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Condition monitoring for wave energy converters

Mathias Johanson, August von Hacht, Charlotte Strang-Moran, Johannes Hüffmeier, Pär Johannesson

Abstract— **An effective condition monitoring system can increase availability and decrease maintenance costs of Wave Energy Converters (WEC). For this purpose, we explore a flexible condition monitoring approach that can be implemented at an affordable cost by re-using existing sensors and relying on a software-centric design. For continuous monitoring, it is possible to make a trade-off between on-board computational power and data communication speed. Operational data captured from in-WEC sensors are communicated and processed to detect abnormal behaviours indicating impending malfunctions, to predict and respond to needs for maintenance before serious damage occurs. Furthermore, the approach enables operational optimisations based on monitored conditions. The hypothesis is that by being able to reliably predict the state of health of individual WECs in a WEC farm from captured sensor data, a required reliability level can be achieved without over-designing components, lowering costs of production, maintenance and operation. Additionally, the data collected for condition monitoring purposes can be reused for simulation model validation and in knowledge-driven product development of next generation WECs. Critical components for condition monitoring are identified from the risk and reliability assessment, for instance by FMECA. A detailed analysis of critical components is performed using the VMEA methodology. A reference architecture design for WEC condition monitoring is suggested and a prototype implementation is presented along with a proof-of-concept demonstrator use case.**

Keywords— **Condition Monitoring Systems, Wave Energy Converters, Reliability, Availability**

I. INTRODUCTION

GLOBALLY the potential of ocean energy is estimated at about 337 GW of installed power with a market value of about 653 billion Euro in 2050. This, in turn, is expected to generate 680,000 jobs directly related to the fabrications and installations while at the same time helping to reduce CO_2 emissions by about 500 million tonnes [1]. In Europe, ocean energy has the potential to secure 10% of Europe's total energy supply in 2050 with established marine energy parks with a total of 100 GW capacity [2]. Data from full-scale demonstration - both individual units and units in marine energy parks - are required to enable commercial future investments in marine energy projects. For other technologies, a number of iterations of prototypes and full-scale tests are required to reach a stage where commercial investors believe the risk is acceptable. By testing and installing marine energy parks, the learning accelerates and the costs will start to decrease, which reduces the total project costs and thus the cost of the electricity produced. For commercial off-shore installations it is further fundamental to increase knowledge about how to optimise the conversion energy by reliable devices. Operational data from the real marine environment is needed to develop the units and create lessons for improving logistics and processes.

Components and systems used in ocean energy converters must be compatible with the marine environment and resist corrosion, the ultimate and fatigue loads they are exposed to. Using, developing and improving materials is the key to energy plants that survive and are reliable enough to produce energy at a competitive cost. High reliability and survival capability need to be ensured in order for ocean energy systems to deliver electricity consistently across the products' life-span, to attract and protect investments.

Wave power is regarded as one of the most promising marine renewable energy technologies. With an estimated total resource of 32,000 TWh annually, out of which 2000-4000 TWh deemed viable for economic exploitation, ocean waves provide a great source of clean, carbon-free renewable energy [3]. Wave energy devices operate in harsh environments, but still need to perform with a high level of reliability in order to lower the levelized cost of energy (LCoE) to a competitive level. One approach to improve the availability of WECs is to rely on condition monitoring for predictive / preventive maintenance and operational optimization.

The survivability of marine energy devices is affected by structural stresses induced by extreme weather conditions, highly variable load cycles, corrosion and bio-fouling. Remote offshore installation locations make operation, service and maintenance expensive and time-

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M. Johanson is with Alkit Communications AB, Sweden (e-mail: mathias@alkit.se). A. von Hacht is with Syncetive Labs, Sweden (e-mail: august.von.hacht@synective.se), C. Strang-Moran is with ORE Catapult, UK (e-mail: charlotte.strang-moran@ore.catapult.org.uk) J. Hüffmeier and P. Johannesson are with RISE, Sweden (e-mail: johannes.huffmeier@ri.se, par.johannesson@ri.se).

consuming. Hence, for a given failure rate, an offshore device will experience more downtime than an onshore installation, particularly since accessibility depends on favourable weather condition. For these reasons, marine energy devices have a need for operation and maintenance strategies based on condition monitoring in order to increase availability and reduce operational costs, improving the competitiveness in relation to other renewable energy technologies.

Condition monitoring solutions for renewable energy systems are widely deployed in the offshore wind industry [4, 5]. However, due to the lower overall Technology Readiness Level (TRL) of the wave energy industry, lack of design consensus in WEC technology, and unavailability of reliability models of core WEC components, the realization of condition monitoring systems for WECs is still in an early phase with considerable challenges [6, 7]. Another obstacle is scarcity of measurement data, in particular failure data, required to design and validate new data-driven CM techniques.

II. CONDITION MONITORING

Condition monitoring (or equivalently, Condition Based Monitoring) is the process of capturing operational data from technological systems in order to identify changes indicative of a developing fault or sub-optimal performance. Condition monitoring systems facilitate early detection of impending component failures, making it possible to design predictive and preventive maintenance strategies. This reduces the number of unplanned maintenance stops and increases uptime.

The main aims of condition monitoring of relevance for marine energy devices include:

- Diagnosis of potential anomalies within the WECs
- Avoidance of unplanned production downtime
- Reduced need for repairs
- Maintenance planning optimization
- Increased availability
- Target system protection
- Reduction of maintenance costs
- Preventive and predictive maintenance
- Leveraging collected data for knowledge-driven product development

The core functionality to realize a condition monitoring system for WECs is to collect measurement data from WECs in operation for analysis, triggering interventions. This involves the following building blocks:

- Sampling of sensor data at well-defined sampling rates
- Collection of other operational data from the WEC control system and external data sources, such as weather and sea state information
- Pre-processing and filtering of captured data
- Communication of data from WEC to onshore back-end server infrastructure
- Storage of collected data sets in a structured way (e.g. database, data warehouse, data lake)
- Feeding data into automated data processing services for fault prediction
- Alerting, triggering of interventions
- Making data available for other analytical processing
- Presentation of data analyses (e.g. visualization), report generation.

A. *System level condition monitoring*

System level condition monitoring can be achieved by monitoring the performance of a complete system, and comparing with the expected performance, or with the actual performance of other systems in operation subject to the same or similar conditions. For WECs, such an approach can be realized by monitoring the electrical power produced by a WEC and comparing it to the average power produced by WECs of the same WEC farm (i.e. total farm output divided by the number of WECs in the farm). For only a single WEC, a model needs to be developed to compute the expected power output from a measured sea state.

If the measured and expected output deviates beyond a threshold value, an alarm can be generated, and fault-tracing initiated. Correlative measurements, such as sensor reading comparisons, can then reveal unhealthy systems inside an individual WEC as compared to the mean over the entire WEC farm. The problem with this somewhat simplistic approach is that it is reactive instead of proactive, i.e. problems are not detected before they start affecting system performance.

B. *Component level condition monitoring*

In component level condition monitoring, a mathematical or statistical model of a single component (or sub-system) is used to detect failures based on monitored data. This includes structural health monitoring of components based on fatigue models, vibration analysis, and control system diagnostics. Component level CM is by necessity highly dependent on the target system design. Contrary to system-level CM, component level CM can identify root-causes of failures or suboptimal performance of WECs, and require detailed reliability assessment and analysis through methodologies such as FMECA (Failure Mode, Effects, and Criticality Analysis) [8] and VMEA (Variation Mode and Effect Analysis) [9]. Component level CM also involves detecting outliers in real time data readings. By estimating a statistical model of the variance in historic data readings under regular healthy operations a large deviation from this curve may indicate component level failures or need for maintenance.

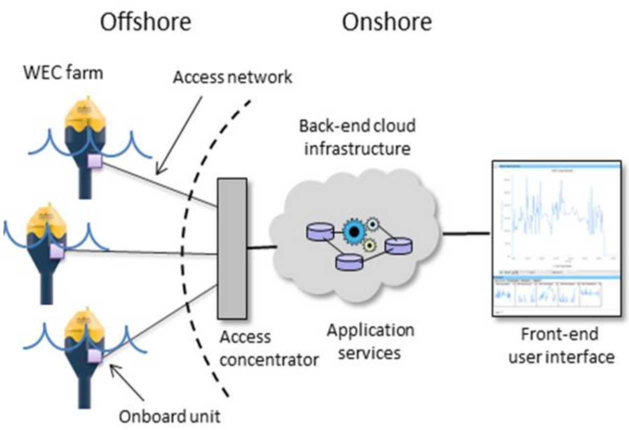

Fig. 1. Reference architecture overview

III. Reference Architecture Design

In this section, a reference architecture for condition monitoring targeting Wave Energy Converters is presented. The proposed architecture is based on a multi-tiered model, designed with a modular System-of-Systems approach [10], promoting open interfaces and affordable Internet-of-Things technology, in contrast to the more traditional monolithic and highly expensive systems available today for e.g. offshore wind applications. Additionally, a distributed data processing approach is proposed, whereby computations required for the analytics can be performed both onboard the WEC and in a back-end data processing infrastructure, enabling trade-offs between onboard computational capacity and communication network bandwidth.

The concept of Smart Monitoring of WECs is introduced to optimize the data communication trade-off and enable secure, robust and efficient communication between onboard processing and back-end offloading by utilizing both wired and wireless communication.

An overview of the reference architecture is shown in Figure 1.

A number of high-level architectural alternatives have been analysed for WEC condition monitoring, forming the design rationale for the reference architecture and the prototype implementation.

C. *Target system integration*

A condition monitoring system for WECs can be designed either as a stand-alone system with external sensor systems or as a component closely integrated with the target system (i.e. the WEC control system). With a stand-alone approach, the sensor system is specifically designed for condition monitoring purposes, whereas an integrated system approach reuses the sensors already available for the operation of the WEC. In the integrated approach, the CMS could be realized as a piece of software running on the same hardware as the WEC control system, whereas the stand-alone approach requires dedicated hardware. There are benefits and drawbacks of both approaches, with the stand-alone approach typically resulting in a more generalized solution and the integrated a more application specific solution.

The approach of the prototype implementation described in section IV, is to use sensors already available in the WEC and used by the WEC control system. With this approach no new sensors will be required solely for the condition monitoring, and hence the cost of the system will be less than if new sensor systems need to be added. However, the execution environment of the CMS is separated from the WEC control system. This is mainly for practical purposes, but also gives a level of isolation between the WEC control system and the CMS, which is desirable for reasons of robustness and modularity. This kind of design is greatly simplified if the WEC sensor system is based on a Fieldbus architecture such as CAN or EtherCAT. The CMS can in this case be connected to the bus to access sensor data without requiring any modifications to either sensor system PLCs or control system.

D. *Sensor data communication approach*

Conceptually, sensor data communication can be supported in two main modes: store-and-forward and capture-and-transmit. In store-and-forward mode, captured data sets are stored to local persistent storage and uploaded at (configurable) regular intervals. In capture-and-transmit mode, each captured data sample is immediately transmitted to the back-end server infrastructure. The main benefit of the store-and-forward approach is that data is not lost when the communication uplink is unavailable. The main benefit of capture-and-transmit is low latency and reduced local storage need on the onboard units. For the reference architecture, a store-and-forward approach is preferable (mainly due to the fault tolerance requirement), but there is nothing preventing both mechanisms to be implemented in parallel. In the prototype implementation, both mechanisms are available, with the capture-and-transmit mechanism, when enabled, transmitting data at a lower rate, to be used mainly for quick manual state of health inspections, whereas the store-and-forward mode is used for the automated data processing.

E. *Distributed vs. centralized processing approach*

Another high-level design option for a CMS is whether to place the computational complexity needed for the analytical data processing close to the data sources (i.e. in the WECs) or in a centralized (possibly cloud-based) back-end server infrastructure.

In the distributed processing approach, the onboard (in-WEC) parts of the CMS processes captured data locally, triggering alerts to remote service management personnel whenever the performance of the monitored systems is not according to plan. In the centralized processing approach, captured sensor data is transmitted to a back-end server infrastructure where it is processed to detect deviations from normal operation. Both approaches have benefits and drawbacks. Hybrids of the two can also be envisioned, where some processing is performed onboard and the remaining processing is performed in the back-end architecture. The distributed data processing approach requires less communication bandwidth and simpler back-end service infrastructure, while requiring more on-board computational capacity. The reverse is true for the centralized (cloud) processing approach. The distributed approach can be considered a more "traditional" architecture for industrial condition monitoring systems, whereas the centralized processing is more in line with emerging Internet-of-Things architectures, which emphasizes simple edge devices and extensive cloud-based processing. (Note that the use of the term "centralized" in this context does not prevent the processing architecture to use distributed computing mechanisms such as cluster computing.)

F. Communication infrastructure

The means of communication from the offshore WECs to the onshore back-end infrastructure can be realized in a variety of ways, including wired communication using fiber-optic cables bundled with the power-grid connection cable and wireless communication based on mobile telecommunication infrastructures (3G/4G/5G). A scheme wherein multiple WECs in a WEC farm communicate locally using short-range communication (e.g. IEEE 802.11), sharing a common uplink, either via fiber or mobile data communication has also been explored. But, whether the communication infrastructure of the offshore WEC farm in any condition can support a stable high data rate uplink, such as a seabed fiber-optic cable network architecture, will be crucial for the final design. Unable to maintain a high data throughput may require custom implementation schemes based on e.g. trigger values, data rate scheduling, local data processing. Such a communication infrastructure must be modular enough to support these customizations. Additionally, considerations regarding cost and power consumption can have an impact in the decision on the most efficient and reliable infrastructure to use. Nevertheless, a Smart WECs scheme has been explored as either a full-fledged communication scheme or as a backup system whenever the main link suffers from major downtime. The Smart WECs concept is a communication scheme which utilizes the short-range communications protocol to forward data, during store-and-forward mode or as a backup mode in case of uplink failure, from offshore WECs to nearshore gateway WECs by passing on data either via nearest neighbour hops or via hubs. These gateways allows for using short-range communication between the onshore back-end server and the first layer of offshore WECs which thereafter can communicate further with the rest of the farm. Choosing the WEC farm topology to support a data forwarding protocol which is distributed in nature, such as ad hoc networks, improves the overall resistance against communication failures due to allowing rerouting of the main data link, making a communication failure between the onshore station and the offshore farm independent of a single WEC failure, a gateway WEC failure and/or a cable network failure.

G. Sensor fusion and signal processing approaches

Since many types of sensor data are available for condition monitoring purposes, from the target system's control system, from dedicated CM sensors and from other data sources, sensor fusion, i.e. the ability to aggregate and combine sensory data from disparate sources is important. How this sensor fusion is done depends on the type of signal processing or analytics approach. A Signal Trending approach relies on comparing corresponding signals from different systems (i.e. WECs), or with signals collected historically from the same system. It is hence an approach based on deviation detection. Artificial Neural Networks (ANN) is a Machine Learning approach whereby patterns can be detected. An ANN must be trained with data sets collected during normal operation, so that a deviation detection metric can be calculated based on collected data. Approaches based on mathematical or statistical models derived from knowledge of the underlying principles fall under the category of Physical models. Hybrids of two or more different data processing approaches are also possible.

The prototype implementation and PoC demonstrator use case relies on an approach based on physical models (see section V).

IV. PROTOTYPE IMPLEMENTATION

In this section a prototype implementation of a WEC CMS based on the reference architecture is described.

The prototype implementation was realized by adapting a data capture and telematics system originally targeting automotive applications [11]. The system architecture is composed of the following main components:

- A Linux-based embedded system for data capture, pre-processing and connectivity, to be installed in target WECs,
- A telematics service architecture, providing secure communication and distributed computing services,
- A cloud-based back-end server infrastructure, providing scalable processing of data, and a high-level Application Programming Interface (API) for access to information resources,
- A data storage system based on a data lake concept,
- A web-based user interface, for configuration, visualization and management.

An important feature of the in-WEC embedded system is that it is primarily a software-based system with a significant focus on allowing remote software updates and powerful configuration management. This is of paramount importance for a system that has a long planned lifetime (many years or decades in case of WECs), since new needs for data capture will emerge over time, and software bugs will be found that needs to be corrected.

The hardware of the in-WEC embedded CM system used for the prototype implementation is based on a dual core ARM Cortex-A9 processor running Ångström Linux, with solid state storage and built-in 4G modem.

The software architecture of the prototype CMS relies heavily on a task multiplexing concept, whereby several independent data capture and analytics processes can coexist simultaneously, serving different CM purposes. For instance, one task can be devoted to pressure sensor monitoring for a fatigue prediction calculation, while another is concerning electrical overload monitoring. The ability to separate different functional components of a complete system condition monitoring provides great flexibility in handling heterogeneous target WECs with different configurations, requiring slightly different monitoring procedures.

Another central feature is that while the condition monitoring in the general case is intended to be running autonomously, i.e. without requiring any human intervention during normal operation, it is at any time possible to request and inspect any data being captured in real time. This type of synchronous "online monitoring" is reminiscent of first generation SCADA systems for supervision of industrial processes, where little or no processing is performed on telemetry data. The ability to request direct visual inspection of any data source is intended to be a useful tool primarily for fault tracing, but also for state-of-health monitoring of WEC components that has no reliability model developed and thus the health cannot be automatically predicted.

The architecture supports sensor data processing both onboard (in the embedded system in the WECs) and offboard (in the cloud infrastructure). This allows a trade-off between communication bandwidth and onboard computational requirements, depending on the type of processing needed. For the proof-of-concept use case, a cumulative damage due to material fatigue in a critical WEC component is continuously calculated based on pressure sensor data input. For this use case, the computation can be done onboard, with only the computed damage value communicated to the back-end. For other use cases, the processing can instead be done in the cloud, requiring the (possibly filtered, or otherwise pre-processed) sensor data input to be communicated to the cloud.

The back-end infrastructure of the prototype CMS is a Linux-based server computing environment, whose key elements include a Java Servlet Container, a Database Management System (DBMS), a Network Attached Storage (NAS) hosting a data lake, and a web server supporting a web front-end user interface as well as a REST-based Machine-to-Machine (M2M) API. The DBMS and the M2M API provide the main integration points of the software platform, which is based on a Service Oriented Architecture (SOA). The SOA paradigm provides a loosely-coupled integration between different software modules, promoting interoperability, transparency and reuse of software components [12]. Due to the SOA approach, the prototype system's back-end software architecture could be designed with a high level of reuse of services initially developed for an automotive telematics system.

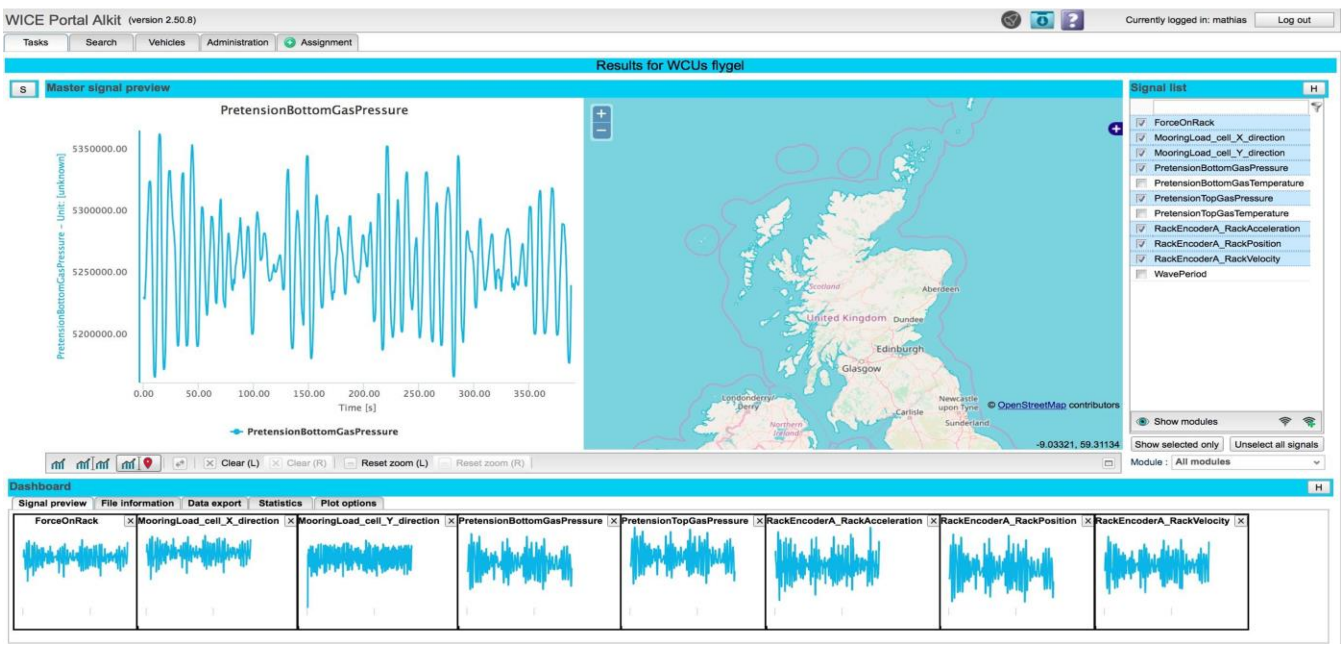

Fig. 2. WEC CMS web front-end showing a signal monitoring view

Fig. 3. CorPower's buoy during installation at Orkney. Image courtesy EMEC.

Secure communication between in-WEC systems and back-end is realized using Transport Layer Security (TLS), with endpoint authentication using a public key infrastructure and X.509 certificates. Correspondingly, communication between the back-end web server and front-end web browser or M2M endpoint is secured through HTTPS.

The user interface is a web front-end application, implemented using the GWT Web Toolkit. It supports configuration management, task control, data visualization, alerts, data export, user access control and more. The user interface is accessible from a standard web browser, without need to install any additional client software.

An example screen-shot of the CMS user interface is shown in Figure 2.

V. Proof of Concept Demonstrator

In this section a proof-of-concept (PoC) demonstrator is described based on a use case focusing on the fatigue life of critical components in the pre-tension system.

H. Target system and demonstrator use case

The target WEC system of the PoC demonstrator is the CorPower half-scale prototype [13], which was test deployed in Scapa Flow during 2018 (see Figure 3). The CorPower WEC is a point absorber with a power take-off system transforming the vertical movement of the buoy into electrical power, and using the patented WaveSpring technology for phase control. During wet testing of the WEC, large volumes of sensor data were captured. These recorded data sets are used as sensory input data sources in the demonstrator, by means of a software wrapper that allows the sensor data capture module in the embedded in-WEC system to read data from a file, instead of the real sensor. By having access to real sensor data, the demonstrator can be run in an office or lab environment, instead of having to be installed in the real target WEC environment, which simplifies experimentation, development and demonstrations.

The demonstrator use case is based on the pre-tension module of the CorPower C3 WEC. Two critical components of the module are the cylinder barrel and the dynamic seals. Monitored signals include forces, position, speed, temperatures and pressures.

I. Failure modes

Monitored signals like temperature, pressure and vibrations are often used as indicators of failure modes, and threshold values can be used for indication of possible failure states or close to failure. For the pre-tension system an elevated temperature may indicate malfunction of the device, while leakage, indicated by the pressure signal, indicates worn-out seals. Further, deterioration of components can be caused by e.g. wear or fatigue. In this case the loads can be monitored and an accumulated damage can be computed. For the pre-tension cylinder the pressure variations gives the accumulated fatigue damage [14]. For the dynamic seals the total travelled distance is the main damage parameter for wear. By using damage models the remaining useful life can be calculated. This information can then be fed into the maintenance planning, enabling improved preventive maintenance strategies.

J. Data processing

The fatigue load of the cylinder barrel can be monitored through the internal pressure in the pre-tension module. The rainflow cycles extracted from the pressure signal are used for computing the fatigue damage. This data processing is performed onboard the WEC. At regular intervals, the computed damage value for that period is communicated to the back-end over the communication infrastructure for continuous evaluation of the accumulated fatigue damage. Similarly, the accumulated loads on the dynamic seals is monitored and communicated to the back-end. In this case the total travelled distance is the main damage parameter for the wear, and the measured position of the rod is used to calculate the travelled distance for each period of time. The monitoring of these aggregated parameters in the back-end allows us to analyse if the damage is accumulated at a faster or slower rate than expected by comparing between neighbouring WEC's condition data or from a WEC's own historic data, or a combination of both.

Different weather conditions cause different sea states and the expected damage accumulation rate depends on this parameter. A sea state is characterized by its significant wave height and period together with the type of power spectrum. During target system testing the significant wave height and period was recorded and was used for calibrating simulation models for the WEC. Thus, simulated values for the damage parameters can be obtained in the back-end, to be compared to the observed values.

In the condition monitoring framework, the monitored accumulated damage values for the cylinder barrel and the dynamic seals are two examples of monitoring parameters for determining the individual conditions of the WECs during operations. For each WEC the residual life of the corresponding component can then be estimated based on the accumulated damage, and this information can be used for maintenance planning.

VI. Discussion

Efficient condition monitoring is an essential tool to optimise the design, development, operation and maintenance of wave energy and tidal energy devices. Learning from other industries, such as wind power indicates savings during the operational phase of about 15-20%, detecting failures months in advance. The required learning and knowledge increase for the technology developers is essential to decrease the risk for investors and derive reliable designs. Challenges connected to the condition monitoring relates to cost efficient monitoring based on partly integrated solutions, that will improve the reliability, availability and maintainability of the devices to a sufficient level.

Availability of operational measurement data is of critical importance for the functioning of a CMS, but it is also vitally important in the development phase of WECs. Data collected for CM purposes can therefore be seen as a valuable asset in product development. By having access to reliable data sets about WEC component performance, design decisions can be made based on knowledge rather than purely model-based simulations and best practices. Hence, data capture in a CMS can serve multiple purposes, particularly in early prototype or pre-production level systems.

A critical component of the condition monitoring framework is the communication infrastructure band-width, uptime and energy consumption. Transmitting data continuously over longer distances requires power which eventually becomes a reduction factor on the power produced by a WEC. Wireless long-range trans-mission has the unsatisfactory scaling factor of being inversely proportional to the square of the distance and is not considered as an infrastructure candidate. Instead, either short-range WEC-to-WEC wireless communication with the nearshore WECs functioning as gateway nodes to the onshore back-end or a fibre-optical infrastructure should be considered; preferably the fibre-optics due to its high bandwidth support and lower power consumption. However, the motion of the WECs has harsh requirements on the fiber-optics in that it has to be able to move with the WEC's connector. This increases the risk of wearing out or even breaking off the fibres due to heavy motion. A better alternative might be to set up one or more wireless access point base stations inside the WEC farm area and have short-range wireless communication with the stations. The fiber-optics would then be firmly secured into the static structure of the access point base station and attached to the seabed, giving it a much higher chance of survival in harsh weather conditions.

Nevertheless, the best implementation to use in terms of reliability is yet to be determined from further research on offshore infrastructure solutions for unpredictably moving objects, as well as real world testing during critical operations.

VII. Conclusion

In this paper we have explored the opportunities and challenges of condition monitoring for Wave Energy Converters. A flexible condition monitoring approach, based on a software-centric design and reuse of components was proposed, providing a cost-effective yet powerful way to improve availability through predictive and preventive maintenance strategies. Furthermore, operational optimizations can be achieved based on analyses of collected data sets, and knowledge-based product development can be realized.

The approach to condition monitoring for WECs proposed is designed for scalability to large WEC farm installations, keeping operational costs at reasonable levels. Flexibility in trading off between computational complexity and communication bandwidth is achieved by having the possibility to process data both in the WEC and in the back-end infrastructure. The communication architecture is designed for robustness, optionally combining both short-range WEC-to-WEC wireless communication and fiber-optic WEC-to-infrastructure communication. The prototype implementation and demonstrator use case clearly illustrate the feasibility of the approach and give encouraging support for the hypothesis that reliability and availability of WECs can be substantially improved by sophisticated condition monitoring.

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