Condition Monitoring Systems of Wave Energy Converters

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Executive Summary

There is a progression towards lowering the price of offshore renewable energy including the wave energy sector. Accessibility is a challenge with offshore generation devices including wave energy converters (WEC) and this is why the deployment of condition-based monitoring systems will be crucial to support operation activities. Condition monitoring systems are used to optimise maintenance and provide early detection while also reducing access constraints. This report study provides an insight into condition monitoring of Wave Energy Converters.

There is a wide range of wave energy technologies, each using different solutions to absorb energy from waves depending on the water depth and location. There is little convergence amongst the wave energy technologies, however, the industry shows many different alternatives to harnessing wave power under different conditions. It is believed that existing monitoring systems within the wave devices developed to date draw directly from current technologies and advances made in the wind and other industries.

Defects and errors can affect the operation or structural integrity of the wave energy device. Failure modes are the various ways in which the WEC could possibly fail and monitoring systems are often used to anticipate complete failure and for fault detection. Based on literature key WECs failure modes identified include, mechanical, electrical, structural and marine environment impact. Based on these failure modes, a number of sensing technologies and systems were proposed to monitor the integrity of the WEC device. The proposed sensors and method of detection must be able to provide effective failure detection and meet the requirements of accuracy, cost effectiveness and long-term stability.

CMS uses detection methods with analogue signals which must be conditioned before being digitised. Signal conditioning is the next stage of processing where the signal is made available for data analyses. Signal conditioning requirements in terms of amplification, attenuation and filtering to improve signal accuracy were also addressed in this report.

Based on IEC 61400-25 standard which addresses all aspects of communication architecture for the monitoring and control of wind power plants, an example of a WEC device communication architecture concept was proposed including the positioning of the monitoring, protection and control information equipment at different location within the device. The concept divides the whole architecture of the WEC into multiple segments where; (i) the device front end (PTO) is equipped with a number of sensing and monitoring equipment, (ii) the controller is located behind the generator and (iii) the grid compliant generated power, metering and user control interface.

General procedures which must be considered when setting up condition monitoring within sub-assemblies of machines like wave energy converters. As such a number of relevant standards and procedures for condition monitoring were summarised. It is believed that the communications for monitoring and control of wind power plants (IEC 61400-25) is conveniently compatible with WEC applications. The basic concept of this IEC is a breakdown of compliant services and the different communication profiles available for data interchange, allowing all data from the devices to follow the same format.

1 Introduction

1.1 RiaSoR background

The goal of the RiaSoR project is to consistently learn from the physical interactions between the devices and their environments, while embedding this understanding and building robustness into marine energy technology designs to improve reliability.

Marine energy devices operate in harsh environments but still need to perform reliably and produce an expected amount of energy, which gives rise to huge engineering challenges.

The OceanERANET-funded RiaSoR 2 project will use the theoretical reliability assessment guideline for wave and tidal energy converters (WEC/TEC) developed in RiaSoR1 and apply it to the field.

This will enable WEC/TEC developers to validate their findings, and establish a practical condition based monitoring platform to prepare for future arrays where big data handling and processing will be vital to drive down operational expenditures (OPEX).
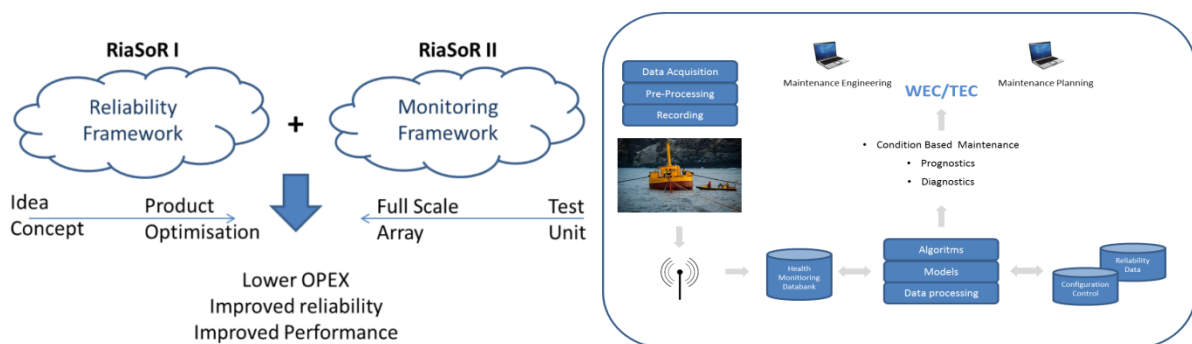
Figure 1 RiaSoR 1 & RiaSoR 2 overview

The RiaSoR 1 reliability guideline built upon established practices from the automotive industry where a monitoring framework is applied to a fleet of test-vehicles. Through design iterations, the reliability is improved and a final reduced set of sensors are deployed in the commercial vehicle.

For RiaSoR 2, the chosen components for monitoring are equipped with several sensors to collect the required data, which will then be fed into the reliability process to reduce uncertainties. Sea tests act as case studies to feed the methodologies and training into the guideline. The findings from this will then be trialled with the other developers.

The key objective of the RiaSoR 2 project is to offer a comprehensive suite of testing methodologies to wave and tidal developers that will enable a systematic approach to achieve optimal reliability and performance, while minimising cost and time-to-market.

2 Aim of condition-based monitoring

In the offshore renewable sector operating and maintenance organisation plays an important role to maintain the operations and efficiency of offshore devices like a WEC. Condition-based monitoring contributes to the safety and economy of the WEC plant.

Condition-based monitoring is used to evade downtime and faults due to unexpected failures in the WEC and to reduce the costs related to maintenance. Typical aims of the condition-based monitoring system include:

- Diagnosis of potential anomalies within the plants
- Avoidance of unplanned production downtimes
- Reduce the need for repairs and optimise planned maintenance
- Increased availability
- Planning of repair
- Plant/system protection
- Reduction of maintenance costs
- Preventive and predictive maintenance (CBM)
- Knowledge driven product development

3 Condition monitoring systems in offshore wind

Condition monitoring systems have been implemented successfully in the offshore wind industry using an extensive array of measurement techniques and analysis methods where both offline visual inspections and online oil, vibration, speed and power quality measurements were used. Typical CMS currently being used in the wind energy sector include vibration measurement to evaluate and quantify gearbox and bearing health, acoustic emission measurement for noise and stress levels of rotating machinery, and oil monitoring to analyse oil moisture, temperature and debris content. There are different analysis and techniques on which monitoring systems are based upon, these are presented in the following sections.

3.1 CMS based techniques & methods

- Vibration analysis

Currently the most extensive technology applied for condition monitoring, especially for rotating equipment. In the case of wind turbines, it has been applied for gearbox, generator bearing and main bearing CM. Generally, a baseline sample of vibration levels is collected for a healthy wind turbine, from which operating vibrations are compared. An "out of range" vibration will signify a fault, which can be further diagnosed by analysing the frequency of the vibration.

- Acoustic Emission

Acoustic Emission (AE) is related to vibration monitoring but with a different principle because in the acoustic monitoring case, the acoustic sensors "listen" to the component

instead of registering its local motion. AE sensors detect the stress waves that are generated during crack initiation and propagation within materials. AE has been shown to detect some faults earlier than vibration analysis. AE has been applied successfully to gearboxes, bearings and blades. The AE technique does not require trending like the vibration method. Although now AE has found limited use so far in the wind energy industry largely due to the lack of sufficient experience with the application of this technique for WT gearbox monitoring, it is predicted this will change in the near future.

- Oil analysis

Oil analysis is mainly carried out offline by taking oil samples for laboratory evaluation. However, for safeguarding the oil quality, application of on-line sensors is increasing since various oil analysis sensors are nowadays available at an acceptable price including wear debris detectors and moisture sensors which measure the presence of water in the lubricant oil of the WT gearbox. Characterisation of parts is often only performed in case of abnormalities. Practically all utility scale WTs employ oil temperature sensors nowadays to avoid overheating of the lubricating oil which may result in combustion and subsequently loss of a WT due to fire.

- Thermography

Thermography is often used for monitoring electrical and electronic components; in particular it could be applied to monitor failure prone power electronics. Currently, this technique is only applied off-line, but the development of on-line monitoring techniques will likely induce a larger uptake of this technology for turbine monitoring.

- Strain measurement

Strain measurement of turbine blades is generally performed with strain gauges; however, the development of a cost effective optical fibre strain measurement device will likely increase the use of strain measurements for turbine monitoring.

- Ultrasonic

Widely used for the analysis of turbine towers and blades, ultrasonic techniques can evaluate the structural integrity of the turbine by detailing the size and location of defects within the material.

- Eddy current inspection

Eddy current sensors are a well-established technology that are commonly used within NDT technology. Using either a permanent or oscillating magnetic field, the passing of conducting material induces eddy currents into the material. This in turn generates an opposing magnetic field, which leads to a change in voltage within the sensing coil. Eddy current inspection can be applied for the detection of fatigue cracks on the WT tower. However, encircling coils have been lately applied for detection of debris in the lubricant as mentioned earlier in this section. Any metallic debris ferrous or non-ferrous passing through the encircling coil will change its impedance response. Depending on the amount and type of change in the impedance response of the encircling coil the nature of the particle, ferrous or non-ferrous that caused the variation in the electromagnetic field within the sensor can be ascertained together with its dimensional range.

- Radiography

Taking X-rays of blades and towers is very rarely undertaken in the wind industry, although it can provide useful information regarding the structural condition of the turbine. Portable radiography-based systems will reduce the cost of this technique which may increase its use within industry.

- Shock Pulse Method

Only occasionally used within industry, the shock pulse method detects shock waves when a rolling element in a bearing comes into contact with a damaged area of the raceway or debris.

- Electrical Effects

Motor Current Signature Analysis or MCSA is used to detect unusual phenomena in electrical components.

- Deflection based methods

Sections of the device which are loaded with a weight or can move free-standing will be subject to warping of some extent. Measuring deflections can be achieved by calculating the relevant distances.

3.2 Condition monitoring of offshore wind turbine main components

Table 1 summarises typical defects commonly detected by wind turbine operators within the nacelle as well as the techniques used to evaluate them. In addition to condition monitoring, periodic inspection of main turbine components is also carried out as part of the maintenance regime. It is anticipated that with current evolution of condition monitoring systems that regular visual inspection will probably be phased out completely in the forthcoming years.

Table 1 Key | A: Severity in case of occurrence, B: Interest in improving detection method; (1=lowest, 5=highest)

Component	CM & Inspection	Severity	
		A	B
Main bearings	Vibration analysis and inspection every 12 months	5	5
Gearbox			
Housing cracks	Standard preventive inspection every 6 months	5	3
Bearings	Vibration analysis, inspection every 6 months (video scope)	4	5
Gears	Vibration analysis, inspection every 6 months (video scope)	5	5
Lubricant	Oil analysis and 6 months inspection	4	5
Coupling			

misalignment	Vibration analysis and alignment every 24 months	3	5
Generator			
Bearing	Vibration analysis and inspection every 12 months	4	5
Unbalance	Vibration analysis and inspection every 12 months	3	3
Other	Vibration analysis and inspection every 12 months	3	5
Yaw			
Yaw Drive	Standard preventive inspection every 6 months	2	4
Yaw gear	Standard visual inspection every 6 months	5	3
Yaw Bearing	Vibration analysis and standard visual inspection every 6 months	5	3
Blades bearings	Standard preventive inspection every 6 months	5	5
Hydraulic system	Oil analysis and 6 months preventive inspection	4	5

Table 1 Typical component defects within wind turbine nacelle and common condition monitoring/ inspection techniques employed

3.3   Typical measurement parameters of condition monitoring systems in an offshore wind turbine

To effectively monitor all components within a wind turbine using conventional CM systems it is conceivable that the requirements stated in Table 2 may be required. The data presented in the table illustrates the amount of data that would typically be collected per day for monitoring a single wind turbine, although the use of sensors with lower class types may result in lower sampling rate and thus a reduced amount of data.

Component	Measurement	Sample Rate (Sa/s)	Quantity
Blade 1	Load (X&Y)	1000	2
Blade 2	Load (X&Y)	1000	2
Blade 3	Load (X&Y)	1000	2
Main Bearing	Vibration (X&Y&Z)	2000	6
Main Bearing	Temperature	1	4

Gearbox LSS Bearing	Vibration (X&Y&Z)	2000	3
Gearbox LSS Bearing	Temperature	1	4
Low Speed Shaft	Torque	1000	1
Gearbox Stage 3	Vibration (X&Y)	2000	2
Gearbox Stage 3	Temperature	1	4
Gearbox Stage 2	Vibration (X&Y)	2000	2
Gearbox Stage 2	Temperature	1	4
Gearbox Stage 1	Vibration (X&Y)	2000	2
Gearbox Stage 1	Temperature	1	4
Gearbox HSS Bearing	Vibration (X&Y)	2000	3
Gearbox HSS Bearing	Temperature	1	4
Generator DE Bearing	Vibration (X&Y)	2000	2
Generator DE Bearing	Temperature	1	4
Generator NDE Bearing	Vibration (X&Y)	2000	2
Generator NDE Bearing	Temperature	1	4
Generator winding	Temperature	1	12
Encoder	Shaft Speed	10	1
Tower	X,Y,Z Sway	1000	3
Converter	Voltage	25000	3
Converter	Current	25000	3
Total samples		207654	
Total data per day (32 bit storage)		72 GB per day	

Table 2 Typical wind turbine monitoring requirements

Clearly, transferring 72GB of data daily per turbine would be inefficient for turbine monitoring as it would add significantly to the technical complexity of any system, and therefore increasing system cost. For this reason, many systems have adopted on-site analysis of data and transfer only a reduced amount of raw or aggregated data.

Furthermore, key parameter indicators (KPIs) can be established for certain components being monitored. In the event where the value of one or more KPIs exceed a certain threshold an alarm can be given and the signal which provided the alarm can be downloaded and assessed further.

Certain commercial systems such as the Bruel and Kjaer's Vibro system transfer high resolution data once readings have passed a pre-defined threshold, which can then be monitored at a central data analysis centre. Another method of reducing data transfer requirements includes Gram and Juhl's turbine condition monitoring. This system uses multiple sensors that feed into an on-site processing unit on the turbine. The results of the analysis are then reported back to the wind farm server system, rather than the raw data.

3.4 Commercially available condition monitoring systems

There are several wind turbine condition monitoring systems which are commercial today. Several of the available commercial wind turbine condition monitoring systems have been certified by DNV GL or other certification organisations. Manufacturers of wind turbine condition monitoring systems can be found from all over the world with a significant number of them based in Europe.

The list of available commercial wind turbine condition monitoring products is constantly growing with more organisations trying to enter the market. There is a particular interest from

SMEs in entering the wind turbine condition monitoring market which is currently dominated by larger industrial organisations.

Wind turbines condition monitoring market is particularly competitive and cost remains a key factor during selection. In the future other factors including stricter insurance company requirements will play a significant role in the selection of CMS and components being monitored.

Practically all industrial wind turbines make use of some sort of CMS which in most cases includes vibration analysis capability apart from temperature measurements. Depending on the system used and the available signal analysis methodologies the reliability of the resulting information gained from the CMS can vary significantly. Sampling rates, types of sensors number of sensors used and signal processing methodologies may differ substantially for CMS provided by different manufacturers.

It is important to minimise the number of sensors required to monitor critical components such as the gearbox, generator, main bearing or power electronics in order to keep the cost of the CMS as low as possible. An acceptable CMS cost cannot exceed €10,000-15,000 for most large scale commercial WTs under the current status quo. In certain cases, operators may opt for manual measurements rather than continuous monitoring.

It is important to acknowledge the effect of variable wind speed and wind turbulence during vibration, AE and oil analysis measurements related to the gearbox and generator. The

value, efficiency and reliability of CMS is yet to be proven due to the very unpredictable and variable loading conditions under which WTs operate.

However, insurance policies do require by default the use of CMS and therefore operators and manufacturers have no other option than to use such systems. However, in the future insurance requirements will become stricter and the exact output of CMS will be taken into account whenever claims are filed. Also, operators will probably become more interested in verifying the exact condition of WTs that pass to their responsibility after the guarantee from the manufacturer has ended.

Previous research efforts [1], [2] have identified commercially available condition monitoring systems, which have been analysed in terms of the monitoring technology and analysis methods. Summary of his previous work is detailed in Appendix A and has been expanded upon with more up-to-date sources.

4 Wave Energy Converters

4.1 Wave devices types

There is a wide range of wave energy technologies, each using different solutions to absorb energy from waves depending on the water depth and location. There is little convergence amongst the wave energy technologies, however, the industry shows many different alternatives to harnessing wave power under different conditions. Wave energy devices can be categorised into six main types: (i) Attenuator; (ii) Point absorber; (iii) Oscillating wave surge converter; (iv) Oscillating water column; (v) Overtopping device; (vi) Submerged pressure differential. Figure 2, presents the concept of the different main types of wave energy converters which were defined by the RiaSoR I project as follow:
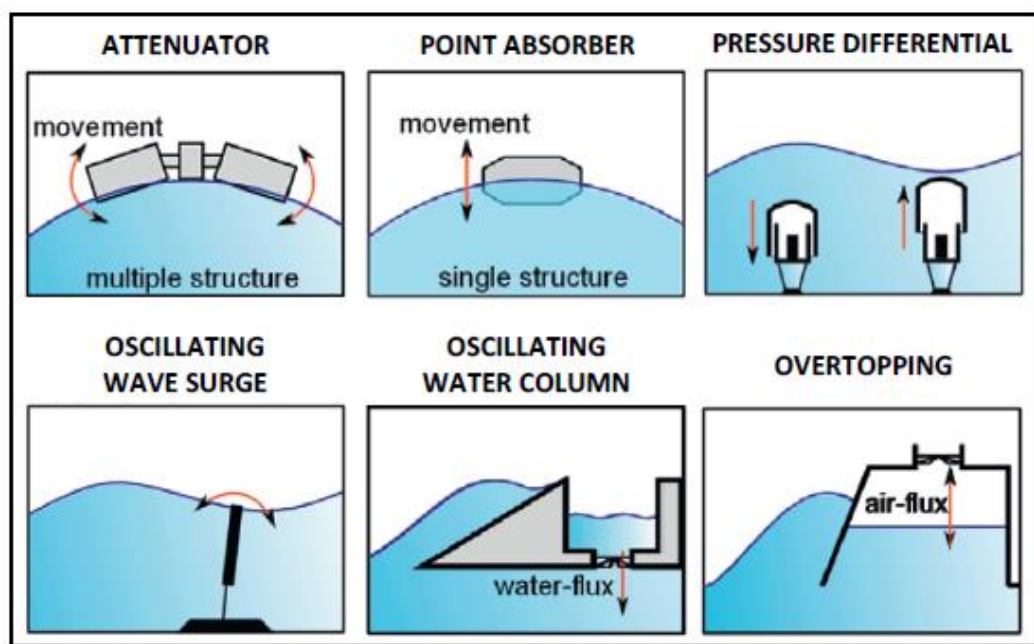

Figure 2 Wave energy converters design concept [3]

4.2.1 Attenuator

An attenuator is a floating device which operates parallel to the predominant wave direction and effectively rides the waves. These devices capture energy from the relative motion of the two arms as the wave passes them. These technologies typically follow the design of long multi-segment structures with each segment following oncoming waves from the crest to trough. The floating pontoons are usually located either side of some form of power converting module. The relative motion between each pontoon can be converted to mechanical power in the power module, through either a hydraulic circuit or some form of mechanical gear train

4.2.2 Point absorber

A point absorber is a floating structure which absorbs energy from all directions through its movements at/near the water surface. It converts the motion of the buoyant top relative to the base into electrical power. The power take-off system may take a number of forms, depending on the configuration of displacers/reactors. A point absorber typically possesses small dimensions relative to the incident wavelength. The structure can heave up and down on the surface of the water or be submerged below the surface relying on pressure differential.

4.2.3 Pressure differential

Submerged pressure differential devices are submerged point absorbers that are typically located near shore and attached to the seabed. The motion of the waves causes the sea level to rise and fall above the device, including a pressure differential in the device. This water pressure above the device compresses the air within the cylinder, moving the upper cylinder down. The alternating pressure pumps fluid through a system to generate electricity.

4.2.4 Oscillating wave surge

An oscillating wave surge converter extracts energy from wave surges and the movement of water particles within them. The arm oscillates as a pendulum mounted on a pivoted joint in response to the movement of water in the waves which then moves in a back and forth motion, exploiting the horizontal particle velocity of the wave. The design typically comprises of a surge displacer which can be hinged at the top or bottom. It can be attached on the seabed, or near the shore. Energy is usually extracted using hydraulic converters secured to a reactor. If the device is used on the shoreline it is common to hinge the displacer above the water, enabling the incoming surge waves to impact on the displacer first, and then be captured within the device to form a water column.

4.2.5 Oscillating water column

An oscillating water column is a partially submerged, hollow structure. It is open to the sea below the water line, enclosing a column of air on top of a column of water. Waves cause the water column to rise and fall, which in turn compresses and decompresses the air column. This trapped air can flow to and from the atmosphere via a turbine. A low-pressure Wells turbine is commonly used in conjunction with this device as it rotates in the same direction irrespective of the airflow direction. The rotation of the turbine is used to generate electricity.

4.2.6 Overtopping

Overtopping devices capture water as waves break into a storage reservoir. The water is then returned to the sea passing through a conventional low-head turbine which generates power. An overtopping device may use 'collectors' to concentrate the wave energy.

4.3 Wave energy extraction

Current WEC designs differ widely in their energy extraction method but all require a power take-off unit (PTO) to convert the irregular mechanical motion of the primary wave interface into electrical generation. Current devices use pneumatically, hydraulically, and mechanically power take off. Figure 3 and Figure 4 present the concept of the different conversion stages of the main different types of WECs and a simplified concept diagram of the PTO options respectively.
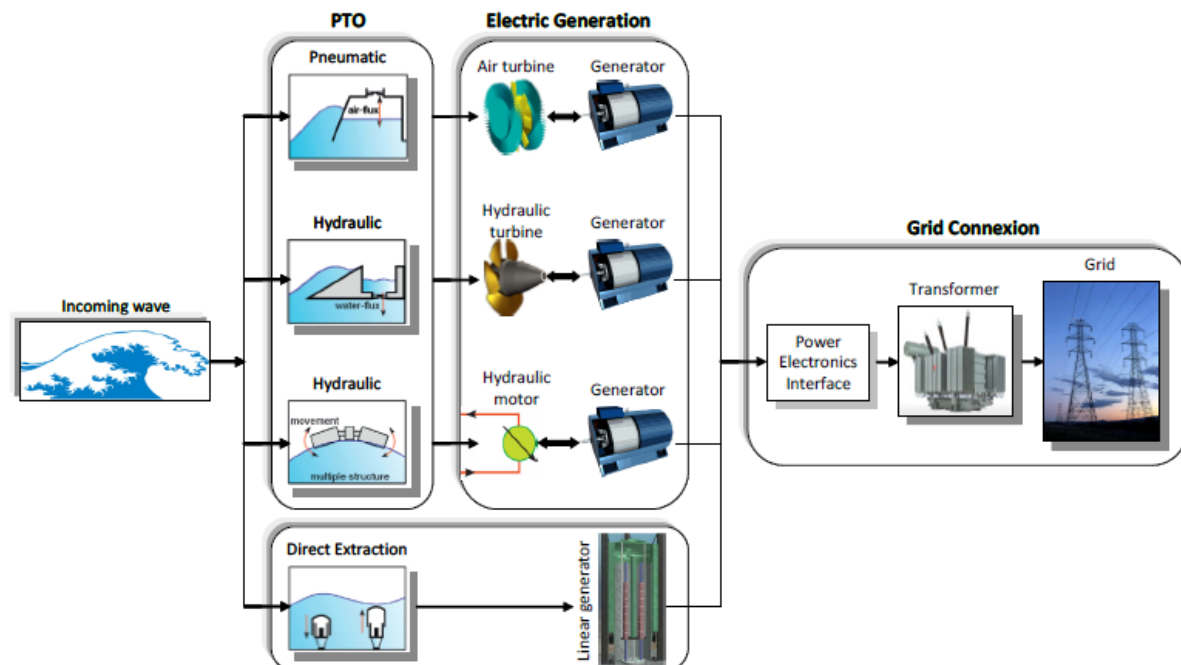

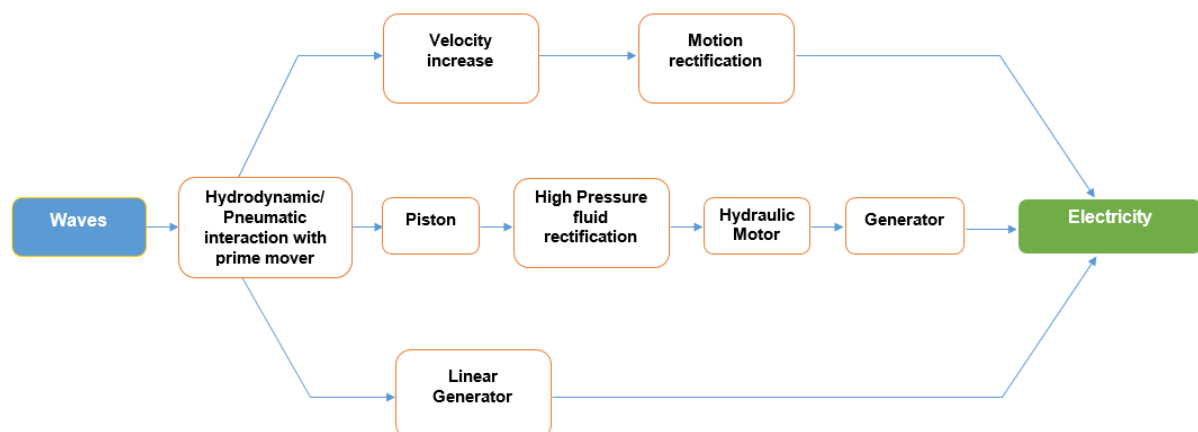**Figure 3 Wave energy extraction concept [3]**

Figure 4 Simplified diagram of the power take off concepts [4]

It is believed that existing monitoring systems within the wave devices developed to date draw directly from current technologies and advances made in the wind and other industries. Monitoring techniques include the monitoring of generators, gearboxes and bearings using a range of sensors such as vibration, acoustic, temperature, speed, oil, current and voltage outputs. In addition, due to the mechanical loading to which most of the WECs are subjected to, sufficient structural health monitoring is required to be in place to detect any potential deformations or fractures of the mechanical structures. More importantly, the monitoring of the functionalities of the control and safety systems needs to be well designed to ensure the WECs are able to respond to system operation and potential faults.

Reliability Centred Maintenance relies on determining the maintenance requirements of a functional system in its operating context while a failure modes and effect analysis (FMEA) is used in order to determine critical failure modes, their consequences and root causes. Using this analysis, measures can be identified to predict and prevent potential failures. As such, due to the various design types of WECs and requirements to define a condition monitoring system framework for these wave energy devices, key monitoring requirements will be based on common failure modes experienced by the main types of devices.

4.4   Failure modes of WEC

Defects and errors can affect the operation or structural integrity of the wave energy device. Failure modes are the various ways in which the WEC could possibly fail and monitoring systems are often used to anticipate complete failure and for fault detection. Failure modes can be ranked high, medium and low priority depending on the probability and severity of specific modes. Common monitored parameters in offshore renewable generation are humidity, oil moisture content, speed and vibration. Each parameter depends on both the sub-system and corresponding failure mode.

FMEA is a method for identifying the different possible failures in a design. FMEA documents the relevant data and action of the risks of failure modes and used during the design process to prevent failures. Through the life cycle of the WEC, FMEA can be used for control to document and prioritise the failures. A list of common failure modes of a WEC is presented in Figure 5.

Based on literature, [5] [6] wave energy converters can be divided into 5 main sub-systems.

- **Moorings:** The mooring of the WEC is achieved using cables which may be affected by entanglement, loss of pre-tension, deformation, disconnection and marine growth. The sub-assemblies are leg, grid and connectors.

- **Structural:** The structural integrity of the WEC can be subject to loss of water tightness, deformation, disconnection and marine growth. The sub-assemblies are the central node and riser, link arm, pumping module and the antinode.

- **Hydraulic:** The failure modes that affect the hydraulics of the WEC include seal failure, burst pipes, water ingress, oil leakages and valve jams. The sub-assemblies are the pumping module, low pressure antinode, PTO module, hydraulic ring main and array connection.

- **Electrical:** The electrical system of the WEC is prone to failures like short circuits, over-voltages, connector faults and generator failure. The sub-assemblies include the

PTO module (generator), low power side, inter-array cables, central junction box and export cabling.

- **Instrumentation:** The failure modes include calibration error, false alarms, software faults, intermittent output and communications failure. The sub-assemblies include the PTO module (generator), auxiliary, data acquisition and control, and communications.
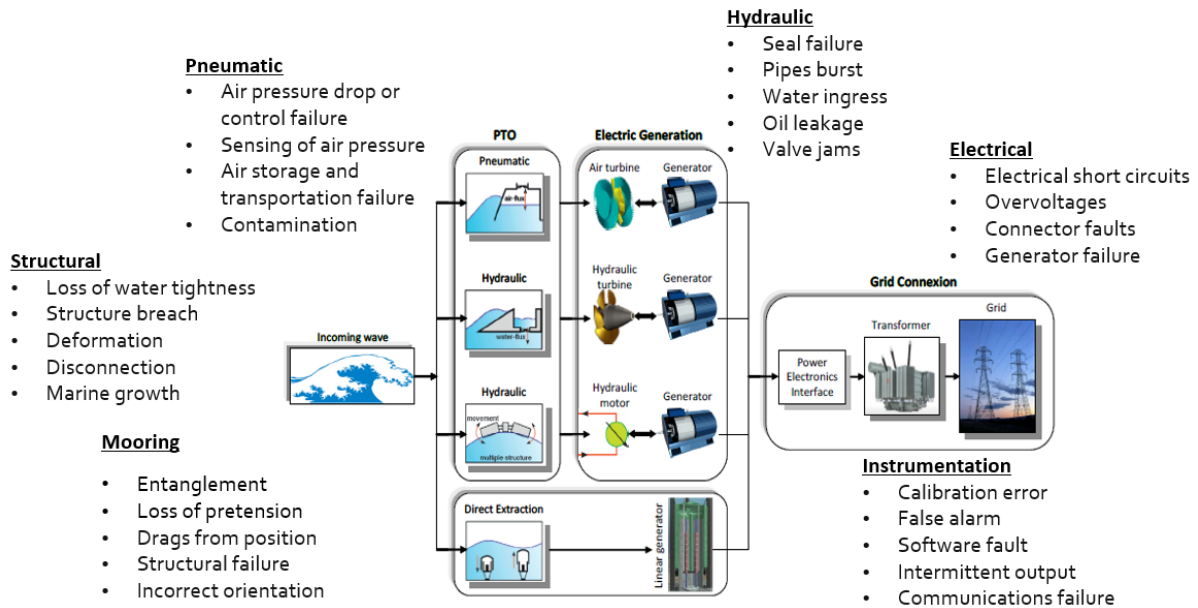
Figure 5 Common failure modes present in WECs

5 WEC condition monitoring system requirements

5.1 General specification

The aim of the following sections is to determine the primary requirements of the monitoring systems of the component deemed to be critical to the operation of the wave energy converters. Condition monitoring to be deployed in in the WEC should be able to monitor the condition of the following critical equipment:

- Structure

- Power take off

- Mooring

- Electrical power transmission and distribution

- SCADA and control

Multiple categories of faults can occur from mechanical, electrical and structural failures. The marine environment also poses risks to the operation and reliability of the WEC and thus increasing likelihood of failure. A detailed list of potential failures is presented in Table 3.

Mechanical	Electrical	Structural	Marine Environment
Corrosion	Calibration error	Design fault	Mooring entanglement
Fatigue	Failure of connection	Service loads	Airborne biofouling
Inadequate lubrication	Electric short	Inadequate installation	Subsea marine growth
Over heating	Insulation failure	Maintenance fault	Impact of ships
Slack bolts	Lightning	Defect in manufacturing	Impacts (foreign bodies)
Serious damaging	Power loss	Hydraulic contamination: Debris	Over pressure: 1. Miscibility–poor mixing
Vibration fatigue	Conducting debris	Moisture	Choked-excessive flow
Degradation of material	Software design fault	Air	

Table 3 Core reasons for WEC failures

5.2 Detection methods

Due to the environmental challenges encountered by WECs, there are various sub-systems where fault detection is needed (Section 4.4). Any condition monitoring system used must require the most state of the art developments of early fault detection [7]. The methods of detection differ depending on the failure mode and nature of the sub-system. Figure 6 presents proposed sensing technologies for each of the failure modes identified in Figure 5.
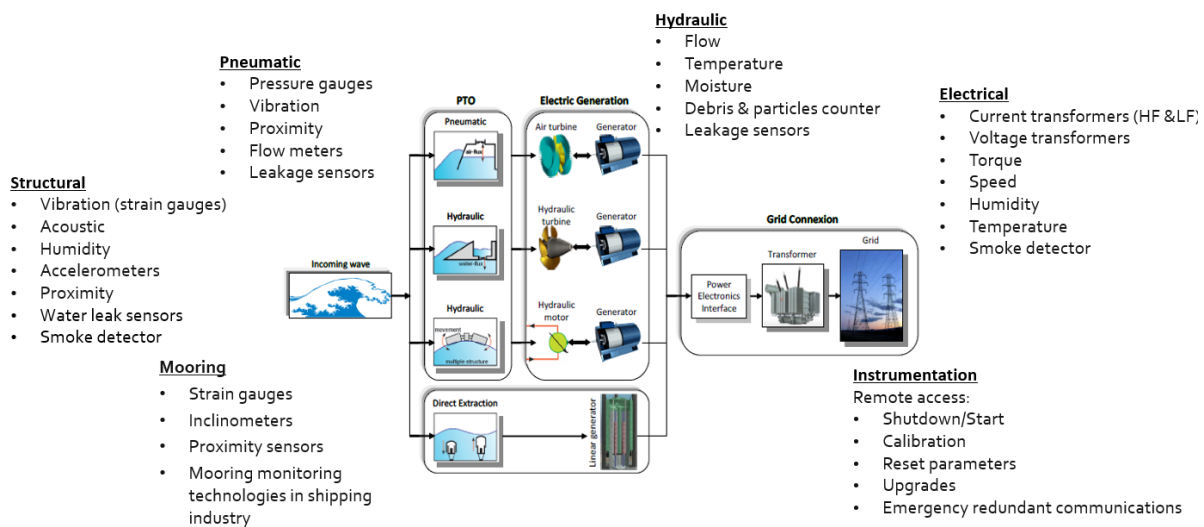

Figure 6 Failure modes sensing technologies

To optimise the operation of the WEC, faults must be found in early stages so that logistics and maintenance can be scheduled according to weather conditions and availability. Early

detection can therefore minimise both loss of revenue and repair costs by reducing the down time. Each sensor/method of detection must be able to meet all the following criteria to provide effective failure detection:

- Accuracy: The signal is closely representing the actual measurand that is being monitored, while also detecting the smallest of changes in value.

- Repeatability: Consistent reproduction of the same output signal for repeat application of the same value of measurand.

- Cost effective: Using sensors which effective for early detection, while keeping the cost low. Consider that the most expensive sensors may not be required for certain measurements.

- Long term stability: Long term monitoring in controlled conditions. Likely that experienced manufacturers and knowledge of the components will increase the quality and the lifetime of the sensor.

5.2.1 Structural Sensing Methods

Structural sub-system faults can be of high priority if the integrity of the structure is in danger. Hence, structural monitoring is used for validating service loads and monitoring the watertight-seal of the WEC. The following section discusses various methods of fault detection for structural sub-systems.

Humidity Sensors

The ocean can cause problems with the structure of the device by entering air tight compartments. Water entering the device can speed up corrosion and can cause growth of microorganisms. For a humidity sensor to be robust it must be able to recover from condensation and be resistant to chemical and physical contaminants.

- **RH Sensors:** The most common humidity sensor is a capacitive relative humidity (RH) sensor. These sensors are used widely in industrial and commercial applications. RH sensors are made from polymer dielectric material with an electrode that would respond to changes in the relative humidity. RH sensors are distinguished by their low temperature coefficient, ability to recover from condensation and an adequate resistance to chemicals (vapers).

- **Dew Point Sensors:** Another sensor used for offshore industrial equipment is the Dew point sensor. This sensor is a thin film capacitance sensor and can detect very low relative humidity. Dew point sensors are built with an integrated circuit which uses a voltage output as a function of humidity. Dew point sensors are more commonly used in the oil and natural gas sector due to its effective results with detecting water and chemical vapours, long life and surviving rough terrain on offshore oil rigs. A challenge when designing with a capacitive sensor is the limited distance allowance from the corresponding circuitry, with a practical distance less than 10ft [8]. However, depending on the WEC design, this won't necessarily be an inconvenience.

Water leak detection

To detect any change in the watertight seal water level detection systems are used. The condition monitoring system can detect any leakage to avoid water damage to the WEC generator and circuitry.

- **A float and counter weight**: The float and counterweight principle is a well-practised method and is basically a floating structure connected to a stainless-steel tape which is attached to a sprocket wheel. As the float changes level, the tape turns the wheel thus detecting movement through a resistance transmitter. The principle is well experienced in offshore technology and the simple mechanical basis of the method allows for a cost-effective device. The transmitter can vary to very high accuracy transmitters making it a competitive product in WEC detection methods.

- **A pressure sensor**: The sensor can detect the pressure level of a compartment and in some cases temperature in a multitude of conditions. The thermal compensation in pressure sensors allows the device to be in rough terrains where temperature can vary. Pressure sensors measure the air in a measuring device and compare the difference in the atmospheric pressure. The difference in pressure can determine the depth of the water intrusion. Piezoelectric pressure sensors use crystals which will result in an electrical charge when pressure causes it to deform. This type of sensor is only useful for rapid changes in pressure which are useful for devices in environments like the ocean where an unexpected break in the structure could lead to a massive intrusion of water.

- **Radar sensors:** Radar sensors measure the distance from the base of the sensor to the surface of the water. Radars use a frequency modulated continuous wave to detect the level of the water. Radar sensors can detect water level without contact as the continuous wave reflects from the water surface and reflects to the device. Radar sensors have relatively easy maintenance requirements, advantageous for isolated offshore environments.

- **Acoustic emission sensors:** The soundwave produced from the AE sensor oscillates as it travels, determining the depth of the water leak in comparison to the lower surface of the WEC. As the wave is converted back into an electrical signal the variation of amplitude, phase, frequency and time delay gives an accurate measurement of the distance the wave has travelled.

Strain Gauges

The resistance varies with applied force. It takes the applied force, for example, the strain or tension within the WEC and outputs as electrical resistance and a measurement can be taken. The WEC is strained by external influences or an internal effect where changes in force, pressure, heat or structure can cause damage. The electrical resistance differs in proportion to the amount of strain and when there is applied force the sensor produces a signal in volts. Each new installation of a strain gauge a new calibration must be set depending on the parameters of the WEC.

- **Fibre Optic Strain Gauge (FOSG):** The fibre optic strain gauge (also known as the fibre optic strain sensor) follows the basic principle of the original strain gauge- to

measure strain in the WEC. FOSG do not use electricity to measure the strain of the device but instead uses light through fibre optic cable. FOSG are in times better in comparison to the original strain gauge because they are completely passive and immune to issues like electromagnetic interference.

Accelerometers

Accelerometers are used for physical disturbance such as movements, vibrations or a force of gravity. The accelerometer can measure acceleration forces like the vibration of bolts in the generator. Acceleration is the measurement of change in velocity and can be measured in two ways; capacitance sensor, or the piezoelectric effect. The capacitance sensor detects the changes in capacitance between the microstructures on the WEC. As the angle of these microstructures change the capacitance will also change and the accelerometer will interpret the capacitance to a voltage output.

Similar to the pressure sensor, the piezoelectric effect uses microscopic crystals that are affected by accelerative momentum. The crystals create a voltage from the stress which can be converted to velocity and orientation.

Accelerometers are commonly used as vibration sensors but struggle to detect the vibrations at an early stage. Acoustic emission sensors tend to be much more reliable for WECs as an early detection method.

Proximity sensors: These sensors can be used to detect the presence of nearby objects without the need for physical contact. Proximity sensors detect anything moving inside or outside the structure. A proximity sensor emits an output of electromagnetic radiation like infrared and compares the changes in the returned signal. The sensor does not measure angular rotation or displacement but the presence of the near object. Proximity sensors are normally used to detect a metallic device at any direction round the sensor, although capacitive and ultrasonic proximity sensors are available which can detect non-metallic devices

5.2.2   Hydraulic Sensing Methods

The hydraulic cycle of a WEC can be affected by extreme wave conditions affecting power take off (PTO), the pumping systems and the low-pressure antinode. Moisture, oil leakages and physical damages can be detected by sensors to avoid long term undetected damages. The cleanliness of the WECs gearbox will be monitored through continuous according to ISO 4406. Oil temperature, cleanliness, and operational cleanliness of the device will be stored for maintenance and monitoring.

Oil Leakage

As soon as the hydraulic system is contaminated, sever problems will occur which can affect the operation of the hydraulics in the WEC [9].

- **Pressure Transducer**: To detect an oil leakage in power take off, a pressure transducer can be used. The system pressure can be measured in a similar fashion to the pressure sensor detecting water leakage. The transducer converts the pressure into an analogue electrical signal. The transducer is made up of strain gauges built into the diaphragm of the known pressure transducer. This stress put on

the bridge of strain gauges by the pressure produces an electrical resistance proportional to the strain

- **Ultrasonic level sensor:** Ultrasonic level measurement sensor detects the level of oil leakage through the employment of sound waves, like radar the signal is reflected from the oil surface and the pulse of the signal can detect the depth of the oil leakage. The ultrasonic sensor uses piezoelectric crystals that oscillate producing electrical signal capable of sending ultrasonic sound waves. The sensor has no moving parts and can measure the oil level without making any actual contact which makes it useful in WECs. Ultrasonic sensors are effective for measuring levels without getting contaminated with the liquid shortening its life cycle.

Inline Contamination Monitor (ICM)

Contamination of water into hydraulic fluids can affect the density of the fluids and can change the accuracy of the hydraulic pump. ICMs can avoid small faults from developing into extreme contamination problems. Some ICMs can also measure the moisture and temperature in contaminated water. In correlation with to ISO 4406 these monitors can measure the cleanliness of fluid through electronic maintenance records.

ICMs use automatic particle counters (APCs) as well as moisture and temperature sensors. APCs detect a fraction of change in particle numbers. This allows detection of very small particle increases in the fluid.

Linear position sensor

The deformation of the hydraulic cylinder can be detected with a linear position sensor by comparing any displacement with the original placement of the device. The sensor can then encode the position into an electronic signal.

The linear position sensor is capable of measuring movements to an accuracy of few millionths of an inch depending on device [10]. The basic topology of a linear position sensor is a primary winding centred in between two secondary windings. Coils are wound around a thermal-friendly hollowed out polymer encased in high permeable magnetic shield, in a stainless-steel housing. The core moves because of movement in the position of the device and this increases one secondary voltage and decreases in the other thus producing a reaction in the sensor.

5.2.3   Electrical Sensing Methods

The electrical systems voltage, current, speed and temperatures can be effective also by faults in the PTO. The detection methods are described as follows:

- **Voltage (VT) and Current Transducers (CT)–** When the generator fails due to overload, voltage and current transducers can be used to sense a change in electrical overloads. VTs and CTs work as a sensor to convert the physical quantity of the power system voltage and current respectively into a signal that is suitable for condition monitoring**.**

- **Linear resistor-** The generator temperature can be measured to detect a fault using a linear resistor. The resistance will change depending on the thermal, mechanical or

electrical influence put on the sensor. Linear resisters can detect issues involving overloads, rapid heat and vibration.

- **Absolute encoder-** Absolute encoders are used to measure the velocity of the generator. This can detect problems in the generator caused by the speed of the PTO module. Absolute encoders have a systematic method of producing a code on a glass disc imprinted with dark and light sections where each combination of squares represent a number/value. As the disc spins the position value is constantly recorded allowing the velocity to be recorded over certain periods of time.

- **Torque transducer-**The torque of the rotating system in the generator can be recorded using a transducer, this can detect coupling and bearing failures. The transducer measures varying, and constant torques on the rotating shaft to detect any irregular behaviour. The torque transducer has a stator with a bearing mount shaft. The shaft uses some of its length to measure the torque with a proportional torsional angle. This is measured between two points of an inductive angular position measurement system- a device which converts the angle of the twist into proportional electrical wave form.

- **Inductive proximity sensor (IPS) –** The layout of the device can be monitored using an IPS, detecting any displacement in the device, like a misalignment in the shaft. The IPS produces a high frequency magnetic field. This reaction triggers electromagnetic induction in the metal target nearing the sensor to produce an eddy current. As the induction flow increases (objects moving towards the sensor), the sensor can detect the attenuation of the current flow and output a detection signal to the system.

Thermocouple – thermocouples are used to detect any change in temperature of the electric circuit within the WEC. Temperature sensors have two junctions of non-comparable metals, i.e. copper and constantan (copper- nickel alloy) welded and crimped together. One junction is cold while the other is kept at a hot temperature. As the temperature become the same temperature the potential difference of the thermos electric effect becomes zero. Therefore, as the temperature on one piece of metal differs a measurement can be taken.

5.2.4 Mooring Sensing Methods

As mooring lines are the permanent structure that secures the WEC, it is important to find all faults as early as possible. Any fault which occurs with the mooring could lead to errors in the positioning of the WEC. This section provides an insight into the various detection methods available to prevent any considerable amount of damage to the mooring lines.

- **GPS-** Mooring line can deter from the original position and the stray mooring must be detected. A global positioning system (GPS) can monitor the positioning of the mooring connection and can alert the system of which mooring connection has been is displaced.

- **Load Shackle-** The shackle can detect if there is entanglement and tension of the mooring cable. The sensor is used for load monitoring to ensure the shackle and mooring continue to hold at the appropriate tension and stress. The shackle load monitoring works through strain gauges or transducers built into the shackle pin to

detect any stresses on the shackle. For subsea use the shackle must be able to monitor the mooring lines in rough terrain and to ensure that the safe operational limits are not exceeded. This is especially the case when the WEC is accustomed to extreme weather conditions.

Inertial Measurement Unit (IMU) - If mooring cable loses pretension the movement of the cable will be detected but the IMU which will alert the system that a failure has occurred. The IMU consists of three accelerometers and three gyroscopes positioned into triads, each at a right-angle axis (yaw, pitch and roll). As the mooring cable loses the pretension, the cable begins to lose the collaborated reference frame measured by position and velocity.

5.2.5   Instrumentation Methods

Instrumentation methods will cover failure modes such as calibration error, false alarms, software faults, intermittent output and communication failure. Instrumentation detection methods must detect errors through the system and the most common procedure is remote diagnoses.

- **Remote diagnoses (RD) –** RD allows the failure to be determined from a distance (i.e. onshore), rather than co-location. This eliminates the accessibility problems faced with WECs. RD can have other uses such as data collections and data processing and useful information for planning routine maintenance. The offshore wind, gas and oil industries use RD for maintenance and prediction purposes as well as detecting faults in the system.

For an appropriate failure rate data analysis of the CMS, collection of data must be carried out over a long period of time to form an accurate conclusion of the most effective form of early detection and instrumentation. Cost and power constraints will have a large impact on the decisions of which method is chosen, however these factors may not out way the cost of repair and replacements for short lived, less reliable methods.

5.3   Standards

The following tables show relevant condition monitoring standards and guidelines which can be used in WEC design. These standards are often referred to in offshore wind sector.

The ISO standards consider the competence of the bodies which undertake inspections and maintenance of the device while the IEC administers and publishes international standards for electro-technologies. General procedures which must be considered when setting up condition monitoring within sub-assemblies of machines like the WEC are also included in Table 4. The following tables are presented as references and documentation of relevant standards and procedures for the condition monitoring framework which will be produced in this project.

ISO Code	Description
ISO/IEC 17020	Conformity assessment – requirements for the operation of various types of bodies performing inspection

ISO 17359	Condition monitoring and diagnostics of machines – general guidelines
ISO 4406	Hydraulic fluid power – fluids – method of coding the level of contamination by solid particles
ISO 5348	Mechanical vibrations – vibration and shock – mounting of accelerators
ISO10816- 1	Mechanical vibrations by measurement on non-rotating parts – guidelines/evaluation
ISO 13373-1	Mechanical vibrations - Condition monitoring/ diagnoses of machines.

Table 4 ISO Standards

IEC Code	Description
IEC 61400-13	Wind turbines -Mechanical load measurements/verifications
IEC 61400-22	Wind turbines -Conformity Testing and Certification
IEC 61400-25	Wind turbines -communications for monitoring and control of wind power plants. General procedures

Table 5 IEC Standards

VDI Code	Description
VDI 3832	Structure-borne sound – rolling element bearings within the machine for evaluation of state condition.
VDI 3834- 1	Wind turbines - Mechanical vibrations – turbines and components
VDI 3834- 2	Typical vibration patterns for electrical machines
VDI 3839- 1	Mechanical vibrations of machines- measuring and interpreting
VDI 3839- 2	Mechanical vibrations of machine – unbalance, bearing faults, incorrect assembly and damage to rotating components
VDI 3839- 5	Mechanical vibrations of machine – typical for electrical machines

Table 6 VDI Standards (Association of German Engineers)

The relevant IEC standards (Table 5) falls under the categorisation of wind turbines. The monitoring of offshore wind will have some corresponding standards with WECs due to the environment, topology and the functions of both machines. The mechanical load verifications

of IEC 61400-13 are mainly focusing on large electricity generating horizontal axis turbines, although can be applicable to mechanical pumpers and other WEC components. The methodology and requirements needed to determine the mechanical load and condition monitoring procedures is relevant to WECs.

The communications for monitoring and control of wind power plants (IEC 61400-25) is conveniently compatible to the CMS of WECs. The basic concept of this IEC is a breakdown of compliant services and the different communication profiles available for data interchange, allowing all data from the devices to follow the same format.

The Association of German Engineers (VDI) (Table 6) has standards for various structural effects which could cause failure and the corresponding state conditioning to prevent them. The standards analyse the measuring procedures and failure modes of vibrating machines where WECs would fall under this category.

5.4 Signal Properties

The DAQ system for the WEC must be compatible with the chosen detection methods and the corresponding analogue circuits. For the analogue signals to be processed by the computer the analogue signals are converted to digital signals. High accuracy is needed when measuring the analogue signals and required for early detection within the WEC system. High resolution DAQ devices will enable a more accurate reading, although in certain cases a high sample rate is not important. When measuring the shape of a signal, the signal is measured in respect to time, where certain signals will rapidly change. CMS in a WEC measures the shape of signals for vibration and deformation therefore a high sample rate and high resolution is needed for measuring the shape. Table 7 presents the type of signals and measurement techniques used for signal handling.

Measurement	Signal	Description
Level	Analogue	Like measuring the state of a digital signal, except an analogue signal can be at any voltage.
Shape	Analogue	Analogue can be at any state in respect to time. Analysis of peak values, integration and slope can be found from measuring the shape.
Frequency	Analogue	Like measuring rate of a digital signal. Must perform software analysis to extract frequency data, normally with Fourier Transform method.
State	Digital	On/Off-measure if the system is on or off
Rate	Digital	Changes state in respect with time. How the signal changes over time

Table 7 Signal Measurements

5.4.1   Signal Conditioning

CMS uses detection methods with analogue signals which must be manipulated before being digitised. Signal conditioning is the next stage of processing where the signal is made available for data acquisition. For example, a thermocouple signal must have the voltage amplified as the signal is too small to be digitalised. Sensors like strain gauges and accelerometers require excitation of the signal to allow for digitisation.

Sensors with high impedance can be lowered. Low output impedance has the ability for cables to transmit long distances through harsh environments and to have little loss in quality of the signal therefore conditioning of the signal is beneficial in these cases.

 Some common types of signal conditioning include [11]:

- **Amplification**- Improves accuracy in final digital signal and reduces the effect of noise. For example, if a thermocouple was sent to the DAQ device without amplification, small degrees of temperature change may not be detected.

- **Attenuation**- The reverse of amplification. Required when voltages are beyond the ADC range. This method decreases the inputs amplitude so that the signal is within the operating range of the ADC. Normally attenuation is necessary with signals over 10V.

- **Isolation**- Isolating transducer signals from the computer is for safety purposes. This is used when the signal has voltage spikes that could potentially damage the computer system, or the operator. Some form of isolation is always needed. Isolation can also be used to deter ground loops. Ground loops can occur when the DAQ device and the signal aren't connected to the same ground potential. Ground loops can create inaccurate readings and representation of the signal.

- **Filtering**- Removes unwanted segments and reduces noise errors of the signal. AC power creates most noise. Low pass filters can remove the unwanted noise from signals. Filtering can remove high-frequency noise and avoid the distortion and error of aliasing.

- **Excitation**- transducers, like strain gauges need low voltage DC power supplies, excitation of signals provides the external voltage or current exit to so. Excitation is normally used for measuring force, pressure, RH, temperature, level and vibration.

- **Linearisation**- Most transducers produce voltage signals that are non-linear. Linearisation is the process of modifying the signal from the detection method and can be done through conditioning the signal or through software.

Measurements & Sensors	Amplification	Attenuation	Isolation	Filtering	Excitation	Linearisation
Strain Gauge	✔		✔	✔	✔	✔
Load, pressure, Torque (mV/V)	✔		✔	✔	✔	✔
Accelerometer	✔		✔	✔	✔	✔
Acoustic Emission	✔			✔	✔	✔
Proximity	✔			✔	✔	✔
LVDT	✔		✔	✔	✔	✔
Capacitive		✔	✔	✔	✔	
Radar	✔		✔		✔	
High Voltage		✔	✔			

Table 8 Signal conditioning per type of sensor and measurements

5.4.2 Sampling rate

The sampling rate dictates which speed the DAQ system's ADC converts the input signals. An accurate sampling period Δt must be selected to correspond with the feedback control system in the DAQ computer system. The sampling must be fast enough to combat aliasing and reduced effectiveness. Although if the system is too fast a higher standard of computer system will be required to keep up with the data acquisition.

The sampling rate is dependent on the maximum frequency of the signal to be measured. According to the Nyquist theorem, the DAQ system must sample at least 2× the maximum frequency component in the signal acquired from the WEC. This will provide a more accurate representation of the detection method input signal. For example, generating a signal at 1Hz, with 1,000 sample points/cycle and 1,000 samples per second will produce a much more detailed representation of a signal which only has 10 points/cycle with a sample rate of 10 S/s.

5.4.3 Aliasing

If the sampling rate is too small for the application, it can result in aliasing. This means the signal produced from sampling is a false representation of the analogue signal. The signal will show as a different frequency than it actually is. To prevent aliasing a sampling rate much faster than required should be used.

5.5 Data acquisition of the WEC

The aim of this section is to provide an overview of the basic hardware used in a DAQ system and software to configure and control the DAQ system.

DAQ measures electrical and mechanical changes, from the failure modes with a computer system. The DAQ system consists of the detection methods (section 5.2), the actual DAQ device and the computer system. The other contributing hardware is a terminal block connecting the outer circuitry to the DAQ system and the cables connecting each architectural block within the system. These building blocks will deliver the measurements of the WEC to a computer for analysis and the presentation of results.
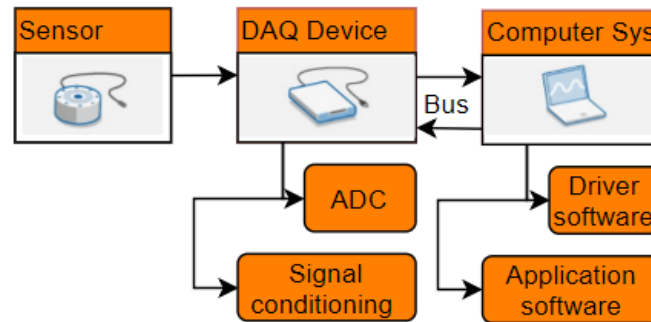
Figure 7 Flow chart of a Data Acquisition system [12]

5.5.1 DAQ Device

The DAQ hardware works as the juncture from the sensor circuitry to the computer system. A basic DAQ device has three interfaces for sending and receiving signals: the I/O connector, the computer I/O interface circuitry and the real time System Integration RTSI Bus. The analogue input signal continues through a number of circuits before continuing through the Analogue-to-digital (ADC). The circuits may consist of a multiplexer and an instrumentation amplifier. Description of key components of the DAQ hardware is presented in Table 9.

The analogue input signal continues through the circuitry before continuing through the Analogue-to-digital (ADC). The circuitry consists of a multiplexer and an instrumentation amplifier.

I/O Connector	• >50 pins, depending on the device • One end connected to the I/O connector • One end connected to the terminal block
Computer I/O Interface Circuitry	• Transfers information from the DAQ device and the computer • Differ depending on the bus protocol, i.e. PCI bus has connections into a PCI slot, but the USB connection requires a cable.
RTSI Bus	• Shares and synchronizes signals between multiple DAQ devices in the same computer
Multiplexer	• A switch that connects to only one of the various input channels to the instrumentation amplifier at a time • Rotates through the channels- connects them one at a time
Instrumentation Amplifier	• Amplifies or attenuates the signal received • Make the signal fill the ADC range as much as possible • Referred to as applying a gain.

Table 9 Hardware and circuitry of the DAQ device [12]

5.5.2 Analogue-to-Digital Converter (ADC)

The ADC is within the DAQ system hardware and will convert the conditioned signal to a digital output which will be accessible by the computer system of the CMS.

The ADC takes the analogue signal produced and converts it into a digital signal for process control. The analogue input signal is conditioned to optimise the digitisation process. The ADC will convert the conditioned signal to digital values corresponding to the analogue signal input. The ADC uses the sample rate of the conditioned signal to capture samples of the oscillating signal and convert them to digital representation.

5.5.3 DAQ resolution

The resolution of the DAQ is crucial in providing an accurate CMS. The unique layers of the signal can be divided into segments to produce the resolution of the signal. The number of layers depends on level of resolution.

To detect the smallest of changes in the input signals the highest resolution must be used. Resolution is the unique binary levels an ADC uses to represent the analogue signal. The figure below illustrates a 3-bit ADC and a 16bit ADC and compares them. A 3-bit ADC can represent 8 discrete voltage levels when a 16-bit can represent 65,536 discrete voltage levels. ADCs can have resolution up to 24 ADC, although this level of accuracy may not be required.
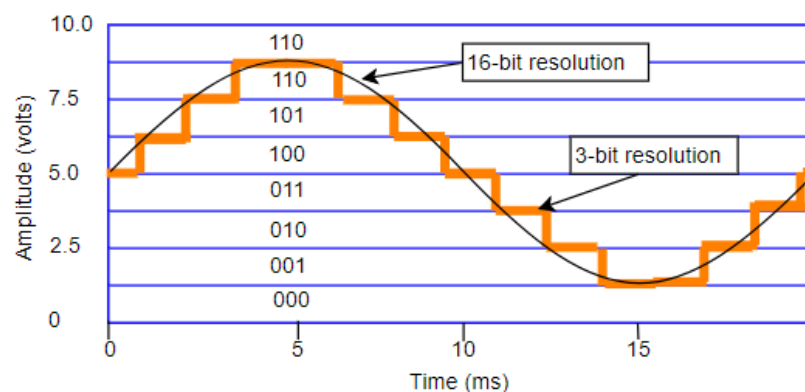
Figure 8 Comparison of 3-bit and 16-bit [13]

The resolution of an offshore wind energy ADC must have a minimum of 12 bits according to IEC 61400-13. Therefore, the WEC should take into account same standard requirements.

A ±10V range, 12-bit resolution DAQ has 4,096 evenly distributed discrete voltage levels and can detect a 5-mV change. A ±10V range, 16-bit resolution DAQ can detect a 300µV change. Although a 12-bit resolution ADC is the minimal requirement according to IEC 61400-13 due to the small sensor measurements and a varied voltage range it is most likely beneficial to have a device with a larger number of discrete voltage levels.

5.5.4 Absolute Accuracy

The DAQ must be accurate to detect early stages of failure. The accuracy will never be greater than the chosen resolution of the device. An ideal measurement of accuracy would

of course be 100% although real-life practical factors mean that devices will record uncertainties such as:

- Gain error

- Offset error

- Nonlinearity

- System noise

The DAQs accuracy can vary depending on the device and the signal produced. If the signal input has a significant noise level the accuracy can be affected.

5.5.5 Data Storage

To maintain appropriate failure rate data analysis of the CMS a collection of data will be collected and stored to form accurate conclusions regarding failure modes and the integrity of the WEC. The data must be stored safely, and automatic reduction of data must be avoided to allow for accurate monitoring results.

It is crucial for the data storage to only store relevant and comparable data and constraints. Results such as comparable operations and output ranges will be stored alongside the data from the detection methods as it is used as meaningful and invaluable information. There must be applicable intervals for each set of data, relevant to the components being monitored. Depending on the monitored components the data could be stored weekly or daily. To record sufficient data for trend analysis as well as early detection of faults appropriate intervals will be required. Raw data from the fault detection sensors must be stored for condition monitoring at least once a day allowing for early exposure of faults.

If for example a DAQ had to process data with following specifications:
- DAQ resolution of 2-bytes per second,

- 80 channels for accelerometers, strain gauges and other sensors sampled at 100 S/s,

- 27 channels sampled at 20kS/s

- Recording frequency every 10 minutes

Table 10 presents the results of storage needed per day.

No. of channels	Samples per second	Recording time	Storage (GB)
1	20,000	10 minutes	0.024
27	20,000	10 minutes	0.648
27	20,000	24 hours	93.31
80	100	24 hours	1.4
Total storage per day			94.7

Table 10 Condition monitoring data storage example

From the above example the DAQ system required substantial storage capacity. 1TB of storage could potentially be filled within 10 days. To overcome storage issues in the event where a large amount of data is generated by the monitoring system, there are a number of techniques which may be used. The following sections provides a brief description of some of the techniques.

- Ring Buffer

Based on the above calculation (Table 10), the data can be kept in a ring buffer for a period of time (a week/10 days) and then a software routine will overwrite the data, starting from the oldest, if the data is not transferred to a permanent location. The drawback of this method is that the user has to check for the validity of the data periodically.

Alternatively, the data can be post-processed and reduced to a lower rate data compatible with any further analysis and only the post-processed data stored long term, or the data could simply be sampled periodically for short periods of time and stored.

- Periodical

Record high frequency data only for a limited time (20 seconds) every 10 mins then overwrite after a period of time to free up storage space.

- Event triggered

Another method of data collection is based on events. To reduce the amount of data to be stored, the data should only be stored if there is an interesting event. Flags can be defined based on events, which trigger storing. The signals can be stored in a temporary buffer for a short period of time and if the flag is triggered the buffer can be stored permanently. The buffer can be defined to store the data for a period of time before the event and after, for example 10 seconds before the event and 10 seconds after.

5.5.6   DAQ Software

The final segment of the DAQ system is the software. The raw data is passed through the software where the system can manipulate and present the data in a way which is user-accessible. The software also allows control of the device and has control over which channel requires data.

The software includes the DAQ drivers and the application software. The drivers set of commands for the device is unique to each device and the applied software will send the commands for the measurements of each sensor. The application software allows the data to be displayed and analysed.

Most software applications will be applicable with various programming languages such as Microsoft Visual C/C++, ANSI C, and LabVIEW.

The DAQs software can be divided into three main key elements; (i) the DAQ device software, (ii) communication and (iii) control application [13].

- **DAQ Device**- The driver software that controls the DAQ device. Most commonly the DAQ control software will come with its own application programming interface (API), hardware configuration and software configuration. The software will communicate

with the I/O devices, the signal conditioning components and switch modules by simplifying the communication.

Before a driver software can be specified these main factors must be considered:

- o Driver compatible with the operating system
- o Driver integrates with application software
- o Diagnoses applications for the driver
- o Adaptable with other devices

- **Communication-** Software that communicates between the device and the application software. The communication software will allow the user to add and modify channels for the various instruments attached. This software will configure the DAQ devices to allow for the DAQ software to communicate with other instruments and devices.

- **Application-** Software that creates a user interface, allowing commands to be sent remotely to the driver and to allow the data to be analysed and presented. This software simplifies the interaction between the computer and the user. Most application softwares are pre-built applications with an anticipated functionality, but programmable software environments are available for customised operation. Usually the programmable applications are used for DAQs with multiple functions, such as user interfaces and signal processing algorithms.

Before an application software can be specified these main factors must be considered:

- o Software development and flexibility requirements.
- o Software integrates with driver, analysis tools and data storage.
- o Software with track record of stability and success.

5.6 Signal Processing

To detect damages or unbalance in the WEC the signals will be processed accordingly. The signals if necessary will be amplified and filtered to characterise a clear distinction between signals of a normal operating WEC and signals showing abnormal conditions.

Signal processing can be performed in several operations, some of which are summarised below:

- **Convolution** - Combine multiple waveforms to describe relationships and probability of each signal.

- **Filtering -** Rid the sample of unwanted noise and other features of the signal that could potentially give false results.

- **Fourier Transform** - Algorithms are used to measure the frequency results to give more of an insight into the signal than the time domain as well as providing spectral content.

- **Spectrum estimation –** Approximation of the power spectral density. The power spectral density is the measurement of signal strength as a function of frequency.

- **Windowing –** Leakage between each period on waveform corresponds to the range of Spectral Leakage. Windowing reduces this leakage.

Due to the high speed and accuracy requirements of the CMS, a special purpose digital signal processing (DSP) chip may be required to perform certain signal processing procedures [14]. In current technology signal processing is achieved digitally. Digital circuits are becoming progressively cost-effective and faster, with characteristics such as repeatability and consistency compared to analogue signals.

5.6.1 Digital Filters

Filtering of the signal is the process of altering the data collected from the DAQ device. Filters adjust and remove any unwanted frequencies and can be classified into the following groups:

- **Lowpass filter** - allows the passing of frequencies below the cut off frequency (f_c) and attenuates frequencies above f_c.

- **Highpass filter** - allows the passing of frequencies above f_c and attenuates frequencies below f_c.

- **Bandpass filter** – allows the passing of frequencies between f_{c1} and f_{c2}.

- **Bandstop filter** – attenuation of frequencies between f_{c1} and f_{c2}.

For an ideal filter the gain should be 1 (0dB) so that the signals amplitude will not change in size. Practical filters are not as accurate and precise but aim for the values seen in ideal filtering.

For filtering the output signal from the DAQ system digital filtering may be used. Digital filtering often makes use of a software-programmable tool to create a more accessible application for signal processing. This method of filtering requires only multiplication, addition and subtraction arithmetic unlike the complexity of analogue filtering. Digital filters are much more reliant and stable than analogue. Analogue filtering is capable of drifting with humidity and temperature and require components with high precision. Digital filtering is cost effective and doesn't suffer from manufacturing errors, erosion or aging.

6 Communication Architecture

The International Electrotechnical Commission (IEC) 61400-25 standard addresses all aspects of communication architecture for the monitoring and control of wind power plants and wave energy developers can make use of this standard for the development of an established communication architecture. There are also other different standards for the communication network requirements of power system, including IEEE C37.1 for SCADA and automation systems, IEEE 1379 for the interoperability of IEDs and RTUs, and IEEE 1646 for communication internal and external to the electric substation

Conventional communication infrastructures of offshore wind farms are switch-based architectures, where each wind turbine is equipped with an industrial Ethernet switch at the base of the tower, and optical fibre cables are used to connect between wind turbines. In the

case of large wind farms, independent sets of switches and communication links are considered to interconnect different applications such as those involved in monitoring, operation and protection. The transmitted data from the wind turbines may take a path through different Ethernet switches in order to reach the control centre.

Based on the approach described above and with a view to propose a communication architecture which will enable the positioning of the monitoring, protection and control information equipment at different location within the device, Figure 9 presents an example of a WEC device communication architecture concept. The concept divides the whole architecture of the WEC into multiple segments; (i) the device front end (PTO) is equipped with a number of sensing and monitoring equipment, (ii) the controller is located behind the generator and (iii) the grid compliant generated power, metering and user control interface.
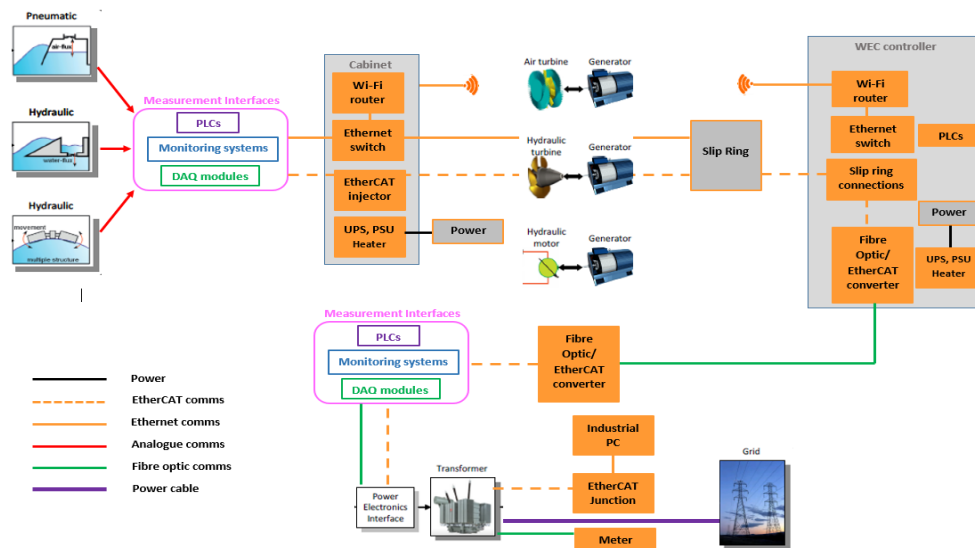

Figure 9 Condition monitoring. Communication architecture

The communication network architecture of a wave energy park can also be divided in the same way into three levels: WEC area network, wave energy park area network and control area network.

6.1 Wave Energy Converter Area network

WEC devices consists of different parts, such as the prime mover, generator, structure, etc. Each part is equipped with different types of sensors, actuators, and measuring devices. A front-end unit with a condition monitoring system is installed inside the WEC device, and it consists of a data acquisition device (sensors and processing units), actuators, main controller, and communication interface. Each measurement point produces different types of data including analogue information, status information, and control information.

To provide a standardised approach of information exchange, it may be useful to make use of the IEC 61400-25 standard where the critical parts within the generating device are identified by logical nodes (LN). e.g. wave device prime mover information (WDPM), wave device generator information (WDGE), wave device structure information (WDST), etc.

6.2 Farm Area Network

The wave energy park will consist of a number of WECs, a meteorological buoy, and control centre. WEC devices will usually include local SCADA systems as a part of the wave energy park where the SCADA function is to communicate with the different WECs, send and receive information, and execute start/stop commands. The meteorological data includes essential information estimated from forecasts of deviations between energy offered to the energy market and real-time power output.

6.3 Control Area Network

The main function of the control centre is to continuously and efficiently monitor the wave energy park. The local control centre is dedicated to a single wave energy park and is responsible for collecting information from the WECs, meteorological buoys, and substations. Independent servers are used for traffic received from different front-end applications of the WECs. The control centre is designed according to the amount of information managed, the criticality of data, and the need to utilize the data in the future.

7 Conclusion

Existing monitoring systems within the wave devices developed to date draw directly from current technologies and advances made in the wind and other industries. Monitoring techniques described in this deliverable include the monitoring of numerous key component such as generator, power take off, hydraulic systems etc using a range of sensors such as vibration, acoustic, temperature, speed, oil, current and voltage outputs. In addition, due to the mechanical loading to which most of the WECs are subjected to, sufficient structural health monitoring is required to be in place to detect any potential deformations or fractures of the mechanical structures. More importantly, the monitoring of the functionalities of the control and safety systems needs to be well designed to ensure the WECs are able to respond to system operation and potential faults.

To optimise the operation of the WEC, faults must be found at early stages so that logistics and maintenance can be scheduled according to weather conditions and availability. This can be carried out using CMSs with early detection capabilities where each method of detection must be accurate, repeatable and cost effective with long term stability.

High accuracy is required when measuring signals for early detection within the WEC system. The CMS measures the shape of signals for any signs of anomalies, therefore a high sample rate and high resolution which will produce a more accurate reading may sometimes be required for detailed signal analyses. Also, the sampling rate must be carefully selected to avoid signal distortions issues such as aliasing, jitter, slew rate, etc.

This document has provided an overview of basic hardware and software functionalities which may be used to configure and/or control the DAQ system. Wave energy developers can make use of existing offshore wind practices and standards in terms of communication for monitoring and control of wave devices.

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Appendix A:

Product	Supplier	Country of origin	Description	Main components monitored	Monitoring technology	Analysis methods	Data rate or sampling frequency	Comment
Ascent	Commtest	New Zeeland	System available in 3 complexity levels. Level 3 includes frequency band alarms, machine template creation, statistical alarming.	Main shaft, gearbox, generator	Vibration (accelerometer)	FFT frequency domain analysis Envelope analysis Time domain analysis	-	
Bruel & Kjaer Vibro	Bruel & Kjaer (Vestas)	Denmark	Vibration and process data automatically monitored at fixed intervals and remotely sent to the diagnostic server. User-requested time waveforms for frequency and time series analysis Time waveform automatically stored before and after user-defined event allowing advanced vibration post-analysis to identify developing faults.	Main bearing, gearbox, generator, nacelle.	Vibration analysis Temperature sensor Acoustic	Time domain FFT frequency analysis	Variable up to 40kHz 25.6kHz	
CMS	Nordex	Germany	Start-up period acquires vibration 'fingerprint' components. Actual values automatically compared by frequency, envelope and order analysis, with the reference values stored in the system. Some Nordex turbines also use the Moog Insensys fibre optic measurement system.	Main bearing, gearbox, generator	Vibration analysis (accelerometer)	Time domain based on initial 'fingerprint'	-	
Condition Based Maintenance System (CBM)	GE (Bently Nevada)	USA	This is built upon the Bentley Nevada ADAPT.wind technology and System 1. Basis on System 1 gives monitoring and diagnostics of drive train parameters such as vibration and temperature. Correlate machine information with operational	Main bearing, gearbox, generator, nacelle. Optional bearing and oil temperature.	Vibration analysis (accelerometer)	FFT frequency domain analysis Acceleration enveloping	-	

			information such as machine speed, electrical load and wind speed. Alarms are sent via the SCADA network.				
Condition Diagnostics System	Winergy	Germany	Up to 6 inputs per module. The system analyses vibration levels, load and oil to give diagnostics, forecasts and recommendations for corrective action. Automatic fault identification is provided. Relevant information provided in an automated format to the operations and maintenance centre without any experts being involved. Information delivered to the appropriate parties in real time. Pitch, controller, yaw and inverter monitoring can also be included.	Main shaft, gearbox, generator	Vibration (accelerometer) Oil debris particle counter	Time domain FFT frequency domain analysis	96kHz per channel
Condition Management System	Moventas	Finland	Compact system measuring temperature, vibration, load, pressure, speed, oil aging and oil particle count. 16 analogue channels can be extended with adapter. Data accessed remotely via TCP/IP. Mobile interface available.	Gearbox, generator, rotor, turbine controller	Vibration Oil quality & particles Torque Temperature	Time domain (Possible FFT)	-
OneProd Wind	Areva (01dB-Metravib)	France	Eight to 32 channels. Instrumentation includes operating condition channels to trigger data acquisitions, measurement channels for surveillance and diagnosis. Data set comparison when relating to similar operating conditions; data alarm systems warn on the repetitive and abnormal shocks enabling the detection of failure modes; built-in diagnostic tool. Optional additional sensors for shaft displacement, for permanent oil quality monitoring, low frequency sensors on the structure	Main bearing on LSS Bearing on gearbox LSS Bearing on intermediate gearbox shaft, on gearbox high-speed shaft, on generator Oil debris, structure, shaft displacement,	Vibration Electrical signature analysis Thermography Oil debris particle counter	Time domain FFT frequency analysis	-

			and current and voltage sensors for generator monitoring.	electrical signals.			
SMP-8C	Gamesa Eolica	Spain	Continuous on-line vibration measurement of main shaft, gearbox and generator. Comparison of spectra trends. Warnings and alarm transmission connected to Wind Farm Management System.	Main shaft, gearbox, generator	Vibration analysis	FFT frequency domain	-
Ω Guard CMS	Bachmann	Austria	Vibration based system based on KPI measurements	Gearbox, tower and pitch	Vibration analysis	Signal envelope, RMS and peak-peak	25kHz gearbox, 250 Hz tower	Six accelerometers with operational range of 0.1 Hz–10 kHz for gearbox, one acceleration sensor each in the axial direction (wind direction), as well at right angles to it with a frequency range of 0.1 Hz–100 Hz for tower
TCM (Turbine Condition Monitoring)	*+Gram & Juhl A/S (Siemens Wind Power A/S) +Enterprise V6 Solution with	Denmark	Advanced signal analysis and process signals combined with automation rules for algorithms for generating references and alarms. M-System hardware features up to 12/24 synchronous channels, interface for structural vibration monitoring and RPM sensors, external process parameters and	Tower, blades, shaft and nacelle Main bearing, gearbox and generator	Vibration (accelerometer) Sound analysis Strain analysis Process signals analysis	FFT and Wavelet frequency domain analysis Envelope analysis RMS analysis Order tracking analysis	

	SCADA Integration		analogur outputs. TCM server stores data and does the post data processing. Control room with web based operator interface.					
WindCon 3.0	SKF (REPower)	Sweden	Lubrication, blade and gearbox oil systems can be remotely monitored through SKF ProCon software. WindCon 3.0 collects, analyses and compiles operating data that can be configured to suit management, operators or maintenance engineers.	Blade, main bearing, shaft, gearbox, generator, tower, generator electrical	Vibration (accelerometer, proximity probe) Oil debris particle counter	FFT frequency domain analysis Envelope analysis Time domain analysis	Analogue: DC to 40kHz (Variable, channel dependent) Digital: 0.1Hz – 20kHz	
WinTControl-1	Flender Service GmbH	Germany	Integrated system combining various sensors for continuous measurements	Nacelle, pitch mechanism, gear unit	Temperature and currents, nacelle vibration	Peak-peak, temperature values, current measurements	30Hz continuous	30 channels including vibration of nacelle in X and Y direction, air temperature, temperature and current of pitch motors, azimuth angle, wind speed, gear unit temperature
WinTControl-2	Flender Service GmbH	Germany	Vibration analysis system integrated with other sensors	Gearbox, generator and main bearing	Vibration analysis, parametric input (RPM, wind speed), temperature measurements	Peak-peak, FFT, signal envelope	Max 150kHz	17 channels vibration of main bearing, gearbox, generator, RPM, Phase position, generator performance, wind

							speed, main bearing temperature, gear unit temperature, generator temperature
WiPro	FAG Industrial Services GmbH	Germany	Measurement of vibration and other parameters given appropriate sensors. Time and frequency domain analysis carried out during alarm situations. Allows speed-dependent frequency band tracking and speed-variable alarm level.	Main bearing, shaft, gearbox, generator, temperature. (Adaptable inputs)	Vibration (accelerometer)	FFT frequency domain Time domain analysis	Variable up to 50kHz	
WP4086	Mita-Teknik	Denmark	Up to 8 accelerometers for real-time frequency and time domain analysis. Warnings/alarms set for both time and frequency domains based on predefined statistical/thresholds-based vibration limits. Operational parameters recorded alongside with vibration signals/spectra and full integration into gateway SCADA system. Algorithm toolbox for diagnostic analysis. Approximately 5000-8000 variables covering different production classes.	Main bearing, gearbox, generator	Vibration (accelerometer)	FFT amplitude spectra FFT envelope spectra Time domain magnitude Comb filtering, whitening, Kurtogram analysis	12-bit channel res Variable up to 10kHz	
HYDACLab	HYDAC Filtertechnik GmbH	Germany	Permanent monitoring system to monitor particles (including air bubbles) in hydraulic and lube oil systems.	Lubrication oil and cooling fluid quality	Oil debris particle counter	n/a	-	
PCM200	Pall Industrial Manufacturing (Pall Europe Ltd)	USA (UK)	Fluid cleanliness monitor reports test data in real-time so ongoing assessments can be made. Can be permanently installed or portable.	Lubrication oil cleanliness	Oil cleanliness sensor	n/a	-	
TechAlert 10 TechAlert 20	MACOM	UK	TechAlert 10 is an inductive sensor to count and size ferrous and non-ferrous debris in circulating oil systems.	Lubrication oil quality	Inductive or magnetic oil debris particle counter	n/a	-	

			TechAlert 20 is a magnetic sensor to count ferrous particles.					
BLADEcontrol	IGUS ITS GmbH	Germany	Accelerometers are bonded directly to the blades and a hub measurement unit transfers data wirelessly to the nacelle. Blades are assessed by comparing spectra with those stored for common conditions. Measurement and analysis data are stored centrally and blade condition displayed using a web browser.	Blades	Accelerometer	FFT frequency domain	= 1kHz	Now part of Bosch Rexroth
FS2500	FiberSensing	Portugal	BraggSCOPE measurement unit designed for industrial environments to interrogate up to 4 Fiber Bragg Grating sensors. Acceleration, tilt, displacement, strain, temperature and pressure measurable.	Blades	Fibre optic	Unknown	Up to 2kHz	
RMS (Rotor Monitoring System)	Moog Insensys Ltd	UK	Modular blade sensing system consisting of 18 sensors, 6 per blade, installed in the cylindrical root section of each blade to provide edgewise and flapwise bending moment data. Can be designed-in during turbine manufacture or retrofitted. Monitors turbine rotor performance, mass and aerodynamic imbalance, blade bending moments, icing, damage and lightning strikes. Possible integration, as an external input, in commercial available CMSs.	Blades	Fibre optic strain	Time domain strain analysis	25Hz/sensor	
Adapt.wind	GE Energy	USA	Up to 150 static variables monitored and trended per WT. Planetary cumulative impulse detection algorithm to detect debris particles through the gearbox planetary stage. Dynamic energy index algorithm to spread the variation over five bands of operation for spectral energy	Main bearing, gearbox, generator	Vibration (accelerometer) Oil debris particle counter	FFT frequency domain analysis Time domain analysis	-	

			calculations and earlier fault detection. Alarm, diagnostic, analytic and reporting capabilities facilitate maintenance with actionable recommendations. Possible integration with SCADA system.					
APPA System	OrtoSense	Denmark	Oscillation technology based on interference analysis that replicates the human ear's ability to perceive sound.	Main bearing, gearbox and generator	Vibration	Auditory perceptual pulse analysis (APPA)	-	
Distributed condition monitoring system	National Instruments	USA	Up to 32 channels; default configuration: 16 accelerometer /microphone, 4 proximity probe and 8 tachometer input channels. Also provided mixed-measurement capability for strain, temperature, acoustics, voltage, current and electrical power. Oil particulate counts and fibre optic sensing can also be added to the system. Possible integration into SCADA systems.	Main bearing, gearbox, generator	Vibration Acoustic	Spectral analysis Level measurements Order analysis Waterfall plots Order tracking Shaft centre-line measurements Bode plots	24-bit res 23.04kHz of bandwidth with antialiasing filters per accelerometer/microphone channel	
Wind AnalytiX	ICONICS	USA	This software solution uses fault detection and diagnostics technology that identifies equipment and energy inefficiencies and provides possible causes that help in predicting plant operations, resulting in reduced downtime and costs related to diagnostic and repair.	Main WT components	Vibration (accelerometer)			
Wind Turbine In-Service	ABS Consulting	USA	Data gathered from inspections, vibration sensors and SCADA system. Ekho for WIND software features regular diagnostics, dynamic performance reports, key performance indicators, fleet-wide analysis, forecasts/schedules and asset benchmarking. It generates	Main bearing, gearbox and generator Gearbox and gear oil, rotor blades and coatings	Vibration Inspections	FFT frequency domain analysis Time domain analysis		

			alarms and notifications or triggers work orders for inspections or repairs.					
Proficy Smart Signal	GE	USA	Based on Similarity Based Modelling (SBM).	Vibration and thermal analysis Critical rotating and non-rotating equipment	Software only, can conceivably compare signals from any existing instrumentation and compare results to a pre-defined threshold.			
Efector Octavis	IFM Electronic	Australia	Either on-site analysis or data transfer to server possible depending upon bandwidth of connection.	Generator, gearbox, rotor bearing. Can be extended to rotor blade and pumps/motors.	Vibration	Trend Recording FFT		Company develop sensors and have since developed a CM system for the wind industry.
Sensor Highway II	Mistras Group	USA	The Sensor Highway™ II (SHII) is an Acoustic Emission (AE) monitoring system with up to 16 high-speed channels and 16 standard parametric input channels (expandable to over 100). The system is designed for unattended and remote monitoring use in structural health, process and condition monitoring applications.		Acoustic Emissions	SHII-DC Basic and low cost system capable of data acquisition and storage with basic processing and alarm signals SHII-N Includes a built in Ethernet hub to connect multiple SHIIs to a base computer for analysis		Primarily developed for structures, in particular bridges

ConWind (Vibroweb XP)	Prüftechnik	Germany	Expert vibration analysis system	Main bearing, Gearbox, Generator, Nacelle	Vibration measured with piezo-electric accelerometers	Vibxpert (mobile CMS) 2 channel FFT data collection. Vibroweb (online CMS) multi-channel FFT data collection.	0.1Hz – 45kHz	System is certified by GL.
Oil Health	Atten2	Spain	Oil degradation measurement performed by relating specific physic-chemical parameter changes to the formation of polymeric molecules.	Gearbox	On-line spectrometric analysis of oil (rather than debris count)			Not specific to wind industry. Tested on Gamesa and Acciona turbines.
MetalSCAN	WindPower Renewable Solutions	UK	Detection of both ferrous and non-ferrous particles from gearbox damage. Sensor placed in-line before the main filter and measures particle count through use of disturbance to applied magnetic field	Gearbox	Inductive based oil debris monitoring system	Particle count		Applied to many current technology turbines: Siemens, Vestas, Acciona, REPower, Gamesa, GE, Suzlon, Nordex
MHC (Machine Health Checker) Acoustic Emission System	Kittiwake Holroyd	US/UK	The AE sensor design uses a novel, very stable and reproducible transducer arrangement	Vibration analysis, acoustic emission and oil analysis	Acoustic	Time domain analysis		
WINDPCM	Feldman Enterprises	Cyprus/ UK	Monitoring KPIs and using specific alarm thresholds to verify severity of damage detected. Can provide reliable diagnosis	Gearbox, main bearing and generator. Application to other rotating machinery of	Integrated acoustic emission and vibration analysis system capable of	Peak-peak, spike energy, Cepstrum, RMS, signal envelope, FFT, signal normalisation	500kHz for AE, 25kHz or 50kHz for vibration analysis, 1kHz for oil	Developed and successfully demonstrate d in the field during the

				the WT possible	incorporating oil analysis input using one debris particle sensor		analysis if present	NIMO projects. Certification pending. 4-5 AE, 8-10 accelerometers. Oil particle and moisture sensors can be integrated as options.

RiaSoR 2 project partners