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Availability Improvements from Condition Monitoring Systems and Performance Based Maintenance Contracts

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Abstract

Condition monitoring systems and performance based maintenance contracts have the potential to significantly reduce the cost of energy (CoE) for offshore wind turbines. This paper describes the condition monitoring systems (CMS) available for offshore wind turbines. It details how CMS can be used in condition based maintenance (CBM) strategies and discusses the advantages and disadvantages of using CBM strategies over time based maintenance (TBM) strategies. The paper also provides and compares the results from an empirical availability analysis on an offshore wind turbine population that has condition monitoring systems and a population that does not. Based on the comparison of these results conclusions are drawn on the value added by condition monitoring systems.

This paper also focuses on performance based maintenance contracts (PBMC) and provides an overview of what performance based contracts are currently on offer and what guarantees they provide. An empirical availability analysis is also carried out on a population of offshore wind turbines with performance based maintenance contracts and a population without. These results are then compared and conclusions are drawn on how much value PBMCs add. These analyses show that offshore wind turbines that utilise CMS have on average ~4% higher availability per year and the population with PBMCs showed an availability ~2.5% higher than the population without.

1. Introduction

As wind farms move offshore the business case for condition monitoring systems (CMS) improve as it is claimed their use leads to reduced downtime through early warning of failures. Wind turbine manufacturers that carry out maintenance also claim that their PBMC increase availability or energy production. These PBMCs come with guarantees in the form of availability or production based guarantees. If these performance guarantees are not met the manufacturers pay compensation and in some case if the guarantees are exceeded the extra generation is shared between the wind farm owner and manufacturer. This is known as upside sharing.

Both CMSs and PBMCs are the focus of this paper. The aim of the literature review and market analysis is to provide an overview of the types of condition monitoring systems currently available or being researched, how they work and their advantages and disadvantages. The use of these systems in condition based maintenance (CBM) strategies and the potential advantages CBM strategies provide over time based maintenance (TBM) strategies is also discussed. It is also the aim of the market analysis to provide an overview of the performance based maintenance contracts currently offered by wind turbine manufacturers. This overview describes how these maintenance contracts work, what they guarantee and their advantages and disadvantages.

The remainder of the paper will detail an empirical analysis that aims to quantify the benefits or drawbacks of the use of CMS and PBMCs in terms of availability improvement or reduction. This empirical availability analysis was carried out on a population of offshore wind turbines from a number of different wind farms located throughout Europe. The majority of the wind farms in the analysis have both CMS and PBMCs. However some did not and it is the analysis and comparison of both population groups that allow for an empirical quantification of benefits or drawbacks.

2. Methodology

The first step in completing this paper was carrying out the literature review and market analysis on CMSs and PBMCs. The next step in this paper was to work with an industrial partner to obtain empirical offshore wind farm availability data. This data was then split into the subgroups detailed in section 4. An availability analysis was then carried out on each failure group. Once the availability difference in failure groups was obtained a rough estimate of the cost of lost production from the failure groups without CMS and PBMCs were obtained using a similar method to that used in reference [1]. In this method an annual lost production cost is obtained by using the availability difference and a production estimate for an average 3.6MW offshore wind turbine [2] and the ROC rate of £45/MWh with two ROCs/MWh for offshore [3]. Conclusions are then drawn on the availability and cost improvements obtained by the use of CMSs and PBMCs.

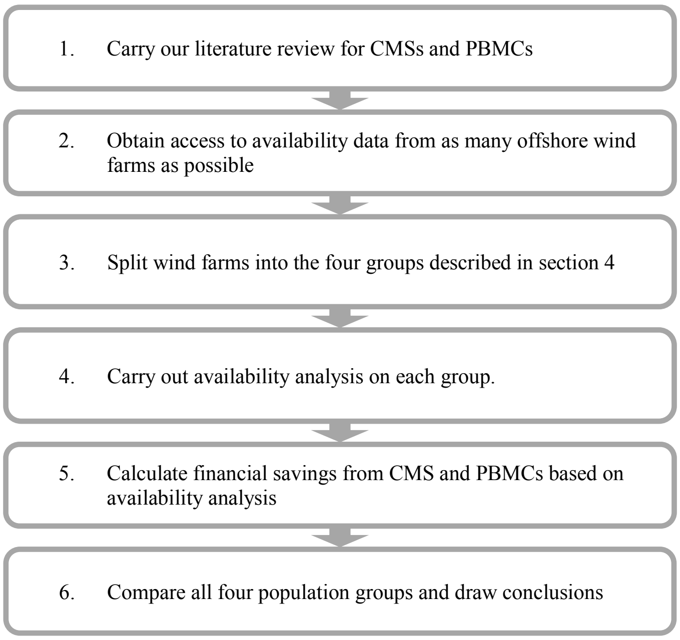


Figure 1. Flow chart showing work carried out

3. Literature Review and Current Market Analysis

This section of the paper looks at the CMS options available, what they monitor and how they contribute to decision making and maintenance strategies. It also provides an overview of the types of PBMC offered by wind turbine manufacturers.

3.1 Overview of CMS systems

The following overview is based on several review studies including the work of Garcia Marquez *et al.* [4], Takoutsing *et al.* [5], Ciang *et al.* [6] and Sinclair Knight Merz [7].

It focuses on remote real time communicating condition monitoring technologies that have been developed to a commercial level for the turbine. This excludes some common static inspection technologies such as thermography or ultrasonic testing which may be able to deliver real time condition in the future. Condition monitoring equipment for the monitoring of offshore cabling allowing the export of power is also excluded from this study. An overview of the technologies and their applicable subsystems taken from the studies above are shown below in Table 1.

	Vibration Analysis	Acoustic Emission	Oil Analysis	Strain	Shock Pulse Method	Displacement	Optical Fibre	Electrical Effects	Temp.
Gearbox	X	X	X		X				X
Generator	X				X			X	X
Bearings and Shaft	X				X	X			X
Blades		X		X			X		
Tower		X		X		X	X		
Foundation		X		X		X	X		

Table 1: Types of CMS and their applicable subsystems

3.1.1 Drive train condition monitoring

The drive train is one of the most commonly monitored systems where the drive train includes, the main bearing, shaft, gearbox and generator. These components have been identified as critical to keeping availability high [8]. As a result, there are many technologies that have been exploited to monitor them. Vibration analysis (VA) is the most common form of monitoring for these components and are a requirement for CMS by insurer Allianz [9]. The same document by Gellerman describes other technologies that are well established and could be expanded into Allianz's scope for a CMS monitoring the drivetrain. These include: displacement sensors for bearings and shafts, oil analysis for the lubrication systems of bearings, electrical parameters for the generator windings and temperature measurement of the entire drive train.

Sensors, such as accelerometers, can be applied to the gearbox, generator and bearings. These tend to have two data collection modes: continuous low frequency (< 50 Hz) and on demand diagnosis high frequency (> 10 kHz) [10]. The low frequency mode is used to collect and compare trend information about the operation of the turbine and components. If the system notices an anomaly, the high frequency mode is activated to collect a diagnostic sample. This can be analysed either by the CMS or sent back to a control centre for further analysis.

There are multiple ways to analyse this data to obtain useful information. First it must be collated with other operational parameters – the current operating conditions of the turbine affect how the drive train rotates and vibrates. Time (wavelets, envelope analysis) and frequency (Fast Fourier Transform – FFT) domain analyses are commonly used. Reviews of these algorithms and techniques can be found in the work of Lei *et al.* [11] and Hameed *et al.* [12].

Vibration analysis has the largest number of commercially available systems compared to other systems [10]. In the study by Crabtree, there are 14 systems mentioned based primarily on drive train vibration, most of which use FFT frequency domain analysis to ascertain the condition of components. Examination shows that some of the smaller companies mentioned have ceased trading, however, the large commercial CMS manufacturers remain the same: Gram & Juhl, Brüel & Kjaer, SKF and Bently Nevada (now owned by GE).

Acoustic Emission (AE) is mentioned in several of the above studies as a possible alternative or addition to VA. Piezoelectric transducers capture high frequency stress waves (> 50 kHz) released by deformations altering the internal structure of materials such as cracks. The sensors record sound directly. AE can achieve higher signal to noise ratios than VA but have a relatively narrow detection band [13]. Curtiss Wright [14] and Mistras Group [15] have both produced documents showing commercial offerings for wind turbines. However, not much information can be found about successful deployment of the technology.

Oil analysis (OA) has been an important tool for monitoring the condition of components for a long time. Monitoring the oil can inform the operator about the state of the lubrication system, any contamination in the system (such as moisture or water) and degradation of components. The majority of tests have taken place offline with sample collection. Hamilton and Quail give a review of online OA techniques [16]. Electromagnetic sensing, screen filtering and optical particle counting are some of the common methods of online analysis. OA can show evidence of deterioration before it is evident with VA [4]. Some of these techniques can be further applied to wind turbine hydraulic systems [8]. There have been commercial sensors available from manufacturers such as GasTOPS, Macom and Pall Corporation.

The Shock Pulse Method (SPM) is used by the manufacturer SPM Technologies and has been endorsed by insurer Allianz for monitoring the drive train [17]. Mechanical shocks in these components are generated and reverberate through the component, for example, when a bearing roller strikes debris or a pit on the raceway. It is this shock level that is used as an indicator of condition.

Displacement sensors are useful for measuring the relative movements of rotating components such as bearings and shafts. This can aid in the determination of loads, degradation and misalignment. Sensors typically use eddy currents or induction to determine distance [9].

Machine current analysis is one of the electrical effects that are used to detect issues with electrical generating equipment. Other techniques are available for power electronic equipment such as transformers or switchgear. These included discharge measurements [8].

SCADA systems are commonly used to monitor the process and operating parameters. These can be used to monitor, trend and improve the performance of the wind turbines. One of the data points commonly recorded is temperature. Temperature can be used to monitor the condition of bearings, oil and generator. In rotating equipment, an increase in temperature can be an indication of increased wear or misalignment. Poor electrical contacts can also increase the temperature of components [5].

3.1.2 Blades, Tower and Foundation

The structural components of the blades, tower and foundation have fewer moving parts and a much longer term outlook than those of the drivetrain. The data collection frequency is typically much lower than that of the drive train (< 5 Hz) [10].

Strain measurement (SM) is a common way of monitoring the loading and vibration being applied to a structural component. Strain gauges are applied to structural hotspots. These can be installed along with accelerometers or displacement sensors to monitor and correlate this data with the sway and movement of the structure [18]. Strainstall are one of the companies that produce strain based offshore structure monitor systems. The grouted connection between the foundation and tower has received much attention recently and the design code was changed after several failures [19]. The monitoring of this transition piece has become common [20]. The processing of collected strain data is covered in the work of Antoniadou *et al.* [21].

This knowledge can extend the life of components by reducing the model uncertainty in the design as well as reduce inspection and repair costs. SM can also be used to conduct modal analysis. Changes in modal properties can be a clear indicator of structural damage. Icing of blades can cause damage and reduce performance. Some blade strain systems can be used as an ice detection system.

Strain can also be measured using optical fibre systems. Optical SM of blades using Fibre Bragg Gratings (FBG) is being offered by manufacturers such as FiberSensing. FBGs are etched optical fibres that can be retrofitted into blades and structures or embedded during manufacture. These etched gratings change shape when strain is applied, changing the properties of the reflected light [17]. Instead of gratings, fibres can also be corrugated to affect the properties of light – known as microbending. Optical SM is not just limited to blades with commercial systems developed by WindForce GmbH utilising FBG [22] for the tower and foundation. Further systems are being developed by the research group BruWind [23] and ECN [24].

Acoustic Emission (AE) for blades and structures has been shown to be effective [25] but there has been limited commercial exploitation of this technology. This is possibly due to large number of AE sensors that would be required to be deployed for complete structural monitoring [6].

Additional systems that are available for use on offshore structures include scour and corrosion systems. Scour occurs when the seabed around the base of a monopole or structure changes. Normally sediment is removed over time, which can undercut foundations. Acoustic echo sensors are available from Nortek AS or OSIL that monitor the level of the seabed. Zensor are a Belgian company that offer several types of probes and electrodes to monitor corrosion. These probes are suspended below the tower into the foundation to monitor corrosion and pass information to a data collection unit in the base of the tower.

3.2 Maintenance Strategies

The CMSs described in the previous section can be used in a condition based maintenance strategies. As turbines move offshore, condition based maintenance strategies or hybrid strategies (combining condition based and time based strategies) will become more common. The following paragraphs explain time and condition based maintenance strategies and how CMSs are utilised within them.

Time based maintenance (TBM), also known as calendar or schedule based maintenance, occurs at set intervals. These intervals can be determined by fixed periods of time, operating hours, cycles or distance. This is useful where components operate with little variation in operating conditions and deteriorate in a reliable, repeatable, well understood fashion.

Condition based maintenance (CBM) uses inspections and monitoring equipment to understand the condition that the equipment is in. This allows for maintenance actions to be scheduled only when required – when it has been observed that a component or system is operating in or approaching a degraded state. This is useful for when the equipment operates in variable conditions, or deteriorates in an uncertain or unpredictable fashion [26].

Offshore wind turbines have particular attributes that separate them from other forms of power generation in terms of maintenance, including onshore wind. Onshore wind farms have most often used TBM strategies to obtain high availabilities but the availability level has dropped offshore [27]. In theory, the major advantages of utilising a CBM strategy over a TBM strategy are the reduction in maintenance actions coupled with the extraction of as much of the remaining useful life and hence value of components as possible [28]. If degradation can be detected far enough in advance, spares levels and other logistic tasks can be managed efficiently reducing overall downtime.

An effective CBM strategy is dependent on having CMSs that are robust and reliable. The CMS itself is an additional system layer with extra costs and maintenance requirements. The measurement system will also have an uncertainty attached to its measurements. Every mechanical system has different parameter trends making condition thresholds difficult to set. The data needed for determining the condition level can be quite large and this needs to be communicated to the operator.

A hybrid maintenance strategy of TBM and CBM has been used for offshore wind farms with CBM being used to adjust the scheduling of TBM actions or group of actions [29].

3.3. Performance Based Maintenance Contracts

Many turbine manufacturers offer PBMCs for their turbines. These vary in their level of support and guarantee. The information below regards the offerings available from Siemens Wind Power [30], Vestas [31] and GE [32]. This list is not exhaustive but chosen for the amount of information publically available about the products. Other manufacturers have indicated that they will offer similar contracts such as Alstom Power [33] and MHI Vestas [34].

Siemens Wind Power’s most basic PBMC that includes an availability clause is the SWPS-200A. This includes remote diagnostic services and servicing. The most advanced PBMC also includes individual component warranties and the inclusion of offshore logistic costs, where – in certain situations – Siemens will utilise their own fleet of helicopters and service vessels.

The AOM (Active Output Management) 5000 is the most advanced PBMC offered by Vestas. This offers an “energy-based availability guarantee that maximises output”. This agreement and some of their lower level PMBCs include a 97% availability clause.

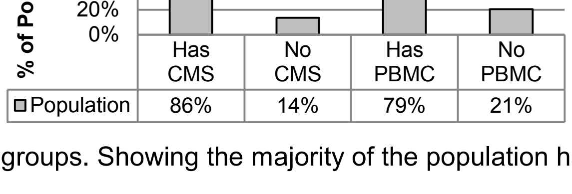
Finally GE’s EPSA (Extended Parts and Services Agreement) and FSA (Full Service Agreement) PBMC include availability guarantees and coverage for completing manual resets. The more advanced FSA further covers unplanned maintenance actions and turbine performance review with an aim for turbine life extension.

These contracts appear to be designed to remove large amounts of perceived risk of offshore maintenance from the operator/owner at a fixed premium. Some contracts focus on the lifetime operation or extension of turbine life while others look to remove the unpredictable costs of service vehicle fleet management. The production based guarantees offered from a couple of manufacturers stand out as particularly interesting– they are of benefit to operators by forcing maintenance actions to be moved to low-wind periods, thereby maximising energy capture.

4. Analysed Population Overview

The overall population size is between 400 – 500 offshore wind turbines. These turbines come from between 7-12 offshore wind farms located throughout Europe. The wind farms operational years range from 3 to 9 years. The turbine types are gear driven turbines with induction type generators. This overall population is made up of two different turbine types with different rated powers and rotor diameters. They have a rated power between 1.5 and 4 MW and a rotor diameter of between 80 and 120 metres. Overall this population provides ~24.2 million turbine hours of operational data which is equivalent to ~2760 turbine years. Exact turbine numbers, location, types, rotor diameters and rated powers cannot be provided for confidentiality reasons.

The overall population can be categorised by two variables: (a) whether there is a CMS or not and (b) whether there is a PBMC or not. These sub-populations can be seen in Figure 2. The first two groups show that 86% of the overall population has CMS and 14% does not have CMS. The next two groups show that 79% of the population is subject to PBMCs and that 21% is not subject to PBMCs.



	Has CMS	No CMS	Has PBMC	No PBMC
▨ Population	86%	14%	79%	21%

Figure 2. Population Sub-groups. Showing the majority of the population has CMS and PBMCs

Turbines in the four groups from Figure 2 can overlap with each other so for example some of the same turbines in the “Has CMS” group are in the “Has PBMC” group. This overlap can be seen from the Venn diagram in Figure 3. It shows that 79% of the population has both CMS and PBMC, 14% has no CMS or PBMC and 7% have CMS but no PBMC.

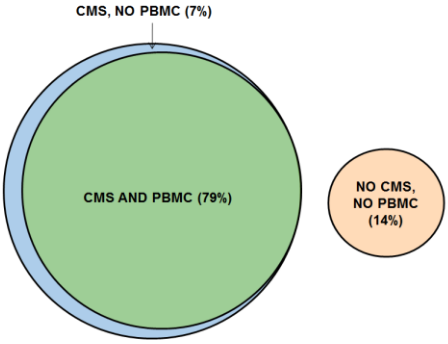


Figure 3. Population Sub-groups. Showing the overlap of sub populations.

In the population group that has condition monitoring systems, the type of condition monitoring systems used are drivetrain vibration and temperature sensors. The population groups that have production based maintenance contracts are a mixture of both production based and availability based guarantees.

5. Results and Discussion

The following results were obtained through an availability analysis of the population groups described in Section 4. Figure 4 shows that there is approximately a 4% difference in availability for the population analysed that had CMS and the population that had no CMS. Availability is determined by the failure rate and the downtime of the populations analysed. The failure rate and downtime can be influenced by many factors such as: distance from shore, population age, rated power of the turbines and mean wind speed. All of the factors mentioned above, except population age, were in favour of the population that had no CMS, i.e. the “No CMS” population group was closer to shore, had a lower rated power and had lower mean wind speeds. Most importantly the “No CMS” population had a slightly lower failure rate overall, indicating that the lower availability for that sub-population can only have been driven by longer mean times to recovery. As the “No CMS” group is closer to the shore this higher downtime is not driven by longer travel times to the turbines. The mean wind speed is also lower, suggesting that the longer downtime is most likely also not driven by weather-related inaccessibility. Together these imply that the difference in availability is down to longer lead and repair times, both of which can be influenced by CMS. Without further study it cannot be said for certain that the reduced downtime and ~4% greater availability for the population with CMS is solely down to the CMS. However the authors feel that it is fair to conclude that the CMS is one of the main reasons for the lower downtime and higher availability due to the better O&M planning that CMSs allow.

Figure 5 shows that there is approximately a 2.5% difference in availability for the population analysed that had PBMCs and the population that had no PBMCs. As with the “No CMS” population, the No PBMC population is closer to shore, has a lower rated power and has lower mean wind speeds. But most importantly the “No PBMC” population also had a slightly lower failure rate overall, once again indicating that the lower availability for that failure group could only have been driven by higher downtimes. As explained earlier, this downtime is not driven by travel times or inaccessible days so it must again be due to increased lead and/or repair times. As with the CMS, while it cannot be said for certain that the reduced downtime and ~2.5%

greater availability for the population with PBMCs is solely down to the PBMC the authors feel that it is fair to conclude that the PBMC is one of the main reasons for the lower downtime and higher availability due to the extra financial pressure the PBMC places on the manufacturer to reduce lead times and carry out the repair tasks as quickly as possible.

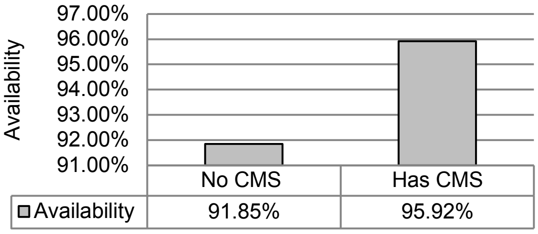


Figure 4. Availability of No CMS population group vs. Has CMS population group. Showing a difference of ~4%.

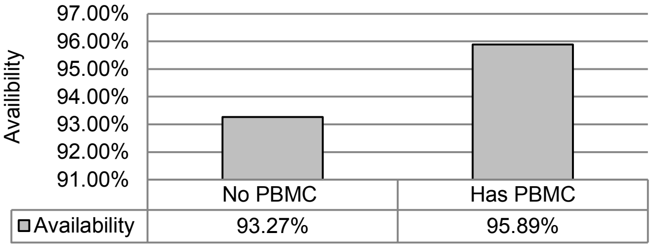


Figure 5. Availability of No PBMC population group vs. Has PBMC population group. Showing a difference of ~2.5%.

As described in Section 2 a rough estimate of lost production costs was calculated based on the difference in availability of both sets of population groups taking the production from an average offshore wind turbine and standard ROC pricing. The lost production costs for the group that had no CMS is ~£47,500 per year higher than the group with CMS and the lost production costs for the group that has no PBMC is ~£30,000 per year higher than the group with PBMC. These figures indicate that the business case exists to have a CMS on an offshore wind turbine if it can be purchased, installed and maintained for less that £47,000 a year. The same can be said for a PBMC if the cost difference between that PBMC and the contract without a performance based guarantee is less than £30,000 per year.

6. Conclusion

The “No CMS” population has a lower failure rate than the CMS population; however the availability is also lower in the “No CMS” group population. This means that downtime must be higher. As the ”No CMS” population is closer to shore the higher down time is not due to travel time so must be a result of other factors. One of the factors could be the CMS allowing for better maintenance planning which in turn leads to shorter downtimes and higher availability for turbines with CMS. This analysis showed a ~4% difference in availability between the population with CMS and the population without, in favour of the population with.

Similar conclusions can also be drawn for PBMCs. As the “No PBMC” population has a lower failure rate and is closer to shore the lower availability can only be explained by longer lead and repair times. These longer repair and lead times in comparison to the “Has PBMC” population could be due to the manufactures being faster at repairing the turbines that they will have to pay downtime compensation for. This analysis showed a ~2.5% difference in availability between the population with PBMC and the population without, in favour of the population with.

Based on the analysis of this population there is a business case for a CMS on an average offshore wind turbine if it costs less than ~£47,500 per year. There is a business case for a PBMC on an average offshore wind turbine if its additional cost is less than ~£30,000 per turbine per year.

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