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Advanced monitoring, simulation and control of tidal devices in unsteady, highly turbulent realistic tide environments

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D4.3: Condition-based maintenance strategies

A report on condition-based maintenance, its impact on monitoring and comparison to other maintenance strategies

WP 4:

Advanced monitoring strategies

WP Leader:

EnerOcean

Dissemination level:

Public

Summary:

This report details the definition of Condition Based Maintenance (CBM) strategies used in the RealTide project and gives a comparison to other maintenance strategies. Based on previous results, a selection of critical components and monitoring techniques to use for them is made. Also a description of the most widely used CBM algorithms and a methodology for the integration into a SCADA system is included.

Objectives:

The objective of Task 4.3 is to provide a baseline for development of a generic Condition Monitoring System (CMS) that can be applied to the majority of tidal turbines being commercialised. Techniques and strategies defined in this report runs in parallel with Task 4.2, where the integration with monitoring techniques is being developed and implemented.

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1 EXECUTIVE SUMMARY

Humanity is facing a pressing need to change the model of energy supply and use. New clean sources of energy are required for climate change adaptation and mitigation. Tidal energy has high potential value as a predictable, concentrated new renewable energy source, but is not yet commercialised nor is it cost-competitive with incumbent energies. Recent cost-reduction trends in wind power, especially offshore, and solar PV are diverting market-introduction funds from tidal energy and hindering the growth of a competitive tidal-power industry. According to [1], a main technical issue holding back development of tidal energy is the relative complexity of maintenance tasks. In addition to being typical for new, immature technologies, this is considered [1] to be due to the difficulty in accessing tidal turbines underwater and the higher operational costs associated to this operation.

The RealTide project aims at improving the reliability of tidal devices through development of novel techniques for reducing downtime due to failures and maintenance activities. These techniques need novel models and designs which, in combination with proper maintenance and monitoring strategies, can lead to a better understanding of tidal turbines and a more efficient Operation and Maintenance (O&M) effort, thereby reducing the cost of energy produced by tidal turbines.

RealTide works to identify main failure causes of tidal turbines at sea and to provide a step change in the reliability and performance of key components, namely the blades and drive train, across several tasks in the work plan. One completed task was the development of a reliability methodology based on Failure Modes and Effect Analysis (FMEA), drawing on partners' experience and existing literature. In this task, the consortium developed an innovative FMEA methodology adapted to 4 generic tidal-stream turbine concepts, representative of the vast majority of tidal energy converters approaching commercialisation. The analysis was performed to highlight the actual failure modes induced by the specific operating conditions of tidal turbines. This methodology and key results from this work was presented in a paper for the 2019 European Wave and Tidal Energy Conference (EWTEC) (see [2]). This paper is included as an Annex to the present Deliverable report.

The work, including the mentioned paper, is part of Work Package (WP) 4, addressing the definition of advanced monitoring techniques, their combination with effective strategies for Condition Based Maintenance (CBM), and the study on the potential impact that these techniques can have on cost reduction. CBM is highly likely to be a more efficient maintenance strategy than other approaches and will contribute to cost reduction for tidal turbines. When using this approach, maintenance is performed only when necessary, as a function of the condition of the component(s) monitored. The CBM strategy is used with theoretical models, which, combined with the monitoring system used, may lead to more robust fault detection and identification. WP4 work began with the definition of the initial monitoring plan (task 4.1) which produced a selection of potential monitoring techniques to be integrated on the most critical elements as identified in the FMEA.

The present Deliverable report serves as a connecting link between work already completed in other tasks (T1.1, T3.1 and T4.1) and the remaining tasks of WP4, which are currently under development. To achieve this goal, a selection of components to be monitored and specific monitoring techniques to be integrated in the Condition Monitoring System (CMS) has been made. In this document, some integration examples of the monitoring techniques are introduced, together with models developed in WP3. A definition of high-level algorithms and a generic SCADA system to be used for CBM has also been made. This deliverable will mean a big push for the project since it underpins the basics in the definition of the final CMS which will be presented in final deliverables.

Building on this report, development of a detailed cost model with the objective of comparing CBM strategies to other O&M strategies also from an economic point of view, will be part of D4.5, dealing with the impact of CBM and the proposed monitoring protocol on cost reduction of tidal devices.

2 INTRODUCTION

This report defines Condition Based Maintenance methodologies that can be adapted and applied to the four generic tidal concepts, categories of tidal turbines, that were defined in Deliverable 1.1 (see [3] and [2]). The report begins with a review of the state of the art of traditional and predictive maintenance strategies used in industry, with a special focus on CBM. A comparison of maintenance strategies is presented as well as a definition of monitoring strategies to be used in the Condition Monitoring System (CMS) adopted by the RealTide project.

The completed FMEA highlighted the most critical elements identified by the criticality assessment for the four tidal concepts. Based on their monitoring needs, as detected in the FMEA, a selection of monitoring techniques to be used for CBM has been made and is described. This selection is based on the initial monitoring plan carried out in task 4.1, also taking into account the models developed in task 3.1, especially for the Model Based Monitoring (MBM) technique. Thus, the relevant section of this report complements the previous work and acts as a connection link with upcoming tasks. Some aspects of the data acquisition being developed in parallel with task 4.3 is also presented.

Next, a review of the most widely used data clustering algorithms for CBM has been made. After that, the methodology for identifying through this technique different working conditions both for environment and machine is defined. As a closely related concept to CBM, more and more used in modern industries, a brief introduction of *"digital twins"* is also included, and, after that, a generic multilevel SCADA system is described with its components. For the latter, key parameters and alarm set-ups to be used have been made according to different criteria.

2.1 Abbreviations & Definitions

AE	Acoustic Emission
ANFIS	Adaptive Neuro-Fuzzy Inference System
API	Application Programming Interface
ARMA	Autoregressive Moving Average
BEMT	Blade Element Momentum Theory
BPM	Basic Permanent Monitoring
CAPEX	Capital Expenditures
CBM	Condition Based Maintenance
CMS	Condition Monitoring System
DFIG	Doubly Fed Induction Generator
DM	Direct Measurement
DT	Digital Twins
FEA	Finite Element Analysis
FMEA	Failure Mode and Effect Analysis
FNAT	First Natural frequency
FRP	Fiber Reinforced Plastic

HMI	Human Machine Interface
HMM	Hidden Markov Model
IDE	Indirect Detection
IVT	Inspection Visit Tools
LRUT	Long Range Ultrasound Testing
MBE	Model Based Estimation
ML	Machine Learning
MTBF	Mean Time Between Failures
MTTR	Medium time to repair
MUID	Multiple Integrated Detection
NCBMP	Number of Condition Based Maintenance Papers
O&M	Operation and Maintenance
OPEX	Operating Expenses
OWF	Offshore Wind Farm
PM	Permanent Monitoring
RMS	Root Mean Square
RNN	Recurrent Neural Network
RPN	Risk Priority Number
RUL	Remaining Useful Life
SCADA	Supervisory Control And Data Acquisition
SM	Spot Measurement
SVR	Support Vector Regression
TEC	Tidal Energy Converter
TNP	Total Number of Papers
TPM	Total Productive Maintenance
UT	Ultrasound Testing
WOS	Web Of Science
WP	Work Package
WTG	Wind turbine Generator

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2.3 Distribution List

This Document is a RealTide Internal Document and is classified as a public Report. It is for distribution. It will also be distributed to all Beneficiaries of the RealTide project and published online.

3 MAINTENANCE STRATEGIES

Industrial maintenance can be defined as a set of standards and techniques established for the improvement and proper operation of machinery and facilities of an industrial plant, in order to provide a better performance in the shortest possible time and it is one of the fundamental axes within the industry. It can be measured by the quantity and quality of production and throughout history it has been subjected to different changes over time. Today's maintenance is seen as an investment that helps to improve and maintain quality in production.

Offshore, due to the complexity of marine operations, Operation and Maintenance (O&M) costs are higher than onshore. This is one of the main handicaps for the development of marine renewable energies. This fact can be seen in the offshore wind industry, more mature than the main focus of RealTide. Crabtree et al [4] report O&M costs for offshore wind as three to five times those for onshore, although source data are limited and from early developments. According to [5], O&M costs are estimated at 14% to 30% of the total cost of an offshore wind farm. Attending to a single turbine, it is estimated at 25% to 30 % of total energy cost and spent mainly in corrective maintenance [6].

This is why all players in the offshore sector are working towards the achievement of more efficient maintenance strategies with the objective of decreasing these numbers in the upcoming years. In this section a classification of the different maintenance strategies is exposed and the state of art for each of them is been presented.

According to [7], maintenance strategies can be classified in the following groups, attending on the mean of detection used for detecting the failure and the time when the faulty component is replaced: Preventive maintenance (Figure 3.1a), corrective maintenance (Figure 3.1a) and condition based maintenance (Figure 3.1b).

Three stages can be distinguished:

- Smooth running: It refers to normal working condition where no anomalies are detected.
- Degradation: A decrease in the performance of the components is detected.
- Failure: The component fails and becomes inoperative.

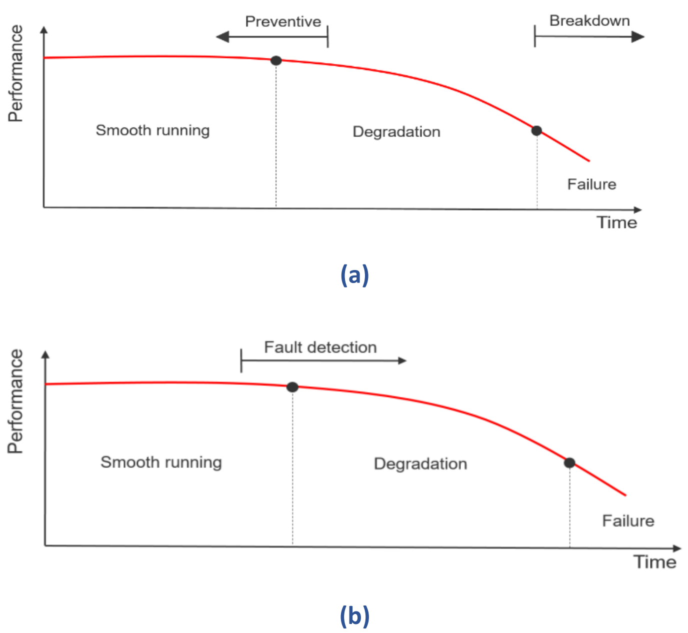


Figure 3.1. Maintenance strategies.

3.1 History and evolution of maintenance

The history of maintenance goes hand in hand with technical-industrial development, since with the first machines began the need for first repairs. At the end of the 18th century, James Watt invented the steam engine, which led to the development of railways, steamships and mechanized agriculture.

All these innovations led to the extraordinary growth of two industries: iron and coal. Day labourers from the countryside migrated massively to cities, working in the new factories of these industries.

At the same time, with the first machines, the need arose for repairing them when broken in order to continue production. Machine stoppages and work-related accidents began to be controlled to avoid or reduce production delays. Around 1920 the concept of **corrective maintenance** begins to be used, conceptually only dealing with the repair of a machine when it has stopped.

In the 2nd World War, the aeronautical industry raised the need to check airplanes from time to time to prevent them from failing in the air. This is when the study of the life of each component began and components were replaced after a certain number of hours of operation. This was how the concept of **preventive maintenance** appeared.

One of the problems with preventive maintenance, which greatly limits its effectiveness, is the degree of uncertainty it presents, since it is not possible to know exactly when equipment needs to be serviced or replaced. In order to address this limitation, **predictive maintenance** arose in the 1960s, based on knowledge of the equipment's operating status.

In 1969, carmaker Toyota developed the concept of TPM (Total Productive Maintenance) which was implemented in the rest of the world by the ‘80s. In the TPM concept, responsibility for maintenance does not only fall on the maintenance department but on the whole productive structure, aiming for zero accidents, zero defects and zero failures.

3.2 Corrective maintenance

Corrective maintenance is where a component is replaced after failure occurs. As such, it is the most basic form of maintenance, as it simply involves replacing or repairing what has been damaged. In this sense, corrective maintenance is a process that basically consists of locating and correcting the breakdowns or faults that are preventing the machine from performing its normal function.

Corrective maintenance was widely used in the past, when modern maintenance techniques were not known. Today, barring unforeseen circumstances, it is rarely used on its own but is combined with, in most cases, preventive maintenance. The logic is to use corrective maintenance only when a component fails unexpectedly or when preventive or predictive maintenance are not justified due to high costs or complexity of operations. In model costs, corrective maintenance is considered as a way to take into account failures that were not foreseen in the maintenance plans [8].

In the RealTide project, due to the lack of information regarding the O&M of tidal turbines, corrective maintenance in wind turbines (WTG’s) is applied by drawing on the similarity between these two technologies as the approach aiming to correct faults once they have occurred. The WTG, when detecting a failure, will go to emergency mode as a protection measure. Depending on the alarm generated, the WTG may try to start again on its own or may be reset by remote control. If this is not possible due to the nature of the alarm, the operators will intervene to try to correct the fault.

In the event that the corrective action required is of such magnitude that intervention with cranes is needed to replace part of the wind turbine, such as generator, gearbox, transformer, etc. it will be considered as a major corrective, as a result of the material and human means to be mobilized. In general, this work will be carried out by specialists and personnel with extensive experience in the technology in which it is carried out.

3.2.1 Types of corrective maintenance

As such, today a distinction is made between two types of corrective maintenance:

- **Contingent corrective maintenance**

Contingent or unplanned corrective maintenance is maintenance that is performed in a forced and unforeseen manner, when a failure occurs, and that imposes the need to repair the equipment before it can continue to be used. In this sense, contingent corrective maintenance implies that the repair is carried out as quickly as possible in order to avoid material and human damages, as well as economic losses.

- **Scheduled corrective maintenance**

The programmed or planned corrective maintenance is the one that has as objective to anticipate to the possible failures or damages that can present a team from one moment to another. In this sense, it tries to foresee, based on previous experience, the moments in which a piece of equipment must be submitted to a maintenance process to identify worn parts or possible breakdowns. Hence, it is a type of maintenance that proceeds with a general revision that diagnoses the state of the machinery. In addition, this type of maintenance allows the time when the overhaul is to be carried out to be set in advance, so that hours of inactivity or little activity can be taken advantage of.

3.2.2 Advantages and disadvantages of corrective maintenance

The main advantage of corrective maintenance is that it extends the useful life of equipment and machinery by repairing parts and correcting faults. In this sense, it frees the company from the need to buy new equipment every time one breaks down, which would raise costs. In addition, another advantage of performing corrective maintenance is the possibility of programming in advance of any damage, so that accidents can be prevented and avoid decreases in production.

The disadvantages of corrective maintenance are related to the impossibility, in many occasions, of predicting a failure, which forces a mandatory stoppage of production while the problem is detected, the spare part is obtained, and the malfunction is resolved. In this sense, the costs and times of repair, when an unforeseen failure occurs, are always an unknown.

3.3 Preventive maintenance

Preventive maintenance is a concept that covers all types of operations aimed at the conservation of equipment, machines and installations through periodic reviews and professional repairs, to ensure their proper functioning, reliability and durability. This type of maintenance is performed while the equipment is in operating condition, as opposed to corrective maintenance, which is applied when the equipment or installation has ceased to function due to damage and must be repaired so that its operation can be restored.

Therefore, we can define preventive maintenance as the type of maintenance that is done before the fail occurs in which the component is replaced periodically without the prior knowledge about its state or condition. The time between replacements is normally based on historical or statistical data. In [7] we can see a summary of most of the failure and degradation modelling that is used in the wind industry. For their similarity, these models can be easily extrapolated to tidal industry.

The fundamental objective of preventive maintenance is to prolong the useful life of the equipment, preventing faults and incidents that may occur due to lack of maintenance. Generally, it consists on the replacement of parts that present wear, the change of oil and lubricants, calibration, cleaning, tightening, greasing, structural inspection, component inspection, etc.

This type of maintenance is done by recommendations of the manufacturers after a certain time of use, by legal rules of use or by inspection of expert technicians. The prevention in the maintenance of any type of equipment, machine or installation is fundamental to guarantee its good operation and to extend its useful life.

The main characteristics of preventive maintenance are as follows:

- It is carried out periodically and routinely.
- It is a type of maintenance whose tasks and budgets are planned. It has a start and an end time.
- It is carried out in conditions of total control to avoid accidents, while the equipment is stopped.
- It seeks to anticipate future failures or damage to equipment.
- The manufacturer generally recommends when to do so, through technical manuals.
- The activities that are carried out follow a previously elaborated program.
- It offers the possibility of updating the technical configuration of the equipment.

More specifically, applied to the RealTide project, and due to the lack of information on the operation and maintenance of tidal turbines, the preventive maintenance of wind turbines (WTG) is defined by appealing to the similarity between these two technologies as the one carried out with the aim of reducing breakdowns caused by a malfunction of the components that make up the whole, foreseeing the causes for which the breakdown is going to occur and by means of periodic reviews to be able to carry out the actions that can correct these breakdowns.

We have three types of preventive maintenance for wind turbines, mechanical preventive maintenance three months after start-up, minor and major preventive maintenance and mechanical preventive maintenance.

- **Preventive 3 months**: It is carried out three months after the start-up of the WTG, and basically consists of checking the tightness in different parts of the WTG such as foundations, between sections, hub union with main shaft, blades, etc. and it is performed with hydraulic tools mainly.
- **Minor preventive**: It is carried out at 6 months and then every 12 months (i.e. at 18, 30, etc.) in each WTG, carrying out tightening in the most unfavourable parts of the machine, crown and bearing greases, checking of levels, temperatures, checking of the fibre, connected checks of Pitch, G.H., blades, gearbox, brakes, cardan, electrical revisions, etc. That is to say, a very extensive overhaul.
- **Major Preventive**: This is carried out at 12 months and every 12 months thereafter (i.e. 24, 36, 48). It is a preventive maintenance with many points in common with the minor.
- **Mechanical preventive**: This is done at 18, and then every 12. It coincides with the minor preventive maintenance. It is an extensive revision of the machine's tightness in all the most unfavourable parts and checking of connections.

3.3.1 Types of preventive maintenance

Preventive maintenance is subdivided into two types:

- **Scheduled preventive maintenance**

This type of maintenance is planned and budgeted, given that the revisions or inspections to the equipment are carried out according to time parameters, operating hours, consumption, among other factors.

- **Maintenance of opportunity**

This is usually done when equipment is taken out of operation for other purpose, such as a turbine in a hydroelectric power plant, thus taking advantage of its resting time, or when other maintenance tasks are performed during scheduled visits for any purpose.

3.3.2 Advantages and disadvantages of preventive maintenance

Among the advantages of preventive maintenance are the following:

- Reduced cost in relation to corrective maintenance.
- Risks due to equipment failures or leaks are significantly reduced.
- Prolongs the useful life of the equipment.
- There is less unplanned downtime caused by equipment failure.
- Fewer errors are generated in day-to-day operations.
- Substantially improves equipment reliability.
- Lower repair costs caused by unexpected equipment failures, which must be corrected quickly.
- Reduces the risk of injury to operators.
- Minimize the likelihood of unplanned plant shutdowns.
- It allows to improve the control on the operation of the equipment and its productivity, as well as the programming of the maintenance that will be applied in it.

Preventive maintenance has a reduce number of disadvantages. Some of these are as follows:

- The maintenance of the equipment must be performed by specialized personnel who are usually outside the company, so it has to be hired.
- Since the maintenance of the equipment is carried out with a certain periodicity, they do not allow the exact determination of the depreciation or wear of the parts of the equipment.
- The company must adhere to the manufacturer's recommendations to schedule maintenance work. For this reason, it may be necessary to replace a part when it may have a longer useful life.

3.4 Predictive maintenance and condition based maintenance

Predictive maintenance determines when repair should be performed according to maintenance advice and the maximum recommended operating time before undergoing repair.

This maintenance can be counted within the preventive type, but it has some substantial differences: predictive maintenance is carried out according to the state of the equipment, the follow-up and the maintenance schedule of these resulting readings (condition-based maintenance). On the other hand, preventive maintenance as such determines when the equipment will be inspected according to the manufacturer's recommendations or also the average life cycle of the equipment.

In this case, maintenance is also performed before the fail occurs but, unlike preventive maintenance, the time between replacements is not based on historical or statistical data but it is based in the status or condition of the component. The information about the condition of the component, it is normally known for being the maintenance strategy integrated in the monitoring system. In the next section the concepts of predictive and condition based maintenance will be studied in more depth.

4 CONDITION BASED MAINTENANCE

In this section we will show the selected techniques for CBM that can be applied in RealTide project and its application to the critical elements of a generic tidal turbine. The decision of using these techniques is based on the results of the initial monitoring plan and the FMEA so, a brief summary of this work has also been included in this section.

4.1 Definition and origins

Condition Based Maintenance concept was presented as an alternative to traditional maintenance strategies and relies on the idea of performing the maintenance tasks only when it is required, based on the information of the condition of the component. The concept was introduced in the late 1940s for the first time by the Rio Grande Railway Steel Company. CBM was used to detect fuel and coolant leaks in diesel engines by reading the changes of pressure and temperature sensor readings. During the 50's, 60's and 70's CBM started to gain more and more popularity thanks to its efficiency that, combined with the emerging monitoring technologies was presented as a more efficient alternative to traditional maintenance strategies. Nowadays, due to the great necessity of decreasing the maintenance cost in a more and more competitive industry, this increment is more noticeable and it is widely used in many industries worldwide. This fact can be seen for instance attending to the number of publication related with CBM in the last years. Next figure shows the number of publication per year in CBM of the WoS database.

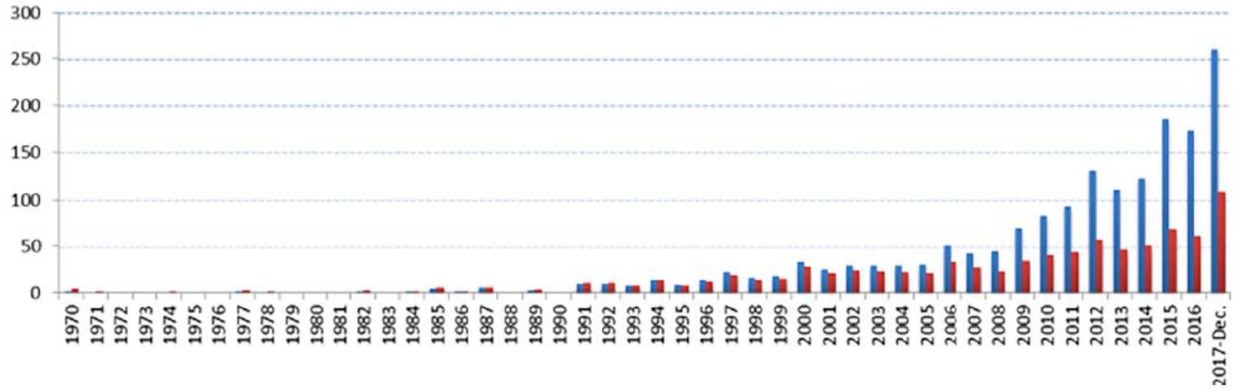


Figure 4.1. Number of publications per year in CBM from 1970 to 2017. The total number of CBM papers are denoted in the blue bars, and the red bars indicates the ratio (NCBMP/TNP) x 10^6. Source: [9].

For tidal turbines, due to the lack of confidence of the devices since the technology is still under development and added to the complexity of marine maintenance operations (large distances, necessity of big vessels, harsh weather conditions, lack of accessibility, etc.), the use of CBM may contribute in decreasing the cost of this technology which will be certainly one of the aspect to tackle for its maturity.

According to the results exposed in [10], the overall reliability of a generic tidal turbine can increase from 45 % to 70 % when including different CBM strategies for the components of the tidal turbine. In [11], the authors developed a model which allows to estimate the influence of different parameters in maintenance of offshore wind turbines. Next figure shows the effect of the use of CBM, compared to only corrective maintenance. As can be appreciated, the number of repairs are larger for the CBM but cheaper so the total cost due to CBM is smaller than corrective. The study was carried out assuming a generic component with a failure rate of 0.5 failures per year [9]. Where "Corr" means corrective maintenance based strategy, "Cond" means condition-based maintenance strategy, "Ins" means inspection visits, "Inspections" are only the cost of the visit performed at regular intervals, and "Repair:ins" are the additional cost of repairs performed during those visits. In both cases "Boat",and "Heli", "Repair: boat" and "Repair: heli" mean corrective repairs performed by boat of helicopter and their associated costs respectively.

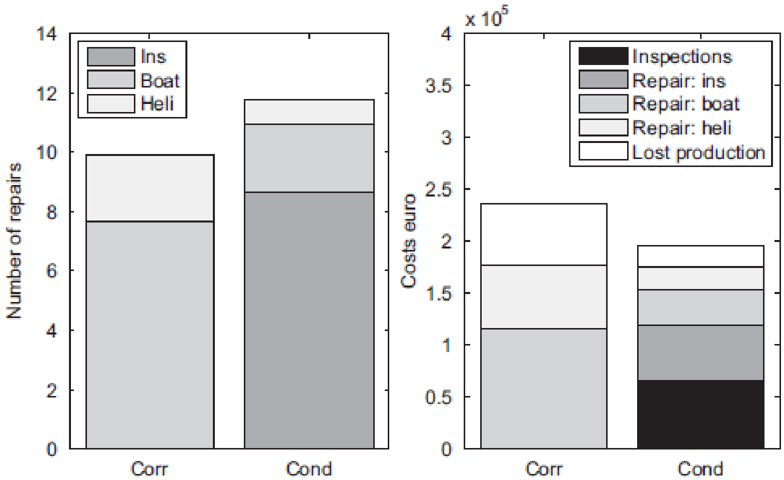


Figure 4.2. Influence of condition-based maintenance versus corrective maintenance strategy. Source: [11].

4.2 CBM strategies

Condition Based Maintenance strategies cannot be defined for all the component and monitoring technologies either because the monitoring technology cannot be easily integrated into the CMS or because the low criticality of the component makes its integration into the CMS economically inefficient. For that reason, it is important to define in which way CBM is going to be done.

Next table, taken from [12] and adapted for RealTide, summarizes accurately the vision in the definition of **maintenance strategies** for the project. As can be seen, CBM is presented as sub-categories of predictive maintenance and there is a distinction depending if maintenance is carried out according to the diagnostic or prognostic of the component.

Table 4.1. CBM vision in RealTide. Modified from [12].

	Maintenance Approaches			
	Reactive	**Proactive**		
Category	**Corrective (Run-to-fail)**	**Preventive**	**Predictive**	
Sub-Category	Fix when it breaks	Scheduled maintenance	CBM- Diagnostic	CBM - Prognostic
When scheduled	No scheduled maintenance	Maintenance based on a fixed time schedule for inspect, repair and overhaul	Maintenance based on current condition	Maintenance based on forecast of remaining equipment life
Why scheduled	N/A	Intolerable failure effect and it is possible to prevent the failure effect through a scheduled overhaul or replacement	Maintenance scheduled based on evidence of need	Maintenance need is projected as probable within mission in time
How Scheduled	N/A	Based on the useful life of the component forecasted during design and updated through experience	Continuous collection of condition monitoring data	+ Forecasting of remaining equipment life based on actual stress loading
Kind of prediction	None	None	Near real-time trend analysis	Real-time trend analysis
Application to tidal turbines	Non adequate	Inadequate due to high costs for repair materials	Adequate	Adequate

As expected, CBM strategies are directly linked to the monitoring strategy to be used. With that in mind, three different **monitoring strategies** have been defined for the application to tidal turbines namely *Spot Measurement (SM), Basic Permanent Monitoring (BPM) and Permanent Monitoring (PM)*.

1. **Spot Measurement (SM)**

Minimum monitoring system. The system is not installed permanently on the TEC (only the transducers or fixing system could be permanent present in the machine) and it is installed in-situ when performing maintenance tasks.

2. **Basic Permanent Monitoring (BPM)**

A permanent installation of the transducer in the critical components that allows performing complete reading during maintenance interventions/visits on the tidal device (included in a periodic review of the machine or in the context of an additional maintenance intervention) and more basic readings during operation. This is the most commonly found installation. Intermediate solution between SM and PM. It might integrate some of the basic measurements that can help to avoid a review trip, like a IP camera, and basic information about the working conditions, thanks to rotational speed and current velocity monitoring. These on the spot complete reading of the status of the device, inside the CBM philosophy, will allow forecasting the substitution of the element in a future intervention, or directly in the current visit to the machine, if some damage is detected. This technique is highly susceptible of used in the blade monitoring system, since it largely reduces the complexity of the system.

3. **Permanent Monitoring (PM)**

A permanent installation of both transducers and interfacing electronics in the tidal device that allows an automatic periodic reading of the sensors remotely in real-time. This strategy allows performing remotely the Condition Monitoring of all the critical or more expensive composite material elements. In this configuration, the monitoring system becomes the SCADA system of the machine, including all the monitoring needed and some actuation capacity, linked to protection of the device in case of a problem appears. It will be communicated with the power electronics/electrical generator control.

4.2.1 Alternative definitions

Despite predictive and condition based maintenance are very similar as they both are based on the condition of the component, there are certain differences in their definition. Some authors do not distinguish between these two definitions and they use them indistinctly (see [9]). Since the boundary between the concepts may be a bit ambiguous, it was decided to dedicate this section in explaining the main differences between them with real examples, at least for the philosophy that was conceived in RealTide project.

As it was seen in Table 4.1, predictive maintenance is a general term that covers two different CBM approaches depending if maintenance is carried out attending to diagnostic or prognostic techniques. Diagnostic techniques are based on statistical methods for data analysis that can be classics or advanced such as machine learning. After that, a prediction model is created which allows predicting future breakdowns. Next table summarizes some of degradation model methods that can be used for this kind of maintenance.

Table 4.2. Degradation modelling approaches for diagnostic techniques. Source: [13].

Approaches	Methods*		Advantage	Drawback
Reliability based approach	Paris law		Ability for interpretation by physics. Provide accurate Remaining Useful Life (RUL) at component level prognostics	Detailed knowledge of the system behaviour is required. Complex systems degradation model is hard for construction
Data driven approach	Statistical methods	Moving average	Understanding the degradation mechanism is not required. Effective in describing the uncertainty of the degradation process	Highly depends on the trend information of historical observations. Less precise in the RUL prediction of complex systems.
		Autoregressive Moving Average (ARMA)		
		Bayesian filter		
		Particle filter		
	Artificial intelligence methods	Recurrent Neural Network (RNN)	Able to learn complex nonlinear relationship between data. Understanding the degradation mechanism is not required. Expected to have a good performance in RUL prediction of complex systems.	Need sufficient data for training. Lack of physical meaning. Difficulty to select the parameters of the models.
		Adaptive Neuro-Fuzzy Inference System (ANFIS)		
		Support Vector Regression (SVR)		
		Hidden Markov Model (HMM)		

**Brief description of the methods in the next paragraphs.*

Model based approaches use physical and mathematical relations in order to model the degradation trend. Some of these models are based in a physical phenomenon (reliability-based approach) like the Paris Law, which is one of the most commonly used models for prediction of failures in bearings. Data drive approach models on the other hand, transform data gathered from sensors into relevant information. Statistical methods estimate the Remaining Useful Life (RUL) by processing the historical data of the machine while artificial intelligence methods are able to find complex relationship between monitoring parameters in an automatic way. They are suitable for complex systems where developing an accurate physical or statistical model is not feasible.

In some cases, artificial intelligence methods are able to predict failures that would be impossible to detect for humans. In the following Figure, we can see an example of advanced fault detection using a deep convolutional neural network. The turbine presents two distinct faults, a rotor bearing fault at time t2, which causes nearly instant failure, and a helical-stage bearing fault that the neural-network algorithm registers as beginning to appear shortly after the first fault was rectified and the machine restarted at t3, but which results in failure only later, at t4. The shaded regions A and B indicate the corresponding time-windows in which a human expert would diagnose the same faults. We can see how the smart algorithm was able to detect the degradation and predict the fault at a point in time several months before a human expert could have.

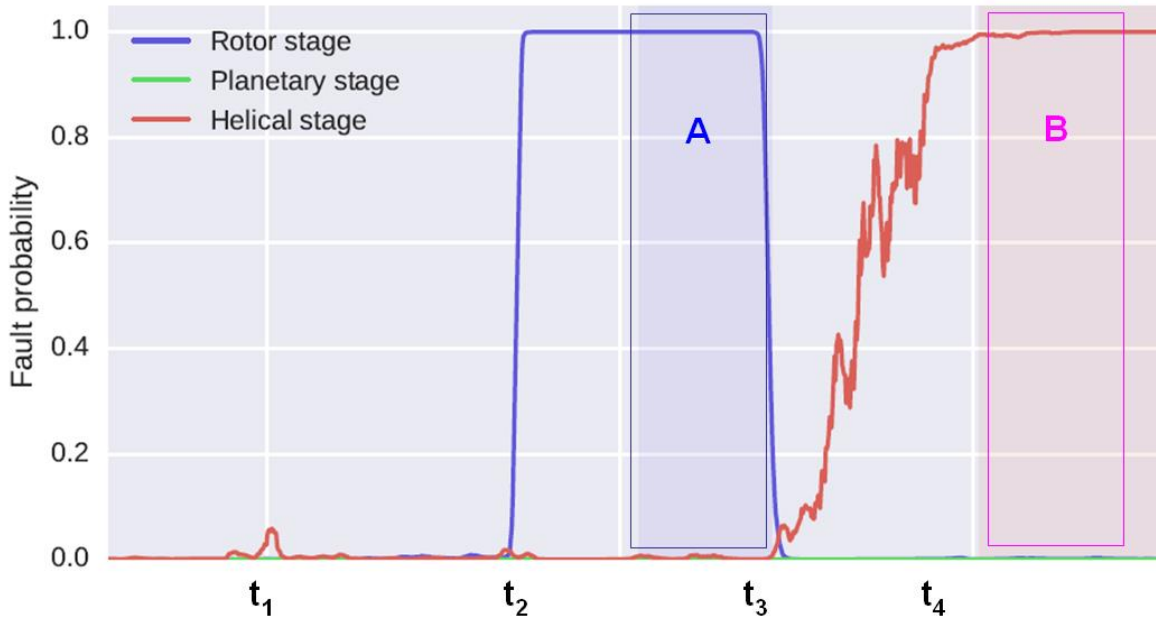


Figure 4.3. Deep convolutional neural network fault probability output as a function of time for a turbine with distinct faults, one rotor bearing fault and one helical stage bearing fault. Adapted from [14].

Techniques described above are characteristic of CBM diagnostic techniques. In prognostic techniques, all described techniques can also be used but the philosophy for failures detection is slightly different. Prognostic techniques rely on the idea of using real time sensors and maintenance is performed only when the component fails or need to be repaired. For that, the condition of the component under study is being continuously monitored and, if the value of the measured parameter exceeds certain threshold (previously defined) an alarm is activated which indicated that repair is necessary. In the following figure we can see de degradation of a bearing temperature by monitoring the temperature residual in time compared to a population of turbines without bearing faults:

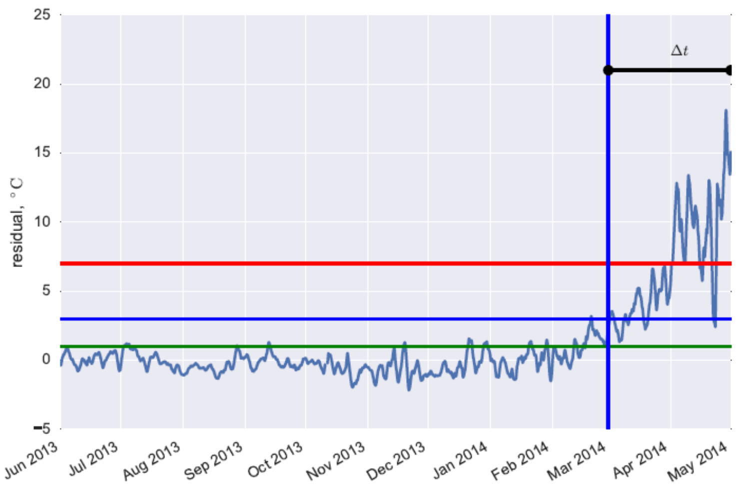


Figure 4.4. Rotor bearing temperature residual plotted for a bearing with a confirmed fault. Source: [14].

The picture above shows three criteria than could be used for alarms definition when monitoring the rotor bearing temperature residual. The three criteria are marked by the green, blue and red horizontal lines. As can be observed, with the green line criteria alarms can occurs even when system is working properly (false positive), instead, if we attend to the criteria given by the red line the fault is not detected until it is too late. In this example can be seen the great importance of having a good criteria when defining alarms and that is something that will be treated in more depth in section 5.5.

4.2.2 Comparative

In this section, a comparison of the maintenance strategies reviewed is made in order to identify when one technique is more appropriate than other. The following table summarizes the pros and cons of each maintenance strategy:

Table 4.3. Maintenance strategies comparative, prepared using data from [12].

Maintenance Strategy	Pros	Cons
Corrective *"Run-to-failure"*	• Machines are not "over maintained" • No condition monitoring related costs	• High risk of secondary failure • High production downtime • Overtime labor • Safety hazardous
Preventive *"Fix it before it breaks"*	• Maintenance is performed in controlled manner • Fewer catastrophic failures • Greater control over stored parts and costs • Unexpected machinery failure should be reduced	• Machines are repaired when there are no faults • There are still "unscheduled" breakdowns
CBM – Diagnosis *"If it isn't broke, don't fix it"*	• Unexpected breakdown is reduced • Parts are ordered when needed • Maintenance is performed when convenient • Equipment life is extended	• High investment cost • Additional skills required
CBM – Prognostic *"Fix it at the right time"*	• Equipment life is extended • Reduced downtime • Reduced overall maintenance costs • Equipment reliability improved • Fewer failures, thus fewer secondary failures	• High investment cost • Additional time invested upfront • Requires a change in philosophy across all management levels.

In the following Table, the maintenance strategies have been combined with the three means of monitoring (Spot, Basic Permanent, and Permanent monitoring) explained in Sec. 4.2. We can see the selection of the most suitable means of monitoring and maintenance strategies.

Table 4.4. CBM and monitoring strategies comparison.

		Maintenance strategies			
		Corrective	**Preventive**	**CBM- Diagnostic**	**CBM- Prognostic**
Monitoring strategies	**SM**	++	+	+	-
	BPM	-	++	+	+
	PM	-	-	++	++

Where:

- "++" denotes that the monitoring strategy is **very suitable** for this maintenance strategy.
- "+" denotes that the monitoring strategy is **suitable** for this maintenance strategy.
- "-" denotes that the monitoring strategy is **non-suitable** for this maintenance strategy.

4.3 Critical elements

In Work Package 1, Deliverable 1.1 established four tidal turbine concepts or categories as a useful classification within the RealTide project. In the following, the main results obtained during the criticality assessment are exposed for each of the four concepts and a selection is made of the components to be monitored. Figure 4.5 shows a summary of the concepts and their characteristics.

Concept 1 - Complex bottom fixed
Horizontal axis
Open rotor
3 blades
Bottom fixed with pile
Pitch control
Yaw mechanism
Gearbox drive

Concept 2 - Simple bottom fixed
Horizontal axis
Open rotor
Multi blade (>3)
Bottom fixed gravity base
No Pitch control
No Yaw mechanism
Direct drive

Concept 3 - Floating multi rotor
Horizontal axis
Open rotor
2 blades
Floating
Pitch control
No active Yaw mechanism
Gearbox drive

Concept 4 - Cross flow turbine
Vertical axis
Close rotor
Multi blade (> 3)
Bottom fixed (gravity or pile)
No pitch
No yaw
Direct drive

Figure 4.5. Generic Tidal Turbine Concepts and features.

Once the four concepts have been identified, they can be subdivided into five levels:

- Sub-systems,
- Assemblies,
- Sub-assemblies,
- Components, and
- Sub-components.

The failure modes and potential effects of failure were defined for each level and concept and their criticality assessed [3] & [2]. After the criticality study, the most critical assemblies and sub-assemblies for each of the concepts could be identified and the results for each concepts are shown in Figure 4.6 at sub-assembly level.

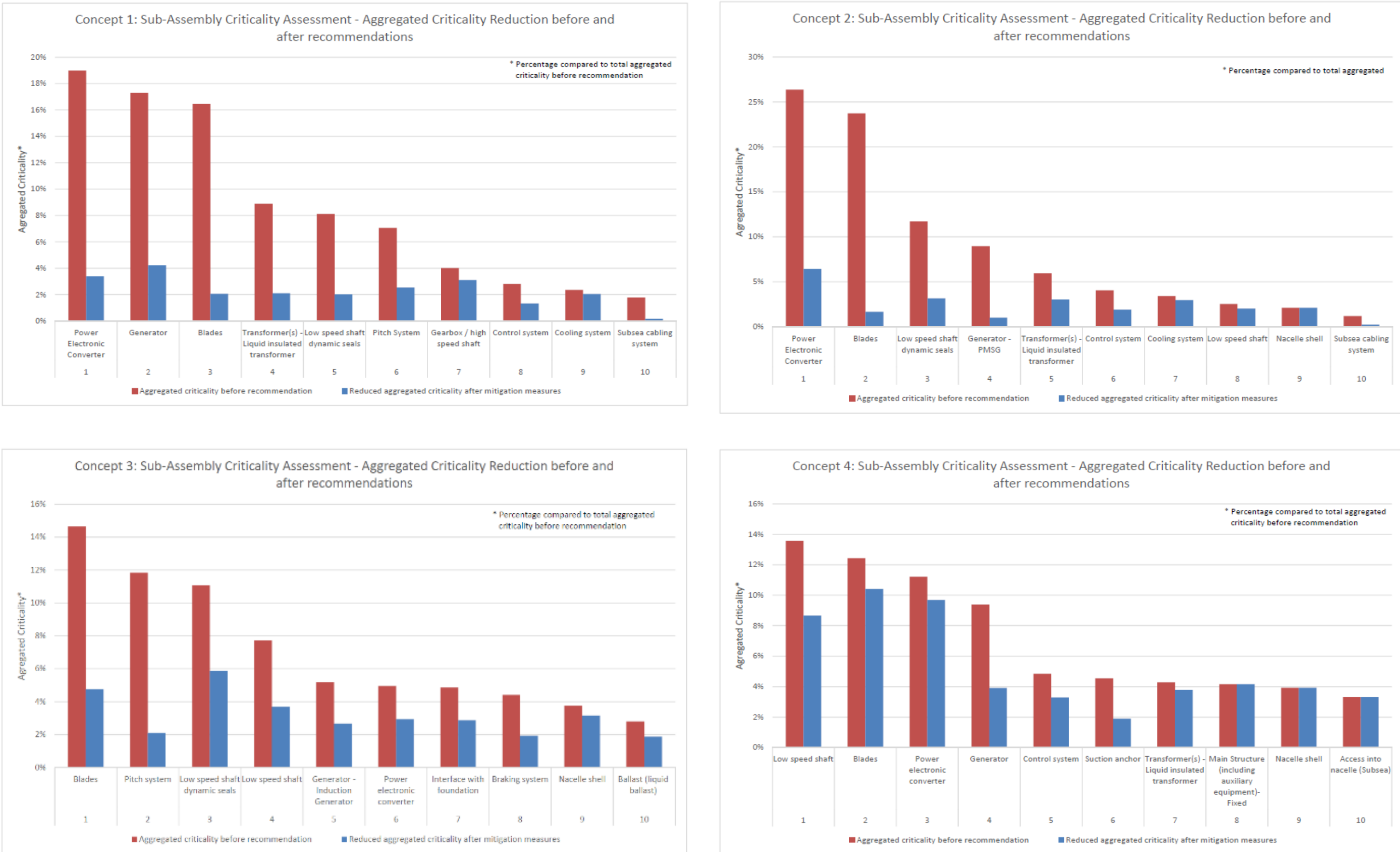


Figure 4.6. Criticality assessment for the four RealTide concepts.

The following Table shows a summary of the most critical assemblies and sub-assemblies that were found during the FMEA and to be integrated in the CMS. Monitoring and CBM strategies are based on the relevant components. (In contrast to wind turbines, the yaw mechanism is not critical for tidal turbines, as it is only used to reverse the assembly at slack tide, operating at low load.)

Table 4.5. Most critical assembly & sub-assembly for CBM as applied to tidal turbines.

Critical Assembly	Critical Sub-Assembly
Electrical System	Power Electronic Converter
	Generator
	Transformer(s)
Drivetrain	Low speed shaft
	Gearbox
Rotor	Blades
	Pitch System

4.3.1 Description of the most critical elements

With reference to a generic tidal turbine (Figure 4.7), an adaptable monitoring system is developed. Most of the sub-assemblies are described using relevant examples from wind turbines.

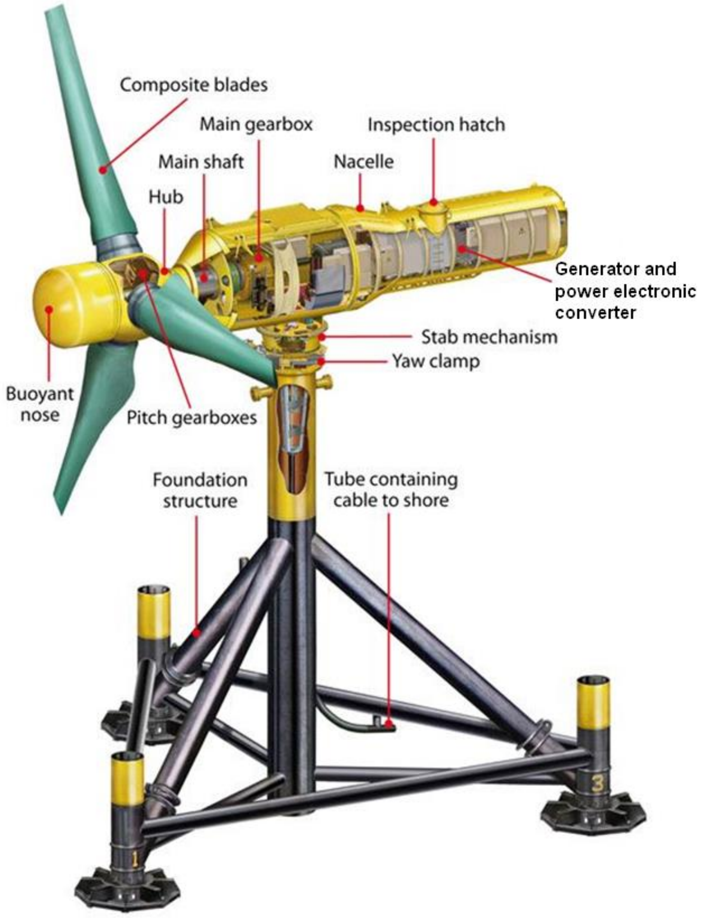


Figure 4.7. Generic tidal turbine of the "complex" RealTide concept category showing sub-assemblies discussed in the following. Adapted from [15].

a. **Blades** are the “prime mover” collecting the energy from the flowing water in a tidal stream. They convert its linear movement to a rotational movement. This energy is transmitted to the hub and from there, usually via a mechanical transmission system to a generator converting the rotational movement (or torque) into electrical energy.

b. The **Blade Pitch System** allows the rotation of the blade around its vertical axis as required by the safety and control system (power generation, start, stop, failures and extreme conditions)**.** The pitch system (motors, gears and bearings) is located between the root of the blade and the hub. The control and safety system drives electric motors until the desired pitch position is reached. The pitch actuator motor drives a pinion through the multiplier. The pinion engages with the pitch crown to position the blade as indicated by the control system. The pitch system consists of:

- An electric motor controlled by the control and safety system.
- A planetary type multiplier usually driven by the electric motor and connected to the multiplier pinion.
- A multiplier pinion that engages with the pitch crown.
- A pitch crown machined directly onto the inside track of the bearing.
- A pitch control box (axial box and batteries).
- An encoder.
- Pitch limit switches.

Modern large turbines, both wind and tidal, have individual blade pitching. Each blade has an independent pitch system, with its own set of emergency batteries. The main braking system is also usually based on the pitch. The existence of independent pitch systems for the three blades, including a stand-alone uninterruptible power supply in each blade, maximizes the safety factor: in case of failure of a system of pitch, the wind turbine is capable of braking.

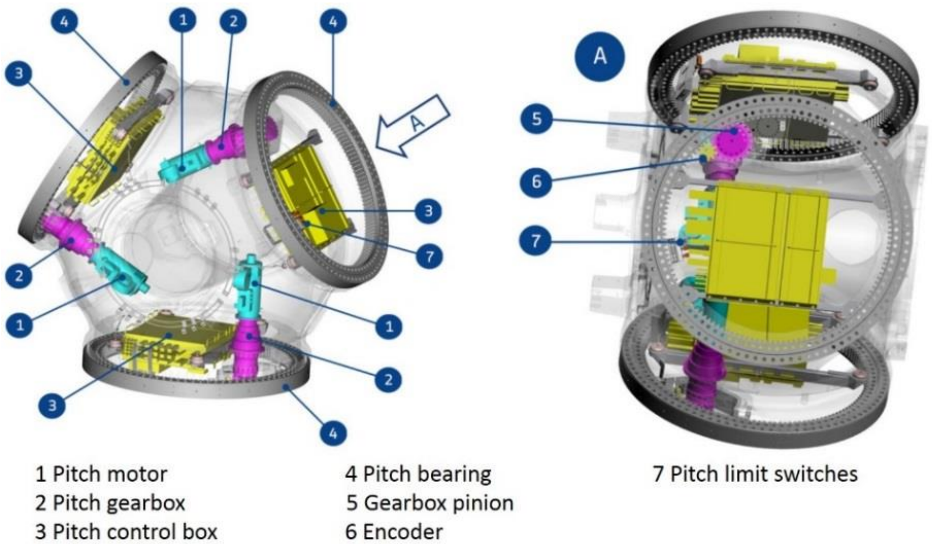


Figure 4.8. Pitch system type. Source: [16].

c. The **Low speed shaft** transmits the rotation to the gearbox (in direct drive systems, to the generator). Normally it is supported by one or two main bearings that should be monitored.

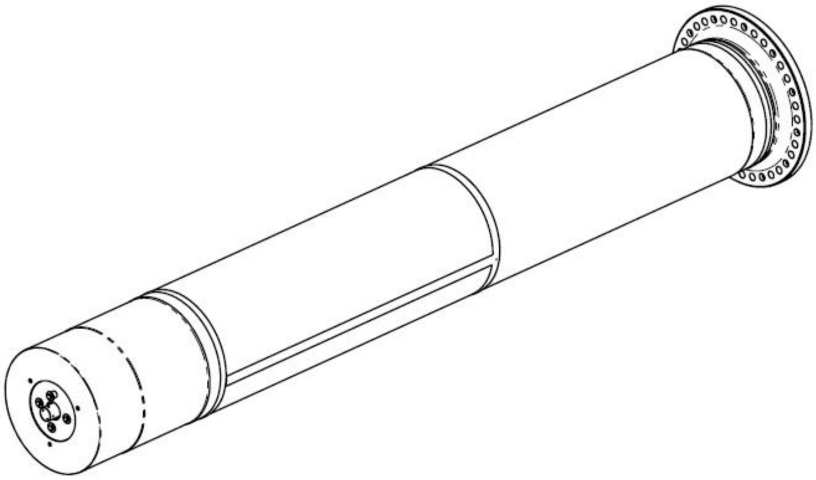
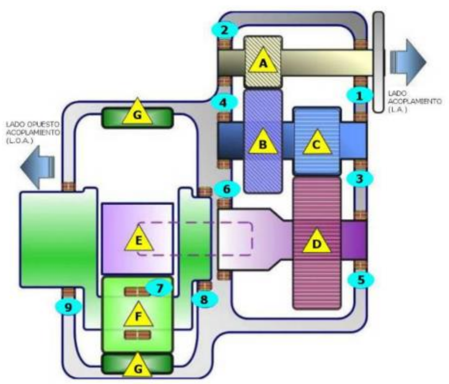


Figure 4.9. Main shaft type. Source: [16].

d. The **Gearbox** contains gears, bearings, shafts, planetary gear, etc. It is used to increase the rotational speed (r.p.m.) to the nominal revolutions of the generator.

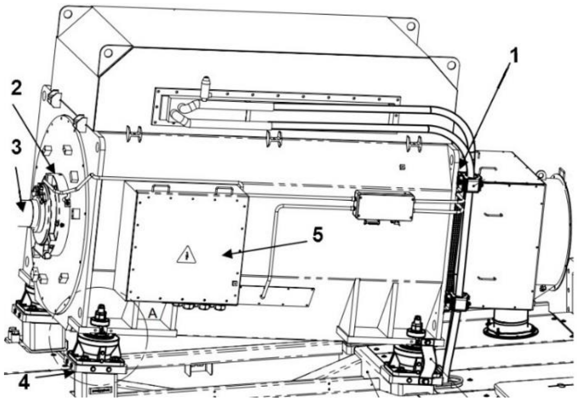


1. Bearing/s fast shaft Coupling side (DE)
2. Fast shaft bearing Opposite side Coupling (NDE)
3. Intermediate shaft bearing Side Coupling (DE)
4. Intermediate shaft bearing Opposite side Coupling (NDE)
5. Bearing slow shaft Side Coupling (DE)
6. Bearing slow shaft Opposite side Coupling (NDE)
7. Satellite Bearings
8. Bearing/s main shaft Side Coupling (DE)
9. Bearing main shaft Opposite side Coupling (NDE)

A. Fast shaft sprocket
B. Intermediate shaft sprocket.
C. Intermediate shaft sprocket
D. Slow shaft sprocket
E. Sun sprocket (main shaft)
F. Satellites (3 units)
G. Planetary Crown

Figure 4.10. Scheme of a gearbox type.

e. The **Generator** is in charge of transforming the mechanical energy into electrical energy.



1. Bearing on the coupling side
2. Bearing on coupling side
3. Rotor shaft
4. Generator Supports
5. Generator connection box

Figure 4.11. Double-powered asynchronous generator. Source: [16].

f. **Power electronic converter.** The power converter serves three main purposes:

- To control the wind turbine so that it can operate in a full range of speeds.
- To adapt the generated power to a suitable waveform to be exported to the grid.
- To enable the wind turbine to ride through voltage dips in a dynamic fashion.

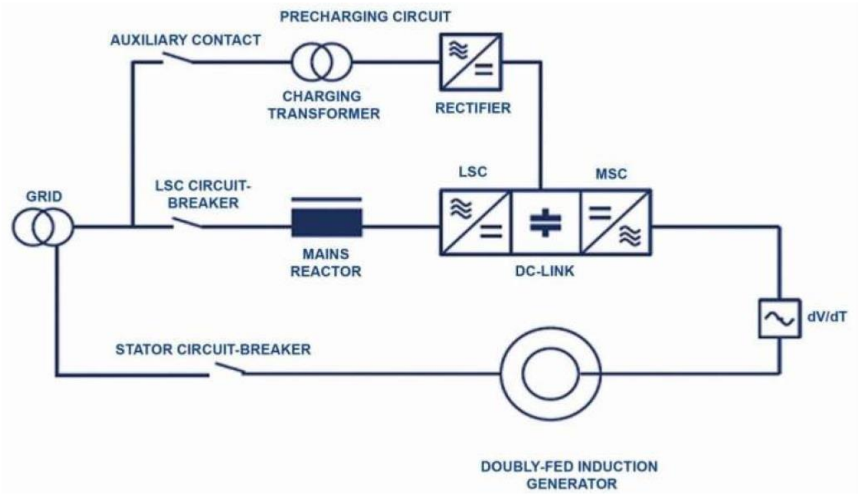


Figure 4.12. Generator converter System. Source: [16].

g. **Transformer.** It increases the generation voltage to the high voltage level of the distribution network, reducing the electrical losses and the heating of the wiring.

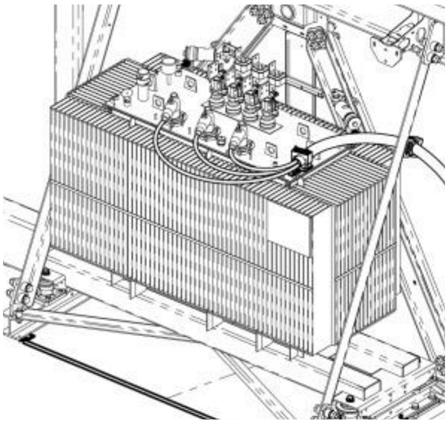


Figure 4.13. Transformer type. Source : [16].

4.4 Monitoring needs

An exhaustive analysis by the RealTide team [3] & [2] produced needs and recommendations to increase the reliability of tidal turbines. In the following, we elaborate on the decisions made in order to adapt them to the particular necessities of a tidal-turbine CMS.

Once we have identified the critical components for each concept, and the monitoring techniques that could be used, it is necessary to focus only in those components and techniques that are more susceptible to be integrated in the CMS. Throughout this section, the monitoring needs are defined as well as the monitoring techniques that are considered as the most appropriate.

4.4.1 Background

The strategies defined in this report build on completed RealTide work, especially the FMEA results in Task 1.1 and the initial monitoring plan in Task 4.1. Figure 4.14 shows a global taxonomy for defining the subsystems and components of a tidal turbine. Figure 4.15 illustrates the methodology followed in the FMEA. Below, this methodology will be described in summarized form.

4.4.1.1 Generic Tidal turbine concepts

The four generic concepts of tidal turbines as described in Figure 4.5 were established drawing on all literature and applying the experience of the RealTide Consortium with the objective of obtaining a better representation of the most commonly used tidal turbines on their way to commercialisation. The guidelines achieved during the study should therefore be easily adaptable to most if not all tidal turbines in the incipient tidal industry. For the four defined concepts, by using similarities with wind turbines and previous studies in the literature, Tidal turbines are divided into various levels of the functional hierarchy.

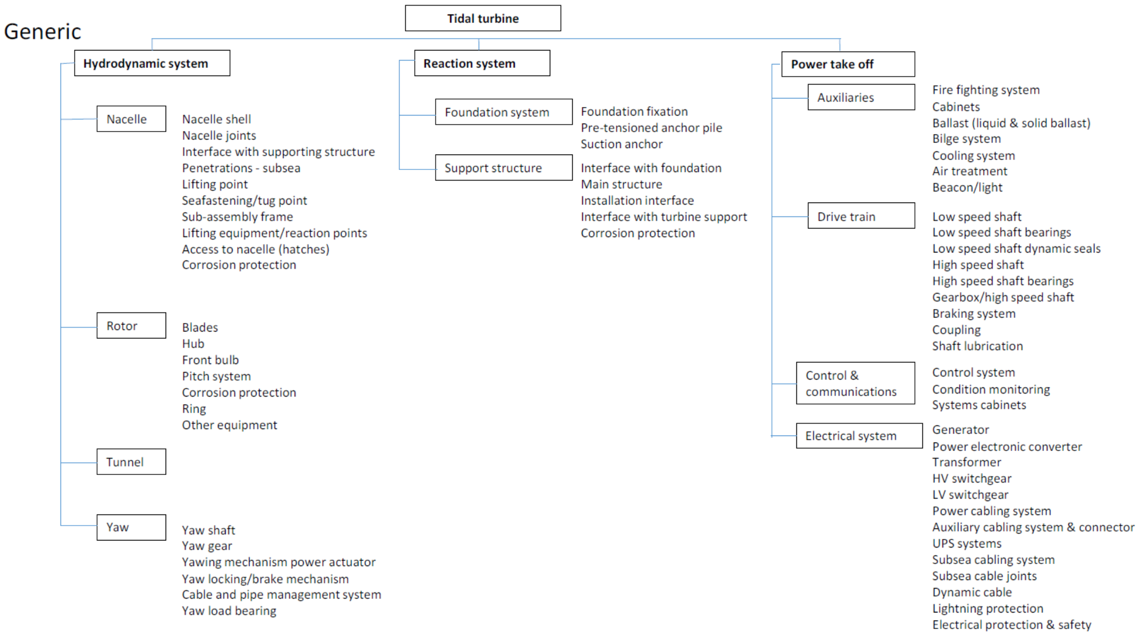


Figure 4.14. Generic Tidal Turbine Taxonomy developed in RealTide, see also Annex.

4.4.1.2 FMEA Methodology

FMEA is a technique applied in the project in order to increase the understanding and reliability of tidal turbines. This is done by recommending actions which could mitigatee or eliminate the critical failures. It was adapted to RealTide's objectives according to the standard IEC 60812:2006 *"Analysis techniques for system reliability — Procedure for failure mode and effects analysis (FMEA)"*.

The methodology illustrated in Figure 4.15 consists of three main parts:

1. **Failure identification:** A number of failure modes has been identified and characterized for each concept. In the characterization the following aspects have been taken into account:
    - Root cause
    - Effect
        - Local effect
        - System effect
        - Production effect
    - Risk reduction measures
        - Design controls generic types
        - In-service monitoring types

2. **Risk assessment:** Based on their criticality the failures modes are classified in "high critical", "medium critical" and "low critical". The methodology used for this classification is the "***R**isk **P**riority **N**umber"* method which allows classification of the failures based on the following aspects:
    - Detectability
    - Occurrence
    - Severity → by three criteria:
        - Economic
        - Environment
        - Health and Safety

3. **<u>Preventive and corrective actions:</u>** Based on the criticality obtained in the risks assessment, it is decided whether or not mitigation actions are needed. The following recommendation levels have been taken into account:
   - Monitoring
   - Redesign
   - Monitoring and redesign

   Apart from these recommendation levels, an aggregated criticality assessment is also carried out in this step. The objective is to take into account the cumulative effect of all failure modes that are susceptible to appear for a certain element. Three methods were proposed:
   - Look-up table
   - Adjusted function
   - Simplified adjusted function

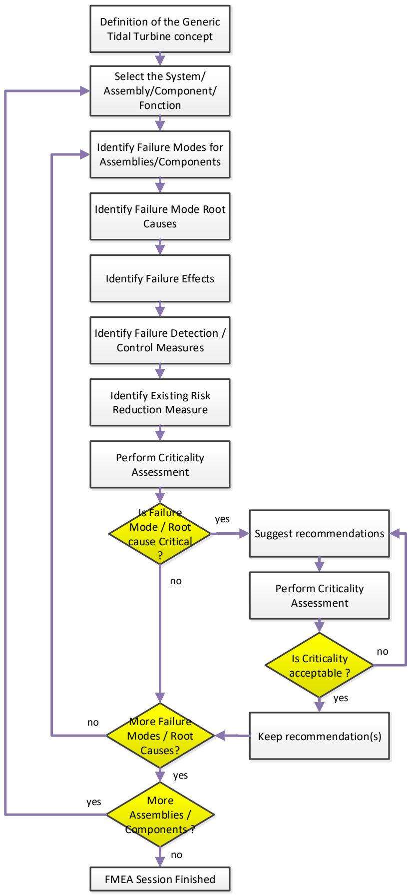


Figure 4.15. Methodology followed in the FMEA. Source: [3] & [2].

4.4.1.3 FMEA results and recommendations

The results of this in-depth analysis establish a total of 243 recommendations for the four concepts, where 137 are recommendations for monitoring and 106 are for redesign. In Table 4.6 is shown an application example of the FMEA. Specifically, this Table shows the procedure followed for selected failure modes related to the blades of Concept 3.

Table 4.6. FMEA: Example of application. Source: [3] & [2].

Sub-system	Assembly	Sub-Assembly	Components	Failure ID	Production effect Category	Detection / Control Measure	Risk Reduction Measure: Design controls	Risk Reduction Measure: In service monitoring	Criticality Assessment: Severity	Occurrence	Detectability	RPN	Crit	SxO	SxD	Recommendation: ¿Actions needed	Maintenance	Monitoring	Redesign
	Nacelle	Nacelle shell		4	3/4	YES	GDP	IVT, IDE	6	6	4	144	High	36	24	Monitoring		IVT, DM, IDE	GDP, DTA
	Nacelle	Interface with supporting structure		14	1	YES	GDP	IVT	5	5	5	125	High	25	25	Redesign & Monitoring		IVT, DM	GDP, RDN
	Rotor	Blades	Blade shell	41	2	YES	GDP, DTA	IVT, IDE	4	7	7	196	High	28	28	Redesign & Monitoring		IVT, IDE, MUID	GDP, DTA, EXP
	Rotor	Blades	Blade shell	42	2	YES	GDP, DTA	IVT, IDE	4	6	6	144	High	24	24	Redesign & Monitoring		IVT, IDE, MUID	GDP, DTA, EXP
	Rotor	Blades	Blade shell	43	2	YES	GDP	IVT, IDE	4	6	6	144	High	24	24	Redesign & Monitoring		IVT, IDE, MUID	GDP, DTA, EXP
	Rotor	Blades	Blade shell	44	3	YES	GDP, DTA	IVT, IDE	5	5	5	125	High	25	25	Redesign & Monitoring		IVT, IDE, MUID	GDP, DTA, EXP
	Rotor	Blades	Blade shell	45	3	YES	GDP, DTA	IVT, IDE	5	6	5	150	High	30	25	Monitoring		IVT, IDE, MUID	GDP, DTA
	Rotor	Blades	Blade structural element	47	3	YES	GDP, DTA	IVT, IDE	5	5	5	125	High	25	25	Redesign & Monitoring		IVT, IDE, MUID	GDP, DTA, EXP
	Rotor	Blades	Blade structural element	49	2	YES	GDP, DTA	IVT, IDE	6	8	5	240	High	48	30	Monitoring		IVT, IDE, MBE	GDP, DTA
	Rotor	Blades	Blade coating	51	2	YES	GDP	IVT, IDE	4	7	5	140	High	28	20	Monitoring		IVT, IDE, MUID	GDP
	Rotor	Blades	Blade coating	52	2	YES	GDP	IVT, IDE	4	9	5	180	High	36	20	Monitoring		IVT, IDE, MBE	GDP

4.4.2 Levels of monitoring

In the FMEA methodology, several techniques were proposed for Risk Reduction Measures, which are the methods or actions currently planned, or already in place, to reduce or eliminate the risk associated with each potential cause of failure identified in the FMEA.

These methods were grouped into two classes: Design controls and in-service monitoring. In this Deliverable we focus on in-service monitoring being more related with the topic of the task. Depending on the type of monitoring performed, five levels of monitoring were defined based on the expected effectiveness, namely:

1. **Inspection visit tools:**

   The monitoring is done by means of direct human actuation or implies human presence in the local area of the system. For example: Divers, dock inspections, ROVs, etc.

2. **Indirect detection. Integrated effect:**

   When using these kind of technique, faults are not detected directly but their consequences for a third system/sub-system. Sometimes it is not possible to obtain the root cause of the failure by using this technique. As an example: An over-temperature in the nacelle indicates that something is not working properly in it, however, this can have many causes, such as the generator, transformer, inverter or cooling system.

3. **Model based estimation**

   As described, this is similar to indirect detection, but in this case, it is possible to find the root cause by correlating several indirect measurements using a proper analytical model. For example: Flow meters in dynamic ballast systems are sometimes used for detecting pump failures. An alternative way to check the pump flow might be by using a model which calculates the time required by the pump to fill a certain water volume (by using level sensors/ switch level sensors) once the pump is working. Comparing the expected time to fill the tank (i.e. the time taken for the pump to reach the highest switch level) with the model-estimated time, one can detect if there exist problems with the pump or with the tank.

4. **Direct measurement – Cause or effect**

   In this case, monitoring is done directly by detecting either the cause or effect of the failure. Example: A broken bearing provoked by shaft imbalance. In this case, failure can be detected by monitoring bearing temperature (effect), or vibrations on the bearing/shaft (cause).

5. **Multiple integrated detection.**

   Direct measurement of possible causes or effects by using both redundant measurements and redundant sensors. For example, monitoring can be done redundantly by using several conventional sensors placed in the same location, or by using a specific redundant sensor with multiple electronic conditioning inside the same encapsulation.

Following this classification, Model Based Estimation is seen to offer a good compromise between economy and effectiveness. It should be noted that this technique can also be used integrated within the level “Multiple integrated detection”, as a way of obtaining redundant measurements. Perhaps the highest potential value of this technique is when used in redundant system for its ability to decrease the cost of monitoring and increase component reliability.

4.4.3 Monitoring technologies

Based on the results of the FMEA, in Task 4.1 a review was made of the state-of-the-art of the most suitable monitoring techniques for tidal turbines. Using as example concept 2, concrete monitoring techniques were defined for each subsystem and a first sensor selection was made. This concept was selected for being the closest to the Sabella machine, for which – being inside the RealTide project – better characterization of the machine. In addition, an initial definition of Model Based Estimation as an alternative to traditional monitoring strategies was suggested. In the following table, techniques identified as the most appropriate for tidal devices are listed (extended from Task 4.1).

Table 4.7. Monitoring techniques proposed (extended from Deliverable 4.1).

Proposed technique	Description
Visual inspection	Monitoring is performed by means of human actuation
Temperature control	Monitoring is performed by reading the change of the temperature
Pressure control	Monitoring is performed by reading the change of the pressure
Tilt measurement	Monitoring is performed by reading the change of the tilting
Torque measurement	Monitoring is performed by reading the change of the torque of the rotation shaft through a set of strain gauges attached to it.
Oil/Debris Analysis	It consists in collecting and analysing oil samples. It can be done offline and online.
Ultrasound Testing (“Classic”)	Detection is done by measuring the reflection produced by a change in the acoustic impedance of the body under analysis
Vibration analysis	It is a technique that looks for changes on the vibration signal of a system.
Acoustic emission	The detection is done by measuring a release of energy, due to the presence of a flaw, in the form of an acoustic emission which propagates through the body. If the propagation occurs in air, and it is in the audible frequency spectrum, this technique is referred to as **sound analysis**.
Thermography	It consists in analysing the images of a thermal pattern of the body.
Long Range Ultrasound Technique (LRUT) and Ultrasonic phase array	The method is to generate acoustic waves that propagate through a body which boundary conditions defines the modes and its velocities of the waves. In phase array, the same principle of classic UT is used but with an organized array of excitation-reception transducers and coordination of signal to concentrate the wave
Current signal analysis	The failure is detected by measuring the change on the current spectra.
Eddy current testing	It consists in analysing the change in the magnetic field which is created by the eddy current created by an alternating magnetic field
Intelligent SCADA analysis	It allows to detect the failure by measuring changes in the monitored variable over long periods

Model based estimation (Power Curve Control)	It allows to detect the failure by comparing the monitored variable with its analogous which has been previously calculated in a model. I.E. Power curve control where Monitoring is performed by comparison between the real and theoretical power curve
Potentiometry	It allows to detect corrosion by an electro-analytical technique allowing measurement of power difference between the monitored element and a reference electrode.
Humidity control	It allows to control the presence of humidity in the environment.

For instance, and considering only established critical assemblies , proposed monitoring techniques and sensors for the rotor and the drivetrain for concept 2 are summarized in the next table:

Table 4.8. Preliminary initial monitoring plan for the rotor and the drivetrain (based on concept 2).

Assembly	Rotor			Drivetrain			
Sub-assembly	**Hub**	**Blades**	**Front bulb**	**Bearing**	**Seals**	**Generator**	**Lubrication system**
Failure mode	• Cracking • Fatigue • Vibration • Corrosion	• Delamination • Cracking • Fatigue • Erosion • Biofouling	• Delamination • Cracking • Erosion • Biofouling	• Fatigue • Cracking • Misalignment • Vibration • Overheating	• Fatigue • Cracking • Particle deposit • Dry running • Poor lubrication	• Isolation loss • Overheating • Vibration • Cracking	• Particle deposit • Overheating • Leaks • Pressure Loss • Loss of oil properties
Monitoring technique	• Vibration analysis • Potentiometry	• LRUT • Visual inspections	• LRUT • Visual inspection	• Vibration analysis • Thermography •Acoustic emission (audible and ultrasound) • Temperature control	• Vibration analysis • Temperature control • Oil/Debris analysis.	• Current signal analysis • Temperature control • Thermography • Power curve control	• Inline analysis of degradation and particles in oil • Temperature control • Pressure control • Intelligent SCADA analysis
Equipment	• CMS (Condition monitoring system) • Potentiometer	• ROV (Remote operated vehicle)	• ROV (Remote operated vehicle)	• CMS (Condition monitoring system) • Thermographic camera • SCADA PLC	• CMS (Condition monitoring system) • SCADA PLC	• MCSA Instrument • Thermographic camera • SCADA PLC	• SCADA PLC
Sensors type (number)	• Accelerometer (2, radial and axial) • Inductive sensor (1, for rpm) • Electrode (2, reference and indicator)	• LRUT transducers (3-6)	• LRUT Transducers (3 - 6)	• Axial accelerometer (3) • Radial accelerometer (3) • Acoustic emission sensor (3). • PT-100 (one for each bearing)	• Axial and radial accelerometers • Contamination sensor module • PT-100 (one for each seal)	• Inductive sensor • Current clamp • PT-100	•Contamination sensor module • PT-100 • Pressure sensors

For the most critical components identified in the FMEA for each concept, appropriate monitoring recommendations were proposed. The following table groups these monitoring recommendations for concept 2 together with the monitoring techniques proposed in the initial monitoring plan, with the objective of unifying both criteria in order to select the most suitable technique/s for the CBM system. The column “Components” refers to the top five critical components identified in the criticality assessment for concept 2 (see Figure 4.6).

Table 4.9. Monitoring recommendations and techniques proposed for concept 2.

Components	Monitoring recommendations (Identified in the FMEA)	Monitoring techniques (proposed in the initial monitoring plan)
Power electronic converter	IDE, MBE	Humidity control, temperature control, thermography, image processing, intelligent SCADA analysis
Blades	IVT, IDE, MUID	LRUT, Visual inspections
Low speed shaft dynamic seals	IDE, DM, MBE	Thermography, vibration analysis, Temperature control, online analysis of oil degradation and particles in oil, power curve control, Eddy current testing, LRUT.
Generator PMSG	DM, IDE	Electrical signal monitoring, thermography, power curve control, vibration analysis, acoustic emission (including sound analysis).
Transformer(s) – Liquid insulated transformer	DM, IDE	Dissolved gas analysis, Online analysis of degradation and particles in oil

4.5 Application to tidal turbines

The next sections develop generic monitoring systems for the most critical components detected:

- Electrical System
- Drivetrain
- Rotor

In the following, the finally proposed **monitoring techniques** to be used in the RealTide project for CBM are described. The proposed techniques have been selected according to the results exposed in Table 4.9 for which a selection of most suitable monitoring techniques for integration into the CBM system has been made. Although techniques are referred to concept two, the final selection made in Table 4.10 is also valid for the other concepts, because application of these techniques to the critical components of all concepts under analysis is very similar. These techniques are being developed in parallel with the ongoing Task 4.2 and will be fully implemented when the monitoring is finished.

Table 4.10. Elements and monitoring strategies defined for being integrated into the CBM system.

Element	Monitoring strategy
Blades	• Model based estimation • LRUT • Extensometry • Acoustic Emissions • Vibration analysis
Drivetrain	• Model based estimation • Current measurement • Vibration analysis

4.5.1 Model Based Estimation

Model Based Estimation (MBE), briefly introduced in Deliverable 4.1, is an alternative to traditional monitoring techniques. A great number of successful applications has demonstrated its efficiency in detection of faults. MBE, being a "virtual monitoring technique", can be used to reduce redundancy of critical sensors or even to eliminate some sensors. Today model-based fault diagnosis techniques are fully integrated in many applications such as vehicle control systems, robots, transport systems, power systems, manufacturing processes, etc.

In a model-based method, the condition of the physical system is represented in a dynamic model. The goal is to reproduce the condition of the physical system in the model and if any mismatch is found between data acquired and the model estimation, the system will act accordingly to achieve a safe state. Figure 4.16 shows a schematic description of a redundant model based parameter estimation applied on a generic tidal turbine. As can be seen, different measurements are collected from the tidal turbine sensors and implemented into two different models. In the model, x_m represent the actual measurement directly or indirectly from the tidal turbine.

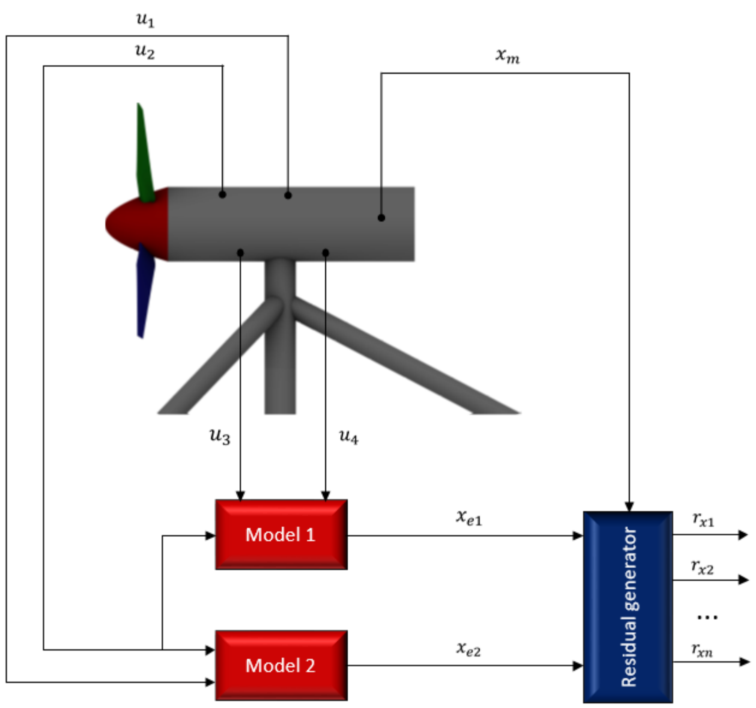


Figure 4.16. Schematic description of the residual generator.

An often applied method to reconstruct x_{m1} is an on-line parallel estimation of input-output relationship, based in a model which describes a certain physical phenomena which allows to estimate x_m analytically. Consider the following nominal model that describes the transfer behaviour of the system or a part of the system under monitoring:

$$x_{e1} = G_{m1}\, u_{n1} \quad \textbf{(Eq. 1)}$$

In this scheme, x_{e1} represents model 1 estimated variable, for which a redundancy will be established, and u_{n1} the model input vector $[u_3, u_4]$ which can be either a measured or model estimated variable. Each model, will estimate the actual measurement (x_m by using different physical principles. In the same way, x_m can also be estimated by using a different model:

$$x_{e2} = G_{m2}\, u_{n2} \qquad \textbf{(Eq. 2)}$$

Where both x_{e1} and x_{e2} are an estimate of x_m and is called analytical or software redundancy. G_{m1} and G_{m2} represent the transfer function for the models 1 and 2 respectively. The output parameters $r_{x1}, r_{x2}, \ldots, r_{xn}$, represent the generated residual after comparing different input signals. These residual can be used later as an estimator in order to check the correct operation of the element under monitoring.

Even though the principle behind this technique promises simple on-line implementation and seems easy to understand, it cannot be implemented in all cases due to the difficulty or even impossibility on generating a precise analytical model for complex processes. For that reason, in order to generate an efficient model, it is necessary to choose the variables involved in it carefully, i.e. they should be easily measurable and comparable to the real device.

This technique will be implemented together with the models generated in WP3, previously adapted, to have estimations of the stresses on the blades. Another application of this technique in RealTide is the detection and characterization of defects in composite materials. In the following, the methodology adopted for these applications is detailed.

4.5.1.1 Application example: Blade stresses estimation

As an application of the MBE concept for the RealTide project, a model for estimation of the stresses along the blade is being made that will allow correlating the stresses obtained on the blade, directly measured by the transducers, with calculated stresses from the BEMT model (finished in task 3.1). The correlation of both sets of stresses values will allow to predict any deviations in the acquisition signal. In the following subsections, descriptions and current development status of each module in Figure 4.17 will be presented.

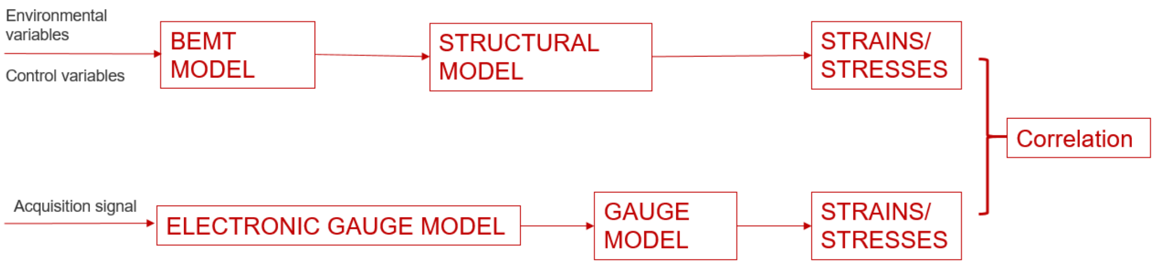


Figure 4.17. Strategy for implementation of MBE in the blade monitoring.

<u>BEMT model</u>

This model was developed in Deliverable 3.1 (see [17]). It was implemented in python and allows the calculation of forces (axial and shear) and bending moments along the blade given a certain set of initial conditions. In the following picture, the general working scheme of the BEMT tool developed during this task is shown.

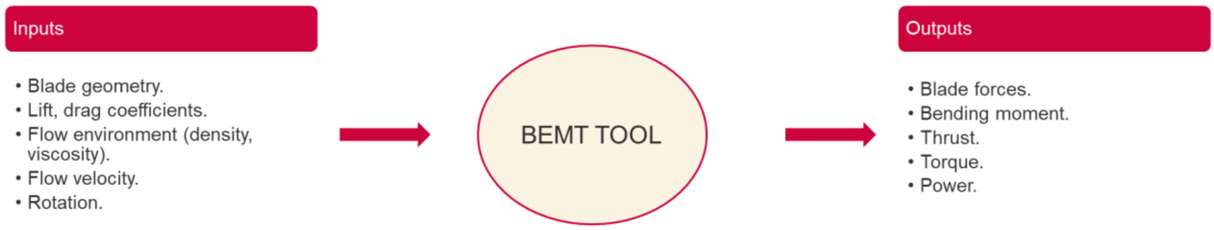


Figure 4.18. BEMT tool calculation scheme. Source: [17].

Figure 4.19 below shows the distribution of forces (axial and shear) obtained by the BEMT tool a generic tidal blade. The blade is considered as a cantilever beam, fixed at its root, and subjected to this force distribution. Thus the shear force and bending moment at any point along the length of the blade can be found.

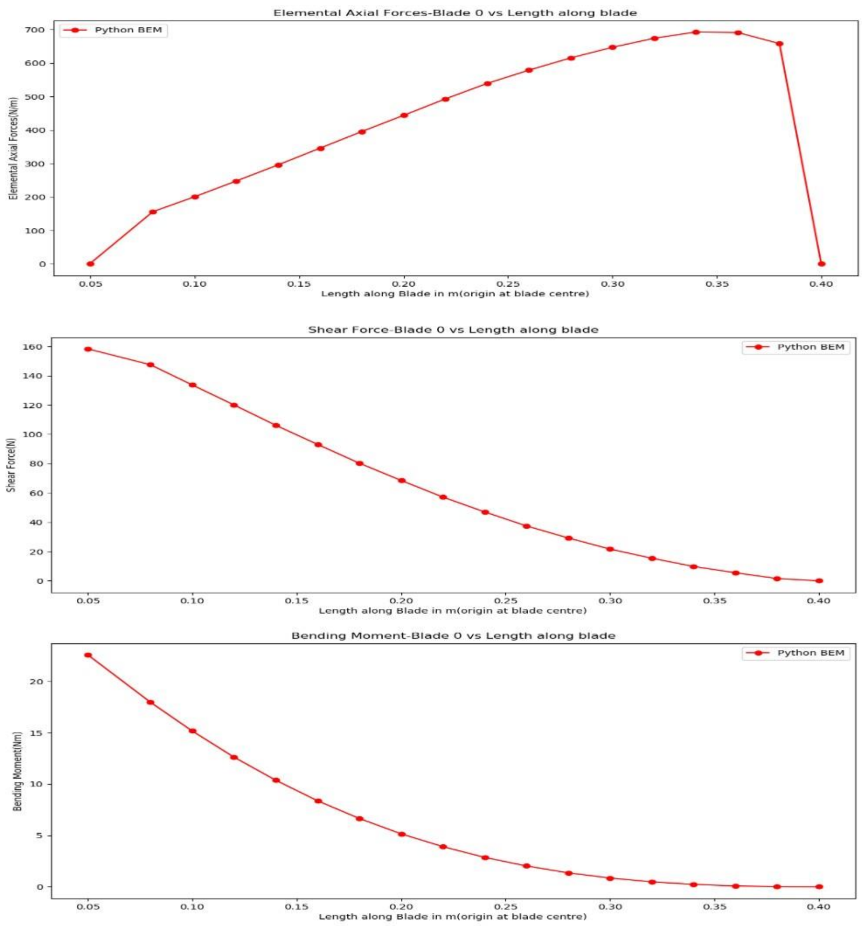


Figure 4.19. Distribution of forces, shear force and bending moment along blade length. Source: [17].

<u>Structural model</u>

It constitutes an adaptation or complement of the BEMT model for stresses calculation based on the forces and bending moment that are obtained from it. It could be based in both analytical methods that are based on a redefinition of the BEMT code implementing the stresses calculation or in a Finite Element Analysis (FEA). In the latter case, forces and bending moments obtained under the analysed conditions are implemented in a FEM blade model and used to obtain the stress values. This method is costly to implement but more precise, however, BEMT appears as a more suitable strategy for real-time monitoring. In [18], we can see a practical example where the BEMT methodology is applied.

General gauge model

The "Electronic gauge model" block is also implicit in this description. The general gauge model is dedicated in obtaining the measured strains and/or stresses by measuring the variation of resistance of the gauge. In the following picture a simplified scheme of this process is show.

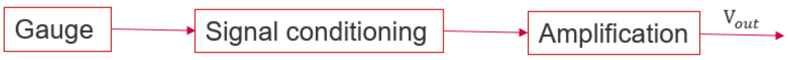


Figure 4.20. Scheme of the gauge model.

4.5.2 Long Range Ultrasound Testing (LRUT)

Long Range Ultrasound Testing (LRUT) uses the generation and reception of ultrasonic guided waves for monitoring the integrity of the monitored volume (see [19] & [20]). The original use of this technique was in pipes and structural tubular profiles mainly in the Oil & Gas industry.

Using several piezoelectric transductor rings, it is possible to generate symmetrical guided waves. In pipelines with a circumferential weld for example, reflected waves will be symmetrical whilst in the presence of corroded points and cracks they will be asymmetrical. Detection of defects in a material using ultrasonic waves usually is because the propagated ultrasonic wave interacts with a different acoustic impedance boundary at the fault. This will cause the propagated wave to reflect back. This reflection not only gives information about the presence of a defect in the test piece, but also about its location and, in some cases, its nature. The location of a defect is determined by the time of flight used in the pulse echo technique. This is usually done by transmitting and receiving the ultrasonic wave from the same location (i.e. the same probe). The travelling velocity of the ultrasonic wave can be derived from the materials properties of the test piece and the time for the signal to travel forward and bounce back is monitored. Figure 4.21 shows the principle of this technique.

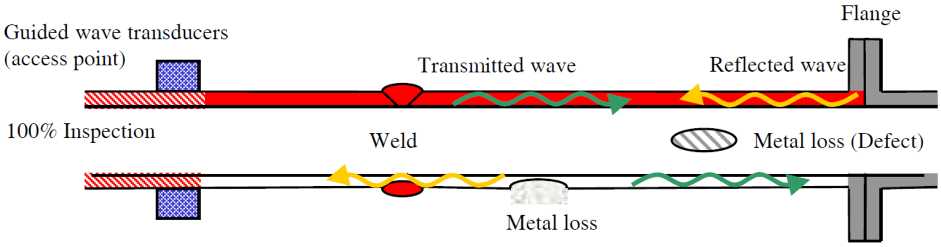


Figure 4.21. Schematic diagram of Long Range Ultrasonic Test. Source: [21].

This technology has reached a high level of maturity in the Oil & Gas industry and has been applied to other fields such as composite material in offshore turbines. LRUT can be used to detect flaws such as delaminations, bond failures, or cracks that might be found in these type of materials. In Figure 4.22 an example of possible flaws that may be detected in a tidal turbine blade is presented:

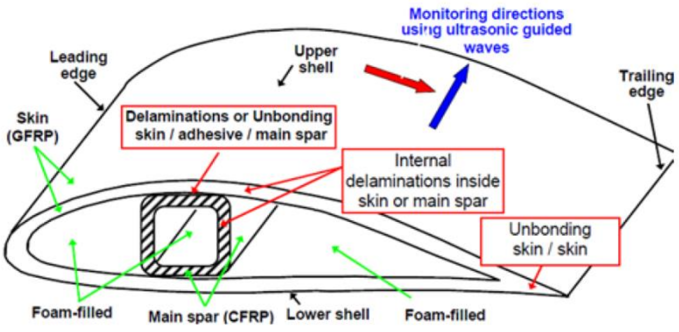


Figure 4.22. Cut view of a tidal turbine. Flaws and possible guided waves propagation. Source: [19].

At least two sensors are necessary: One to emit the signal and another one to receive it. Nevertheless, the use of 4 or more sensors are commonly employed in order to improve the detection of the defect using triangulation.

In the following figure, two ultrasonic signals are presented, with and without defect, red and blue respectively. As can be appreciated, the fundamental mode of propagation is affected.

Guided waves propagation depends very little on some composites parameters such as: structure, geometry, layer orientation, material, etc. As a result, even small structural changes may lead to measurable changes in the guided waves propagation parameters, thus, technical inspection should be developed and tested in areas as close as possible of the structure.

On the positive side, high sensitivity means that low damage levels can be detected, and can be used even for identifying manufacturing deviations.

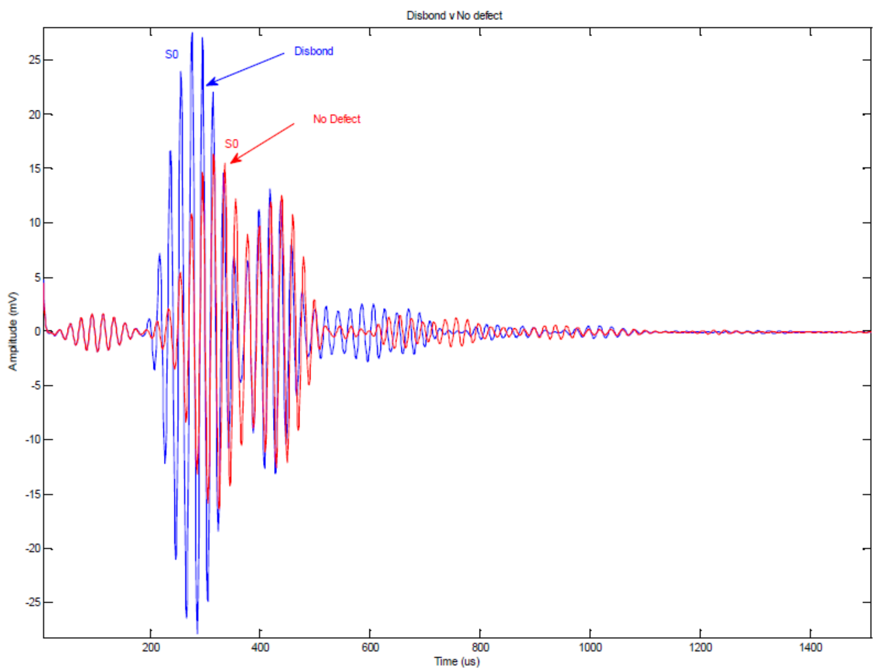


Figure 4.23. Ultrasound signal comparation, with and without defect. Source: [22].

4.5.2.1 Application example: Failure detection and characterization in composites

In this case, the objective is to develop a methodology that allows detection and characterization of flaws of different nature. For this purpose, in RealTide four specimens (fiber glass plates) have been instrumented and tested using the LRUT method as described above. In the following picture we can see the arrangement chosen for the tests:

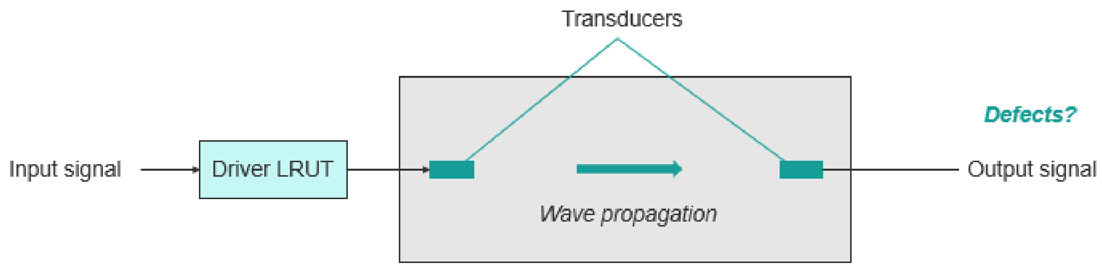


Figure 4.24. Plate tests set-up.

As can be seen, the plates have been instrumented with two piezoelectric transducers and installed on the plates in opposite sides. Three different flaws have been reproduced in three different plates, and the remaining one has been tested without the presence of any flaw with the objective of using it as reference. Test conditions have been carefully chosen in order to ensure that the result will not be affected by external factors:

- Flaws have been created carefully in a CNC milling machine.
- The size of the plates is the same and transducers have been carefully placed according to EnerOcean internal protocol to ensure that there is no distance deviations between a plate and another.
- Four silentblocks have been installed in the plates acting as support in order to avoid the transmission of external excitation coming from the work table or the floor. The holes for the support allocation have been also performed carefully and using a CNC milling machine.

The objective of these tests is to characterize the change of the signal under the presence of a known flaw. By comparing the signal acquired on the three plates with the plate without flaws, system must be able to detect whether or not there is a flaw and its nature.

In the next table the defect sizes on the plates are summarized:

Table 4.11. Defect sizes on the plates.

Plate ID	Defect	Number of holes
1	No defect	-
2	Single hole	1
3	Multiple holes	3
4	Groove	-

The following picture shows the acquired signal using this frequency in different plates:

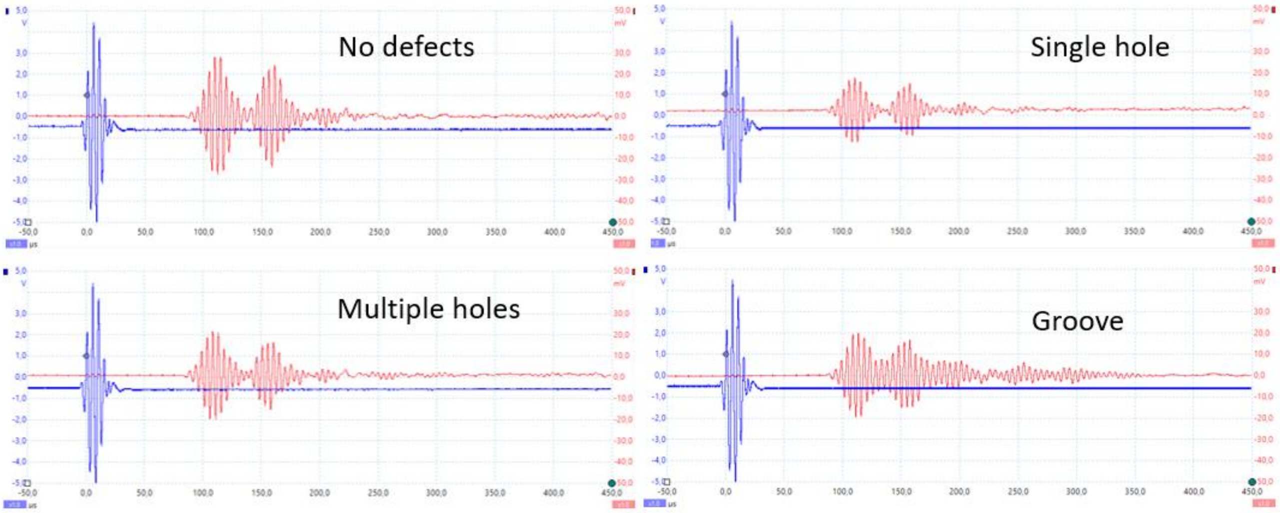


Figure 4.25. LRUT acquired signal.

As can be observed, the transition between echoes is quite smooth. Comparing the results of the plate 2 and 3, a greater distortion can be observed between echoes in plate 3. Regarding plate 4, the distortion between echoes is greater in this case and some reflection can be appreciated. This is due to the shape and size of the groove.

4.5.3 Extensometry

Extensometry concerns the measurement of changes in length and as such is helpful when applied to stress-strain measurements and gauges as well as other health condition monitoring systems.

Strain gauges offer a simple, economical and highly sensitive method for monitoring strain and therefore the stress applied to a material, assuming the Young's modulus is known and the strain gauge is correctly calibrated. Strain gauges offer a number of opportunities for the structural health monitoring of marine energy machines. In addition, strain gauge outputs can be used in verifying numerical models that predict the performance and loading at key areas of a device.

Strain gauges work by monitoring a change in electrical resistance of the gauge as it deforms with a deforming material on which they are stucked. This change in electrical resistance is related to the material's strain by the gauge factor.

Due to their sensitivity and nature, strain gauges are not particularly robust, and if not well protected they can only be relied upon for long term monitoring in harsh marine environments if a proper en-capsulation and protection system for the gauge and its cabling is designed. Although they are simple devices, it is important to consider their positioning carefully. Due to their vulnerability, access is important, as is their location in verifying design work (e.g. finite element models). Temperature is also a consideration, as it can have significant effect on the performance of the gauge.

In [23], a relevant methodology was applied for strain measurements on a wind blade by using strain gauges. The blade was instrumented along its length and was tested under a cyclical flapwise load. For every 0.2 m, strain was measured at four locations as shown in the following figure:

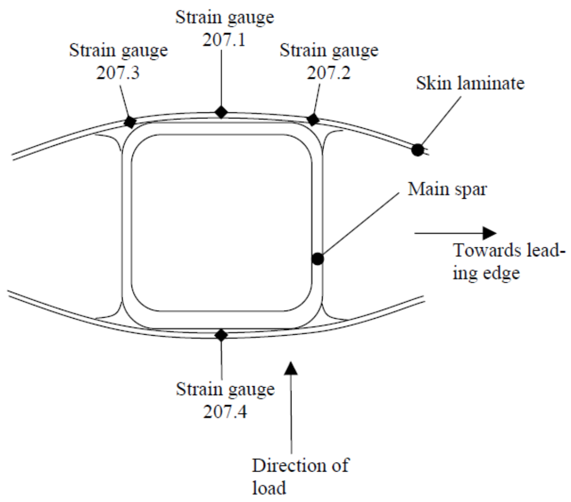


Figure 4.26. Location of strain gauges, example for a section 20.7 m from the root section. Source: [23].

In the next figure we can see the strain measurements, in normal conditions, obtained by the four strain gauges in a section given at 20.7 m from the root. The strain values were normalized (divided by the same number) for confidentiality reasons.

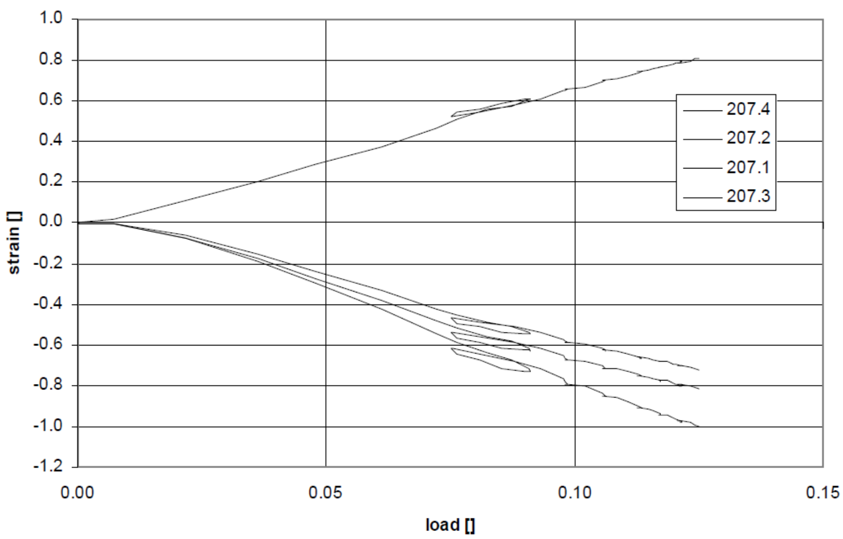


Figure 4.27. Strain gauge measurement during test of section 1, at 20.7 m from root section. Source: [23].

In the test, the blade is partially unloaded from a level of approximately 0.09 to 0.07 and then loaded up again resulting in the small loops. During the tests, the blade failed at 4.4 m from the root (close to the largest chord). In the following picture we can see the obtained stresses around this area:

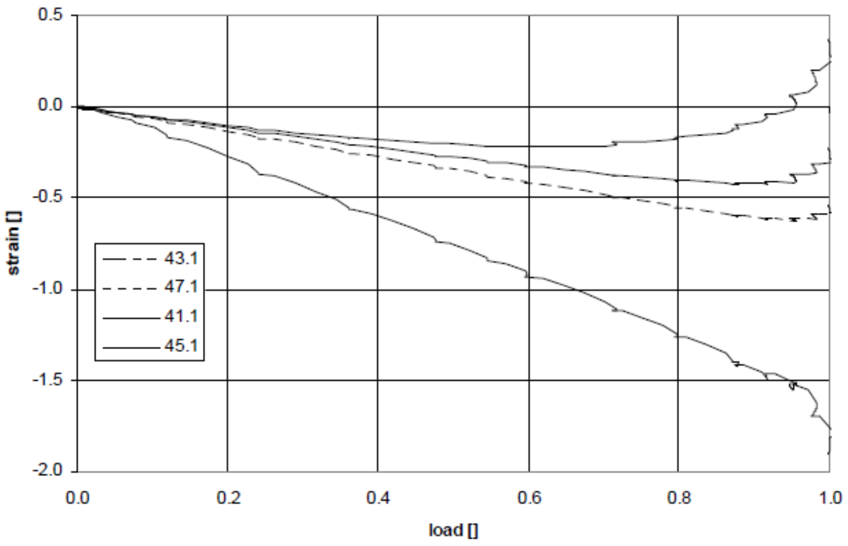


Figure 4.28. Measured strain on four locations during test of section 3, showing non-linear behaviour. Source: [23].

As can be appreciated, the strain is seen to be non-linear, especially for strain gauge "45.1" which is close to the location where the blade finally failed.

4.5.4 Acoustic Emission (AE)

Acoustic Emission (AE) is a wave generated by the rapid release of energy within a material when an 'event' occurs, typically the extension of a crack. By detecting these emissions, AE equipment can identify, locate and monitor defects (Figure 4.29). Various parameters are used in AE to identify the nature of the source, including: count, duration, amplitude, rise-time, energy, frequency and RMS (Root Mean Square).

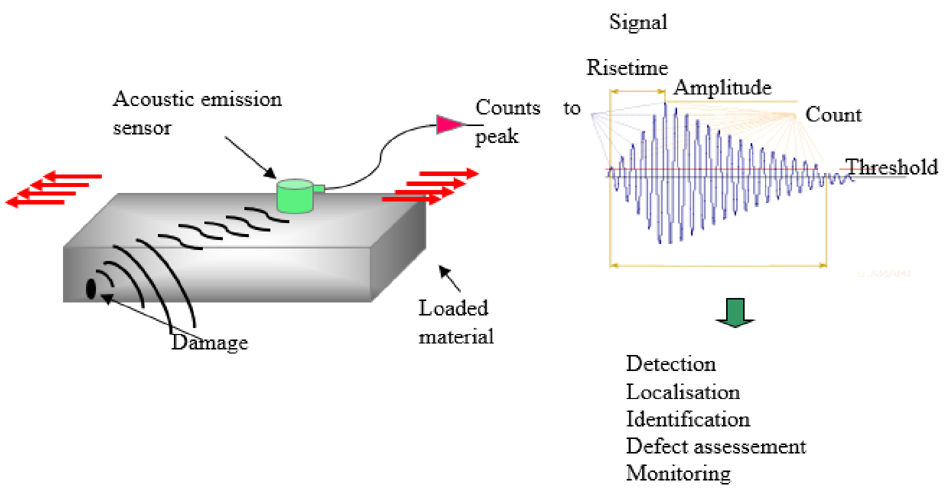


Figure 4.29. Principle of the acoustic emission technique. Source: [22].

AE is in the ultrasonic regime, typically within the range 100 kHz to 1 MHz. Acoustic emissions can be monitored and detected in frequency ranges under 1 kHz and have been reported up to 100 MHz. Rapid stress-releasing events generate a spectrum of stress waves starting at 0 Hz and typically falling off at several MHz, but one strength of the technique is that background noise, particularly airborne, falls off more quickly, so the signal-to-noise ratio reaches an optimum value around the conventional frequency range. A commonly accepted definition for AE is a transient elastic waves within a material due to localized stress release. Hence, a source which generates one AE event is the phenomenon which releases elastic energy into the material, which then propagates as an elastic wave. AE events can also come quite rapidly when materials begin to fail, in which case AE activity rates are studied as opposed to individual events. AE events that are commonly studied include the extension of a fatigue crack, or fibre breakage in a composite material among material failure processes. AE is related to an irreversible release of energy, and can be generated from sources not involving material failure including friction, cavitation and impact. Transducers are attached to the material to detect these waves. Most of these sensors are in the frequency range of 20 kHz to 650 kHz. Some geophysical studies with AE use much lower frequency sensors, while sensors in the MHz range are also available commercially. A major limitation of acoustic emission technique is defect sizing.

When a component is stressed, this non-destructive technique can provide a great deal of information about the presence or otherwise of defects. Sensitive to plastic deformation and phase transformation, AE can provide information on the formation and progress of a crack. In metals, it can detect growing weld defects, corrosion (general, localized or pitting), friction, mechanical impact and leaks and can be used to detect defects in service.

AE is now a well proven technology for steel structures and is used for monitoring nuclear vessels, oil storage tanks, etc. One of the most common materials used in the construction of large wind turbine blades is glass-fibre reinforced plastics (FRP). The mechanisms that cause acoustic emission events in FRP monitoring include the following:

Fibre cracking

Fibre interfacial debonding

Fibre / plastic deformation

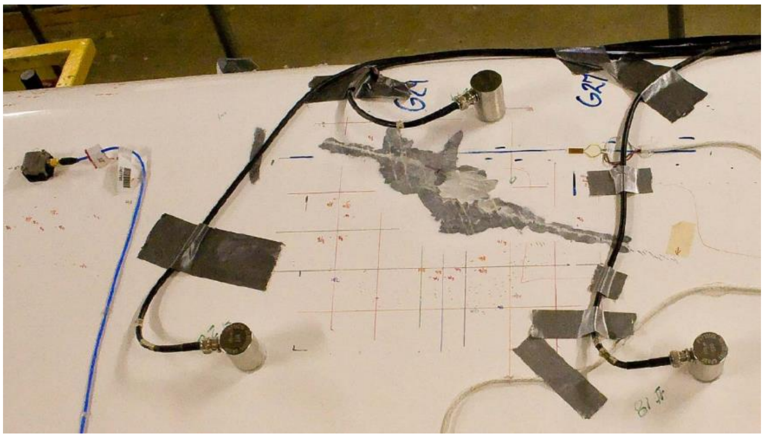
Matrix plastic deformation and cracking

Interlaminar debonding

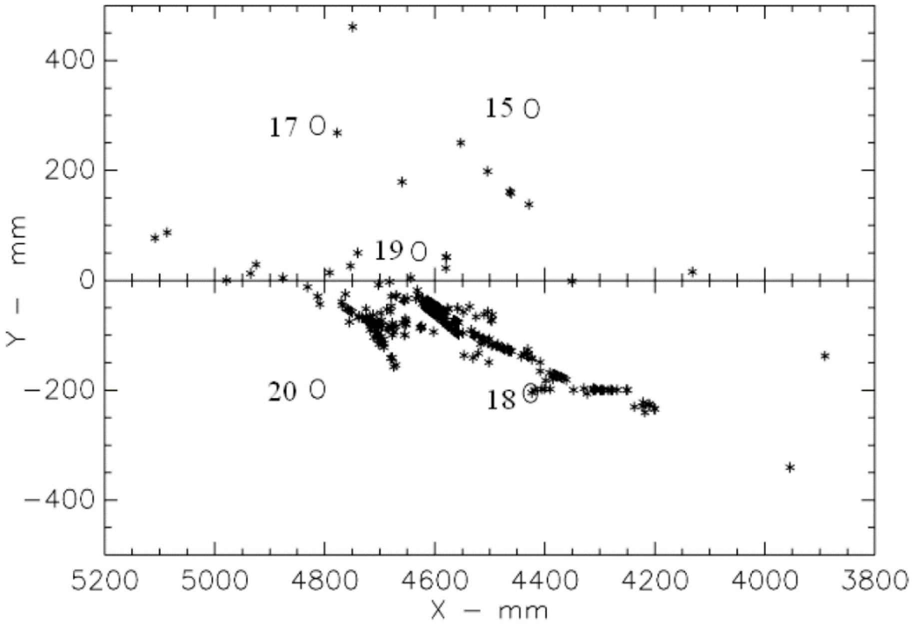
Chafing of fibre against the matrix

The two most significant failure mechanisms in a tidal turbine blade are cracking in the bond between two pieces of the structure, such as the joint between a spar and the skin, and tears in the skin or spar. Both involve the progressive fracture of many fibres. At laboratory scale, AE has been very successful at detecting all of these failure mechanisms and sometimes at identifying them from amplitude analysis of the AE signals. However, in large structures, the high acoustic attenuation in FRP precludes amplitude analysis unless the origin of the individual signals can be identified and corrections for the distances travelled can be applied to the signal amplitude.

The usual method of testing FRP structures has been to use an array of sensors spaced so that a moderate amplitude AE signal occurring midway between them will just barely trigger each sensor. One then looks at broad areas of damage defined as the area within the range of each individual sensor. In the following picture, we can see a real example in which this technique was successfully implemented for detection of a crack on a blade after 2000 kcycles. As can be seen, the presence and location of the crack were detected in an accurate way.



(a)- Picture of surface crack on tension side of blade around 2000 kcycles.



(b)- Final source location of same area of blade around 2000 kcycles.

Figure 4.30. Application of AE technique to blade defects detection. Source: [24].

4.5.5 Vibration analysis

Vibration analysis is a technique that looks for changes on signature vibration of a system. The vibration of a system in motion is characterized by the frequency and amplitude of the motion. Any modification on these parameters can be the sign of a defect or changes of the base operation conditions. It is widely used in rotatory assemblies for its characterization and monitoring. The methodology can be divided into four principal domains:

- Time domain. Based on the signal as received with basic signal processing.

- Frequency domain. Based on the Fast Furrier Transform applied to the time domain signal what provides extra information in terms of the energy distribution at each frequency.
- Joint domain (time/frequency domain). Based in a combination of the two previous techniques.
- Modal analysis. This is based in a complex analysis of the modes of vibration to determine the origin of the defect.

The most extended method for vibration detection and analysis is through accelerometers attached to the point locations to be controlled. As it was already exposed in deliverable 4.1, vibration analysis is applied mostly in the following assemblies: shaft, bearings and gearbox. In the following, we expose some of the most common failures that may appear in these assemblies which can be detected by vibration analysis.

4.5.5.1 Shaft

It is the element in charge of transmitting the rotation produced by the rotor to the gearbox (in systems without gearbox the transmission will be direct to the generator). Normally it is supported by one or two main bearings that are also monitored (see Figure 4.9).

Some of the failures that are susceptible to appear in the shaft are:

Unbalance. A rotating machine is unbalanced when the centre of gravity of the rotor does not coincide with its centre of rotation.

Misalignment Occurs when there is a deviation of the geometrical shafts of two coupled shafts.

Eccentricity Occurs when the centre of rotation and the geometric centre do not coincide.

Bent shaft. It is produced by the permanent curvature of the axis (without taking into account the flexion by one's own weight).

4.5.5.2 Gearbox

It is composed of gears, bearings, shafts, planetary gear, etc. It is responsible, depending on its ratio, to raise the revolutions of the fast shaft to the nominal revolutions of the generator.

Some defects that are typically found in gears are:

Misaligned gears: Occurs when there is a deviation in the movement of gears. Misalignments can be parallel or angular in reference to the plane of action.

Tooth wear: It provokes a bad engagement of the gears due to a bad tooth profile.

Inadequate tooth geometry: The effect is similar to tooth wear. Normally due to manufacturing errors.

Broken tooth: The appearance of a broken tooth can be detected by measuring the separation of the lateral bands provoked by the failure. The separation of these bands corresponds to the frequency of rotation.

Appearance of phantom frequencies: Normally due to machining error.

4.5.5.3 Bearings

The information exposed here is valid for any bearing of the tidal turbine assembly. Vibration caused by impacts between rolling elements and imperfections in the raceways cause impact waves, high frequency and small amplitude, are better detected with the vibration acceleration measure. Next list shows the typical problems that can be normally found in bearings:

Wear: The material is gradually removed due to frictions between parts.

Race damage: Deformed races cause a vibration than can be detected by vibration analysis.

Lubrication problems: They can be due to excessive or insufficient lubricant.

Incorrect mounting: Some of the most common problems of incorrect mounting are: outer race deformed or concave support, inner race deformed and skewed installation.

4.5.5.4 Blades

The approach with vibration analysis of oscillating structures is to identify changes in the oscillation behaviour of the blade. Damages in the inner structure will lead to reduced stiffness. This in consequence will shift natural frequencies to lower values. Therefore, the natural frequencies need to be monitored and a trend analysis of the frequency values have to be performed.

The shift of natural frequency is also influenced by several external parameters, e.g. the pre-tension of the material and/or the stiffness of material depending on the environmental temperature. The following Figure 4.31 and Figure 4.32 show an example of a 2.5MW wind turbine blade. The mentioned influences (and possible others) need to be considered when performing the natural frequency trend analysis.

Figure 4.31 shows the amplitude of 1st blade bending mode of a wind turbine's rotor blade vs. power output of wind turbine (red: scatter data, green: trend line). According to the higher pretension of the blade, the natural frequency is shifted to higher values.

Figure 4.32 shows the amplitude of the 1st blade bending mode vs. environmental temperature (red: scatter data, green: trend line of amplitude; cyan: scatter data, blue trend line of temperature). The data show an inverse correlation, since higher temperatures cause a decrease in the stiffness of the material. Only data points are selected for the evaluation, where the wind turbine power output was around 1MW.

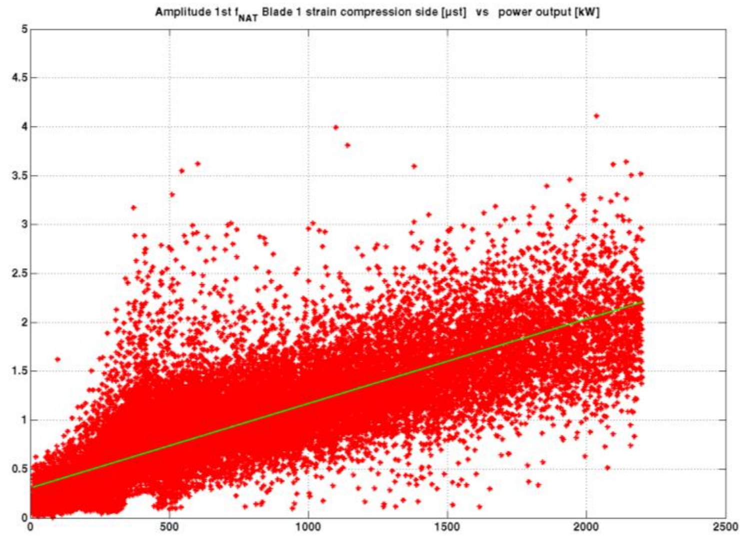


Figure 4.31. Amplitude of 1st natural frequency (fNAT) of one generic tidal blade in compression side strain signal vs. power output (kW). Source: [22].

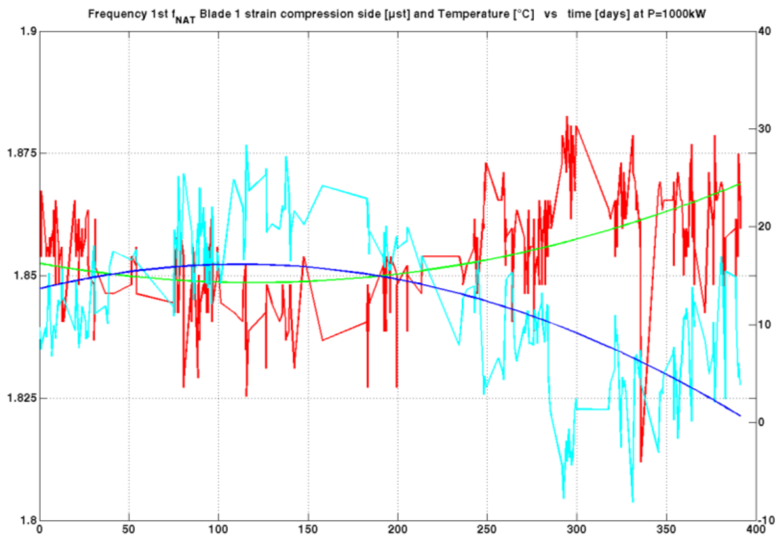


Figure 4.32. Trend plot of 1st fNAT Frequency and temperature of one generic blade. Strain in compression side vs. time at P=1 MW. Source: [22].

4.5.6 Current measurement monitoring

For electrical condition based diagnosis, mainly oriented to the turbine generator, the measurement points will be as follows:

- Output current for each of the phases of the generator stator.
- Input/output current for each of the phases of the generator rotor.
- Input current to the grid side converter (optional). It is possible to read current in the grid side converter, at its input. Split-Core probes would also be installed for each phase.
- Generated voltage and mains (optional). Read directly from the magneto-thermal of the converter cabinet.

- Temperature and humidity inside the converter.

In the following, the most characteristic faults that can be detected by using this technique will be mentioned and will be described in the forthcoming deliverable D4.2.

Electrical faults

- Faults in the stator.

Mechanical faults

- Misalignments
- Bearing failures
- Gear failures
- Eccentricities: static and dynamic

4.6 Monitoring plan for tidal devices

In Table 4.8 above, a typical monitoring system that can be applied for the tidal turbine concept 2 was shown. Based on the FMEA developed in D1.1 [3] & [2], the fault modes were defined for each sub-assembly and in D4.1 [25] the monitoring techniques for each of these fault modes were established and the necessary equipment and sensors introduced.

In this section, a more detailed description of all the characteristics and specifications that the drive train and blade monitoring systems must meet has been made. This is applicable to the four tidal turbine concepts that are the object of study in this project. In continuing work, a final monitoring plan and specific characteristics will be described and is part of Deliverable 4.2.

It is evident that the configuration and installation of the equipment and sensors for each tidal turbine concept will be conditioned by the design (space, accessibility...) and the type/model of components (bearings, gears, power equipment...), as well as by the design and concept of each turbine itself. Thus, for the final configuration of the systems, it is advisable to take into account the following points:

- The main shaft monitoring must be done with low frequency accelerometers; this means that for tidal turbines without gearbox (direct drive) all vibration sensors must be of this type.
- For the spectral analysis of the vibration signals in floating tidal turbines, the natural frequencies of the waves in their location must be taken into account.

4.6.1 Generic monitoring system for drivetrain

In Figure 4.33, a general scheme is shown of the complete drivetrain monitoring system. It details and describes the equipment and sensors that compose it:

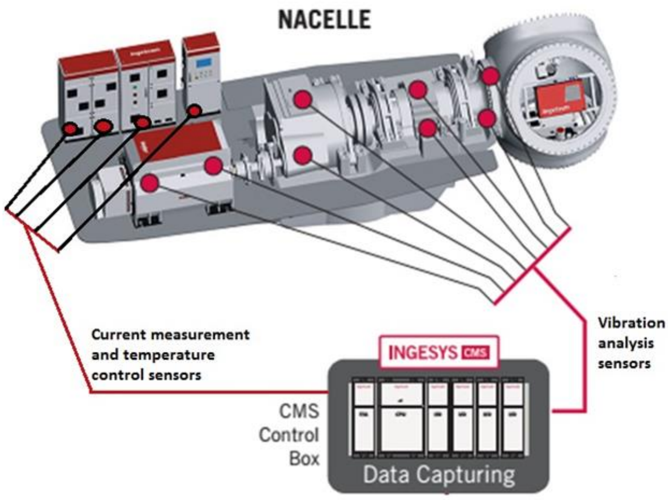


Figure 4.33. General scheme of the drivetrain monitoring system.

4.6.1.1 Ingesys® CMS

The INGESYS® CMS equipment consists of the CPU control unit and IC3 data acquisition module(s) assembled in the same communications port (obtaining a single Rack), the PLC power supply and module for reading is 24 Vdc.

The communication with the PC and analysis software can be carry out On-line, either by the Internet network of the facilities or by mobile router with data download, or Off-line, directly connecting the CPU of the CMS equipment to the PC with the analysis software by means of the Ethernet cable.

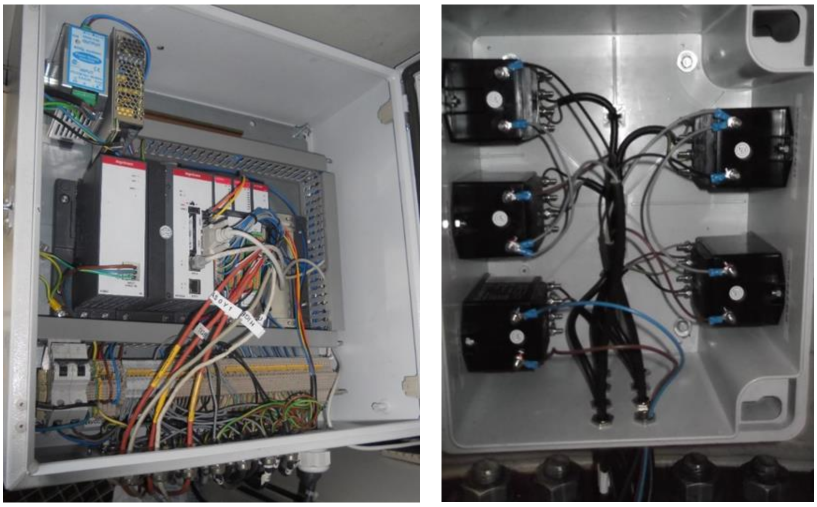


Figure 4.34. INGESYS® CMS.

4.6.2 Generic monitoring system for blades

Regarding the blades, it was decided to follow the same strategy for the four concepts, as at least for the three first concepts, they are very similar. The blade monitoring system will consist in several modules that will be installed along the blade. In each module, all the sensors needed are integrated in a single unit. This is presented as a more cost effective and robust solution compared to traditional blade monitoring systems. Each module will allow measuring the stresses on the blades as well as the defect detection and characterization. In the next figure, we can see a schematic of a generic monitoring system for the blades composed by 3 modules:

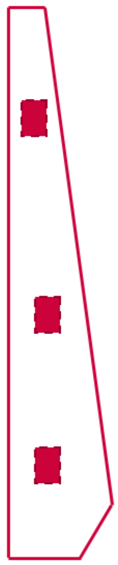
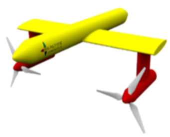
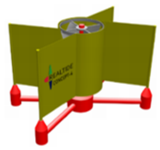


Figure 4.35. Generic monitoring system for blades.

4.6.3 Sensors

In the Table 4.12 below can be seen in detail the characteristics, equipment and sensors needed for the monitoring system of each of the element of the four tidal turbine concepts.

Table 4.12. Drive train and blades monitoring plan developed.

			CONCEPT 1	CONCEPT 2	CONCEPT 3	CONCEPT 4
		IMAGE				
		DENOMINATION	Complex bottom fixed	Simple bottom fixed	Floating multi rotor	Cross flow turbine
		CHARACTERISTICS	• Horizontal axis • Open rotor • 3 blades • Bottom fixed with pile • Pitch control • Yaw mechanism • Gearbox drive	• Horizontal axis • Open rotor • Multi blades (>3) • Bottom fixed gravity base • No pitch control • No yaw mechanism • Direct drive	• Horizontal axis • Open rotor • 2 blades • Floating • Pitch control • No active yaw mechanism • Gearbox drive	• Vertical axis • Close rotor • Multi blades (>3) • Bottom fixed (gravity or pile) • No pitch • No yaw • Direct drive
DRIVE TRAIN MONITORING	Monitoring equipment		Ingesys® CMS	Ingesys® CMS	Ingesys® CMS	Ingesys® CMS
	VIBRATION SYSTEM	Main shaft sensors	**Minimal monitoring:** - 1 low-frequency radial accelerometer per bearing - 1 low-frequency axial accelerometer **Optimal monitoring:** - 1 low-frequency radial accelerometer per bearing - 1 low-frequency axial accelerometer per bearing	**Minimal monitoring:** - 1 low-frequency radial accelerometer per bearing - 1 low-frequency axial accelerometer **Optimal monitoring:** - 1 low-frequency radial accelerometer per bearing - 1 low-frequency axial accelerometer per bearing	**Minimal monitoring:** - 1 low-frequency radial accelerometer per bearing - 1 low-frequency axial accelerometer **Optimal monitoring:** - 1 low-frequency radial accelerometer per bearing - 1 low-frequency axial accelerometer per bearing	**Minimal monitoring:** - 1 low-frequency radial accelerometer per bearing - 1 low-frequency axial accelerometer **Optimal monitoring:** - 1 low-frequency radial accelerometer per bearing - 1 low-frequency axial accelerometer per bearing
		Gearbox sensors	**Optimal monitoring:** - 1 radial accelerometer per stage - 1 axial accelerometer per stage	N/A	**Optimal monitoring:** - 1 radial accelerometer per stage - 1 axial accelerometer per stage	N/A
		Generator sensors	**Minimal monitoring:** - 1 radial accelerometer per bearing - 1 axial accelerometer **Optimal monitoring:** - 1 radial accelerometer per bearing - 1 axial accelerometer per bearing - 1 Temperature sensor per bearing - 1 temperature sensor per wound	**Minimal monitoring:** - 1 radial accelerometer per bearing - 1 axial accelerometer **Optimal monitoring:** - 1 radial accelerometer per bearing - 1 axial accelerometer per bearing - 1 Temperature sensor per bearing - 1 temperature sensor per wound	**Minimal monitoring:** - 1 radial accelerometer per bearing - 1 axial accelerometer **Optimal monitoring:** - 1 radial accelerometer per bearing - 1 axial accelerometer per bearing - 1 Temperature sensor per bearing - 1 temperature sensor per wound	**Minimal monitoring:** - 1 radial accelerometer per bearing - 1 axial accelerometer **Optimal monitoring:** - 1 radial accelerometer per bearing - 1 axial accelerometer per bearing - 1 Temperature sensor per bearing - 1 temperature sensor per wound

	CURRENT MEASUREMENT SYSTEM	**Converter sensors**	**Optimal monitoring:** *For the inverter and the rectifier:* - 1 current sensor per phase *For the stator:* - 1 current sensor per phase *For Vcc Bus:* - 1 voltage sensor per phase *For Vca generated and Vca grid:* - 1 voltage sensors per phase - 1 temperature sensor for converter cabinet - 1 humidity sensor for IGBT´s cabinet	**Optimal monitoring:** *For the inverter and the rectifier:* - 1 current sensor per phase *For Vcc Bus:* - 1 voltage sensor per phase *For Vca generated and Vca grid:* - 1 voltage sensors per phase - 1 temperature sensor for converter cabinet - 1 humidity sensor for IGBT´s cabinet	**Optimal monitoring:** *For the inverter and the rectifier:* - 1 current sensor per phase *For the stator:* - 1 current sensor per phase *For Vcc Bus:* - 1 voltage sensor per phase *For Vca generated and Vca grid:* - 1 voltage sensors per phase - 1 temperature sensor for converter cabinet - 1 humidity sensor for IGBT´s cabinet	**Optimal monitoring:** *For the inverter and the rectifier:* - 1 current sensor per phase *For Vcc Bus:* - 1 voltage sensor per phase *For Vca generated and Vca grid:* - 1 voltage sensors per phase - 1 temperature sensor for converter cabinet - 1 humidity sensor for IGBT´s cabinet
BLADES MONITORING	LRUT	**Hardware**	**Piezoelectric sensor:** - Transmitter - AD receiver - Capture - Communications	**Piezoelectric sensor:** - Transmitter - AD receiver - Capture - Communications	**Piezoelectric sensor:** - Transmitter - AD receiver - Capture - Communications	**Piezoelectric sensor:** - Transmitter - AD receiver - Capture - Communications
	EXTENSOMETRY	**Hardware**	**Strain gauge:** - Wheatstone bridge **Piezoelectric sensor:** - Integrator	**Strain gauge:** - Wheatstone bridge **Piezoelectric sensor:** - Integrator	**Strain gauge:** - Wheatstone bridge **Piezoelectric sensor:** - Integrator	**Strain gauge:** - Wheatstone bridge **Piezoelectric sensor:** - Integrator
	Acoustic	**Hardware**	**Piezoelectric sensor:** - Receiver AD - DSP	**Piezoelectric sensor:** - Receiver AD - DSP	**Piezoelectric sensor:** - Receiver AD - DSP	**Piezoelectric sensor:** - Receiver AD - DSP
	Modal	**Hardware**	**Strain gauges and Piezoelectric sensors:** - Random decay	**Strain gauges and Piezoelectric sensors:** - Random decay	**Strain gauges and Piezoelectric sensors:** - Random decay	**Strain gauges and Piezoelectric sensors:** - Random decay

5 HIGH LEVEL ALGORITHMS FOR CBM

As already described, Condition-Based Maintenance (CBM) is a maintenance strategy that monitors the actual condition of an asset to decide which maintenance is required. Verification of a machine for these indicators can include non-invasive measurements, visual inspection, performance data, and scheduled tests.

Unlike planned maintenance (PM), where maintenance is performed at predefined scheduled intervals, condition-based maintenance is only performed after a degrading on the condition of the equipment has been observed.

The goal of condition-based maintenance is to anticipate equipment failures so that maintenance can be proactively scheduled when necessary. Asset conditions must trigger maintenance within a sufficient period of time before a failure occurs, so that work can be completed before the asset fails or performance falls below optimum. Critical systems that require considerable initial capital investment, or that could affect the quality of the product being produced, require up-to-the-minute data collection. When performed correctly, condition-based maintenance is a minimally invasive form of maintenance that reduces overall costs, risk to workers and downtime due to unexpected breakdowns.

The previous step to the development of prediction algorithms, anomaly detection, etc., is the application of clustering methods to discover the structure of the data and see if it is possible to separate data sets so that later algorithms have less computational cost and more precision.

5.1 Data clustering

The concept of data clustering refers to the idea of grouping a data set into specific groups based on similar features. It is a major task of exploratory data mining and a common technique for statistical data analysis, used in many fields, including unsupervised automatic learning.

Clustering can be achieved through various algorithms that differ significantly in their understanding of what constitutes a cluster and how to find them efficiently.

The notion of clustering cannot be defined precisely, which is one of the reasons why there are so many clustering algorithms. There is a common denominator: a group of data object. However, different researchers use different clustering models, and for each of these clustering models different algorithms can be given.

Clustering techniques are highly relevant in RealTide project in order to categorize efficiently the great amount of information that we work with namely environment conditions (waves, tidal flow, turbulence, etc) and machine working condition (temperature, vibrations, currents, etc.). There exists so many different techniques of data clustering available for different nature of application; according to [26] clustering procedures can be classified into the following categories:

1. **Hierarchical Clustering Methods:** It consist in creating a group of nested clusters structured as a visualized and hierarchical tree as a dendrogram. The algorithms can be classified in agglomerative or divisive.
2. **Partitioning Clustering Methods:** It result in a group of M clusters, each item belonging to a unique cluster.
3. **Density-based Clustering Methods**: The density based clustering algorithms discover the cluster in arbitrary shape. From region of low density, objects are separate into denser regions. They are connected until satisfying density criteria.

4. **Model-based Clustering Methods:** They are a set of advanced techniques that attempt to optimize the fit between the data and some mathematical model.
5. **Grid-based Clustering Methods:** It is used for reducing computational complexity. It consists in creating a grid structure then calculates cell density and after that identifies cluster centers.
6. **Fuzzy Clustering:** It is referred to soft computing and the data points belong to more than one cluster.

Understanding these clustering techniques is key to understand the differences between the different algorithms. Typical **clustering algorithms** include: connectivity models, centroid models, distribution models, density models, subspace models, etc. In the next table, some of them are show:

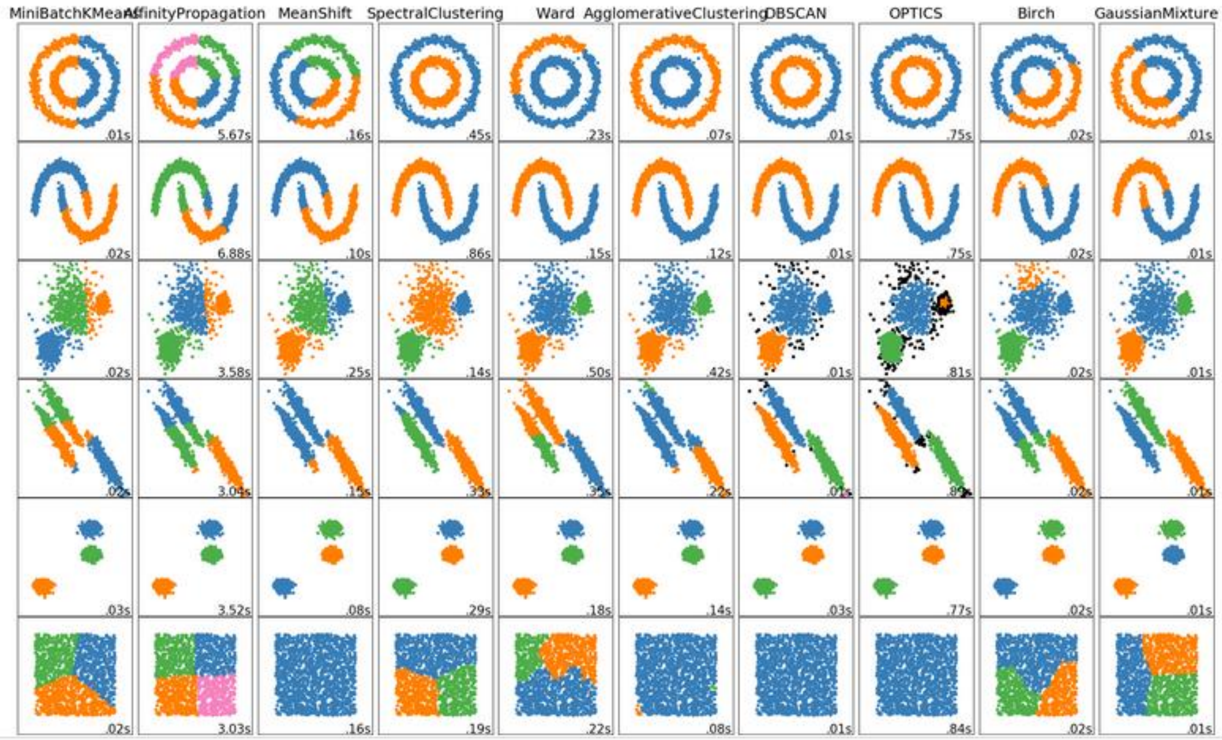


Figure 5.1. Clustering algorithms in different types of datasets. Source: [27].

There is no objectively correct clustering algorithm, the most appropriate clustering algorithm for a particular problem often needs to be chosen experimentally, unless there is a mathematical reason to prefer one clustering model to another. An algorithm that is designed for one type of model will generally fail in a data set that contains a radically different type of model.

Table 5.1. Clustering algorithms and features. Source: scikit-learn.org.

Method name	Parameters	Scalability	Usecase	Geometry (metric used)
K-Means	number of clusters	Very large n_samples, medium n_clusters with MiniBatch code	General-purpose, even cluster size, flat geometry, not too many clusters	Distances between points
Affinity propagation	damping, sample preference	Not scalable with n_samples	Many clusters, uneven cluster size, non-flat geometry	Graph distance (e.g. nearest-neighbor graph)
Mean-shift	bandwidth	Not scalable with n_samples	Many clusters, uneven cluster size, non-flat geometry	Distances between points
Spectral clustering	number of clusters	Medium n_samples, small n_clusters	Few clusters, even cluster size, non-flat geometry	Graph distance (e.g. nearest-neighbor graph)
Ward hierarchical clustering	number of clusters or distance threshold	Large n_samples and n_clusters	Many clusters, possibly connectivity constraints	Distances between points
Agglomerative clustering	number of clusters or distance threshold, linkage type, distance	Large n_samples and n_clusters	Many clusters, possibly connectivity constraints, non Euclidean distances	Any pairwise distance
DBSCAN	neighbourhood size	Very large n_samples, medium n_clusters	Non-flat geometry, uneven cluster sizes	Distances between nearest points
OPTICS	minimum cluster membership	Very large n_samples, large n_clusters	Non-flat geometry, uneven cluster sizes, variable cluster density	Distances between points
Gaussian mixtures	many	Not scalable	Flat geometry, good for density estimation	Mahalanobis distances to centers
Birch	branching factor, threshold, optional global clusterer.	Large n_clusters and n_samples	Large dataset, outlier removal, data reduction.	Euclidean distance between points

After doing a literature research, it was found that **k-means** algorithm is one of the most widely used for condition monitoring. In the following, we show a couple of examples where this algorithm has been used for working conditions categorisation and faults detection in wind turbines.

In [28], the authors use the data collected from the SCADA system of an operational wind farm. The parallel factor analysis (PARAFAC) to process the data coming from the SCADA and the k-means method for classifying such data into “Normal”, “Fault” or “Alarm” condition. In the following picture, the active power output is represented against wind speed, where the blue dots represent normal measurement points while the green triangles represent fault points and the red stars represent alarm points.

The following features can be appreciated:

- The active power normally increases with wind speed until it reaches as stable value of 2.5 MW.
- During the fault operation the active power is reduced to around 1.5 MW despite the increase in wind speeds.
- Discrete points marked in red stats indicate short excursions of the active power outside the normal range.

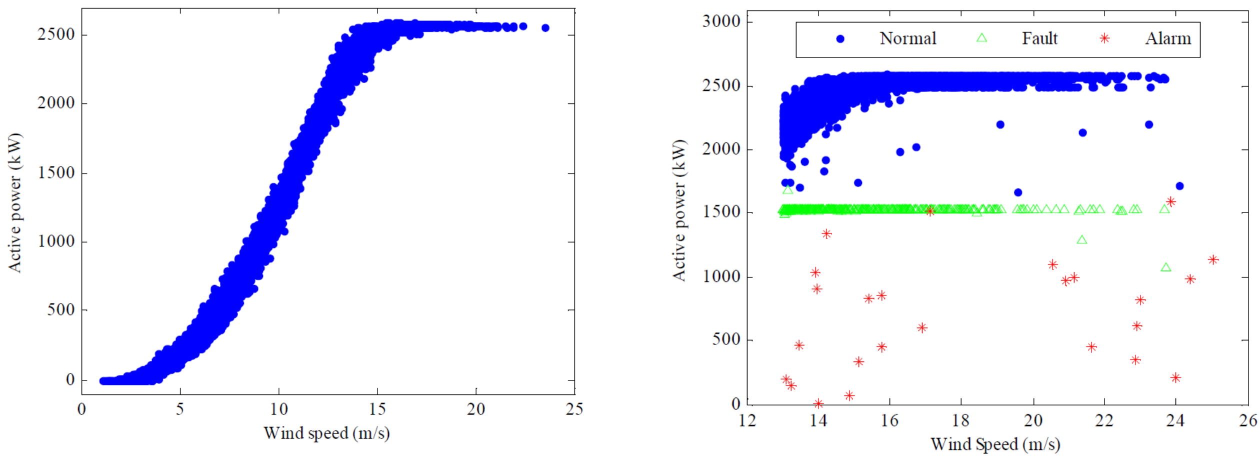


Figure 5.2. Active power output for fault detection: (a)- Fault free turbine; (b)- Turbine with confirmed faults. Source: [28].

In [29], the authors use also the k-means algorithm for clustering the data coming from the SCADA. In this case, the vibration of the drive train and the tower of a wind turbine were monitored and the anomalies were detected based in these parameters. For instance, we represent the obtained clusters after analysing the data of the drive train acceleration for being more related to tidal turbines:

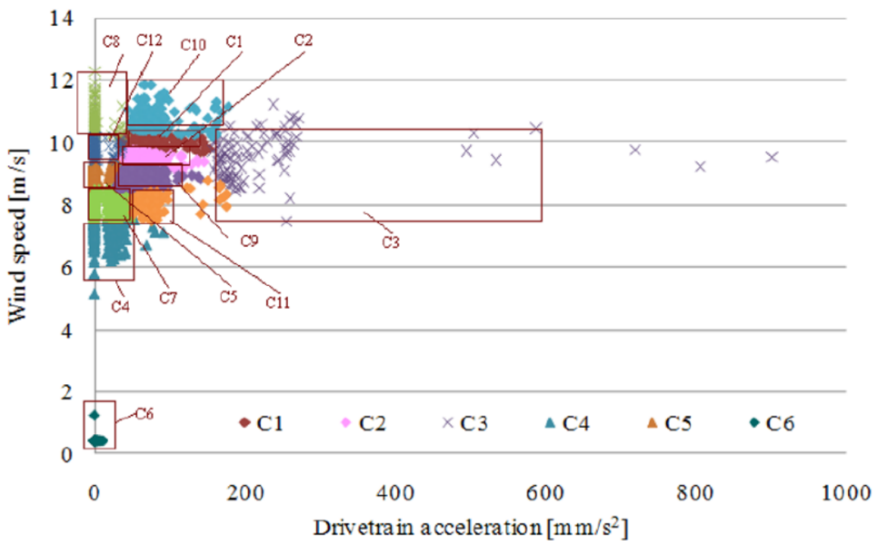


Figure 5.3. Clustering results from monitoring drivetrain acceleration. Source: [29].

Table 5.2 collects the criteria chosen for the definition of the cluster exposed above. Clusters 1, 2, 6, 9, 10 and 11 represent the normal vibration status of the drivetrain system. We can observe for example the cluster 3 which is associated with a fault status since the acceleration is too high for a low wind speed. Clusters 4,5,7,8 and 12 correspond to a period that turbine is shut down after the fault of cluster 3.

Table 5.2. Clustering criteria. Source: [29].

Cluster number	Drivetrain acceleration (mm/s^2)	Wind speed (m/s)	Generator torque (Nm)	Number of points	Percentage
1	71.96	9.98	75.06	313	8.76
2	65.84	9.42	61.08	295	8.25
3	233.92	9.58	41.36	96	2.69
4	17.42	7.13	1.11	240	6.71
5	3.37	8.99	0	437	12.22
6	0.37	0.40	0	217	6.07
7	18.14	8.10	0	410	11.47
8	0.77	10.57	0	419	11.72
9	62.05	8.81	51.46	283	7.92
10	81.75	10.68	83.12	181	5.06
11	83.81	8.11	56.12	101	2.83
12	0.93	9.79	0	583	16.31

5.1.1 Site conditions

In the absence of real data today, a SCADA data set has been obtained from an on-shore wind turbine maintained by Ingeteam. These data contain ten-minute data of multiple signal types from 2013-06-30 to 2019-08-31, for site conditions have the following: *WindSpeed*, *Temperature* and *WindDeviation*.

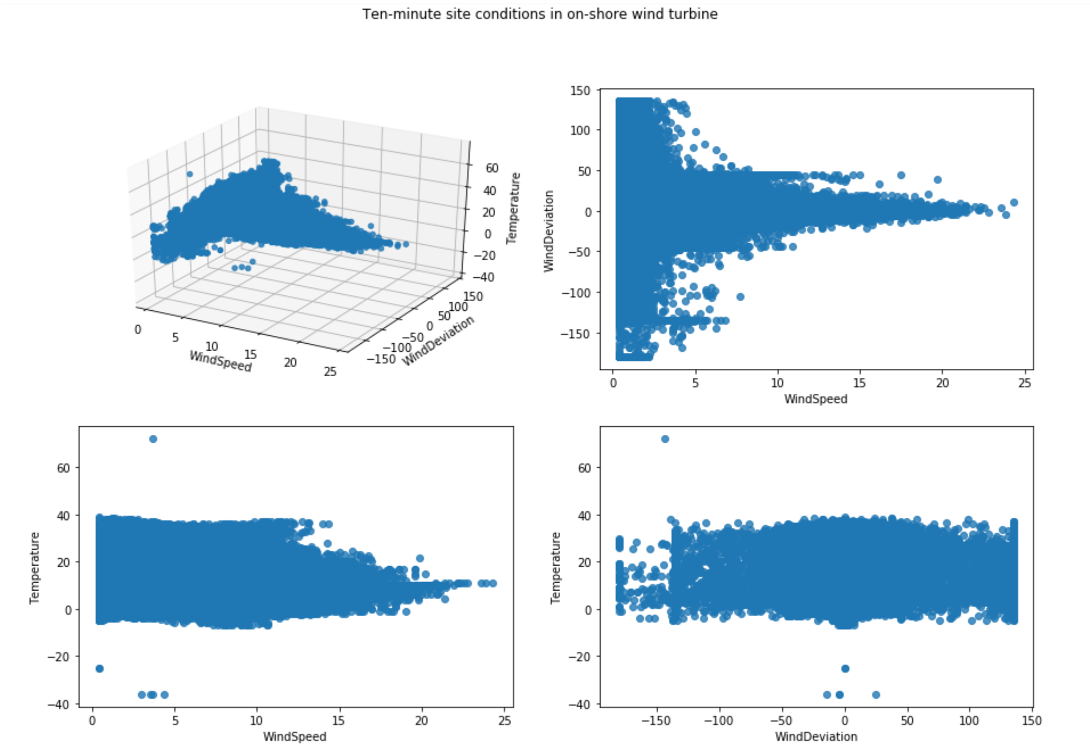


Figure 5.4. Ten-minute site conditions data points.

This dataset alone does not show a structure with apparent and well-differentiated clusters Figure 5.4. Even so, clustering can be interesting to differentiate the different types of day, differentiate them in later analysis and help train the model. Different unsupervised learning algorithms will be applied to make the clusters and then compared using the *Silhouette Coefficient*.

The *Silhouette Coefficient* is calculated using the mean intra-cluster distance (`a`) and the mean nearest-cluster distance (`b`) for each sample. The Silhouette Coefficient for a sample is `(b - a) /max(a, b)`. To clarify, `b` is the distance between a sample and the nearest cluster that the sample is not a part of. Note that Silhouette Coefficient is only defined if number of labels is:

2 <= n_labels <= n_samples – 1   Reference [30]

This data set alone does not show a structure with apparent and well-differentiated clusters. However, clustering can be useful to obtain the different types of days, either to differentiate them in later analysis or to help train the model we can apply different algorithms and use the Silhouette Coefficient to compare the goodness of the clusters.

The algorithm to be applied must be computationally light to be able to iterate faster in the tests. In this sense, the algorithm used to segment the climatic measures was the k-means [31] with a number of clusters of 11.

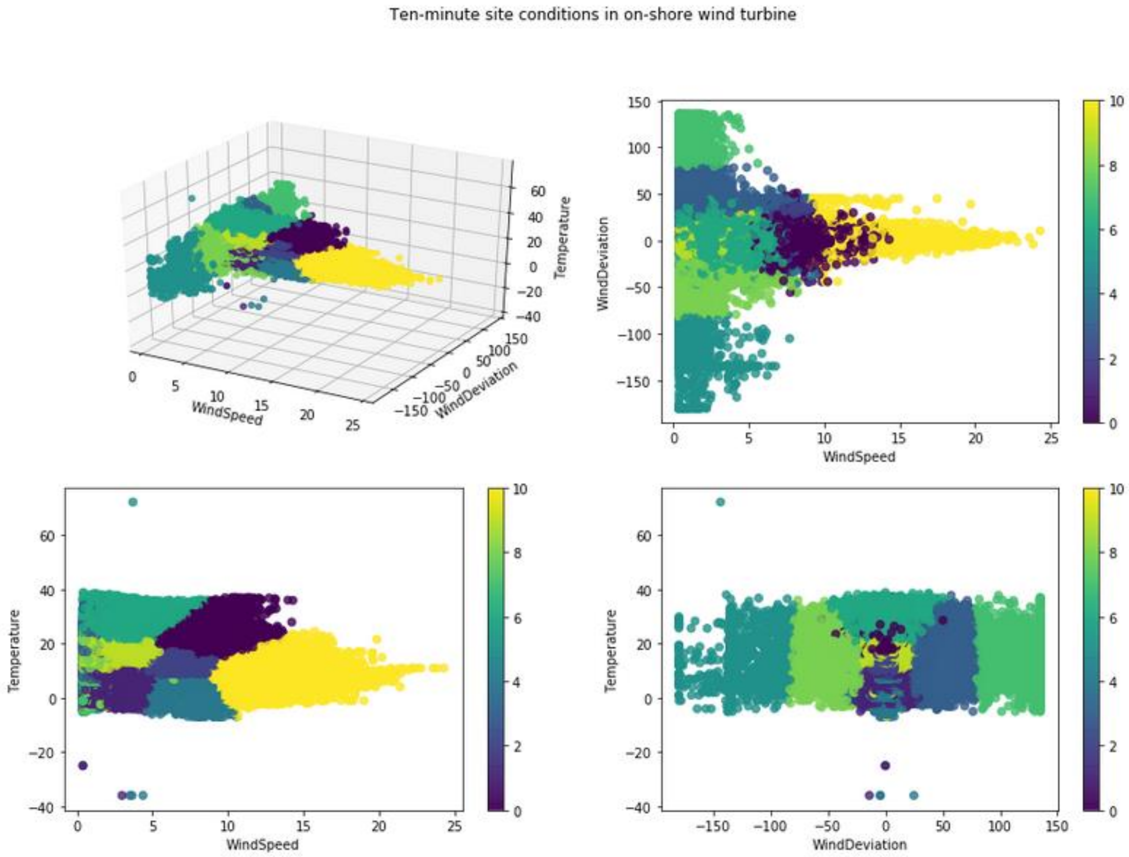


Figure 5.5 Ten-minute site conditions with KMeans clustering.

This segmentation by site conditions is done to make a first segmentation of the data. The characteristics of the clusters can be found in the Table 5.3.

Table 5.3. KMeans clusters features.

		WindSpeed				WindDev				Temp			
Cluster	Count	Min	Max	Mean	Std	Min	Max	Mean	Std	Min	Max	Mean	Std
0	37146	5.08	14.31	7.66	1.42	-55.65	51.03	0.36	6.06	14.66	37	20.59	3.56
1	49449	0.40	5.18	3.24	1.15	-29.69	29.04	0.21	7.78	-36	11	5.61	2.95
2	59560	4.52	9.56	6.71	1.11	-43.68	39.05	0.21	5.32	8.3	17.79	12.46	2.26
3	12804	0.4	8.65	1.36	1.07	16.55	79.69	40.41	9.84	-5	37.84	11.7	7.24
4	47764	3.51	10.57	6.82	1.17	-46.61	45.12	0.18	5.36	-36	8.64	4.44	2.66
5	1381	0.4	7.72	1.29	1.09	-180	-79.99	-124.5	24.03	-5.01	72.29	12.87	9.14
6	29298	0.4	8.69	3.84	1.53	-53.3	53.65	0.34	10.85	20.81	38.94	26.68	3.58
7	2034	0.4	5.61	1.03	0.68	78.09	135	118.3	19.44	-5	37.86	13.08	8.94
8	9560	0.4	8.31	1.41	1.03	-83.26	-15.8	-39.7	10.52	-3.53	36.10	10.75	7.04
9	43487	0.4	5.59	3.36	1.15	-26.27	28.04	0.61	7.68	10.54	22.19	15.76	2.99
10	30134	8.73	24.31	11.22	1.84	-44.36	45.13	0.46	5.02	-7	24.59	8.08	4.11

5.1.2 Machine conditions

Once the first segmentation is done, the clusters will be selected one by one and treated separately to apply clustering to machine conditions.

For the following example, cluster 10 (yellow) will be used, which meets the optimal operating conditions of an on-shore machine and whose clustering by machine conditions could be interesting.

There are 67 machine conditions variables, among which are: power, tower deflection, reactive power, voltage, current, generator speed, rotor speed, blade positions, gearbox temperatures, bearing temperatures, etcetera.

As this data set has many variables, a dimensional reduction is needed to make the task easier for the clustering algorithms. In this case a dimensional reduction has been applied using t-SNE (*t-distributed Stochastic Neighbor Embedding*) manifold.

T-SNE goal is to take a set of points in a high-dimensional space and find a faithful representation of those points in a lower-dimensional space, typically the 2D plane. The algorithm is non-linear and adapts to the underlying data, performing different transformations on different regions [32].

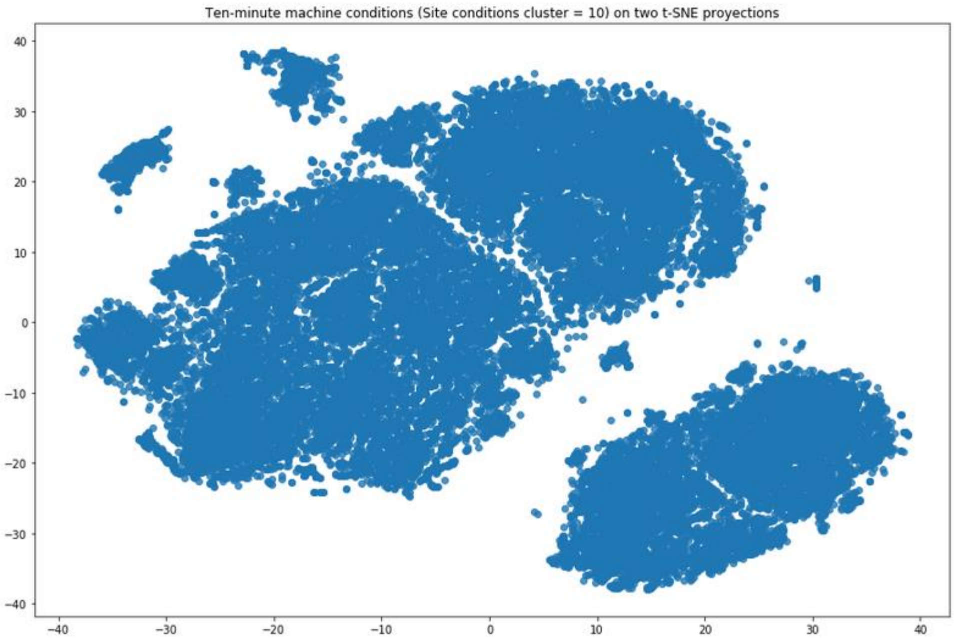


Figure 5.6 Ten-minute machine conditions on two t-SNE projections.

In Figure 5.6 Ten-minute machine conditions on two t-SNE projections are seen at first glance the dgroups of clearly differentiated points. A series of algorithms were applied to see which obtained a higher silhouette coefficient and the best result was obtained by DBSCAN. The following figure shows the division made by the algorithm in the points projected by the t-SNE.

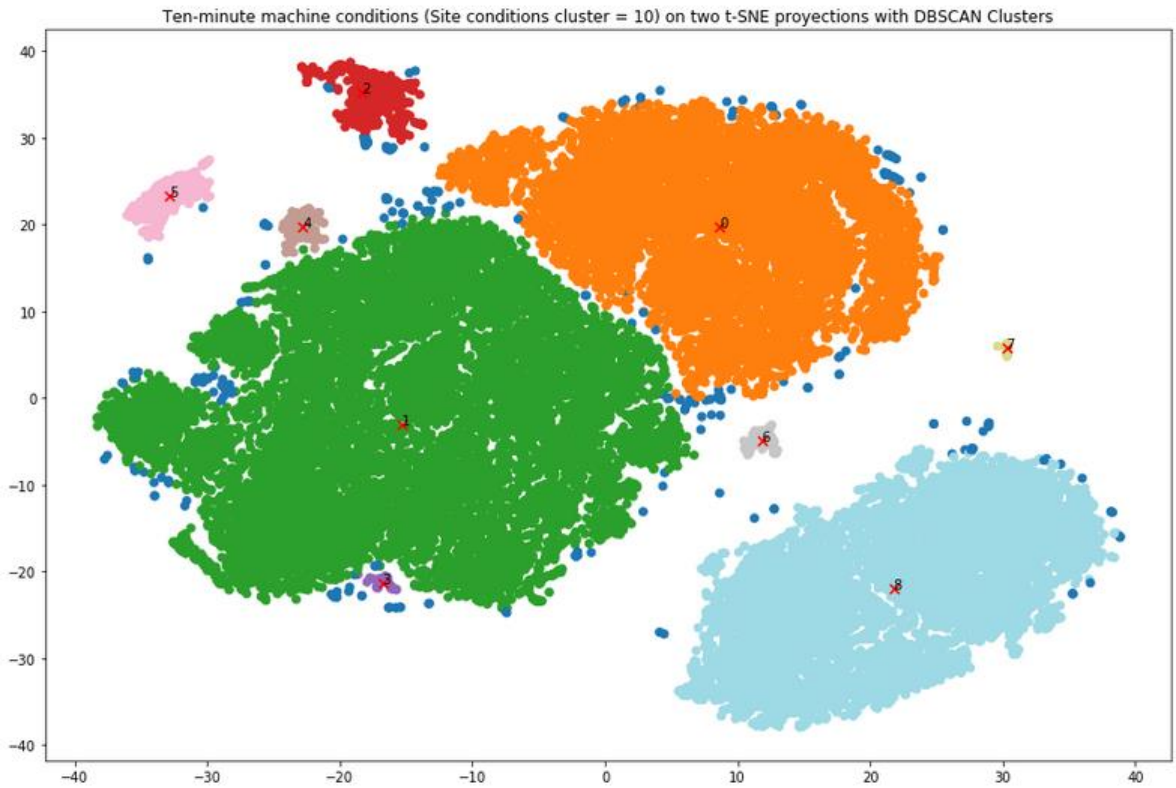


Figure 5.7 Ten-minute machine conditions on two t-SNE projections with DBSCAN clusters.

To understand how to cluster the ten-minutes, the algorithm is used boxplots of each signal to see the difference between the clusters. The most significant differences are found in the following figure. The variables that appear in the figures are shown in Table 5.4.

Table 5.4. Signals descriptions using in boxplots.

SIGNAL	DESCRIPTION
SIG001	Power
SIG002	Tower deflection
SIG013	Blades, actual value
SIG014	Wind speed
SIG015	Nacelle position
SIG018	Wind deviation
SIG034	Temp. Bearing A
SIG039	Temp. Generator Cooling Air
SIG041	Temp. Shaft Bearing
SIG056	Hydraulic pressure

To see what really the algorithm does, boxplots were made in Figure 5.8 to see the distribution of clusters in each machine condition and site condition variables.

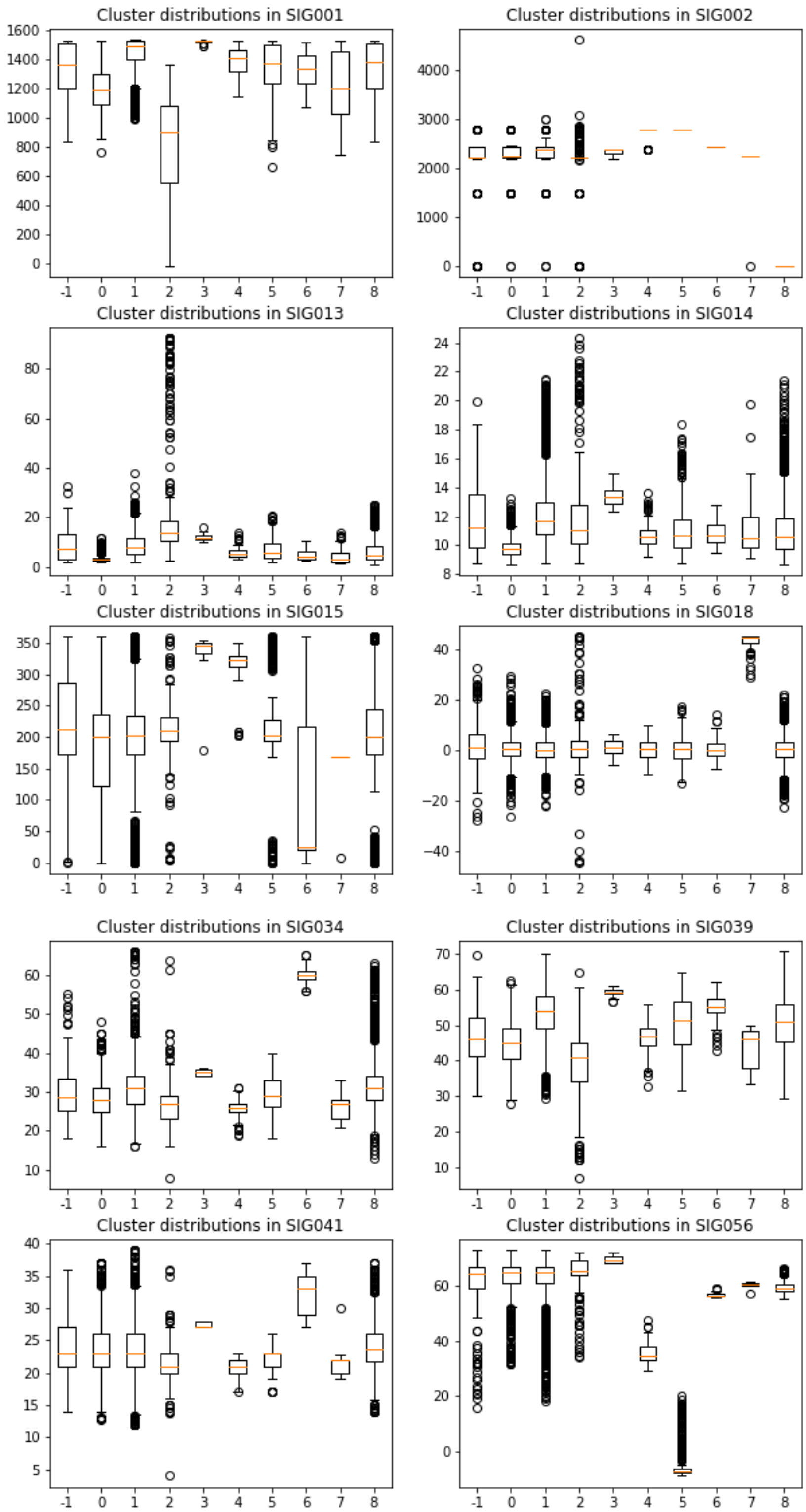


Figure 5.8 Cluster boxplots by signal.

Analysing the previous graphs, the following descriptive table of the clusters has been extracted.

Table 5.5. DBSCAN clusters descriptions.

Cluster	Count	Color	Description
0	8105		Good performance, low relative wind speed
1	13129		Best performance
2	699		Machine Stopping
3	43		Generator cooling problem
4	111		Low hydraulic pressure
5	581		Hydraulic pressure failure
6	149		High bearing temperature
7	67		Unstable wind direction
8	7489		Good performance but possible tower deflection sensor is broken

5.2 Model based monitoring & Digital twins

The Digital twin is a concept that is taking more and more importance in the modern industry. It refers to the digitalization of a physical system based on data collected from it and/or models representing the real system. In the following picture, we can see the graphic representation of this concept applied to a generic tidal turbine:

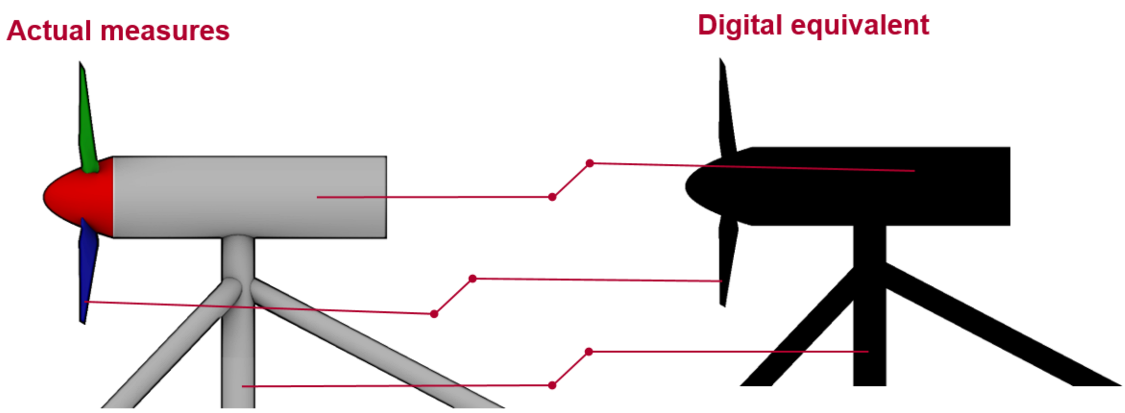


Figure 5.9. Concept of digital twin.

Among others, one of the most relevant application of DT is the combination with the CMS for predictive maintenance purpose. As the topic of the deliverable is the implementation of condition based maintenance strategies in tidal turbines, we will only focus on this approach.

According to some recent studies, it is estimated that digitalization of products and services can add more than EUR 110 billion of annual revenue to the European economy in the next five years [33]. Some milestones of DT development in the recent years are shown in the following picture:

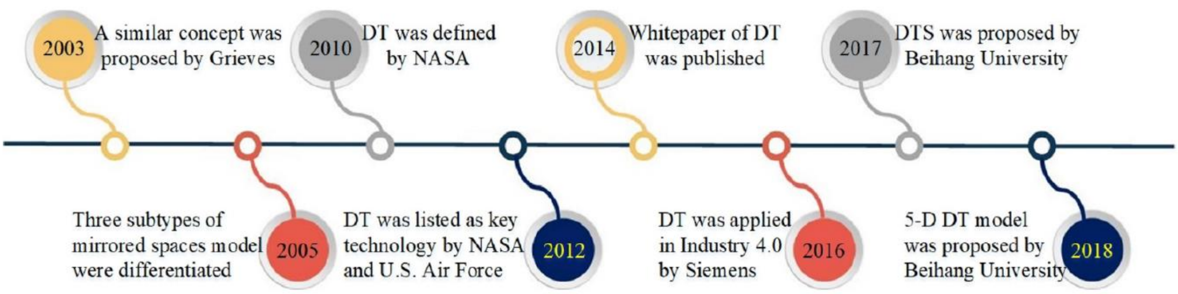


Figure 5.10. The milestones of DT development. Source: [34].

According to [35], the basic DT model consist of three main parts:

a) Physical products in Real Space: It refers to the actual measures which are collected from the real system: Torque, speed, currents, temperature, etc.
b) Virtual products in virtual Space: It refers to the magnitudes that are obtained from a virtual model and they do not be necessarily equivalent to the real measurement. This have been significantly improved in the last years thanks to the emergence of ML that, combined with the models, it allows a more efficient implementation of DT since the system can be modeled without having a vast knowledge about it [36].
c) The connection of data and information that tie the virtual and real products together: This is the most relevant aspect when using DT. First of all, it is necessary to make a selection of variables that are representative enough for maintenance purpose which must be easily measurable. Once done the selection of such variables, it is necessary to think in how they can be integrated in the digital equivalent system and if they can be easily estimated by using models. Therein lies the real power when using digital twins, there can be a great amount of options to make an estimation of the real measurement so we have just to seek the most efficient one for our particular system according to our possibilities and the degree of accuracy we would like to reach.

In the next figure we can see the routine that is being applied for detecting failures in data centers by using Digital Twin approach in order to improve the anomaly detection on them.

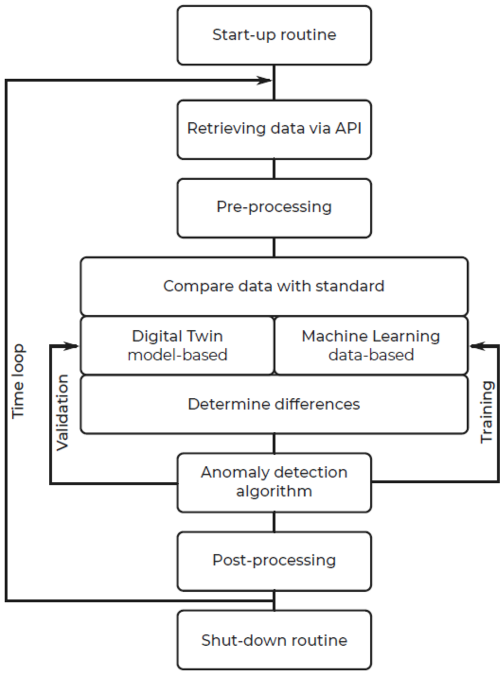


Figure 5.11. Routine for faults detection in data centers by using Digital Twins. Source: [37].

5.3 SCADA integration

5.3.1 Definition

Supervisory Control and Data Acquisition (SCADA) is a control system architecture, that uses programmable logic controller (PLC) and discrete PID controllers to interface with the machinery and graphical user interfaces for high-level process supervisory management.

The SCADA shows us the digitalization of the machine, which is the representation of the signal, usually analogy, in a series of numbers that describes a discrete set of its points or samples. This is called digital representation or, more specifically, a digital image.

Digitization provides valuable support in tidal turbines, providing operation with fewer problems and without interruptions, more powerful and reliable components, perfectly integrated and with optimal availability.

5.3.2 SCADA description

The Figure 5.12 shows all SCADA levels, their description and their integration with the different information available.

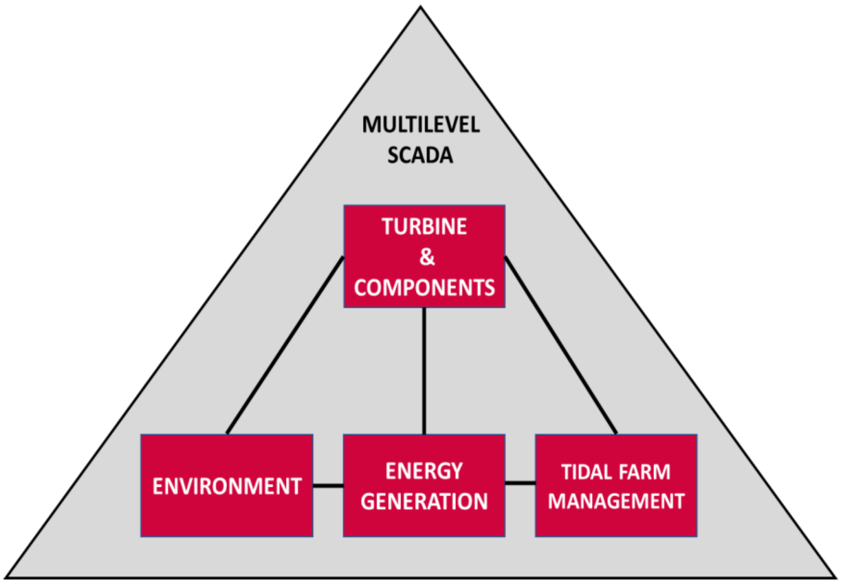


Figure 5.12 Ingeteam Multilevel SCADA.

As seen in the figure, four SCADA levels have been proposed, with which it is intended to develop a monitoring system based on the scalability of the processes.

1. **Turbine and components:**

Providing a consistent digitalization and precisely attuned components the digital twin of the tidal turbine is obtained.

1.1. Digitalization

All processes associated with a tidal turbine can be established from the prototype stage in a common data model. The digital twin allows digital design and testing of marine energy farms. This saves valuable time and costs, while increasing the quality of engineering. The digital twin of a tidal turbine also allows a simulation of the critical phase, as well as a safe implementation.

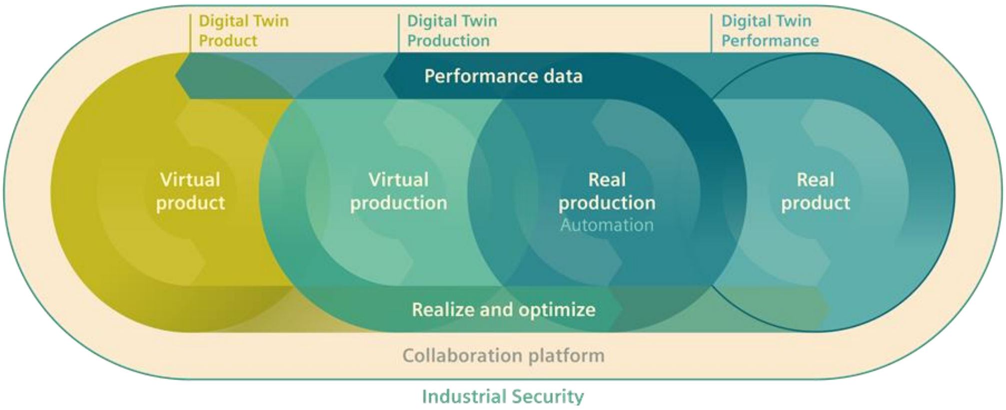


Figure 5.13 Digital twins for continuous improvement. Modified from [38]

According to deliverable 4.1: “Initial monitoring plan for tidal devices”(see [25]), the SCADA will show the digitalization of the following elements:

1.1.1. Nacelle and frame (electrical & mechanical)
1.1.2. Blades
1.1.3. Hub & Shaft bearings
1.1.4. Generator (electrical & mechanical)

This digitalization will be carried out by the following sensor:

1.2. CMS & SHM sensors

1.2.1. Displacement sensors
1.2.2. Inclinometers
1.2.3. Accelerometers
1.2.4. Current sensors
1.2.5. Voltage sensors
1.2.6. Pressure sensors
1.2.7. Temperature & humidity sensors
1.2.8. Oxidation sensors
1.2.9. Strain gauge
1.2.10. LRUT transducer

The Table 5.6 shows the necessary steps to integrate the monitored sensors from the tidal turbine in the SCADA system:

Table 5.6. Definition of monitored sensors for tidal turbine.

Definition of monitored COMPONENTS				
TIDAL TURBINE	**CMS**		**SHM**	
COMPONENT	**Mechanical**	**Electrical**	**Movement**	**Surface**
Nacelle shell				Oxidation sensors
Frame			Inclinometers	
Blade			Strain gauge	LRUT transducer
Blade bearing	Accelerometers			Temperature sensor
Hub seals	Accelerometers			Humidity sensors
Rotor bearing	Accelerometers			Temperature sensor
Shaft bearings	Accelerometers			Temperature sensor
Drive train	Accelerometers			
Generator	Accelerometers	Voltage sensors, Current sensors		Temperature & humidity sensors
Converter		Voltage sensors, Current sensors		Temperature & humidity sensors
Transformer		Voltage sensors, Current sensors		Temperature & humidity sensors
Cabling system	Pressure sensors		Strain gauge	
Protections				LRUT transducer

2. Environmental conditions:

Thanks to the combination of physics-based simulations with analysis of environmental data, it allows to obtain a digital twin of the completely virtual marine environment. Additional data is generated when the tidal turbine or the farm is put into operation. Operational performance data is recorded, analysed and returned for incorporation into the development. This is used to support the optimization of production processes and the optimization of the tidal turbine.

2.1. Weather conditions

2.1.1. Offshore Wind speed
2.1.2. Offshore Wind direction
2.1.3. Temperature & humidity

2.2. Marine conditions:

Current and wave measurement for site selection, design and performance monitoring, and environmental impact studies. Real-time wave-current measurement for decision making during production.

2.2.1. Tidal flows
2.2.2. Wave current speed and direction
2.2.3. Temperature sensor

Table 5.7. Definition of monitored sensors for environmental conditions.

Definition of monitored COMPONENTS		
ENVIRONMENT	**WEATHER CONDITIONS**	**MARINE CONDITIONS**
Speed	Anemometer	ADCPs sensor
Direction	Vane	ADCPs sensor
Temperature	Temperature sensor	Temperature sensor
Humidity	Humidity sensor	-

3. <u>Energy generation:</u>

With highly efficient tidal generators and converters, a highly effective means of reducing the cost of energy is obtained. The digitalization advantage is clear: lower operating costs for maintenance and operation, higher electricity yields and, therefore, reduced energy costs in a sustainable way.

3.1. Turbine generation

With an individual digital system for each generator, an exact and real-time parameterization of each of the power quantities is obtained:

Table 5.8. Definition of monitored sensors for turbine generation.

Definition of monitored COMPONENTS		
	COMPONENT	**SENSOR**
GENERATOR		
	Winding	Voltage sensors, Current sensors. Temperature sensor
	Rotor	Voltage sensors, Current sensors. Temperature sensor
	Magnet	Temperature sensor
	Insulator	Temperature sensor
	Frame	Temperature sensor & Accelerometers
	Bearings	Temperature sensor & Accelerometers
CONVERTER	**COMPONENT**	**SENSOR**
	Rectifier	Voltage sensors, Current sensors. Temperature sensor
	Cooler	Temperature sensor
	Converter	Voltage sensors, Current sensors. Temperature sensor
	Transformer	Voltage sensors, Current sensors. Temperature sensor
	Capacitor	Voltage Sensor
	Crowbar	Power dissipator sensor
	Power cabling	Acoustic emission sensor

3.2. Turbine protection

A functioning tidal turbine is a power plant designed to generate electricity, although it is continually subject to a variety of environmental influences. For this reason, a tidal turbine needs to remain available and functional at all times, against short circuits and overloads, control and protection of electric drives, protection for personnel and a gradual concept of protection against lightning and surges. A measurement and monitoring system equipped with communication capacity is necessary to ensure a high level of transparency of the farm.

Table 5.9. Definition of monitoring sensors for turbine protections.

Definition of monitored COMPONENTS		
	COMPONENT	**SENSOR**
PROTECTIONS	Main circuit	Short circuits, ground faults and overloads sensors
	Electrical protections	Fuse, circuit breakers and switch disconnectors
	Safety protections	Lightning strike or overvoltage sensor
	Fire protections	Fire detectors

4. **Tidal farm management:**

To keep the costs of the electricity generated as low as possible, a highly efficient power generation is necessary and continues smoothly with a cost-effective and low-loss transmission in the tidal turbine.

4.1. Power transmission and distribution

Industrial communication is the basis for automation and digitalization, and ensure the reliable and highly available communication in the networking of tidal farms

Table 5.10. Definition of monitoring sensors for tidal farm management.

Definition of monitored COMPONENTS		
FARM ITEMS	**COMPONENT**	**SENSOR**
Turbines	**Power output**	**Voltage & Current sensors**
Turbines Location	-	GPS device
Power Busses	DC & AC buses	Voltage & Current sensors
Communication Busses	Communications device	Communications line
Generated Power	Power buses	Voltage & Current sensors
Consumed Power	Power buses	Voltage & Current sensors
Alarms	Alarm bus	Control system

4.2. Cloud-based condition monitoring system.

Table 5.11. Definition of monitored sensors for turbine monitoring system.

Definition of monitored COMPONENTS		
	COMPONENT	**SENSOR**
TURBINE		
	Temperature	Temperature sensor
	Torque	Torque transducer
	Vibrations	Accelerometer
	RPM	Tachometer
	Component resonance	Accelerometer
	Alignment error	Alignment sensor
	Field error	Voltage sensor
	Bearing damage	Accelerometer

5.3.3 HMI

HMI (Human-Machine Interface) is a 'man-machine interface', a control panel designed to achieve interactive communication between operator and process / machine, with the function of transmitting orders, graphically visualizing the results and obtaining a process situation / machine in real time.

The Figure 5.14 shows the multilevel SCADA and the four proposed HMI.

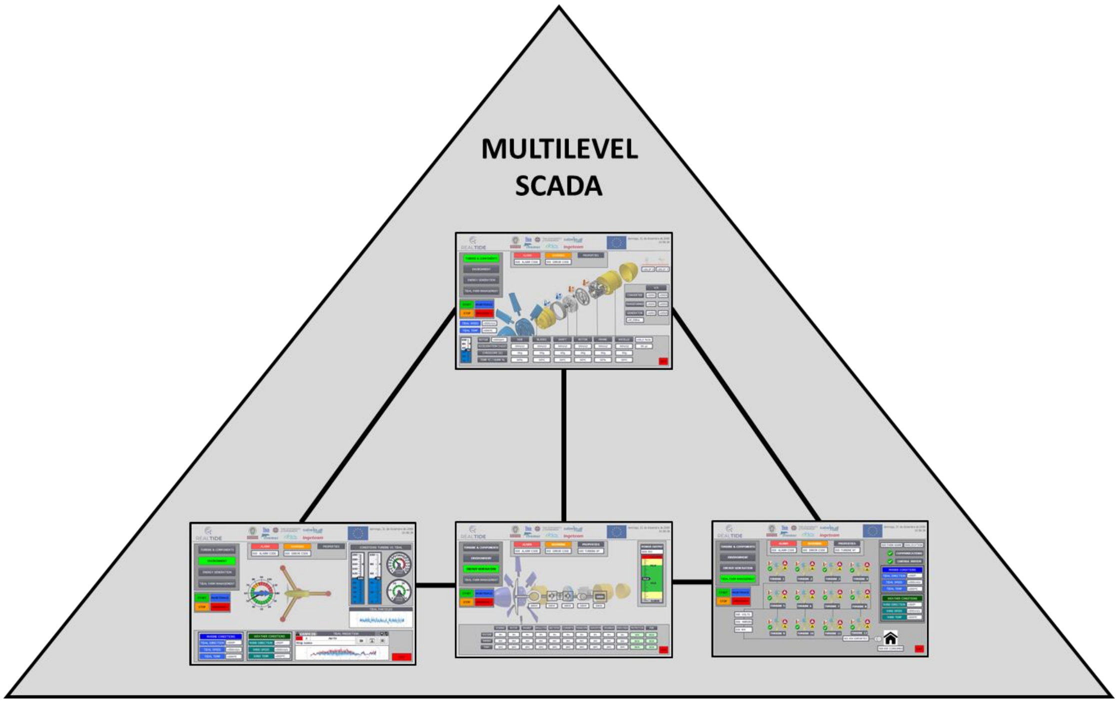


Figure 5.14 Proposed HMI.

The first HMI shows the turbine components and monitor the real-time status for all of them.

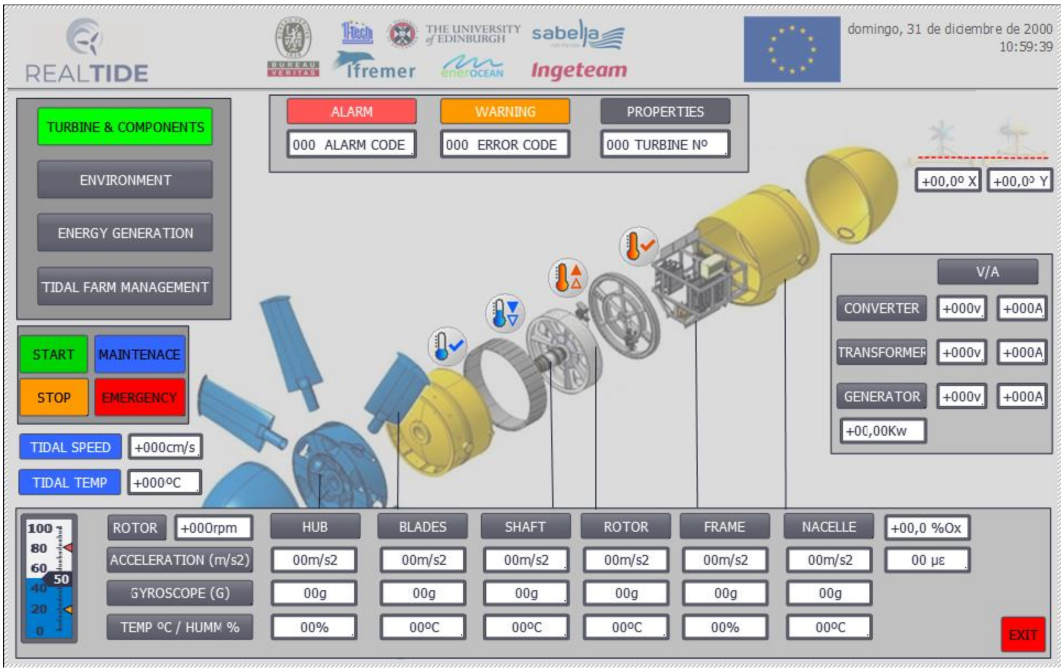


Figure 5.15 Turbine HMI.

The second HMI shows the complete environment analysis:

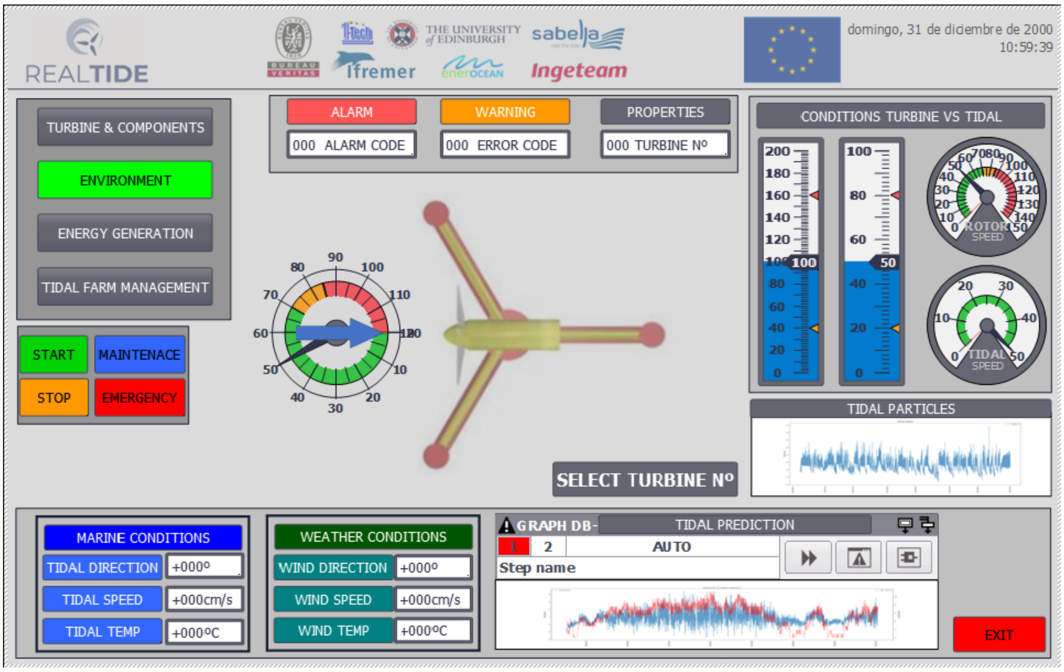


Figure 5.16 Environment HMI.

The third HMI shows the unifilar sheme of the power electronics devices inside the tidal turbine and its parameters:

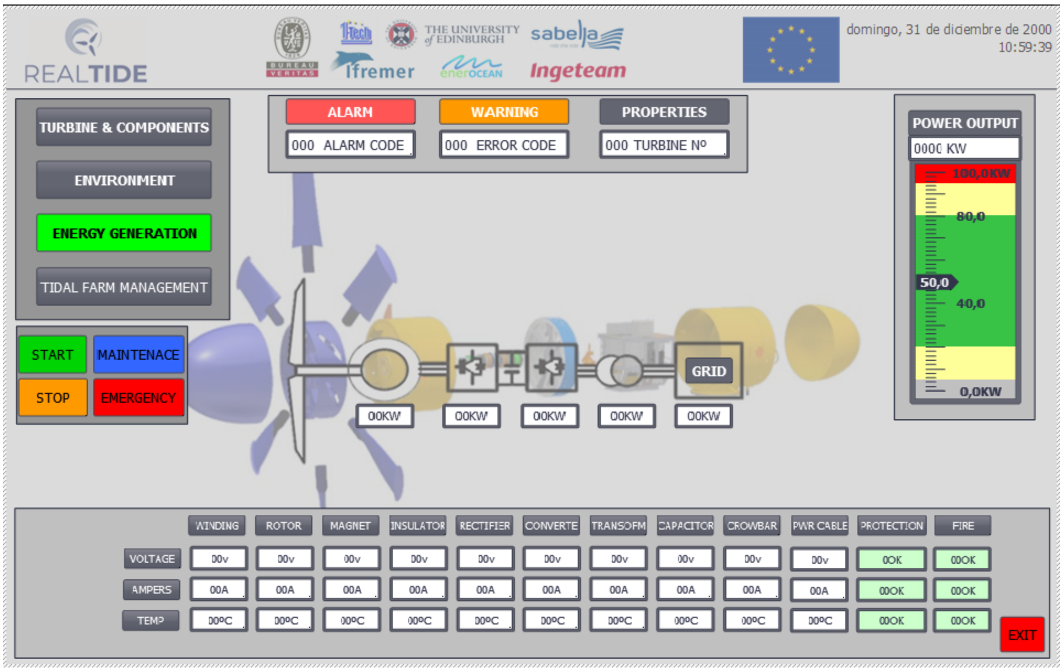


Figure 5.17 Energy export HMI.

The last one shows the complete tidal farm management HMI:

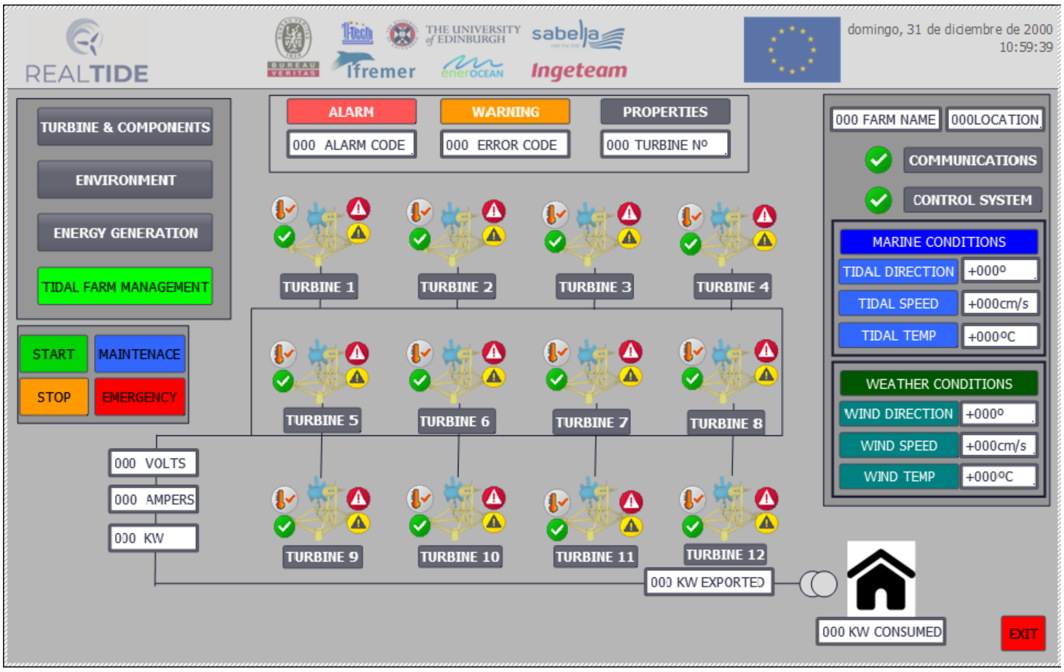


Figure 5.18 Farm management HMI.

5.3.4 Data analysis

Some software for data analysis are mentioned in order to integrated business intelligence and analytics solution (Figure 5.19) [39], that helps to analyse key business data and generate meaningful insights. The software collect data from multiple source points such as SQL databases, spreadsheet etc. to create a collective dataset.

Power BI Vs Qlik Sense Vs Tableau — Data Flair

	Power BI	Qlik Sense	Tableau
Visualization Capabilities	Easy-to-use Platform	Self-service Analytics Tool	Perfect Graphics and Visualization Capabilities
Advances Analytics Capabilities	Supports R Language-Based Visualizations	Does not support R or Python-based objects.	Provides fully integrated support for R and Python
Cloud Capability	Compatible with Microsoft Azure	Offers a SaaS cloud product	Compatible with robust cloud platforms like, Azure, AWS etc
Big Data Integration	Places the solution above Tableau and Qlik	Lets you access and manage all your data, big and small, within a single environment	Connect to nearly any data repository, ranging from MS Excel to Hadoop clusters
Storage Limits	10GB cloud storage	500GB of cloud storage	100GB data storage

Figure 5.19 Software comparison. Source: [39].

Tableau is a visual software for analytics and interactive dashboard, that allow slicing & dicing datasets for generating relevant insights and exploring new opportunities. Users can create interactive maps and analyse data across regions, territories, demographics and more. Tableau helps to create a narrative story of the data analysis with interactive visualizations that can be shared with their audience.

Microsoft Power BI is Microsoft's very own data visualization tool. It becomes better than the rest in some ways as it is compatible best with Microsoft Azure and Microsoft cloud environment. Also, users can connect to Excel to import data and create personalized data dashboards.

Qlik Sense is a simple and interactive data visualization tool which enables users to import and aggregate data from varied big data sources. They can further use the data visualization tools of the software to shape raw data into meaningful information. Qlik also claims QlikView as a potential contender as an efficient big data tool as it can also capable of integrating with multiple data sources at a time.

SAS software is a high-performance analytical program that enables the implementation of data analysis in cloud environments. In addition, SAS facilitates data management as standard.

This software includes high-performance features that divide analytical tasks into parts to accelerate processing. As your data grows and you need more complex analytics, your high-performance code automatically scales to run in a distributed environment.

5.3.4.1 Software for data aggregation.

Once these different solutions have been studied, the use of the Ingeboards® platform is proposed, due to its specific approach to power generation farms, O&M – CBM oriented tool and direct and expert support an Independent Service Provider for renewable industry like the Service Division form Ingeteam.

The software created by Ingeteam Ingeboards® is proposed in this case in order to satisfice the data aggregation software.

Advanced Exploitation Tool:

- Data analysis operations.
- Analysis of errors, alarms, defects and stops.
- Predictive data analysis and inspections.
- Visualization and comparison of variables.
- Data processing service.

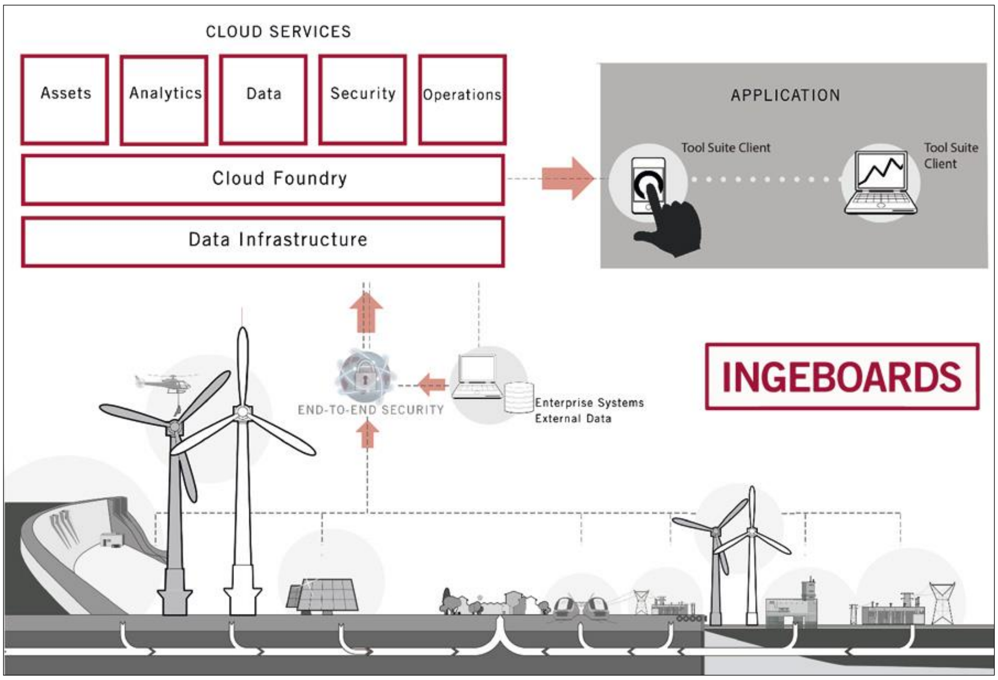


Figure 5.20 Ingeteam Ingeboards scheme.

Some examples tested of results in the management of the O&M are the following:

- Determination of the best maintenance team to perform a specific corrective work based on variables such as:

- Better resolution time (optimal MTTR).
- Effectiveness in resolution (optimal MTBF).
- Less time to resolve the fault.
- Lower added cost (direct plus loss of profit) in the resolution of the breakdown.

5.3.4.2 KPI´s

Ingeboards® is a web platform that integrates any type of information from the daily operation of a tidal farm, in such a way that it allows data to be imported both online and offline, adapting to the way in which they are registered and / or exported.

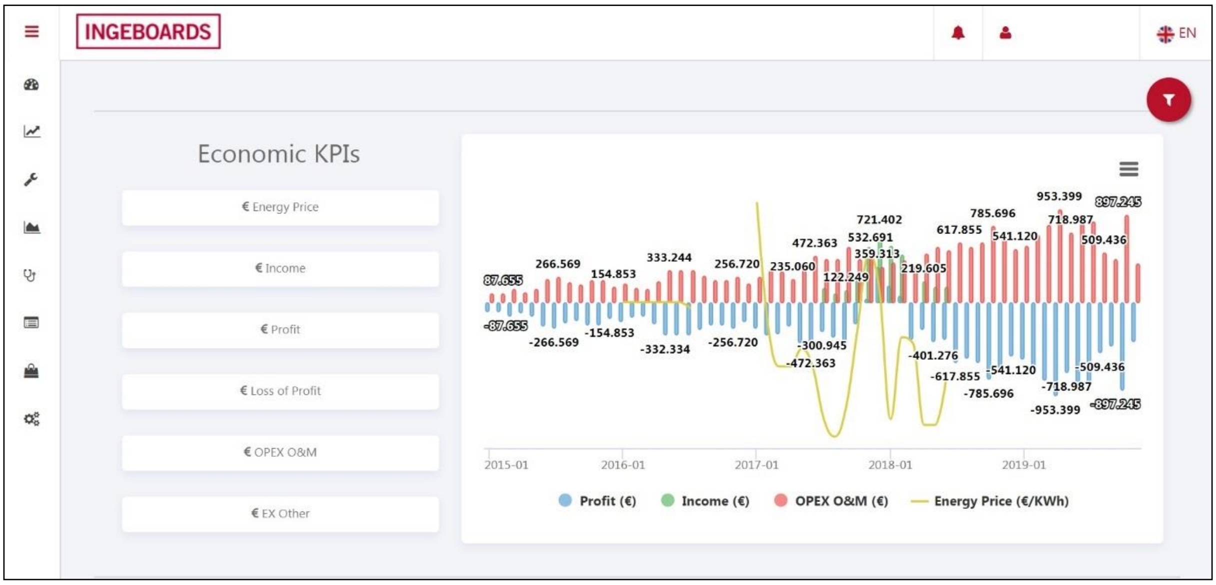


Figure 5.21 Ingeboards® economic KPIs.

Ingeboards® can try all kinds of file formats and read data directly from a form enabled on the platform itself.

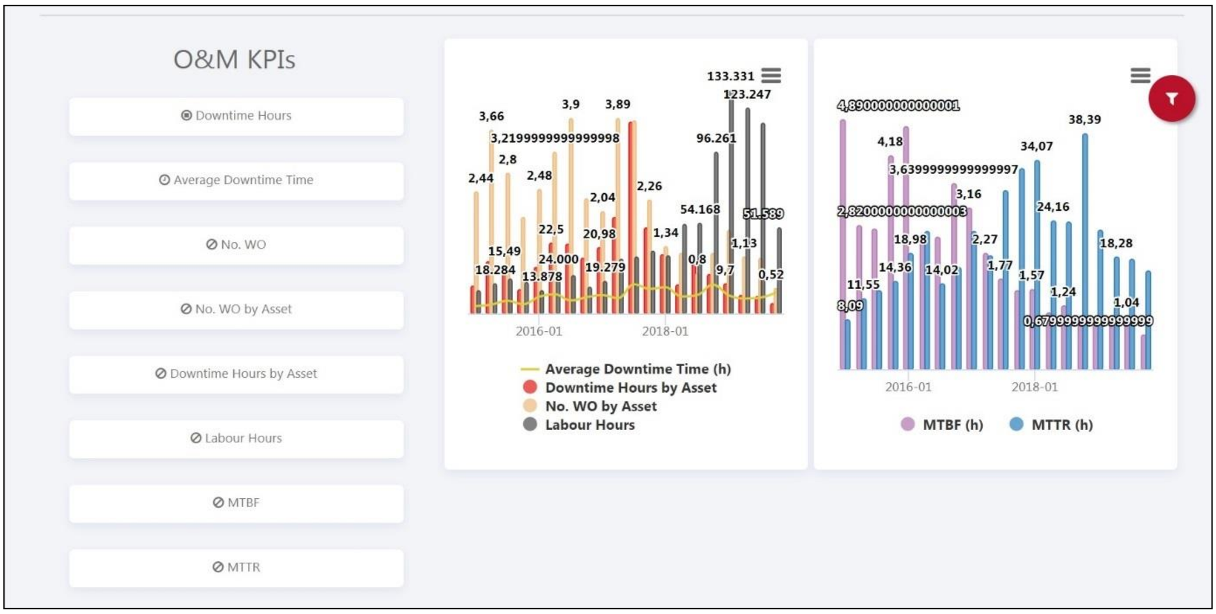


Figure 5.22 Ingeboards® O&M KPIs.

As outstanding features in terms of treatment of operational and predictive data, for the analysis of the errors, Ingeboards® provides a very powerful graphical interface that determines the root causes that cause the unavailability (temporary and energetic) analysing from the general to the particular, being able to see from the data added by company to the work part individual performs comparative and statistical analysis of the variables, efficiency analysis, calculation of the deviation of the power curve and the generation of alarms based on anomalies.

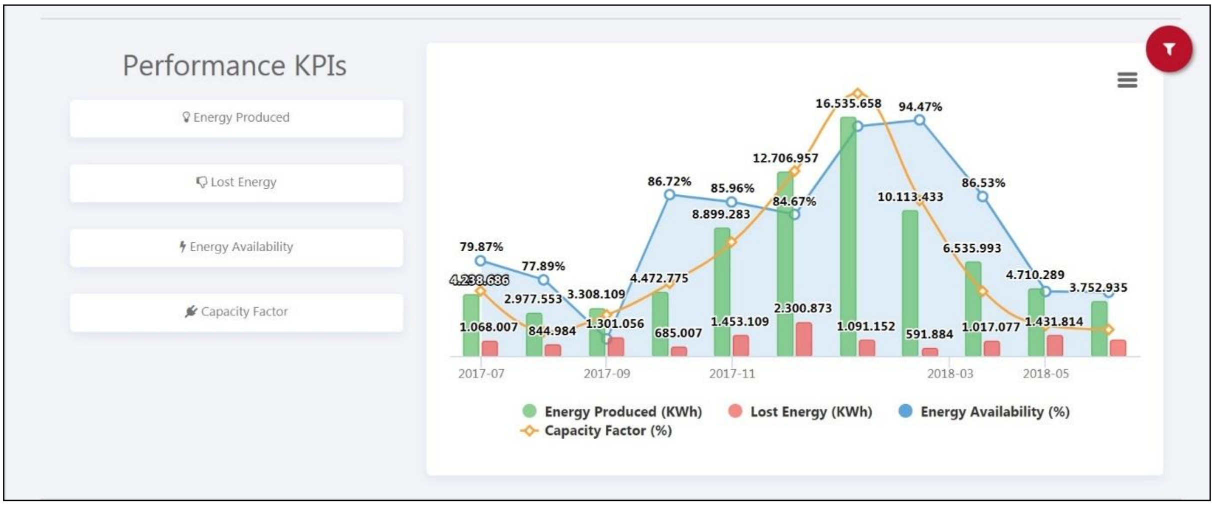


Figure 5.23 Ingeboards® performance KPIs.

5.4 Key parameters definitions

Based on the state condition monitoring, the following physical magnitudes are established to define of the key parameters involved in the definition of a maintenance strategy: direct, indirect and heuristic measures.

5.4.1 Direct physical magnitudes

Table 5.12 Key parameters for physical magnitudes.

Element	Direct physical magnitude
Environment	Tidal Velocity
	Tidal direction
	Tidal temperature
Nacelle	Nacelle shell oxidation
	Inclination
	Pressure
	Deformation
Blades	Cracks
	Deformation
Bearings	Accelerations
	Vibrations
	Temperature
Drive train	Accelerations
	Torque
Generator	Accelerations
	Voltage
	Current

	Temperature
Converter	**Accelerations**
	Voltage
	Current
	Temperature
	Humidity
Transformer	**Accelerations**
	Voltage
	Current
	Temperature
	Humidity
Cabling	**Deformations**
	Temperature
	Pressure
Protections	**Temperature**
	Smoke
	Voltage
	Current

5.4.2 Indirect parameters

Indirect measurement is a method of using proportions to find an unknown physical parameter.

Table 5.13 Key parameters for indirect measurements.

Element	Indirect parameters
Blade	*Resonance time*
Bearings	*Energy lost by hot*
Drive train	*Energy lost*
Generator	*Energy generated*
Converter	*Power output*
Transformer	*Energy exported*
	Energy consumed

5.4.3 Heuristics indicators

In human-computer interaction, several steps are followed to create systems that are user friendly. In the evaluation step, two types of tests are performed: usability and expert. In the latter, the heuristics created by Jakob Nielsen [40] are used to evaluate the design of the user interface:

- Visibility of the system status.

- Relationship between the system and the real world.
- User control and freedom.
- Consistency and standards.
- Error prevention.
- Recognize rather than remember.
- Flexibility and efficiency of use

Table 5.14 Heuristics indicators.

Element	Indirect parameters
Environment	*Tidal speed prediction*
	Temperature prediction
Blade	*Compound fatigue*
Bearings	*Life extension*
	State prediction
Generator	*Fail probability*
	Interventions prediction
	Life time
	Availability prevision
Converter	*Intervention prediction*
	Error prevention
	User control facility
Transformer	*Life time*
	Intervention predictions

5.5 Alarms set-up

Based on the information about the status of the machine, a common criterion is defined for alarms set-up, criticality levels and multilevel integration, to do properly a maintenance strategy.

5.5.1 Operator defined limits

The following table shows the alarms setup limits and critically levels defined on a standard wind turbine.

Table 5.15 Operator defined limits and critically levels.

Alarm description	Defined limit	Critically level
Cold Oil	*-10ºC*	*-10ºC defined*

Gearbox pressure	*3.5bar*	*5bar defined*
Control cabinet temperature	*55ºC*	*60ºC defined*
Power cabinet temperature	*60ºC*	*65ºC defined*
Blades Vibrations	*5%nom*	*>5% defined*
Tower Vibrations	*10%nom*	*>5% defined*
Transformer temperature alarm	*80ºC*	*85ºC defined*
Pitch	*+-3º*	*+-6º*
Pitch 1 Incoherence	*3º*	*>3% defined*
Pitch 2 Incoherence	*3º*	*>3% defined*
Pitch 3 Incoherence	*3º*	*>3% defined*
Anemometer	*1.5m/s*	*>2% defined*
Low wind	*2m/s*	*1.5m/s*
High wind	*23m/s*	*25m/s*
High nacelle temperature	*50ºC*	*>5% defined*
High environmental temperature	*45ºC*	*50ºC defined*
High Gear Oil temperature	*80ºC*	*>5% defined*
High Gen1 temperature	*150ºC*	*>5% defined*
High transformer temperature	*150ºC*	*>5% defined*
Low Gen1 temperature	*-20ºC*	*>5% defined*
Low nacelle temperature	*-5ºC*	*>5% defined*
Low frequency	*<45Hz*	*>5% defined*
High frequency	*>55Hz*	*>5% defined*

5.5.2 Based on standards

Next table shows the alarms proposed on standard tidal turbine:

To understand the table, a legend is shown with the description of the effect produced by the alarms.

- **Alarm description:** Describe the type of failure produced in the element.
- **Control name**: Displays the label used by the HMI in the alarm list.
- **Effect on turbine**: Describe the state in which the turbine enters once the alarm has occurred.
- **Soft stop:** Turbine shutdown occurs slowly and in a controlled manner.
- **SOFT STOP + fault YAW**: The turbine is stopped in a slow and controlled manner and the yaw system enters into error mode.
- **SOFT STOP + fault:** Turbine shutdown occurs slowly and in a controlled manner and it goes into error mode, forcing a manual reset.
- **SOFT STOP + WARNING**: Turbine shutdown occurs slowly and in a controlled manner and it goes into warning mode, needing an automatic reset.

- **Fault GRID + SOFT STOP:** It causes the decoupling of the network and also the turbine shutdown occurs slowly and in a controlled manner.

Table 5.16 Alarms set-up based on standard.

Alarm description	Control name	Reaction
System Error	System-Error	SOFT STOP
Cold Oil	Gear-Cold	SOFT STOP
Gearbox Oil Level	Gear-Level	SOFT STOP
Failure gearbox lubrication system	Gear-Flow	SOFT STOP
Gearbox pressure	Gear-OilPr	SOFT STOP
Control cabinet temperature	Tem-Cab	SOFT STOP
400v Protection	400V-Surge	SOFT STOP + fault YAW
690v Protection	690V-Surge	SOFT STOP + fault YAW
Overvoltage protection	OverVolt	SOFT STOP + fault YAW
Converter fuses	Conv-Fuse	SOFT STOP + fault
Hydraulic level error	HydLevError	SOFT STOP + fault
Main switch 690V	MainS	SOFT STOP + fault
Power cabinet temperature	Tem-Cab	SOFT STOP
Blades Vibrations	Vib-Blade	SOFT STOP
Transformer temperature alarm	Tem-Trf	SOFT STOP
Inverter fault	Inv-Fault	SOFT STOP
Manual Stop	ManualStop	SOFT STOP
Encoder error	Inv-Encoder	SOFT STOP
Inverter Cooling	Inv-Cooling	SOFT STOP
Pitch	PthError	SOFT STOP
Blade 1 Emergency	PthEmergB1	SOFT STOP
Blade 2 Emergency	PthEmergB2	SOFT STOP
Blade 3 Emergency	PthEmergB3	SOFT STOP
Pitch 1 Error	Pth1	SOFT STOP +fault
Pitch 2 Error	Pth2	SOFT STOP +fault
Pitch 3 Error	Pth3	SOFT STOP +fault
Warning pitch general	Main-Pth	SOFT STOP +fault
Yaw Brake bloked	Yaw-BrBlock	SOFT STOP +fault
Anemometer	Anem-Check	SOFT STOP
Low wind	Low-Wind	SOFT STOP
High wind	Hi-Wind	SOFT STOP
Preventive maintenance	Prev-Maint	SOFT STOP + WARNING
Corrective maintenance	Cor-rMaint	SOFT STOP + WARNING
High nacelle temperature	HiTempNacell	SOFT STOP
High environmental temperature	HiTempEnviro	SOFT STOP
High Gear Oil temperature	HiTempGear	SOFT STOP

High Gen1 temperature	HiTempGen1	SOFT STOP
High transformer temperature	HiTempTrf	SOFT STOP
Low Gen1 temperature	LoTempGen1	SOFT STOP
Low nacelle temperature	LoTempNacell	SOFT STOP
Low frequency	Low-Freq	Fault GRID + SOFT STOP
High frequency	High-Freq	Fault GRID + SOFT STOP
System Error	System-Error	SOFT STOP
Cold Oil	Gear-Cold	SOFT STOP
Gearbox Oil Level	Gear-Level	SOFT STOP

6 CONCLUSIONS

The objective of the task 4.3 has been achieved by the development of a methodology that can be applied for Condition Based Maintenance of the four RealTide tidal turbine concepts which are representative enough to cover most of the cases that can be found in the current tidal market.

The first step was to perform a study of the state of the art of the maintenance strategies that are used in the industry. It has been seen how predictive maintenance and, more specifically, CBM strategies are gaining more and more relevance and they are gradually replacing traditional maintenance strategies which are based purely in preventive and corrective maintenance or a combination of both. According to the maintenance strategies exposed, three monitoring strategies were defined and they will be taking into account for the development of the electronics: Spot Measurement (**SM**), Basic Permanent Monitoring (**BPM**) and Permanent Monitoring (**PM**).

After the analysis of the critical components identified in the FMEA it was decided to focus only on the **blades** and the **drivetrain** to be integrated on the CMS for being critical in tidal turbines and worth to be monitored. This decision is premised in the fact that apart of being the most critical ones, they are very significate in the tidal industry since they are not so well-known as other elements that highly resemble to tidal turbines. A selection and description of suitable monitoring techniques to be integrated into the Condition Monitoring System has also been made, where we can highlight the use of the Model Based Estimation (**MBE**) as an alternative to traditional monitoring techniques. In the case of the blades, two different Model Based Estimation approaches have been defined. One of them will combine the actual reading of the blade stresses acquired by the CMS with the estimated value coming from the BEMT model. The other one, which can be very useful for SM strategy, will allow to detect and characterise defects that might appear in the blade. After defining the monitoring techniques to be used, the specifications that the drive train and blade monitoring must meet have been presented, including a list with sensors considered. These sensors are currently being tested as a part of the work to be developed in WP2.

In last instance, a review of the state of the art of most widely use cluster techniques for CMB was made, and also an application to tidal turbines was presented. Particularly, the **k-means** algorithm is used satisfactorily to cluster the environmental data of a turbine. Based on a representative cluster of the environmental conditions data set, a clustering technique for the machine condition data set has been presented. In this case, as there are many variables involved, the **t-SNE** algorithm has been used to perform a dimensional reduction of them and the **DBSCAN** clustering algorithm has been found as the most appropriate for this purpose obtaining good clustering which collects representative operating condition of the machine.

After that, the methodology for the integration of CBM strategies into a SCADA system was set up as well as the definition of KPIs and alarms. Multilevel SCADA allows to manage and control in real time all the aspects related to the tidal farm. The following levels have been proposed: environment, energy generation, tidal farm management and turbine & components. A review of the most widely used data analysis package has been performed, where the use of an **already commercially available** package (Ingeboards®) has been recommended. KPI's and alarms set-up

The final goal of the work undertaken here is that the methodology serves as a benchmark that can be applicable to CBM in tidal turbines as well as a starting point for the integration of these techniques with the electronic that runs in parallel in the rest of the tasks of WP4 and the models being developed in WP3. Here are the next steps to take, following the work exposed in this document:

- Integration of the already finished models with the electronic that is being developed in parallel within WP4. It will be included in D4.2: *"Report on the performance of the new* *integrated monitoring strategy*" and D4.4: *"Test report Mechanical loading of instrumented blade".*

- Fully integration data acquisition system, including models, into the SCADA system.
- A development of a detailed cost model in further steps will be done with the objective of comparing CBM strategies to other maintenance strategies also from an economic point of view. It will be included in D4.5: *"Publishable summary on the impact of monitoring in cost reduction of Tidal Devices and proposed Monitoring protocol draft".*

7 Annex: Paper presented at 13th European Wave & Tidal Energy Conference (EWTEC), Sept. 1-6, 2019, Naples.

Improving reliability of tidal turbines: a new step by step methodology for initial quantification of criticality and recommendations

Pedro M. Mayorga, Vincent P. Le Diagon, Ana I. Mayorga, Ningxiang Li, Manunggal Sukendro, José M. Barranco, Mairi Dorward and Jan E. Hanssen

Abstract—**In order to understand and contribute to increased reliability of tidal energy devices, the EU project *RealTide* aims to develop a reliability methodology based on Failure Modes and Effect Analysis (FMEA) methodology with inputs from the experience of project partners and existing literature. The methodology has been applied to four generic tidal turbine concepts resulting in recommenddations such as design improvements and condition monitoring, activities intended to reduce or eliminate the probability or the severity of critical failures.**

This paper presents the FMEA methodology that has been adapted to obtain a reliability analysis in line with the specificities of tidal turbines.—The recommendations are selected based on the criticality of the mitigated failure mode in order to prioritize the recommendations that are most likely to increase tidal turbine reliability, generating a method to choose the best action, or potential course of action, from the potential set of options available to the developer.—The FMEA analysis performed in the four generic tidal turbine concepts resulted in a total of 243 recommendations where 137 are monitoring recommendations and 106 are redesign recommendations. The specificities of each design strongly affect the type and number of recommendations.[2]

Keywords—**Tidal Turbine, Reliability, FMEA, Methodology.**

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I. Introduction

THE Horizon 2020 project "Advanced monitoring, simulation and control of tidal devices in unsteady, highly turbulent realistic tidal environments" (Real Tide) [14], runs from 2018 throughout 2020 and includes partners Bureau Veritas, EnerOcean, Sabella, Ingeteam Power Technology, Institut Français de Recherche pour l'Exploitation de la Mer; 1-Tech; and The University of Edinburgh. The RealTide project aims at developing the next generation of tidal devices in line with energy market and environmental policies expectations to identify main failure causes of tidal turbines at sea and to provide a step change in the design and advanced monitoring of key components, namely the blades and power take-off systems, adapting them more accurately to the complex environmental tidal conditions.

Tidal turbine technology has gained prominence due to its simplicity, the ability to harvest energy directly from tidal currents and its limited ecologically intrusive nature. This emergent technology is still under development and there is limited data available about the operating reliability of tidal turbines.

Three important factors limit the development of maintenance and monitoring plans for tidal turbines:

- Given that this technology is at an early stage of development, the data used must be that which is gained from accumulated experience in similar technologies such as wind turbines [1].
- There is not a single design of tidal turbine, R&D continues into different types of tidal turbines (horizontal axis, vertical axis, floating tethered, seabed fixed, etc.) [2].
- Tidal turbines must be designed to withstand and operate in the harsh marine environment

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with associated considerations relating to accessibility for maintenance [1].

In order to understand and contribute to the increased reliability of tidal turbines, one of the RealTide project objectives is to develop a reliability methodology based on Failure Modes and Effect Analysis (FMEA) methodology with inputs from partners' experience and existing literature. FMEA is a systematic and comprehensive analysis that aims to increase reliability of equipment and systems by identifying actions which will mitigate or eliminate the critical failures.

This paper presents the FMEA methodology that has been adapted in order to obtain a reliability analysis in line with the objectives and specificities of the RealTide project goals but also to demonstrate a methodology that is applicable to any type of tidal turbine.

II. RealTide objectives

One of the objectives of the RealTide project is to conduct a reliability analysis on a generic tidal rotor using the Failure Mode and Effects Analysis (FMEA) methodology, with the FMEA being based on partners' experience and existing literature.

Many traditional failure modes of components in offshore conditions are already referenced in databases such as OREDA -offshore and onshore reliability data and ISO 14224 - "petroleum and natural gas industries – collection and exchange of reliability and maintenance data for equipment" [15], both are from the oil & gas sector.

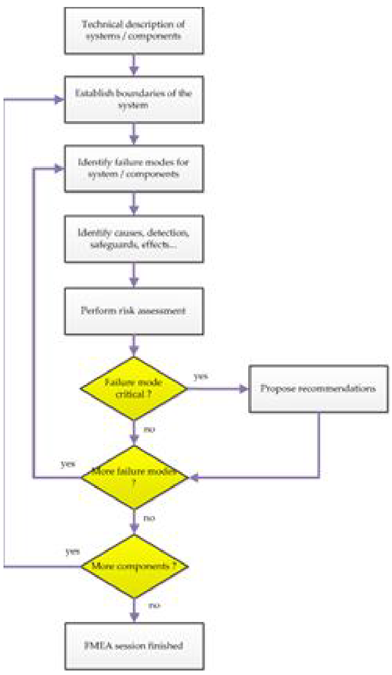

Fig. 1. Generic FMEA methodology.

In addition, as tidal turbine power trains have similarities to wind turbines, they share a significant number of failure modes that are relatively well known and documented, *e.g.*, by the ReDAPT (Reliable Data Acquisition Platform for Tidal) project [4].

This FMEA was performed to highlight new failure modes induced by the specific operating conditions of tidal turbines.

Given that tidal turbines will operate for many years in remote and harsh environments, enhanced turbine design and monitoring contribute to preventing the occurrence of failures and consequently to reducing operational costs and increasing performance over its lifecycle.

This is why the methodology focuses on generating recommendations for design improvements and/or monitoring activities to be implemented on tidal turbines. The recommendations are selected based on the criticality of the mitigated failure mode in order to prioritize the recommendations most likely to increase the reliability of the tidal turbine.

III. FMEA Methodology

A. Introduction

The FMEA is a methodology widely used in the industry to increase the reliability of assets identifying requirements for design improvements, better manufacturing and operational procedures or maintenance optimization.

The FMEA methodology, the principles of which are described in standard IEC 60812:2006 "Analysis techniques for system reliability – Procedure for failure mode and effects analysis (FMEA)" [5], has been adapted to the Real Tide objectives.

B. Objectives and Principle

Failure Mode and Effects Analysis (FMEA) is a method designed to:

- Identify and fully understand potential failure modes and their causes, and the effects of failure on the system or end users, for a given product or process.
- Assess the risk associated with the identified failure modes, effects and causes, and prioritize issues for corrective action.
- Identify and carry out corrective actions to address the most serious concerns.

The FMEA is based on a "single failure concept" so that each considered component is assumed to fail by one probable cause at a time. The effects of the failure mode are analysed and classified according to their severity. Such effects may include secondary failures effects (or multiple failures effects). The generic FMEA methodology process is shown graphically in Fig. 1.

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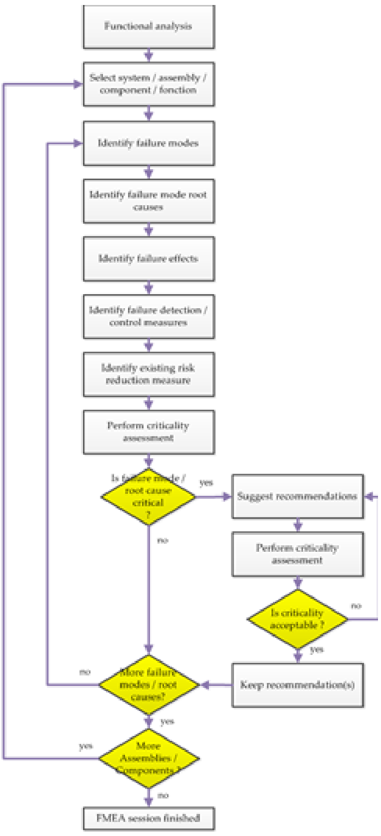

Fig. 2. RealTide adapted FMEA methodology.

IV. FMEA Methodology for Tidal Turbines

C. Overview

Despite there being several FMEA standards and guidelines setting up the process and principles of the methodology such as IEC 60812 [5], SAE J1739 [11], AIAG FMEA-4 [12] and MIL-STD-1629A [13], modifications to the methdology are required given project objectives, the scope and the context.

Since the objectives of the RealTide project are to recommend improvements in tidal turbine design and to establish a monitoring strategy to enhance reliability, the partners made the necessary adaptations to the methodology resulting in the process presented in Fig. 2.

D. Steps and definitions

1) Functional analysis

After defining the system boundaries of the tidal turbine, a top-down process of splitting up the tidal turbine system can be used to define the individual components and their functions that are to be assessed in the FMEA.

The tidal turbine, as a system, is divided into various levels of functional hierarchy, such as sub-systems, assemblies, sub-assemblies etc down to individual component level, the lowest level of the FMEA analysis.

Fig. 3 presents an example of a functional breakdown for a generic tidal turbine to sub-assembly level. The figure was generated by using similarities with wind turbines and previous studies available in the literature [1-2], [6-8].

The function is the purpose for which the sub-assembly or component is designed to ensure the operation and integrity of tidal turbines.

The function supports the FMEA analysis by defining the failure modes and also helps define the local and system effects of the failure modes.

2) Identification of failure modes

The failure mode is defined as the means by which a failure is observed on the failed unit. As per OREDA 2009 [3], the failure modes describe the loss of required system function(s) that result from failures, or an undesired change in state or condition.

The failure mode description may include:

- the failure to perform a function within defined limits;
- inadequate or poor performance of the function;
- intermittent performance of a function;
- performance of an unintended or undesired function;

The failure mechanism is the physical phenomenon leading to the failure mode (e.g.: corrosion, fatigue, erosion, wear, friction, overheating…).

The failure modes of a component are studied according to the component's design, its function and operation, and are assumed to occur one at a time.

3) Identification of failure mode root causes

A root cause is an initiating cause of either a condition or a causal chain that leads to the failure mode. The root cause, by definition, is extrinsic to the item being studied.

The FMEA focuses on the following root causes:

- Causes due to the marine environment (e.g.: turbulence, overload due to excessive tide, algae growth, presence of sand/rocks in water, fouling);
- Chain effect: causes coming from defects that have occurred on other assemblies/components (e.g. rotor vibration due to mooring line failure;
- Failure due to design defects, poor manufacturing practices, or installation errors should also be recorded as per analysts' experience.

It is assumed that there is only one possible cause at a time. Since a failure mode may have more than one cause, the potential independent causes of each failure mode are identified.

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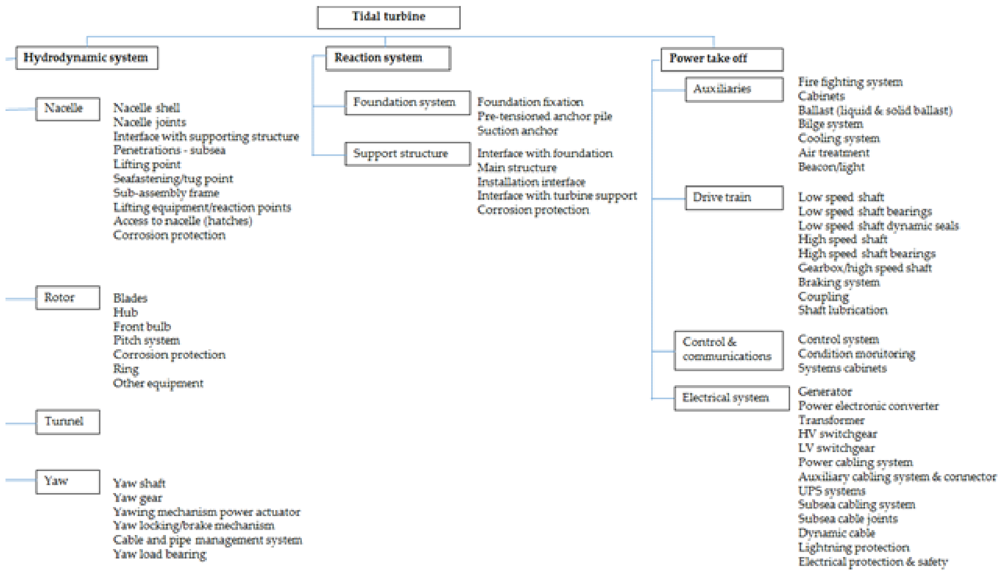

Fig. 3. Generic tidal turbine functional hierarchy.

4) Identification of failure effects

The consequence of a failure mode on the operation, function, performance or status of a component or a system is called a "failure effect". Failure effects on a specific sub-system or component under consideration are called "local failure effects". In some cases, there may not be any local effect beyond the failure mode itself.

The impact of a failure mode on the system is called an "end effect" or "system effect". The "end effect" takes into account all safeguards included in the design (such as redundancy, by-passes...) that minimize the impact of the failure on the system, sub-system or function. The safeguards must be able to reduce the likelihood of occurrence of the failure mode or to prevent or reduce the effects of the failure mode.

Effects may include secondary failure effects (or multiple failure effects). In such cases, all effects of each failure mode are identified.

The end effects are categorized according to their impact on Personnel safety, Environment and Economics.

5) Identification of failure detection and control measures

Detection and control measures are the means of detection of the failure mode by the maintainer, operator or built in detection system.

In other words, detection and control measures describe how the occurrence of a failure mode is detected and made evident.

Detection and control measures are intended to increase the likelihood of detecting the failure mode before it results in the end effect; mitigating the consequence at system level.

Failure detection and control measures can be visual or audible warning devices, automatic sensing devices, sensing instrumentation or other unique indicators, and have to be identified in the FMEA for unacceptable failures when existing. Failure detection is almost immediate when it results from a monitoring system tripping. Where failure is detected by occurrence of its effects, detection might be immediate or postponed. Failure detection, if not linked to an automatic action (equipment tripping, back-up equipment starting ...), warns maintenance staff, in order that action can be taken without delay and before the situation worsens.

Failure detection and control measures are to be identified and taken into account to evaluate failure effects, particularly for unacceptable failures.

6) Identification of existing risk reduction measures

Risk reduction measures are safeguards which can reduce the likelihood of occurrence of the failure mode or prevent or reduce the effects of the failure mode.

More precisely, risk reduction measures are the methods or actions currently planned, or that are already in place, to reduce or eliminate the risk associated with each potential cause.

Risk reduction measures are divided into two categories:

1. Design controls: methods applied during product development that prevent or detect potential failures on the system in order to improve its design, such as:
    a. General design practices. Rules, practices and standard;

b. Detailed analysis. CAE (computer aided engineering): FEM (finite element model), CAD (computer-aided design), CFD (computational fluid dynamics), etc.;
c. Redundancy;
d. Experimental campaign (simple), scale prototypes;
e. Extended experimental campaign, full scale components.

2. In-service monitoring: action that detects the imminence of a failure during service before it occurs or it becomes catastrophic, such as:
   a. Inspection visit tools;
   b. Indirect detection (integrated effect);
   c. Model based estimation;
   d. Direct measurement (cause or effect);
   e. Multiple integrated detection.

There can be both design controls and in-service monitoring associated with a failure and its cause.

Design control is usually intended to reduce the occurrence of the failure mode while in-service monitoring is intended to increase its detection.

7) Criticality assessment

As defined in the standard IEC 60812:2006 "Analysis techniques for system reliability — Procedure for failure mode and effects analysis (FMEA)" [5], criticality is the impact or importance of a failure mode that would demand it to be addressed and mitigated. The purpose of a criticality analysis is to quantify the relative magnitude of each failure effect as an aid to decision making to prioritize actions to mitigate or minimize effect of certain failures.

One of the most common methods of determination of criticality is the "Risk Priority Number", RPN. Risk is here evaluated by a subjective measure and combination of:

- the *severity* of the effect ;
- the expected probability of its *occurrence* (for a predetermined time period assumed for analysis); and
- the chance of *detection* of the failure mode before it affects the system.

The success of the FMEA methodology in industry is due to the fact that criticality can be assessed quickly, utilising a work team's experience and common sense rather than extensive data. This is particularly relevant when the criticality assessment is carried out on new concepts or in research and development projects where data and operating experience are unavailable or very limited.

The RPN and the criteria for *severity*, *occurrence* and *detection* are described below.

a. RPN Calculation:

The RPN is expressed as follows:

$$RPN = S \cdot O \cdot D \qquad (1)$$

Where:

S - severity: is a ranking number for severity, i.e. an estimate of how strongly the effects of the failure will affect the system or the user.

O - occurrence: is a ranking number for probability of occurrence of a failure mode for a predetermined or stated time period;

D - detection: is a ranking number for the chance to identify and eliminate the failure before the system or customer is affected.

b. RPN criteria : severity, occurrence &detection:

Based on criteria proposed by Peter Tavner on wind turbines [7], the RealTide partners developed criteriamore relevant to specificities of the tidal industryand ranking scale for *severity*, *occurrence* and *detection*

Each criterion is divided into 4 levels in which the partners defined a range of ranking scale to be selected for each failure mode. The ranking scale varies from 1 to 10, where 1 is the value that least impact the criticality and 10 is the value that impacts criticality the most.

The assessment of RPN criteria for a given failure mode is made in a funnel-type process that consists in:

- first, selecting the level which corresponds to the failure mode based on information given for root cause, failure effects, detection / control measure, and risk reduction measure;
- then, selecting a ranking scale value within the range proposed in the corresponding level.

This funnel-type process gives flexibility in fine tuning the criticality assessment for failure modes that are in the same criteria level.

The criteria and ranking scale for *severity*, *occurrence* and *detection* are described as follows.

i. Severity

Severity is a ranking number associated with the most serious effect for a given failure mode based on the criteria presented in the Table I.

Severity criteria are divided into 3 categories: economic, environment and health & safety.

When a failure mode presents effects that impact more than one category (e.g. economic and environment), the worst affected category will be selected.

Severity is determined without regard to the likelihood of occurrence or detection.

ii. Occurrence

Occurrence is a ranking number associated with the likelihood that the failure mode and its associated cause will occur during the operating life cycle of the system. It is based on the criteria presented in Table II.

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TABLE I
S - SEVERITY RANKING SCALES

Scale	Description	Economic Criteria	Environment criteria	Health &safety criteria
1-3	Minor	No losses to < 2% of the total amount invested	Temporary imperceptible impact / Permanent Imperceptible impact / Temporary slight impact	No significant injury / Minor Injury / Accident without time off work
4-5	Marginal	From 2% to < 10% of the total amount invested	Permanent slight impact / Temporary moderate impact	Accident with time off work < 6 months
6-7	Critical	From 10% to < 50% of the total amount invested	Permanent moderate impact / Temporary severe impact	Accident with time off work > 6 months / Partial disability
8-10	Catastrophic	From 50% to > 100% of the total amount invested or total loss of turbine	Permanent severe impact / Temporary major impact / Permanent major impact	Full permanent disability / Severe disability / Death

Occurrence has a relative meaning rather than an absolute value and is determined without regard to the severity or likelihood of detection.

iii. Detection

Detection is a ranking number associated with the chance of detecting and then acting onthe failure mode before it affects the system based on criteria presented in Table III.

Detection is determined without regard to the severity or likelihood of occurrence.

The *detection* scale is ranked in reverse order from the *severity* or *occurrence* scales: the higher the detection value, the less probable the detection is. The lower probability of detection consequently leads to a higher RPN, and a higher priority for mitigating or eliminating the failure mode.

c. Criticality Matrix and Risk Acceptance Criteria

TABLE II
O - OCCURRENCE RATING SCALE

Scale	Description	Criteria
1-2	Extremely unlikely	A single Failure Mode probability of occurrence is less than 0.001 per year
3-5	Remote	A single Failure Mode probability of occurrence is more than 0.001 per year but less than 0.01 per year
6-8	Occasional	A single Failure Mode probability of occurrence is more than 0.01 per year but less than 0.10 per year
9-10	Frequent	A single Failure Mode probability greater than 0.10 per year

TABLE III
D - DETECTION RATING SCALE

Scale	Description	Criteria
1-2	Almost Certain	Current monitoring methods almost always detect the failure
3-5	High	Good likelihood current monitoring methods will detect the failure
6-8	Low	Low likelihood current monitoring methods will detect the failure
9-10	Almost impossible	No known monitoring methods available to detect the failure / Detection before fail not possible or needs special equipment/destructive testing

The criticality is presented on a criticality matrix, as shown in Fig. 4. The *severity (S)* is presented in Y-axis and increases with the ascending order of ranking scale from 1 to 10. The X-axis represents product of ranking scales of *occurrence* and *detection* (*O* x *D*), and is represented in ascending order from to 1 to 100 (which corresponds to the minimum and maximum value of *O* x *D*).

The criticality matrix gives a visual indication whether failure mode is critical or not according to the risk acceptance criteria adopted by project partners as described further below.

The red zone corresponds to the *unacceptable* area, i.e., the failure modes in this area are considered to be of high criticality and need to be mitigated or eliminated by design improvement and/or extra monitoring.

The yellow zone corresponds to the *tolerable* area, i.e., the failure modes in this area are considered to be of medium criticality. The failure modes can be mitigated or

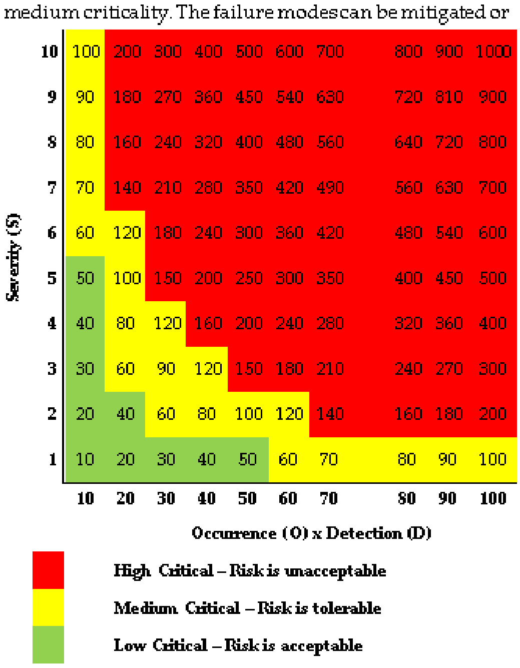

Fig. 4. RPN Criticality Matrix.

eliminated by design improvement and/or extra monitoring if the implementation of these actions is cost effective.

The green zone corresponds to the *acceptable* area, i.e., the failure modes are considered low criticality. In this case the failure mode does not impact economic, environment nor health & safety categories and doesn't need to be mitigated or eliminated.

Risk acceptability and the definition of the three zones were defined subjectively by RealTide project partners based on their experience in previous FMEA studies.

The limits between the criticality zones have been defined as follows:

- High criticality components are those that present a scale ranking of at least "5" for each criticality criterion (S, O and D). It means that the RPN of a critical element is : RPN ≥ 5 x 5 x 5 =125;
- The value to define the limit between medium and low criticality zones was set as being half the value of the limit between high and medium criticality (RPN = 125÷2 ≈ 60).

8) Recommendations

As explained in the previous section, recommendations shall be made for high criticality failure modes, i.e., where risk is considered unacceptable.

Recommendations are the actions identified by the work team to reduce or eliminate the risk associated to the failure mode.

They should consider:

- existing controls (i.e., risk reduction measures);
- relative importance (prioritization) of the issue;
- cost and effectiveness of the corrective action.

There can be many recommended actions for each failure mode.

As the objective of the methodology is to increase reliability, improve design and elaborate an effective monitoring plan for tidal turbines, RealTide partners have developed a methodology to prioritise the recommendations for failure modes in terms of redesign and condition monitoring as follows:

1. The first step is to consider the RPN value. If the RPN of the failure mode is:
   - RPN >125, then actions are required, and recommendations shall be proposed;
   - 63 ≥ RPN ≥125, then actions could be required, and recommendations should be proposed;
   - RPN <63,then actions are not required and recommendations don't need to be proposed.
2. In order to determine whether the action to mitigate the failure mode should be associated with condition monitoring and/or redesign, criterion were devised, inspired by the concept of sensitivity:

$$\left|\frac{\partial Y}{\partial X_i}\right|_{x^0} \quad (2)$$

i. Condition monitoring:

Applying this concept to identify the parameters most affected by *detection* results in the following finding:

$$\frac{\partial RPN}{\partial D} = S \cdot O \quad (3)$$

Where:

$$RPN = S \cdot O \cdot D$$

In that case, we should consider the highest product *S x O* to affect the detection by using condition monitoring.

The proposed criterion is:
If *S x O* ≥ 40, then it is recommended that the risk is mitigated via condition monitoring.

ii. Redesign:

In the same way, to identify the parameters most affected by *occurrence* we should consider the highest product *S x D*:

$$\frac{\partial RPN}{\partial O} = S \cdot D \quad (4)$$

The most obvious way to affect the *occurrence* is by redesign. The proposed criterion used to determine if redesign shall be recommended is:
If *S x D* ≥ 40, then it is recommended to mitigate the risk via redesign.

iii. Criteria limits:

The value of 40 comes from aiming to focus on the top 30% of the products *S x O* and *S x D*. Indeed, among the 100 possibilities of *S x O* and *S x D* (i.e, 1 x1, 1 x 2, 1 x 3 … 5x3 x 5, 5 x 6… 10 x 8, 10 x 10), 32 of them is equal or higher than 40.

As it is not possible to get exactly 30%, it was decided to keep to the closest value above 30%, i.e. 40.

i. Particular cases:
In some cases, RPN is higher than 125, however the products *S x D* and *S x O* are both lower than 40 as for the following example:

RPN = S x D x O = 7 x 4 x 5 = 140 → RPN ≥ 125
S x D = 7 x 4 = 28 → S x D < 40
S x O = 7 x 5 = 35 → S x 0 < 40

When this case occurs, it is proposed to focus on the highest product. In the example, the highest product is *S x O*, so condition monitoring should be prioritised.

3. Check if both condition monitoring and re-design are required:
Sometimes this threshold is insufficient and both redesign and condition monitoring are required, for example if the product *S x O* and/or *S x D* are very high for a certain failure mode.
The proposed criterion used to determine if both redesign and condition monitoring are to be recommended is:
If S x O ≥ 63 or S x D ≥ 63; then failure mode needs to be mitigated by both redesign and condition monitoring.

9) Criticality assessment after recommendation

After recommendation, a new criticality assessment is performed taking into consideration the actions that have been recommended. Normally after the recommendation, the RPN target criteria should be reduced to medium or low criticality. This demonstrates the potential effective-

$$Cr = \sum_{i=1}^{N_{failures}} W_S(S) \cdot W_O(O) \cdot W_D(D) \qquad (5)$$

ness of the recommendation to mitigate or eliminate the risk presented by the failure mode.

In case the new RPN is not low enough to reach at least the medium criticality level, new or further recommendations have to be made and re-assessed.

Sometimes, after several iterations, it is not possible to reduce the RPN to the medium criticality level. In such cases, the recommended actions can be validated by undertaking an As Low As Reasonably Practicable (ALARP) analysis in order to demonstrate that the cost involved in reducing the risk further would be grossly disproportionate to the benefit gained [9].

If that analysis concludes that the two strategies (monitoring or redesign) are not sufficient to reduce the criticality of the failure mode, then a systematic preventive maintenance could be recommended.

However, given that tidal turbines are generally in remote areas where accessibility is limited, excessive preventive maintenance activities requiring presence of personnel, complex logistics and costly maintenance utilities should be avoided.

This is why the methodology prioritises design improvements and enhancement of monitoring strategies to increase tidal turbine reliability and durability.

V. Aggregated Criticality Assessment – Cumulative Effect Calculation

The critical element selection criteria exposed here is based on the cumulative effect of all failure mode that are susceptible to appear for a certain element (system, subsystem or component).

RPN index is an indicator that allows to quantify the relevancy of a particular failure mode, and it is specific for each element. Nevertheless, if one wants to compare different RPNs, this cannot be done just by adding them up since they have exponential nature. In order to avoid this problem, several techniques of aggregated criticality assessment can be used. The aggregated criticality assessment allows to compare the criticality of assemblies and sub-assemblies across different tidal turbine concepts.

One of them consist in obtaining a linear indicator that will allow to add terms in the same scale. Thus, criticality can be defined as:

$$Cr = \sum_{i=1}^{N_{failures}} f(S, O, D) \qquad (6)$$

Where: $N_{failures}$ is the number of failures that can be found for a certain element.

An alternative way of RPN is to define some weights $W_S(S)$, $W_O(O)$, $W_D(D)$ which replace the severity, occurrence and detectability factors respectively in the RPN, in order to make them comparable. The criticality function can be defined as:

Where:

- $W_S(S)$: is the severity weight. It is defined according to the economic criteria within severity (see Table IV), since it is the only criteria defined in the severity tables which allows the severity to be quantified numerically. For health & safety or environment impact, we assume this number to be equivalent to that in the economic scale.
- $W_O(O)$: is the occurrence weight (see Table IV).

- $W_D(D)$: is the detectability weight (see Table IV). It reflects the planning difficulties and risk derived from the lack of timely detection of a failure.

TABLE IV
CRITICALITY ASSESSMENT - LOOK-UP TABLE: SCALE X WEIGHT

Scale	$W_S(S)$	$W_O(O)$	$W_D(D)$
1	0.002	0.0005	0.016
2	0.005	0.001	0.025
3	0.01	0.002	0.040
4	0.02	0.005	0.063
5	0.05	0.01	0.100
6	0.1	0.02	0.160
7	0.2	0.05	0.250
8	0.5	0.1	0.400
9	1	0.2	0.630
10	2	0.5	1.000

The methodology has been adapted to the RealTide project and was initially proposed and implemented by EnerOcean and Ingeteam as a part of the FMEA analysis in the H2020 DemoWind project "WIP10+" [10].

In this predecessor project, three different methods were proposed for obtaining the criticality function:

1. Look-up table (LUT):
   The weights can be obtained directly from Table IV.
2. Adjusted function:
   In this case we create the weight value for each indicator (S, O and D) with the following structure:
   T
   h
   i
   s

$$W_x = d_x \cdot 10^{\frac{x}{x_0}} \quad (5)$$

   This method allows for easy computer implementation. From Table IV, we have obtained the parameters presented in Table V.
3. Simplified adjusted function:
   In this case, one single indicator is needed. Criticality can be calculated as:
   F
   o
   r

$$Cr = \sum_{i=1}^{N_{failures}} d_{RPN} \cdot 10^{\frac{S+O+D}{RPN_0}} \quad (6)$$

   t
   For this method, tables are required to be in the same scale, i.e., S_0, O_0 and D_0 coefficients must be the same. RPN_0 can be calculated as:

TABLE V
CRITICALITY ASSESSMENT - ADJUSTMENT FUNCTION PARAMETERS

	S	O	D
d_x	$1.00 \cdot 10^{-3}$	$2.20 \cdot 10^{-4}$	0.016
x_0	3	3	0.025

VI. APPLICATION, RESULTS AND PERSPECTIVES

The FMEA methodology presented here was implemented in four generic tidal turbine concepts which were chosen and defined to reflect designs that may be developed commercially in the future:

1. Complex bottom fixed;
2. Simple bottom fixed;
3. Floating multi rotor; and
4. Cross flow turbine.

The features of each concept are summarized in Table VI whereas Fig. 5 illustrates each of these concepts.

During the FMEA process, an exhaustive list of failure modes and causes was produced for each component of the 4 tidal turbine concepts. This list will be addressed in further phase of the project for the development of a reliability database dedicated to tidal turbines.

The FMEA resulted in a total of 243 recommendations for all of the 4 concepts where 137 are monitoring recommendations and 106 are redesign.

The most commonly proposed monitoring recommendation types were the model based estimation method and multiple integrated detection.

The most commonly proposed design recommendation types were detailed analysis. CAE, redundancy and extended experimental campaign (full scale components).

The concept with the highest number of recommendations is Concept 1 - complex bottom fixed tidal turbine. Because of its complexity, this concept is the one with the highest number of critical failure modes (90). At the opposite, Concept 4 - cross flow turbine - is the one with lowest number of recommendation (29) which is the result of the simplicity of this concept (less assemblies than the others). Concepts 2 and 3 - simple bottom fixed and floating multi rotor- had the same number of recommendations (62).

It was observed that the more complex the tidal turbine, the greater the number of critical failure modes.

However, a more complex device may be able to harness a greater fraction of available energy and / or operate over a greater proportion of the tidal cycle. The

TABLE VI
GENERIC TIDAL TURBINE CONCEPTS AND FEATURES

Complex bottom fixed	**Simple bottom fixed**	**Floating multi rotor**	**Cross flow turbine**
Horizontal axis	Horizontal axis	Horizontal axis	Vertical axis
Open rotor	Open rotor	Open rotor	Close rotor
3 blades	Multi blade (>3)	2 blades	Multi blade (> 3)
Bottom fixed with pile	Bottom fixed gravity base	Floating	Bottom fixed (gravity or pile)
Pitch control	No Pitch control	Pitch control	No pitch
Yaw mechanism	No Yaw mechanism	No active Yaw mechanism	No yaw
Gearbox drive	Direct drive	Gearbox drive	Direct drive

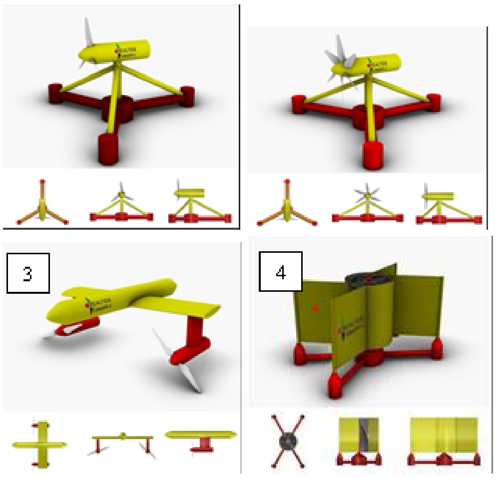

Fig. 5. 3D models of generic tidal turbine concepts: 1 (upper left). Complex bottom-fixed; 2 (upper right). Simple bottom-fixed; 3. (lower left) Floating multi-rotor; 4. Crossflow turbine.

finding must be taken in context of power curve, device cost and associated revenue, operation & maintenance.

The aggregated criticality assessment was performed to compare the criticality of assemblies and sub-assemblies of the 4 tidal concepts.

This aggregated criticality assessment highlighted that the most critical assemblies are:

- Electrical system;
- Rotor; and
- Drivetrain.

These assemblies are the most vital assemblies to energy production, presenting high costs and time to repair. Although the electrical system is the most critical assembly, when compiling the results of the 4 concepts, the system is less vulnerable in floating concept given better access to the tidal turbine andthereby reducing time of repair and limiting the costs and loss of production in the event of a failure.

From these assemblies, the most critical sub-assemblies highlighted in the analysis are:

- Blades;
- Power electronic converter;
- Generator;
- Low speed shaft;
- Low speed shaft dynamic seals;
- Transformer(s);
- Pitch System.

Thus, special attention on those assemblies and sub-assemblies will be given during the subsequent phases of RealTide project consisting in the definition, planning, and implementation of advanced monitoring techniques to provide highly reliable subsystems.

This will result in an integrated Condition Monitoring System (hardware and software together with a Monitoring Protocol) to acquire data from the critical components identified in the FMEA.

Furthermore, the FMEA recommendations related to design improvements will be used in the phase dedicated to optimize the design and improve the reliability of the main components of the next generation turbine's rotor.

In this phase exploratory studies will be performed on alternative materials and a cost model will be donein orderto optimize components reliability and maintenance operations.

Ultimately, the aims of the RealTide effort are to reduce the initial cost of the overall components, to reduce the number of components that have to be changed during maintenance phase, and to improve the reliability of the global device to allow longer maintenance intervals, which requires expensive marine operations to recover the turbine.

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