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TECHNICAL PAPER

Failure analysis of spar buoy floating offshore wind turbine systems

Mahmood Shafiee[1]

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Abstract

Floating offshore wind energy is a new form of marine renewable energy which is attracting a great deal of attention worldwide. However, the concepts of floating offshore wind turbines (FOWTs) are still in early stages of development and their failure properties are not yet fully understood. Compared to bottom-fixed wind turbines, FOWTs are subject to more extreme environmental conditions and significant mechanical stresses which may cause a higher degradation rate and shorter mean-time-to-failure for components/structures. To fill the research gap, this paper aims to conduct qualitative and quantitative failure studies on an OC3 spar-type FOWT platform with 3 catenary mooring lines. The failure analyses are performed based on two well-established reliability engineering methodologies, namely, fault tree analysis (FTA) and failure mode and effects analysis (FMEA). The most critical FOWT components are prioritized according to their failure likelihood as well as the risk-priority-number. Our results show a good agreement between the two methods with regard to failure criticality rankings. However, some differences between the results are also observed that are attributed to the difference between FTA and FMEA methodologies as the former incorporates the causes of various failure modes into analysis, whereas the latter is mainly adopted for a single random failure analysis. The results obtained from the FMEA study for the FOWT system will also be compared with those reported for bottom-fixed offshore wind turbines and some interesting conclusions are derived.

Keywords Failure analysis · Floating offshore wind turbine (FOWT) · Materials and structures · Mooring system · Fault tree analysis (FTA) · Failure mode and effects analysis (FMEA)

Introduction

The development of renewable wind energy was initially stimulated in the 1970s due to the increase in fossil fuel prices as well as rising concerns about energy security. It was supported later on by the need to reduce greenhouse gas emissions and the potential to mitigate the effects of climate change [1]. Currently, there are various wind turbine models with rated power ranging from 100 KW up to 15 MW that are manufactured to convert wind energy into electrical energy in an eco-friendly way. The wind turbines are installed either onshore (on land) or offshore (at sea). Offshore wind turbines have gained more attention than onshore wind turbines across the world in recent years. This is mainly because the offshore wind resources are abundant, stronger, and blow more consistently than land-based wind resources. In addition, offshore wind turbines are more visually appealing and less noisy than onshore wind turbines [2].

Currently, most offshore wind farms have been constructed using conventional fixed-bottom substructure technologies (such as monopile, tripod and jacket) within a few miles of the coastline in shallow waters (up to 50 ms water depth) [3]. In order to take advantage of the greater wind resources and wider open spaces further away from the coast, offshore wind turbines require to be sited in regions of deeper water. Floating offshore wind technology is regarded as an ideal solution for locations at water depths between 50 and 200 m [4]. Floating offshore wind energy is anticipated to have a significant growth in the near future. Out of all the continents in the world, Europe is at the forefront of floating offshore wind technology in the world. Figure 1 shows the ongoing and forecasted capacity of offshore floating wind installations in different parts of the world, including Europe, Asia, and Americas. As shown in the figure, the global installed capacity of floating offshore wind energy is anticipated to reach about 13 GW by 2030.

✉ Mahmood Shafiee
m.shafiee@kent.ac.uk

[1] Mechanical Engineering Group, School of Engineering, University of Kent, Canterbury, UK

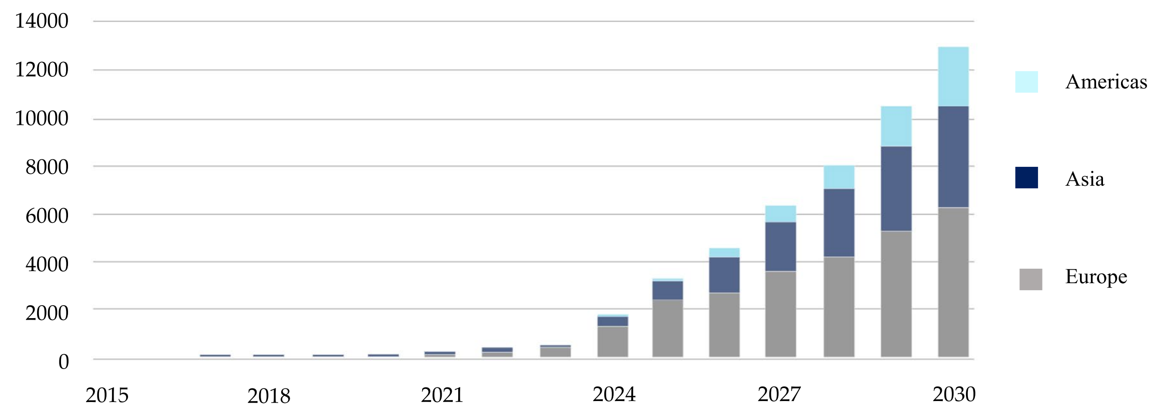

Fig. 1 The predicted offshore floating wind energy capacity in MW [5]

Up-to-date, a number of floating offshore wind technologies such as Hywind, WindFloat and Floatgen have been prototyped and the industry has made good progress with pilot programs to test these technologies in controlled environments [6]. Many research programs have aimed at optimizing the manufacturing and maintenance processes to improve floating offshore wind energy generation; for example, the readers can refer to [7–11]. Hywind is the first megawatt-scale floating offshore wind project which was commissioned by Statoil (currently Equinor) in October 2017. The wind farm is located 25 km off the coast of Aberdeenshire in Scotland. It consists of five 6 MW floating wind turbines which provide power to more than 20,000 households. Each of the wind turbines is mounted on a spar-buoy type platform which is moored by three catenary chains to the seabed [12].

In spite of all recent developments, the technologies of floating offshore wind turbines (FOWTs) are not yet mature enough and their failure properties are not yet fully understood [13]. The future growth of floating wind power is heavily reliant on the failure performance of systems and their components throughout the lifecycle. Compared to bottom-fixed wind turbines, FOWTs are subject to more severe loads caused by wind, waves, current, tides, etc. The severe loading conditions in deep waters can lead to structural defects and an associated higher failure risk and/or shorter mean-time-to-failure for components. An unexpected failure in FOWTs may result in undesirable consequences such as reduction in electricity production, loss of asset, or even more catastrophic events such as personal injuries or loss of life of personnel. Early detection of potential failures and taking appropriate remedial measures for eliminating their causes can help wind farm managers save operation and maintenance (O&M) costs [14].

A brief review of the literature shows that very few studies have been carried out to evaluate various failure mechanisms associated with FOWTs and their supporting structures. Guo et al. [15] conducted a qualitative fault tree analysis (FTA) for FOWTs and showed that mooring system, lubrication system of gearbox, cooling system, and yaw system were among the riskiest components. A dynamic FTA study for FOWTs was also conducted by Zhang et al. [16]. The authors took all the relationships between modules and failure mechanisms into consideration and based on system grading they derived a series of high-risk factors that resulted in failure of the whole system. Kang et al. [17] performed a failure mode and effects analysis (FMEA) study on FOWTs and then compared the results of their analysis with those obtained by a reliability index vector (RIV) method. Kang et al. [18] adopted the FTA method for qualitative and quantitative failure analyses of semi-submersible FOWTs. It was shown that marine conditions, especially the salt-spray and high wind speed have the highest impact on FOWT performance. More recently, Li et al. [19] extended the conventional FMEA methodology to analyze the failures of support structures in FOWTs. Based on the analysis, some suggestions were made on maintenance actions aiming at ensuring the safe and economic operation of support structures.

From the reviewed studies, it is evident that there is so far no study in the literature comparing the performance of various methodologies for failure analysis of FOWT technologies. A comparative study will be useful to decide on the most efficient way of analyzing damage mechanisms or failure modes of the FOWT components. In addition to this, the existing studies do not evaluate the severity of failure modes associated with underwater components of FOWTs, including the platform, mooring system, and connection cables. In order to overcome these gaps, this study aims to provide a comparative analysis between 2 well-established reliability engineering methodologies, namely FTA and FMEA for an OC3-Hybrid spar-type FOWT system. Such comparative analysis will help operators and asset managers better understand the performance of different failure assessment methodologies and choose the method that is more appropriate for them. Our analysis covers all major mechanical, electrical, and structural subassemblies of the system, including floating platform, mooring lines, tower structure, pitch and hydraulic system, blade control system, gearbox, generator, etc. Failure information of the FOWT subassemblies is collected from previous studies, industry databases such as 4C Offshore, as well as the reports published by floating wind power companies such as Equinor, BW Ideol, Principle Power. The most critical FOWT subassemblies are identified and ranked according to their failure likelihood and also risk priority number (RPN). The results obtained from both FTA and FMEA methods are compared and analyzed. Our findings reveal a good agreement between the 2 methods with regard to failure criticality rankings. However, some differences between the results are also observed that are attributed to the difference between FTA and FMEA methodologies as the former incorporates the causes of various failure modes into analysis whereas the latter is mainly adopted for a single random failure analysis. The results obtained from the FMEA study are also compared with those reported for bottom-fixed offshore wind farms. The RPN rankings from present work show good agreement with the literature.

The remainder of this article is organized as follows Section 2 presents a brief overview of FOWT technologies and failure analysis methodologies so as to set the background for the main contribution of the paper. Section 3 describes the FTA and FMEA methodologies adopted for failure analysis of the OC3-Hywind spar-type FOWT technology. Section 4 presents the results and discusses the findings. Section 5 concludes the study with suggestions on future areas of research.

Research background

FOWT technology

The potential for floating offshore wind power is significantly greater than conventional bottom-fixed offshore wind power. A floating wind turbine is a wind turbine mounted on a floating platform that is connected to the seabed by mooring lines. Therefore, the platform and mooring system are crucial parts of a FOWT technology. The FOWT platforms are typically categorized into 3 major concepts, including: spar-buoy, semi-submersible, and tension-leg. These 3 concepts are shown in Fig. 2 and are explained briefly in the following sections.

This study focuses on a floating wind turbine concept based on an OC3-Hywind spar type of platform that is moored to the seabed with three anchor piles. The spar-buoy platform is characterized by small plane area and large cylindrical mass below the water surface, a design that is favorable for deep water applications. This concept allows installations in water depths of greater than 100 m [4]. The top section of the structure is lighter than the bottom section, which raises the center of buoyancy. In order to achieve static stability, it uses ballast weights that are placed low in the buoy, making the center of gravity lower than the center of buoyancy. Therefore, it provides high resistance to the rotational motions of pitch and roll. Spar-buoy platforms are usually made from either concrete or steel, while the ballast weights can be water or solid material. Mooring lines with embedded anchors to the seabed help not only to keep the structure in place but also contribute towards minimizing surge and sway motions. Typical mooring line materials include fiber ropes, steel cables or anchor chains.

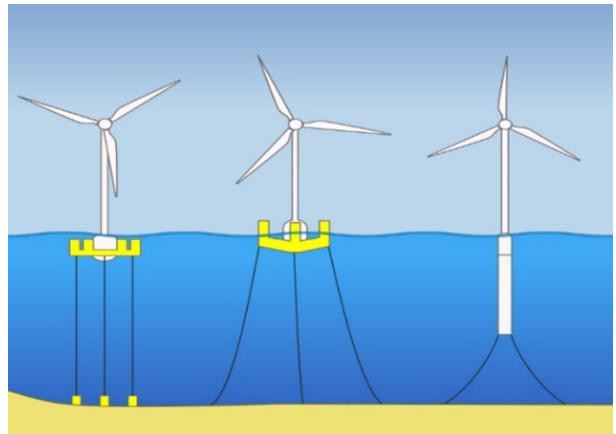

Fig. 2 Floating offshore wind platforms: spar-buoy (right), semi-submersible (center), and tension-leg (right) (https://windeurope.org/)

Over the past decade, extensive research has been performed to evaluate the mechanical performance of spar-buoys as FOWT platforms. Jonkman et al. [20] and Jonkman [21] reported the mechanical properties of an OC3-Hywind FOWT system carrying the NREL 5 MW reference wind turbine. Karimirad and Moan [22] investigated the feasibility of deploying spar-type floating wind platforms at moderate water depth. The authors used the aeroelastic code HAWC2 (Horizontal Axis Wind turbine simulation Code 2nd generation) for calculating the wind turbine's response in time domain. This code was originally developed by the aeroelastic design research programme at Risø DTU in Denmark. In another study, Karimirad and Moan [23] compared the power performance, structural integrity, and dynamic responses of 2 spar-based FOWT platforms using different codes such as SIMO-RIFLEX and TDHMILL3D. The platforms included one called shortspar and another called deepspar, which were deployed, respectively, in moderate and large water depths. Nematbakhsh et al. [24] proposed a nonlinear computational model, based on the Navier–Stokes equations, to simulate the motion of a 5 MW spar buoy floating wind turbine in extreme sea states including waves over 17 m height. Chen et al. [25] conducted a series of comparisons on dynamics characteristics of spar-buoy and semi-submersible floating wind turbines. It was found that the spar-buoy floating wind turbine is more sensitive to wind loading, whereas the semi-submersible floating wind turbine is more sensitive to wave loading. Sultania and Manuel [26] proposed two-dimensional and three-dimensional inverse first-order reliability methods for a spar-supported floating offshore 5 MW wind turbine under variable environmental and load conditions. Ahn and Shin [27] developed an OC3 spar-buoy floating wind turbine model moored by a 3-leg catenary spread mooring system with a delta connection. They verified the results obtained from numerical simulation tools with the performance of OC3-Hywind platforms in combined wave and wind environments. Lin et al. [28] proposed a simulation model to estimate dynamic responses of spar buoy and tension-leg floating offshore wind turbines. The study developed a modular system based on MATLAB SIMULINK in combination with a boundary element method (BEM) solver and visualization software ParaView. Bashetty and Ozcelik [29] reviewed the historical developments and progresses in the design of different types of FOWT platforms including spar type, semisubmersible, and tension leg platforms. The dynamics characteristics of the FOWT platforms for a single turbine and multiple turbines under various operating environmental conditions were also discussed.

Failure analysis methodologies

Fault tree analysis (FTA)

FTA is one of the most popular and effective methods for failure analysis of onshore/offshore wind turbines [30]. It is a top-down, deductive failure analysis method through which undesired states of a system can be identified. The method uses a logic diagram which begins with an undesired top event and then works backward toward identifying different sub-events that contribute to the top event [31]. The sub-events are connected via logic symbols (known as gates) which show the relationship between successive levels of the tree. The most common symbols and logic gates used in FTA are shown in Fig. 3. AND gate means that the output event will occur only if all the input events occur simultaneously, whereas OR gate means that the output event will occur if at least one of the input events occurs.

FTA can also be used to determine the likelihood of occurrence of the top event. However, extensive calculations are required and sometimes discrepancies may exist between actual failure in practice and reliability estimations. The probability of a gate's output event depends on the type of the gate as well as input event probabilities. An AND gate represents the intersection of the events attached to the gate. Assuming A and B are 2 independent events, then the probability of their intersection is just the product of their probabilities. Thus,

$$P(A \text{ AND } B) = P(A \cap B) = P(A) \times P(B) \tag{1}$$

On the other hand, an OR gate corresponds to set union and thus the probability of the OR gate output is given by:

$$P(A \text{ OR } B) = P(A \cup B) = P(A) + P(B) - P(A \cap B) \tag{2}$$

Since failure probabilities on fault trees often tend to be small (<0.01), $P(A \text{ AND } B)$ usually becomes a very small error term, and the output of an OR gate may be conservatively approximated by using an assumption that the inputs are mutually exclusive events:

$$P(A \cap B) \approx 0 P(A \text{ OR } B) \approx P(A) + P(B) \tag{3}$$

Failure mode and effects analysis (FMEA)

Failure mode and effects analysis is one of the most popular failure analysis methods in the wind energy industry (e.g., [32, 33]). This method involves creating a series of linkages between failure modes of a system, their effects on the system performance, and the underlying causes of the failure. In this method, the criticality of a failure is assessed based on an index called the risk priority number. The RPN is obtained by multiplying the scores of 3 factors, namely, the probability of failure occurrence (O), severity of failure consequence (S), and probability of not detecting the failure (D). In the wind energy industry, O, S and D are evaluated using four-point scales given in summary in Tables 1, 2 and 3 as proposed in [34].

According to the above rating scales for O, S and D, the RPN value for each failure mode will range between 1 and 200 ($=5 \times 4 \times 10$). The FMEA method is most beneficial when carried out as an iterative process during the preliminary design stages, allowing for improvements and reliability monitoring.

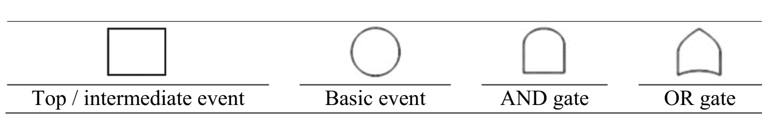

Fig. 3 The most important logic symbols used in FTA

Table 1 Four-point scales for occurrence of failure

Rank	Description	Criteria
1	Level E (extremely unlikely)	The probability of occurrence is < 0.001
2	Level D (remote)	The probability of occurrence is > 0.001 but < 0.01
3	Level C (occasional)	The probability of occurrence is > 0.01 but < 0.10
5	Level A (frequent)	The probability of occurrence is > 0.10

Table 2 Four-point scales for severity of failure

Rank	Description	Criteria
1	Category IV (minor)	Electricity can be generated but an urgent repair is required
2	Category III (marginal)	Reduction in ability to generate electricity
3	Category II (critical)	Loss of ability to generate electricity
4	Category I (catastrophic)	Major damage to the wind turbine

Table 3 Four-point scales for detection of failure

Rank	Description	Criteria
1	Almost certain	Current monitoring methods almost always will detect the failure
4	High	Current monitoring methods will highly likely detect the failure
7	Low	Current monitoring methods will low likely detect the failure
10	Almost impossible	No known monitoring method is available to detect the failure

Failure analysis of FOWT

Previous studies about the failure analysis of FOWTs are all focused on semi-submersible floating platforms. In this study, a failure analysis on an OC3-Hywind spar-type FOWT model is performed using the FTA and FMEA methodologies. The FOWT model was designed to support a 5 MW NREL offshore baseline wind turbine mounted on an OC3-Hywind spar platform [20]. The FOWT is moored by a system of three catenary lines to the seabed. The lines are attached to the platform via a delta connection to increase the yaw stiffness of mooring lines.

Since the available failure data for the OC3-Hywind spar-type FOWT model was limited, the failure information for the analysis was obtained from the published industry reports (mainly by Carbon Trust, Equinor, Ørsted, and BW Ideol) as well as expert opinions. Our analysis focused on estimating the probability of failure of the whole system as well as each of the sub-systems/components. The subsystems/components considered in this study include: spar-buoy platform, mooring system, tower structure, electronic components, rotor blades, yaw system, drivetrain system (consisting of gearbox, generator and the brake unit), and pitch and hydraulic system. The software tool used for this study is PTC Windchill (formerly Relex), version 11.0 (https://support.ptc.com/products/windchill/quality/). This software can be used for a variety of purposes such as reliability prediction, FTA, Markov modeling and Weibull analysis as well as drawing reliability block diagrams (RBDs).

FTA of OC3 spar-type FOWT

The fault tree diagram of the OC3-Hywind spar-type FOWT model is shown in Fig. 4. As the subassemblies/components are connected to each other in series, an OR gate was used to connect the fault categories to the top event. In what follows, the fault tree diagrams of individual sub-assemblies are constructed.

Spar-buoy platform

The spar-buoy platform is well-known for its inherent stability due to its low center of gravity. The fault tree diagram for a spar-buoy floating platform is depicted in Fig. 5. As can be seen, the spar-buoy floating platform may fail due to 5 known basic events: mooring system failure, strong wind/wave, typhoon, crash with vessels and biological collision. If the mooring system fails, the floating platform will still stay afloat albeit with the risk of wandering further from its site. However, if harsh environmental conditions like strong winds or high waves occur at the same time they could cause the structure to capsize. Thus, the mooring system failure and strong wind/wave were connected with each other via an AND gate. The floating platform may also be damaged

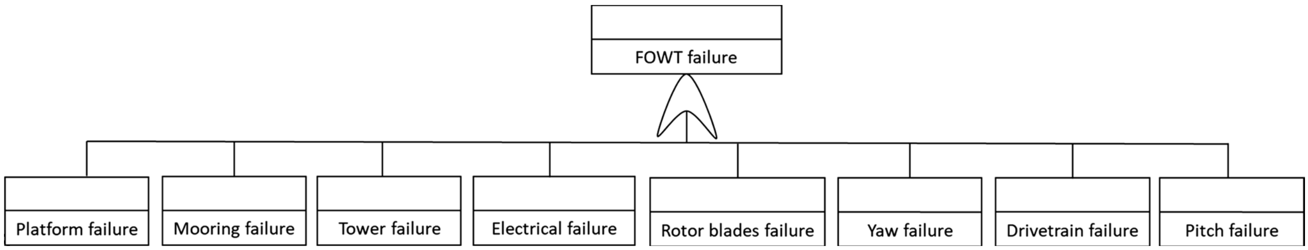

Fig. 4 Fault tree diagram of the OC3 spar-type FOWT model

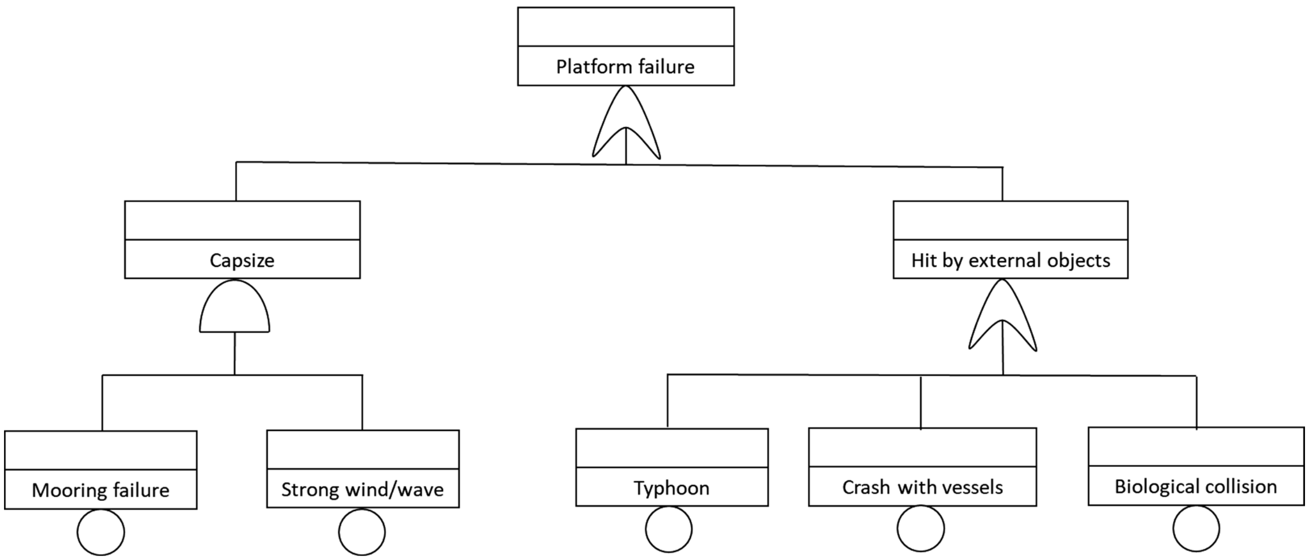

Fig. 5 Fault tree diagram of a spar-buoy floating platform

Table 4 Failure rates of the basic events for a spar-buoy platform

Intermediate / basic event		Failure rate (h^{-1})
Capsize	Mooring system failure	2.04×10^{-4}
	Strong wind/wave	5.00×10^{-5}
External objects	Typhoon	1.00×10^{-4}
	Crash with vessels	1.00×10^{-6}
	Biological collision	5.00×10^{-6}

by external factors including typhoons, crash with vessels or biological collision. These factors were therefore connected via an OR gate. The rates of the failure causes for an OC3 Hywind spar-buoy floating platform have been reported in [16] and [18] and are given in Table 4.

Mooring system

The mooring system keeps the position of the floating platform within an allowable region and avoids the drift caused by wind, current and hydrodynamic forces. The fault tree diagram for mooring system is constructed by dividing the system into its constituent parts, e.g., mooring lines, fairlead, anchor, etc. The failure of either of these parts would cause the mooring system to fail. Thus, the basic events are linked with each other using an OR gate, as shown in Fig. 6.

As can be seen, the spar-buoy mooring system may fail due to nine known basic causes, namely, mooring line fatigue, chain corrosion, abnormal stress, friction chain wear, transitional chain wear, poor operation environment, insufficient emergency measures, fairlead fatigue, fairlead corrosion and anchoring failure. Even though the anchoring failure is considered as one of the major failure modes for a spar-buoy mooring system, due to insufficient data it is not expanded further in this study. Table 5 gives the rates of the failure causes for a spar-buoy mooring system.

Tower structure

The tower structure is considered as one of the most important components of FOWTs, because any damage to the tower will put the entire system in jeopardy. The fault tree diagram for a wind turbine tower structure is represented in Fig. 7.

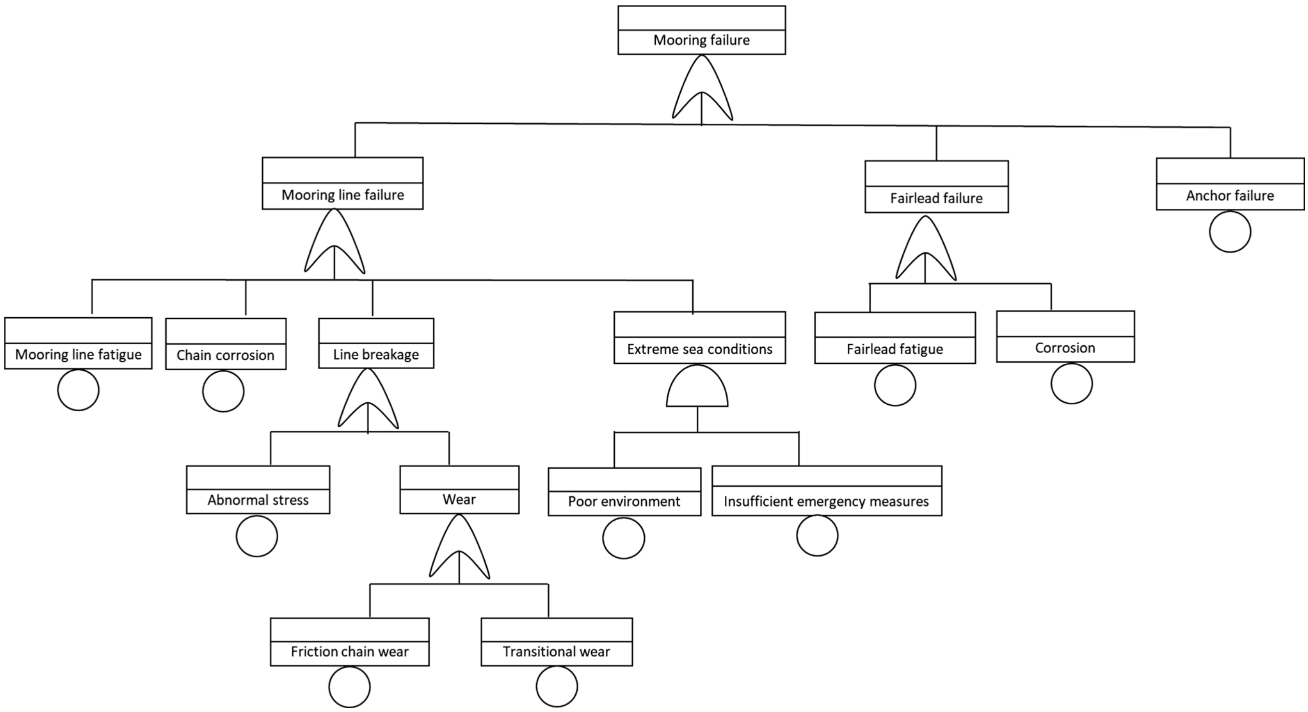

Fig. 6 Fault tree diagram of a spar-buoy mooring system

Table 5 Failure rates of the basic events for a mooring system

Basic / intermediate event			Failure rate (h^{-1})
Mooring line failure	Mooring line fatigue		1.70×10^{-5}
	Chain corrosion		5.38×10^{-6}
	Mooring lines breakage	Abnormal stress	4.07×10^{-5}
		Friction chain wear	6.93×10^{-6}
		Transitional chain wear	1.01×10^{-5}
	Extreme sea conditions	Poor operation environment	7.80×10^{-5}
		Insufficient emergency measures	1.00×10^{-6}
Fairlead failure	Fairlead fatigue		1.70×10^{-5}
	Corrosion		1.00×10^{-5}
Anchor failure			1.80×10^{-5}

As can be seen, all the intermediate and basic events are connected to the top event via an OR gate, meaning that if either of these events occurs it will lead to failure of the entire tower system. Welding defects may occur either during manufacturing process or later during operation phase. External damages are considered as another reason for the failure of the tower structure. These damages include: lighting strike, heavy storm and strong wind/wave. Table 6 gives the rates of the failure root causes for a wind turbine tower structure.

Electrical components

The fault tree diagram for electronic components of a wind turbine system is shown in Fig. 8. As can be seen, the basic failure events were categorized into 2 types: mechanical faults and electrical faults. The corrosion due to moisture and salty atmosphere, presence of dirt, and damage in terminals were identified as the main reasons for mechanical faults, whereas the electrical faults were caused by short circuit, open circuit, and gate drive circuit.

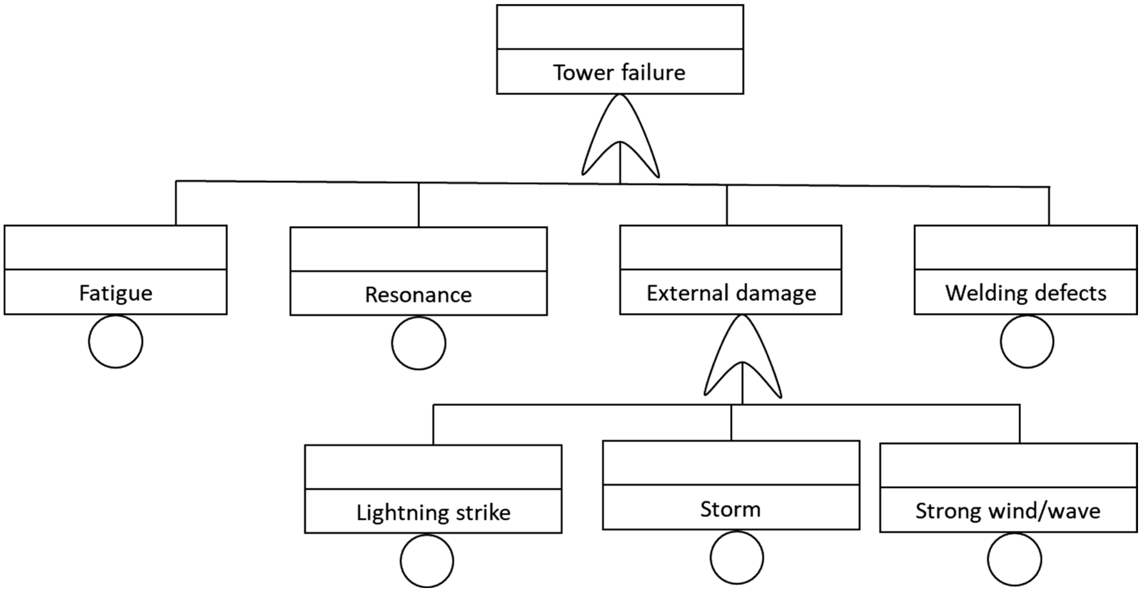

Fig. 7 Fault tree diagram of a wind turbine tower structure

Table 6 Failure rates of the basic events for a wind turbine tower structure

Basic / intermediate event		Failure rate (h^{-1})
Fatigue		1.10×10^{-5}
Resonance		5.00×10^{-6}
External damage	Lighting strike	7.00×10^{-6}
	Storm	5.50×10^{-5}
	Strong waves/winds	5.00×10^{-5}
Welding defects		7.00×10^{-6}

Rotor blades

In order to draw the fault tree diagram for rotor blades, two separate subtrees for blade structural failure and the rotor system failure were constructed and connected together via an OR gate. The fault tree diagram for the rotor blades system is shown in Fig. 9. The subtree diagrams for the blade structural failure and rotor system failure are shown in Figs. 10 and 11, respectively.

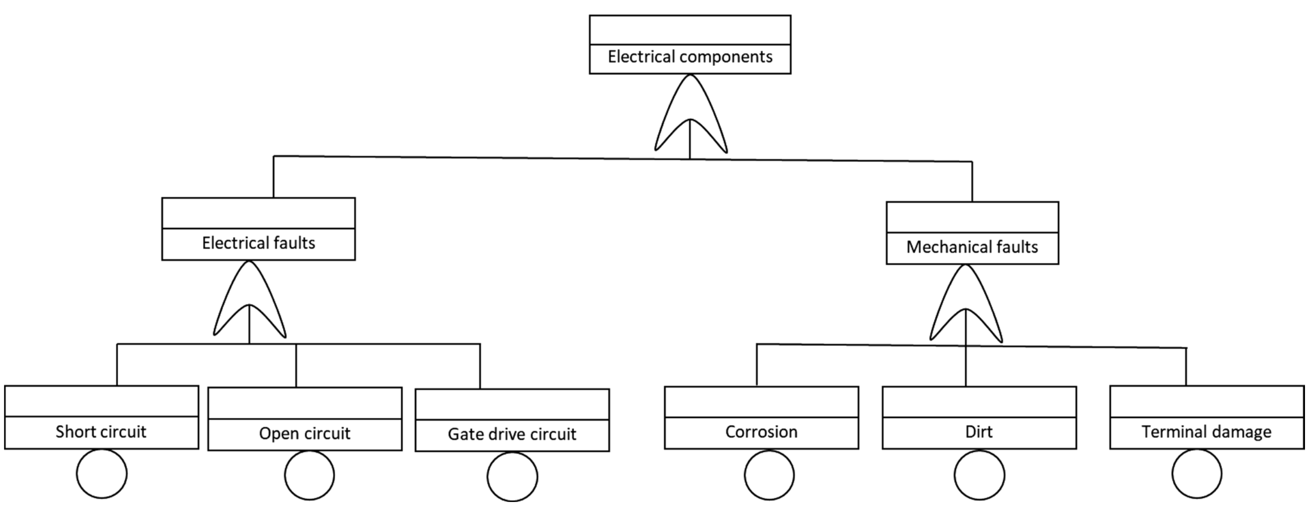

Fig. 8 Fault tree diagram of electrical components

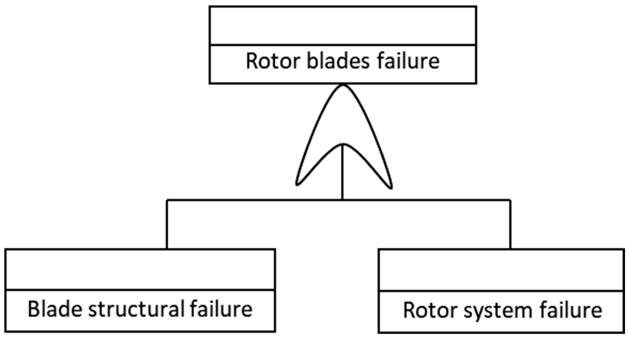

Fig. 9 Fault tree diagram of a wind turbine rotor blades system

As can be seen in Fig. 10, the structural failures in wind turbine blades may occur either due to edge damage or shell damage. FOWTs are often exposed to harsh environmental conditions and therefore wind turbine blades are susceptible to natural phenomena such as lightning strikes. Erosion, cracking and delamination of the composite material are also primary events that can result in blade failure.

As Fig. 11 shows, the three principal events that can trigger the rotor system failure are abnormal vibration, rotor bearings damage and rotor hub fault. Rotor bearings can fail as a result of abrasive wear, corrosion, pitting or insufficient lubrication. Failure of the rotor hub on the other hand can occur as a result of cracks on the hub, surface roughness, mass imbalance of the blades and pitch maladjustment. Major factors that contribute to the occurrence of these events are closely related to environmental conditions and salty air [16].

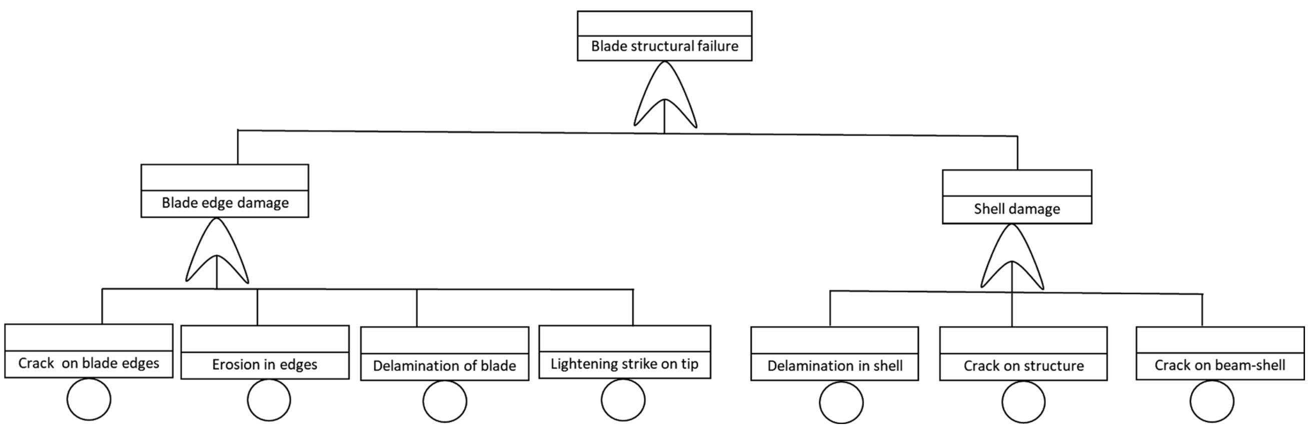

Fig. 10 Fault tree diagram of wind turbine blades

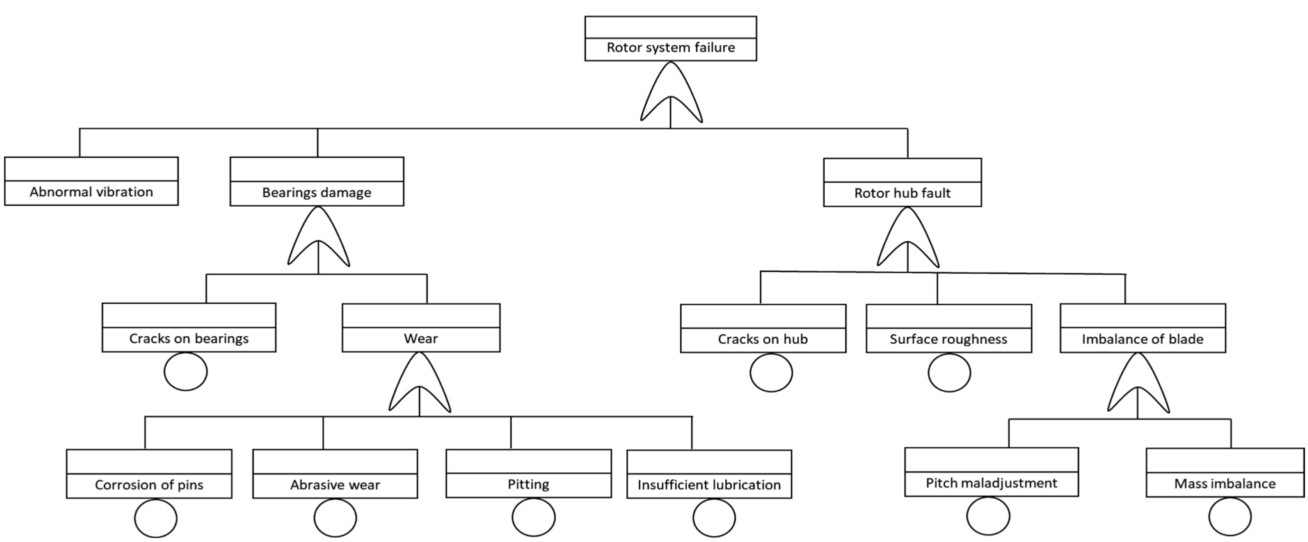

Fig. 11 Fault tree diagram of a wind turbine rotor system

Yaw system

The yaw system adjusts the orientation of the wind turbine rotor towards the wind. Load variations due to wind speed can affect the yaw system and put the wind turbine at risk. The yaw system is susceptible to damages mainly because of the fluctuation and change in rotor torque during yawing. The fluctuation in loads excites the whole system with vibration and will therefore cause some damage to the wind turbine. The fault tree diagram of a wind turbine yaw system is represented in Fig. 12.

Drivetrain system

To draw the fault tree diagram for drivetrain system, three separate subtrees for gearbox, generator and brake unit failures were constructed. The fault tree diagram of the drivetrain system is shown in Fig. 13. The gearbox, generator and brake unit are known as the most important components in drivetrain and the failure of any of these components would lead directly to the failure of drivetrain system as seen in the fact that these 3 components were connected to the top event via an OR gate.

The fault tree diagram of a wind turbine generator system is represented in Fig. 14. The rates of the failure causes for a wind turbine generator system were collected from different references, e.g., [18, 35, 36]. This information is reported in Table 7.

Mechanical and electrical failures are the main contributors to the generator failure. Mechanical failures may occur due to either potential damage to generator bearings or failure of rotor or stator components. Asymmetry, structural deficiency or any kind of abnormal vibration due to external factors are the basic events causing severe damage to generator bearings, while overheating and broken bars are known as the major causes of rotor and stator failures. For electrical failures, the two basic events considered are wire fault and synchronization failure. It should be noted that synchronization failure can normally be considered as a root cause for the rotor and stator components failure, but in this study, it has been considered as an electrical cause and hence it was analyzed separately.

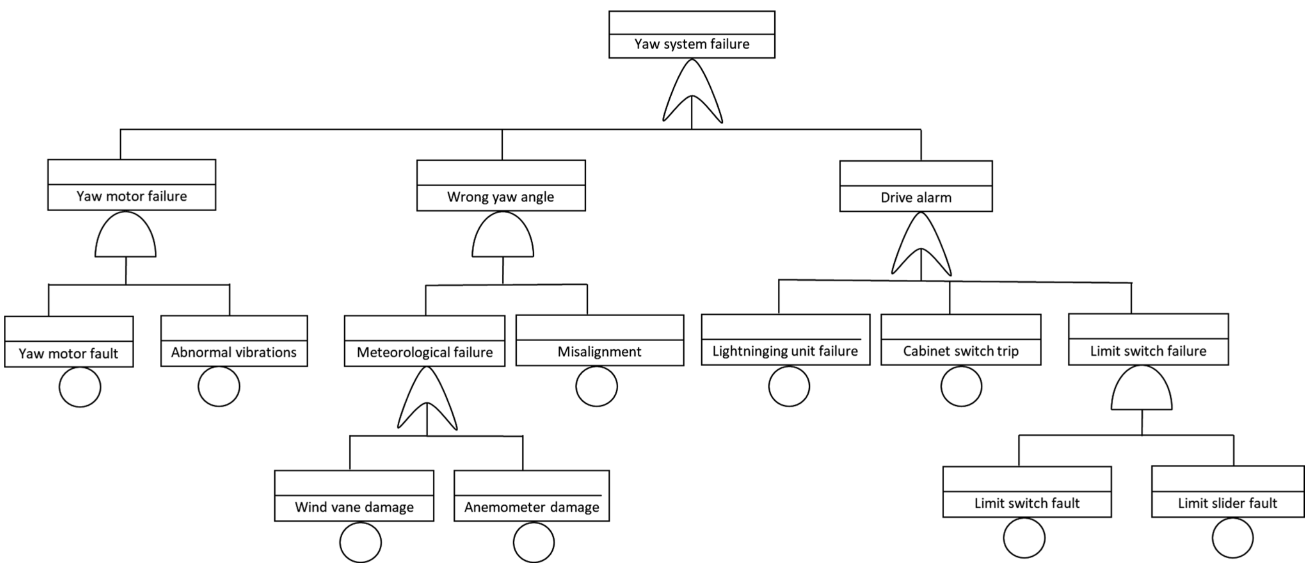

Fig. 12 Fault tree diagram of a wind turbine yaw system

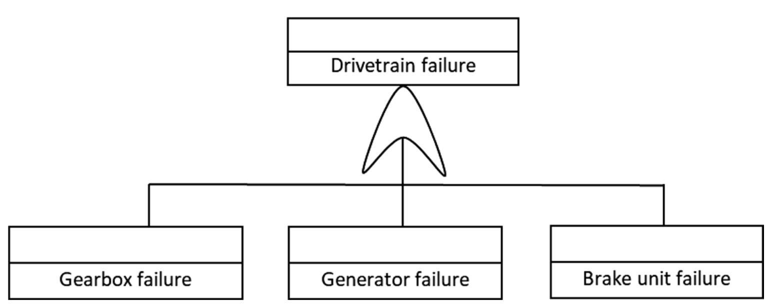

Fig. 13 Fault tree diagram of a wind turbine drivetrain system

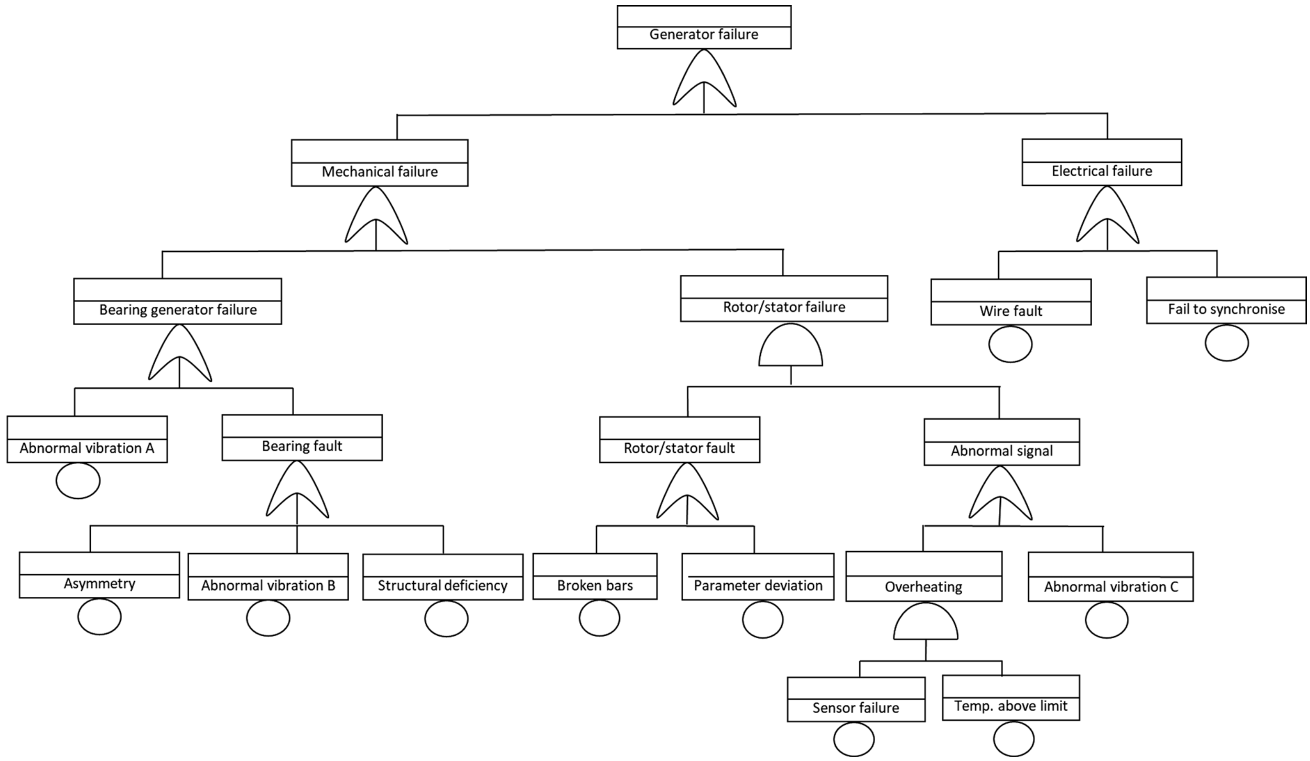

Fig. 14 Fault tree diagram of a wind turbine generator system

Table 7 Failure rates of the basic events for a wind turbine generator system

Basic / intermediate event			Failure rate (h^{-1})
Mechanical failure	Bearing generator failure	Abnormal Vibration A	2.14×10^{-6}
		Asymmetry	5.85×10^{-6}
		Abnormal vibration B	2.14×10^{-6}
		Structural deficiency	1.17×10^{-6}
	Rotor and stator failure	Broken bars	2.10×10^{-7}
		Parameters deviation	1.63×10^{-5}
		Abnormal vibration C	2.14×10^{-6}
		Sensor failure	7.08×10^{-6}
		Temperature above limit	7.20×10^{-7}
Electrical failure	Wire fault		1.00×10^{-7}
	Synchronization failure		3.61×10^{-6}

The gearbox is one of the most failure prone components within the drivetrain system. Some of the major causes of gearbox failure include: bearing and gear defects that result from wear, excessive pressure, pitting, fatigue, gear tooth deterioration, poor design of teeth, and poor material quality. Another important factor which may significantly impact the functioning of a gearbox is poor lubrication. Poor lubricant quality, presence of dirt and debris, and problems in filter can cause severe malfunction to rotating parts of the gearbox system, and eventually lead to a sudden failure. The fault tree diagram of the gearbox system is represented in Fig. 15.

The failure rates of the basic events for a wind turbine gearbox system are given in Table 8. The potential damages to the brake unit can cause the drivetrain system to fail. Oil leakage, damage to brake disk, extreme loads that can lead to overpressure, cracks on high-speed shaft and brake overheating are considered to be the primary causes for the brake unit failure. The fault tree diagram of a wind turbine brake unit is shown in Fig. 16. The data for the construction of this fault tree were collected from different sources, e.g., [18, 37].

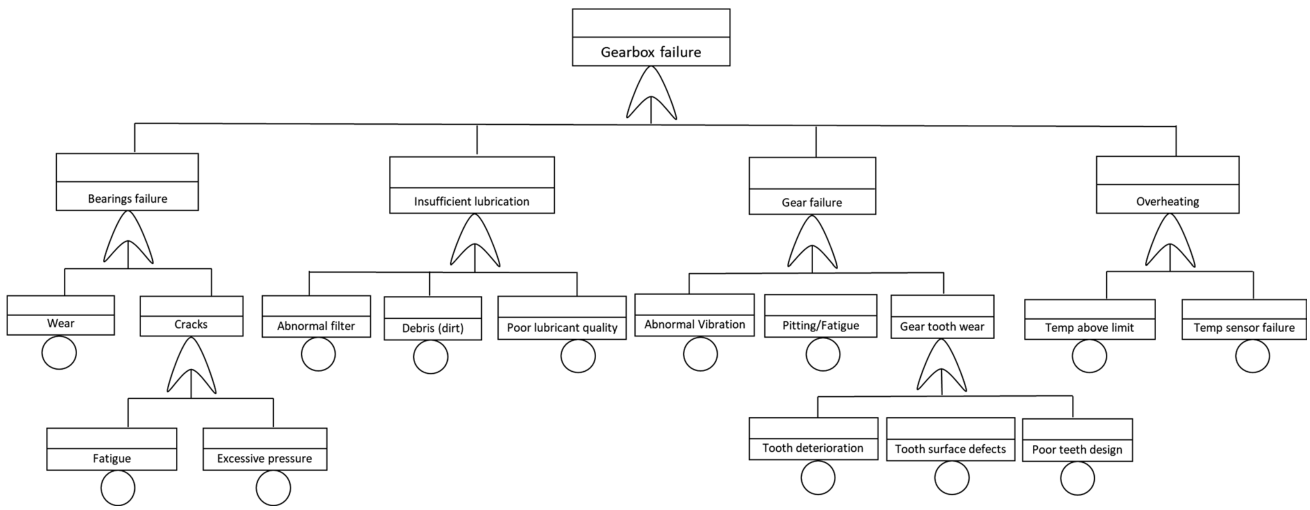

Fig. 15 Fault tree diagram of a wind turbine gearbox system

Table 8 Failure rates of the basic events for a wind turbine gearbox system

Basic / intermediate event		Failure rate (h^{-1})
Bearings failure	Wear of bearings	1.00×10^{-5}
	Fatigue	3.00×10^{-7}
	Excessive pressure	1.00×10^{-6}
Insufficient lubrication	Abnormal filter	1.80×10^{-6}
	Debris (dirt)	2.14×10^{-6}
	Poor lubricant quality	1.80×10^{-6}
Gear failure	Abnormal vibration	2.14×10^{-6}
	Pitting/fatigue in gears	1.30×10^{-6}
	Gear tooth deterioration	3.00×10^{-7}
	Tooth surface defects	3.00×10^{-7}
	Poor design of teeth	1.00×10^{-6}
Overheating	Temperature above limit	7.08×10^{-6}
	Temperature sensor failure	7.20×10^{-7}

Pitch system

The pitch system controls the orientation of the turbine blades in relation to the wind. The major contributors to pitch system failure include hydraulic system failure, wrong blade angle, and drive alarm failure. Leakage in the hydraulic system, overpressure and hydraulic motor failure are the major root causes for hydraulic system failure. The pitch system may fail as a result of wrong blade angle, which in turn is caused by meteorological unit failure. The meteorological unit provides necessary wind data to the wind turbine control system. The most common failures to the meteorological unit include damages to the wind vane and anemometer. Figure 17 shows the fault tree diagram of a wind turbine pitch system. The failure rates of the basic events for a wind turbine pitch system are given in Table 9.

FMEA of OC3 spar-type FOWT

An FMEA was performed on the OC3-Hywind spar-type FOWT model to assess the criticality of different failure events identified by the FTA method. In a similar fashion to FTA, the FOWT components included in the FMEA study were spar-buoy platform, mooring system, tower structure, blade system, yaw system, drivetrain system (consisting of gearbox, generator, and the brake unit), electronic components, pitch system and hydraulic system. For each of these components, failure modes were designated, which can occur through some failure mechanisms, and the effects of these failures on the system were evaluated. The 3 factors of O, S and D for each failure mode were determined by interviewing experts (including designers, wind turbine operators, inspectors, maintenance technicians, etc.) using FMEA questionnaire. The fault diagnosis and prognosis techniques include visual inspection, vibration analysis, non-destructive testing (NDT), SCADA based condition monitoring, structural health monitoring as well as remote inspections using remotely operated vehicles, aerial drones and underwater sonar technology. The results of the FMEA study for the OC3-Hywind spar-type FOWT model are presented in a worksheet format in Table 10.

Discussion

FTA

After analyzing the fault tree diagrams in Figs. 4and17, the failure rates of different subsystems of the FOWT model

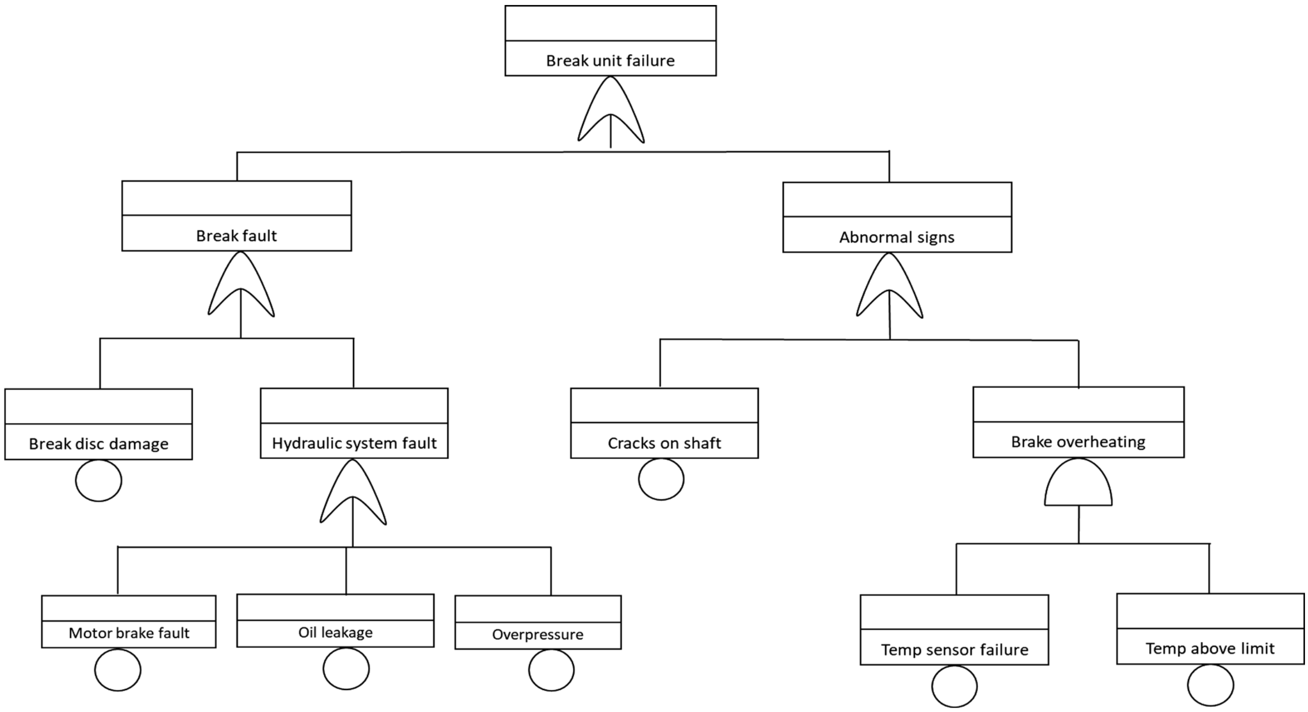

Fig. 16 Fault tree diagram for a wind turbine brake unit

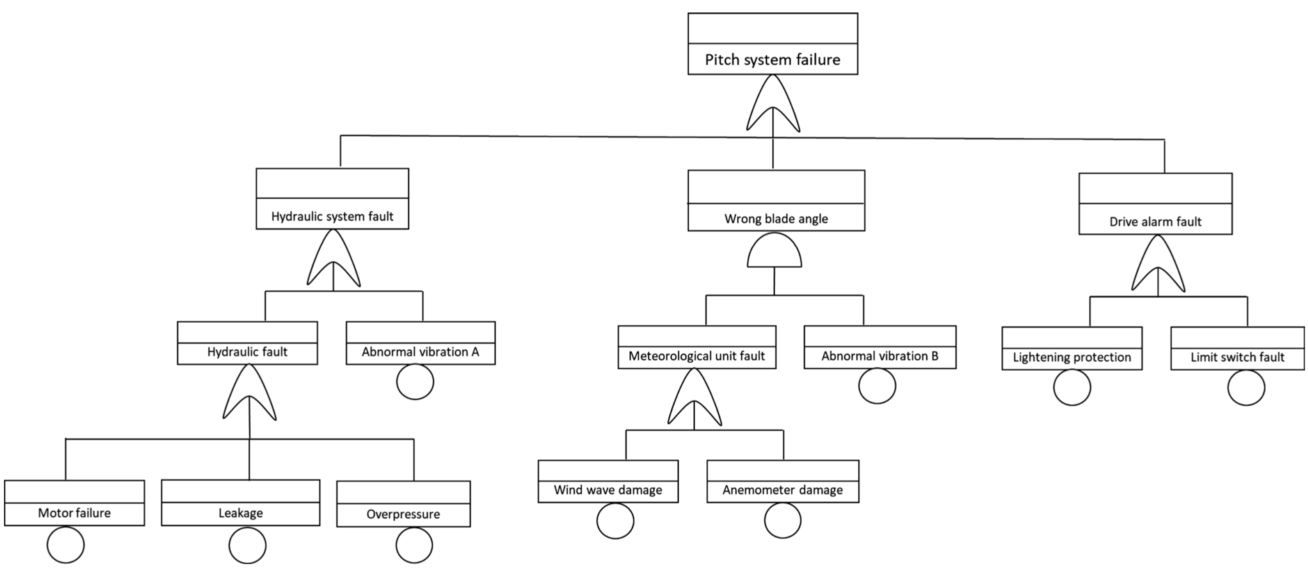

Fig. 17 Fault tree diagram of a wind turbine pitch system

were obtained. The results of the analysis are reported in Table 11.

It can be seen from Table 11 that tower structure and mooring system with mean failure rates of respectively 1.35×10^{-4} and 1.25×10^{-4} (per h) are the most prone subsystems to failure. These components are followed by electronic components and pitch system with failure rates of 1.15×10^{-4} and 1.10×10^{-4} per h. Since these subassemblies/components are connected together in series, the total failure rate of the FOWT system is calculated by summing up the failure rates of all the individual subassemblies. Therefore,

Table 9 Failure rates of basic events for a wind turbine pitch system

Basic / intermediate event		Failure rate (h^{-1})
Hydraulic fault	Abnormal vibration A	2.14×10^{-6}
	Hydraulic motor failure	1.00×10^{-5}
	Leakage in hydraulic system	4.80×10^{-5}
	Overpressure in hydraulic system	3.00×10^{-5}
Wrong blade angle	Abnormal vibration B	2.14×10^{-6}
	Wind vane damage	7.00×10^{-6}
	Anemometer damage	1.80×10^{-5}
Drive alarm fault	Lighting protection fault	1.00×10^{-5}
	Limit switch fault	1.00×10^{-5}

$$\lambda = \sum_i \lambda_i \quad (4)$$

where λ_i represents the failure rate of the subassembly $i\ (=1, 2, \ldots)$ and λ is the failure rate of the FOWT system.

The failure rate of the FOWT system was estimated to be approximately 7.01×10^{-4} per h, indicating that the mean time between system failures (MTBSF) is about 1426.7 h. The MTBSF estimated in this study is approximately 20% larger than the value reported in [18]. This difference between the results can be explained as follows:

- In this study, some further failure modes with more detailed basic causes were considered.
- This paper focused on spar-type floating platforms, whereas [18] studied the failure scenarios for a semi-submersible platform.
- The mooring system in this study was considered as an individual component of the FOWT model as opposed to [18] in which mooring system failure was incorporated into the FOWT platform system.

After identifying the most critical components that can cause the FOWT system to fail, minimal cut sets were computed to determine the most critical failure events. Cut sets are unique combinations of component failures that can cause system failure. A cut set is said to be a minimal cut if, when any basic event is removed from the set, the remaining events collectively are no longer a cut set. The results for the probability of failure of tower structure as well as mooring system due to different basic events are given in Tables 12 and 13, respectively.

As can be seen, the damages from external environmental conditions like heavy storms, strong wind or wave, and fatigue are the most dominant causes contributing to the tower failure. On the other hand, abnormal stress, anchor failure and fairlead fatigue are the main three causes of mooring system failure.

FMEA

The risk priority number value for each component was determined by summing up the RPNs associated with its failure modes. Table 14 presents the RPN values for different FOWT subassemblies/components.

As can be seen, the mooring system has the highest RPN value, indicating that the mooring lines can be critical for the safety of FOWT systems. This is followed by rotor blades, gearbox, and tower structure. Among the three failure modes contributing to mooring system failure, the mooring line breakage with a RPN value of 364 was the most dominant failure mode. Among the failure events causing the rotor blades system to fail, the blades' structural damage was identified as the most critical failure mode.

The results obtained from the FMEA study for the OC3-Hywind spar-type FOWT model were compared with those reported for bottom-fixed offshore wind turbines. The comparisons were made based on RPN rankings obtained for all components that both FOWT and bottom-fixed wind turbines have in common. As an example, the results of a comparison between this study and our earlier study [26] are presented in Table 15. As Table 15 shows, both studies ranked the blade system as well as generator in the same order. However, the studies presented minor differences in some other components such as gearbox and pitch system. The results obtained by both FTA and FMEA techniques were also compared with each other. The failure criticality rankings obtained by both techniques are presented in Table 16.

As can be seen from the results of the FTA and FMEA techniques, it is clear that there are some agreements between the results. However, some differences were also observed that might be attributed to the difference between FTA and FMEA methodologies. The FTA is known to incorporate the causes of various failure modes, whereas the FMEA is mainly used for a single failure analysis. In terms of robustness, the decision as to which method to choose for performing failure analysis depends greatly on the input information which is available. If failure data such as probability of failure on demand (PFD) or rate of occurrence of failures (ROCOF) are available, the FTA technique would be a more robust approach for failure analysis than the FMEA technique. However, in the absence of quantitative failure data or when the quality of data is insufficient, the FMEA technique would be a more helpful method to use as it can incorporate qualitative information through avenues like expert elicitation.

Table 10 The FMEA study results for the OC3-Hywind spar-type FOWT model

Item (ID)	Function	Potential Failure Mode	Severity of effect		Probability of occurrence		Ability to detect					
			Potential Effects	SEV	Potential Causes of Failure	OCC	Current Design Controls	DET	RPN (cause)	RPN (Failure mode)	RPN (component)	RANK
Mooring system	To keep the position of the floating platform	Mooring lines breakage	FOWT shutdown	4	Fatigue	5	Visual inspection; NDT	7	140	364	664	1
		Fairlead failure			Wear	3	Sonar	7	84			
		Anchor failure			Abnormal stress	5	Visual inspection	7	140			
					Fatigue	5	Visual inspection; NDT	7	140	220		
					Corrosion	5	Visual inspection	4	80			
					Joint failure	2	Visual inspection; ROV	4	32	80		
					Scour	3	ROV/ Sonar	4	48			
Tower structure	To integrate the nacelle to substructure part	Tower structural damage	Structural failure	4	Lightning strike	2	Visual inspection	4	32	184	184	4
					Strong wind/waves	3	Visual inspection	4	48			
					Resonance	3	Structural health monitoring	4	48			
					Welding defects	2	NDT test	7	56			
Floating platform	To support the FOWT	Structural damage	FOWT shut down	4	External objects	2	Visual inspection; ROV	4	32	32	64	9
		Loss of stability			Mooring failure	2	Visual inspection; ROV	4	32	32		
Blade system	To capture wind	Rotor system failure	Reduction in or loss of power production	**3**	Damage to bearings	3	Vibration measurements	4	36	123	273	2
					Crack in rotor hub	3	Visual inspection	7	63			
					Imbalance of blades	2	Vibration measurements	4	24			
		Blade structural damage			Lighting	2	Visual inspection	7	42	150		
					Erosion	2	Visual inspection	7	42			
					Cracks	2	NDT test	7	42			
					Delamination	2	Visual inspection	4	24			
Yaw system	To align WT with wind direction	Yaw motor failure	Reduction in power production	2	Abnormal vibration	3	Vibration measurements	7	42	42	106	8
		Drive alarm failure			Switch failure	2	Visual inspection	4	16	32		
					Lightning unit failure	2	Warning system	4	16			
		Meteorological unit failure			wind vane damage	2	Visual inspection	4	16	32		
					Anemometer damage	2	Visual inspection	4	16			

Table 10 (continued)

Item (ID)	Function	Potential Failure Mode	Severity of effect		Probability of occurrence		Ability to detect					
			Potential Effects	SEV	Potential Causes of Failure	OCC	Current Design Controls	DET	RPN (cause)	RPN (Failure mode)	RPN (component)	RANK
Gearbox	To increase the low-speed rotational speed	Gears failure	Shutdown of the WT and loss of power	3	Tooth wear	3	Visual inspection	4	36	123	195	3
					Erosion	2	Visual inspection	4	24			
					Abnormal vibration	3	Condition monitoring	7	63			
		Bearing failure			Wear	3	Visual inspection	4	36	72		
					Fatigue	3	NDT test	4	36			
Generator	To convert mechanical energy to electrical energy	Mechanical failure	Shutdown of the WT and loss of power	3	Abnormal vibration	3	Vibration measurements	7	63	123	177	5
					Bearing damage	3	Vibration measurements	4	36			
					Rotor/stator failure	2	Visual inspection	4	24			
		Electrical failure			Fail to synchronize	1	Warning system	4	12	54		
					Wire failure	2	Visual inspection	7	42			
Brake system	To decelerate or decrease the speed	Hydraulic system failure	Shutdown of the WT	4	Oil leakage	3	Visual inspection	1	12	20	52	10
					Motor brake failure	2	Visual inspection	1	8			
		Overheating			Temp. sensor fault	2	Warning system	4	32	32		
Electronic components	To integrate the WT into power grid	Mechanical fault	Shutdown of the WT	3	Corrosion	3	Visual inspection	4	36	72	114	7
					Dirt	3	Visual inspection	4	36			
		Electrical fault			Short/open circuit	2	Alarm system	7	42	42		
Pitch system failure	To pitch the rotor blade	Meteorological unit failure	Shutdown of the WT	3	Wind vane damage	2	Visual inspection	4	24	48	135	6
					Anemometer damage	2	Visual inspection	4	24			
		Hydraulic system failure			Abnormal vibration	3	Vibration measurements	4	36	87		
					Fluid Leakage	5	Visual inspection	1	15			
					Hydraulic motor fault	3	Alarm system	4	36			

Conclusions and future work

In this study, a failure analysis was performed for a floating offshore wind turbine (FOWT) concept based on an OC3-Hywind spar type of platform moored to the seabed with three anchor piles. The floating platform supports the NREL 5 MW reference wind turbine with a rotor diameter of 126 m and a tubular tower. All major mechanical, electrical and structural subassemblies of the system, including spar-buoy platform, mooring lines, tower, blade system, yaw system, gearbox, generator, brake unit, electronic components, pitch and hydraulic system were included in the analysis. The failure analysis approach relied on two well-established reliability engineering methodologies, namely, fault tree analysis and failure mode and effects analysis.

The most critical subassemblies of the FOWT system were identified by constructing fault tree diagrams and estimating the rate of occurrence of failures. Since the failure data for the FOWT subassemblies were scarce, the information was collected from the reports published by industries as well as expert opinions. Based on the results, the tower structure and mooring system were determined as the most failure-prone components in the FOWT system. These components experienced failure rates of 1.35×10^{-4}/h and 1.25×10^{-4}/, which correspond to mean time between failures of, respectively, 309 and 334 days. Also, in order to identify the most critical failure modes and causes of FOWT components, the minimal cut sets were computed. The overall failure rate of the FOWT system was estimated to be approximately 7.01×10^{-4} per hour, indicating that the system would fail about six times per year.

In addition to the FTA analysis, an FMEA study was also performed to assess the ‘criticality’ of different failure mechanisms in the FOWT subsystems. The failure criticality was evaluated based on an index called the risk priority number, which is the product of severity (S), occurrence (O), and undetectability (D) ratings. These 3 ratings were determined based on four-point scales being adopted and widely used for bottom-fixed wind turbines in the wind energy sector. The results showed that the mooring system and rotor blades cause the highest risk to the FOWT system, followed by the gearbox and tower structure. Among different failure modes contributing to mooring system failure, the mooring line breakage was found to be the most dominant failure mode. Similarly, among different failure events causing the rotor blades system to fail, the blades structural damage was rated as the riskiest failure mode. The results obtained from the FMEA analysis for the FOWT system were compared with those reported for bottom-fixed offshore wind turbines. The RPN rankings obtained in our work were in good agreement with the previous studies in the literature.

Table 11 Failure rates of different FOWT subsystems

No	Subsystem	Failure rate (hour^{-1})
1	Spar-buoy platform	1.06×10^{-4}
2	Mooring system	1.25×10^{-4}
3	Tower structure	1.35×10^{-4}
4	Electronic components	1.15×10^{-4}
5	Rotor blades	4.52×10^{-5}
6	Yaw system	2.17×10^{-5}
7	Gearbox	2.21×10^{-5}
8	Generator	1.47×10^{-5}
9	Brake unit	0.62×10^{-5}
10	Pitch system	1.10×10^{-4}

Table 12 Probability of tower failure due to different basic events

Basic event	Probability of failure
Storm	1.65×10^{-7}
Strong waves/winds	1.50×10^{-7}
Fatigue	3.30×10^{-8}
Lighting strike	2.10×10^{-8}
Welding defects	2.10×10^{-8}
Resonance	1.50×10^{-8}

Table 13 Probability of mooring system failure due to different basic events

Basic event	Probability of failure
Abnormal stress	1.23×10^{-6}
Anchor failure	5.40×10^{-7}
Fairlead fatigue	5.10×10^{-7}
Mooring line fatigue	5.10×10^{-7}
Corrosion	3.00×10^{-7}
Transitional wear	3.00×10^{-7}
Friction chain wear	2.10×10^{-7}
Chain corrosion	1.50×10^{-7}
Extreme sea conditions	7.02×10^{-14}

Comparing the results obtained from the FMEA study with those obtained from the FTA, a good agreement was observed for failure criticality rankings. However, some differences were also found between the results which mainly are attributed to the difference between FTA and FMEA methodologies. The FTA methodology has the capability of incorporating the basic causes of various failure scenarios, whereas the FMEA methodology is often used for a single random failure analysis. In addition, the FTA is suitable in situations where some historical data such as probability

Table 14 RPN values for FOWT subsystems

No	Subsystem	RPN	Rank
1	Spar-buoy platform	64	9
2	Mooring system	664	1
3	Tower structure	184	4
4	Electronic components	114	7
5	Rotor blades	273	2
6	Yaw system	106	8
7	Gearbox	195	3
8	Generator	177	5
9	Brake unit	52	10
10	Pitch system	135	6

Table 15 RPNs and ranks for each FOWT subsystem

Components	RPN	Our rank	[26]
Spar-buoy platform	64	9	–
Mooring system	664	1	–
Tower structure	184	4	1
Electronic components	114	7	–
Rotor blades	273	2	2
Yaw system	106	8	13
Gearbox	195	3	2
Generator	177	5	5
Brake unit	52	10	11
Pitch system	135	6	7

Table 16 Ranking comparisons between FTA and FMEA

Rank	FTA	FMEA
1	Tower structure	Mooring system
2	Mooring system	Rotor blades
3	Electronic components	Gearbox
4	Pitch system	Tower structure
5	Spar-buoy platform	Generator
6	Rotor blades	Pitch system
7	Gearbox	Electronic components
8	Yaw system	Yaw system
9	Generator	Spar-buoy platform
10	Brake unit	Brake unit

of failure on demand (PFD) or rate of occurrence of failures are available. However, the FMEA is a helpful method to use during the preliminary design stages of floating wind technologies, i.e., when there is lack of quantitative failure data.

The work performed in this study can be extended to other FOWT concepts developed by Hexicon (https://www.hexicon.eu/) or Principle Power (https://www.principlepowerinc.com/). In addition, upscaling the results to a wind farm level can greatly increase the effectiveness of maintenance activities which are proposed and scheduled as a result of the failure analysis performed.

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Declaration

Conflict of interest Authors declare that there is no conflict of interest on this study.

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