



A photograph of several offshore wind turbines in the ocean under a clear blue sky. The central turbine is in sharp focus, while others are visible in the distance, slightly out of focus. The water is a deep blue with gentle ripples.

Challenges and Expected Improvements in Operation and

Maintenance of Offshore Wind Turbines

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Growth in capacity and size of wind turbines (>10 MW) and installations at greater distances from shore prompted by new technologies such as floating foundations give rise to tougher challenges in operation and maintenance (O&M) of offshore wind turbines. Standard O&M strategies with time-based periodic maintenance and repairs are going to be no longer acceptable if the availability is to be kept at an acceptable level, say greater than 95%.

Important improvements for offshore wind turbines in the future are expected in:

- Development of project specific suitable maintenance strategies,
- Advanced condition monitoring strategies including big data handling,
- Development of inspection strategies for components above and subsea level,
- Handling concepts for components,
- New materials,
- Crew transport and accommodation concepts.

This essay aims at evaluating the challenges and outlining the potential developments and improvements to overcome these challenges.

Development of Project-specific Maintenance Strategies

Customized or project-specific new strategies and approaches, which take into account the location of the project and its predominant environmental conditions, are necessary for increasing the feasibility of operation and maintenance of offshore wind farms.

In the past, maintenance for wind turbines used to be entirely time-based: every six months or so a team would check the wind turbine to lubricate the moving parts and replace the worn ones, if necessary. During the time in between, a somewhat advanced control system operated for continuously monitoring the turbine to give alarm in case of a break down or operation over the specified limits. In time, more advanced condition monitoring systems (CMS) have

been introduced to get a better picture of the conditions of critical components between the maintenance visits as well as early detection of the component degradation as it approaches a critical level. However, the integration between CMS and maintenance planning has never been quite satisfactory.

A change towards condition-based maintenance rather than the customary reactive response appears to be the key for fulfilling the availability requirements and expectations, productivity, and feasibility of offshore wind turbines today and in the future. Also, the operation strategies must be included to get a comprehensive O&M strategy such as reducing the turbine loads by intentionally lowering the power output to prevent component failure when a certain stage below critical level is reached. Thus, the maintenance operation can be postponed until possible or the next scheduled one. Such deferring gives time for getting the components with long leads.

Due to relatively greater distances of the new offshore wind farms from the shore, the environmental conditions (weather, ice, etc.) must be integrated into the O&M strategy to have parts and crew on site when needed. All these indicate that standard O&M strategies are not suitable anymore and project specific adaptations must be done to take into account the overall conditions like the particular environment, water depth, available operation window, distance to shore, availability of parts and tools, and of course the technical details concerning the wind turbine and foundations. Decision making tools can be very helpful to adjust the strategies continuously during the operations as conditions change constantly. In what follows, the key points that give important input for setting up a suitable project specific strategy are discussed.

Advanced Condition Monitoring Strategies including Big Data Handling

Sensor technology generates big data that necessitates definite strategies for handling and utilization. Proper use of available




Figure 1: Improvements and advancements in computational facilities and data collection provide a perfect basis to predict the lifetime of components, for instance, by generating a digital twin model of a wind turbine with all its critical and monitored components.

big data is the key for setting up predictive models of improving robust operation and availability of wind turbines.

Improvements in computational facilities have led to better prediction capabilities for behaviour change of components during wear and tear. At the same time, condition monitoring systems using sophisticated sensor technologies are currently able to record enormous amounts of data (Figure 1). Such advancements provide a perfect basis to predict the lifetime of components, for instance, by generating a digital twin model of a wind turbine with all its critical and monitored components. The digital twin is a computer model, which, together with machine learning algorithms, can predict the estimated failure time. This is achieved by combining the operational data (environmental data, loads, number of emergency stops, etc.)

with component degradation records. The prediction models are continuously refined and adjusted by the utilization of the data from all available sensors attached to the wind turbine and foundation.

Failure-time predictions are essential for maintenance strategies, as these predictions make it possible to plan replacement before failure of components in a condition-based approach instead of the usual time-based approach, thus avoiding potential failure and subsequent loss of energy production.

All these applications show how important it is to have constant, uninterrupted, and timely collection of data from a range of sensors on the turbine and foundation. The immediate transmission and well-organized storage of data is also crucial. In the past, data was used to be stored predominantly for later



Figure 2: Drones operated by humans are used for inspections of rotor blades and tower surfaces. New software solutions for autonomous operation are going to make the drones independent so that inspections will be carried out automatically.

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error sourcing while continuously received data was utilized for operation supervision (thresholds, operation decisions by the turbine controller, etc.) and alarm triggering. This is still valid but online data-utilization for operation and maintenance predictions by implementation of machine learning and artificial intelligence techniques is becoming a key for future wind turbines with highest availability and production. For the purposes of post processing, online processing, and predictions, a clear specification containing sampling rate, storage period, and availability of data must be provided. Any unutilized data that is stored is lost for online processing and predictions.

Development of Inspection Strategies for Components Above and Below Sea Surface

Fully-automated inspection methods by independently operating drones and remotely operated vehicles (ROVs). Drones with swarm technology to complement each other for different inspection technologies such as optical, infrared, ultrasound, etc. Integration in CMS.

The drone technology has developed considerably over recent years, resulting in increased payloads as well as improved accuracy in flights. Presently, drones operated by humans are used for inspections of rotor blades and tower surfaces. New software solutions for autonomous operation are going to make the drones independent so that inspections will be carried out automatically (Figure 2). Collected data as well as definite detections requiring an alarm can be transmitted to the control system and the operation centre. A fully-integrated condition monitoring system can prompt the drone for inspection when a predefined operation time or a specified turbine load level is reached. For inspections inside the tower, nacelle, or foundation, these inspections may be carried out basically independent of weather conditions; it is enough to ensure that the movement of the parts to be inspected remains within defined limits. On the other hand, for inspections on components or surfaces outside the turbine, prerequisite environmental conditions of an inspection

must be met – such as precipitation and humidity on surfaces, and wind speeds must be within definite ranges. However, as the drones would operate independently, the inspection can start at any time when the specific conditions are met without any delay and independent of the availability of human operators. With a variety of optical and ultrasonic sensors being available, inspections on coated surfaces for coating thicknesses and corrosion, on weld seams for fractions as well as tension control on bolts by using ultrasonic or acoustoelastic methods are possible. Rotor blades can be checked for cracks, delamination, or abrasion on leading edge surfaces.

Use of drones for inspection with autonomous activation and execution helps to increase early detection of wear and damages. To accomplish these, the most important factor is, of course, the availability of properly working technology. Any fault on the operation of drones takes away almost all advantages. Therefore, the industry is currently working on the next level of drone applications beyond autonomous operation; namely, the swarm technology. The swarm technology is interactive cooperation and task sharing of multiple drones, which also implies redundancy of sources for all tasks. Use of multiple drones that individually can carry out the same tasks but also complement one another has the following advantages:

- Reduced execution time that provides flexibility for the periods necessary for suitable operation conditions; e.g., less of a time needed for low wind speed conditions in order to do outside inspections or repairs if multiple drones share the work.
- Redundancy to execute the tasks uninterrupted even if 80% or more functions of a drone are inoperable due to faults.
- Double checking of findings.
- Complementary work steps taken by more specialized equipment; if a drone detects a fault, it can activate another one for more thorough inspection or repair.

Besides additional new technology, some design changes in drones are needed to handle all these tasks. Also, drone docking and charging stations are necessary inside and outside of turbines or facilities to exit turbines if stationed inside. Openings in platforms and flight paths should be available for drones to reach the areas of inspection as well as a local 5G network and a positioning system for safe operation.

Quite similar approaches are possible for underwater inspections by using ROVs for tasks such as monitoring and protection of corrosion, scouring, mooring lines, and anchors. Either above or below sea level, utilization of data from drones or ROVs is the key to any O&M strategy. Data are needed for communication between different drones as well as a drone and the control system for instantaneous crucial decision making. Examples include reducing the turbine operation loads to curb fault progress of parts or setting the turbine out of service, detection of weak spots, or design flaws. If available, the data also must be incorporated into a digital twin model to further enhance the lifetime prediction of the whole turbine as well as specific parts. For all these reasons and more, a clear data management strategy with rules for sampling rates, averaging periods, transmission, and storage is essential.

Handling of Components

New features built into wind turbines for reducing the working height in case of replacing key components. Reduced size of replaceable components for better handling. Spare parts and ordering strategies.

Even in the construction phase, the future handling of replaceable parts – in particular wearable ones, but also parts with higher probability of breaking down – should be considered. Especially for larger components, this consideration is a must as these parts first need to be shipped to the site within a suitable time frame and then lifted up to their specific location, supposedly accessible



Figure 3: The future handling of replaceable parts should be considered. These parts first need to be shipped to the site within a suitable time frame and then lifted up to their specific location, supposedly accessible from the ship. There are new concepts under development, for example, that aim at tilting the wind turbine so that exchange of components will be possible with the crane of the ship.

from the ship, and necessary openings in the turbine are available to place them to their proper locations (Figure 3). In such operations, the possibility for disassembling of larger components (segmented rotor blades, generators, inverters, etc.) plays a crucial role as turbine sizes keep growing by time. Floating foundations could be submerged to reduce the necessary lifting needs; telescopic wind turbine towers can also lower the nacelle substantially to the reach of smaller lifting equipment. Also, there are

new concepts under development that aim at tilting the wind turbine so that exchange of components will be possible with the crane of the ship. All these indicate that a combination of segmentation of large components and additional features to lower working heights can reduce the size of necessary equipment for replacement of main components, hence, reduce the repair time as equipment is easier to reach and work can be executed in a relatively wider range of environmental conditions, faster, and more economically.



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Before any component can be handled, it must be available. Typically, spare part pools located on land for larger parts and inside the project at sea for smaller parts are common. However, for a better anticipation of when components are needed, prediction models based on CMS in the form of a digital twin model must be used in order to determine early thresholds of wear or damage for preordering large or long-lead components with the goal to replace them before any break down occurs. Also, better

computer models are needed in the future to anticipate the needs and to integrate preventive replacement of components with condition-based maintenance for keeping the number of visits to turbines to the minimum necessary. This approach works in two ways: either a preventive exchange of parts is done in connection with a due maintenance or a maintenance is carried out in case of a repair task even though the maintenance might not be due but is anticipated. Here, decision tools for the task to be carried out (repair,



Figure 4: Distance to shore, weather windows, and purpose of the mission are all important factors and the size of the project undertaken defines the amount of crew transport necessary. For relatively long distances, helicopter transport is a feasible option over sea transport; however, besides the restriction to fly at night, the weather conditions are important limiting factors.

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preventive exchange, maintenance) and the means of handling the components needed (barge, crane, tugging a floating turbine into the port, etc.) are playing a key role for successful executions in timely manner.

New Materials

Self-healing features of components and reparability without replacing.

For reducing the rate of replacement of parts and shortening the time of repair, new materials for various components are expected to play a big role in the future. Also, new sensor technologies will help to predict the wear and lifetime of components.

Currently, rotor blades are built from epoxy based resins. These, once cured, can only be repaired by replacing the materials at damaged areas in the way original manufacturing was done. Thermoplastic resins are offering a very promising improvement as they have self-healing effects when heated. For example, when drones detect cracks or other damages on the rotor blades, the healing process can be started by appropriately heating the damaged area to activate the self-healing properties of the material. This can be done by drones with suitable equipment from the outside or by embedded heating elements inside the laminae of the blade in a very short time. Obviously, large structural damages in the rotor blades

still require complete replacement. A similar approach is applicable to the coatings with self-healing properties that can be activated by heating. These coatings are suitable for composite surfaces but might be used for steel surfaces as well in the future.

Concrete will play a substantially larger role in the future of offshore wind turbines in the foundations, especially for floating wind turbines but also for fixed ones. As these parts are mainly underwater, any sort of repair is time consuming and costly. Concretes with embedded materials exhibit self-healing properties which provide a substantial improvement in saving time and cost. Several technologies are in development or already available. Such improved concretes are also expected to be useful for structural surfaces underwater and structures in splash zones as waterproof concretes do not need coatings.

New sensor technologies based on nanotubes embedded in rotor blade laminate as well as intelligent sensors with AI functionality are likewise anticipated to improve the CMS and therefore the predictability of components wear and lifetime.

Crew Transport

Availability of crew on site is essential to reduce downtimes and better plan maintenance.

Distance to shore, weather windows, and purpose of the mission (inspection, repair, etc.) are all important factors and the size of the project undertaken defines the amount of crew transport necessary. Economical evaluations for selecting the means of transport must be done (ship or helicopter; Figure 4). For large projects far offshore, hotel platforms might be considered with crew permanently on site (replacement of crew in regular missions, but flexible enough for weather conditions). Also, hotel ships are an option.

While technology plays a major role to keep the turbine availability on high levels and

optimize the energy production, manpower is still essential for maintenance and repairs. A key challenge here is the availability of crew in the wind farm when needed. With the impetus of new foundation technologies, floating offshore platforms would become more mature, thus making projects with larger distances to the shore possible. For reaching long distances, the use of available short weather windows is a real challenge as the transport is quite time consuming. For relatively long distances, helicopter transport is a feasible option over sea transport; however, besides the restriction to fly at night, the weather conditions are important limiting factors. A presently used solution is to resort to service operation vessels (SOV) that can stay at wind farms for up to several weeks while hosting the technicians like a hotel ship. This choice gives the possibility to use short weather windows and makes technicians available on the site. Another solution, especially for larger projects or several projects in the same area, are hotel platforms to host technicians. This alternative is more convenient than SOVs, as hotel platforms are more weather independent and stable.

New technologies in crew transfer vessels (CTV) that bring personnel to turbines have, to some extent, reduced the restrictions from environmental conditions. Ships can operate at severe sea conditions with higher waves and hydraulic gangways that compensate the effects of wave forces make wind turbines more safely accessible. Yet, further developments for safe and fast access to the turbines are necessary, in particular for cargo transfer (tools and parts) from the CTVs to the turbines.

Operation and maintenance strategies should aim at reducing break downs by the use of CMS and, if necessary, employing reduced power operations so that maintenance and replacement of parts can be planned ahead and no repairs due to break downs are needed. It must always be borne in mind that if a turbine is to stop due to an error or break down, then setting it back to operation requires personnel

and such an operation reduces the availability. Every 87.6 hours of stop due to error or break down reduces the availability by 1%, and 3.6 days of unfavourable weather conditions are not unusual especially in winter time.

Concluding Remarks

Preceding arguments clearly reveal that the classic approach of time-based maintenance and operation until break down and then repair is not only outdated but also putting any offshore wind energy project at risk of being unfeasible. The credo must be the least possible maintenance with the highest flexibility, and only when anticipated. Therefore, a fully integrated approach is needed, combining the latest developments of wind turbine technologies and material science with strategical decision tools, predictive models, and strategies for crew availability in order to make offshore wind a reliable backbone of the future energy supply. ∞



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