-i.

www.promotion-offshore.net, Deliverable 3.4: Results on control strategies of WPPs connected to DR-HVDC

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Some results – Frequency control

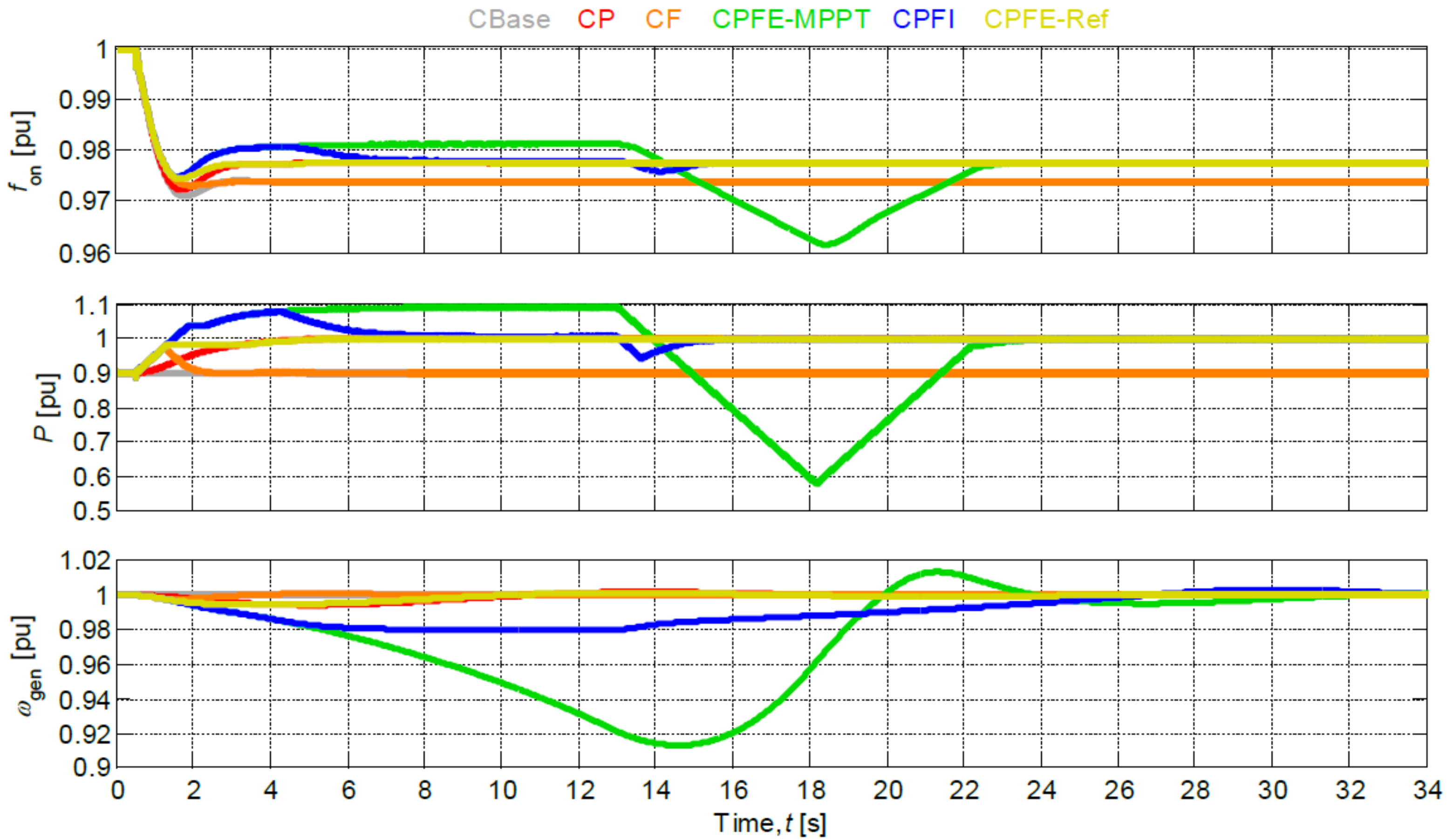

Figure 3-12: Case 12 – OWF's response to an onshore under-frequency event $(t = 0.5\text{s})$ at high wind speed – Reserves: 10% – Overloading released at $t = 13\text{s}$ – CBase: $\hat{P} = P^*$, CP: $\hat{P} = P^* + \Delta P_{\text{PFR}}$, CF: $\hat{P} = P^* + \Delta P_{\text{FFR}}$, CPFE-MPPT: $\hat{P} = P_{\text{MPPT}_0} + \Delta P_{\text{PFR}} + \Delta P_{\text{FFR}}$, CPFI: $\hat{P} = P_{\text{MPPT}} + \Delta P_{\text{PFR}} + \Delta P_{\text{FFR}}$, CPFE-Ref: $\hat{P} = P^* + \Delta P_{\text{PFR}} + \Delta P_{\text{FFR}}$

www.promotion-offshore.net, Deliverable 3.5: Performance of ancillary services pro-vision from WFs connected to DR-HVDC

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Black-start - Progress Towards Demonstration

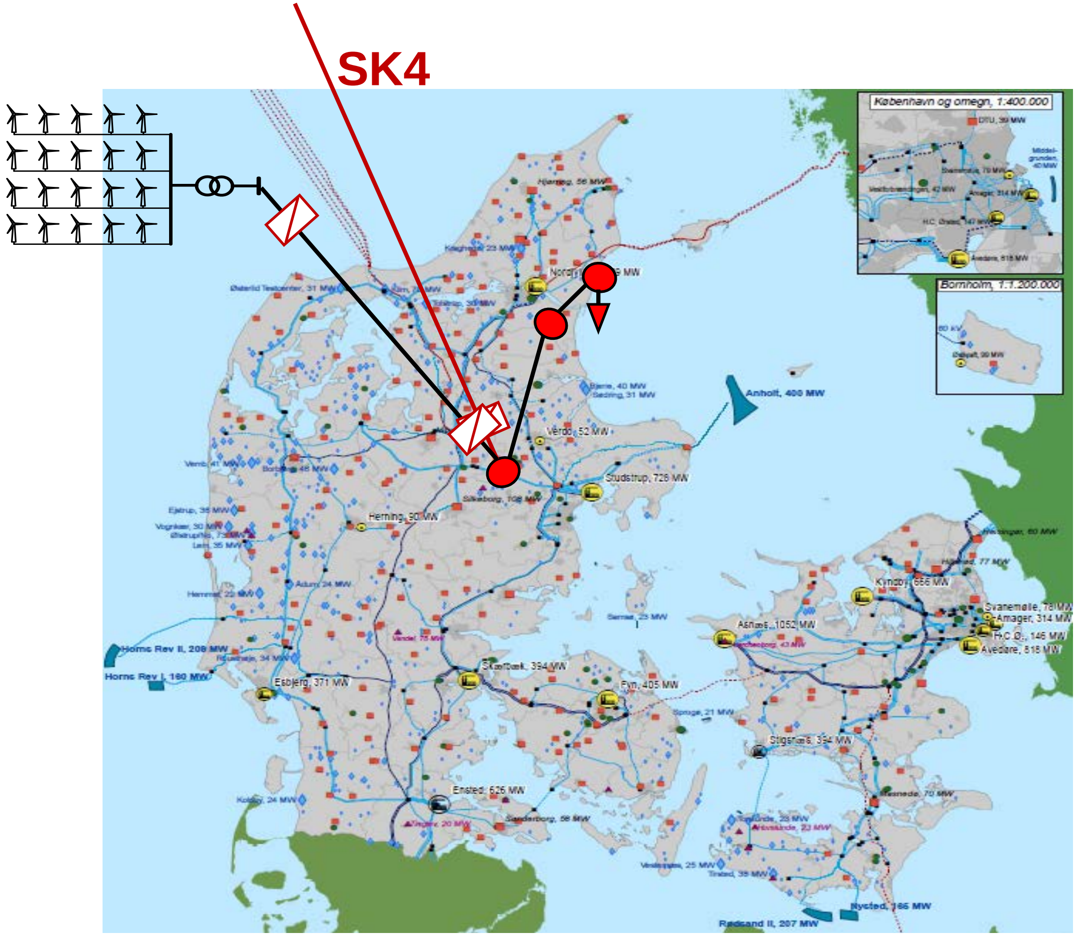
Outside PROMOTioN
Energinet performs Black Start field test with Skagerrak 4 (SK4) HVDC interconnector

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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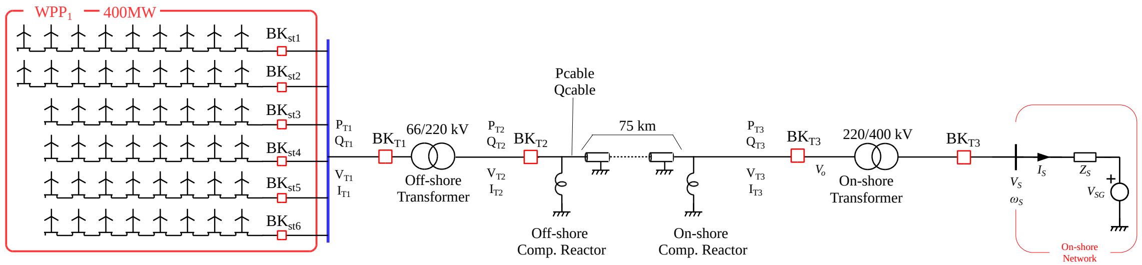
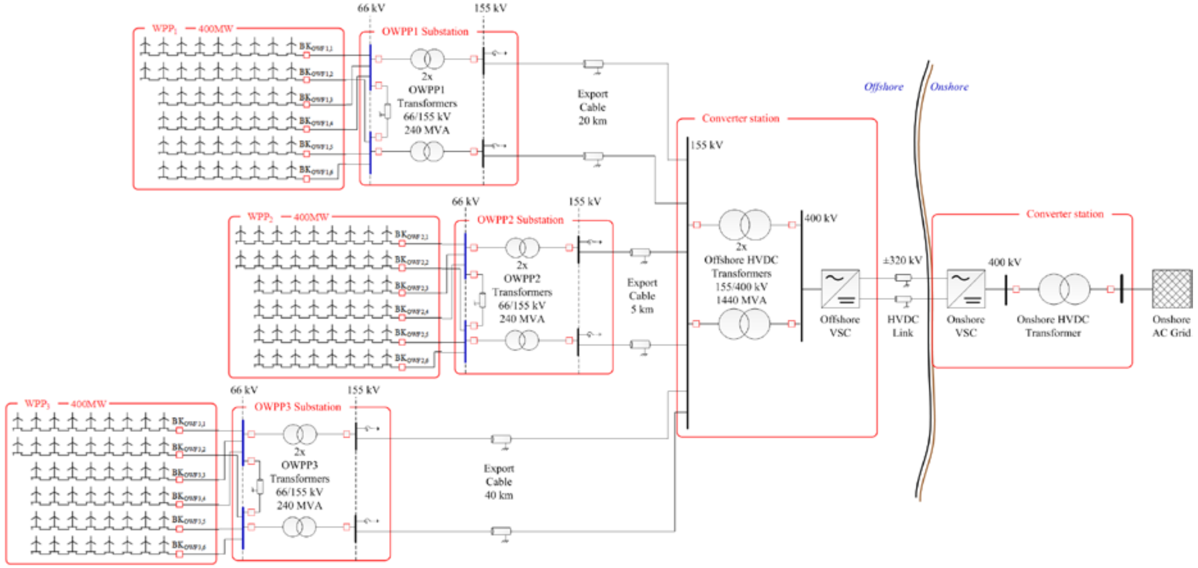
Control challenges for grid integration

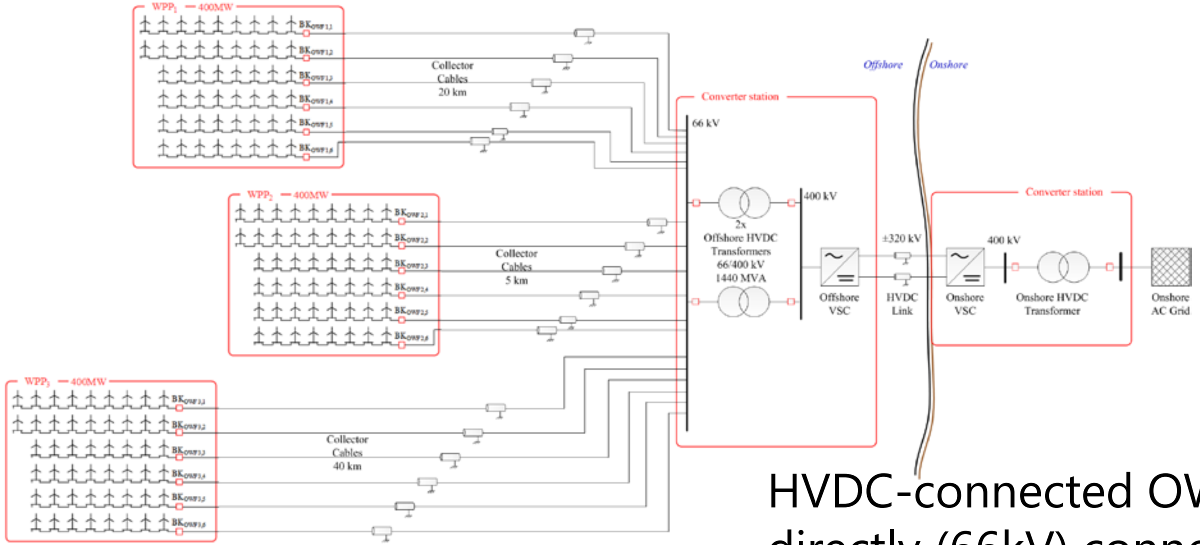
Scenarios – Self-Energization & Black Start



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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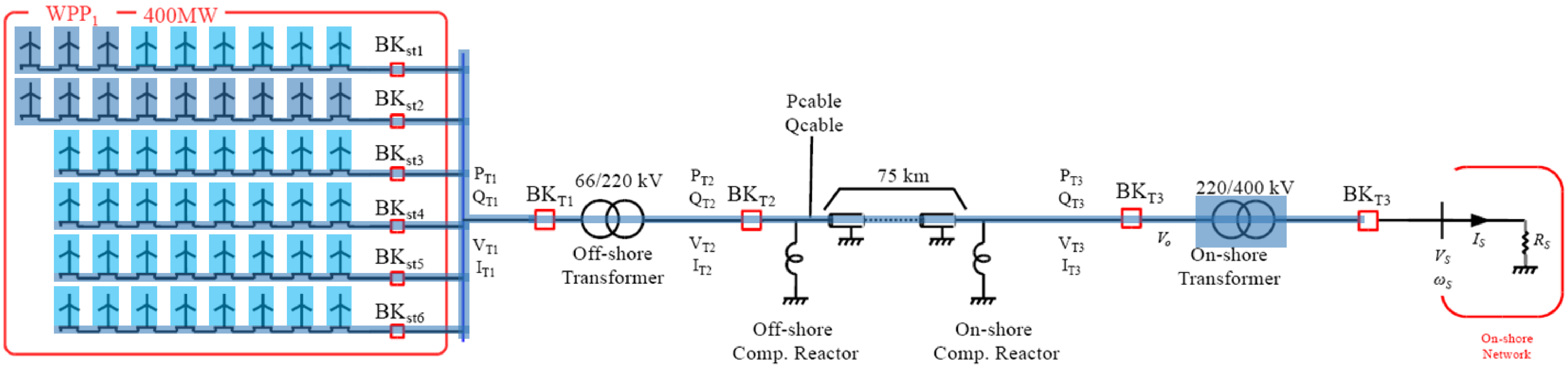
Some results – black-start



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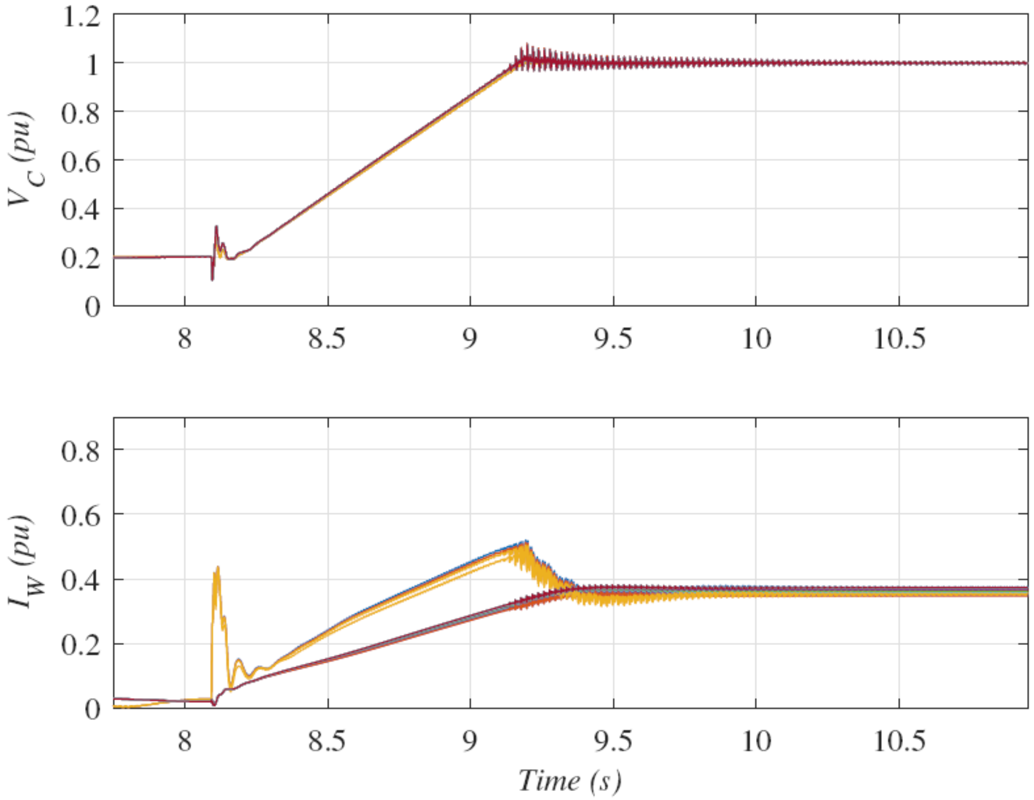
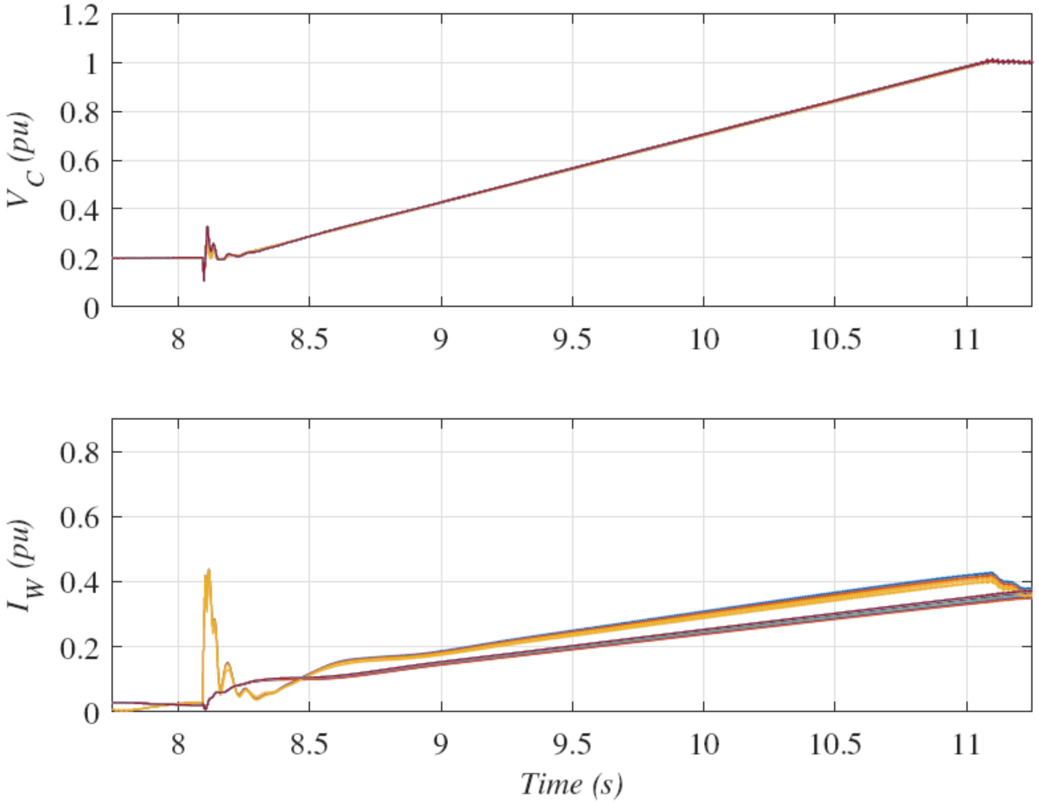
Some results – black-start





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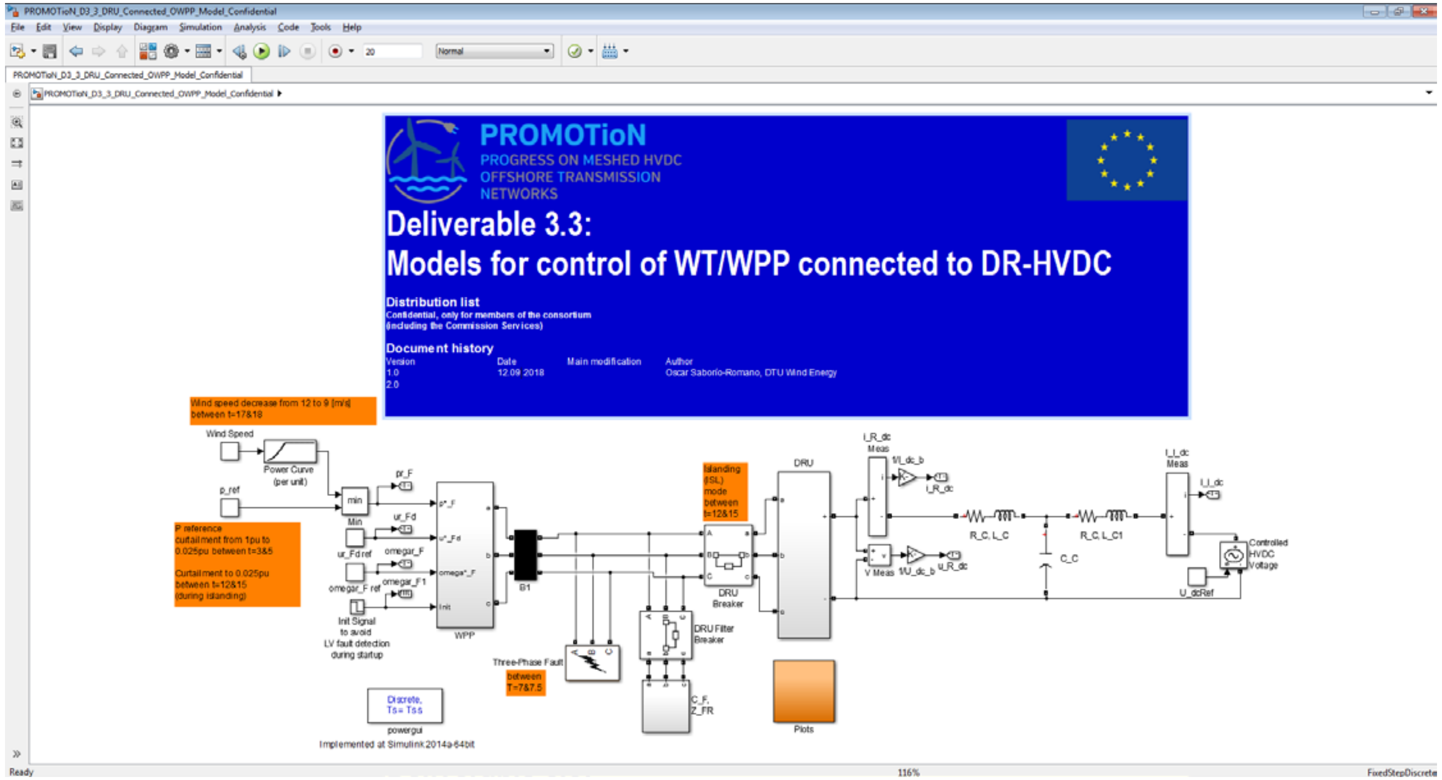
Models for Control of WT/WPP Connected to DR- HVDC

~~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

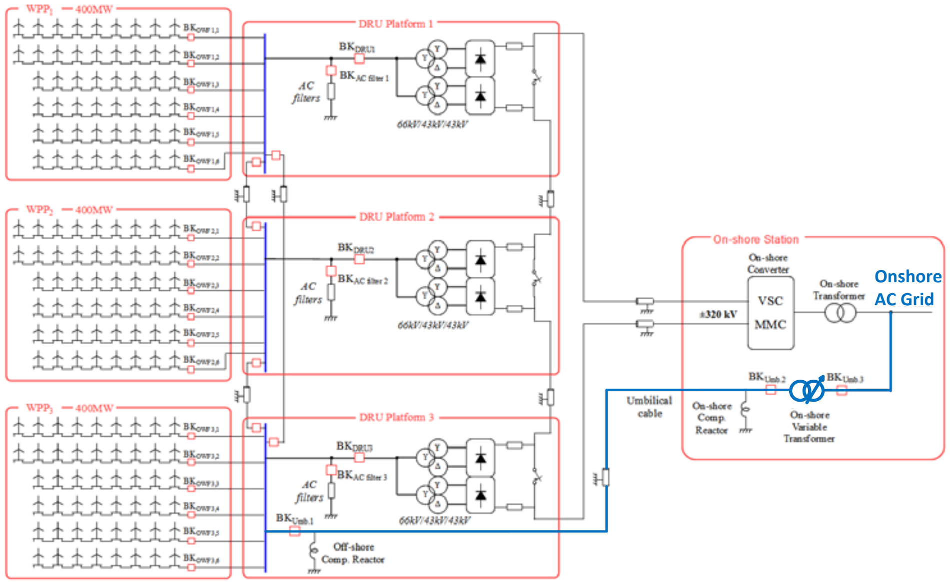
- DRU inherent response to DC link voltage eases onshore AC fault ride-through

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?

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