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Catalogue of high-impact low-probability disturbance scenarios in clusters of offshore wind farms

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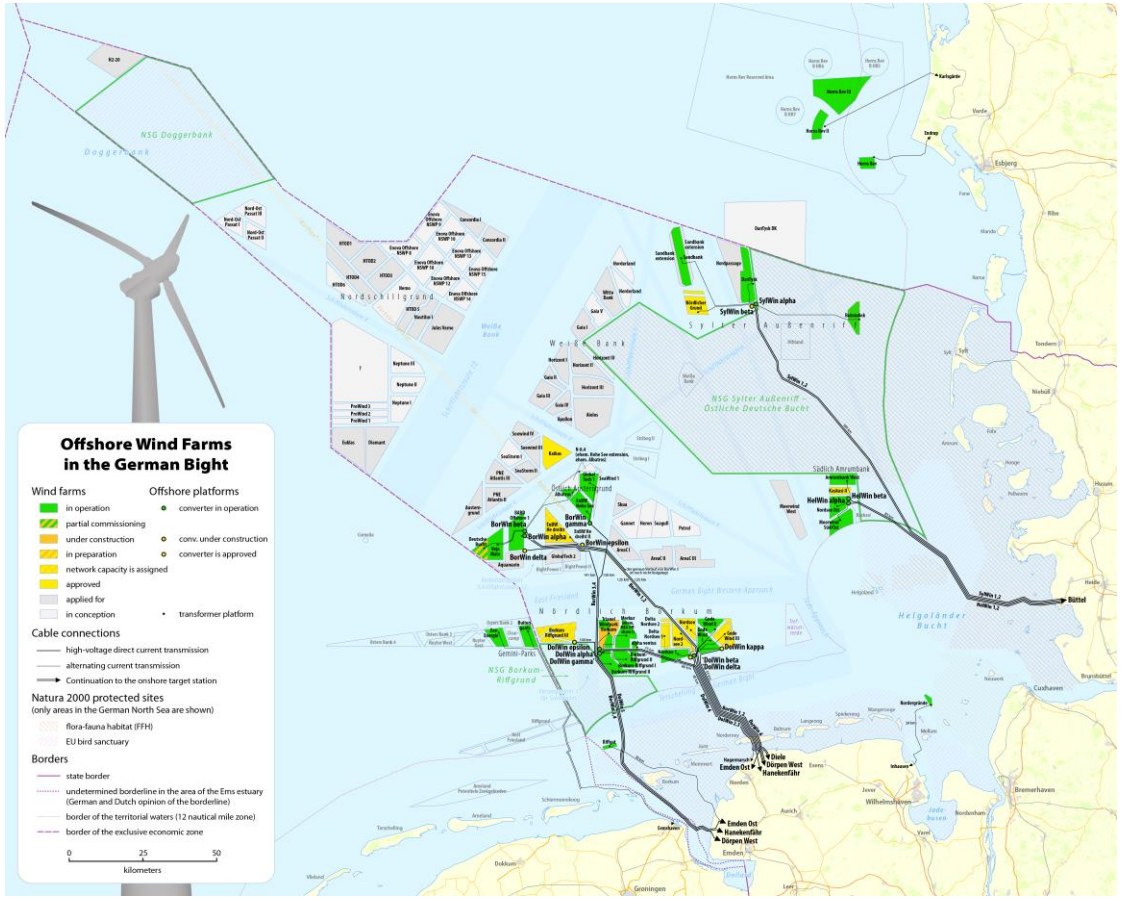
Background and motivation

Clusters of Offshore Wind Farms (OWF) – critical energy infrastructures:

- Currently around 5 % and in 2050 more than 20 % of the net German electricity production
- Capacities of their grid connection points close to the frequency containment reserve (FCR) of 3 GW in the European power grid



Clusters of Offshore Wind Farms in the German Bight (North Sea)

https://commons.wikimedia.org/wiki/File:Map_of_the_offshore_wind_power_farms_in_the_German_Bight.png

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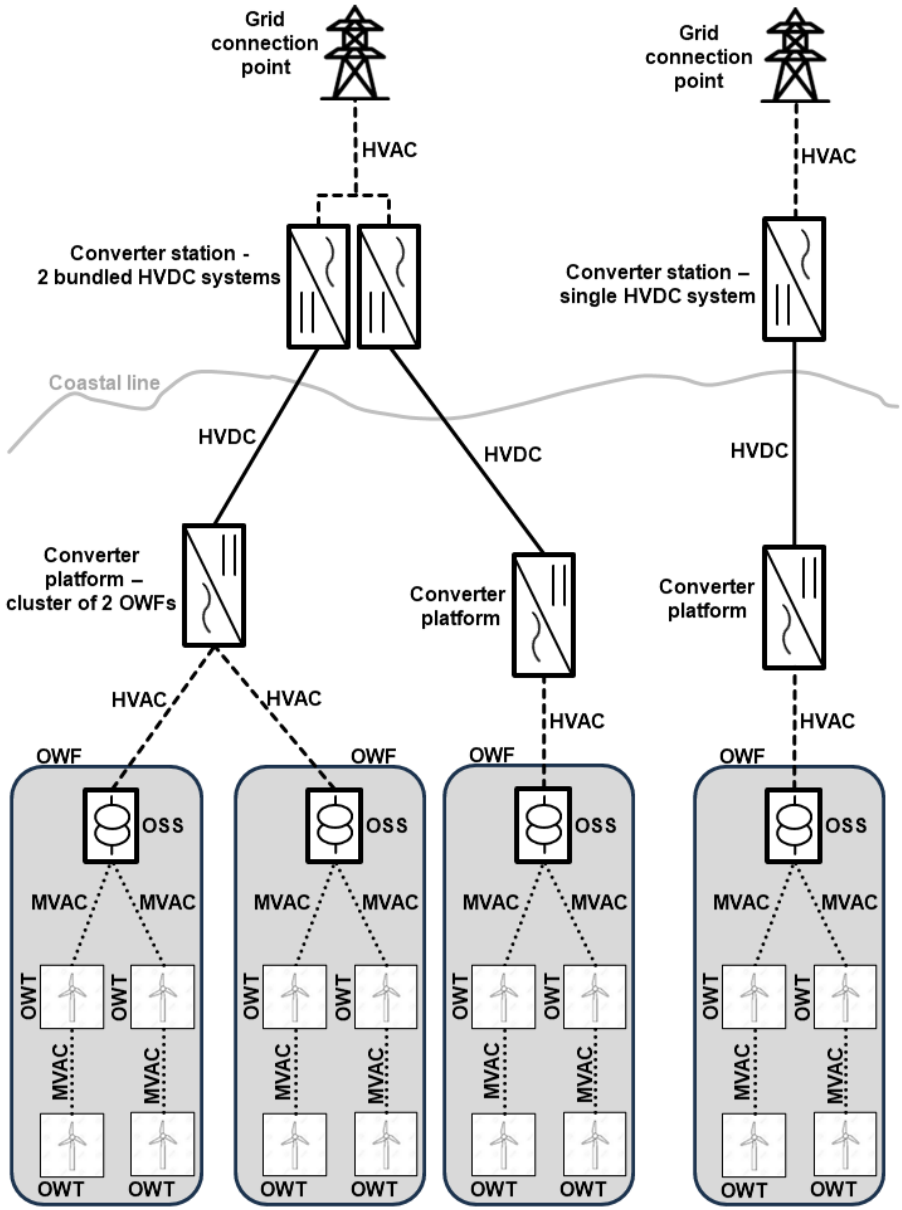
Generic architecture of the clusters of offshore wind farms

Main distinctive features:

- Connection of several (1-3) offshore wind farms (OWF) to a converter platform via AC (alternating current)
- Transmission of the energy to the land via HVDC (high-voltage direct current)
- Bundling of several HVDC transmission systems onshore



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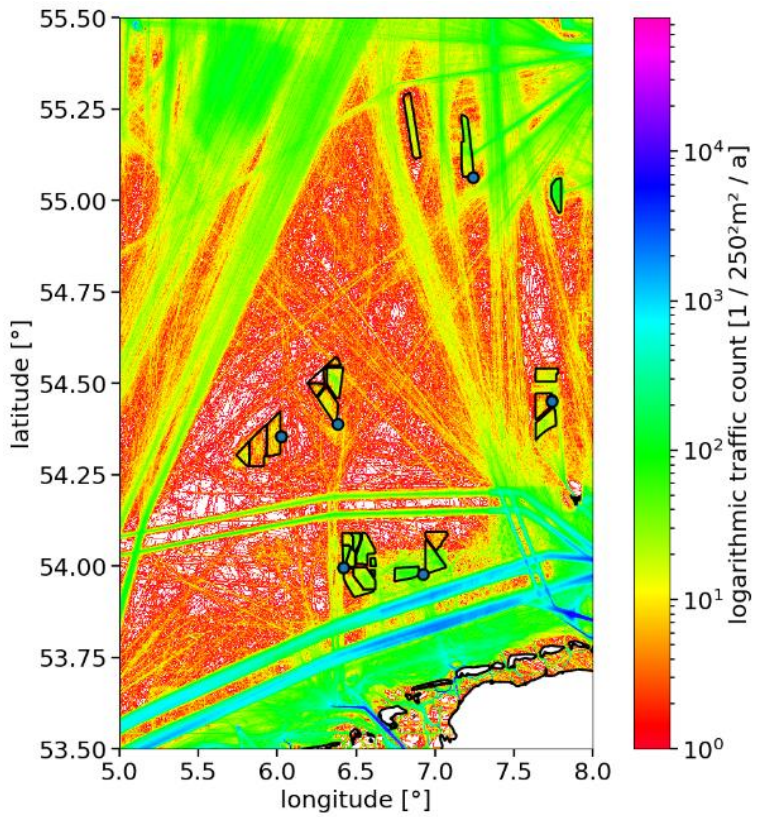
Threats and their quantitative characterization

Various threats regarding the clusters, however focus on:

- Collision threat for the cluster infrastructures (esp. offshore transformer/ converter platforms) through the shipping and air traffic in the North Sea region
- Undersea cable damage through emergency or malicious anchoring *(Eagle S incident in 2024)*, or fishing nets



Density map of the shipping traffic in the German North Sea.

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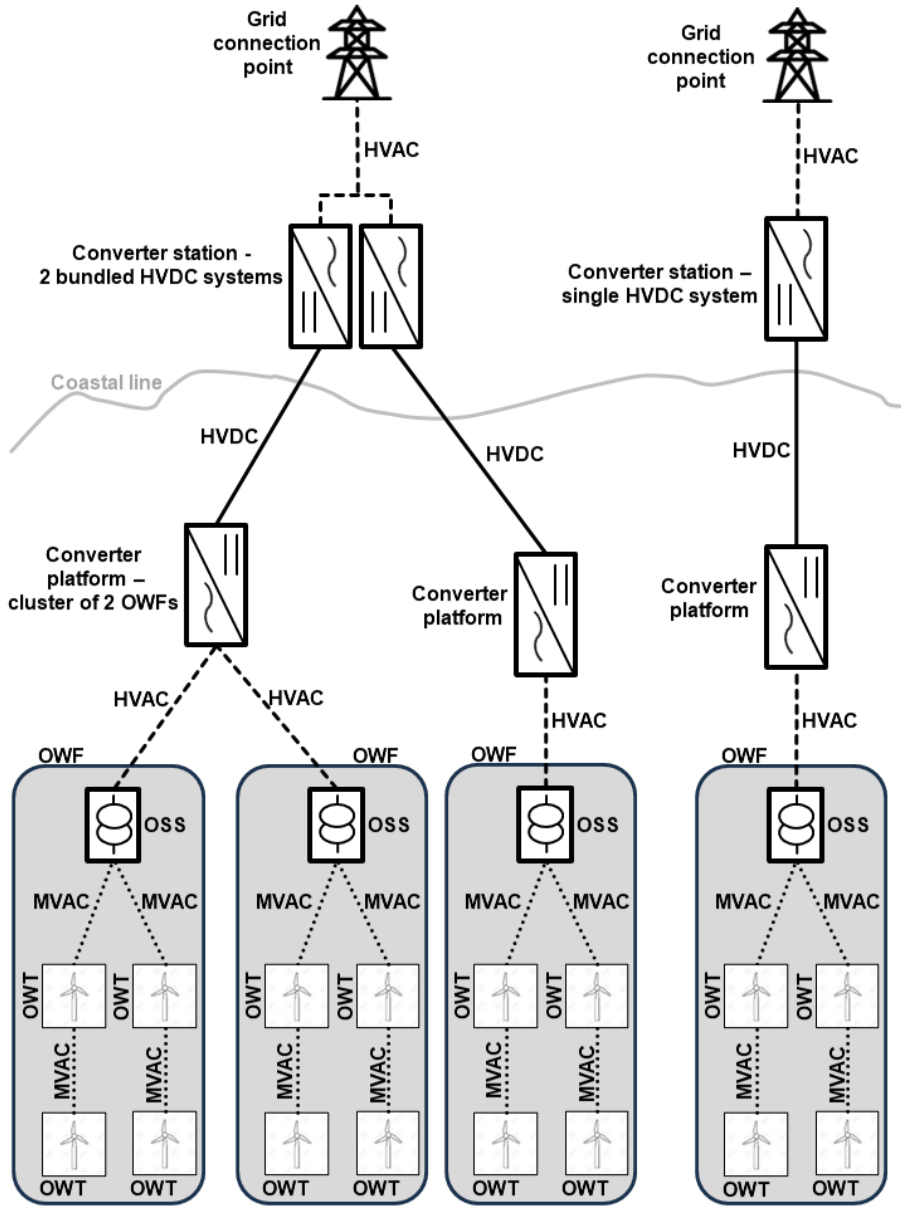
Disturbance catalogue

- Scenarios – disturbing events through accidents/incidents, natural hazards or attacks
- 3 main types of resulting disturbances of the power system of the clusters:
  - Open-circuit
  - Short-circuit
  - Parameter manipulation through “false data injection” into the control systems
- Consequences
  - Significant power loss at the grid connections points
  - Drastic deviations of the electrical parameters propagating into the grid



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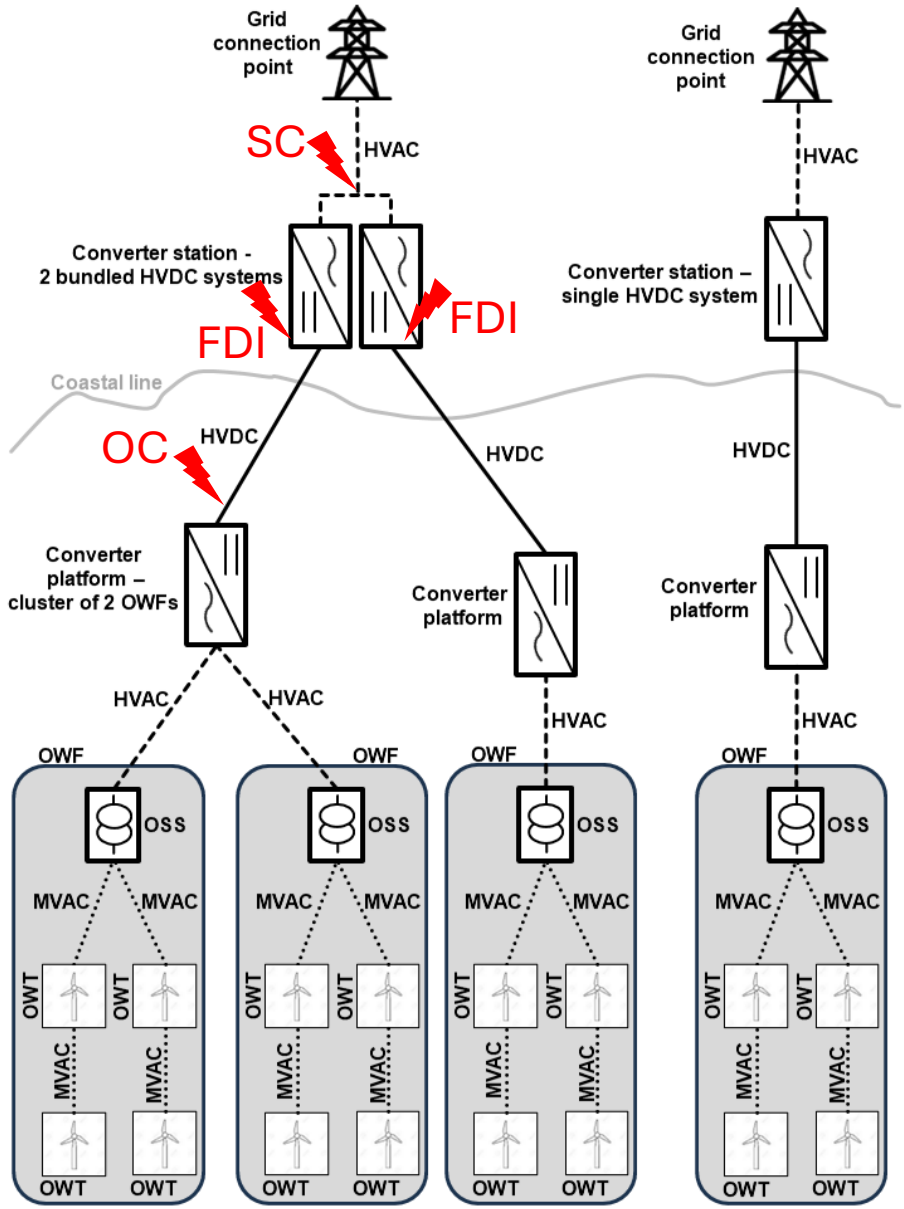
Disturbance catalogue (continued)

- Single clusters/grid connection systems affected
  - Example: Anchor damage of the HVDC cables causing an open-circuit (OC) [Eagle S, 2024] → *initial simulation on the next slide*
- Cluster bundling/combinations - several grid connection systems affected
  - Example: Flooding of the onshore converter station causing a short-circuit (SC) in the common HVAC system
  - Example: Cyber-attack on the control systems of the onshore converter station resulting in a parameter manipulation "false data injection" (FDI)



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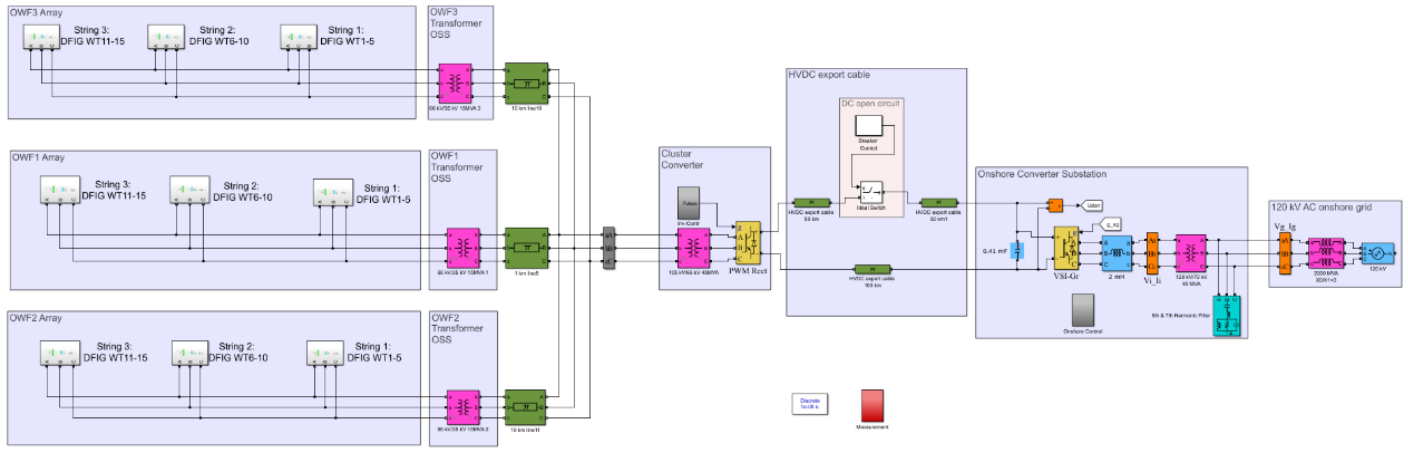
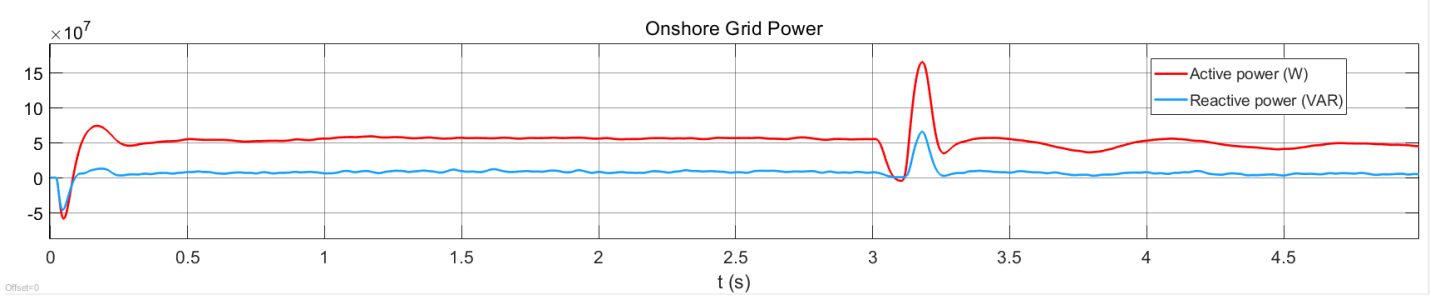
Simulation example - Results & Discussion

- Single cluster of 3 OWFs
- Transient open-circuit (for 0.1 s) at the HVDC cable
- Total power loss at the grid connection point within 0.2 s of the disturbance start – criticality fulfilled (impact within less than 30 s)
- Peak after that – extreme deviations of currents/voltages



Generic simulation model (EMT) with Simscape of a cluster with 3 identical OWFs and an open-circuit implemented at the positive pole of the HVDC line.



Temporal evolutions of active and reactive power at the grid connection point of the OWF cluster

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Conclusions & Outlook

Identified potentially dangerous scenarios for the German/European power grid:

- the FCR limit of 3 GW can be reached and exceeded through a single event
- a combination of 2 events is enough to surpass the FCR limit almost twice

Future work:

- Further numerical simulations of the scenarios
- Quantitative resilience evaluation through the simulation results

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Thank you for your attention!

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Safety, reliability risk assessment, and management of socio-technological system

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