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

Nikolai Kulev, Jannik Klemm, Arto Niemi, Frank Sill Torres

Department for Resilience of Maritime Socio-Technical Systems, Institute for the Protection of Maritime Infrastructures, German Aerospace Center (DLR), Germany. E-mail: Nikolai.Kulev@dlr.de

Offshore wind energy generation with HVDC transmission represents already a critical energy infrastructure in Germany and its share of the German electricity production is expected to rise to above 20 % in 2050. Currently, the corresponding HVDC grid connections points of the offshore wind farm (OWF) clusters in North Sea are in the vicinity of the originating point of the 2006 European blackout. Their capacities are close to the frequency containment reserve (FCR) of 3 GW in the whole ENTSO-E region. Accordingly, a sudden power loss at these points can trigger a wide spread outage within the German or European grid, especially if the FCR limit is violated. Motivated by the above mentioned, we have created a catalogue of high-impact low-probability disturbance scenarios of the OWF cluster infrastructure with HVDC connections in the German North Sea. We present here this catalogue where a single or more HVDC grid connection systems are affected. In this manner the scenarios describe both power losses beneath and above the FCR limit. The catalogue is accompanied by a quantitative characterization of some of the threats which can initiate the scenarios, with a special attention to ship collision with a OWF infrastructure and cable damage through ship anchors or fishing ship nets. Recent events, such as the ship collision with a wind turbine of the Gode Wind 1 OWF in 2023 and the damage of the subsea cable of the EstLink 2 HVDC link in 2024, confirm the validity of these scenarios. In this way, the scenarios can serve for the evaluation and improvement of the power system resilience defined as "the ability to limit the extent, severity and duration of system degradation following an extreme event". A numerical OWF cluster model and a simulation of one of the scenarios are also presented.
Keywords: critical energy infrastructure, offshore wind farm, high-impact low-probability, disturbance, HVDC.

1. Background and motivation

Offshore wind energy generation with HVDC transmission represents already a critical energy infrastructure in Germany and its share of the German electricity production is expected to rise to above 20 % in 2050 (Federal Maritime and Hydrographic Agency 2025). Currently, the corresponding HVDC grid connections points (GCPs) of the offshore wind farm (OWF) clusters in North Sea are in the vicinity of the originating point of the 2006 European blackout (Chunyan, Sun and Chen 2007). Their capacities are close to or of the same magnitude as the frequency containment reserve (FCR) of 3 GW valid in the whole ENTSO-E region (ENTSO-E 2019). Doerpen is above 2.5 GW and Brunsbuetel above 2 GW, respectively. Accordingly, a sudden power loss at these points can trigger a wide spread outage within the German or European grid as mentioned above (Chunyan, Sun and Chen 2007), especially if the FCR limit is violated with multiple HVDC GCPs affected.

Motivated by the above mentioned, we have created and present in this paper a catalogue of high-impact low-probability disturbance scenarios of the OWF cluster infrastructure with HVDC connections in the German North Sea. The catalogue is accompanied by a quantitative characterization of some of the threats which can initiate the scenarios, with a special attention to ship collision with a OWF infrastructure and cable damage through ship anchors or fishing ship nets. Recent events confirm the validity of these scenarios. A ship collision with a wind turbine of the Gode Wind 1 OWF occurred in 2023 (Chen et al. 2026) and the subsea cable of the EstLink 2 HVDC link was damaged in 2024 by the anchor Eagle S (ENTSO-E 2025). In August 2024 four onshore converters (with maximal capacities of 800-900 MW each) of HVDC connections of offshore wind farm clusters in North Sea were shut down by their protection systems due to harmonic instability disturbance (50Hertz et al. 2025).

2. Generic architecture of the clusters of offshore wind farms

The definitions of the disturbance scenarios are based on the characteristics of the generic architecture of offshore wind farms clusters, so we present first this generic architecture in its present state in North Sea. All HVDC grid connection systems of offshore wind currently used are exclusively point-to-point connections (no multi-terminal HVDC connections) with VSC converters (voltage source converters) which are self-commutated, i.e. self-controlled, not grid controlled (He et al. 2025, Gabriel and Jahn 2018). Up to 3 such individual HVDC grid connection systems are bundled at the HVAC side of an onshore converter station, see Figure 1 (Gabriel and Jahn 2018, Bundesnetzagentur 2025). In this way all the energy generated by the clusters in the German North Sea with a maximum value of round 8 GW is fed into the grid only through 4 onshore converter stations (Bundesnetzagentur 2025). The generic architecture of an OWF cluster with its HVDC grid connection system according to the current 900 MW transmission standard consists of the following main system elements (Figure 1):

(i) 1 to 3 offshore OWFs as arrays of offshore wind turbines (OWTs)
(ii) MVAC (medium voltage AC) undersea cables connecting the OWTs among themselves and with the offshore transformer sub-station
(iii) offshore transformer sub-station (OSS) -1 per OWF
(iv) HVAC (high voltage AC) undersea cables from the transformer platform to the offshore converter station
(v) Offshore converter platform
(vi) HVDC export cable (undersea + Wadden sea + island crossing route + land)
(vii) Onshore converter station
(viii) HVAC land cable from the onshore converter station to the grid connection point

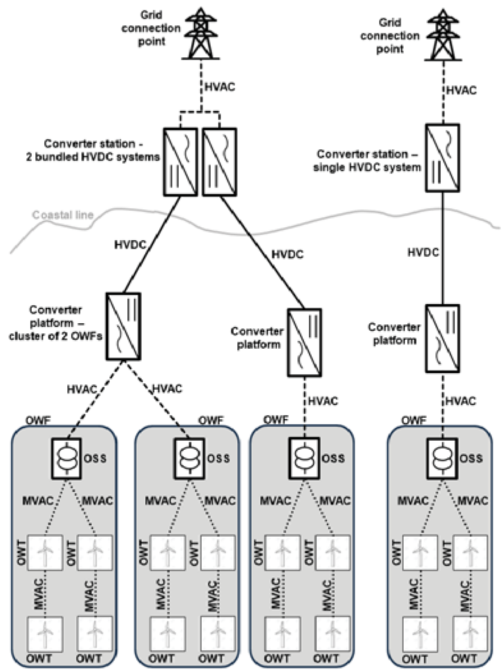

Fig. 1. Schematics of the generic architecture of the OWF clusters. On the left is shown the bundling of 2 HVDC grid connection systems at the converter station belonging to a cluster of 2 OWFs and to a single OWF cluster, respectively. On the right is shown the single HVDC grid connection system of a cluster with one OWF.

3. Quantitative characterization of threats as trigger events of the OWI disturbances

A quantitative characterization of some of threats, which can initiate certain disturbance scenarios, was done in order to show the plausibility of the scenarios. Especially two threats are considered:

(i) Collision threat for the cluster infrastructures (OWTs, OSS, offshore, converter platform) through the shipping and air traffic in the North Sea region
(ii) Undersea cable damage through emergency (or malicious) anchoring or fishing nets

For that purpose, the density of the shipping traffic in the North Sea region was ascertained and presented though specific density maps (Fig. 2). The results represent a quantitative indication for the plausibility of the disturbance scenarios, i.e. the triggering events cannot be not ruled out and a certain likelihood exists.

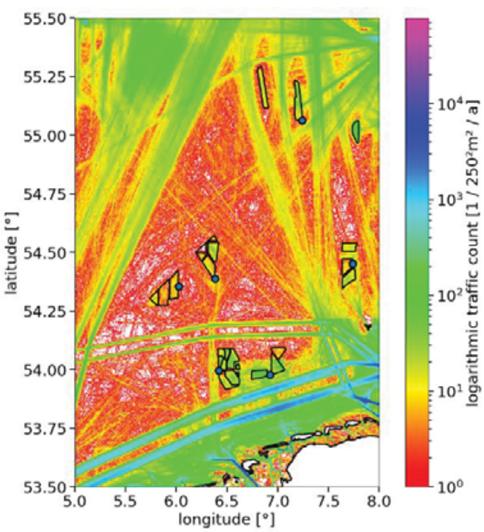

Fig. 2. Density map for the shipping traffic in the German North Sea.

The density maps for shipping traffic are generated by the following procedure using Automatic Identification System (AIS) data from (Lloyd's List Intelligence 2025) for 2020. First, the trajectory points are filtered out when they have a higher time distance to their next and previous trajectory point than 60s. The density map is a summed two-dimensional histogram of all trajectories presented in grid. The grid interval is in this paper in latitudinal and longitudinal direction 50m. If a trajectory is crossing a grid cell, but no point of this trajectory is inside the trajectory, a new point is created by using data of the last point such as the speed. If a two consecutive trajectory points are in the same grid cell, the last one is removed to count only how many ships are crossing this place.

4. Preliminaries to the definitions of the disturbance scenarios of the offshore wind clusters

4.1. *Criticality criteria for the HILP disturbance scenarios*

Since we consider here only HILP (high-impact low-probability) disturbance scenarios we need some criteria for the criticality of these events. The following criteria were determined by the qualitative studies of possible outages/disturbances in offshore wind industry (Gabriel and Jahn 2018):

(i) Loss of more than 1 GW transmitted offshore wind energy or complete loss of transmission capacity (e.g. of single grid connection systems or of a single converter station) within 30 seconds.
(ii) Loss of more than 3 GW offshore wind energy.
(iii) Failures of components with long shut-down/repair times through which the transmission of significant capacities of offshore wind is impaired. (e.g. OSS transformers, converters at the converter platform/station, HVDC/HVAC cables.

As consequence only such scenarios are defined, through which the failure or the impairment of whole OWFs, clusters, cluster bundling or combination is meant.

4.2. *Disturbance scenarios in the context of the dynamical modeling of the OWF clusters*

The disturbance scenarios correspond to certain disturbances (abnormal/erroneous inputs) in relevant dynamical models of the OWF clusters (electrical energy generation/transmission systems with control systems), which cause the failures or impairments. Therefore, the definitions of the scenarios contain also the corresponding disturbances as numerical model inputs.

By the disturbance scenarios some initial damage is caused which in turn the actual disturbance is caused. The following types of the disturbances are considered (Tleis 2019):

- Open-circuit -DC, AC 1-3 phase
- Short-circuit - DC pole-to-pole or pole-to-ground), AC 1-3 phase phase-to-ground
- Parameter manipulation as "false data injection" into the control systems of converter (converter platform or station, OWTs)

5. Disturbance catalogue

5.1. *Single clusters/grid connection systems*

5.1.1. *Short-circuit within the offshore HVAC system*

Causes: Ship collision with the OSS or with the converter platform; Damage of the HVAC cable through anchors, fishing nets; Fire at the OSS; Damage of the isolators due to component failures through aging (e.g. transformers, cables).

Initial Damage: Damage of the isolation of the HVAC cables or deformation and contact of non-isolated conductor surfaces

Impact/Impairment: Shut-down of all OWTs within the OWF through their protection systems due to a violation of operational limits due to the short-circuit. Maximal power loss currently ~ 520 MW.

Disturbance modeling within an OWF-cluster

Model: Short-circuit (1- to 3-phase pole-to-ground) at the corresponding place within the HVAC system (e.g. between OSS-Transformer and HVAC cable, between HVAC cable and converter platform transformer, converter platform transformer and converter).

5.1.2. *Short-circuit within the HVDC system*

Causes: Converter platform: helicopter crash, ship collision, fire in the converters hall.

Converter station: helicopter crash, fire in the converters hall, flooding.

Export HVDC cables: isolator damage through anchor.

Initial Damage: Damage of the isolation of an HVDC cables; Deformation and contact of non-isolated surfaces of the conductors

Impact/Impairment: Shut-down of the converter platform/station through the protection system due to a violation of operational limits due to the short-circuit (and so of the whole HVDC grid connection system). Damage of the power electronics of the converters due to due to the extreme values (currents, voltages) because of the short-circuit. Maximal power loss currently ~ 900 MW.

Disturbance modeling within an OWF-cluster

Model: Short-circuit (pole-to-pole or pole-to-ground) at the HVDC system (e.g. cables, converter terminals)

5.1.3. *Severing of the HVAC submarine cables or of their junctions*

Causes: emergency anchoring or fishing nets; sabotage; helicopter crash or ship collision at the OSS/converter platform

Initial Damage: Damage of the cable conductors or of the cable junctions at the HVAC busbars of the OSS and converter platform

Impact/Impairment: Disconnection of a single OWF within the cluster, Maximal power loss currently ~ 520 MW

Disturbance modeling within an OWF-cluster

Model: Open-circuit at the corresponding places within the HVAC system (e.g. 1- to 3-phase at the HVAC cables or at the busbars)

5.1.4. ***Severing of the HVDC export cables or of their junctions***

Causes: emergency anchoring or fishing nets; sabotage; helicopter crash or ship collision at the converter platform

Initial Damage: Damage of the HVDC cable conductors or of their cable junctions at the converter platform

Impact/Impairment: Disconnection of the whole cluster, Maximal power loss currently ~ 900 MW

Disturbance modeling within an OWF-cluster

Model: Open-circuit at the corresponding places within the HVDC system (e.g. at the HVDC cables or their junctions)

5.1.5. ***Manipulation of the parameter of the control systems of OWTs in an OWF***

Causes: Cyber-attack (e.g. of against the OWF operator, the remote-control center of the OWF or the maintenance company of the OWF)

Initial Damage: Inducement of abnormal values in the offshore MVAC network (especially if the manipulation affects the MVAC-side converter of the OWTs)

Impact/Impairment: Violation of operational limits and therefore shut-down of the OWTs by their protection systems; Maximum power loss currently ~ 520 MW.

Disturbance modeling within an OWF-cluster

Model: ”False data injection” as values of the control parameters in the OWTs.

5.2. ***Cluster bundling/combinations (several grid connection systems affected)***

5.2.1. ***Loss of a pair of converter platforms***

Causes: ship collision, plane crash; sabotage

Initial Damage: Damage of conductors and components

Impact/Impairment: Loss of bundling of 2 clusters at the same converter station; Power loss currently: 1.2 GW -1.7 GW

Disturbance modeling within an OWF-cluster

Model: Open-circuit in the HVDC system at both converter platforms (e.g. between converter and HVDC cable)

5.2.2. ***Loss of function of a whole converter station (all corresponding grid connection systems affected)***

Causes: plane crash, flooding, sabotage, vandalism

Initial Damage: Damage of conductors and components in all HVDC grid connection systems or within the joint HVAC system (switch yard)

Impact/Impairment: Loss of all bundled HVDC grid connection systems or of the joint HVAC system (switch yard); Power loss currently > 1 GW, Maximal power loss currently ~ 2.5 GW.

Disturbance modeling within an OWF-cluster

Model: Open-circuit at corresponding places - DC in all HVDC systems (e.g. HVDC cables or junctions to converters) or AC (e.g. between HVAC connection to the onshore grid transformer station)

5.2.3. ***Severing of several HVDC connections (single event)***

Causes: emergency (or malicious) anchoring in undersea HVDC cable corridors, plane crash or sabotage at an island HVDC cable tract.

Initial Damage: Damage of cable conductors (sea bottom/land) or the cable joints (boxes) on land

Impact/Impairment: Loss of several not bundled clusters or of a cluster bundling (onshore). Maximal power loss by cluster bundling ~ 2.5 GW. Maximal power loss currently by damage of a land cable tract ~ 3 GW. Maximal power loss currently by damage of an undersea HVDC cable within a corridor ~ 3.9 GW.

Disturbance modeling within an OWF-cluster

Model: Open-circuit at the corresponding place of HVDC cable

5.2.4. ***Short-circuit within the HVAC system of the onshore converter station***

Causes: fire, flooding, vandalism, drone-attack; isolators failure due to component failures through aging (e.g. transformers, cables).

Initial Damage: Damage of the HVAC cable isolation or deformation and contact of non-isolated conducting surfaces

Impact/Impairment: Shut-down of the converters by the protection system due to the violation of operational limits, damage of the power electronics; abnormal values propagating into the onshore transmission grid. Maximal performance loss currently ~ 2.5 GW.

Disturbance modeling within an OWF-cluster Model: Short-circuit (e.g. 1- to 3-phase phase-to-ground) at the corresponding place within the HVAC system.

5.2.5. ***Manipulation of the parameter of the control systems of all converters at an onshore converter station (all HVDC grid connection systems affected)***

Causes: Cyber-attack (converter station, remote-control center of grid operator)

Initial Damage: Abnormal values within the HVDC system or also within the HVAC system, disturbance of operation of all converters

Impact/Impairment: Loss of whole converter station, abnormal values propagating into the onshore transmission grid; Maximal performance loss currently ~ 2.5 GW.

Disturbance modeling within an OWF-cluster Model: ”False data injection” as values for the control parameters for all converters

5.2.6. ***Loss of a converter station & severing of several unrelated HVDC connections (combination of 5.2.2. & 5.2.3 triggered by two separate events)***

Causes: Combination of 5.2.2. & 5.2.3.

Initial Damage: Combination of 5.2.2. & 5.2.3.

Impact/Impairment: Loss of several clusters or of onshore bundlings of clusters; Maximal power loss currently if a land cable tract is affected ~ 5 GW, Maximal power loss currently if an undersea HVDC cable corridor affected ~ 5.9 GW.

Disturbance modeling within an OWF-cluster Model: Combination of 5.2.2. & 5.2.3.

5.2.7. ***Loss of a pair of converter platforms & severing of several unrelated HVDC connections (combination of 5.2.2. & 5.2.3 triggered by two separate events)***

Causes: Combination of 5.2.1. & 5.2.3.

Initial Damage: Combination of 5.2.1. & 5.2.3.

Impact/Impairment: Loss of several clusters or of onshore bundlings of clusters; Maximal power loss currently if a land cable tract is affected ~ 4.3 GW, Maximal power loss currently if an undersea HVDC cable corridor is affected ~ 5.2 GW.

Disturbance modeling within an OWF-cluster Model: Combination of 5.2.1. & 5.2.3.

6. Discussion

The scenarios represent the increase of the power loss at the grid connection points in relation to the disturbance severity in a qualitative manner. The scenarios with the smallest severity would lead to a performance loss only of a single OWF. More severe scenarios can affect a whole cluster of OWFs whereas the most severe scenarios impair combinations of clusters or the bundling of clusters at an onshore converter station. This correlation between the degradation/impairment of the OWF clusters and the disturbance severity/characteristics can help the evaluation of the resilience of the cluster systems to the scenarios, given the CIGRE definition of power system resilience as “the ability to limit the severity and duration of system degradation following an extreme event” (Ciapessoni, E., et al. 2023).

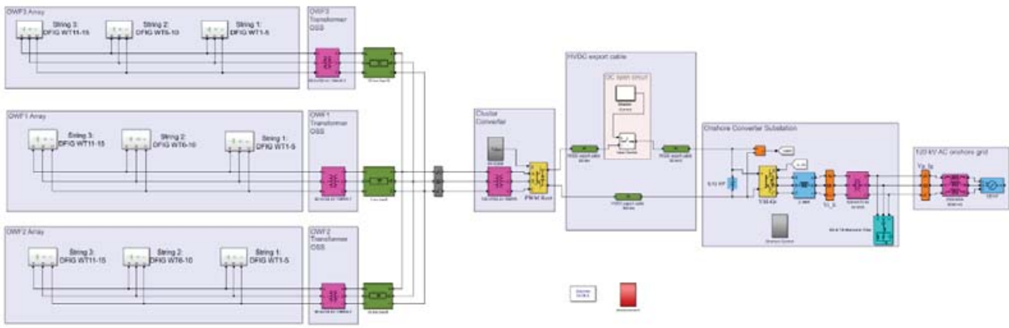

Fig. 3. Generic simulation model of a cluster with 3 identical OWFs and an open-circuit implemented at the positive pole of the HVDC export cable. From left to right: each OWF array connects 3 strings with MVAC cable and each string aggregates 5 OWTs (each OWT with 1.5 MW). Every OWF array is connected through MVAC cables to the OWF transformer OSS, which in turn connected through HVAC cables (10 km,1 km and 10 km) to the offshore converter platform. 100 km HVDC export cables connect the offshore converter platform to the onshore converter station. The onshore converter station is connected via HVAC to the onshore grid.

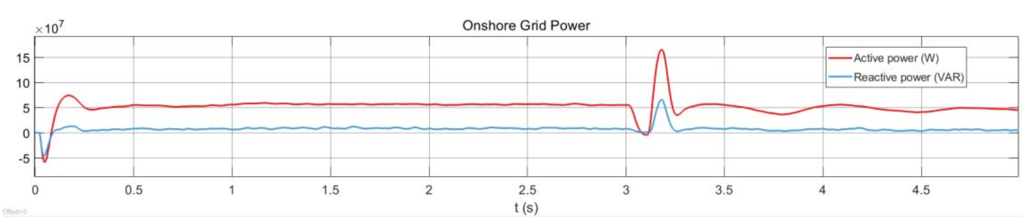

Fig. 4. Temporal evolutions of active and reactive power at the grid connection point of the OWF cluster by open-circuit disturbance

On the other hand, the disturbance scenarios can help the evaluation of the resilience of the power grid to which the OWF clusters are connected. Since the minimum FCR available at all times is 3 GW, ensuring the frequency stability within the continental European synchronous area (ENTSO-E 2019) the scenarios with a power loss close to or especially above this value can be problematic and can cause a non-resilient behaviour (power outages) within the German/European power grid. The scenario described in section 5.2.3 causes a disturbance where FCR limit is reached and exceeded through a single event, which calls for dedicated countermeasures in terms of preventing or at least minimizing the degradation. Besides this Scenarios 5.2.6. and 5.2.7. show that a combination of 2 events is enough to surpass the FCR limit significantly (almost twice in the case of 5.2.6.) which can trigger wide-area outages or even blackouts within the German or even the European power grid. Again, any effective countermeasures against these two scenarios, as mentioned above, would lead to an improvement of the resilience of the power grid.

7. Initial simulation of the scenarios

Here we present a quantitative characterization of the scenario 5.1.4 through a simulation of the corresponding disturbance in an EMT (electro-magnetic transients) model of an OWF cluster, Figure 3. For this we have used the Simscape™ Electrical™ Specialized Power Systems within the MATLAB/Simulink environment (Perelmuter 2016). The overall transient behavior and extreme values must be thereby considered through which the impairment is caused according to the criticality criteria in Section 4. An open-circuit was implemented in in the middle of the HVDC cable a single HVDC transmission system without bundling of the positive pole of the HVDC cable (Figure 3). The open-circuit starts at t = 3 s and has a duration of 0.1 s. It is apparent from Figure 4 that the drop of the power fed into the onshore grid to a zero value (i.e. total power loss) occurs very fast within 0.2 s. This simulation result shows in a quantitative way the fulfilment of the first criticality criteria (i) in Section 4.1., which justifies the validity of the scenario.

8. Conclusions and Outlook

We presented in this paper a catalogue with disturbance scenarios of the OWF clusters in the German North Sea. Additionally, we presented quantitative characterization of some of threats initiating the scenarios, expressing the credibility of the scenarios. The scenarios express the increase of the power system degradation and power loss through the variation of the severity and type of the disturbing event. We identified potentially dangerous scenarios for the German/European power grid where the power loss from the OWF clusters due to scenarios reaches or exceeds (even significantly) the current FCR value.

As a future work we intend to extend the quantitative investigation the scenarios presented in Section 7 similarly to (Kulev and Torres 2022). Based on the simulation results a quantitative resilience evaluation will be done.

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