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Development of a Condition Monitoring System for an Articulated Wave Energy Converter

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Development of a Condition Monitoring System for an Articulated Wave Energy Converter

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ABSTRACT: Condition monitoring systems (CMS) in renewable energy devices allow for the detection of oncoming faults, providing data to undertake pre-emptive maintenance. By defining a systems functional requirements and identifying of critical failure modes, proactive maintenance strategies to be produced. The lack of operational data in the marine energy industry, and lack of consensus in operating principles between devices, means that a non-standardised CMS package is available for wave energy converters (WECs). In this study a Failure Modes and Effects Analysis (FMEA) is undertaken in order to identify the critical failure modes of an articulated WEC, measurement priorities are identified and a set of monitoring solutions provided. Installing a CMS provides the framework for collecting quality component reliability data, however further development is required for building a proactive maintenance strategy and for continuous reliability improvement.

1 INTRODUCTION

1.1 *Wave Energy and Condition Monitoring*

Challenges due to reliability and availability, and the cost of operations and maintenance have proved to be a technical and economic barrier to the viability of commercial wave energy farms. Operations and maintenance costs for a commercial wave energy array may be significant, with predictions ranging from £200,000/MW/year for a commercial project to £300,000/MW/year for a demonstration project (Ernst & Young 2010). Another study shows that planned and unplanned maintenance activities may count for up to 29% and 28% of total operational expenditure respectively (Carbon Trust 2006).

Condition monitoring systems in renewable energy devices allow for the early detection of component failures, resulting in the implementation of control functions and interventions in response to a detected fault. This reduces the number of unexpected shutdowns and increases availability. In turn this lowers operations and maintenance costs and promotes increased energy production by increased availability, lowering the levelised cost of energy (Wiggelinkuizen 2008).

Condition monitoring techniques are widely implemented in industries such as the offshore wind industry. However, a lack of design consensus in the Wave Energy industry presents challenges in providing a standardized condition monitoring package for each device. This study describes a methodology used to provide condition monitoring solutions for an articulated wave energy converter.

In section 2, the application of condition monitoring techniques in the offshore wind, wave and tidal energy industries, and the principles of reliability centered maintenance is reviewed. The operating principles of the articulated wave energy array are described in section 3. A failure modes and effect analysis is performed in section 4 and finally, a list of measurement priorities is established in section 5.

2 STATE OF THE INDUSTRY

2.1 *Offshore Wind*

Condition Monitoring Systems (CMS) have been implemented successfully in the offshore wind industry, using an extensive array of measurement techniques and analysis methods. Offline visual inspections, oil sample analysis and vibration measurements may be used, however online CMS installations allow for continuous measurement and analysis, enabling alarming functions and instantaneous feedback. Typical measured parameters include vibration measurement for gearbox and bearing health, acoustic emission measurement for noise and stress levels of rotating machinery, and oil monitoring for particulates, moisture and temperature (Marquez 2012 and Kusiak 2013).

The monitoring of individual components are particularly useful when the anticipated life of the component is shorter than that of the entire system. Specific examples include the monitoring of a mechanical brake by examining the voltage and current outputs of 3 phase hydraulic motor (entezami 2012), the development of an online particulate sensor for hydraulic lube oil (Yin 2003) and the monitoring of rotor blade operational loads using a fibre-optic strain gauge sensor system (Schroeder 2006).

Performance monitoring of the wind turbine as a whole also allows for assessment over a range of operating conditions, as opposed to monitoring independent instances. Yang (2013) investigates the use of poor correlations between SCADA data sets, such as tower vibration, generator speed and rotor speed with wind speed, in order to indicate a fault of the component in question. Schlechtingen (2013) builds upon the use of SCADA data by employing Adaptive Neuro-Fuzzy Interference Systems. The system is trained to set a baseline for normal behaviour of components and detects anomalies, providing diagnosis and condition classification.

2.1.1 *Wave and Tidal*

Condition monitoring systems in the wave and tidal industry draw directly from advances in the offshore wind industry. Kelly (2013) discusses the range of condition monitoring techniques that may be drawn from wind turbines and applied to WECs. These techniques include the monitoring of the generator gearbox and bearing health by vibration, acoustic emission and temperature sensors, in addition to stator and rotor health by evaluating current output, power and flux. In addition, Ambühl (2015) suggests that sufficient structural health monitoring must be in place to detect cracks and deformations, in addition to the monitoring of oil condition and leakages. More importantly, the monitoring of the functionality of control and safety systems ensures the WEC is able to respond to system faults.

Marnoch (2016) discusses the topology of a tidal turbine condition monitoring system, drawing principles and learnings from SKF's established offshore wind industry branch. Multiple components are monitored, including generator bearings, gearbox, shaft misalignment, shaft deflection, mechanical looseness, tower blade vibration, lubrication oil level and hydraulic lubrication oil quality.

2.2 *Reliability Centered Maintenance*

The principle of traditional Reliability Centered Maintenance relies on determining the maintenance requirements of a functional system in its operating context (Moubray 1997). A failure modes and effect analysis (FMEA) is used in order to determine critical failure modes, their consequences and root causes. Using this data, measures can be identified to predict and prevent each failure. Finally, proactive solutions to maintenance tasks can be provided.

An FMEA conducted by Ambühl (2013) was used to identify the main failure modes of the electrical and mechanical systems of a WEC, in addition to the monitoring equipment and control system. In turn this data was used to analyse the effect of failure on the overall structural reliability. Higher risk failure modes are prioritized for condition monitoring and risk based inspection.

In practice, condition monitoring systems can predict and detect failures, but are unable to eliminate them entirely. By monitoring critical machinery, root causes of failure may be identified, enabling long term solutions to be developed. Continuous improvement and quantification of “bad actors” must be undertaken into order to improve overall system reliability at the concept level.

3 OPERATING PRINCPLE

The Squid 6 Series is a 7.5kW articulated wave energy converter comprised of a series of nodes and links, as seen on Figure 1. As waves pass over the device, the buoyancy floats and central riser move in an elliptical orbit, causing the reciprocating motion of a series of six pumping modules connected to a hydraulic ring main. In turn this motion delivers high pressure fluid to a hydraulic power take off module, located in one of the buoyancy floats (antinodes), where a hydraulic motor is used to drive an electrical permanent magnet generator.

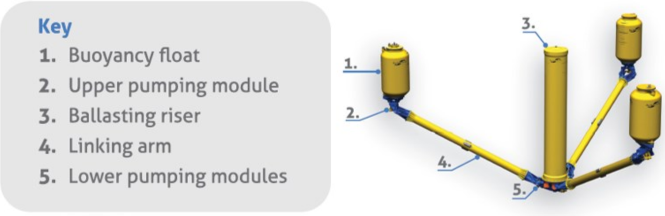

Figure 1. Squid 6 Series Wave Energy Converter

Increased generation capacity is achieved in two ways; array scale and device size. By joining multiple units together, a WaveNET is formed, altering hydrodynamic properties of the wave energy array and reducing costs by economies of scale.

In development is the Series 12 concept, by increasing the physical size of the device, an increased generating capacity of 75kW is achieved. This provides a greater cost and power budget for the deployment of a condition monitoring system.

4 FAILURE MODES AND EFFECT ANALYSIS

4.1 *Set Up*

Guidance for the FMEA process may be found in DNV-RP-203 Qualification of New Technology (DNV 2011), the objective of the process is to identify all possible failure modes and their related mechanisms. Though the process assumes all failures are independent, where in reality a single fault may trigger cascading failures, an FMEA provides a useful overview of all potential modes of failure and their level of perceived risk.

Traditionally, probability and consequence risk rankings are attributed to each FMEA entry. A score of 1-5 is assigned depending on a predetermined level of likelihood and severity, and a Risk Priority Number (RPN) calculated by the product of probability and consequence. A greater RPN represents a higher risk failure mode.

In this study the addition of a detection ranking was also assigned. The inclusion of detection rankings in the calculation of the RPN helped to inform where critical RPN ratings can be reduced by adding online monitoring equipment, such as being able to detect hydraulic leakages immediately due to a sudden drop in pressure. Detection classes are described in Table 1. Inclusion of a detection class resulted in a maximum RPN of 100.

Table 1. Detection Classes.

Class	Likelihood of Detection	Time To Detect
1	Current monitoring methods almost certainly detect	<1 hour
2	Good likelihood current monitoring methods will detect	<24 hours
3	Low likelihood current monitoring methods will detect	Within 1 week
4	No known/current monitoring methods in place	Over 1 week

4.2 *Execution*

A sub-systems approach was taken to categorise the Squid 6 Series WEC into its constituent sub-assemblies. The WEC was divided into 5 sub-systems: Moorings, Structural, Hydraulic, Electrical and Instrumentation. A list of sub-assemblies is given in Table 3, whilst a further breakdown of sub-assembly into component level is given in Table 4.

Table 3. List of WEC Sub-Assemblies

Sub-System	Sub-Assembly
Moorings	Leg
	Grid
	Connector
Structural	Central Node and Riser
	Link Arm
	Pumping Module
	Antinode
Hydraulic	Pumping Module
	Low Pressure Antinode
	PTO Module (manifold, motor)
	Hydraulic Ring Main
	Array Connection
Electrical	PTO Module (generator)
	Low Power Side
	Inter Array Cabling
	Central Junction Box
	Export Cabling
Instrumentation	PTO Module (generator)
	Auxiliary
	Data Acquisition and Control
	Communications

Table 4. Sub-Assembly Component Breakdown Example

Sub-System	Component Level
Hydraulic	Manifold Block
	HP Accumulator
Sub Assembly	Hydraulic Motor
Power Take Off	Piping
	Connectors
	Solenoid Valve
	Fittings
	Manual Valves

Common failure modes of each sub-system are listed in Table 2, failures are not exhaustive or representative of the entire system. With reference to section 2.2, the cause of each failure will result in the WEC being unable to performance its intended function, i.e. the capture, conversion and export of electricity. Root causes of failure (Failure Mechanisms) were adapted from an FMEA conducted for an offshore wind turbine (Arabian 2010) and made suitable for a WEC. These are listed in Table 5.

Table 2 Common Failure modes of a WEC.

Moorings	Structural	Hydraulic	Electrical	Instrumentation
Loss of pretension	Loss of watertight integrity	Seal failure	Electrical short	Calibration error
Entanglement	Hull breach	Hose burst	Connector fault	False alarm
Drags from position	Structural failure	Water ingress	Generator failure	Software fault
Structural failure	Deformation / yielding	Oil leakage	Electrical overload	Intermittent output
Incorrect orientation	Disconnection	Valve jams shut/open	Battery failure	Comms. failure

Table 5. Root causes of failure (Failure Mechanisms) of WECs

Mechanical	Electrical	Structural	Marine Environment
Corrosion	Calibration Error	Design fault	Entanglement - moorings
Fatigue Limit State (FLS)	Connector failure	Service loads	Biofouling (airbourne)
Ultimate Limit State (ULS)	Electrical short	Poor installation	Marine growth (subsea)
Accident Limit State (ALS)	Insulation failure	Maintenance fault	Ship impacts
Insufficient lubrication	Lightning strike	Manufacturing defect	Foreign body impacts
Overheating	Loss of power		
Bolt loosening	Conducting debris	Hydraulic	
Malicious damage	Software design fault	Contamination - Debris	Overpressure
Vibration fatigue		Contamination - Moisture	Miscibility – poor mixing
Material degradation		Contamination - Air	Choked – excessive flow

4.3 *Results*

A total of 210 FMEA entries were analysed, of these, entries with a Risk Priority Number of 15 or above were considered to be critical. These critical failure modes were given the highest priority for inclusion in the CMS. All further entries above 10 were considered important, and were attributed a medium priority level for monitoring. Entries with an RPN below 5 were considered as low priority. Methods for monitoring the signals of each failure mode are described in section 5.

5 MEASUREMENT PRIORITIES AND METHODS OF DETECTION

In Table 6, the proposed methods of detection for high priority failure modes are presented in order of sub-system. Likewise, Table 7 and Table 8 display proposed condition monitoring solutions for medium and low priority failure modes respectively.

High priority failure modes are prioritised as such due to their high probability and consequence. In Table 6, a focus in condition monitoring is on the system hydraulics and electrical generator. This includes the typical monitored parameters – oil condition, water ingress, and system pressure, as well as generator bearing health, current and voltage outputs, and battery status. In addition, watertight integrity of the Antinode housing the PTO module is suggested, as well as the remote monitoring of data quality from PTO instrumentation.

Additional condition monitoring solutions for medium and low priority modes add further resolution to hydraulic and electrical subsystem monitoring. This includes overpressure, choking and pressure spikes in the hydraulic cylinders, as well as generator shaft alignment and torque. Structural monitoring of connection bolts is recommended for validating service loads. Finally, monitoring the forces on the moorings using a load shackle allows detection of multiple modes of failure of the moorings sub-system.

An illustrated schematic of proposed instrumentation is displayed on Figure 2.

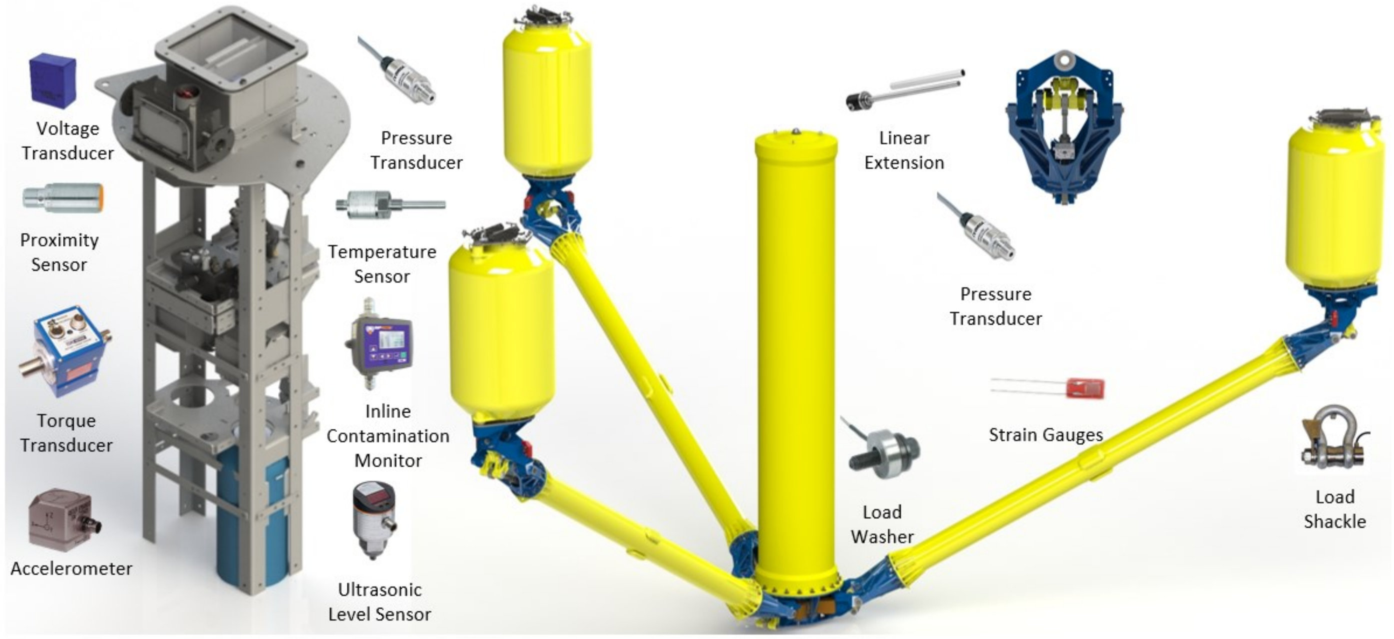

Figure 2. Illustrated schematic of proposed condition monitoring instrumentation.

Table 6. Proposed methods of detection for high priority failure modes

Sub-System	Sub-Assembly	Failure mode	Measured parameter	Method of detection
Structural	Antinode	Loss of watertight integrity	Relative humidity	Humidity Sensor
Hydraulic	PTO module	System overpressure, oil leakage, hose burst	System pressure	Pressure transducer
	PTO module	Water ingress	Oil moisture content	Moisture sensor
	Low pressure antinode	Oil leakage (gradual)	LP accumulator reservoir level	Ultrasonic level sensor
	Low pressure antinode	Oil leakage (sudden)	LP accumulator pressure	Pressure transducer
Electrical	Low power side	Electrical overload, short, connector fault, battery failure	Battery Voltage, Status	Battery charger
	PTO module	Generator failure, electrical overload	Generator voltage, current	Voltage and current transducers
	PTO module	Generator failure	Generator temperature	Linear resistor
	PTO module	Generator failure	Generator speed	Absolute encoder
	PTO module	Generator failure	Bearing vibration	Accelerometer
Instrumentation	PTO module	Intermittent output, communications failure	Sensor output continuity	Remote diagnostics

Table 7. Proposed methods of detection for medium priority failure modes

Sub-System	Sub-Assembly	Failure mode	Measured parameter	Method of detection
Moorings	Connector	Loss of station keeping,	Displacement, position	GPS
	Connector	Loss of pretension, ship impacts, entanglement	Mooring loads	Load shackle
Structure	Connection bolts	Bolt disconnection, structural failure	Forces on Bolts	Load washer, M20/24 bolts
	Connection bolts	Deformation, yielding	Bolt pre-tension, loading	Strain gauges
	Pumping module	Deformation, structural failure	Mechanical linkages and bearings strain	Strain gauges
Hydraulic	PTO Module	Choking	Flow Rate to PTO Module	Ultrasonic flow sensor
	PTO Module	Contamination, water ingress	Particulates, moisture, oil temperature	Inline Contamination Monitor
	Filter	Failure of filter	Oil Filter Cleanliness	Pressure transducer
	Pumping Module	Hydraulic cylinder rod deformation	Hydraulic Cylinder Extension	Linear position sensor
	Pumping Module	Hose burst from pressure spoke	Hydraulic Cylinder Pressure	Pressure transducers
Electrical	PTO Module	Motor-generator coupling failure, bearing failure	Generator Torque	Torque transducer
	PTO Module	Motor-generator shaft misalignment	Shaft Alignment	Inductive proximity sensor
Instrumentation	Auxiliary	Intermittent output, communications failure	Sensor output continuity	Remote diagnostics

Table 8. Proposed methods of detection for low priority failure modes

Sub-System	Sub-Assembly	Failure mode	Measured parameter	Method of detection
Moorings	Grid	Loss of pretension - abnormal response	Motion and accelerations of nodes	Inertial Measurement Unit
Structural	Antinode, Riser	Deformation of node structure	Strain, displacement	Fibre optic strain gauge

6 DISCUSSION

Though an extensive list of proposed condition monitoring solutions has been provided for the WEC system, the proposed solutions are not exhaustive. Failure rate data will need to be collected over time to inform the choice of instrumentation, in turn this failure data can be used to feed in to reliability analysis of the WEC system (Thies 2009), allowing for continuous reliability improvement.

Though a greater resolution of condition monitored data allows for a higher chance of diagnosing failure events, cost and power constraints must be taken into account for a commercial device. This is especially important in the Squid 6 Series, which, due to its limited rated capacity, does not provide as great an instrumentation cost and power budget as the Squid 12 Series. Where cost and power of condition monitoring solutions may be an issue, offline monitoring methods, such as oil sampling and visual inspections during scheduled maintenance may suffice.

6.1 *Future Work*

Castanier (2015) discusses the optimization of operations and maintenance procedures for an offshore wind farm using condition based decision policies. Wind turbine degradation level, and the current and future weather conditions are taken into consideration for running the turbines at full output, half breaking and complete stoppage. By using forecasted data, maintenance actions can be anticipated and the turbines run at a reduced output level in order to extend their operating life before maintenance is required.

Li (2015) also describes a condition-based maintenance policy based upon the economic dependence of components. If two components are in parallel configuration, strategic maintenance decisions can be made, either (1) preempting the failure of one component or (2) postponing the maintenance of a set of components until they fail. This policy may be used to reduce the frequency of intervention. By collecting quality WEC condition data, condition-based maintenance policies can be applied.

7 CONCLUSION

An FMEA has been conducted for a WEC, with a list of condition monitoring solutions covering high, medium and low priority failure modes provided. At present there is a lack of operational data in the marine energy industry. By investing in a capable condition monitoring system for the wave energy array, systems can be put in place for the collection of valuable data, with the goal of continuously developing a reliability centered maintenance strategy, and reducing total operational expenditure.

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