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Condition Monitoring Philosophy for Tidal Turbines

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Abstract: Renewable energy is currently considered as the main solution to reduce greenhouse gas emission. This has led to great developments in the use of renewable energy for electricity generation. Among many renewable energy resources, tidal energy has the advantage of being predictable, particularly when compared to wind energy. Currently the UK is the world leader in extracting energy from the tide; an estimation shows a potential of 67 TWh per year. In order to ensure safe operation and prolonged life for tidal turbines, condition monitoring is essential. The technology for power generation using tidal turbines is new therefore the condition monitoring concept for these devices is yet to be established. Also, there is a lack of understanding of techniques suitable for health monitoring of the turbine components and support structure given their unique operating environment.

In this paper the condition monitoring of a tidal turbine is investigated. The objective is to highlight the need for condition monitoring and establish procedures to decide the condition monitoring techniques required, in addition to highlighting the impact and benefits of applying condition based maintenance. A model for failure analysis is developed to assess the needs for condition monitoring and identify critical components, after which a 'symptoms analysis' was performed to decide the appropriate condition monitoring techniques. Finally, the impact of condition monitoring on system reliability is considered.

1 Introduction

Renewable energy generation has significantly increased globally over the last decade with an increment of 33% in the UK as at 2011 [1]. Marine energy is one of the promising energy resources, especially in the UK; estimates show a capability for producing 36 GW from tidal energy alone. By 2020 Europe plans to increase installed capacity of tidal turbines to 1.95GW and 50% of these will be installed in the UK.

The technology of extracting energy from tides can be traced to Medieval period where mills were used to drive machinery for grinding cereal. These mills utilised the tidal flow in bays and estuaries. However the use of the traditional tidal mills was limited due to failure by tide surges [2]. The first project to utilise the tide for electricity generation was constructed in France between 1961 and 1967. This facility is located near the Rance River in Brittany, France. The station generates 240 MW using 24 turbines [3]. The largest power plant utilising the tidal energy is Sihwa Lake tidal power plant in South Korea [4]. The plant was commissioned in 2011 with a total capacity of 254 MW generated by 10 bulb turbines. Development of the tidal energy using barrages, such as those in the Rance River is challenged by high capital costs and long construction periods [3]. Therefore, designers are now exploring other technologies for extracting energy from tidal flow.

The development on tidal turbine technology is ongoing with focus on several aspects, including hydrodynamics, operation, environment, *etc*. One of these areas of development

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is condition monitoring, typically condition monitoring systems focus on the health of each component of the turbine and structure.

A condition monitoring system for tidal turbines is important for maintenance planning and detecting faults at an early stage. Furthermore, the cost for offshore maintenance and inspection is high (harsh weather, large distances involved, modes of transport required) therefore unnecessary repairs and inspections should be avoided at all costs [5]. Moreover, due to lack of accessibility, turbine reliability is critical and condition based maintenance (CBM) technologies can offer a means of reducing the maintenance frequency [6].

2 Need for Tidal Turbine Condition Monitoring

Tidal turbines are still in the early stages of development, therefore not many actual failures exist. However, some failures have been reported over the last 5 years. The first turbine failure was reported in the Bay of Fundy in the United States in 2009. The open hydro (1 MW) was deployed in November 2009, thought the turbine blades failed after three weeks due to fatigue [16]. Another failure was reported in the UK in 2010, involving a AK1000 tidal turbine deployed by Atlantis Resources in Orkney. This design had a blade length of 22.5 m and the unit had two sets of blades in a single unit. The blades were made from a fiberglass composite. One of the turbine blades has failed after just two months of operation. The blade peeled away due to a manufacturing fault during the fabrication process [17]. In 2011 the Race Rock tidal turbine came out of the water due to a significant reduction in the power generated. The turbine was deployed in 2006 to the north of Middle Island in Canada. The loss of performance was related to a build-up of micro-algae on the turbine blades and structure as shown in Figure 1 [18].
Evidence of these failures highlights the need for a condition monitoring scheme that encompasses structural and mechanical integrity as well as performance.



Figure 1: Race Rock turbine after deployment [18]



Figure 2: ADCP before installation under water [7]



Figure 3: ADCP after 2 years under water [7]

Typically tidal turbines run at low rotational speeds between 10-20 RPM, however, due to the density of the media in which they operate, the turbine rotor will experience very high torque loads. Comparisons by Winter [7] showed that the tidal turbine torque is 50% greater than in wind turbines for the same rated power. This high torque will affect the integrity of the drivetrain, especially the gearbox. According to a survey of wind

turbine failures in Sweden, gearbox downtimes were the longest when compared with other components [7]. It is expected that the gearbox in the tidal turbines will experience even longer downtimes. Therefore, more attention should be paid to the gearbox's design and operation. Another challenge facing the tidal turbines is the harsh marine environment. Existence of the turbine in the seabed may lead to marine growth build-up on the blade's surface. In wind turbines the effect of surface fouling due to very small debris such as insects, icing *etc*., can reduce the power generated by 50% [8]. Marine growth build-up for two years under water are considered very significant as shown in Figure 2 and Figure 3[7]. These figures show material on the rotor blades may cause a significant reduction in energy extracted; therefore it is extremely necessary to monitor such degradation. In addition to the accumulated marine matters, tidal turbines are subjected to high thrust due to the high density of the water. The maximum thrust can be estimated from

$$T_{max} = \frac{1}{2}\,\rho\, C_t\, A\, V^3 \tag{1}$$

where A is rotor area, $\rho$is fluid density, C_t is the thrust coefficient ($C_t \cong 0.9$), and V is the flow speed. Table 1 shows a performance comparison between a wind turbine and a tidal turbine of similar capacity and specification. From equation () it can be inferred that the thrust load in a tidal turbine could be as much as 5 times that of a wind turbine for a power rating of 1 MW. Therefore, manufacturers have considered stronger blade materials for tidal turbines instead of fiberglass composites that are used for wind turbine blades. Thus blade load needs to be monitored to avoid overloading [9; 10].

Table 1: Parameters Comparison forWind and Tidal Turbines with same Capacity

Wind Turbine Parameters	**Tidal turbine Parameters**
Density = 1.22 kg/m^3	Density = 1000 kg/m^3
Rotor diameter 27.1 m	Rotor diameter 9.31 m
Velocity 12 m/s	Velocity 2.6 m/s
Thrust load =146 KN	Thrust load =675 KN
Torque = 546 KNm	Torque = 837 KNm

Also, a tidal turbine is subject to high fatigue loads due to changes in the tide's current speed, direction of water flow, turbulence and water level. The cyclic fatigue load in drivetrains is especially concentrated in the blades and gearbox. As experienced in wind turbines, the failure due to the fatigue in the gearbox and blades should be monitored to avoid catastrophic failures.

For machines working under water, a phenomenon known as cavitation should be considered for which formation depends on operating conditions, blade geometry, and water quality. Cavitation occurs on a blade's surface due to a decrease of pressure less than the vapour pressure, hence a release of water bubbles. This phenomenon can cause blade erosion or unhealthy vibration [11].

As tidal turbines are installed in the sea, marine mammals may affect them through interference. Therefore, a condition monitoring scheme must be extended to monitor the marine environment for any damage on the turbine blades caused by impact from the marine mammals.

3 Tidal Turbine Model for Failure Analysis

3.1 Model Description:

The single tidal turbine considered for developing a failure model consisted of three fixed pitch blades connected to the hub. The hub is connected to the rotor which is supported by a main bearing. The rotor is coupled to the gearbox which is steps up rotor speed to drive a generator. All these components are enclosed inside the nacelle. A hydraulic actuated mechanism known as yaw system is used to rotate the turbine to face the flow direction and the hydraulic mechanism includes an electrical motor to drive a pump and hydraulic actuator. The main components of the turbine are shown in figure 5.

A failure analysis was undertaken to identify the effect of component failure on the system and to decide the best detection method from fault symptoms. The Tidal Turbine System was modelled using MADe software [19]. The model represents the function of each component, expected failure modes and failure symptoms for each failure. The model is shown in Figure 4, the lines connecting components represent the flow of the functional output between them [20].

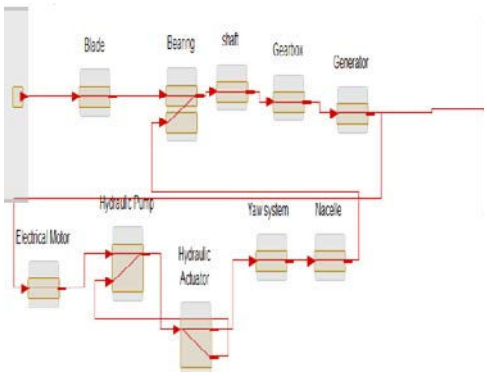


Figure 4: System Model using MADe Software

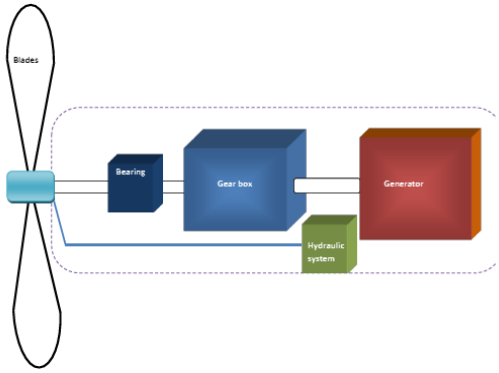


Figure 5: Tidal Turbine Main Components

The following characteristics are specified for each component:

- Component function
- Failure cause, mechanism, faults and symptoms of the failure.
- Criticality of failure, including: occurrence, severity, and detectability.

Occurrence is a ranking from 1 to 10 of the relative likelihood or frequency with which a failure is expected to occur. Occurrence categories are based on the RAC / MIL-STD-1629A guidelines [21] as shown in Table 2.

Table 2: Occurrence Categories

Ranking	Category
10	Frequent
7-9	Reasonably probable
4-6	Occasional
2-3	Remote
1	Extremely unlikely

Severity refers to the impact of the failure mode on the end-effect nominated for the system model, and severity is ranked in terms of the impact of failure on the system and mission. The severity impact ranking is shown in the table 3.

Table 3: Severity Rankings based on the Standard MIL-1629a [21]

Ranking	Category	Class	Description
10	Catastrophic	I	Total loss of turbine and cannot be repaired
7-9	Critical	II	Loss of turbine generation, extensive repair required
4-6	Marginal	III	Degraded, significant repair required
2-3	Minor	IV	No effect on power generation, some repair required
1	Minor	IV	No effect on power generation, minor repair required

Detectability is a ranking from 1 to 10 of the relative difficulty of detecting a failure of that flow property; the Table 4summarises detectability categorisation.
The risk Priority Number (RPN) is calculated for every active failure path within the system model. The RPN of any Functional Failure Mode is the multiplication of Occurrence (O), Severity (S) and Difficulty of Detection (D) values, and this is used to evaluate components criticality [22].

As part of the failure analysis a failure diagram was defined for each part of the turbine, this diagram was used to calculate the criticality of each casual path (the casual path used to detail the physical processes of failure starting from the root cause of failure) starting from the initial cause to end effect. The failure diagram consists of four levels, including failure Cause, Failure Mechanism, Fault, and Symptom, an example of this diagram is shown in Figure 6, due to the lack of failure information for tidal turbines, experience from different industries (Aerospace and Wind turbines) was used to define the failure diagram, a representative snapshot of part of the failure diagram is presented in Figure 6.

With the developed model the contribution for each element in the failure diagram can be estimated based on probability of occurrence of each failure path. In order to illustrate the analysis method applied an example using figure 6 is considered. In this example the failure paths have the same probability of occurrence, the probable failure paths leading are:

- Mechanical shock - Ductile fracture – Fractured
- Vibration Loading- fatigue- Crack
- Vibration Loading- fatigue- Fracture

The contribution of each failure path C_i is estimated by [23] :

$$C_i = \frac{P_i}{\sum_{i=1}^{m} P_i} \; X \; 100\ \% \tag{2}$$

The contribution of event C_{ie} (cause, mechanism, faults, and symptoms) is calculated by:

$$C_{ie} = P(e).\sum_{j=1}^{n} P_j \; X \; 100\ \% \tag{3}$$

where, P is the failure path probability, m is the number of possible failure paths, n is the number of paths related to this event $P(e)$ probability of a event.
So if failure occurs, then the probabilities of the cause of failure are: Mechanical shock 33.33% are Vibration loading 66.66%.
Similarly for the failure mechanisms, faults, and symptom probabilities can be calculated. This analysis method is applied to the tidal turbine model described previously. Owing to lack of failure information; this analysis is based on the assumption that each failure path has the same probability of occurrence. The result of this analysis is shown in the next section.

Table 4: Difficulty of Detection Ranking

Ranking	Category	Description
10	Non-detectable	Non-detectable or only detectable by destructive/physical inspection.
7-9	Out of water inspection	Detectable only by disassembly
4-6	Out of water inspection	Detectable by testing and diagnostics
2-3	In operation test	Detectable by real-time system
1	Continuously observable	Automatic detection by sensor

3.2 Result of Failure Analysis

Using this model the Failure Mode Effect and criticality analysis FMECA can be obtained. FMECA allows investigation of the critical parts in the tidal turbine and facilitates the identification of an appropriate monitoring system [22]. The criticality of the turbine component is shown in Figure 7. Results show the gearbox is the most critical component in the tidal turbine with a RPN of 180. In addition, the hydraulic system, blades, and generator show high criticality. Therefore, condition monitoring of these components needs to be more robust in order to detect the failure as early as possible. The results mirror analysis conducted on wind turbines [24], the only difference is that electric equipment is not considered in this study. Comparisons to wind turbine should be taken with caution due to different operating conditions. This result can be enhanced over time as actual tidal turbine failure data becomes available in the future.

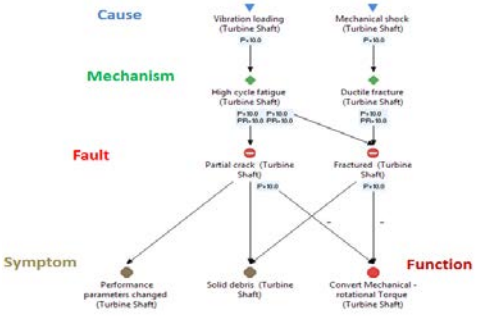


Figure 6: Example of Simple Failure Diagram

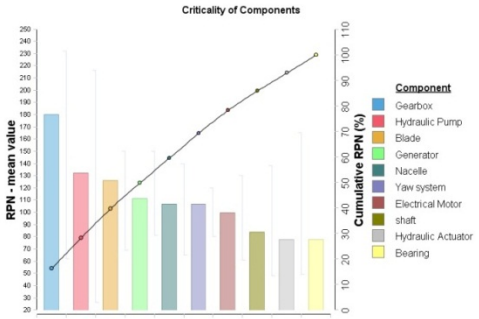


Figure 7: Criticality of Tidal Turbine Components

The failure model was used to estimate the common causes of failure leading to turbine shutdown; the calculation is based on a probabilistic approach as illustrated in the example discussed previously. The result illustrates that solid particle contamination is one of the most common failures caused in many components of tidal turbines. This includes the gearbox, hydraulic system, generator and blades. As shown in figure 8.

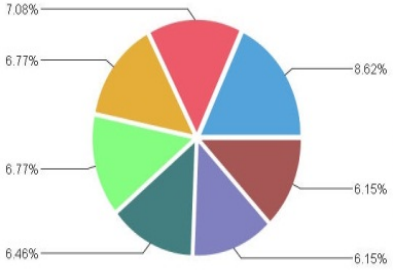


Figure 8: Top Seven Causes of Failure in the Turbines

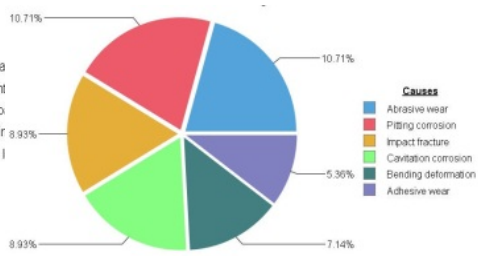


Figure 9: Failure Mechanism in the Gearbox

The failure analysis of the gearbox was further investigated, this included the mechanisms of the failure in the gearbox and gearbox faults. Results showed that pitting and abrasive wear are the most common failure mechanisms in the gearbox as shown in Figure 9. These two mechanisms lead to faults such as scratches due to debris and cracks due to the surface pitting.

Symptom analysis plays an essential role in designing of condition monitoring systems, therefore analysis of symptom is considered for each component in the next section.

3.3 Symptoms Analysis for Component Failure

This analysis of failure in the gearbox highlights the importance of the condition monitoring system. The decision of the monitoring approach based on this failure model for the gearbox is dependent on the detection of the failure symptoms. Failure models permit symptom analysis for each component which is then linked to a specified fault [22]. Each fault is connected to certain failure mechanisms and causes as shown in the failure diagram in Figure 10 . The outcome of this analysis helps in the building of a robust tool for fault diagnosis. The development of robust condition monitoring for tidal turbines depends on the detection of the fault symptoms, therefore analysis of the symptom is essential for the selection of monitoring techniques. As shown in Figure 11 monitoring of symptoms such as oil debris, temperature, vibration and torque lead to identification of 45% of the faults in the gearbox.

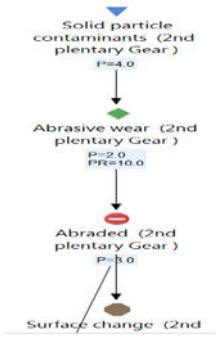


Figure 10: Example of of Gearbox Failure Diagram

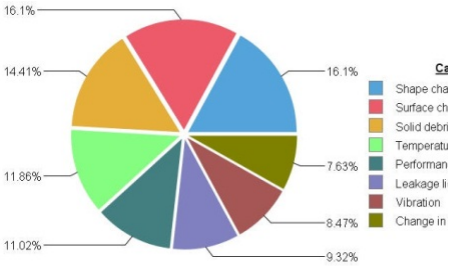


Figure 11: Failure Symptoms in the Gearbox

In the same manner, analysis of failure symptoms for other critical components such as the blades can lead to the establishment of a condition monitoring concept for these components as shown in Figure 12. The use of current, vibration, and temperature as monitoring tools results in the detection of the majority of generator faults. Also the application of strain, vibration and performance monitoring in blades results in the detection of fault symptoms such as profile and surface changes. According to the symptoms analysis, condition monitoring techniques can be selected as shown in Table 5.

Table 5: Condition Monitoring Techniques

Components	Condition Monitoring Techniques
Blades	Strain Monitoring, Performance Monitoring
Gearbox	Oil Debris Analysis, Vibration Analysis, Torque Monitoring
Yaw system	Pressure monitoring, Performance monitoring
Hydraulic system	Pressure monitoring, Pump's Motor MCSA, Oil Debris
Nacelle	Leakage monitoring

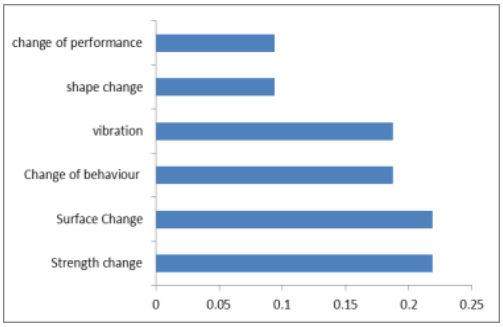


Figure 12: Failure Symptoms in Blades

4 Impact of Condition Monitoring on System Reliability

The condition monitoring approach has been used recently as a proactive defect elimination strategy, which relies on detection of a fault, so as to isolate it before failure occur, this lead to improvement of system reliability and availability [25-27]. The impact of the selected monitoring strategy on the tidal turbine reliability was investigated using a reliability model.

4.1 Reliability Model

The model for reliability is based on the same model of failure analysis described previously. Functional reliability analysis is utilised to investigate the system reliability. In this analysis the system failure is traced from end-effects, which is the system failure to perform its function, to the series of events that leads to this failure. This process is considered by fault tree analysis FTA, figure 13 presents an example for one event failure leading to the system failure.[28]

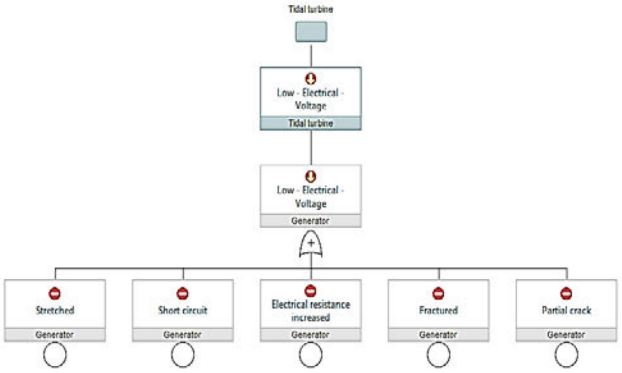


Figure 13: FT for One Event Failure Path

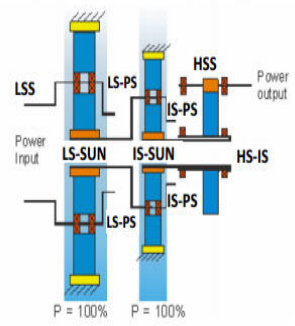


Figure 14: Gearbox Configuration [31]

The functional reliability of each component is estimated using the failure data and duration of operation, the estimation is based on the exponential distribution of time to failure. This calculation is summarised in the following steps: [29]

- Calculating the probability of component failure using the following equation:

$$(f) = 1 - \mathrm{EXP}(-\mathrm{t}\,\lambda_p) \tag{4}$$

where, t is duration of operation and λ_p is component failure rate.

Compute the probability of occurrence of each functional failure mode FFM in the considered component. This is based on the failure mode ratio. This is performed by the following equation:

$$P(FFM) = \alpha_{FFM}\, P(f) \tag{5}$$

where, α_{FFM} is failure mode ratio, this ratio relates to the probability of failure due to certain failure mode to component failure probability.

Compute the probability of failure of each component considering only functional failure modes leading to the failure of component function.

Estimate system failure probability considering only the failure paths leading to system function failure.

4.2 Data for Reliability Analysis

In order to perform reliability analysis, it is important to obtain failure rates for each component. The data for reliability analysis is obtained for each subassembly from reliability data of similar components used in the wind turbine industry [24, 30]. This data was collected from 1994 to 2004. The data for the main components are summarised in Table 6.

Table 6: Failure Data for Components [24, 30]

Component	Failure rate per year	Component	Failure rate per year
Shaft	0.015	Yaw system	0.105
Rotor blades	0.18	Gearbox	0.08
Generator	0.11	Bearing	0.02
Hydraulic system	0.125	Nacelle	0.005

In the following section an example of a reliability study shows in detail for a gearbox to illustrate the procedure for analysis, and then this analysis is extended to all components.

4.3 Gearbox Reliability

One objective of this study is to investigate the effect on reliability of applying the CM techniques proposed from failure analysis. The proposed monitoring techniques are:

- Oil debris Monitoring
- Vibration
- Torque

The reliability analysis is based on modelling the gearbox components using a MADe environment for failure analysis; the gearbox considered for this analysis is a gearbox with three gears increasing stages which is expected to be used in tidal turbines. The data collected for this analysis is data for a wind turbine gearbox, specifically the data collected by the Reliawind project [31].

4.3.1 Gearbox Failure Data

The data used for this gearbox analysis is reported in [31], and shown in Table 7.

Table 7: Failure Data for Gearbox [31]

Component	**Failure rate/year**	**Component**	**Failure rate/year**
Low speed shaft	0.0025	Parallel stage	0.028
Low speed planetary stage	0.014	Housing	0.005
Intermediate speed planetary stage	0.018	Oil pump	0.005
Intermediate speed shaft	0.0025	Heat exchanger	0.005
High speed shaft	0.0025	Filter	0.005

4.3.2 Gearbox Reliability Model

In order to perform reliability analysis firstly the gearbox is modelled, and components of gearbox considered are shown in Figure 14, and for each part a function and failure mode is defined, then the reliability is calculated using the steps described previously. In this analysis two reliability models were considered, the first model considered the reliability without including the effect of applying condition monitoring considering CM, while the second model considered the effect of including condition monitoring system.

Fault Tree Analysis was used to compute the gearbox inherent reliability, the top event in this analysis is defined as the failure of the gearbox to perform its function. The failure of the gearbox can be due to any failure of sub-assemblies as shown in the fault tree, for this reason detailed faults are considered for each part. A quantitative measure of benefits from applying condition monitoring on offshore wind turbine shows significant reduction in failure rate in all 30 simulation models of wind turbines [5]. The reduction in failure frequency of simulated wind turbines reached 70% after applying the condition monitoring, therefore the same hypothetical reduction was applied across all failure

modes modelled for tidal turbine.For each part of the gearbox the probability of failure is calculated using the data in table 7. This probability is assumed to be distributed equally over the expected failure modes of that part. While in the second model the probability of gearbox failure due to the monitored fault is decreased by 70%. For instance the probability of failure of the input shaft will be distributed equally into the expected faults, however, when CM applied the faults probability is decreased for monitored faults. The faults probabilities for the gearbox input shaft after and before of CM are shown in Figure 15.

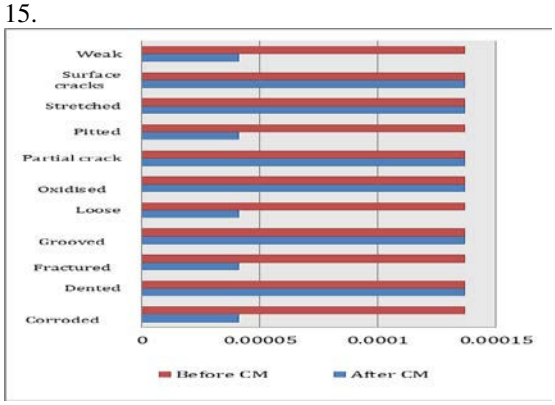


Figure 15: Shaft Failure Probabilities before and after Applying CM

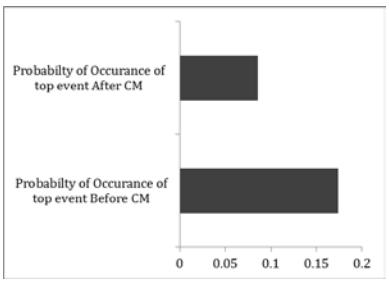


Figure 16: Probability of Occurrence of Top Event

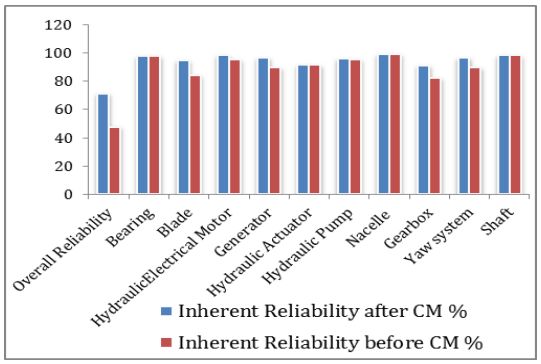


Figure 17 Impact of applying CM in System Reliability

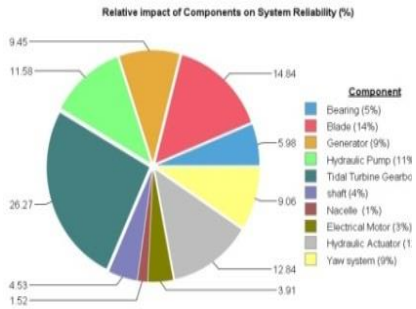


Figure 18 Relative Impact of Components in System Reliability

4.3.3 Gearbox Reliability Analysis Result

The analysis shows the probability of the gearbox failing to perform its function is decreased significantly as shown in Figure 16. This leads to an increase of gearbox inherent reliability. In addition the model suggests condition monitoring decrease the probability of gearbox failure by 9%.

4.4 Impact of CM in System Reliability

In order to investigate the reliability of the entire system each component should be considered individually, for each component the inherent reliability is computed before and after applying condition monitoring. Following the same procedure applied to the gearbox, the probability of each component failure is estimated. This analysis was performed based on the data described previously. The reliability analysis after applying condition monitoring is considered using the same condition monitoring techniques as employed for the symptoms analysis described previously.

The result of this analysis shows a significant reduction in the probability of system failure, which leads to an improvement of system functional reliability as shown in Figure 17. This result shows good agreement with wind turbines reliability published in [30; 31].

The highest improvement is identified in the blades, gearbox, yaw system and generator in sequence; according to this the gearbox and blades have the largest impact on the system reliability of tidal turbine as shown in Figure 18.

5 Conclusion

The application of the condition monitoring leads to improved maintenance management and helps to avoid catastrophic failure. In addition the condition monitoring contributes to the reduction of the environmental impact of tidal turbines.

The approach for developing a condition monitoring system for tidal turbines is introduced; the approach is based on FMECA and symptoms analysis to decide system needs. These analyses depend on the experience from similar renewable energy technologies due to the lack of information on tidal turbines industries. The analysis presented in this paper was based on generic information so consequently results can vary depending on the actual turbine design, however the concept applied is valid for decisions on condition monitoring needs. The failure model introduced can be more accurate as failure data for this type of turbine become available.

Examination of the impact of condition monitoring on the system inherent reliability shows significant improvement, this due to the fact that, application of condition monitoring will reduce the probability of catastrophic failure occurrence.

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