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# Vulnerability Assessment of the Offshore Wind Farms by Using the Functional Resonance Analysis Method

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The German authorities have imposed a legal requirement to expand offshore wind energy generation to a total capacity of 70 GW by the end of 2040, making it a critical source of energy supply. The Europe-wide power outage in 2006 was caused by a poorly planned disconnection of an extra-high voltage line is a good example of the consequences when the energy supply is interrupted. In these kinds of events, intervening promptly and appropriately could be challenging due to the location of the incident. Furthermore, maintenance and repairs can take a long time due to the special technical equipment and thus may limit energy supply during the course of a failure. Apart from that, attacks or accidents can also occur at various places in the infrastructure and may have a wide range of damaging effects. This study presents a method to identify the most vulnerable functions of an Offshore Wind Farm (OWF) whereby the analysis is carried out in two distinctive phases. In the first phase, a Functional Resonance Analysis method (FRAM) is carried out to visualize the wind generation process starting from wind flows to power generation, power transmission and to the onshore substations. In the second phase, a vulnerability assessment using the Krings method is conducted whereby additional factors such as the effect of failures and downtimes are considered in order to define vulnerabilities. The results of this assessment are then compared with vulnerability perceptions of stakeholders in the offshore wind energy sector based on interviews. The study finds that industry stakeholders tend to overrate the vulnerability of offshore wind turbines while the FRAM model indicates a higher vulnerability for offshore platforms.

*Keywords*: Offshore Wind Farm, Critical Infrastructure, Vulnerability Assessment, Sea Cable.

## 1. Introduction

Offshore Wind Farms (OWFs) are essential for German energy supply (The Federal Government of Germany 2022). A wind farm consists of several wind turbines that are used to generate electricity. The wind required for this is more reliable offshore than on land (Hau 2014). The Federal Republic of Germany intends to install 70 GW of offshore wind energy capacity by the year 2040 (The Federal Government of Germany 2022). Due to their increasing importance for the security of electrical supply and their growing energy performance, OWFs are considered critical infrastructures (CI) that require special protection. Incidents related to cables damages in the Baltic Sea show how vulnerable such infrastructures are and how failures can affect the economy and civilian population (Jochecová 2025). CI depends on various technical and physical variables that are considered as necessary resources for infrastructure operations. In addition to wind, these include other control and safety equipment (E. Hau 2014). Yet in order to better protect OWFs effectively, one first needs to identify their most vulnerable components, areas, and processes.

This study conducts a formal vulnerability assessment of offshore wind farms based on a Functional Resonance Analysis method (FRAM) and Krings' methods (Krings 2013). The results of this model are then compared with vulnerability perception of stakeholders in the offshore wind sector collected based on interviews.

The paper is organised as follows. The main components of an OWF and their significance for the infrastructure are explained in the Section 2. The process of assessing the vulnerability is explained in Section 3. Followed by results and conclusions in Section 4 and Section 5, respectively.

## 2. Offshore Wind Farm (OWF)

In 2024, a total of 29 OWF were operational in Germany. This includes 24 OWFs with a capacity of 7.3 GW, generated by 1,324 wind turbines, in the North Sea, and 5 OWFs with 278 wind turbines and a capacity of 1.5 GW in the Baltic Sea (Deutsche Windguard GmbH 2024).

Similar to onshore wind farms, each OWF requires an Offshore-Substation (OSS), where the incoming energy from the wind turbines is bundled, transformed, and transmitted to land via a cable. However, the standardised alternating current (AC) transmission is less economical compared to high-voltage direct current (HVDC) transmission due to the capacitive load from a length of more than 50 kilometres. Therefore, a HVDC platform is required after the OSS, which includes a converter station to enable transmission. Several wind farms and their OSSs can be connected to one converter station. The wind turbines connected via an OSS are referred to as a cluster (Hau 2014). In upcoming projects, it is planned to integrate the OSS and the HVDC platform into one platform with a capacity of 2 GW (TenneT TSO GmbH 2023).

### *2.1. Wind turbine (WT)*

The process in the wind turbine is characterised by several steps in a linear sequence. When power demand is present and the WT is to be switched on, the pitch system regulates the blade position so that the blades move to the load position. The wind then is applied on the blades and sets the rotor in motion. The rotor on the hub is connected directly to a shaft, which is connected to the gearbox or directly to the generator. In the case of a gearless wind turbine, there is no second shaft between the gearbox and generator (direct drive). Up to this step, all components in the wind turbine are mechanically connected to each other. The electricity production depends on the wind speed. The generator has an energy loss in the form of heat, which must be dissipated via a cooling system (E. Hau 2014). Within the WT, the medium voltage must be smoothed and changed to a usable frequency of 50 Hz by using two converters. The converters are not necessary if the system has a generator and gearbox that operate at a fixed speed (asynchronous generator), but this type is now only used in a minority of cases (Bundesverband WindEnergie e.V. n.d.).

### *2.2. Inner Grid*

This subsection briefly describes the inner grid which is the connection between the WTs and the OSS by an AC cable connection in the range of 20 kV to 36 kV. The connection of the WTs to the OSS can have different types of connection, such as ring connection or series connection (see figure 1).

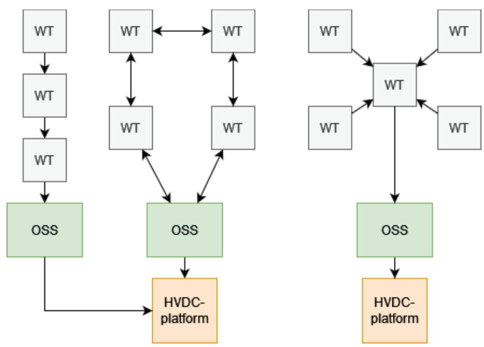


Fig. 1. Different OWF connections. From left to right: Series connection of WTs to an OSS; ring connection to an OSS. Both OSSs connected to a common HVDC platform; star connection to an OSS via a central WT.

It is well-known that a ring circuit provides the highest security of supply, as the energy can still be transmitted in the other direction if there is a line fault. With a series and star connection, there is always a loss of power in the event of a line fault in a line between two WTs. In the case of a star, either a single WT is disconnected or the entire power is lost in the event of a line fault between the central WT and the OSS. If the series connection is interrupted, total power of followed WTs are lost (Hottmann n.d.). In today's OWFs in the North Sea, the connection of WTs to the HVDC platform is via OSS (except three OWFs). However, in upcoming OWF projects, the wind turbines will be connected directly to the HVDC platform using 66 kV AC cables (TenneT TSO GmbH 2023)

### *2.3. Platforms*

The OSS and HVDC platforms are of central importance for offshore wind farms. They are central points in the grid where the power lines are bundled and then the energy is transmitted to the transmission grid. Some of the platforms are staffed, so that timely intervention is possible in the event of repairs and incidents. The HVDC-platform and the OSS require large electrical systems for their essential function. This includes for example transformers and busbars in the switchgear for the cable connection and cable outlet (Robak and Raczkowski 2018).

#### *2.3.1. Offshore-Substation*

The Offshore-Substation is a central part of each OWF. All WTs of an OWF are connected to an OSS, which receives the power and exports it to the external grid. The OSS transforms the medium voltage of the inner grid into transmission voltage of 155 kV. In the Baltic Sea a voltage level of 220 kV is used. There will be no current conversion happening in the OSS (Robak and Raczkowski 2018).

#### *2.3.2. High voltage direct current platform*

The main task of a HVDC platform is to first transform the input voltage to a higher voltage level of 320 kV and then convert the voltage from AC to DC using a converter (Robak and Raczkowski 2018). A cooling system is essential for this process, as there is a high heat dissipation in the components due to power losses. Without the cooling system, HVDC-platform components would overheat and needed to so be switched off.

### *2.5. HVDC-link*

The cable connection to the coast is designed with two cables (positive and negative poles). One HVDC platform has transmission capacity of 2 GW, with a transmission voltage of 525 kV. These cable systems are designed with three cables, two pole cables and a return conductor. If one pole cable is interrupted, transmission will be reduced by 50 % yet continue through the return conductor (TenneT TSO GmbH 2023). Table 1 lists the different cables in an OWF and their respective transmission voltages. The higher the transmission voltage, the more energy is transmitted and the higher the protection rating of the cables.

Table 1. Variations of grid connections inside an OWF.

| Grid connection | Trans-mission voltage | Curr. type |
|---|---|---|
| WT to OSS | 33 kV | AC |
| WT to HVDC-Platform (next generation) | 66 kV | AC |
| OSS to HVDC-Platform | 155 kV | AC |
| OSS to Onshore Substation | 110 to 220 kV | AC |
| HVDC-Link (state of the art) | 320 kV | DC |
| HVDC-Link (next Generation) | 525 kV | DC |

## *3. Methodology*

This section describes the methodologies that is used in the present study to carry out vulnerability assessment. There are various ways of carrying out a vulnerability assessment. Vulnerabilities are a result of dependencies within a system, among other things. These dependencies can be identified using the functional resonance analysis method. In this work the FRAM is used to visualise the process from electricity generation in the WT to onshore grid feed-in with its dependencies. The process is a sequence of several steps that represent various functions. These functions are then be evaluated with regards to their vulnerability.
Finally, the results from this vulnerability assessment will be compared with industry stakeholder assessment collected through expert interviews in the OWF sector with the perspective of industry stakeholders.

### *3.1. Procedure*

The evaluation of the FRAM model is carried out in three steps. First, the FRAM model for the OWF is created and verified using various expert interviews while its feasibility is verified with the help of a software solution. The functions are then evaluated, considering the dependencies from the FRAM. Insights from the interviews are used to identify vulnerable areas and to compare expert stakeholder assessments with the FRAM evaluation.

### *3.2. Functional resonance analysis method)*

A FRAM model enables the analyst to visualize a socio-technical system and its links to different functions. The execution of functions is linked to various inputs and outputs. In the model, these functions are hexagons in which one of six aspects of the function can be attached to each corner (see figure 2) (Hollnagel 2012).

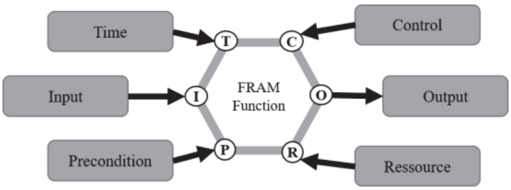


Fig. 2. Abstract depiction of a function in FRAM.

- Input (I): what the function processes or converts or what starts the function.
- Output (O): the result of the function, either an entity or a change of state.
- Preconditions (P): conditions that must be fulfilled before a function can be executed.
- Resources (R): what the function needs when it is executed (execution condition) or what it consumes to produce the output.
- Time (T): time constraints that affect the function (in terms of start time, end time or duration).
- Control (C): how the function is monitored or controlled

Moreover, the functions in the FRAM model can be divided into five different types. The foreground functions are the main functions in FRAM. A status change takes place within these functions. The foreground function requires an input and a further input aspect, otherwise it is only a pass-through function. An entry function only generates output, which must be connected to an input of another function. In addition, the output can also be linked to other functions as another aspect. Background function only generates outputs which a linked as control, time, precondition or resource. The exit function is the end of a process that only has an input (Hollnagel 2012).

### 3.3. *Vulnerability assessment methods*

To determine vulnerability in a model, a suitable method must first be selected. The Holmgren method cannot be used with the FRAM model as the analysis of vulnerability is dependent on empirical data to determine the probability of negative effects (Holmgren 2007).
Krings' method is based on points of exposure, susceptibility, and the coping capacity of systems (Krings 2013). The vulnerability of a system component can be determined depending on these three assessment criteria. The scheme is an algorithm with five questions. The end of the algorithm is always the categorization into one of five vulnerability classes. There are different scenarios which can occur in systems. These include but are not limited to accidents, attacks and technical failures that cause damages. But a scenario can just affect one element while not affecting another element at all. The different scenarios that are selected with the aim of emulating a process that would result in a damage or an interruption. Note that wear failures have not been considered in this assessment. According to Krings, the five classes of vulnerability are defined as follows (Krings 2013):

(i) Class I: No exposure of an impact for a part of the infrastructure
(ii) Class II: No functional susceptibility of a component to the existing exposure.
(iii) Class III: Replaceability in technical and organisational terms is given
(iv) Class IV: Technically only partially replaceable. Organisationally replaceable
(v) Class V: Technically or organisationally irreplaceable

However, since this method does not address the effects of a system failure, it must be supplemented by other assessment approaches. Krings' method is therefore supplemented by partial aspects of Baker's method that relate to a cascade effect and the failure effect. (Baker 2005).
An additional assessment factor outside the two methods is the mean time to repair (MTTR), which describes the time required for a repair. The MTTR therefore describes a minimum downtime without taking delivery times into account. The MTTR, should be as short as possible for a resilient system. Vulnerability is determined for all functions that are in the core process. Some functions are not assessed as they are identical to other functions or their vulnerability is a result primarily from a background function. Identical functions exist in particular for the control and safety systems.

### 3.4. *Interviews*

Interviews are an efficient method of gaining direct insights, perspectives and experiences from experts. There are three main types of interviews: structured, semi-structured and unstructured interviews.

Structured interviews have an identical interview guide, while unstructured interviews are conducted freely and can vary in their focus. The analysis can be quantitative or qualitative. The quantitative analysis allows a simple counting of answers, while the qualitative analysis generates different answer categories with a higher level of detail. (Mayring and Fenzl 2019).

## 4. *Evaluation*

This section evaluates the vulnerability of an OWF using the methods described in section 3.

### 4.1. *FRAM of an OWF*

The model is based on a 0-state, so all states are initially undefined. The grid operator's detection of the electricity demand is selected as the starting point and the onshore grid feed-in is defined as the end. The process of power generation in the WT, power transmission to the OSS and then to the HVDC platform and to the onshore connection is initially set up linearly with connections between the input and the output. Furthermore, 27 functions are created for the process that contains physical changes or performs transfer functions. These are then followed by functions that are connected to precondition, control, time and resources.
For example, both platforms require a cooling system as an essential resource, and the control function is realised with a control unit in each case. The interaction between the control unit and the cooling system also generates a relationship for both systems so that the two functions are also created as a main function with further dependencies. Further functions can be found in the ongoing development and in other external factors that affect the system and thus represent further entry functions. End functions that do not represent the intended process output are also included.
In total, 121 functions are in the final FRAM model. There are 63 main or passthrough functions, 8 entry function, 4 exit functions and 46 background functions. These functions were then divided into four categories (network, cables, platforms and WT)

#### 4.1.1. *Entry and Exit functions*

As mentioned above there are 8 entry functions in the model. In addition to the grid operator function, which monitors the grid and electricity demand, there are other start-up functions. These intuitively include the OWF operator, who monitors the wind farm and turbines, and the wind, which acts on the rotor and affects the wind sensors. Other sensors that are considered start functions, due to their arrangement in the system, are the vibration sensor of the WT and the sensors or data for cable monitoring. The sensors supply the data for the System Control and Data Acquisition (SCADA) system and cable monitoring and are the input for the functions. The other WT and OSS functions are positioned so that they indicate that further devices can be connected to the system and are by definition input functions.
Four functions are defined as exit functions. The exit functions do not only cover the planned positive output of the grid feed-in, but also negative outputs.

(i) Failure of a WT:
(ii) Partial power failure in the OWF due to several WT failures
(iii) Critical infrastructure disrupted: Power transmission from one or more OWF is no longer possible.
(iv) Grid connection

### 4.2. *Vulnerability*

The vulnerability assessment according to Krings followed the algorithm with the questions of exposure, susceptibility and replaceability. In addition, the questions of a cascade effect, the failure effect and the duration of the failure were considered for all the main functions within the FRAM.
The five vulnerability classes by Krings can be represented as a numerical value (Eg. (1)).

$$V_K \in \mathbb{N}\,[1;5] \qquad (1)$$

The cascade effect is either present or absent in the valence, so that the valence range is defined as in (Eg. (2)).

$$C_E \in \{0;1\} \qquad (2)$$

The failure effects cannot be described directly as a mathematical expression. It is possible to express the power loss in terms of the actual power loss. However, all OWFs should be comparable with this vulnerability assessment. The failure effects are classified as an integer like the level of failure (Eg. (3)).

$$F_E \in \mathbb{N}\,[1;5] \qquad (3)$$

(i) Failure of one Wind turbine
(ii) Failure of WTs grid connections
(iii) Failure of the whole OWF energy
(iv) Failure of an OWF-Cluster (*Not possible for coastal OWFs without a HVDC-platform*)
(v) Failure of more than on OWF-Cluster

The MTTR is also included as an evaluation criterion and converted into days (*d*). As the values are highly scattered, value ranges are defined from which a natural number can be derived (Eg. (4)).

$$F_t = \begin{cases} 1\ if\ d < 7 \\ 2\ if\ 7 \leq d < 30 \\ 3\ if\ 30 \leq d < 90 \\ 4\ if\ 90 \leq d < 365 \\ 5\ if\ d \geq 365 \end{cases} \qquad (4)$$

There is no generally valid formula for calculating the overall vulnerability that includes the factors considered here. It does not make sense to create a generally valid formula here, as it is not possible to verify and validate such a formula. Therefore, a categorisation is made here with if-then functions. The functions can be mapped algorithmically in 250 possible combinations of the four variables. The vulnerability classes must therefore be clearly and individually reclassified. The key factors here are the vulnerability class according to Krings, which indicates no signs of failure up to level 2, and the failure effect as a key factor from level 3, as this is where there is a disruption to the critical infrastructure. The new vulnerability class is then defined as $R_A$ with a range from 0 to 5. Table 2 shows examples of the analyses for different functions.

Table 2: Vulnerability assessments of various functions from the FRAM

| Cat. | Function | Exp. | Susp. | replacea. technical | repl. org. | $V_K$ | $C_E$ | $F_E$ | $F_t$ | $R_A$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Cables | Inner Grid | Yes | Yes | Yes | Yes | 3 | 0 | 2 | 3 | 2.5 |
| Network | SCADA-System | Yes | Yes | Yes, partly | Yes | 4 | 1 | 3 | 3 | 4.5 |
| Platform | HVDC-platform | Yes | Yes | No | | 5 | 1 | 5 | 5 | 5 |
| Platform | Cooling syst. HVDC-pl. | Yes | Yes | Yes, partly | Yes | 4 | 1 | 4 | 1 | 4 |
| Platform | Cable outlet OSS | Yes | Yes | No | | 5 | 0 | 3 | 2 | 4 |
| WT | Rotor system | Yes | Yes | No | | 5 | 1 | 1 | 1 | 2.5 |
| WT | Shaft | No | | | | 1 | 1 | 1 | 2 | 1 |

### *4.3. Interviews*

As a part of the research project ARROWS (German Aerospace Center n.d.), various stakeholders active in the offshore wind sector were interviewed. A total of 15 people was interviewed with a guideline-based interview. The interviews were conducted partly in person and partly online. The interviews were recorded for subsequent processing. The interviewees were officials in authorities and organisations with security tasks, operators, insurers and direct marketers. Other interviewees were working directly in the wind farms as occupational safety specialists, design engineers or medical specialists. The exact interview question was "*Which areas of the OWF or the platforms and the entire offshore system do you consider to be the most critical or most vulnerable?*"

#### *4.3.1. Interview results*

In all interviews, there were answers to the question regarding the vulnerable areas. The most frequent mentions were related to wind turbines and platforms (24 in total). The digital infrastructure and cable systems were only mentioned 11 times in total. Most of the mentions were not specified, but referred to the facilities in general terms. However, in the case of the WT, 8 out of 13 mentions related to components of the turbine housing. Out of these, four referred explicitly to the rotor and three to the gearbox. Two mentions of the WT were related to the foundation structure.

For the most part, reference to the platforms were unspecific and did not indicate any specific distinction between an OSS and HVDC platform, therefore it was not possible to differentiate between them. Specific mentions were only made about the cooling system (four times) and the safety system of the platforms. The cable system and IT network infrastructure were also mentioned, but no subcategories were specified here. The cable system was referred to 6 times and the IT network 5 times.

### 4.4. *Comparison of the results*

In order to compare the answers of the categories in the interviews with the actual vulnerabilities, a network diagram is shown in Fig. 3. The diagram is aligned in such a way that any relationship between number of references and vulnerability is visible. The value range is displayed linearly and the range is defined from 0 to 5. These are mapped one-to-one to the vulnerability values and the relative frequency between 0 and 1 on the scale.
The categories are analyzed in individual steps where each category considers all functions that can be assigned to it. The same applies to the sub-categories. The subcategories are as follows:

- WT: Rotor, turbine and gearbox (also included in the turbine)
- Platforms: Cooling system and support systems

Fig. 3 shows that vulnerability is overestimated for WT and turbines because the number of references in interviews is higher than the level of vulnerability indicated in the formal models. In contrast, there is an underestimation for the cable, network and platform categories.

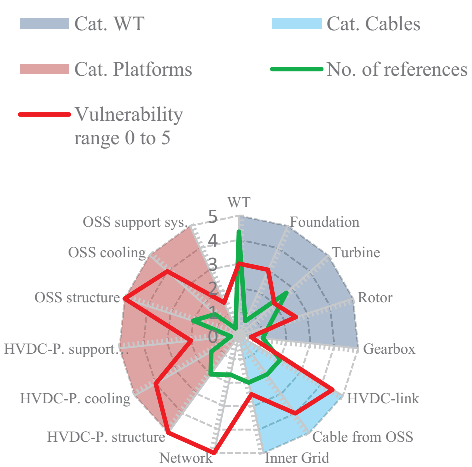


Fig. 3. Comparison between interview results and vulnerabilities of the functions

FRAM can be used to simplify a complex infrastructure system. The level of detail is variable and must be defined in advance. However, the dependencies and logical processes can already be recognized at a simple depth. Each connection represents a process step and can be disrupted if the function cannot be performed. It is clear that the platforms are a bundling of energy and their transmission cables are particularly worth protecting, as their failure always means a supply failure. Redundancies in components such as multi-terminal connections are still being planned and can reduce the vulnerability of a line failure. The interviews have shown that the focus is primarily on the WT. However, the failure of individual WTs or partial lines can be easily compensated for. The focus should be placed in particular on the platforms and external connections. The possibility of cyber-attacks must also be considered more clearly.

### 4.5. *Discussion*

A problem with the questions on the critical areas was that some of the answers related not only to the vulnerable areas (security), but also to occupational safety. In the 15 interviews, 35 codes were categorized for the vulnerable areas and 43 codes for the area of occupational safety. Out of the total of 78 codes, 50 codes were related to WTs, which corresponds to a share of 64.1%. The analysis of the interviewees also revealed that only two of the interviewees assume direct responsibility for the platforms. Most of the interviewees were responsible for construction, maintenance and rescue in WTs. The other interviewees came from the land-based authorities and organizations with security and rescue tasks and from insurance companies.
The results should be viewed critically. Many WTs are represented in the OWFs. In a theoretical assumption that the platforms and the WTs have an identical relative failure rate of X, the absolute failures are significantly higher for the WTs due to their totality. This can give the subjective impression that the WTs are much more vulnerable.

## 5. *Conclusion*

In this paper, Vulnerability assessment of the offshore wind farms by using FRAM is carried out. A visualization has been done of the process starting from wind flow to the power generation then over the transmission and to the onshore substations. Then a vulnerability assessment using Krings' method is conducted, whereby additional factors such as failure effects and downtimes are considered in order to define vulnerabilities. Finally, these results were compared with vulnerability perception of stakeholders in the offshore wind energy sector, which were collected from interviews. From this comparison, it can conclude that the interview participants tend to overrate the vulnerability of the offshore wind turbines while the FRAM model indicates a higher vulnerability for the offshore platforms.

## *6. Acknowledgement*

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