13th EWTEC 2019
Proceedings of the 13th European Wave and Tidal Energy Conference 1-6 Sept 2019, Naples, Italy

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

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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.**

Paper ID number: 1632; Conference track: Operations, maintenance and decommissioning.

This work has received funding from the EU research & innovation programme Horizon 2020 under Grant Agreement 727689.

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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

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.

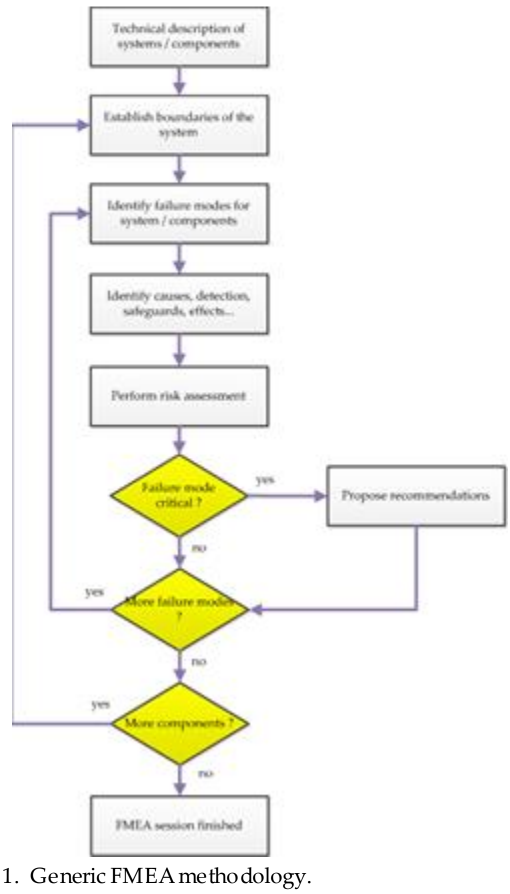

Fig. 1. Generic FMEA methodology.

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.

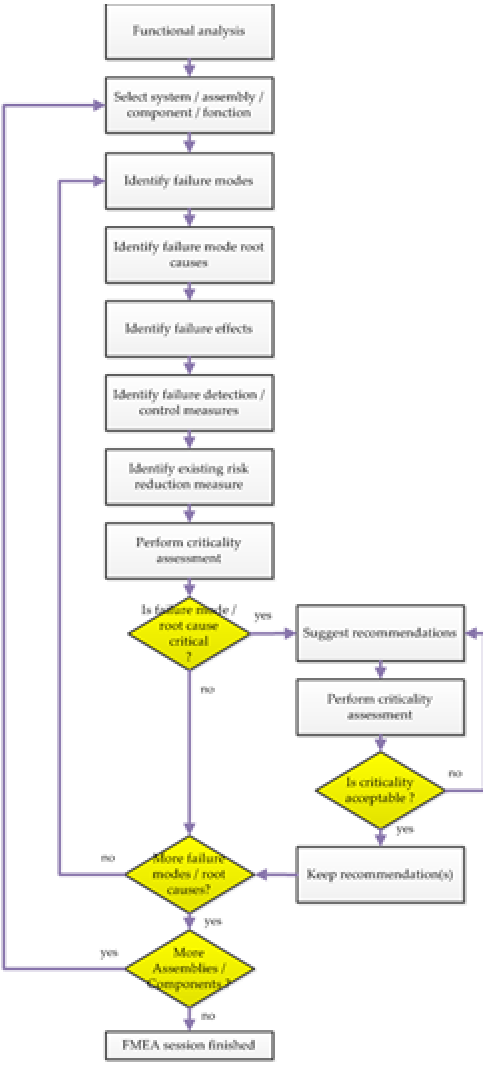

Fig. 2. RealTide adapted FMEA methodology.

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 componentsand 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.

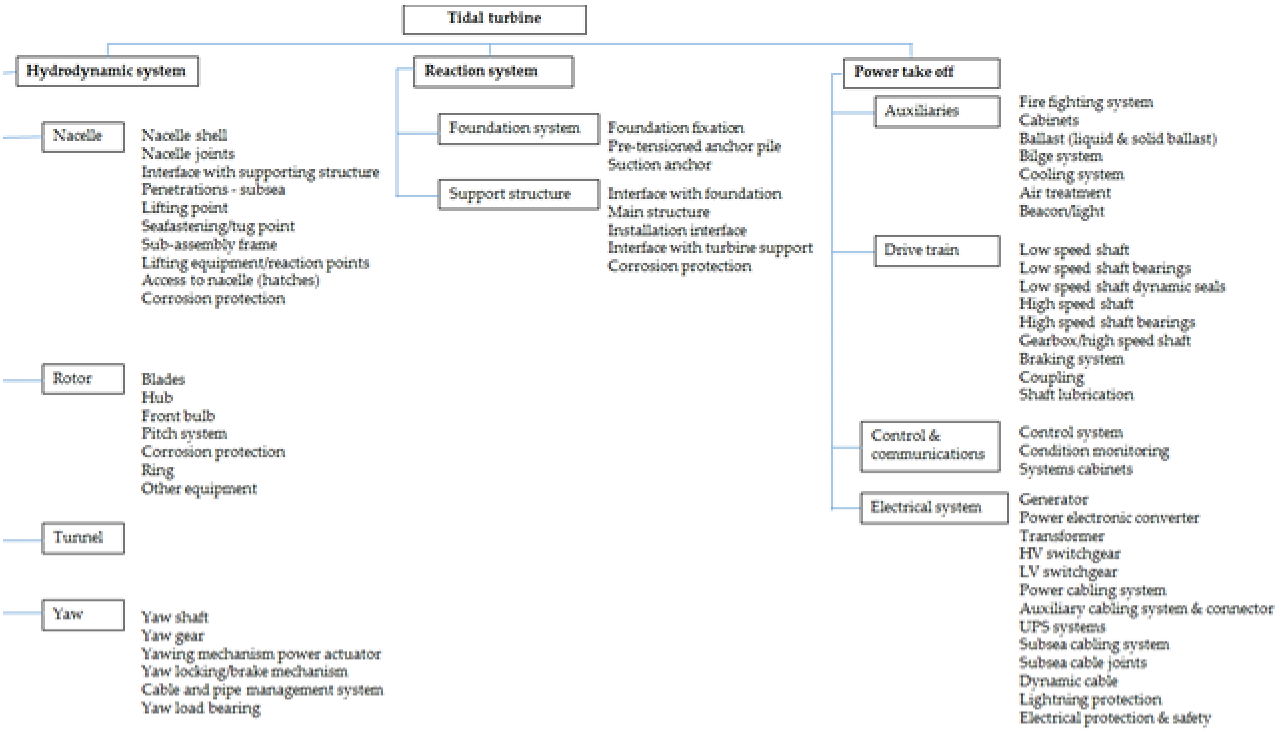

Fig. 3. Generic tidal turbine functional hierarchy.

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 FMEAmethodology 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.

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 on the 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

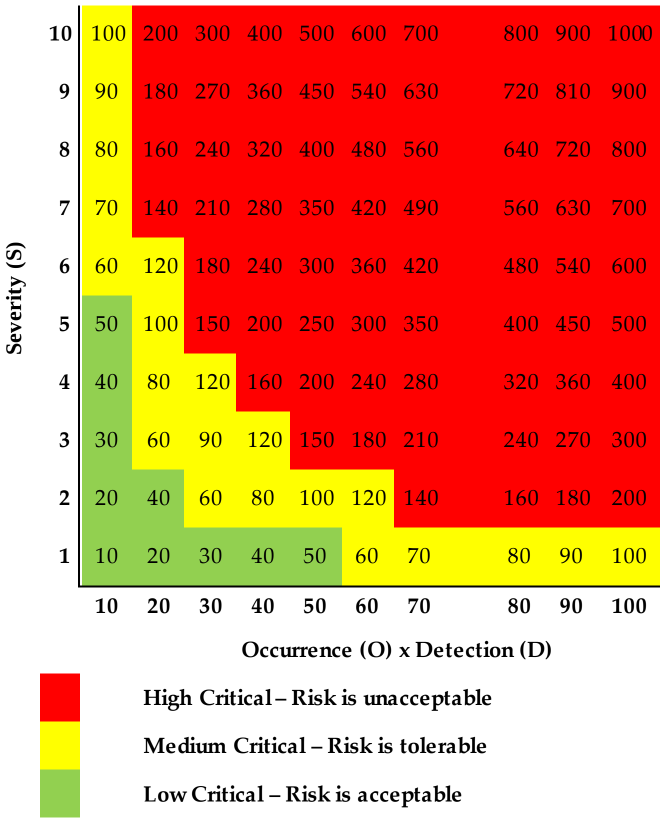

Fig. 4. RPN Criticality Matrix.

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 than40 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*, socondition 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 tobe recommended is:
   If S x O ≥ 63 or S x D ≥ 63; thenfailure modeneeds 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 toincrease 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 t
   $$Cr = \sum_{i=1}^{N_{failures}} d_{RPN} \cdot 10^{\frac{S+O+D}{RPN_0}} \quad (6)$$
   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

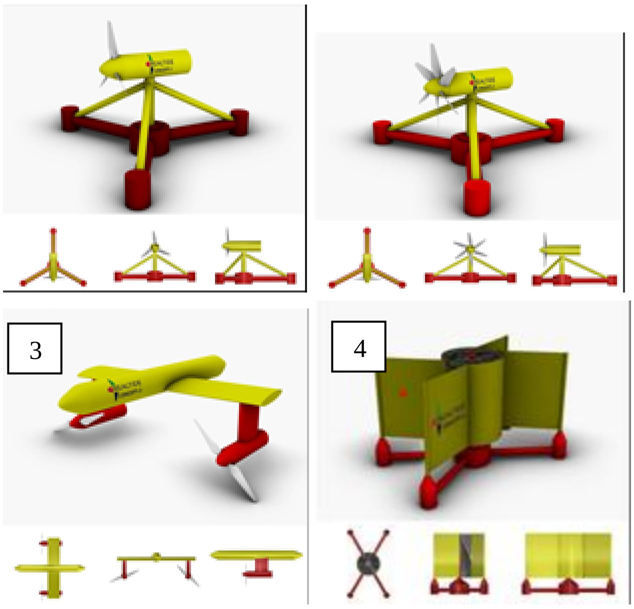

Fig. 5. 3D models of generic tidal turbine concepts: 1 (upper left). Complex bottom-fixed; 2 (upper right). Simple bottom-fixed; 3. (lower left) Floating multi-rotor; 4. Cross flow turbine.

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 order to 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.

References

[1] M. Allmark, R. Grosvenor, C. Byrne, F. Anayi, and P. Prickett, "Condition monitoring of a tidal stream turbine: development of an experimental methodology", presented at the *9th European wave and tidal energy conference*.

[2] T. Delorme et al., "Tidal stream devices: reliability prediction models during their conceptual & development phases," 2014.

[3] SINTEF, "OREDA - offshore reliability data", 5th Edition, 2009

[4] Energy technologies institute, "Reliable data acquisition platform for tidal energy (ReDAPT)",2013.

[5] *Analysis techniques for system reliability – procedure for failure mode and effects analysis (FMEA)*, International standard (IEC), IEC60812, Second edition, 2006.

[6] M. Sukendro, "Failure mode and effects analysis (FMEA) for Sabella D10", *Advanced master of marine renewable energy*, ENSTA Bretagne, 2013.

[7] Tavner, Peter, "Offshore wind turbine - reliability, availability, and maintenance", *IET Renewable Energy Series*, 2012.

[8] *Tidal turbines*, DNG-GL, DNVGL-ST-0164, Oct. 2015.

[9] New Zealand government, "Reasonably practical", *WorkSafe*, Jul. 2017.

[10] Era-Net DEMOWIND, "Wind integrated platform for 10+ MW, 2018.

[11] Surface Vehicle Recommended Practice: (R) Potential Failure Mode and Effects Analysis in Design (Design FMEA), Potential Failure Mode and Effects Analysis in Manufacturing and Assembly Processes (Process FMEA), and Potential Failure Mode and Effects Analysis for Machinery (Machinery FMEA), Society of Automotive Engineers (SAE), SAE J1739, Jan 2009.

[12] Potential Failure Mode and Effects Analysis (FMEA), Automotive Industry Action Group (AIAG), Fourth Edition, Jun. 2008.

[13] Procedures for Performing a Failure Mode Effects and Criticality Analysis, US Department of Defense, MIL-STD-1629A, Nov. 1980.

[14] RealTide: Advanced monitoring, simulation and control of tidal devices in unsteady, highly turbulent realistic tide environments. [Online]. Web site at https://www.realtide.eu/

[15] Petroleum and Natural Gas Industries – Collection and Exchange of Reliability and Maintenance Data for Equipment, International Organization for Standardization (ISO), ISO 14224:1999, 1st Edition, 1999.