Reliability Analysis of Wave Energy Converters

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Abstract—**Using generic defined wave energy converters, sub-system block diagrams and reliability diagrams are developed. Devices have common aspects such as moorings or seabed fixings, but the method of electrical power conversion can differ depending upon the device. Reliability analysis is applied to the different electrical power take off mechanisms employed, in particular hydraulic, direct drive and turbine based generation systems. Both a qualitative and quantitative analysis is performed using surrogate reliability data in order to compare the different systems. Critical components are identified and the failure modes analysed in order to provide guidance to improve component design.**

Keywords—wave energy, reliability, electrical power take off.

I. INTRODUCTION

Wave energy has the potential to supply 7% of the UK's electricity demand [1], but as yet no single device has been fully commercialized. There have been a number of successful full scale demonstrators, eg. Pelamis [2], SeaBased [3] Oyster [4], LIMPET [5], and Archimedes Wave Swing [6] to name a few. Each of these devices has very different operating principles. Unlike wind or tidal energy, there has been no technology convergence in wave energy. In wind the horizontal axis wind turbine with a gearbox DFIG drivetrain has dominated. Tidal energy is adopting a similar approach, with trends towards direct drive systems replacing gearbox technology as is the case for offshore wind. Some degree of technological convergence across the sector in the early stages of development enables the technology to become more established leading to maturity. The common theme for energy conversion in wind and tidal is the interaction of a fluid with an axial flow turbine producing continuous rotation, the main difference being the fluid. The interaction of waves with a wave energy converter produces a reciprocating motion, which can be linear or rotary. The energy stored in this motion is then used for moving a fluid, which could be water, oil or air. The the geometry of the absorber converting the wave energy into a fluid motion can be very different, as highlighted by each of the devices listed above. In choosing a particular technology, each device developer is striving for optimum conversion efficiency, reliability, availability, survivability and affordability. O&M costs dominate the cost of energy, and hence affordability, which is heavily dependent upon reliability, and in turn affects availability. Efficiency is important, but without a reliable and robust design it does not matter how efficient the device is. This paper will focus on assessing the reliability of different types of wave devices, and the critical components used in wave devices.

There have been numerous studies on the reliability of wind with many years of operational data available from onshore wind. Delorm [7] applied the same techniques as Tavner to assess reliability in tidal energy devices. Delorm classified tidal devices into generic categories: semi-submerged tethered, semi fixed (monopole or gravity based), floating tethered and submerged tethered [7]. Unlike with wind there is not a large database of component failures from which to work with, and so Delorm used surrogate data from various databases such as Oreda and US Military Handbooks [8-10]. Reliability diagrams of the various generic devices were developed, and an overall reliability was estimated using the surrogate data. This research enabled a comparison to be made and it highlighted the critical components within a device. Surrogate data cannot be used with confidence to arrive at an accurate reliability result, because the failure rate data depends upon the operational loads and environment, which are very different in the existing databases compared to a marine renewable application. However, such an exercise is still useful for comparative purposes.

For wave energy converters Wolfram highlighted the challenges of determining the reliability [11], and Thies [12] published a more comprehensive analysis in which he showed the importance of understanding the operational environment and the loadings on the device. Thies presented system reliability analysis for a generic hydraulic based wave energy converter using reliability block diagrams and surrogate data. Although such an approach is limited by the appropriateness of the data available, Thies states that such techniques can still provide useful information for reliability assessment. Thies presents a methodology based on Baysien techniques to combining existing databases, new numerical and experimental results with field trials to provide a more robust assessment of component failure rates, which he applies to moorings and cables.

In this paper the principles of a bottom-up approach based on reliability block diagrams and known failure modes of components will be applied to generic wave energy converters in order to compare their reliability in a qualitative way. The paper will start with a summary of the generic wave energy devices, and their operational principles. Each device will be broken down into sub-assemblies from which reliability block diagrams will be produced. A comparison will be made based on component surrogate data, from which the components in the critical sub-assemblies will be investigated further using failure modes effect analysis.

II. GENERIC WAVE ENERGY CONVERTERS

Wave energy devices have been categorized in various ways over the last 20-30 years, but in this paper the classification defined by the SI Ocean project is used [13]. These five classifications represent some of the various types of device demonstrated at scale at sea over the last 10 years.

A. *Attenuator Device*

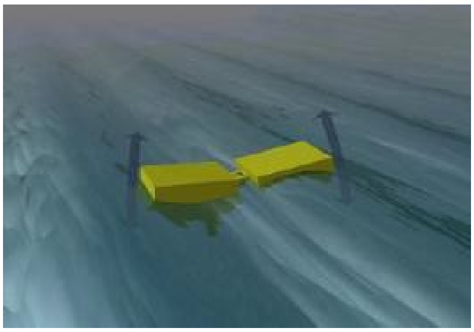


Figure 1: Attenuator Device

An attenuator device has its axis perpendicular to the incident waves. A hinged device is shown in Figure 1, which would be similar to the Pelamis device. Motion at the hinge can be used to pump hydraulic fluid driving a hydraulic motor connected to an electrical generator. With such systems the generator can be controlled to operate at constant speed, so that direct connection to the grid is possible negating the need for power electronics.

B. *Point Absorber*

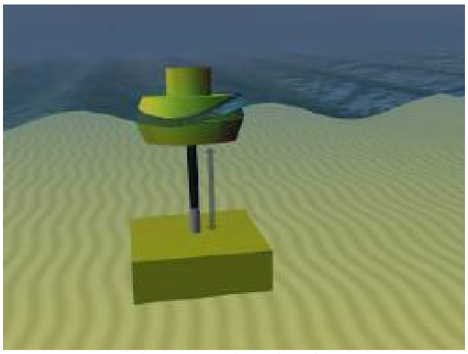


Figure 2: Point Absorber

A point absorber consists of a bouy, and is small compared to the incoming waves. It can absorb energy from all directions and has a capture width greater than the physical width or diameter of the buoy. Once again the motion can be used to pump hydraulic fluid, or a direct drive linear generator can be used, with a good example being SeaBased.

C. *Oscillating Water Column (OWC)*

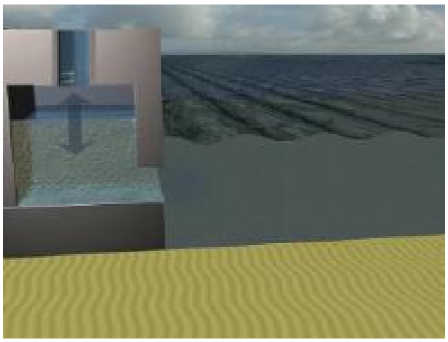


Figure 3: Oscillating Water Column

The OWC consists of a chamber open to the sea so that incoming and outgoing waves cause the water level in the chamber to fall and rise. The change in water level produces a bidirectional airflow in an orifice at the top of the chamber, which is able to drive a Wells turbine coupled directly to an electrical generator. OWCs can be built into the shoreline, built into harbor walls and also be floating devices.

D. *Pressure Differential Device*

Figure 4: Pressure Differential Device

A pressure differential device operates according to the difference in pressure between a crest and a trough. A wave crest pushes the device down and a trough brings the device back up again. These devices are submerged below the water surface, and thus are not in the splash zone. The resulting motion can be used to pump hydraulic fluid or can be used to drive a linear generator. The Archimedes Wave Swing is a member of this family of devices.

E. *Overtopping Device*

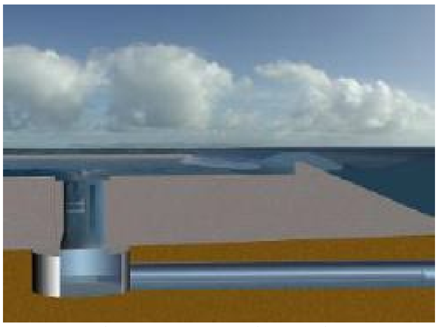


Figure 5: Overtopping Device

An overtopping device is essentially a floating reservoir. Waves over top and fill the reservoir. Once at a certain level the water than empties back into the sea driving a conventional hydro turbine and synchronous generator. Wavedragon is an overtopping device.

III. GENERIC POWER TAKE OFF SYSTEMS

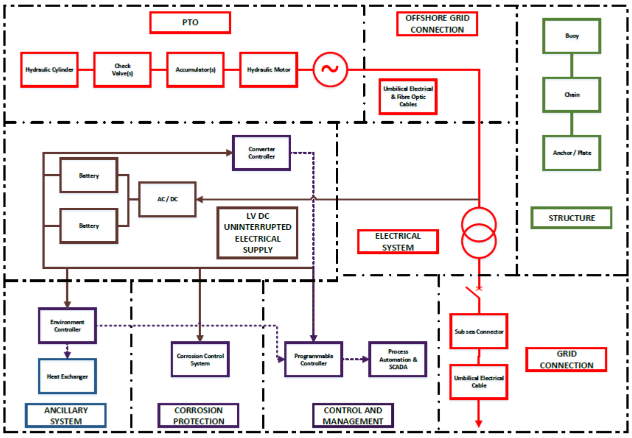
The electrical power take off converts the energy captured through the hydrodynamic interaction of the device with the incoming waves. As can be seen from the description in the previous section the hydrodynamic interaction with the waves results in a reciprocating motion, which can be used to pump a fluid. Alternatively air or water turbines are used. There are therefore three main types of electrical power take off used: direct drive linear generators, hydraulic systems and turbines. Both direct drive linear generators and hydraulic systems can be applied to attenuators, point absorbers and pressure differential, whilst turbines are used in OWCs and overtopping devices. In the remainder of the paper two device will be analysed in more detail incorporating the three different types of electrical power take off.

IV. SUBSYSTEM ANALYSIS

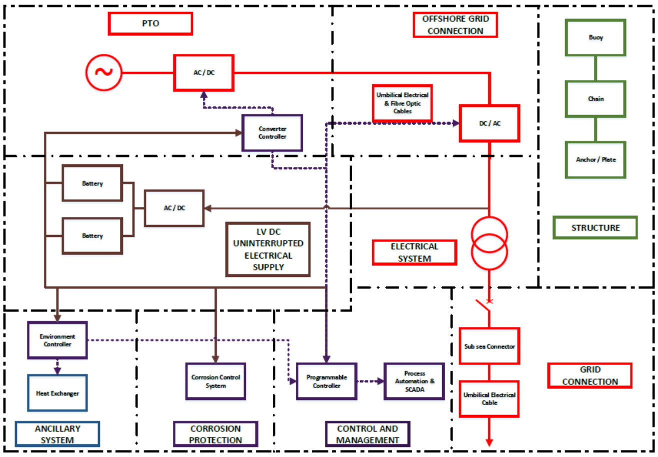
Only two devices are presented for subsystem analysis: heaving buoy and oscillating water column. In these two devices the main power take off mechanisms can be utilized: direct drive linear generator, high pressure oil hydraulics, and air-turbines. In accordance with the approach taken by Delorm [ref], subsystem reliability block diagrams have been produced for the point absorber and the OWC. A device can be divided into 6 main sub assemblies: structure, PTO, Electrical System, LV DC power supply, (including corrosion protection and control and management), and Grid Connection. There are common sub-assemblies associated with both types of device: LV DC power supply, Electrical System and Grid Connection. In these common sub-assemblies it is assumed the same technology is used and hence the failure rates will be the same. The main differences lie in the Structure and PTO type.

A. Point Absorber

The reliability block diagrams for the point absorber with direct drive PTO and hydraulic PTO are shown in Figure 8.



(a) Diret drive power take off, fixed to sea bed.



(b) Hydraulic power take off, fixed to sea bed.

Figure 8: Point Absorber Reliability Block Diagrams with different PTOs

The type of PTO used and the method of integration with the buoy will affect the reliability and availability of the device.

B. Oscillating Water Column

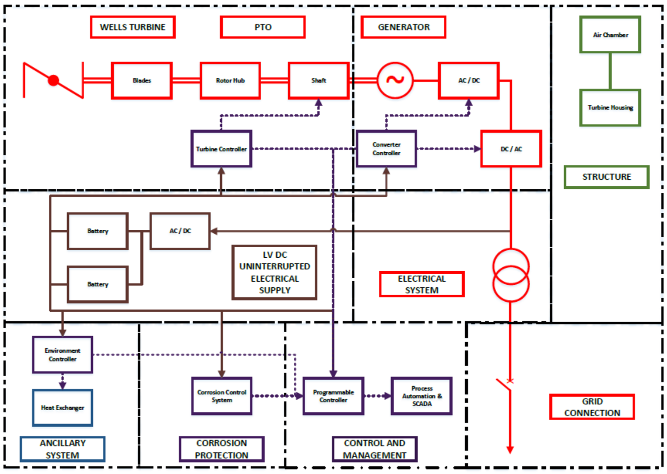


Figure 9(a) Shoreline OWC Reliability Block Diagram

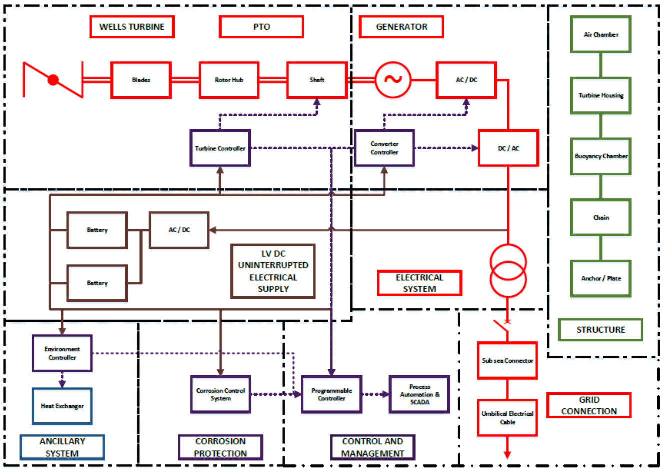


Figure 9(b): Floating OWC Reliability Block Diagram

The oscillating water column can either be floating or fixed to a structure, such as the coastline or to a harbour wall. If floating a mooring system is required.

V. PTO COMPONENT RELIABILITY BLOCK DIAGRAMS

In the sub-assembly block diagrams in figures 8 & 9, the PTO is shown as a linear machine, a hydraulic system or an air turbine with generator. All three of these blocks can be further sub-divided into components.

A. Hydraulic PTO for Heaving Bouy

The generic hydraulic subsystem consists of hydraulic cylinder, manifold, accumulator(s), hydraulic motor and generator. The hydraulic subsystem consists of hydraulic cylinder, manifold, accumulator, check valves, hydraulic motor and generator. A generic in-series reliability block diagram of the subsystem broken down into components is shown in Figure 10.

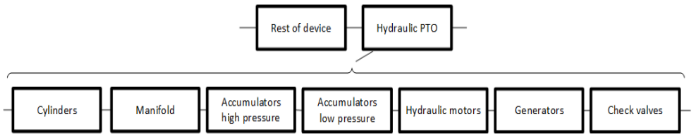


Fig. 10: Reliability block diagram of the Hydraulic PTO's subsystems

Further detail of components embedded in the hydraulic subsystem is then developed as shown in the reliability block diagrams of Fig. 11 (hydraulic cylinder), 12 (accumulators), 13 (hydraulic motor), and 14 (electrical generator).

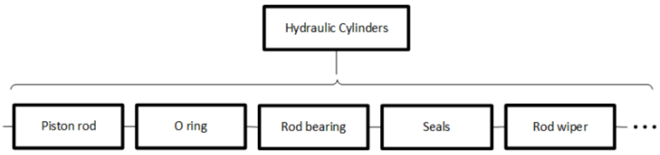


Fig. 11: Reliability block diagram of a Hydraulic cylinder

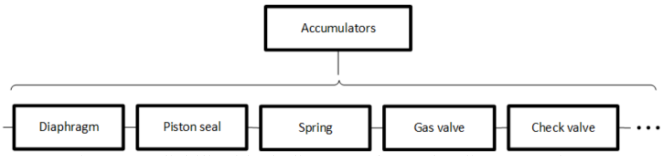


Fig. 12: Reliability block diagram of a Hydraulic accumulator

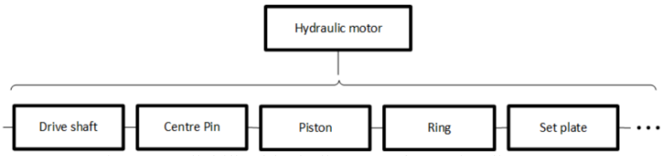


Fig. 13: Reliability block diagram of a Hydraulic motor

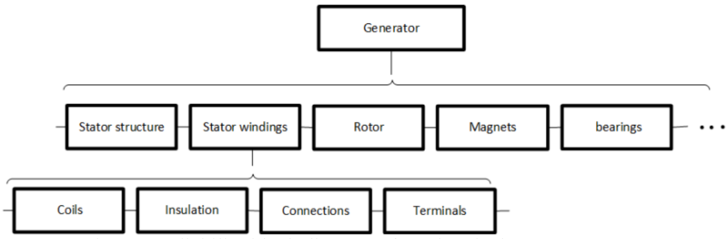


Fig. 14: Reliability block diagram of an electrical generator

There is a total of 31 components in the various sub-systems of a hydraulic PTO, demonstrating the complexity of such systems.

B. Linear Generator PTO for Point Absorber

The linear generator is essentially the PTO for the heaving bouy. For the case of a point absorber with hydraulic PTO, the hydraulic subsystem would replace the linear generator subsystem. The reliability diagram for the linear generator is shown in Figure 15. In comparison to the hydraulic PTO the system is much less complex, with only 11 sub-systems compared to 31 for hydraulic PTO.

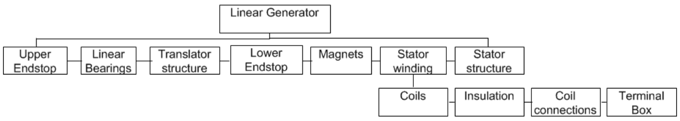


Figure 15: Reliability Block Diagram of the Linear Generator

C. OWC Power Take Off

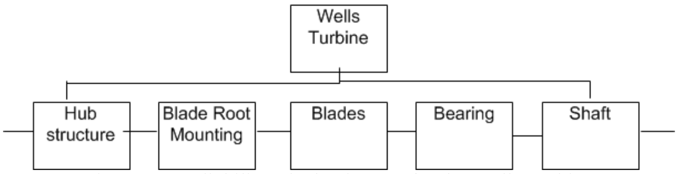


Figure 16: Reliability Block Diagram for the Wells Turbine

The electrical power take off in an OWC is made up of the Wells Turbine and Electrical Generator. The reliability block diagram of the Wells Turbine is shown in Figure 16, and for the generator it is the same as shown in Figure 14. There are 14 sub-systems within the OWC electrical power take off.

VI. SYSTEM RELIABILITY ANALYSIS

The overall reliability of a system is a function of the number of components. Based on the reliability block diagrams presented in the previous section the hydraulic power take off is more likely to fail than either the linear generator direct drive or the OWC power take off. This can only be proved through a quantitive analysis by using component failure rate data from various reliability databases. Failure rate data in data bases such as OREDA [8] and US military handbooks [9 & 10] have been determined for different applications where the operational and environmental loads are very different compared to wave energy. As yet no such similar database has been established for marine renewables. Since the data is not specific to marine energy applications, the authors cannot categorically claim that the final failure rate results for the complete system are a true reflection. However, reliability analysis using such databases provides an indicator for comparative purposes and to highlight critical components and sub-assemblies. The approach adopted by Delorm in [7] was applied to the point absorber and the OWC giving the results shown in Table 1. It should be noted that no environmental or load factors have been applied, because of the uncertainty surrounding their use in marine energy applications.

Table 1: Sub-system Failure Rate estimation (failures/year)

	OWC Fixed	OWC Floating	Point Abs DD	Point Abs hydraulic
Structure	0.008	0.18	0.30	0.30
PTO	1.40	1.40	0.93	1.42
Elec Sys	0.30	0.30	0.30	0.30
LV DC	0.15	0.15	0.15	0.15
Aux	1.74	1.74	1.74	1.74
Grid	N/A	0.14	0.14	0.14

As expected the differences between the devices lie in the Structure and PTO. The PTO and Auxiliaries exhibit the highest overall failure rates. The hydraulic PTO has the highest failure rate, which is expected due to the number of components, but the Well's turbine PTO is similar. In a hydraulic system there is no power converter, and so the comparable Wells' PTO value is due to the power converter, which as shown from experience in wind is a critical sub-system with one of the highest failure rates. Auxiliaries include controllers, heat exchangers, and the SCADA system. The grid connection to shore for the shoreline OWC clearly has no failure rate. The fixed OWC structure can be a harbour wall, and so there are no moorings or sea-bed fixing points as in the case in the floating OWC, hence the difference between failure rates for structure.

VII. FAILURE MODES EFFECTS ANALYSIS

A Failure Modes Effects Analysis (FMEA) of the critical components can be used get a better understanding of where to focus for the improved design of such components to reduce failure rates. The methodology involves estimating the probability of a failure, its impact from which a measure of the criticality of that component is determined, and is outlined in the following bullet points. Due to lack of space only the quantitive results are presented in the paper.

- **Failure Mode:** a description of the type of failure that could happen on a component.
- **Impact:** Direct consequences of the failure.
- **Probability, Consequence:** Probability and consequence have been evaluated following the below table. For each failure mode a factor is given a score from 1, a minor consequence (a very unlikely probability) to 5, a high consequence (a very high probability). The consequences include material and human damages, and their cost impact.
- **Type of Maintenance:** Type of maintenance to prevent failure or to reduce the risk of failure.
- **Type of Repair:** The type of repair after the fault occurred.
- **Criticality** is the multiplication of consequence factor and probability factor. The number summarizes how critical is the component fault, and its value lies between. 1 and 25 (Table 2).

The colours shown in Table 2 give an indication of the severity of the fault, red being very severe.

Table 2: Criticality Matrix for FMEA

CONSEQUENCE PROBABILITY	1 MINOR	2 Slight	3 moderate	4 high	5 Very high
(1) VERY unlikely	1	2	3	4	5
(2) UNLIKELY	2	4	6	8	10
(3) POSSIBLE	3	6	9	12	15
(4) HIGH	4	8	12	16	20
(5) VERY HIGH	5	10	15	20	25

An FMEA was performed on components in the hydraulic PTO (Figure 17), electrical generators (Figure 18) & Wells' turbine PTO (Figure 19). In the case of electrical generators this was generic and applicable to any generator type, as the sub-components are found in all types of generator. The results were based on a qualitative analysis of the failure modes, to which an estimate was made of the severity of the probability and consequence. In the following graphs the first bar represents *the Probability Factor,* the second represents the *Consequence Factor* and the 3rd bar is a measure of the *Criticality*, with the colour of the criticality corresponding to Table 1.

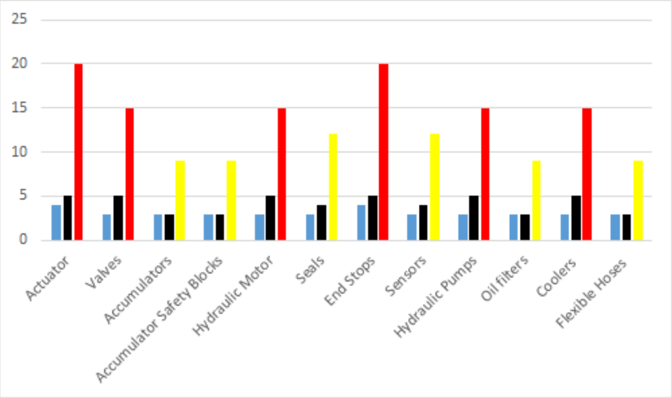


Figure 17: Criticality Estimation for Hydraulic Components

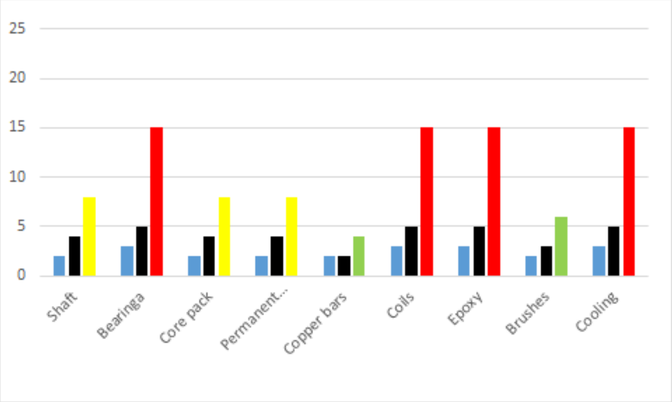


Figure 18: Criticality Estimation for Electrical Generator Components

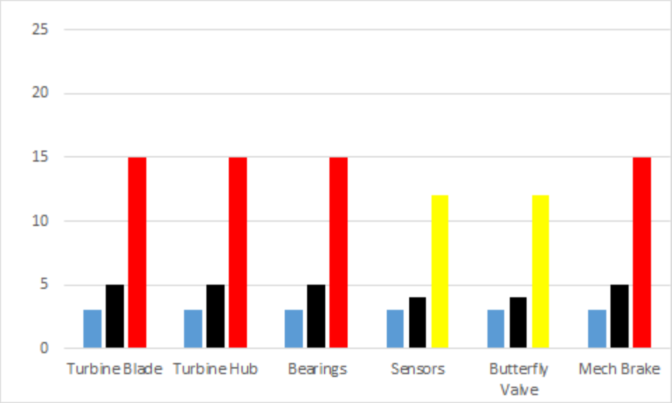


Figure 19: Criticality Estimation for Wells' Turbine Components

VIII. DISCUSSION

It should be noted that the analysis presented in the paper is for generic wave energy converters, and not for specific devices being commercially developed. The failure rate data used to generate the results in Table 1 do not necessarily reflect the application in question, and hence does not reflect the operational environment. There is not enough marine energy operational experience to provide more accurate and relevant data. Environmental factors and loading factors can be used as discussed in [11 & 12], but these factors have been developed for military applications and environments. So for marine energy, environmental factors based on naval applications are used by Delorm [7]. Such environmental factors have not been used in this paper because of the uncertainty associated with applying them to this application. The results presented in Table 1 are adequate in terms of identifying the critical sub-assemblies requiring further design attention. The FMEA process undertaken in this paper should only be used as indicative to highlight those components which should be modelled or tested in more detail.

The probability factor for most of the components was chosen as 3, possible failure, and the consequence factor was chosen to be 5, very high, for those components where failure would result in failure of other components and shut down of the plant. In the case of hydraulics (Figure 17), the device will be shut down if the any of components with red criticality factor fail. If the other components fail the system can continue operating but at reduced performance. For example leakage through a faulty seal will reduce pressure and hence performance. In the case of electrical generators the three critical components are closely linked in terms of failure and its impact. If the coils fail then the machine has to be shut down. A failure with the epoxy in an air-cored machine will lead to coil failure. A cooling system failure will result in an increase in temperature in the machine ultimately resulting in coil failure. For the Wells' PTO turbine structure itself is critical to reliable operation. If the brake fails then there could be a runaway condition leading to mechanical failure of the turbine.

In order to obtain a more robust estimate of failure rates accelerated life testing can be applied to critical components making sure that the correct operational loading regimes are used, with the component in the correct environment. The load regime can be determined from detailed multi-physics modelling. Such a hybrid approach involving experimental and modelling is appropriate for emerging technologies where there is little operational experience, and existing component data is not really applicable.

IX. CONCLUSION

A reliability analysis for generic wave energy converters has been presented with an estimation of sub-system failure rate based on existing surrogate data. Although not specific to the application, the data allows a useful comparison between devices, and identifies sub-systems for further analysis. FMEA performed on the PTO sub-systems identified critical components. Refinement of component failure rate could be achieved using a hybrid experimental-modelling approach.

ACKNOWLEDGMENT

The authors would like to acknowledge Wave Energy Scotland for funding to undertake this work as part of the C-GEN Direct Drive PTO Project, and Lopez would like to acknowledge Conacyt, Mexico for funding for his PhD.

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