Offshore Wind Turbines

Subjects: Energy & Fuels

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Keywords: offshore renewable energy ; O&M planning ; condition monitoring ; condition-based maintenance ; SCADA ; fault diagnosis/prognosis ; floating wind ; digitalisation ; soft sensors ; robotics ; Industry 4.0

1. Introduction

The offshore wind sector has grown significantly over recent years, reaching a total of 29.1 GW (over 10% of global wind installations) [1]. Previous experience with onshore wind turbines, combined with noteworthy investments, has allowed offshore wind to become one of the most viable and profitable ways of generating electricity [2]. Besides, in order to exploit stronger and more stable winds and to overcome the limitations related to the use of seabed-fixed foundations, there is a growing interest in floating offshore wind [3]. With offshore wind turbines at a mature stage, and considered reliable and consolidated machines, the margins for enhancement of the technology itself and of already installed turbines themselves are becoming increasingly limited. Nonetheless, there is a necessity to operate and maintain these assets efficiently and effectively, allowing them to reach high levels of availability and productivity.

Operation and Maintenance (O&M) has been recognised as one of the main contributors to the overall cost of energy, typically amounting to 25–30% of the lifecycle costs [4]. Production losses due to downtime over 20 years of operation have been estimated at around 12 m€/year for a 500 MW offshore wind farm situated 50 km offshore in the North Sea [5]. Assuming this would be representative for other sites, the average annual production loss would be €24 k/MW. Therefore a suitable trade-off that allows us to keep the farm availability high while maintenance costs remain low is required [6]. To achieve this goal, a decision maker, such as an ORE farm operator, can generally act on two main aspects of the farm management: (i) the reliability and maintainability of the devices, e.g., number of interventions and redundancy measures, or (ii) the supportability, e.g., choice of the most suited vessels or helicopters and allocation of related routing and technicians.

This work mainly focuses on the first aspect, i.e., the maintenance of the components and subsystems of an ORE asset. The aim of the paper is to provide a holistic and exhaustive overview of the currently available methods and techniques, as well as identify future trends in the ORE O&M sector. For this scope, established maintenance strategies usually available for ORE devices are reviewed. Health monitoring, diagnosis and prognosis methods, which together open the way to condition-based maintenance, are addressed. Maintenance practices in other industries are reviewed to explore the extent of knowledge transfer to the ORE sector. Recent efforts at and future trends towards automation and digitalisation of the maintenance tasks for offshore assets are investigated and discussed.

2. Operation and Maintenance of Offshore Wind Turbines

A number of established and innovative solutions for ORE devices O&M have been investigated, together with techniques currently used in other industries but with the potential to be applied also in the ORE sector. In this section, these methods are discussed taking into account the different perspectives of various stakeholder categories, namely a farm owner, a technology developer and a maintenance contractor.

A farm owner aims mainly at maximisation of the profitability, and should prefer a holistic approach able to optimise several aspects at once, including risks reduction. For this reason, maturity of the technology and potential for cost reduction will be favoured, together with solutions that are practical to implement and easily extendable to a large number of devices. Although the use of CM is consolidated in the ORE sector, a number of challenges remain in the integration of CM systems with automation and controller systems. Meaningful organisation of the information retrieved from different sources is required to obtain an understanding of the asset with a single scrutiny, instead of different and separated analyses which do not necessarily provide the full picture. The technological challenges and additional expenses caused by the integration of sensing and communication instrumentation, and the consequent increased energy consumption, as well as the creation of standards and protocols to collect, store and process data, must be taken into account. In this regard, while trade-offs exist between accuracy of fault prediction and additional costs of sensors, the use of operational data collected through SCADA can improve diagnosis and prognosis at no extra cost [7]. Besides, solutions to power the sensors and to deliver the signal are needed for an effective implementation of CM systems. In this regard, cabled solutions would be easier to maintain due to power requirements, but wireless solutions are more practical for non-invasive monitoring. Energy management solutions to guarantee continuous data collection and transmission are also an important aspect of this integration. While most CM systems are based on NDT techniques, the progress in monitoring electrical components and control systems has been slower and component specific.

A maintenance contractor will look mainly at the feasibility and practicality of the O&M solution, preferring solutions that are simple, effective and safe to deploy. For instance, in offshore wind turbines, the harsher environment, remote location and increased complexity in accessibility make the application of novel technologies more challenging compared to their onshore counterparts. However, as shown in the works reviewed for this paper, these limitations are additional reasons to justify the adoption of modern computational approaches in the O&M of offshore wind farms. Risk minimisation (health and safety) is the utmost priority, but the business is focused on reaching pre-contracted reliability, availability and maintainability (RAM) targets. Robots will play an increasingly important role in producing easier, safer and more productive maintenance practices for offshore renewables. Currently, a mix of fully autonomous (i.e., able to work independently) systems and technologies requiring manual support (remote control) is considered the most appropriate approach at this stage. As the use of automation increases and maintenance management becomes digitalised, suitable measures are needed to ensure that vulnerable processes, the equipment and the generated data are resilient and protected. This creates the need for new requirements in cybersecurity and good practices in the offshore sector, governed by data sharing and collaboration among operators. The ORE Catapult is currently addressing these issues by promoting a “Wind Digital Innovations Forum” [8]. Blockchain [9][10] is another novel technology that can offer support in this topic, by providing a decentralized, verified and secure way of handling the exchange of data and information. These actions can be summarised as the creation of a digital supply chain which guarantees the effective and successful generation, transmission and elaboration of data. The most needed data types in this context will be those related to the current and expected reliability of the various components. However, even if deterioration and RUL can be precisely estimated, and therefore the right time for maintenance accurately identified, other factors like supportability and accessibility have to be taken into account. These restrictions assume higher importance as the distance from shore increases, because the opportunities for maintenance will be narrowed down to fewer weather windows. On a related note, although sensors and other instrumentation can provide valuable support in establishing adequate maintenance and inspection intervals, the accurate assessment of other resources, e.g., materials and labour, remains fundamental in order to establish the optimal maintenance framework.

Technology developers want to propose innovative solutions aiming at impact maximisation, actively involving industry and academia and investing in those solutions with greater potential for cost reduction or RAM increase. Intelligent predictive maintenance relies on a series of innovative techniques which build the fundamentals of Industry 4.0. These techniques, e.g., AI, DM and IoT, need to be further investigated and developed according to the specific requirements of the ORE sector. The benefit of data mining techniques and Big Data lies in the more effective and efficient use of existing and additional data streams, in order to establish and utilise the relationships between the environment, operation, performance and reliability of offshore wind assets. The challenge in the specific application will be to decide which part of the data stream is processed at the edge (e.g., wind speed is typically recorded and 10 min averaged at the turbine) or streamed to the data centre and computed there. An effective dashboard and alert system will be important to enable the overview of the asset status and the prioritisation of O&M tasks.

Another important aspect in this regard is the reliability of the data collection network. Recently, due to the Covid-19 pandemic, weather forecast accuracy has significantly decreased due to the loss of the data provided by commercial aircraft, on which weather models rely for their calibration [11]. Similarly, since prognostic models rely on the data from the ORE project, inaccessibility to data due to any sort of prolonged disruption in the collection and transmission network would negatively impact the automated decision making. Maintenance operations might be anticipated or delayed, or human intervention required. Thus, redundancy and reliability of sensing and transmission devices under unexpected situations are important to transition to an automated O&M model. Soft sensors provide a valuable alternative to the purchase and installation of hardware instrumentations. As long as real-time measurements can be taken from a different source and a representative correlation and estimation algorithm is implemented, the use of soft sensors can open a wide range of possibilities in the condition monitoring scenarios. Several classifications and ramifications exist for modern techniques of machine automation and intelligent algorithms. The boundaries between one field and the other, as well as the links between topics such as AI, ML, DM and statistics, are not well defined. The choice of one methodology over the other, or a combination of them, is problem and constraint specific.

The increased use of innovative digital and data-based techniques, in the renewables sector, is part of the "energy digitalisation" [12]. Three main branches of digitalisation are shaping the energy sector. These are graphically summarised in Figure 1, and to different extents are all transferable to the ORE sector, either directly or after adaptation.

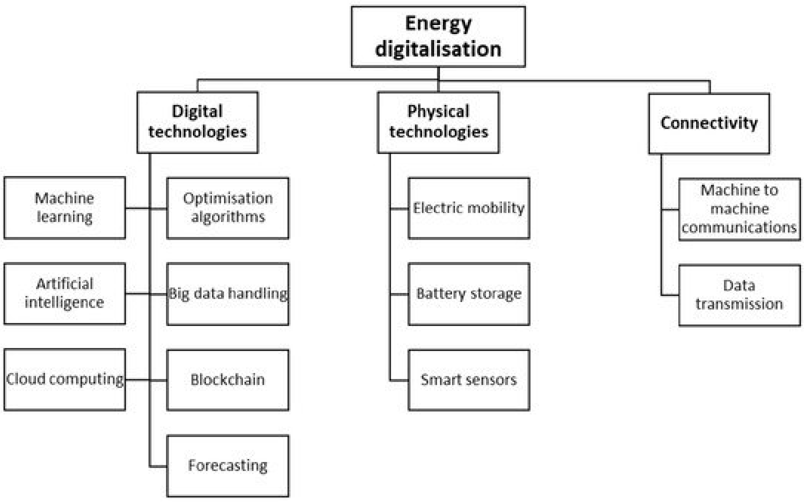

Figure 1. Technological changes defining the shift towards energy digitalisation. Adapted from [12].

In the light of these considerations, the methods and technologies investigated throughout the paper have been ranked against a range of eight categories in order to assess innovative solutions and obtain recommendations for stakeholders in the ORE sector. The outcomes of this ranking (in a score of 1–5, where 1 = lowest contribution and 5 = highest contribution to the selected category) are shown in Figure 2. It should be noted that a high score is not necessarily positive (e.g., investment), and as such, an aggregated score is not calculated. Anyhow, comparing different technologies on the basis of a single score would be limiting because these act on different aspects of the O&M support and should be seen as complimentary to each other (provided case-specific feasibility) rather than competing.

Category	Method / Technology	Practicality	Maturity	Complexity	Suitability to ORE	Investment needed	Industrial participation	Potential (Cost reduction)	Potential (RAM* Increase)
Traditional technologies	Mathematical models	4	5	4	4	1	1	3	2
	Computational tools	5	4	4	4	3	4	4	3
	Condition monitoring	3	4	3	4	5	5	4	5
	Condition-based maintenance	3	3	5	5	3	4	5	5
Physical technologies	Inspect-and-repair robots	3	2	4	5	4	5	4	3
	Drones	3	4	3	4	2	4	3	2
	Autonomous Vessels	2	2	5	4	3	5	3	3
	Soft sensors	4	2	4	3	2	4	4	4
Digital technologies	Digital Twins	3	3	5	4	4	5	5	5
	Data mining	2	2	5	4	3	4	3	4
	Machine learning	3	4	3	3	2	4	3	4
	Artificial intelligence	2	3	5	4	3	4	5	4
Connectivity	Internet of Things	2	2	5	3	4	4	5	4
	Big data	1	1	5	4	4	5	4	3

Figure 2. Assessment of the investigated O&M methods and techniques. * RAM = Reliability, Availability, Maintainability.

From this table it can be observed that all methods are widely suitable to the ORE sector and require intense industrial participation. Solutions requiring a greater investment are generally more complex and less mature, but also those with the highest potential for cost reduction and RAM increase. Due to their complementarity, one technology should not be favoured over another. Besides, as discussed above, different stakeholders may have different interests. Hence, traditional technologies, which are practical and inexpensive, should be preferred by project managers during the initial phase of a project, e.g., development and consenting. Physical technologies should be of interest to maintenance contractors and asset operators concerned with daily O&M interventions, improving them with digital technologies once enough experience with the project (i.e., data) has been accumulated. Finally, innovative connectivity solutions should be considered by site managers in order to support the overall O&M effectiveness.

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