Technical challenges of floating offshore wind turbines

An overview

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Abstract

Floating offshore wind (FOW) holds the key to 80 % of the total offshore wind resources, located in waters of 60 m and deeper in European seas, where traditional bottom-fixed offshore wind (BFOW) is not economically attractive. Many problems affecting floating offshore wind turbines (FOWT) were quickly overcome based on previous experience with floating oil rigs and bottom-fixed offshore wind. However, this technology is still young and there are still many challenges to overcome.

This paper shows that electrical failures are amongst the most significant errors of FOWT. The most common cause was corrosion. It is also stated that the control system is most often affected, and that the Generator is frequently involved. Material corrosion is also the key factor when it comes to the most common overall reason for failures. A particular attention must be paid to mooring line fracture. Mooring lines are especially vulnerable to extreme sea conditions and the resulting fatigue, corrosion, impact damage, and further risks. It must be stated that the primary challenge is that of economics. Over time technological costs will decline making FOW more competitive and hence attractive for greater depth.

Keywords: floating offshore wind power, challenges, wind turbine, mooring line, Windkraftanlage

Abbreviations

BFOW = Bottom-fixed offshore wind
CMA = Concept Marine Associates
TLP = Tension Leg Platforms
FOW = Floating offshore wind
FOWT = Floating offshore wind turbines
RPN = Risk Priority Number

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1 Introduction

Floating offshore wind (FOW) holds the key to an almost inexhaustible resource potential in Europe. 80 % of the total offshore wind resources in European seas is located within water depth of 60 m and deeper, where traditional bottom-fixed offshore wind (BFOW) is not economically attractive [1]. Many problems affecting floating offshore wind turbines (FOWT) were quickly overcome based on previous experience with floating oil rigs and bottom-fixed offshore wind. However, this technology is still young and there are still many challenges to overcome. This paper will combine information gathered from several studies to determine the most common causes of failure which FOWT experience and provide suggestions for possible solutions.

2 Specific technical challenges for floating offshore wind turbines

A floating offshore wind turbine is composed of many different system-relevant parts. This is why it make sense to categorize failures according to areas of occurrence.

2.1 Rotor-blades

Rotor-blades are the components with the highest chance of failure and also responsible for the highest percentage of a FOWT downtime. Many of these failures are due to structural failures and material fatigue. These failures are greatly due to the missing experiences associated with the heavier weather conditions floating wind-turbines experience compared with their fixed counterparts. Other failures include cracks, erosion and flaking. These usually occur around the edges of the wind-blades. One of the most common problems associated with wind-turbine-blades are failures in the yaw and pitch systems. These are used to control the blades angle in correspondence to the wind [2].

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2.2 Electrical components

Wiring is one of the biggest cost factors when it comes to FOWT. The connecting cables must be durable and flexible to be able to withstand constant movement. The biggest cost factor when it comes to faults in this category is caused by the generator and related parts. Generator faults may be caused by mechanical as well as electrical failures. Electrical issues are mainly caused by open-circuits or short-circuits within the rotor or overheating of the stator. Mechanical problems are due to corrosion and dirt [2].

2.3 Transmission system

The transmission system is composed of the coupling, main bearing and gearbox. The main bearing is used to control the torque during start and shutdown of the wind-turbine. The gearbox functions as a means to transform high-torque to low-torque or the low speed of the main bearing to the high speed to the generator. It is often damaged by sudden changes in wind-speed and the resulting shock as well as erosion [2].

2.4 Support system

The support system includes the nacelle, the tower and the foundation. The main reason for failures in the support-system are fatigue, corrosion, welding cracking and collisions with the hull. During extreme weather conditions movement and vibration of a FOWT can become so intense that the hull may be damaged more easily than with their fixed counterparts [2].

2.5 Mooring line

The amount and intensity of stress a mooring line endures is greatly dependent on the technology in use. The mooring lines of Tension Leg Platforms for example experience a continuous tension, while those of barge and spar-buoy foundations experience high tension only during extreme weather [2]. Mooring lines are also responsible for FOWT limits when it comes to water-depth. Although a theoretical 80 % of offshore resources lie within depth of over 60 m and are therefor too deep for conventional bottom-fixed offshore wind (BFOW), most of this area is momentarily too deep for FOWT as well. Currently most FOWT are being built within depth of less than 100 m. It would also be possible to install them in depth of around 200 m when using a special taut-leg (or semitaut) mooring design. However, the deeper the ocean, the more mooring line must be deployed. The mooring line and the foundation will have to endure greater traction and deployment, installation and maintenance costs will rise [3].

2.6 Auxiliary system

The auxiliary system consists of lightning protection, the hydraulic system and cooling system. Due to their height offshore wind turbines are likely to suffer from lightning strikes. These can burn electrical components, control systems and sensors. The hydraulic system provides the pressure needed to control the pitch and yaw systems. It can suffer from pressure loss, temperature errors, responsive issues and motor failure. In order to tackle overheating of generator, converter, hydraulic system and electronic components, a cooling system is required. So far wind-based cooling systems are in general use, but because offshore wind turbines are generally getting bigger, water-based cooling systems with higher thermal capacities are moving into focus [2].

3 Foundation types

Momentarily there are several different approaches to how the base of a FOWT should function. Each one of these designs has proven to hold different advantages and disadvantages over the other. To be seen in Fig. 3.

3.1 Ballast stabilized

Represented by the spar-buoy foundation, to be seen as the left FOWT in Fig. 1. A ballast stabilized foundation provides stability by using a below hanging central buoyancy tank as ballast, creating a correcting moment. It provides high inertia resistance to pitch and roll movement and usually enough draft to offset heave motion. Ballast-dominated designs are likely to heavier and therefor more expensive to build [4].

3.2 Mooring-line stabilized

The tension leg platforms (TLP) represent mooring-line stabilized foundations. To be seen as the central FOWT in Fig. 1. They rely purely on their updraft and mooring line tension to hold them in place. Due to this, they need considerably less mooring line length, but apply more traction on these and the anchors. Tension leg platforms have their base completely submerged [4].

3.3 Buoyancy stabilized

The barge FOWT seen on the right in Fig. 1 represents a buoyancy stabilized foundation. These kinds of foundations rely solely on their up drift. They float above the surface and stabilize thanks to their wide surface contact. Buoyancy-stabilized foundations are more likely to be subject to higher wind loading which in turn has a negative impact on the turbine's dynamics [4].

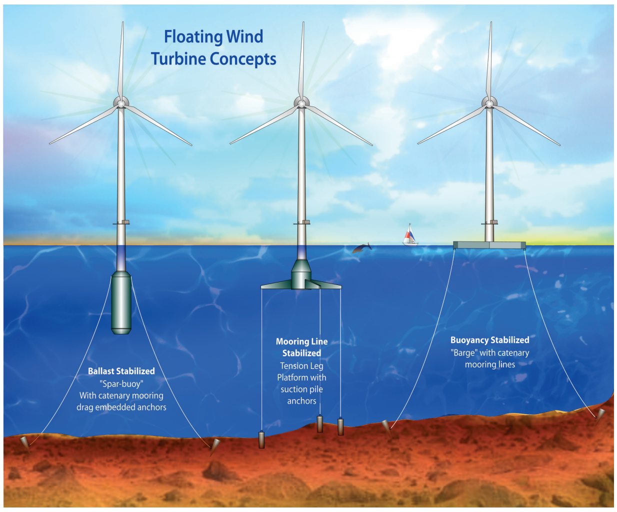

Fig. 1: Ballast-, mooring line-, and buoyancy stabilized FOWT. Image by: (Jonkman, 2009 [5])

3.4 Semi-submerged

Each of these platform types are to be considered idealized vessels with limited properties and each of them provides advantages over the other given specific circumstances. For example, the idealized spar buoy will have a tank with zero water surface friction while providing sufficient ballast below the waterline to offset the tower's movement. The mooring lines would only function to keep the construct in place. Similarly, the idealized TLP would be a weightless tank with zero surface friction and held only by the tension of the vertical mooring lines. Finally, the idealized barge would be weightless and moored only to prevent drifting. Its weighted water plane would be sufficient to stabilize the platform under static load conditions [4]. In practice, none of the above concepts are possible and not favoured in the first. Instead, combinations of the above have proven to provide the most benefits. One of the most popular models these days is a semi-submerged foundation, as seen in Fig. 2. Semi-submerged foundations benefit from both a buoyancy foundation's weighted water friction as well as a ballast foundation's weight stabilization and possibly mooring line tension [4]. Fig. 3 shows several different foundation-designs within the technology-triangle. To be seen are the single-technology designs, namely spar-buoy, barge and TLP. As well as the most commonly installed Concept Marine Associates (CMA) tension leg platform, a semi-submerged type foundation and the Dutch Tri-floater.

3.5 Design tools and methods

The complexity of the task of developing accurate modelling tools will increase with the degree of flexibility and coupling of turbine and platform. Usually this leads to faster response and movements counter-

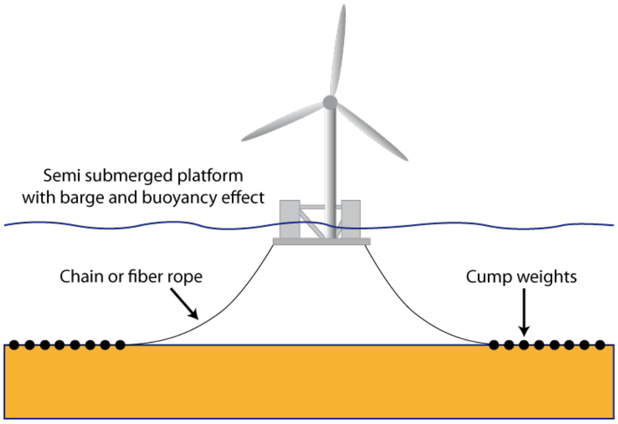

Fig. 2: Semi-submerged platform.

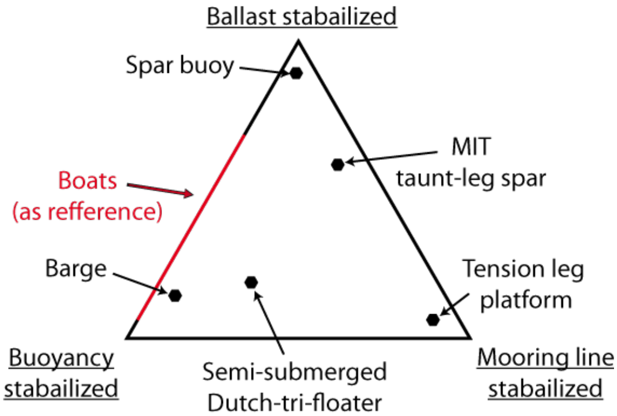

Fig. 3: Floating Platform Stability Triangle showing methods of achieving static stability. According to: (Butterfield et al., 2007 [4])

ing wave and wind loads. Predicting wave loads and dynamics for a relatively stable platform such as the TLP requires new analytical tools but is likely to be less of a problem than for platforms that are exposed to wave loading. Platforms like the barge, which have much of their structure near the free surface, encounter greater pitch, roll, and lift forces. A barge is likely to be more complex to model and validate. Spar concepts have smaller spire movements compared to the barge but can still be exposed to nonlinear wave forces that require more advanced tools.

Additionally, less predictable external influences such as floating debris must be calculated for, when developing design and modelling tools. This also counts for icebergs hitting the structure and marine growth [4].

Tab. 1 provides an overview of relative advantages and disadvantages of idealized platform types. Showing that most commonly the differences are but a matter of costs and are therefore dependent on the local conditions.

Tab. 1: Platform design trade-offs for stability criteria. According to: (Butterfield et al., 2007 [4])

Platform design challenge	Buoyancy barge	Mooring line TLP	Ballast spar
Design Tools and Methods	-	+	-
Buoyancy Tank Cost/Complexity	-	+	-
Mooring Line System Cost/Complexity	-	+	-
Anchors Cost/Complexity	+	-	+
Load Out Cost/Complexity (potential)	+	-	
Onsite Installation Simplicity (potential)	+	-	+
Decommissioning and Maintainability	+	-	+
Corrosion Resistance	-	+	+
Depth Independence	+	-	-
Sensitivity to Bottom Condition	+	-	+
Minimum Footprint	-	+	-
Wave Sensitivity	-	+	+
Impact of Stability Class on Turbine Design			
Turbine Weight	+	-	-
Tower Top Motion	-	+	-
Controls Complexity	-	+	-
Maximum Healing Angle	-	+	-

Key: + = relative advantage; - = relative disadvantage; blank = neutral advantage

4 Risk assessment

One way to determine which parts of a Floating offshore wind turbine (FOWT) are most prone to damage is called risk assessment. This system has been used by (Kang et al., 2016 [2]) to analyse failures and rate them according to their severity (tab. 2), the frequency they appear (tab. 3) and how easy these failures can be detected (tab. 4). Tab. 5 provides a rating of categorized failures by multiplying their severity, occurrence and detection rate. This results in a so called risk priority number (RPN). For example a generator winding failure caused by flawed cable insulation is rated with severity 4, occurrence 8 and detection 5. Resulting in an overall RPN of 160.

4.1 Rating criteria

Tab. 2: Failure severity rating scale for FOWT. According to: (Kang et al., 2016 [2])

Scale	Description	Criteria
1	Minor	Electricity can be generated but urgent repair is required
2	Marginal	Reduction in ability to generate electricity
3	Critical	Loss of ability to generate electricity
4	Catastrophic	Major damage to the turbine as a capital installation

Tab. 3: Failure occurrence rating scale for FOWT. According to: (Kang et al., 2016 [2])

Scale	Description	Criteria
1-2	Unlikely	Probability of $< 0,01\,\%$
3-5	Remote	Probability of $\geq 0,01\,\%$
6-8	Occasional	Probability of $\geq 0,1\,\%$
9-10	Frequent	Probability of $\geq 1\,\%$

Tab. 4: Failure detection rating scale for FOWT. According to: (Kang et al., 2016 [2])

Scale	Criteria
1-2	Current monitoring methods almost always detect the failure
3-5	Good likelihood of detecting the failure
6-8	Low likelihood of detecting the failure
9-10	No known methods available to detect the failure

4.2 Overall rating

5 Results

Tab. 5 shows that electrical failures are amongst the most significant errors of FOWT. From a total of 4872 risk priority number (RPN), 1992 RPN are determined to have an electrical origin. Of these the most common cause was corrosion. It is also stated that the control system is most often affected, and that the generator is frequently involved. Material corrosion is also the key factor when it comes to the most common overall reason for failures.

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Tab. 5: Overall failure rating for FOWT. According to: (Kang et al., 2016 [2])

Scale	Criteria	RPN
Generator	Bearing deformation	676
	Overheat	396
	Winding failure	912
Electrical controls	Convert failure	630
	Transform winding failure	618
	Output voltage inaccuracy	411
	Yaw positioning inaccuracy	333
Support structure	Mooring line fracture	340
Auxiliary system	Cooling system failure	556

It is worth stating that structural components have a much lower failure rating than electrical components. Direct-driven generators have proven especially prone to damage. Giving it the highest RPN value among all sub-systems.

A particular attention must be paid to mooring line fracture. Mooring lines are especially vulnerable to extreme sea conditions and the resulting fatigue, corrosion, impact damage, and further risks. Large-scale wind turbines can be built to over 100 m in height, movement of the floating foundation may cause strong vibrations and swinging of the upper structure. This leads to high material stress on the blades, as well as the transmission and control system. Strongly dependent on the foundation design, determining the perfect balance of flexibility, strength and stiffness of mooring lines has proven to be challenging because even a minor failure could lead to serious consequences [2].

FOWT has only recently matured enough to seriously consider overcoming the technical challenges required to design successful machines. And while floating oil rig stations have provided FOWT with enough technology and experience to overcome these technical challenges, it must be stated that the primary challenge is that of economics [4]. It is technically possible to deploy FOWT in depth of over 200 m but mooring line, foundation support, deployment, installation and maintenance costs will rise. The later three not just because of the additional depth, instead costs will also increase due to the extra distance that has to be overcome when departing from shore. Over time technological costs will decline making FOWT more competitive and hence attractive for greater depth.

6 Solution approach

1. Material corrosion:
   This paper suggests strengthening the preservation layer of the equipment as an effective way to improve the systems reliability [2]. It is extreme important to not only choose the material and layout scheme of the mooring lines, but also optimize floating foundation design in order to minimize the impacts on the construct as well as the marine environment [2].

2. Electrical failures:
   Due to corrosion being the most frequent cause for electrical failures to appear, this issue should be addressed first. However, the control systems are shown to be the most affected and backup systems should be installed. The generator is shown to be involved in many instances of electrical failures which is most likely due to a FOWT encountering more vibration and swinging than their fixed counterparts. This paper recommends developing a more vibration dampening setup for FOWT.

3. Design tools and methods
   Further data must be gathered in regards to the influences of marine life, floating debris, icebergs or marine traffic on FOWT. While certain information gathered from bottom-fixed offshore wind (BFOW) and floating oil platforms can be obtained, FOWT might behave differently when encountering these issues. For example, a FOWT that has been in operation for over 15 years will have a different centre of gravity depending on where marine life has settled along the foundation and mooring lines. Improving the coating of these objects will reduce the influence this effect has on the turbine stability.

4. Maximum water depth
   Although at the moment it is technically only possible to deploy FOWT in depth of up to around 200 m, this is not a technical problem. There is simply no need in researching in this direction, as it would not make any economical sense at this point. Most FOWT are deployed in depth of up to 100 m as overall costs rise depending on water depth and there is still plenty of space in shallower waters. Prices for FOWT technology will decrease over time and once FOWT has become a competitive energy source, technologies for deeper deployment will be developed.

   These results could be useful for FOWT design improvement and maintenance optimization.

7 Outlook

When considering that many failures stand in direct correlation with each other, the system of RPN rating used in (Kang et al., 2016 [2]) seems rather imprecise. There are for example many electrical failures but focusing on improving the wiring might not be the most effective solution to this issue. As many of these failures only occur due to the generator issues. Rather than concentrating on the symptoms the core problems should be addressed.

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