European Commission
H2020 Programme for Research & Innovation

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

REALTIDE
LOADS FLOWS IMPACT

Grant Agreement number: 727689

Project Acronym: RealTide

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

Deliverable 1.1
FMEA Report

WP 1
Increased Reliability of Tidal Rotors

WP Leader: Bureau Veritas

Task Leader: Bureau Veritas

Dissemination level: Public

Summary: This report forms Deliverable 1.1 and details the work of Task 1.1 within WP1 of RealTide. It provides the description of the work carried out on the reliability analysis that have been developed on generic tidal turbines. It covers the description of generic tidal turbines, the development of the reliability methodology based on Failure Mode and Effect Analysis (FMEA) and the resulting recommendations in terms of indication of design improvements and condition monitoring activities to be implemented in order to reduce the occurrence of critical failures.
This report also provides the provision elements from Task 1.1 to the other tasks and work-packages, which are the generic tidal turbine failure mode list and analysis to be addressed to Task 1.2 (RAM study) and Task 1.6 (Reliability Database development) and a list of critical failure modes to be mitigated or eliminated by redesign and/or monitoring that will be further analysed and developed in WP5 and WP4 respectively.

Objectives: RealTide will go beyond the state of the art by using Failure Mode and Effects Analysis (FMEA) to highlight new failure modes induced by the specific operating conditions of tidal turbines. The analysis will identify means of mitigation, leading to recommendations on the design and/or additional failure monitoring features to be implemented on generic tidal turbines to increase reliability of tidal turbines. Identified monitoring activities will be recommended to WP4 and redesign will be recommended to WP5. Strong interactions between the partners and other WPs are expected to ensure that these monitoring needs are considered in an optimal tidal turbine design.

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Abbreviations & Definitions

ALARP	As Low As Reasonably Practicable
BV	Bureau Veritas
BV M&O	Bureau Veritas Marine & Offshore
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAPEX	Capital Expenditure
CFD	Computational Fluid Dynamics
D	Deliverable; Detection
DFIG	Doubly-Fed Induction Generator
DM	Direct Measurement
DTA	Detail Analysis
EO	EnerOcean
ETI	Energy Technologies Institute
EXPC	Extended Experimental Campaign
EXPS	Experimental Campaign (Simple)
FEM	Finite element method
FMECA	Failure Mode, Effect and Criticality Analysis
FMEA	Failure Mode and Effect Analysis
GA	Grant Agreement
GDP	General Design Practices
HO	HydrOcean
IDE	Indirect Detection
IFR	Ifremer (Institut Français pour la Recherche et l'Exploitation de la Mer)
IFREMER	Institut français de recherche pour l'exploitation de la mer
ISSA	Ingeteam Power Technology
IVT	Inspection Visit Tools
LRUT	Long Range Ultrasonic Testing
LUT	Look-up table
MBE	Model Based Estimation
MRE	Marine Renewable Energy
MUID	Multiple Integrated Detection
O	Occurrence
O&G	Oil and Gas
OPEX	Operational Expenditure
OREDA	Offshore Reliability Database
PMP	Project Management Plan
PTO	Power Take Off
RAM	Reliability, Availability and Maintainability study
RDN	Redundancy
RPN	Risk Priority Number
ROV	Remote Operated Vehicule
S	Severity
SAB	Sabella
UEDIN	The University of Edinburgh
WP	Work Package
1-T	1-Tech

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Distribution List

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

1 EXECUTIVE SUMMARY

At present, there is a great energy demand in the whole planet. This demand has led to important technological advances in all branches of the energy sector in recent decades and of course a huge boom in renewable energy. This boom has led to the study and research of new methods for the extraction of energy through natural resources, promoting alternatives such as tidal energy technology.

Governments and industry are making efforts to move towards a form of tidal energy device that will harness the free-flowing tidal stream and ocean current. Tidal stream power technology has gained prominence because of its simplicity, the ability to harvest energy directly from tidal currents, and the ecologically non-intrusive nature of the system. Obviously, this emergent technology is all under development and consequently there is no bank of information about their operating reliability.

There are three important factors that limit the development of maintenance and monitoring plans for tidal turbines:

- The fact that this technology is at an early development threshold makes it necessary to use data from the accumulated experience in similar technologies such as wind turbines [6].
- Research and development of different types of Tidal Turbines (horizontal axis, vertical axis, floating tethered, seabed fixed, etc.) [7].
- The harsh marine environment and problems with accessibility for maintenance [6].

With the objective to understand and increase the reliability of tidal energy devices, the Task 1.1 aims at developing 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 with objectives increase the reliability by recommending actions which will mitigate or eliminate the critical failures.

The first step was to define the taxonomy of a generic tidal turbine, i.e., its technical decomposition into systems, assemblies and components. With the diversity of existing Tidal Turbines concepts and components technologies, taxonomy has been defined for 4 generic tidal concepts in order to reflect as much as possible future likely commercial design: 1) Complex bottom fixed; 2) Simple bottom fixed; 3) Floating multi rotor; and 4) Cross flow turbine. The combination of these 4 concepts resulted to a general taxonomy for a generic Tidal Turbine (sections 0 and 4).

Then, the FMEA methodology was redefined in order to obtain a Reliability analysis in line with the objectives and specificities of RealTide project and which is adapted for an application on a "generic" Tidal Turbine. The challenge was to reach a methodology that allows an exhaustive analysis of Failure Modes but without going too much into details otherwise the methodology is not applicable to a "generic" tidal turbine concept (sections 5 and 6).

Further, the analysis was conducted on the 4 generic tidal concepts. Many traditional failure modes of components in offshore conditions are already referenced in databases such as the OREDA one (from the O&G sector). In addition, tidal turbine power trains have similarities to wind turbines, so they share a significant number of failure modes that have been identified and are relatively well known and documented. Failure Mode and Effects Analysis (FMEA) was performed to highlight new failure modes induced by the specific operating conditions of tidal turbines.

The analysis identifies types of means of mitigation to increase reliability of tidal turbines, leading to recommendations on the design and/or monitoring activities to be implemented on generic tidal turbines. Recommendations on design will be addressed in WP5 and the identified monitoring activities will be recommended in WP4. The recommendations are selected based on the criticality of

the mitigated failure mode in order to prioritize the recommendations with most chance of increasing reliability of the Tidal turbine (section 7).
The FMEA resulted in a total of 243 recommendations for all of the 4 concepts where 137 are monitoring recommendations and 106 are redesign recommendations. Those recommendations will be respectively addressed in WP4 and WP5 for further analysis.
The concept with the highest number of recommendations is the concept 1 - Complex bottom fixed tidal turbine (90). At the opposite, the Concept 4 - Cross flow turbine - is the one with lowest number of recommendation (29) and Concepts 2 and 3 - Simple bottom fixed and Floating multi rotor- had the same number of recommendations (62).
The analysis highlighted that the most critical assemblies are:

- Electrical System;
- Rotor; and
- Drivetrain.

which are the most vital assemblies to energy production.
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;
- Control system.

Thus, special attention on those assemblies and sub-assemblies should be paid during the further tasks and WP. As the RealTide project activities globally focuses more on Rotors and Drivetrains, the Electrical System may need to be further studied in a more specific project dedicated to this system.

Finally, the failure mode and causes analysis will be further addressed to Task 1.2 as an input for RAM analysis and Task 1.6 for the development of the reliability database.
These first FMEA versions will be the basis for other WPs especially those with high iteration with the WP1. The FMEA is a dynamic process and, according to the progress of theses WPs, the FMEAs will be subject to adjustments and modifications all along the project.

1 INTRODUCTION

The RealTide project aims at developing the next generation of tidal devices in line with energy market and environmental policies expectations. This FMEA report related to Work Package 1 "increased reliability of tidal rotors" provides a set of results oriented to understand and increase the reliability of tidal energy devices. A part of the work is related to generic tidal turbine designs, leading to a generic reliability database that will be further addressed to and developed in Task 1.6. To improve and really add value to this generic work, specific set of documents provided by the various partners directly involved in operational phases of tidal turbine development has been used.
Reliability of tidal turbines is extremely difficult to assess due to very limited field experience and confidentiality issues related to the emerging stage of development of the tidal sector. The lack of experience regarding tidal device failure rates in the harsh tidal environmental conditions induces high uncertainties on OpEx costs and it is expected that output of this WP1 will lead to a reduction of uncertainties in the business models thanks to recommendations in design improvements that will be analyzed and developed in WP5 and to an enhanced condition monitoring strategy which is being interactively developed in WP1 and WP4.
The Reliability, Availability and Maintainability assessment that will be further conducted in task 1.1 with the inputs from FMEA will finally help refining the cost model developed in WP5 taking in consideration revenues and OpEx.
In order to go beyond the economic consideration, a comparative study will be conducted to assess the environmental benefit achieved thanks to the higher reliability level and the associated reduction of maintenance visits.

2 DESCRIPTION OF TASK 1.1

2.1 Objectives

This deliverable includes the participation of partners Bureau Veritas, UEDIN, EnerOcean, SABELLA SAS, 1-Tech, IFREMER, ISSA. Deliverable 1.1 describes how generic tidal turbine concepts have been defined, the Failure Mode and Effects Analysis (FMEA) methodology that have been applied to each generic tidal turbine concepts, results and recommendations from the FMEA to be addressed to other Tasks and Work Packages.

The objective of this task is to conduct a reliability analysis on a generic tidal rotor using the Failure Mode and Effects Analysis (FMEA) methodology based on partners' experience and existing literature. The analysis was conducted on 4 generic tidal concepts in order to reflect as much as possible future likely commercial design.
Many traditional failure modes of components in offshore conditions are already referenced in databases such as the OREDA one (from the O&G sector) [4].
In addition, tidal turbine power trains have similarities to wind turbines, so they share a significant number of failure modes that have been identified and are relatively well known and documented as it is case in .ReDAPT (Reliable Data Acquisition Platform for Tidal) project [13].
Failure Mode and Effects Analysis (FMEA) was performed to highlight new failure modes induced by the specific operating conditions of tidal turbines.

The analysis identifies mitigation to increase reliability of tidal turbines, leading to recommendations on the design and/or monitoring activities to be implemented on generic tidal turbines. Recommendations on design will be addressed in WP5 and the identified monitoring activities will be recommended in WP4. 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.
Finally the failure mode and causes analysis will be further addressed in Task 1.2 as an input for RAM analysis and Task 1.6 for the development of the reliability database.

The Figure 2-1 summarises the Task 1.1 process, objectives and interactions with other Tasks and Work Packages.

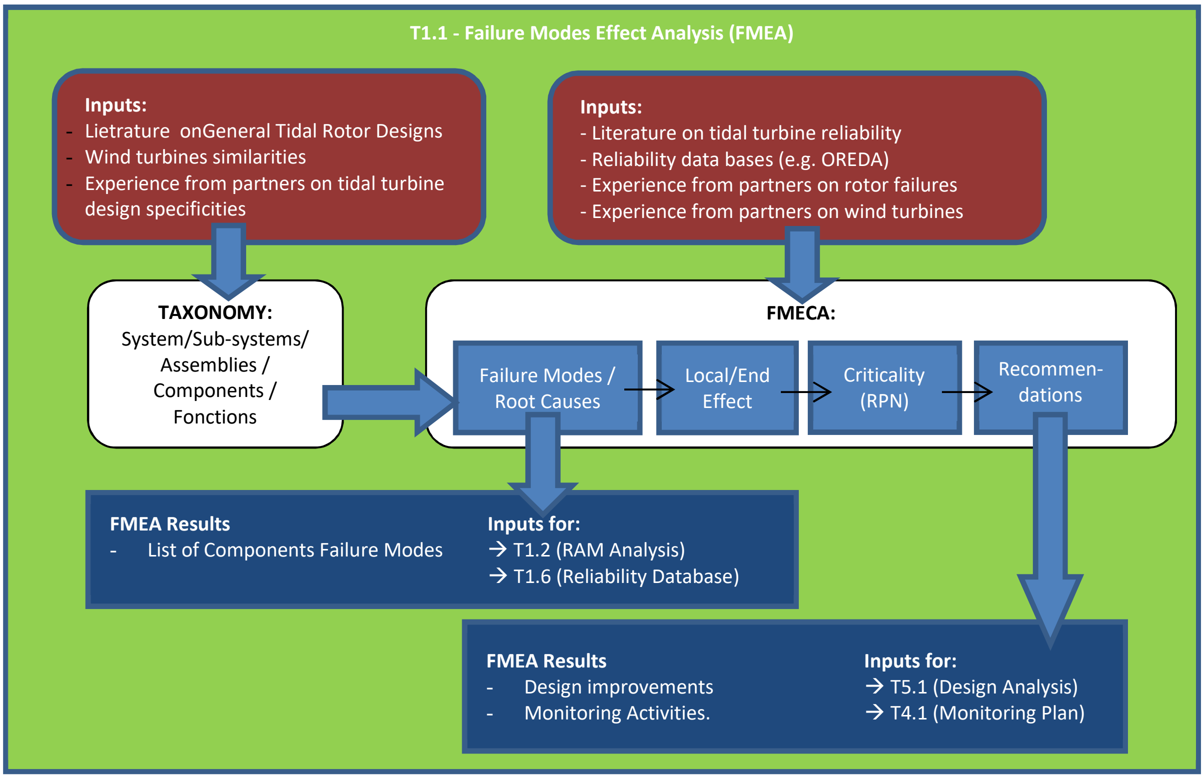

Figure 2-1 - WP1- T1.1 FMEA - Process and interactions with other tasks

2.2 Subtasks

The Table 2.1 presents the sub-tasks developed by the partners:

Table 2.1. - List of sub-tasks for Tasks T1.1- FMEA

SHORT NAME	SUB TASK DESCRIPTIONS
1. Generic Tidal Turbine Concepts Definition	**A review and consolidation of existing Tidal Turbine concepts** Based on literature on Tidal Turbine and experience from partners, definition of 4 most common concepts currently applied in industry.
2. Generic Tidal Turbine Taxonomy	**Definition of the breakdown taxonomy for the generic concepts** Break down of each tidal turbine Concepts into Assembly, Sub-Assembly and components. Definition of function of each sub-assembly and components.
3 FMEA Methodology Definition	**Definition of reliability methodology based on FMEA methodology** Definition of the FMEA methodology in order to make the necessary adaptions givens the objectives of the RealTide project.
4. FMEA development	**Development of the FMEA methodology to the 4 Tidal Turbine Concepts**. Application of the FMEA methodology or the 4 Tidal Turbine Concepts based on partners experience, databases and literature.
5. FMEA Results and Recommendation	**FMEA result gathering and recommendation** Compilation of the results and recommendation to be assigned to WP4 and WP5.

3 GENERIC TIDAL TURBINE CONCEPTS

3.1 Introduction

FMEA analyses all potential Failures that can occur on the System or Asset defined in the scope of the study. For complex systems such as tidal turbines, it is recommended to adjust the analysis to the level for which information is available to establish definition and description of functions [10].
Furthermore, the breakdown of the generic tidal turbine should include (in theory) all components of all concepts of Tidal Turbines. As there are hundreds of concepts of Tidal Turbines, it is almost impossible to cover all of them. Therefore, it was decided to limit the elements of the generic tidal turbine to the 4 most common tidal turbine concepts currently in operation in order to represent a global view of the market.
For each concept the principal features have been chosen for position of the axis, type of rotor, number of blades, type of foundation, presence of pitch control & yaw mechanism, and the type of drive (direct drive or gearbox).
A summary of the four concepts and their features are presented in Table 3.1.

Table 3.1 - Generic Tidal Turbine Concepts and features

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
Flaoting
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

The **complex and simple bottom fixed concepts** (concepts 1 & 2) are similar in that both have horizontal axis rotors (i.e. axis of rotation parallel to the flow direction) with 3 blades and are fixed to the seabed via a gravity base. The blades in the complex fixed concept have pitch control while the device has a yaw mechanism and a gearbox drive. In the simple concept, there is no pitch control of the blades or yaw mechanism on the device. The concept is direct drive.
Concept 2 is a simplified version of the Concept 1 with less sub-assemblies and components. The consortium agrees to add this simplified concept in order to consider the will of tidal turbine manufacturers to reduce the complexity of the traditional concepts in order to reduce CAPEX and OPEX and make those devices as cost effective as possible.

The **floating multi-rotor concept (concept 3)** has a horizontal axis rotor which is connected to two blades. It has pitch control and no active yaw mechanism although the floating structure can rotate around the turret which is moored to the seabed via mooring lines. A gearbox is connected to the drive.

The **Cross flow turbine (Concept 4)** - i.e. axis of rotation is perpendicular to the flow - is fixed to the seabed via a gravity base anchor or a pile. The tidal stream rotates the rotors around the vertical axis to generate power. The device has more than 3 blades but these have no pitch or yaw. It is a direct drive concept. The tunnel increases the mass flow rate over the rotor, achieving equivalent power from smaller rotor diameters.

The more detailed description of the four concepts are presented in section Generic tidal turbine concepts3.2.

3.2 Generic tidal turbine concepts

3.2.1 Concept 1 - Complex bottom fixed

The **complex bottom fixed concept** has horizontal axis rotors (i.e. axis of rotation parallel to the flow direction) with 3 blades and are fixed to the seabed via piling. In the complex fixed concept, the blades have pitch control, whereas the nacelle is completed with the yaw mechanism in order to maximize the produced energy. It also has a gearbox to represent indirect drive turbine. The selected type of generator for this concept is DFIG (Doubly-Fed Induction Generator). In order to capture various type of foundation, piling is included in this model. Overall, this model is selected to be analysed since it is one of the most common model developed by various turbine companies.

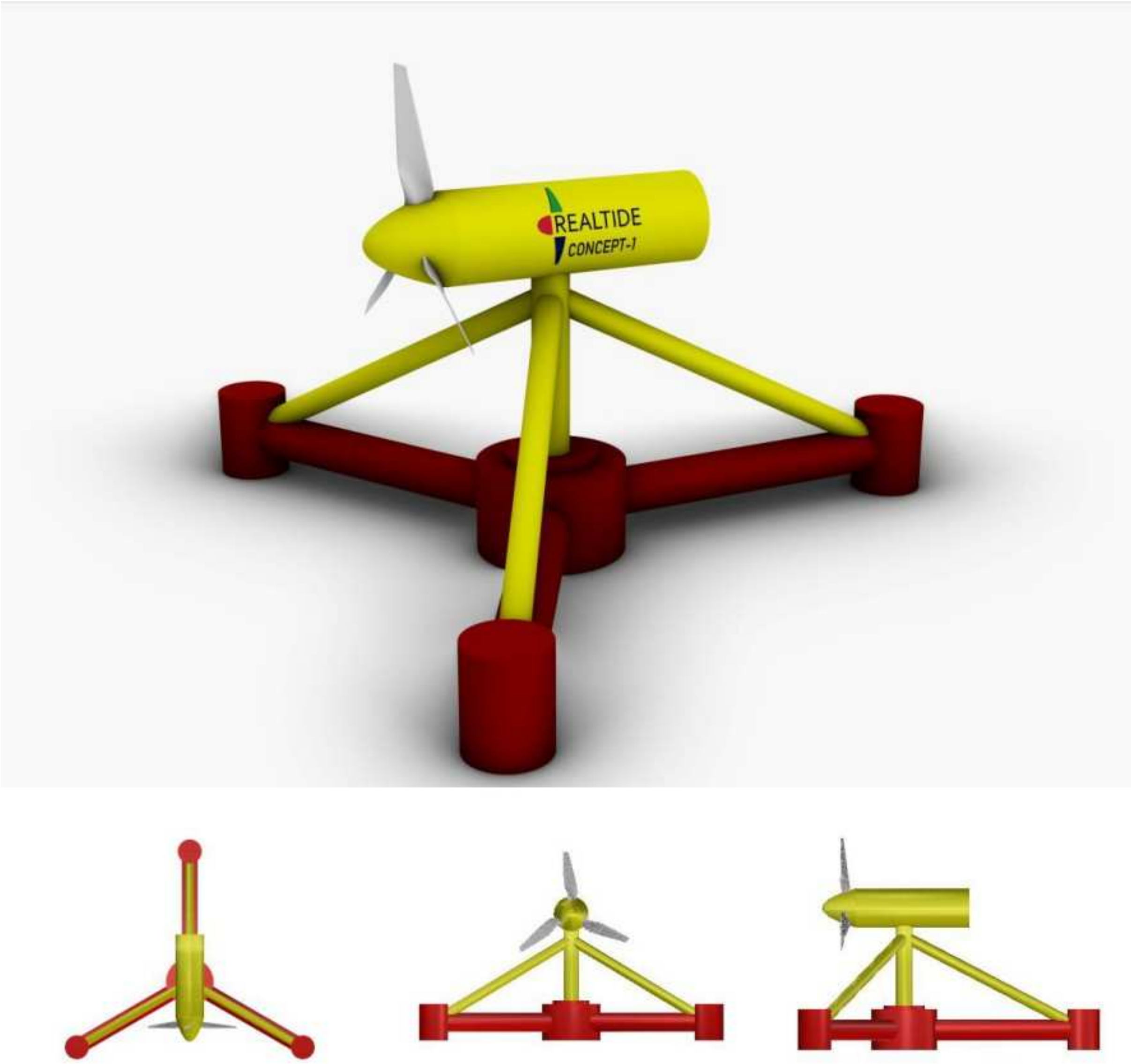

Figure 3-1 - Complex bottom fixed tidal turbine concept - 3D Model

Some projects develop turbines that resemble the complex bottom fixed concept, such as:

- **Andritz Hydro**

Andritz hydro Hammerfest is a horizontal axis tidal turbine Designed for water depths between 35 and 100 m, the tidal turbines are deployed on the seabed and kept in position by gravity, pins or pilings (depending on the seabed and tidal stream characteristics). Its rated power is between 500 up to 2000 kW (site dependant). It is equipped with variable pitch control and yawing system.

Figure 3-2 - Andritz Hydro Hammerfest
(Source: https://www.andritz.com/resource/blob/61614/cf15d27bc23fd59db125229506ec87c7/hy-hammerfest--1--data.pdf)

- **SIMEC Atlantis Energy**

The AR1500 is a Lockheed Martin designed, 1.5MW horizontal axis turbine with 18 m rotor diameter and equipped with active pitch and yaw capability. The nacelle weighs approximately 150 tonnes in air and has a design life of 25 years.

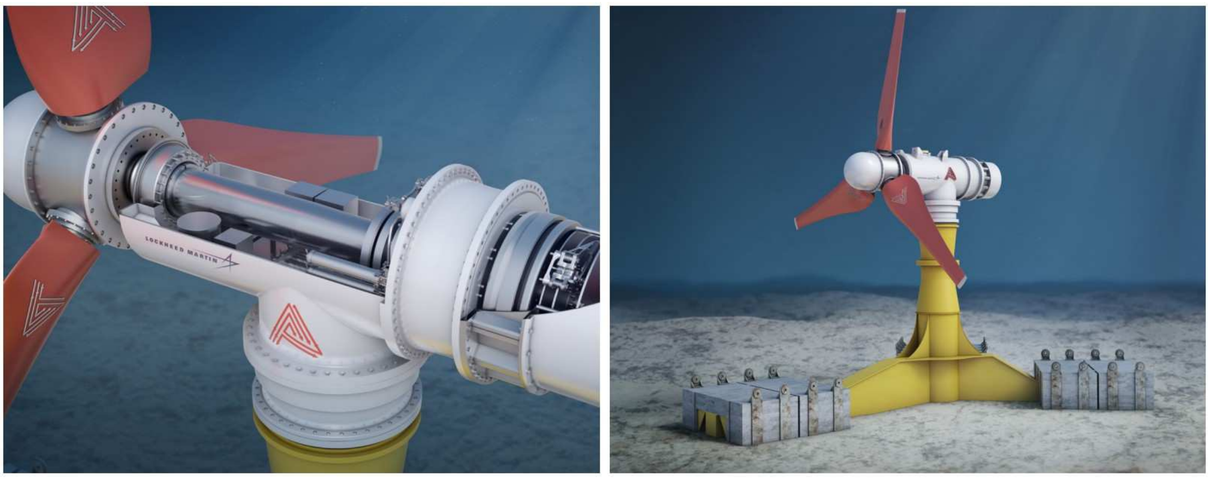

Figure 3-3 - Atlantis AR1500 tidal turbine
(Source: https://simecatlantis.com/wp/wp-content/uploads/2016/08/AR1500-Brochure-Final-1.pdf)

- **Nova Innovation**

Nova Innovation develop 100 kW tidal turbine called M100 with a conventional geared drivetrain. Its rotor diameter is 9 meter with rated operating speed around 15 to 25 rpm.

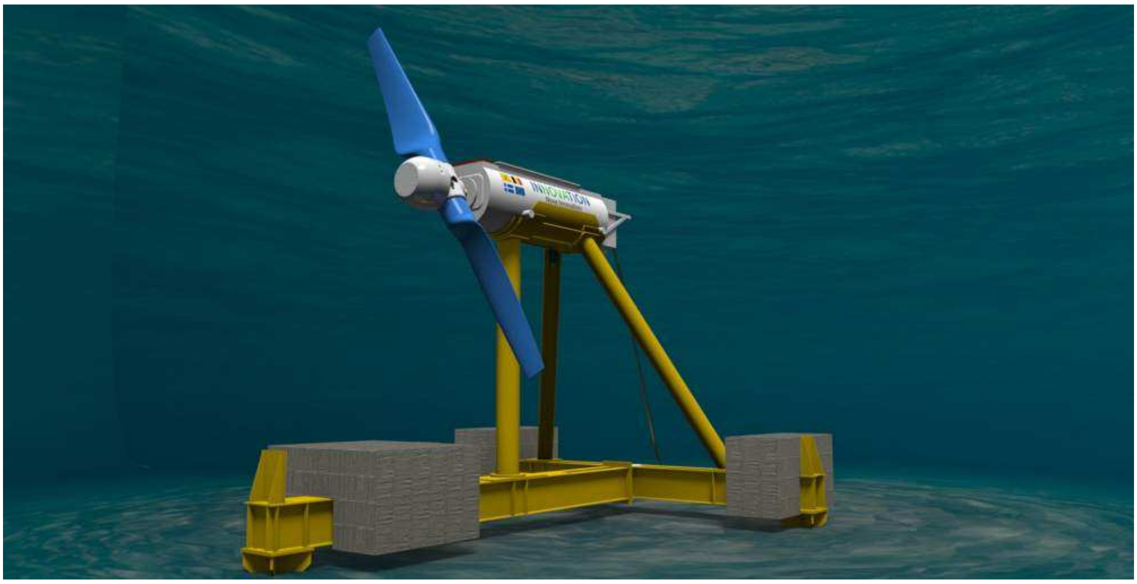

Figure 3-4 - Nova Innovation M100 Tidal Turbine
(Source: https://www.novainnovation.com/nova-m100)

3.2.2 Concept 2 - Simple bottom fixed

In general the **simple bottom fixed concept** is similar with the complex bottom fixed. Understanding the maintenance challenge of the tidal turbine, some turbine developer pursue simpler turbine design, hence they remove the presence variable pitch control, yaw mechanism, and gearbox. The simple bottom fixed is included in the analysis In order to represent this design choice. In this concept PMSG (Permanent Magnet Synchronous Generator) is selected to represent direct drive generator without gearbox. The turbine is fixed to the seabed via gravity based foundation.

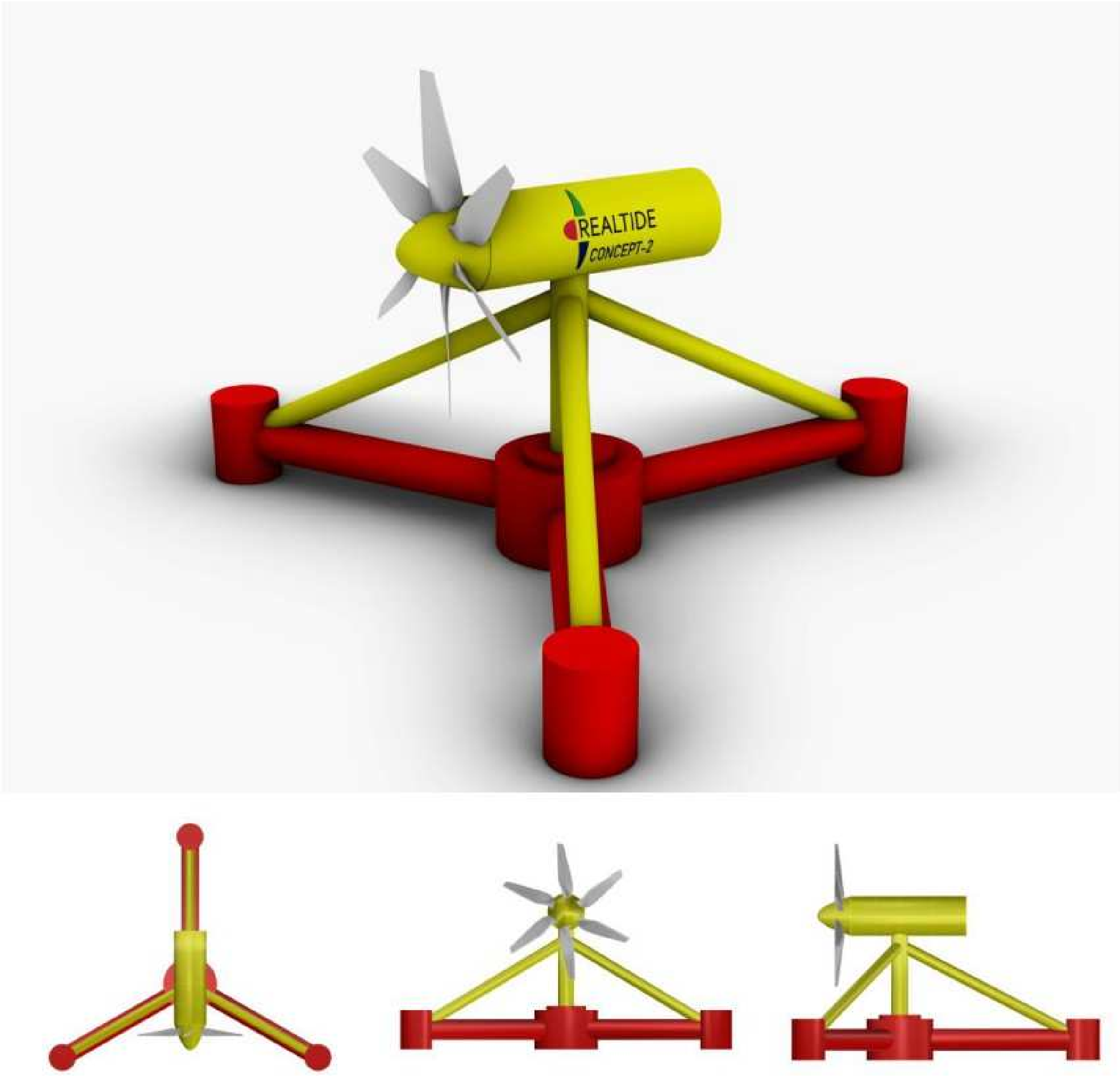

Figure 3-5 - Simple bottom fixed tidal turbine concept - 3D Model

Sabella is one of the companies who develop this kind of concept. At the moment Sabella is developing D10 tidal turbine with nominal capacity of 1 MW at 4 m/s current speed. It has 10 m rotor diameter and its total weight is 450 ton.

Figure 3-6 - Sabella D10 tidal turbine

3.2.3 Concept 3 - Floating multi rotor

The **floating multi-rotor concept** has a horizontal axis rotor which is connected to two blades. It has pitch control and no active yaw mechanism although the floating structure can rotate around the turret which is moored to the seabed via mooring lines. A gearbox is connected to the drive.

The present concept was chosen with the objective of taking into account a generic floating multi rotor concept. As can be seen in Figure 3-7, the concept consists of a floating structure with two braces alongside that hold both turbines. The device is moored through 3-5 lines attached to the seabed by anchor piles. The device is able to face the stream flow thanks to the passive yaw mechanism which allows the platform self-orientation. Nevertheless, an active yaw mechanism has been also included, as an alternative option, in the FMEA analysis.

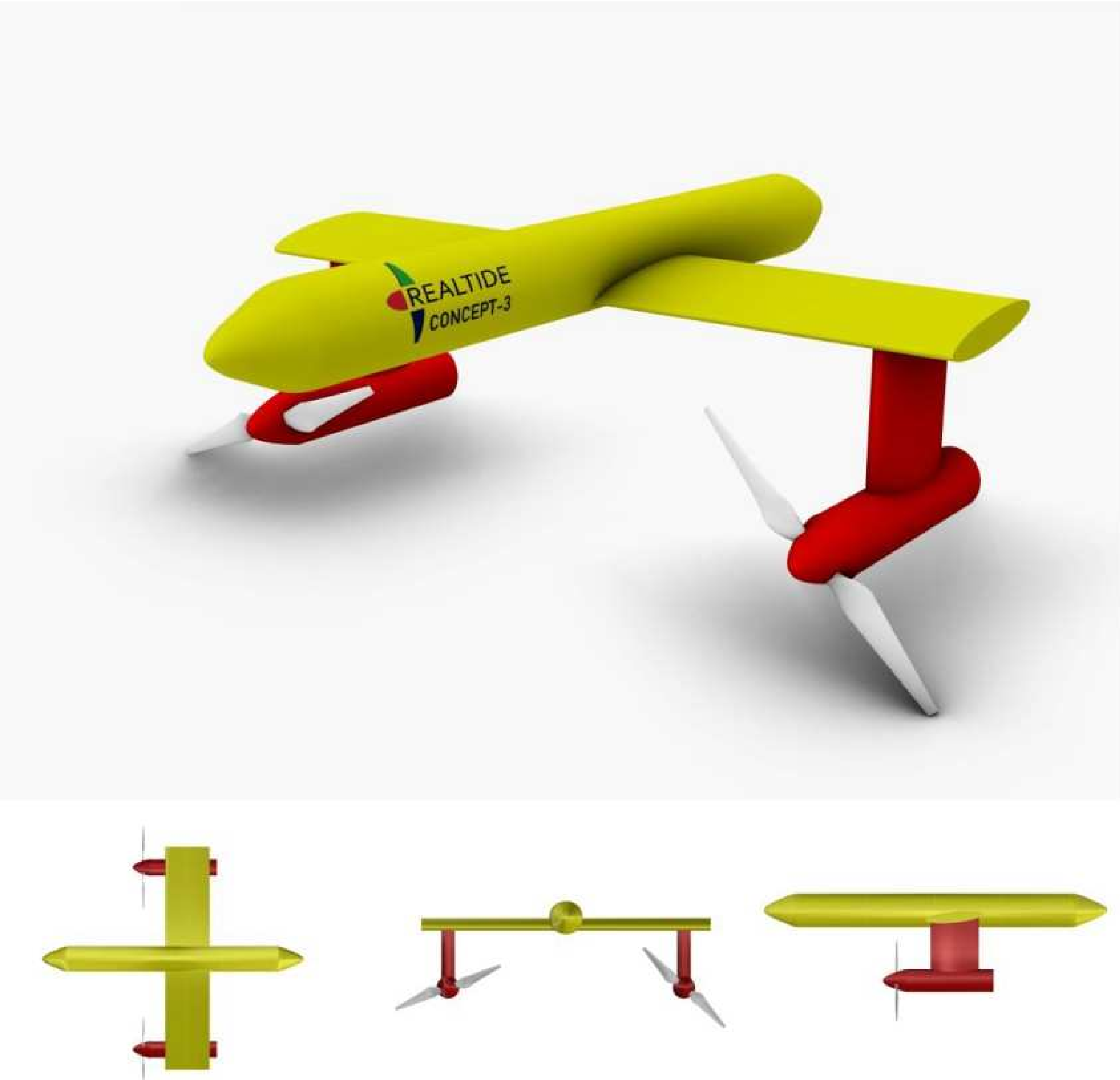

Figure 3-7 – Floating multi rotor - 3D Model

Some devices under development that could be representative of this RealTide concept include:

- OCEAN_2G- Magallanes Renovables;
- FloTec- Scotrenewables Tidal Power Ltd;
- BlueTEC- Bluewater;
- Gesmey- SOERMAR/UPM;
- Cormat- Nautricity Ltd;
- Evopod- Oceanflow Energy Ltd;
- UFS- Tocardo Tidal Power.

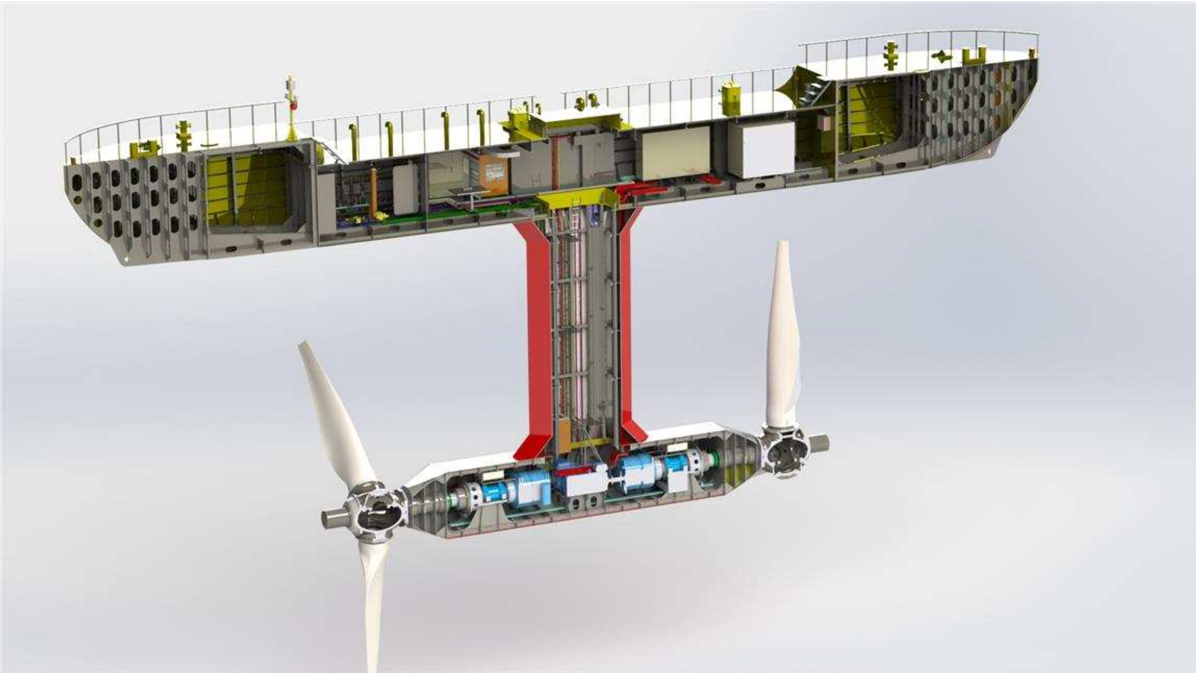

Figure 3-8 - OCEAN_2G project of Magallanes Renovables

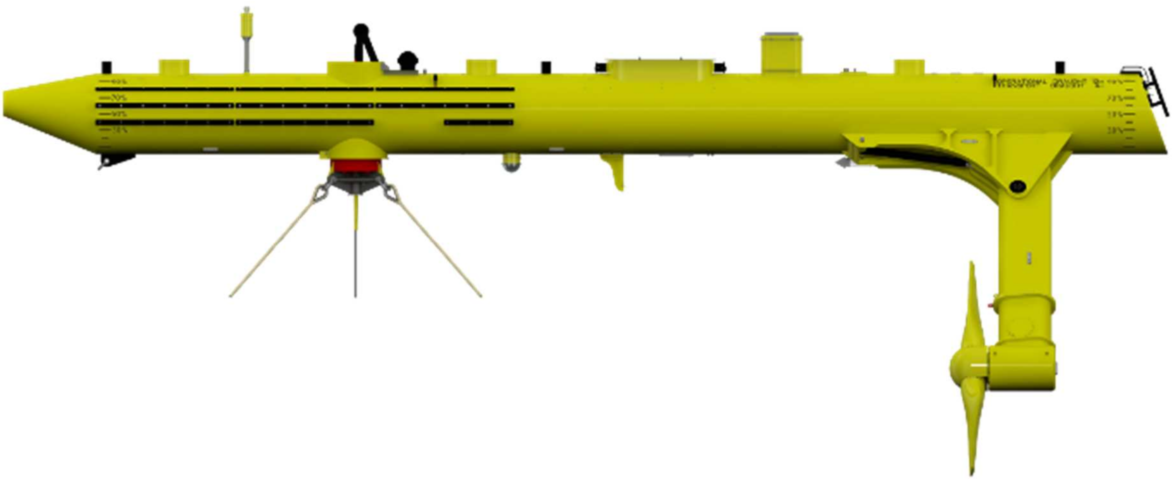

Figure 3-9 - SR2000 prototype of Scotrenewables Tidal Power

3.2.4 Concept 4 - Cross flow turbine

The **crossflow tidal turbine** (i.e. axis of rotation is perpendicular to the flow) is fixed to the seabed via a gravity base anchor or a pile. The tidal stream rotates the rotors around the vertical axis to generate power. The device has more than 3 blades but these have no pitch or yaw. It is a direct drive concept. The tunnel increases the mass flow rate over the rotor, achieving equivalent power from smaller turbine dimensions (diameter and height).

This concept represents a collection of characteristics that appear in several designs and were not considered or incorporated in the previous three concepts such as the presence of a flow concentrator and the use of not so conventional "wind turbines" inspired designs (Kobold, Savonius, Darrieus, …).

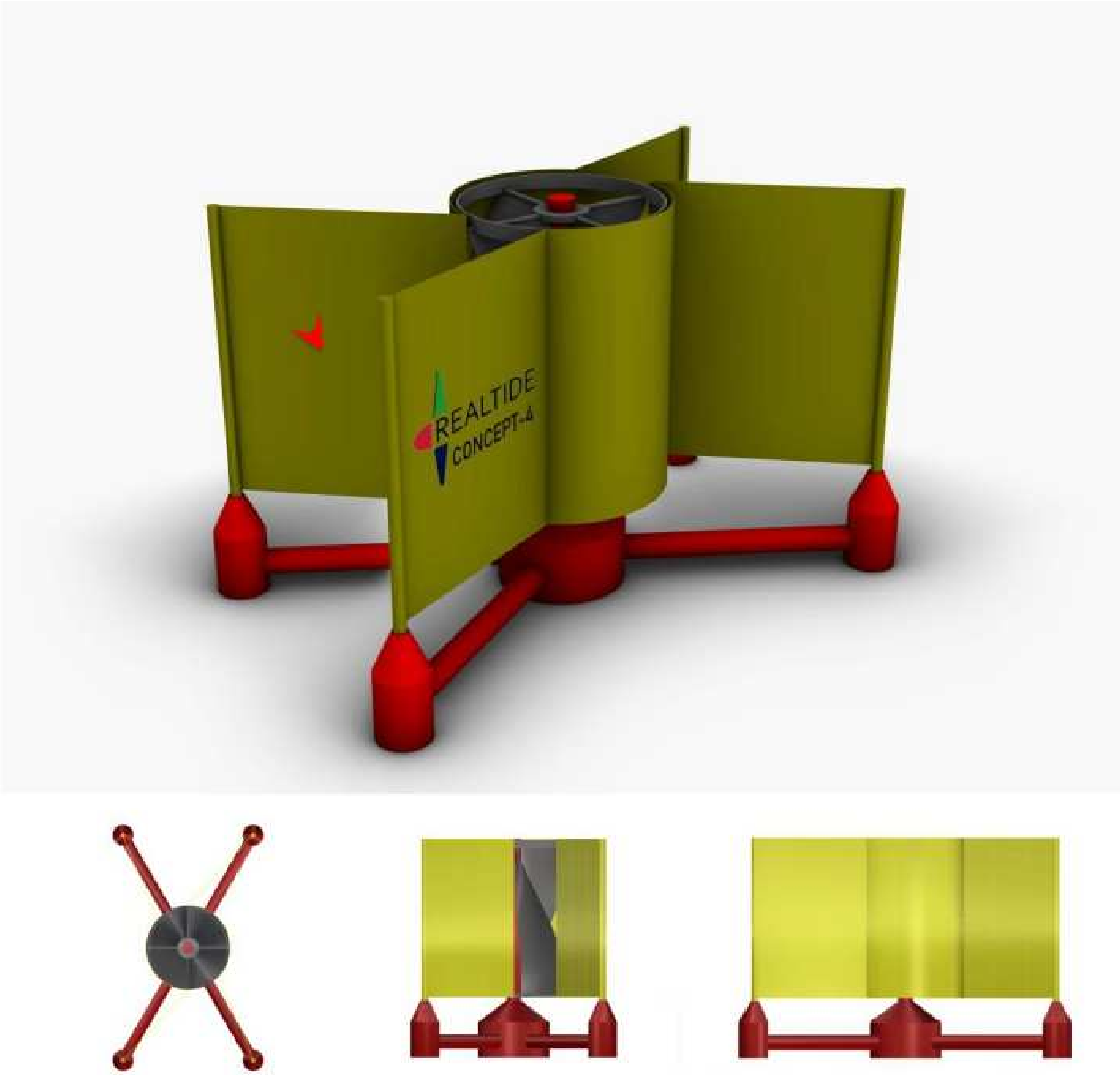

Figure 3-10 - Crossflow tidal turbine concept - 3D Model

Some devices under development that could be representative of this RealTide concept include:

- Wave Rotor- IHCTidal/Tocardo Ltd;
- TidGen Power System- ORPC;
- Flumill- Flumill;
- Cormat- Nautricity Ltd;
- Proteus- Neptune Renewable Energy

Figure 3-11 - TidGen ® Power System of ORPC (Ocean Renewable Power Company)

Figure 3-12 - HydroQuest Ocean of HydroQuest

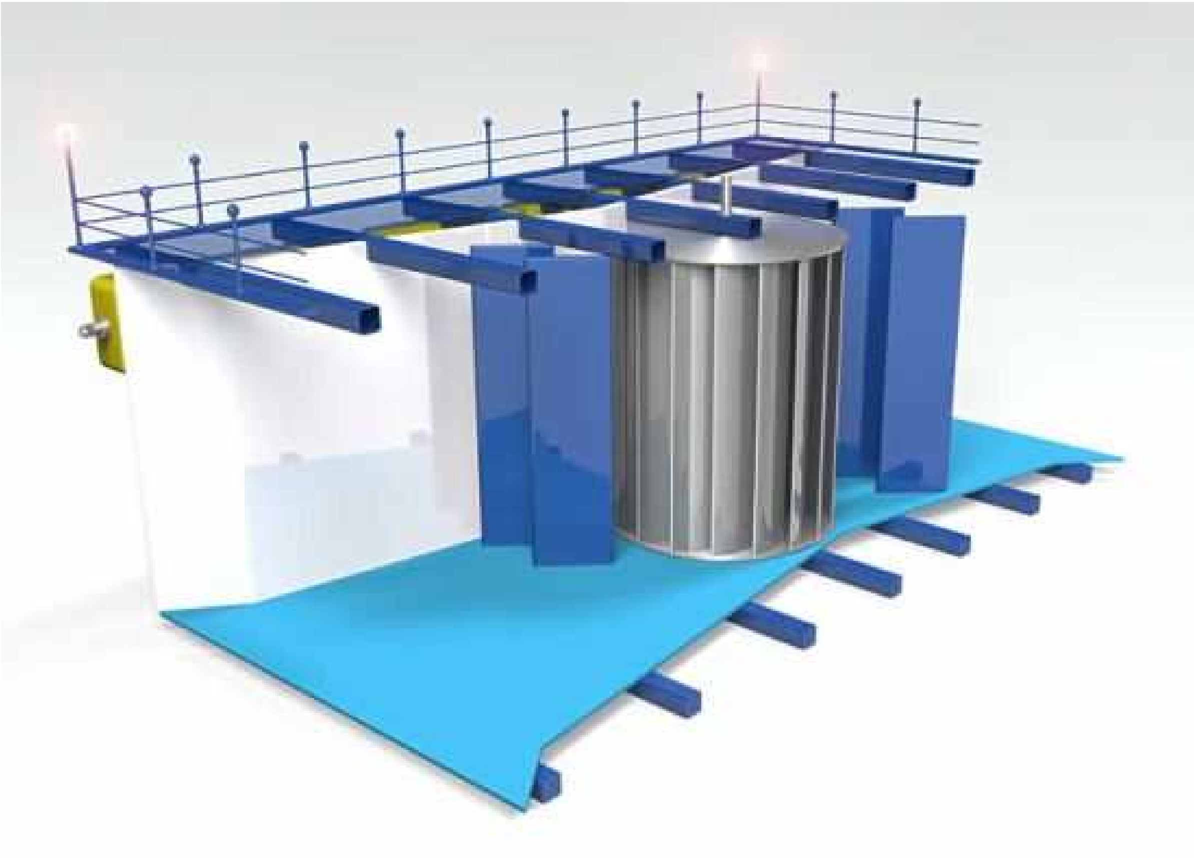

Figure 3-13 - Proteus of Neptune Renewable Energy

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4 TAXONOMY

4.1 Introduction

Taxonomy has been developed by the partners in a top-down process of splitting the tidal turbine system into individual components.
By using similarities with wind turbines and previous studies available in the literature [5][7][8], the Tidal turbines have been divided into various levels of the functional hierarchy as presented below:

- ↳ **System**
  - ↳ **Sub-Systems**
    - ↳ **Assemblies**
      - ↳ **Sub-Assemblies**
        - ↳ **Components**
          - ↳ **Sub-components**

The main function of each Sub-Assemblies or corresponding components has been defined in order to assist the FMEA.

4.2 Systems & Sub-Systems

The system is the Tidal Turbine itself which main function is to converts the movement of water coming from change in tide, the kinetic energy, into electricity
The sub-systems are the functional groups which any Tidal Turbine consists of whenever its concept.
The tree sub-systems defined by the partners are:

- **Hydrodynamic System** :
  The primary function of the **Hydrodynamic System** is to capture the movement of the tidal stream by moving in response to the energy contained within the stream. The system consists of the nacelle and the rotor (and, if they exist in the device concept, the yaw system and the tunnel). The degree of "tuning" of the hydrodynamic system, e.g. yaw and pitch, in response to variation in the tidal stream, is device dependent.
- **Reaction System :**
  The function of the **Reaction System** is primarily structural. The system consists of the foundation and support for the device. As such, the device is secured to the seabed, loads can be transferred between different parts of the structure and hydrodynamic loads on the structure can be resisted.
- **Power Take Off** :
  The function of the **Power Take Off (PTO) System** is primarily to convert kinetic energy into electrical energy of a quality which can be exported from the device. This requires integration of control features e.g. sensor management and auxiliaries e.g. cooling systems. Consequently, the PTO system consists of the electrical system, the drive train, the auxiliaries and the control & communication system. For the purposes of RealTide, the PTO does not include the export cable or any onshore substation or power management system.

4.3 Assemblies & Sub-Assemblies

Each Sub-system have been divided into Assemblies and then in Sub-Assemblies. They consist of groups of components which are fitted together in order to ensure the functions of the Tidal Turbine.
Assemblies and Sub-Assemblies can be similar to all concepts or specific to a concept depending on the applied technology, its structure or installed devices. For example, all 4 concepts have a Drivetrain (Assembly) with a Low speed shaft (Sub-Assembly). However only concepts 1 and 3 have a Drivetrain with the Gear-box coupled to a High Speed Shaft. Moreover, only concept 3 needs Beacon/Lights and Dynamic cables due to the fact that this is a floating tidal turbine (the other concepts are fixed underwater, so there is no need of such assemblies/sub-assemblies).
Taking into consideration the particularities of these concepts, the different alternatives of technology and materials that currently available, each sub-assembly was divided into different types.

4.4 Components & Sub-Components

When sub-assemblies consist of various parts, these were divided into components and those with high complexity were divided into sub-components.
As well as sub-assemblies, the different types of components have been detailed when relevant to the study.

4.5 Functions

The main function of each Sub-Assembly or corresponding components has been defined. The function is the purpose for which the sub-assembly or component is designed in order to ensure tidal turbine operations and integrity.
The function is required to support the FMEA analysis in order to define the Components Failure Modes and also to help to define the local and systems effect of the failure modes by going up to the functional hierarchy.

4.6 Taxonomy

The resulting taxonomy for a generic tidal turbine is presented in the table in APPENDIX A - Generic Tidal Turbine taxonomy.
The Sub-assemblies and components included in each concept are also presented in this table.

Table 4.1 presents an extraction of the taxonomy of the Drivetrain assembly.

Table 4.1 – Sample of Taxonomy for Generic Tidal Turbine

Proposed Generic Tidal Turbine Taxonomy								Concepts			
Sub-System	**Assembly**	**Sub-Assembly**	**Sub-Assembly type**	**Component**	**Component type**	**Sub Component**	**Function**	**1**	**2**	**3**	**4**
Power take off	Drivetrain	Low speed shaft					Transfer torque from hub to drive train gearbox Transfer torque to generator (if relevant) Resist ultimate loads Resist fatigue loads	X	X	X	X
		Low speed shaft bearings					Transfer thrust and bending moments to nacelle	X	X	X	X
		Low speed shaft dynamic seals					Provide water tightness	X	X	X	X
		High speed shaft					Transfer torque from gearbox to generator Resist ultimate loads Resist fatigue loads	X		X	
		High speed shaft bearings					Allow rotation of high speed shaft Resist misalignment induced loads Resist fatigue loads	X		X	
		Gearbox / high speed shaft		Coupling			Step up rotation speed of main shaft and support main shaft through bearings Transmission of torque loads into nacelle	X		X	
				Gears			To transmit torque	X		X	
				Bearing			Transfer thrust and bending moments to nacelle	X		X	
				Shaft			To transmit mechanical power	X		X	
				Casing			To provide enclosure for the gearbox components	X		X	
				Gearbox Lubrication system			Interface between gearbox and sub-frame	X		X	
		Braking system		Low speed brake		Braking disks, pads	Brake the drivetrain from low speed shaft	X	X	X	X
				Generator rear brake (disk)		Braking disks, pads	Brake the drivetrain from generator shaft	X	X		
				Parking / Blocking brake		Braking disks, pads	Keep turbine stopped after braking operation	X	X	X	
				Braking actuator	Hydraulic power unit		Provide hydraulic power to braking mechanism	X		X	

Proposed Generic Tidal Turbine Taxonomy								Concepts			
					Electrical		Provide electrical power to braking mechanism		X		X
		Couplings	Shrink fit couplings	Key connections			Allow couplings of parts along the main drive train to transfer torque, and bending moments if relevant	X		X	
			Torsionally elastic couplings					X			
			Torque limiters (Mechanical, hydraulic or magnetic Type)				Provide physical decoupling between shafts Cap transmitted torque along the main drive train	X			
		Shaft Lubrication system					Provide lubrication to the shaft	X	X	X	

The resulting taxonomies for the Generic tidal turbine and each Tidal turbine concepts are presented in the diagrams below.

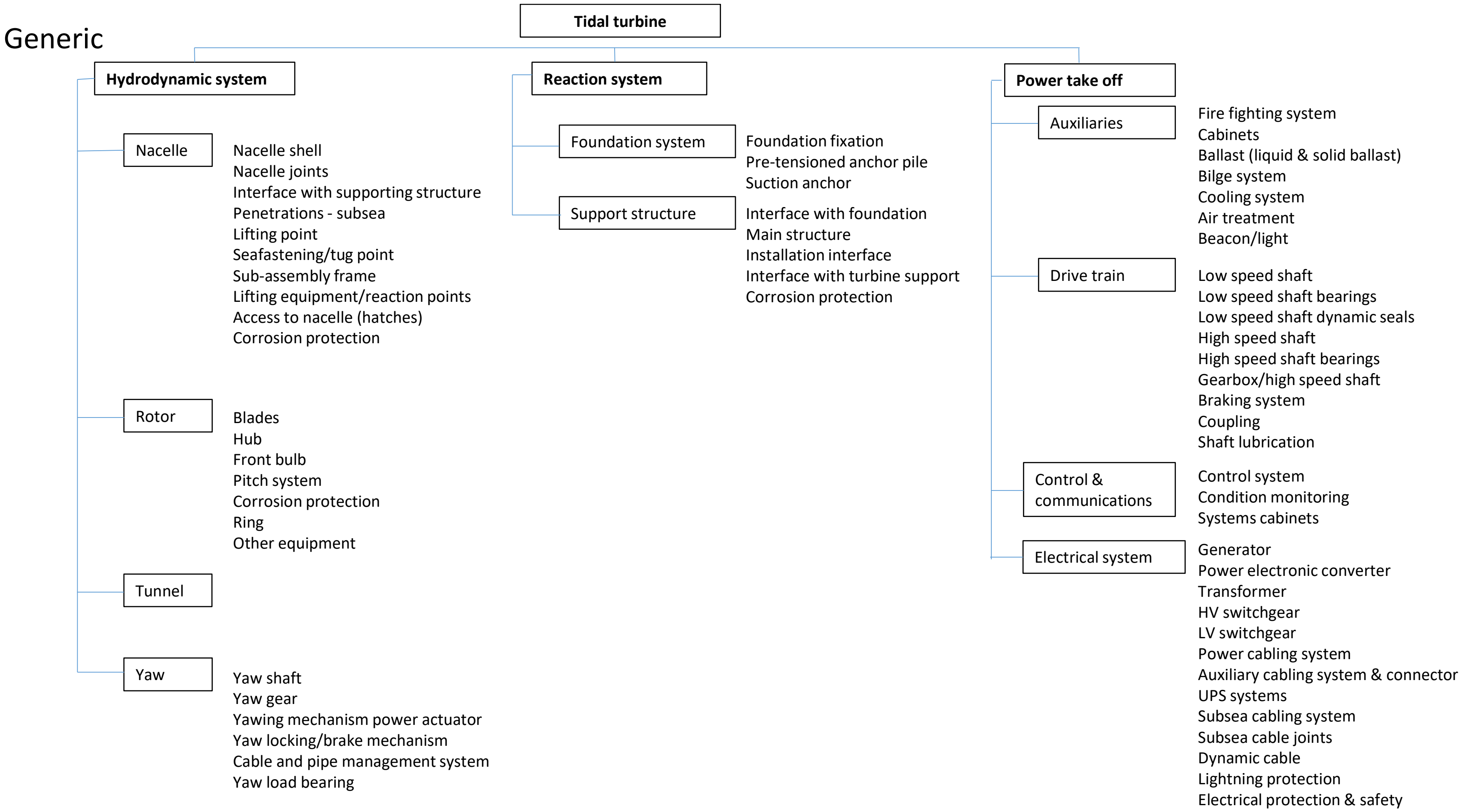

Figure 4-1 - Generic Tidal Turbine Taxonomy - General Diagram

1

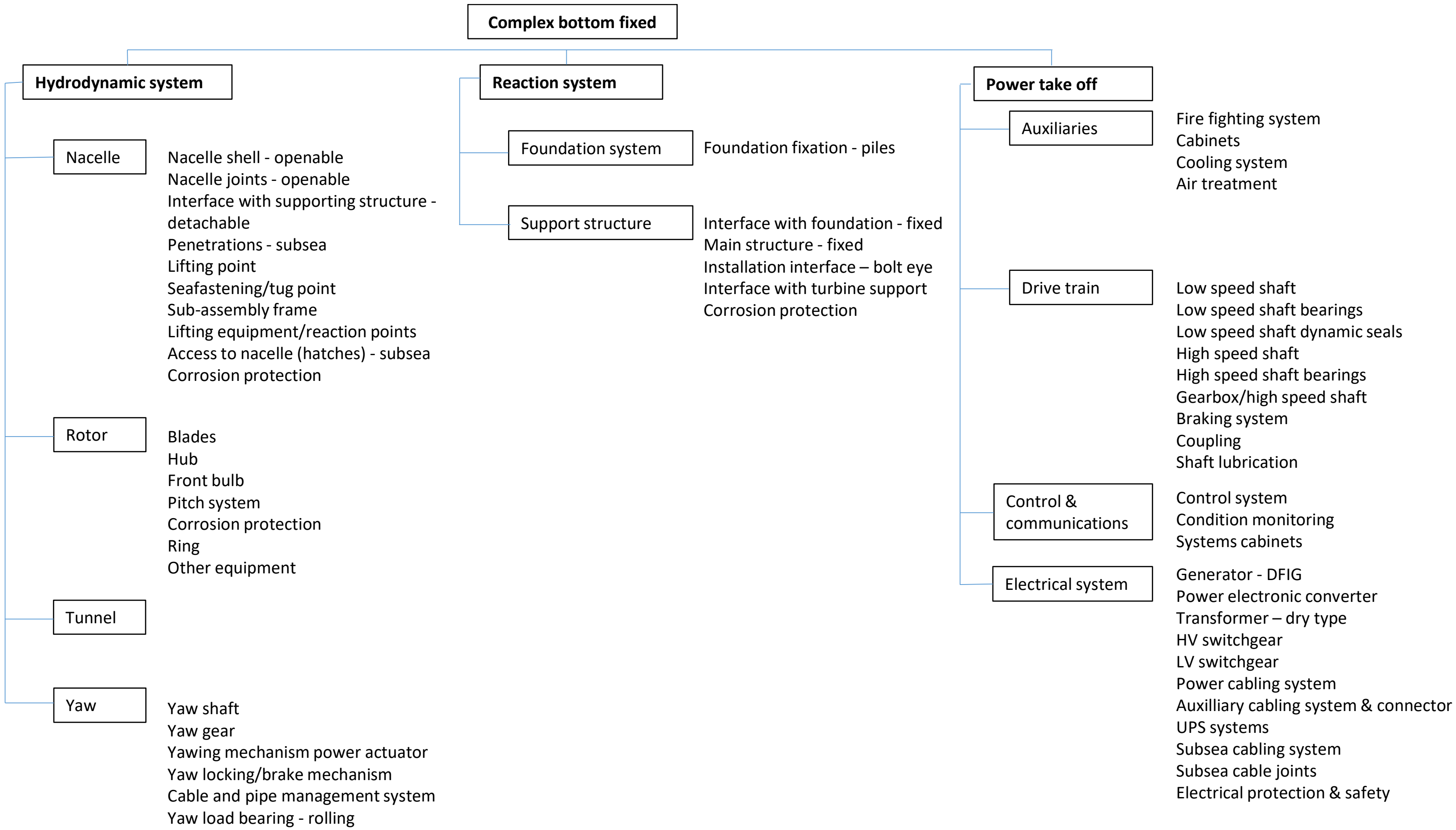

Figure 4-2 - Concept 1 Tidal Turbine Taxonomy Diagram

2

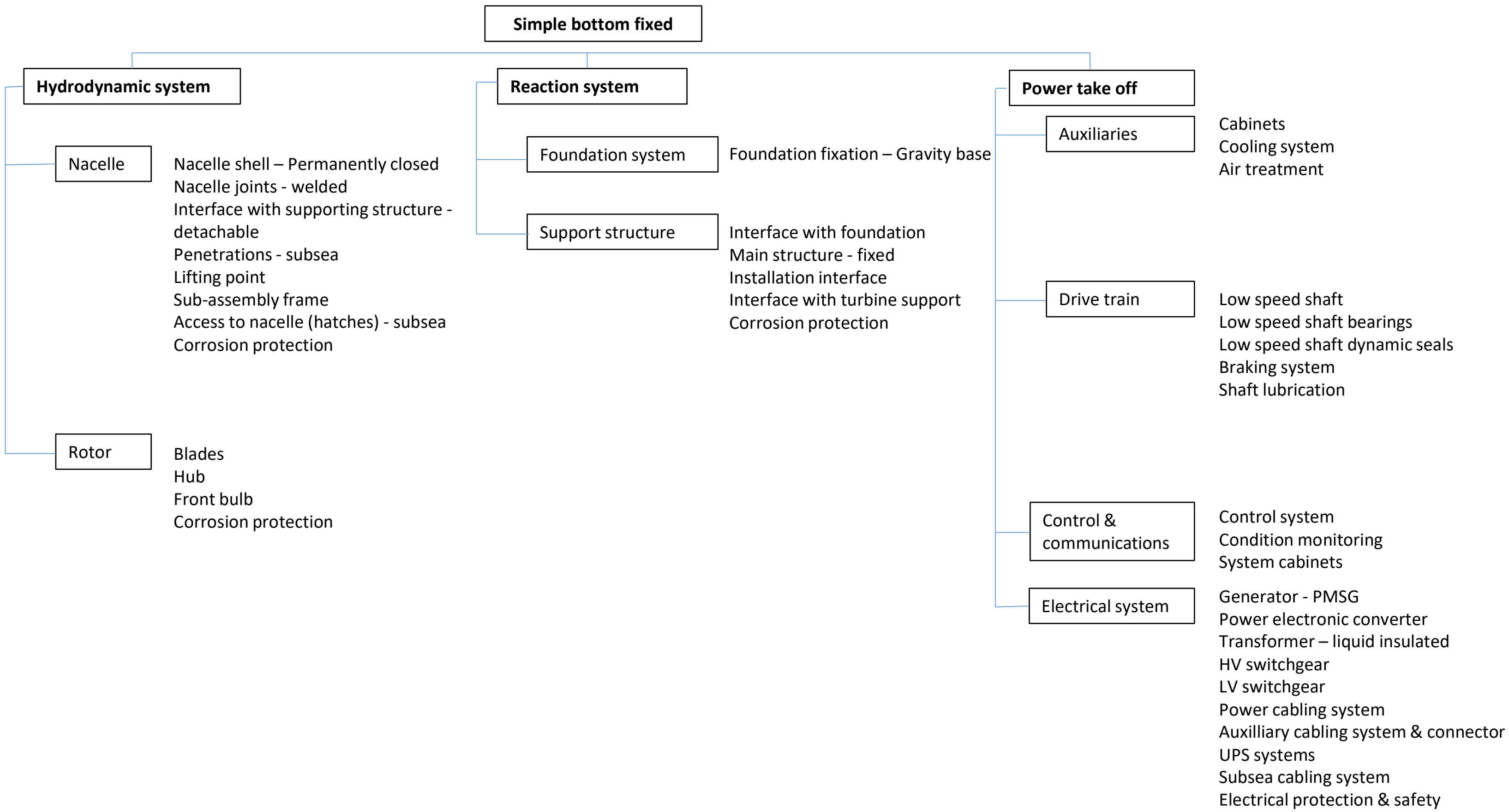

Figure 4-3 - Concept 2 Tidal Turbine Taxonomy Diagram

3

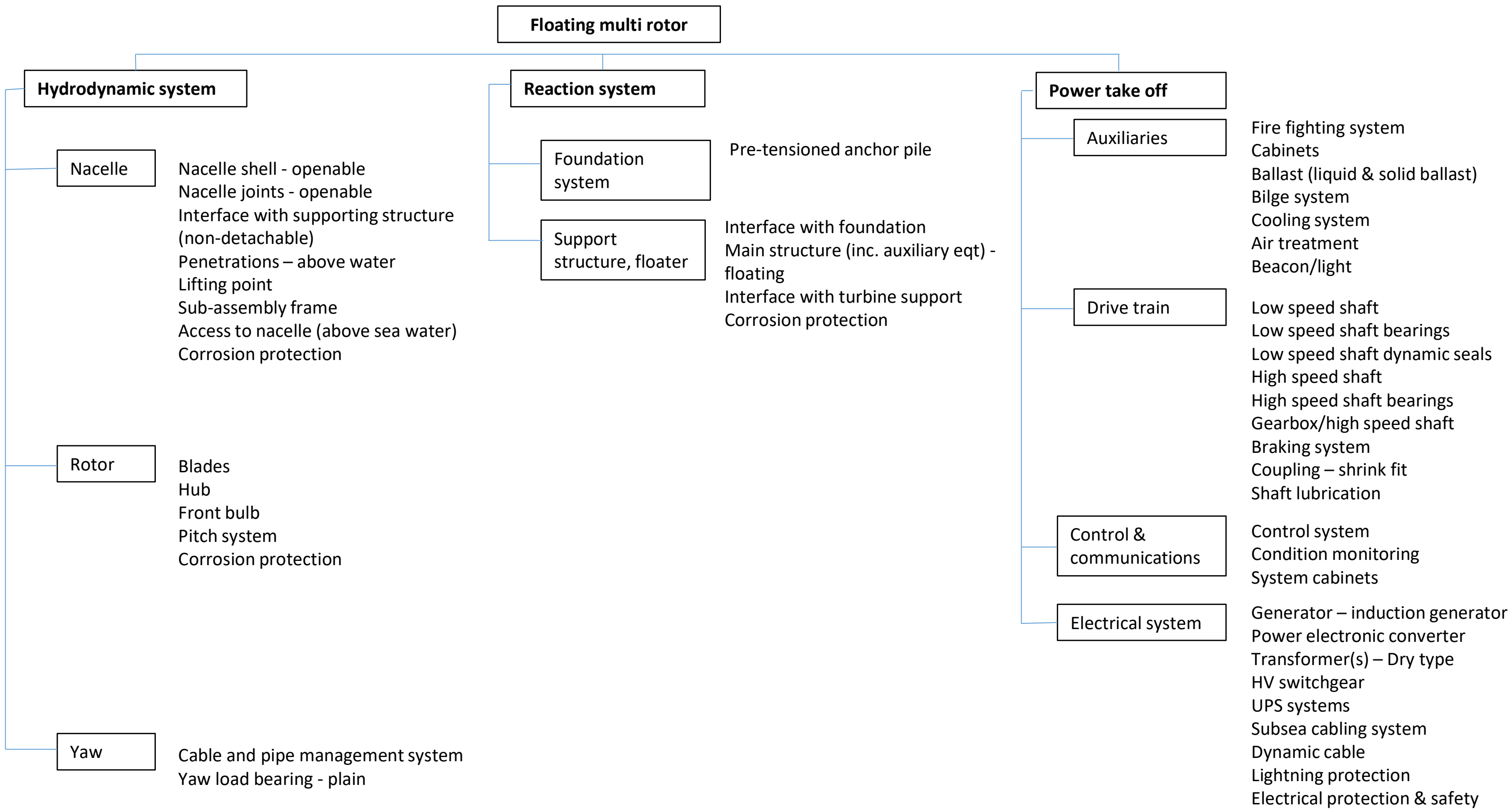

Figure 4-4 - Concept 3 Tidal Turbine Taxonomy Diagram

4

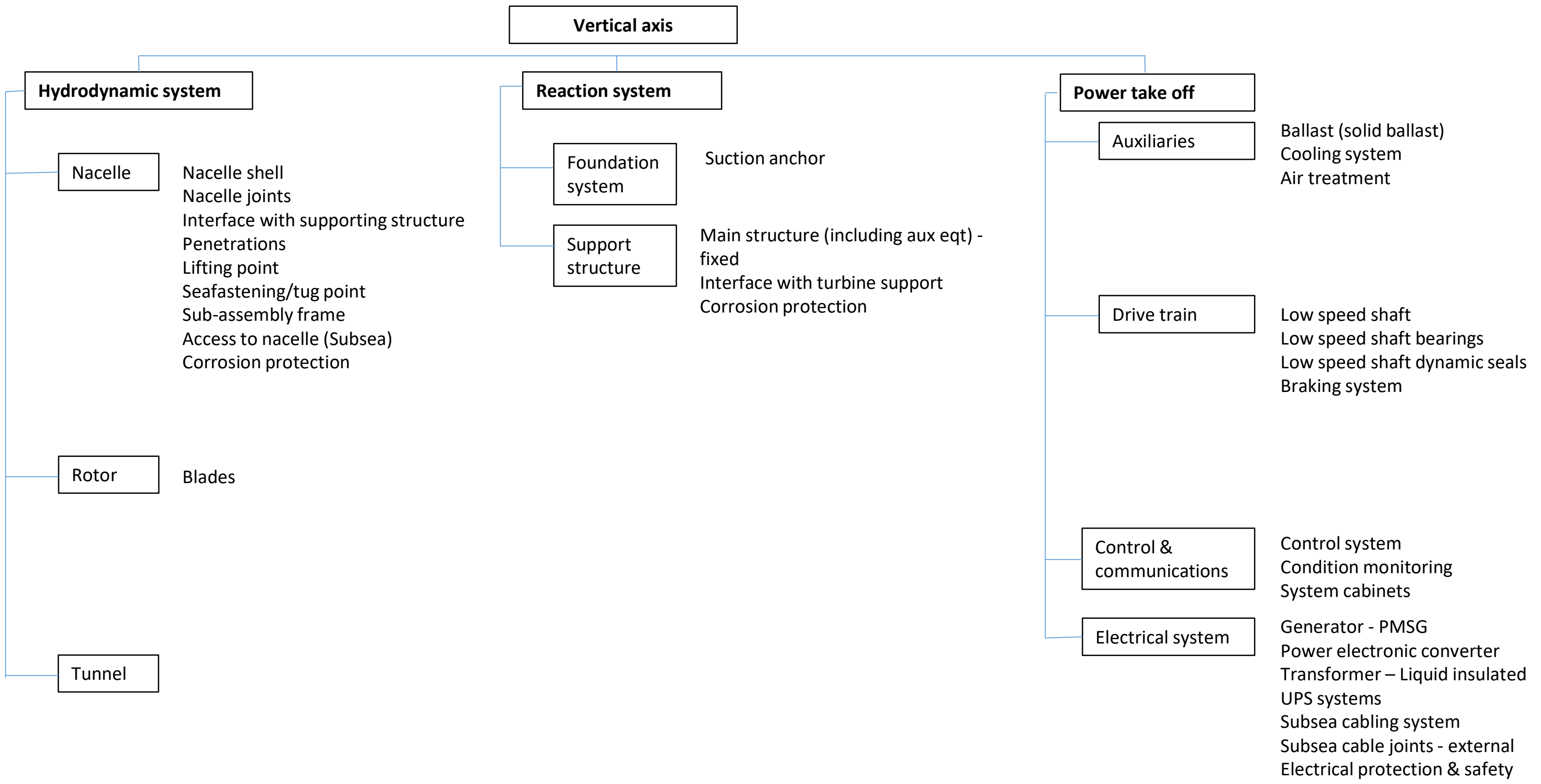

Figure 4-5 - Concept 4 Tidal Turbine Taxonomy Diagram

5 FMEA METHODOLOGY

5.1 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)" [10] - has been adapted to the Real Tide objectives.

This section presents the objectives and the Failure Mode and Effect Analysis (FMEA) methodology that have been developed during Task 1.1.

5.2 Objectives of FMEA

5.2.1 General Objectives

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.

5.2.2 RealTide Objectives

The purpose of the FMEA developed in the RealTide project is to provide a systematic and comprehensive analysis of a range of generic tidal turbines present on the European tidal market.

In a generic way, the objectives of this FMEA are:

- To identify single failure modes and possible causes;
- To evaluate the relevant potential consequences of each failure mode on tidal turbines production, safety and the environment;
- To identify the existence of failure detection methods;
- To identify the risk reduction measures commonly put in place;
- To assess the risk associated to each failure mode; and
- To recommend solutions provided to prevent the occurrence of the critical failure modes in terms of monitoring and design improvements.

5.3 Principles of the FMEA

5.3.1 General presentation

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 FMEA methodology process is shown graphically on Figure 5-1

The FMEA methodology complies with Standard IEC 60812:2006 “Analysis techniques for system reliability — Procedure for failure mode and effects analysis (FMEA)” [10].

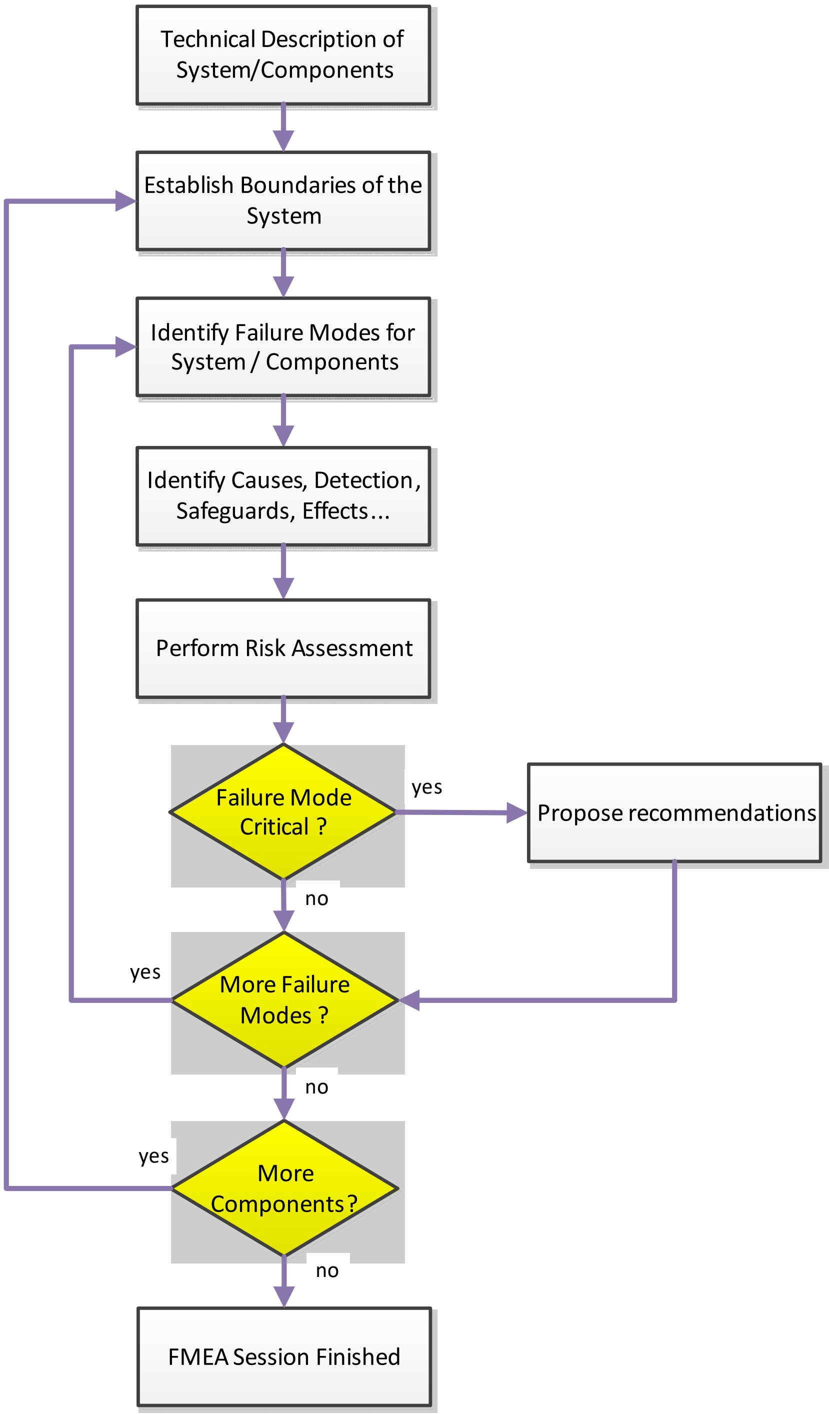

Figure 5-1 - General FMEA Methodology

5.3.2 General definitions and considerations

5.3.2.1 Identification of failure modes, causes & effects

Failure mode is the manner by which a failure is observed. It generally describes the way the failure occurs and its impact on the component. A failure mode of a component could also be the inherent failure cause of a system failure.

The failures of a component are studied according to component's design, its function and operation. Each component is considered starting from the component's functional output, and failure is assumed by 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.

The consequence of a failure mode on the operation, function or status of a component or a system is called a "failure effect". Failure effects on a specific sub-system or equipment 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 of component or a sub-system on the system or a function is called an "end failure effect" (i.e. System effect in FMEA analysis). 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 end effects are categorized according to their impact on the Personnel safety, Environment and Economic.

5.3.2.2 Failure detection and safeguards

Failure detection and safeguards are to be evaluated for failures effects, in particular for those that are not acceptable.

In the FMEA, failure detection can be visual or audible warning devices, automatic sensing devices, sensing instrumentation or other unique indications, and have to be identified for unacceptable failures. 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. The failure detection, if not linked to an automatic action (equipment tripping, back-up equipment starting …), is to warn the maintenance staff in time, so that the safeguard can be taken without delay and before worsening of the situation.

5.3.2.3 Safeguards, Design and Monitoring considerations

The safeguards must be able to palliate the occurrence of the failure mode or to prevent or reduce the effects of the failure mode.

Given that the tidal turbine will be in operation for many years in a remote place and unsuited environment to maintenance activities, the way the installation will be designed and monitored can contribute to prevent the occurrence of failures and can thus be considered in the FMEA. Therefore, the design controls of each component are to be considered together with monitoring program recommended by the manufacturer.

5.3.2.4 Criticality

Criticality is the combination of the Severity of the failure effect with the occurrence and level of detection of the failure (i.e. RPN = S x O x D, see chapter 5.4.3.7). The criticality assessment is performed on each failure mode to evaluate the acceptability of risk presented to each failure modes and prioritize the further recommendations proposed to reduce the risk to an acceptable level.

5.3.2.5 Recommendations and Maintainability considerations

Whenever a critical component is not duly covered by monitoring or design measure a recommendation is made.
Depending on the failure characteristic, the recommendation to reduce the criticality from occurring can be relative to:

- monitoring strategy - to be addressed to WP4, and/or
- redesign suggestion - to be addressed to WP5.

The "design suggestions" could be of different types:

- To implement permanent arrangements (ex: safety devices, protective plating …);
- To implement arrangements which starts/operates automatically after detection (ex: redundant or back-up equipment/system or safety devices operating automatically after a monitored parameter is out of acceptable range) ; and
- To implement arrangements which are manually started/operated in time by the crew being warned (failure detected by an appropriate alarm) (ex: redundant or back-up equipment/system, emergency procedures, and alternative modes of operation).
- To implement innovative components, technologies or materials that better resists the environmental and operational constraints.

In case the two strategies (monitoring or redesign) are not sufficient to reduce the criticality of the failure mode, then a systematic preventive maintenance should be recommended.
However, given that the tidal turbine are generally in remote areas where accessibility is difficult, excessive preventive maintenance activities requiring man presence, complex logistics and costly maintenance utilities should be avoided.
This is why RealTide focuses in priority on design improvements and enhancement of monitoring strategy in increase tidal turbine reliability and durability.
Therefore, Preventive Maintenance strategy is out of the scope of RealTide project by the moment and should be considered in a further study taking into account the conclusions made on the WP4 and WP5.

5.4 FMEA Methodology applied to RealTide project

5.4.1 Scope of the FMEA Study

For the Realtide project, the FMEA will be applied to each of the concepts presented in section 0

5.4.2 FMEA Methodology overview

Despite there are several FMEA standards and guidelines that set the process and principles of the methodology, the users are free to make the necessary adaptations according to the specificities of the project objectives, the scope and the context. For example, the methodology allows setting the level of the study at system level or at component parts level. The criticality can also be included or not in the study and the criteria used for the criticality can be (and have to be) redefined according to the project specificities.

In view of that, the FMEA methodology was discussed between the partners during several meetings in order to make the necessary adaptations of the methodology for the RealTide objectives (which are to recommend improvements in tidal turbine designs and set a monitoring strategy in order to enhance their reliability) but also to define the basis and the definitions to be used during the FMEA analysis.

The resulting methodology is summarized in the Figure 5-2 which presents the different steps to be followed.

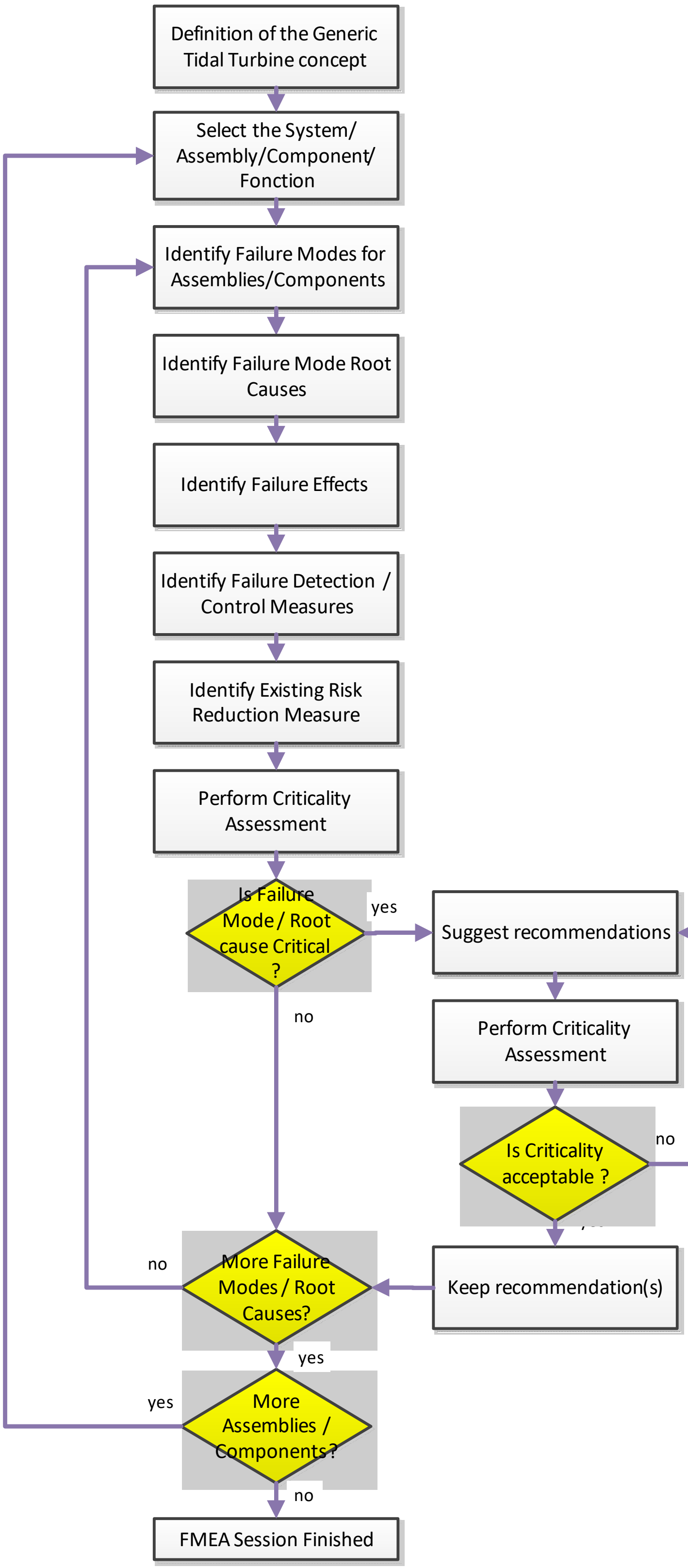

Figure 5-2 – RealTide FMEA Methodology

Once the Tidal turbine concept is selected, the FMEA consists of a systematic process which aims at identifying the following information/data:

- Sub-system
- Assembly
- Sub-Assembly
- Components
- Function
- Failure Modes
- Root Cause
- Failure Effect:
  - Local Effect
  - System Effect
  - Production Effect category
- Control Measure
- Criticality Assessment (before recommendation):
  - Severity
  - Occurrence
  - Detectability
  - RPN
- Risk Reduction Measure
  - Design controls
  - In service monitoring
- Recommendation
  - Monitoring
  - Maintenance
  - Redesign
- Criticality Assessment (after recommendation):
  - Severity
  - Occurrence
  - Detectability
  - RPN

The information and data are collected in an FMEA worksheet as presented in the Table 5.1 below. Each data, information and definition to be used in each step are described in the following sections.

Table 5.1 - RealTide FMEA Worksheet

Subsystem	Assembly	Subassembly	Component	Sub Component	Colonne1	Failure Mode	Root Cause	Failure Effect			Detection / Control Measure	Risk Reduction Measure		Criticality Assesment (before recommendation)					Recommendation			Criticality Assesment (After recommendation)				
								Local Effect	System Effect	Production Effect Category		Design controls	In service monitoring	Severity	Occurrence	Detection	RPN	Crit.	Maintenance	Monitoring	Redesign	Severity	Occurrence	Detection	RPN	Crit.

5.4.3 Steps and Definitions

5.4.3.1 Sub-system / Assembly / Sub-Assembly / Components / Function

Sub-systems, Assemblies, Sub-Assemblies, Components and functions are those defined in the section 4.

5.4.3.2 Failure Modes

Failure mode is the manner in which the item or operation potentially fails to meet or deliver the intended function and associated requirements.
The failure more 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;
- Failure mechanisms: Intrinsic failure of the component which is the physical phenomenon leading to the failure mode (e.g.: corrosion, fatigue, erosion, wear, friction, overheating…).

As per OREDA 2009 [4], the Failure Mode is defined as the failure by which a failure is observed on the failed unit. 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 is related to the lowest level in the taxonomy (i.e.; **Sub-Assembly, Component or sub-component** levels); the failure mode is a description of the various abnormal state/conditions of Sub-Assembly, and the possible transition from correct to incorrect state.

Table 5.2 - Example of Failure Modes

Failure Mode
(1) External leakage
(2) Structural deficiency

5.4.3.3 Root Cause

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 should focus on the following Root Causes:

- Causes due to 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 occurred on other assemblies/components (e.g.: rotor vibration due to mooring line failure)
- Failure due to design defects should also be recorded as per partners' experience.

Table 5.3 - Example of Root Cause

Failure Mode	Root cause
(1) External leakage	Inadequate seal material
(2) Structural deficiency	Impact /shock

Manufacturing/Process defects and causes are not the focus of RealTide project, thus those root causes are not included in the scope of the FMEA.

5.4.3.4 Effect

An effect is the consequence of the failure on the system or end user.
This can be a single description of the effect on the top level system and/or end user, or two levels of effects (local and system effect).
There can be more than one effect for each failure mode. However, typically the FMEA team will use the most serious of the end effects for the analysis.

In RealTide FMEA, the effects of each failure mode were documented in two levels: local effect (affecting the equipment and / or immediately upstream / downstream parts of the process) that escalates to the system effect (affecting the whole or significant portions of the entire plant).

The three information collect in the effect analysis are:

Local Effect:
The failure effect as it applies to the item under analysis.

System Effect:
The failure effect at the highest level or total system.

Production Effect Category:
The failure category is the level of impact on production and damage on turbine. It should be selected among the 4 criteria presented in the table below:

Table 5.4 - Production Effect Category Scales

Scale	Description	Criteria
1	Category IV (minor)	Electricity can be generated but repair is required
2	Category III (marginal)	Reduction in ability to generate electricity
3	Category II (critical)	Loss of ability to generate electricity
4	Category I (catastrophic)	Loss of ability to generate electricity due to Major damage to the Turbine as a capital installation

Production Effect Category will be further used in Task 1.2 for the Generic Tidal Turbine RAM analysis

Table 5.5 - Failure Effect Examples

Failure Mode	Failure Effect		
	Local Effect	System Effect	Production Effect Category
(1) External leakage	Water infiltration, Rust	Production interrupted	Loss of ability to generate electricity
(2) Structural deficiency	Friction, vibration	Reduced turbine performance, jerky, slowed	Reduction in ability to generate electricity

5.4.3.5 Detection / Control Measure

Detection / Control Measures are the means of detection of the failure mode by maintainer, operator or built in detection system, including estimated dormancy period (if applicable).

In other words, Detection / Control Measure describe how a failure mode is ***detected*** (not prevented) when it happens.

They are intended to increase the likelihood of detecting a problem (Failure Mode) before it reaches the end user; and consequently mitigate the consequence at system level (final effect).

As the study is carried out on a “Generic Tidal Turbine”, it is not possible to define the exact Detection / Control Measures that are generally in place. Each tidal turbine will be a different case, but it is possible to inform if yes or no, a detection / control measure general exists on current Tidal turbines.

Thus, Detection/Control Measure consists in informing if “detection/control measure” generally exists (or is generally possible) in order to detect the occurrence of the failure mode, as proposed below:

- **Yes: detection/control measure generally exists or is possible;**
- **No: generally detection/control measure does not exist or is not possible.**

Table 5.6 - Detection / Control Measure Examples

Failure Mode	Detection / Control measure
(1) External leakage	Yes
(2) Structural deficiency	No

It is to be noted that devices or procedures that detects the effect of the failure mode but that cannot give a clear indication that what is the failure mode are not considered as detection/control measure (for example, it is easily detected that tidal turbine losses production efficiency, however it is not possible to know with this indication what failure modes is causing this effect).

5.4.3.6 Risk Reduction Measure

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.
Controls can be the methods to prevent or to detect the cause during product development (Design Control), or actions to detect a problem during service before it becomes catastrophic (In service monitoring).
There can be both Design Control and In service Monitoring associated to a cause.
Design Control is usually intended to reduce the occurrence of the failure mode and In Service Monitoring is intended to increase its detection.

As the study is carried out on a “Generic Tidal Turbine”, it is not possible to define the exact Risk Reduction Measures that are in place. Each tidal turbine will be a different case, but it is possible to inform what kind of Risk Reduction Measure is generally applied on existing Tidal turbines.

Thus, Risk Reduction Measure consists in informing which type of Design control and In Service Monitoring is usually adopted on Tidal Turbines among the categories below:

A. <u>Design controls generic types</u>

- GDP. - General design practices. Rules, practices and standard;
- DTA. - Detail analysis. CAE (computer aided engineering): FEM, CAD, CFD, etc.;
- RDN. - Redundancy;
- EXPS - Experimental campaign (simple), scale prototypes;
- EXPC - Extended experimental campaign, full scale components.

A more detailed explanation of the “diagnostic control generic types” is included bellow:

1. **General design practices. Rules, practices and standard:**
   At this early stage of the industry, with the absence of code and standard specifically for tidal turbine, several oil and gas offshore code and standard can be used as the reference during the design process, such as for the support structure part conformity check of the construction can be referred to the norm NR-426-DT-R01-E Construction Survey of Steel Structures of Offshore Units and Installations. Design basis and loading condition can refer to Design calculation based on norms DNV-RP-C205 Environmental conditions and environmental loads.

2. **Detail analysis. CAE (computer aided engineering): FEM, CAD, CFD, etc.:**
CAE can be utilised extensively during the design process of the tidal turbine, for example Finite element method (FEM) is utilised during the design of the nacelle, blades, bulb, and support structural parts. For example, in Sabella D10Tidal turbine, the following computation are conducted using FEM:
    - Stability calculation
    - Stress and displacement for various loading cases calculation
    - Eigen mode calculation

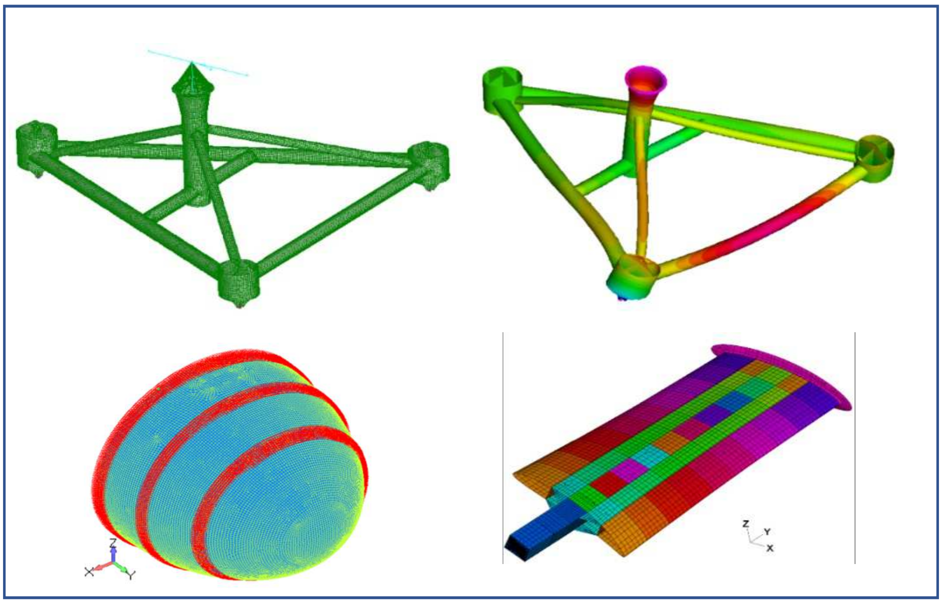

Figure 5-3 – FEM Model of various parts of Sabella D10 tidal turbine

3. **Redundancy:**
Reliability data for similar components in another industries indicates that there are several electrical components that exhibit high failure rate. In this case, redundancy of the component can be adopted as the strategy to improve the overall tidal turbine. This technique can be based in the reduction of the severity of a failure by a design that includes a redundant solution (it will work even after a failure appears, maybe at reduced performance), or even in the use of modularity, allowing to replace a smaller/less costly component/subcomponent or the use of fuses of any type (electrical fuses or even mechanical ones like a pin or shaft key) very cheap and easy to replace in case of an overload.

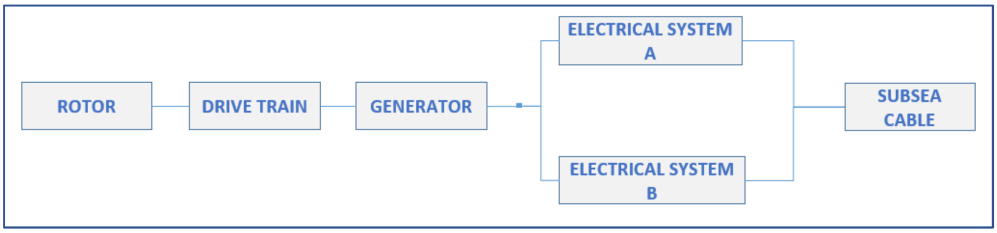

Figure 5-4 – RBD diagram of typical tidal turbine with redundancy for the electrical system

4. Experimental campaign (simple): Scale prototypes:

Prior to the development of full scale model, various type and purpose of prototype are developed and tested in order to confirm and verify the preliminary design. In 2008 Sabella started a field test for their first tidal turbine prototype, the Sabella D03, a 1/3 scale. The tidal turbine prototype was submerged off the cost of Bénodet, in the estuary of Odet, at 19 m depth. The test was conducted for a year from April 2008 to April 2009. The objectives of the test were:

- To determine the behavior and performance of the machine
- To assess the environmental impact
- To verify the structural integrity
- To validate the construction, installation, and operation process
- To identify areas of improvement
- To model the electrical production

Figure 5-5 – Sabella D03 tidal turbine trial

The D03 test result created the basis for the development of the pre-industrial scale tidal turbine D10.

In 2013 scale model of Sabella D10 was tested in INSEAN lab in Italy, in order to verify the hydrodynamics model for the tidal turbine.

Figure 5-6 – Sabella D10 scale prototype and full scale comparison

5. **Extended experimental campaign: Full scale components:**
After gathering sufficient design data, tidal turbine project can proceed with full scale development. For example Sabella D10 tidal turbine construction was completed in first quarter of 2015. Afterwards, the installation of the turbine in strait of Fromveur between the island of Ouessant and Molene at 55 m depth was accomplished on 25th June 2015, whereas the final connection to the grid was completed in September 2015. Various monitoring on the performance of the turbine was conducted from September 2015 until May 2016, covering structural integrity, tidal components performance and behavior, and environment monitoring.

Figure 5-7 – Sabella D10 full scale sea trial

B. <u>In service monitoring generic types*</u>

- IVT. - Inspection visit tools;
- IDE. - Indirect detection. Integrated effect;
- MBE. - Model based estimation;
- DM. - Direct measurement. Cause or effect;
- MUID. - Multiple integrated detection.

The “In service monitoring” generic types are listed from the less effective type to the most effective one. A more detailed explanation of the “in service monitoring generic types” is included bellow:

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

2. **Indirect detection. Integrated effect:**
When using this kind of techniques, fault is not detected directly but its consequences over a third system/subsystem. Sometimes it is not possible to obtain the root cause of the failure by using this technique. For example: An over-temperature in the nacelle indicates that something is not working properly in it, nevertheless, this can be caused by many causes such us: generator, transformer, inverter or cooling system.

3. **Model based estimation:**
The concept is similar to indirect detection except that in this case, it is possible to find the root cause by relating several indirect measurements using a proper analytical model. For example: flowmeter in dynamic ballast systems are sometimes used for detecting pumps failures. An alternative way to check the pump flow might be by using a model which calculates the required time 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.
This concept is described in the deliverable *D4.1 Initial monitoring plan for tidal turbines*.

Next figure shows a schematic description of a redundant model based parameter estimation applied on a generic tidal turbine, where both x_{e1} and x_{e2} are an estimate of x_m (sensor measurement) that adds information of the status of the system.

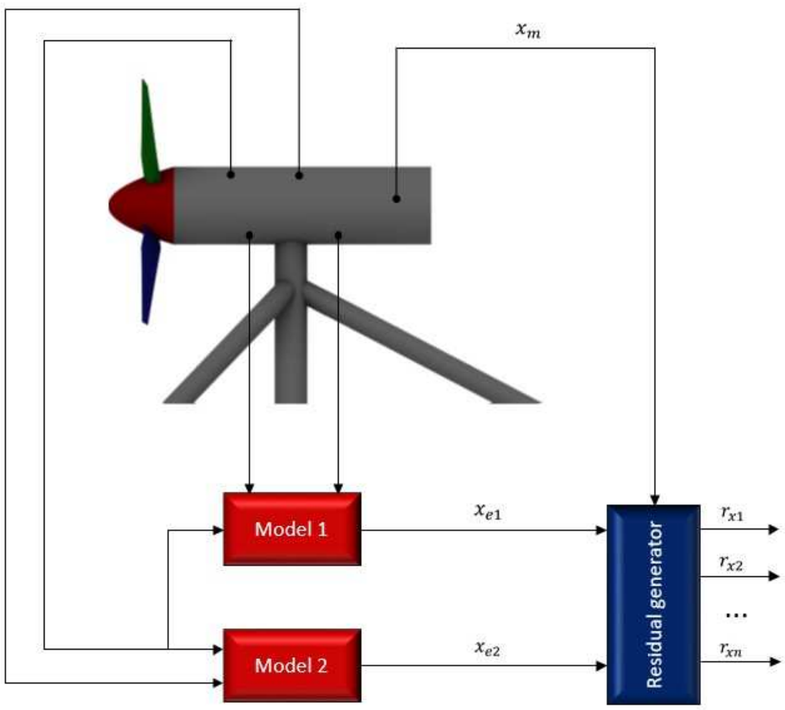

Figure 5-8 – Schematic description of the model based estimation

4. **Direct measurement. Cause or effect:**
The monitoring is done directly by detecting either the cause or the effect of the failure. For example: Let us think in a broken bearing provoked by shaft imbalance. In this case, the failure can be detected by monitoring the temperature in the bearing (effect), or the vibrations on the bearing/shaft (cause).

5. **Multiple integrated detection**:
Direct measurement of possible causes or effects by using either redundant measurements or redundant sensors. For example: monitoring can be done redundantly either by using several conventional sensors placed in the same location or by using a specific redundant sensor with multiple electronic conditioning in the same encapsulation.

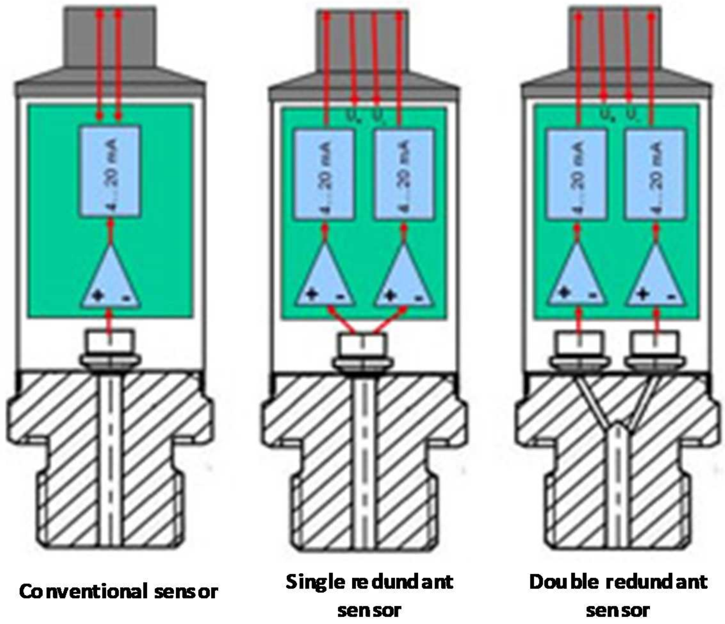

Figure 5-9 – Integrated redundant sensor

Another example: dynamic redundancy, also described in the deliverable *D4.1 Initial monitoring plan for tidal turbines*, that combine multiple sensor measurements or model based estimates to decide which the best value is.

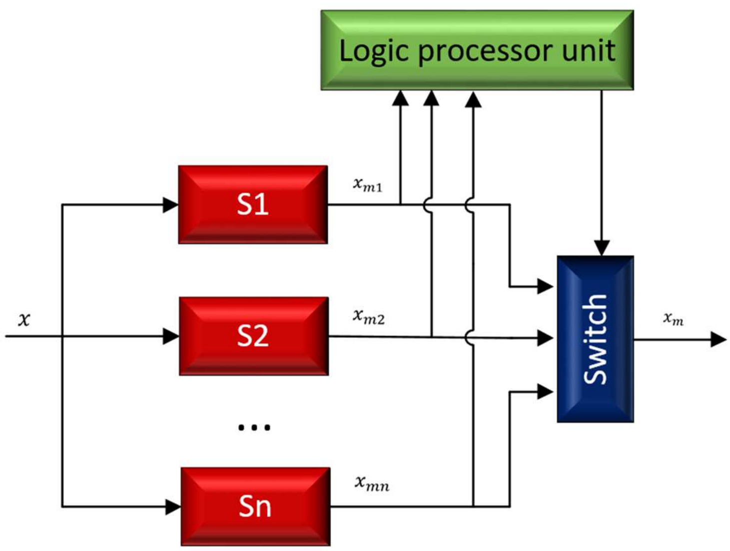

Figure 5-10 Dynamic redundancy integration

As for another example, a combination of Acoustic Emission or LRUT can be used to detect structural defects in some critical components, combining it with extensometry data and piezoelectric accelerometers to estimate the relation between efforts, deformations and potential appearance of cracks in elements of the tidal turbines like the blades or the support structure.

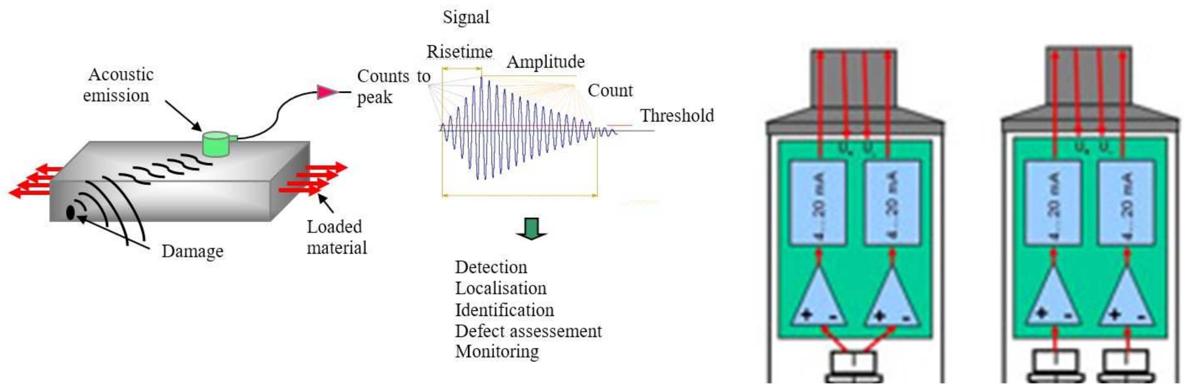

Figure 5-11 – Left: Acoustic emission technique. Right: Different Redundant Piezoelectric sensor

Table 5.7 - Risk Reduction Measure Examples

Failure Mode	Risk Reduction Measure	
	Design Control	In service monitoring
(1) External leakage	EXPS- Experimental campaign (simple), scale prototypes	IDE. - Indirect detection. Integrated effect
(2) Structural deficiency	GDP. - General design practices. Rules, practices and standard	DM. - Direct measurement. Cause or effect

5.4.3.7 Criticality (before recommendation)

As defined in the standard IEC 60812:2006 “Analysis techniques for system reliability — Procedure for failure mode and effects analysis (FMEA)” [10], 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: 1) the **severity** of the effect; 2) the expected probability of its **occurrence** (for a predetermined time period assumed for analysis); and 3) the chance of **detection** and elimination of the failure mode before it affects the system or the final user.

The success of this methodology in industry is due to the fact that Criticality can be assessed very quickly without necessarily the need of extensive and accurate data, where most of time, work team’s experience and common sense are enough to achieve to an agreed criticality assessment. This is even more relevant when the Criticality Assessment is carried out on new concepts where data and operating experience are notable unavailable, as it is similarly the case in RealTide project.

The RPN and the criteria for Severity, Occurrence and Detection are described below.

a) RPN Calculation

The RPN is expressed as follows:

$$RPN = S \times O \times D$$

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 [8], the RealTide partners developed their own criteria and ranking scale for Severity, Occurrence and Detection
Each criterion is devised 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:

6. 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;
7. then, selecting a ranking scale value within the range proposed in the corresponding level.

This "funnel type" process allows giving the flexibility to work team to "fine tune" the criticality assessment for failure modes which are in the same criteria level.

The criteria and ranking scale for Severity, Occurrence and Detection are described as follows.

1. 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 5.8.
Severity criteria are divided into 3 categories: economic, environment and health & safety. Each
When a failure mode presents effects that impacts more than one category (e.g. economic and environment), only the highest scale of the scenarios is be selected.
Severity is determined without regard to the likelihood of occurrence or detection.

Table 5.8 - Severity Ranking Scale

Economic

Scale	Description	Criteria
1-3	Minor	No losses to < 2% of the total amount invested
4-5	Marginal	From 2% to < 10% of the total amount invested
6-7	Critical	From 10% to < 50% of the total amount invested
8-10	Catastrophic	From 50% to > 100% of the total amount invested or total loss of turbine

Environment

Scale	Description	Criteria
1-3	Minor	Temporary imperceptible impact / Permanent Imperceptible impact / Temporary slight impact
4-5	Marginal	Permanent slight impact / Temporary moderate impact
6-7	Critical	Permanent moderate impact / Temporary severe impact
8-10	Catastrophic	Permanent severe impact / Temporary major impact / Permanent major impact

Health & Safety

Scale	Description	Criteria
1-3	Minor	No significant injury / Minor Injury / Accident without time off work
4-5	Marginal	Accident with time off work < 6 months
6-7	Critical	Accident with time off work > 6 months / Partial disability
8-10	Catastrophic	Full permanent disability / Sever disability / Death

2. **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.
Occurrence considers the likelihood of occurrence during production and is based on the criteria presented in Table 5.9.
Occurrence has a relative meaning rather than absolute value and is determined without regard to the severity or likelihood of detection.

Table 5.9 - 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

3. Detection

Detection is a ranking number associated with the best control from the list of detection-type controls (service monitoring). Detection is the chance of detecting and eliminate he failure mode before it affects the system or the final user and is based on criteria presented in Table 5.10.
Occurrence determined without regard to the severity or likelihood of occurrence.

Table 5.10 - Detection 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 Occurrence 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.

4. Criticality Matrix and Risk Acceptance Criteria

The criticality is presented on a criticality matrix, as shown in Figure 5-12. 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 rather failure mode is critical or not according to the Risk Acceptance Criteria adopted by RealTide Partners described further below.

The red zone corresponds to the “Unacceptable” area, i.e., the Failure Modes are considered as High Critical 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 are considered as Medium Critical. The Failure Modes can be mitigated or eliminated by design improvement and/or extra monitoring in case the implementation of these actions is cost effective.
The green zone corresponds to the “Acceptable” area, i.e., the Failure Modes are considered as Low Critical. In this case the Failure Mode is not a threat for operation, environment or Health&Safety and doesn’t need to be mitigated or eliminated.
Risk acceptability was defined subjectively by the partners based on their experience in previous FMEA study.

Risk acceptability and the definition of the three zones were defined subjectively by the partners based on their experience in previous FMEA study:

RPN>125: Failure Mode is considered **High Critical**, thus risk is unacceptable → recommendation has to be made and implemented in order to reduce the Criticality to at least a tolerable level (Medium Criticality);

63 ≥RPN ≥125: Failure Mode is considered **Medium Critical**, thus risk is tolerable → recommendation can be made and its implementation should be further analysed taking into consideration for example a "Cost x Benefit Analysis" when applicable, but it is recommended to do this analysis after considering the effect of the mandatory mitigation actions imposed by High Critical failure modes (RPN>125).

RPN<63: Failure Mode is considered **Low Critical** and risk is acceptable → no need to make recommendation.

Severity (S)	10	20	30	40	50	60	70	80	90	100
10	100	200	300	400	500	600	700	800	900	1000
9	90	180	270	360	450	540	630	720	810	900
8	80	160	240	320	400	480	560	640	720	800
7	70	140	210	280	350	420	490	560	630	700
6	60	120	180	240	300	360	420	480	540	600
5	50	100	150	200	250	300	350	400	450	500
4	40	80	120	160	200	240	280	320	360	400
3	30	60	90	120	150	180	210	240	270	300
2	20	40	60	80	100	120	140	160	180	200
1	10	20	30	40	50	60	70	80	90	100

Occurrence (O) x Detection (D)

High Critical – Risk is unacceptable

Medium Critical – Risk is tolerable

Low Critical – Risk is acceptable

Figure 5-12 – RPN Criticality Matrix

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

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

Table 5.11 - Criticality Assessment Examples

Failure Mode	Criticality assessment				
	Severity	Occurrence	Detection	RPN	Crit
(1) External leakage	7 (the highest rate is economic)	4	6	168	High
(2) Structural deficiency	7	6	2	84	Medium

5.4.3.8 Recommendation

As explained in the previous section, recommendation shall be made for failure modes with High Criticality which means that the Risk is considered unacceptable.
Recommendations are the actions recommended 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 RealTide is to improve design and elaborate an effective monitoring plan for Generic Tidal Turbine, partners have developed a methodology in order to address the most relevant recommendations for Failure Modes in terms of redesign and condition monitoring as follows:

1. The first step is to attend to the RPN value. If the RPN of the failure mode is:

   RPN >125 then some actions are required, and recommendation shall be proposed;

   63 ≥ RPN ≥125 then some actions could be required, and recommendation should be proposed;

   RPN <63 then actions are not required and recommendation doesn't need to be proposed.

2. Then, the philosophy for recommendations consists in mitigating the risk by "condition monitoring" and/or "redesign".

   The criterion that allows choosing between the 2 criteria was inspired by the concept of sensitivity:

$$\left|\frac{\partial Y}{\partial X_i}\right|_{x^0}$$

Applying this concept to find the parameters that are most affected by detection, it results in the following finding:

$$\frac{\partial RPN}{\partial D} = S \times O$$

Where: *RPN = S x O x D*

In that case, if we should attend the highest product *S x O*.
The most obvious way to affect the detection is by using **condition monitoring**.

The proposed criterion used to determine if condition monitoring shall be recommended is:
If ***S x O ≥ 40*** → It is recommended to mitigate the risk by using **condition monitoring.**

In the same way, if we want to find the most affected parameters by Occurrence we should attend the highest product *S x D*:

$$\frac{\partial RPN}{\partial O} = S \times D$$

And 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*** → It is recommended to mitigate the risk by using **redesign.**

The value of 40 comes to the will of focusing on the 30% highest range of the products *S x O* and *S x D*. Indeed, among the all 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 can be observed in Table 5.12.
As is not possible to get exactly 30%, it was decided to keep the closest value above 30%.

Table 5.12 - S x D and S x O quantification matrix

S x X =

S		X=1	2	3	4	5	6	7	8	9	10
S	**1**	1	2	3	4	5	6	7	8	9	10
S	**2**	2	4	6	8	10	12	14	16	18	20
S	**3**	3	6	9	12	15	18	21	24	27	30
S	**4**	4	8	12	16	20	24	28	32	36	40
S	**5**	5	10	15	20	25	30	35	40	45	50
S	**6**	6	12	18	24	30	36	42	48	54	60
S	**7**	7	14	21	28	35	42	49	56	63	70
S	**8**	8	16	24	32	40	48	56	64	72	80
S	**9**	9	18	27	36	45	54	63	72	81	90
S	**10**	10	20	30	40	50	60	70	80	90	100
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**

X = O or D

S x X ≥ 40 (orange cells)

Quantity of « S x X » possibilities : 10 x 10 = 100

Quantity of cases with "S x X" ≥ 40 : 32 (orange cells)

In some cases, RPN is higher than 125, however the products *S x D* and *S x O* are both lower to 40 as shown in the examples in Table 5.13:

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 kind of case happens, it is proposed to focus on the highest product. In the example, the highest product is the *S x O* then condition monitoring should be recommended in priority.

Table 5.13 - Criticality Assessment Example 2

Failure Mode	Criticality assessment				
	Severity	Occurrence	Detection	RPN	Crit
Failure Mode	**7**	**4**	**5**	**140**	**High**

3. Check if we have to do both condition monitoring and redesign:

   Maybe sometimes, for the failure criticality, this criteria is not enough and we need to use both redesign and condition monitoring if we found the product *S x O* and/or *S x D* very high for a certain failure mode.

   The proposed criterion used to determine if redesign and condition monitoring shall be recommended is:

If ***S x O ≥ 63 or S x D ≥ 63*** → The RPN needs to be mitigated by using **redesign and condition monitoring.**

For the failure modes for which monitoring are recommended, they are assigned to WP4 in order to define what condition monitoring techniques can be applied with the most effectiveness to monitor and prevent the failure mode.

In the same way, the failure modes for which redesign are recommended, they are assigned to WP5 in order to assess the effect of the design improvement in the occurrence of the failure mode.

It should be noted that a "Maintenance" column have been included into the recommendations. This column should be filled as an alternative solution in case the WP4 and WP5 conclude that neither Monitoring nor Redesign is effective enough (as expected in the FMEA performed in task 1.1) to mitigate or eliminate the risk.

After WP4 and WP5 conclusions, the monitoring and redesign columns should be filled with the final recommendation and the Criticality Assessment reviewed.

An example of application of the methodology to select the most appropriated risk reduction measure is included bellow. In this table a selection of high risk failure modes identified during the FMEA is listed. We have added two additional columns (*SxO* and *SxD*) and accordingly to the values of the RPN and these new columns, we have established four potential results:

- **Nothing**: meaning no actions.
- **Monitoring**: meaning to reinforce the detection capacity by taking most effective monitoring approach.
- **Redesign**: Trying to reduce the severity or occurrence of a potential failure by applying a more comprehensive design method.
- **Monitoring & Redesign**: Combining the two previous approaches as a way to reduce the risk.

Risk Reduction Measure		Criticality Assessment							Recommendation			
Design controls	In service monitori	Severity	Occurren ce	Detectab ility	RPN	Crit	SxO	SxD	¿Actions needed	Mainte nan	Monitorin g	Redesign
GDP	IVT	5	5	5	125	High	25	25	Redesign & Monitoring		IVT, DM	GDP, RDN
GDP, DTA	IVT, IDE	4	7	7	196	High	28	28	Redesign & Monitoring		IVT, IDE, MUID	GDP, DTA, EXPC
GDP, DTA	IVT, IDE	4	6	6	144	High	24	24	Redesign & Monitoring		IVT, IDE, MUID	GDP, DTA, EXPC
GDP	IVT, IDE	4	6	6	144	High	24	24	Redesign & Monitoring		IVT, IDE, MUID	GDP, DTA, EXPC
GDP, DTA	IVT, IDE	5	5	5	125	High	25	25	Redesign & Monitoring		IVT, IDE, MUID	GDP, DTA, EXPC
GDP, DTA	IVT, IDE	5	6	5	150	High	30	25	Monitoring		IVT, IDE, MUID	GDP, DTA
GDP, DTA	IVT, IDE	5	5	5	125	High	25	25	Redesign & Monitoring		IVT, IDE, MUID	GDP, DTA, EXPC
GDP, DTA	IVT, IDE	6	8	5	240	High	48	30	Monitoring		IVT, IDE, MBE	GDP, DTA
GDP	IVT, IDE	4	7	5	140	High	28	20	Monitoring		IVT, IDE, MUID	GDP
GDP	IVT, IDE	4	9	5	180	High	36	20	Monitoring		IVT, IDE, MBE	GDP
GDP	IDE, DM	6	7	7	294	High	42	42	Redesign & Monitoring		IDE, DM, MBE	GDP, RDN
GDP	IDE, DM	5	6	6	180	High	30	30	Redesign & Monitoring		IDE, DM, MBE	GDP. DTA
GDP	IVT, IDE	5	7	5	175	High	35	25	Monitoring		IVT, IDE, DM	GDP

Figure 5-13 - Example of recommendation selection (actions needed)

5.4.3.9 Criticality (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 level. This demonstrates the potential effectiveness 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 assessed again.
Sometimes, after several iterations, there is no possibility 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 [12].

As it is not defined yet in this stage of the project, what would be exactly the recommendation in terms of monitoring and redesign, the Criticality after recommendation will be roughly done by the work team. Thus, the Criticality Assessment after recommendation should be reviewed after WP4 and WP5 conclusions when condition monitoring techniques and design improvements will be defined.

5.4.3.10 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 can be used. 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:

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

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:

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

Where:

- $\boldsymbol{W_s(S)}$**:** Is the severity weight. It is defined attending to the economic criteria within severity (see Table 5.14), since it is the only criteria defined in the severity tables which allows to quantify the severity numerically. For those severity numbers assigned in the RPN calculation not referring to the economic scale, i.e. health and safety or environment impact, we assume this number as its equivalent in the economic scale.
- $\boldsymbol{W_O(O)}$**:** Is the occurrence weight.
- $\boldsymbol{W_D(D)}$**:** Is the detectability weight. It is defined in a range of 0.44 up to 1, depending of the detectability. It reflects the planning difficulties and risk derived from the lack of timely detection of a failure.

The methodology has been adapted to RealTide project particularities and was firstly implemented in the deliverable *D3.1 - Generalised tide-to-wire model* [14]. In the mentioned document, the criticality assessment method exposed in the current section, was initially proposed by EnerOcean and Ingeteam and implemented as a part of the FMEA analysis that was included in the H2020 project “WIP10+” [15].
In this document, three different methods were proposed for obtaining the criticality function:

1. **Look-up table (LUT):**
   The weights can be obtained directly attending to the following table:

Table 5.14 – 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

2. **Adjusted function:**
   In this case we create the weight value for each indicator (S, O and D) with the following structure:

$$W_x = d_x \cdot 10^{\frac{x}{x_0}}$$

   This method allows for easy computer implementation. From the table exposed above, we have obtained the following parameters:

Table 5.15 – Criticality Assessment – Adjustment function parameters

	S	**O**	**D**
dx	1.00E-03	2.20E-04	0.016
x0	3	3	0.025

3. **Simplified adjusted function:**
   In this case, one single indicator is needed. Criticality can be calculated as:

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

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

$$RPN_0 = S_0 = O_0 = D_0$$

6 APPLICATION OF THE FMEA

6.1 Scope

The FMEA described in section 5.4 has been carried out for the 4 generic tidal turbine concepts selected for the project (see section 3.2).
The FMEA worksheets have been populated by the partners based on their own knowledge, experience, references and data.
The FMEAs that have been developed for each concept are presented in Annexes B, C, D and E.
Due to confidentiality issues, only the analysis from Failure Mode to System Effects are published in this document. The information that have not been published are either subject to confidentiality or are subject to be modified along RealTide project as the FMEA will be interacting with the other tasks and WP.

6.2 Limits of the Generic Tidal Turbine FMEAs

It should be noted that the FMEA worksheets has been populated by the partners based on their own knowledge, experience, references and data. Considering that the tidal turbine technology application is relatively new in the renewable energy sector and the lack of feedback on those kinds of devices, the FMEA can present gaps compared with the reality.
Moreover, the scope of the study is "Generic" Tidal Turbines, and it intends to be applicable for any tidal turbine, thus the analysis has been performed as general as possible and does not allow going deep in the details or deepening on the specificities of special cases.

The criticality assessment has been performed based on partner's judgement on scale values for severity, occurrence and detectability if the Tidal turbine is in a conventional situation, i.e., excluding extreme situations of operations (deep sea, extreme cold waters, bad weathers zone, extremely polluted or hostile waters…). It has been assumed in the analyses that adequate maintenance tools, teams, logistics and spare parts are available in case of Tidal Turbine failure. The values of severity, occurrence and detectability have been chosen according to what the partner's judges to be the "mean" value in this hypothetic situation

The consortium draws the attention that this FMEA shall not be used as it is for a "real project".
This study can be used as a basis for other FMEAs, and it is highly recommended to review every data and information according to the project context and specificities.

Even with these restrictions, the RealTide consortium has tried to make their best to include a global analysis of all potential failure modes that could appear in the different subsystems that a present or future tidal concept design could include. The designers can use the provided information and methodology to build a suitable a comprehensive initial FMEA that will be complemented with the specificities of the actual design. As an example, a design that includes a flow concentrator on a floating platform with pitch-regulated turbine, can build up its FMEA taking inspirations from our concept 1 (potential pitch failures), concept 3 (floating platform) and concept 4 (tunnel).

7 FMEA RESULTS AND RECOMMENDATION

7.1 Overview

The Table 7.1 summarizes the results from the FMEA developed for the 4 concepts described in section 3.2 and Table 7.2 presents the number of recommendations resulting from this analysis.

Table 7.1 - FMEA result summary

	Total of Failure Modes	Criticality High Critical Failure Modes	Number of failure modes that need to be mitigated by monitoring (a)	Number of failure modes that need to be mitigated by redesign (b)	Number of failure modes that need to be mitigated by redesign and monitoring (c)	Total correction actions needed (a)+(b)+2x(c)
Concept 1	**375**	**19,2%**	35	19	18	**90**
Concept 2	**280**	**16,4%**	13	17	16	**62**
Concept 3	**290**	**15,9%**	24	6	16	**62**
Concept 4	**216**	**10,2%**	8	7	7	**29**

Table 7.2- FMEA recommendations summary

	Number of monitoring Recommendations (a)+(c)	Number of redesign Recommendation (b)+(c)	Total Recommendation (a)+(b)+2x(c)
Concept 1	53	37	**90**
Concept 2	29	33	**62**
Concept 3	40	22	**62**
Concept 4	15	14	**29**

The concept 1 is the one with the highest number of Failure Modes (375). This is due to the fact that this concept includes the highest number of sub-assemblies and components than the other concepts. The complexity of concept 1 associated to the difficulty to repair and maintain underwater turbines when it fails lead to the high amount of critical failure modes (19.2%). This configuration results to a high amount of recommendations (90) which is around 50% more than the number of recommendations for Concepts 2 and 3 (62) and three times more than the number of recommendations for Concept 4 (29).

Concepts 2 and 3, despite being technically and operationally different (concept 2 has 1 multi blade rotor and is gravity based whereas concept 2 is floating and has 2 rotors) presents similarities in terms of number of failure modes (280~290), number of critical failure modes (around 16%) and number of recommendations (46).

The difference between the two concepts are that concept 2 needs more redesign (in order to reduce the occurrence of failures) and concept 3 needs more monitoring (in order to increase failure detectability).

Concept 4 seems to be the concept with the best performance, with only 10,2 of critical failures leading to a relative low number of recommendations (29). This is due to its simple design (less sub-assemblies/components than the others) and higher reliability.

7.2 Assembly and Sub-System Criticality Ranking

In order to be able to compare the criticality between assemblies and components, it was adopted the concept of Aggregated Criticality whose methodology is presented in section 5.4.3.10.
The following sections shows the results for each of the 4 concepts. The tables and charts compare the Aggregated Criticality before recommendations and the expected decrease of the Aggregated Criticality after implementation of recommendations. As it can be seen, the mix of monitoring and redesign recommendations reduces significantly the criticality of the Assemblies/Sub-Assemblies with the highest priority ranking.
As it can be observed in the summary in Table 7.3, the most critical assemblies are:

- **Electrical system**
- **Rotor**
- **Drivetrain**

These tree assemblies are the core of the tidal turbine to produce energy. Electrical system is the most critical for concepts 1, 2 and 3 because of the big quantity of possible failure modes on this assembly produces very high severity due to high cost of repairing and loss of production. In concept 3 the Electric System is less critical than in the other concepts because it is much easier to repair electrical elements in a floating device (repair can be done on the device without the necessity of removing the turbine from water), with a reduced time to restore.
The rotor and drive train consist of several mechanical parts, which occurrence of failure is relatively higher than other parts. The impact of the failure on the components of this assemblies are very severe due to immediate loss of production associated with cost of repair and long time to repair.
In concept 4, the rotor is less critical thanks to the simplicity of this assembly compared to the other concepts. Indeed, in concept 4, the rotor is mainly constituted by Blades and Ring, while other concepts includes extra sub-assemblies such as Pitch system, Hub and Front Bulb.

Table 7.3 - Assembly priority ranking summary

Assembly	Priority ranking			
	Concept 1	Concept 2	Concept 3	Concept 4
Electrical system	1	1	3	1
Rotor	2	2	1	4
Drivetrain	3	3	2	2
Nacelle	4	4	4	3
Auxiliaries	5	5	5	8
Control & Communication system	6	6	7	5
Support Structure	7	7	6	6
Foundation system	8	8	9	7
Yaw system	9	N/A	8	N/A
Tunnel	N/A	N/A	N/A	9

By observing the summary in Table 7.4 - Sub-assembly priority ranking summary (Top 10 list for each concept)Table 7.4, the 10 most critical sub-assemblies can be defined as follows:

- **Blades;**
- **Power Electronic Converter;**
- **Generator;**
- **Low speed shaft;**
- **Low speed shaft dynamic seals;**
- **Transformer(s);**
- **Pitch System;**
- **Control system;**
- **Nacelle shell;**
- **Cooling system.**

A part from the Nacelle shell, all of these sub-assemblies are included in tree most critical Assemblies listed above. These sub-assemblies have the particularity of presenting very high severity in case of failure, due to cost of repair, long time to repair and loss of production.

Table 7.4 - Sub-assembly priority ranking summary (Top 10 list for each concept)

Sub-Assembly	Priority ranking			
	Concept 1	Concept 2	Concept 3	Concept 4
Blades	3	2	1	2
Power Electronic Converter	1	1	6	3
Generator	2	4	5	4
Low speed shaft		8	4	1
Low speed shaft dynamic seals	5	3	3	
Transformer(s)	4	5		7
Pitch System	6	20	2	
Control system	8	6		5
Nacelle shell		9	9	9
Cooling system	9	7		
Subsea cabling system	10	10		
Suction anchor				6
Gearbox / high speed shaft	7			
Interface with foundation			7	
Braking system			8	
Main Structure (including auxiliary equipment)				8
Ballast (liquid ballast)			10	
Access into nacelle (Subsea)				10

7.2.1 Concept 1

a) Assemblies

Table 7.5 - Concept 1 - Aggregated Criticality Assessment – Assemblies

Priority ranking	Assembly	Aggregated criticality before recommendation	Number of failure modes that need to be mitigated by monitoring	Number of failure modes that need to be mitigated by redesign	Number of failure modes that need to be mitigated by redesign and monitoring	Total correction actions needed	Reduced aggregated criticality after mitigation measures
1	Electrical system	28%	3	1	4	8	20%
2	Drivetrain	19%	3	2	1	6	14%
3	Nacelle	15%	0	0	1	1	15%
4	Rotor	14%	2	1	0	3	11%
5	Control & Communication system	7%	0	3	0	3	6%
6	Support structure	7%	0	0	0	0	7%
7	Foundation system	5%	0	0	1	1	2%
8	Auxiliaries	3%	0	0	0	0	3%
9	Tunnel	1%	0	0	0	0	1%
Total aggregated criticality		100%	8	7	7	22	78%

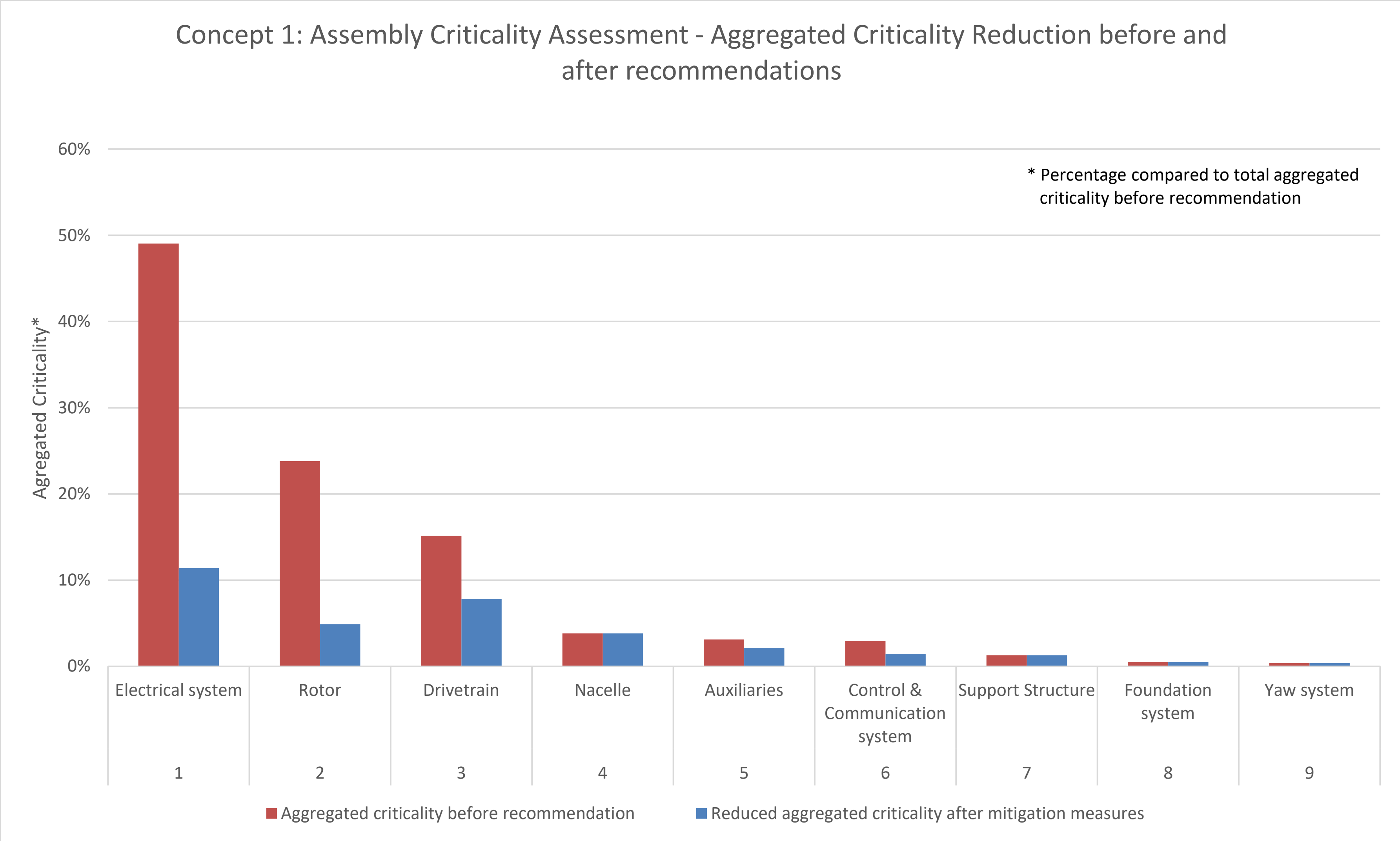

Figure 7-1 - Concept 1 - Aggregated Criticality Assessment Chart– Assemblies

b) Sub-Assemblies

Table 7.6 - Concept 1 - Aggregated Criticality Assessment – Sub-Assemblies Top 10

Priority ranking	Sub-Assembly	Aggregated criticality before recommendation	Number of failure modes that need to be mitigated by monitoring	Number of failure modes that need to be mitigated by redesign	Number of failure modes that need to be mitigated by redesign and monitoring	Total correction actions needed	Reduced aggregated criticality after mitigation measures
1	Power Electronic Converter	19%	5	6	3	14	3%
2	Generator	17%	3	0	3	6	4%
3	Blades	16%	2	7	5	14	2%
4	Transformer(s) - Liquid insulated transformer	9%	6	0	2	8	2%
5	Low speed shaft dynamic seals	8%	2	0	2	4	2%
6	Pitch System	7%	9	0	2	11	3%
7	Gearbox / high speed shaft	4%	4	0	0	4	3%
8	Control system	3%	0	2	0	2	1%
9	Cooling system	2%	1	0	0	1	2%
10	Subsea cabling system	2%	0	0	1	1	0%
Total aggregated criticality		88%	32	15	18	65	23%

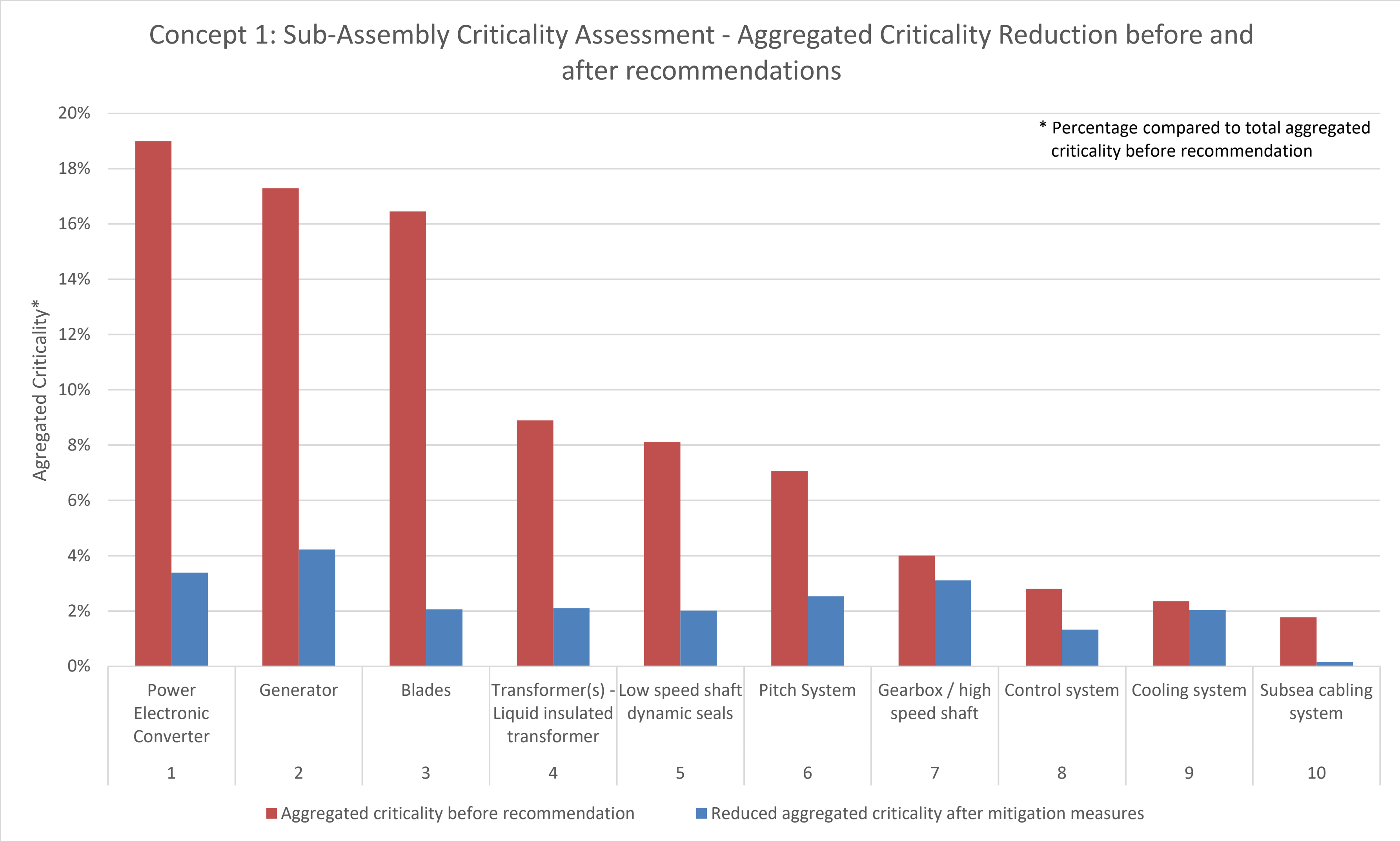

Figure 7-2 - Concept 1 - Aggregated Criticality Assessment Chart– Sub-Assemblies Top 10

7.2.2 Concept 2

a) Assemblies

Table 7.7 - Concept 2 - Aggregated Criticality Assessment – Assemblies

Priority ranking	Assembly	Aggregated criticality before recommendation	Number of failure modes that need to be mitigated by monitoring	Number of failure modes that need to be mitigated by redesign	Number of failure modes that need to be mitigated by redesign and monitoring	Total correction actions needed	Reduction in aggregated criticality after mitigation measures	Reduced aggregated criticality after mitigation measures
1	Electrical system	45%	5	8	9	22	73%	12%
2	Rotor	25%	2	7	5	14	89%	3%
3	Drivetrain	16%	5	0	2	7	57%	7%
4	Nacelle	5%	0	0	0	0	0%	5%
5	Control & Communication system	4%	0	2	0	2	50%	2%
6	Auxiliaries	3%	1	0	0	1	13%	3%
7	Support Structure	2%	0	0	0	0	0%	2%
8	Foundation system	0%	0	0	0	0	0%	0%
Total aggregated criticality		100%	13	17	16	46	100%	34%

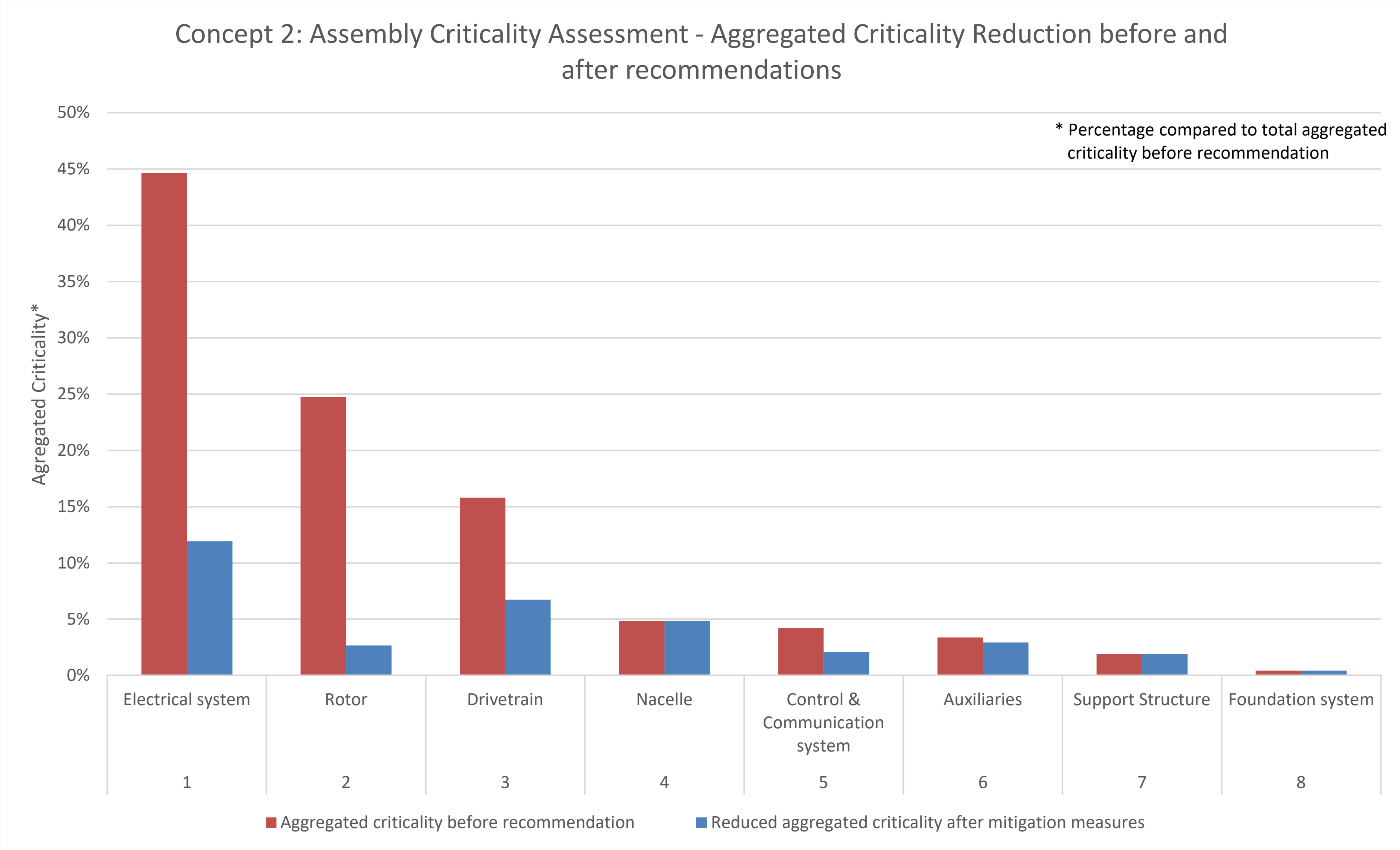

Figure 7-3 - Concept 2 - Aggregated Criticality Assessment Chart– Assemblies

b) Sub-Assemblies

Table 7.8 - Concept 2 - Aggregated Criticality Assessment – Sub-Assemblies Top 10

Priority ranking	Sub-Assembly	Aggregated criticality before recommendation	Number of failure modes that need to be mitigated by monitoring	Number of failure modes that need to be mitigated by redesign	Number of failure modes that need to be mitigated by redesign and monitoring	Total correction actions needed	Reduction in aggregated criticality after mitigation measures	Reduced aggregated criticality after mitigation measures
1	Power Electronic Converter	26%	5	2	3	10	76%	6%
2	Blades	24%	2	7	5	14	93%	2%
3	Low speed shaft dynamic seals	12%	2	0	2	4	73%	3%
4	Generator - PMSG	9%	0	1	2	3	89%	1%
5	Transformer(s) - Liquid insulated transformer	6%	0	2	4	6	49%	3%
6	Control system	4%	0	2	0	2	53%	2%
7	Cooling system	3%	1	0	0	1	13%	3%
8	Low speed shaft	3%	3	0	0	3	21%	2%
9	Nacelle shell	2%	0	0	0	0	0%	2%
10	Subsea cabling system	1%	0	1	0	1	82%	0%
Total aggregated criticality		90%	13	15	16	44	66%	24%

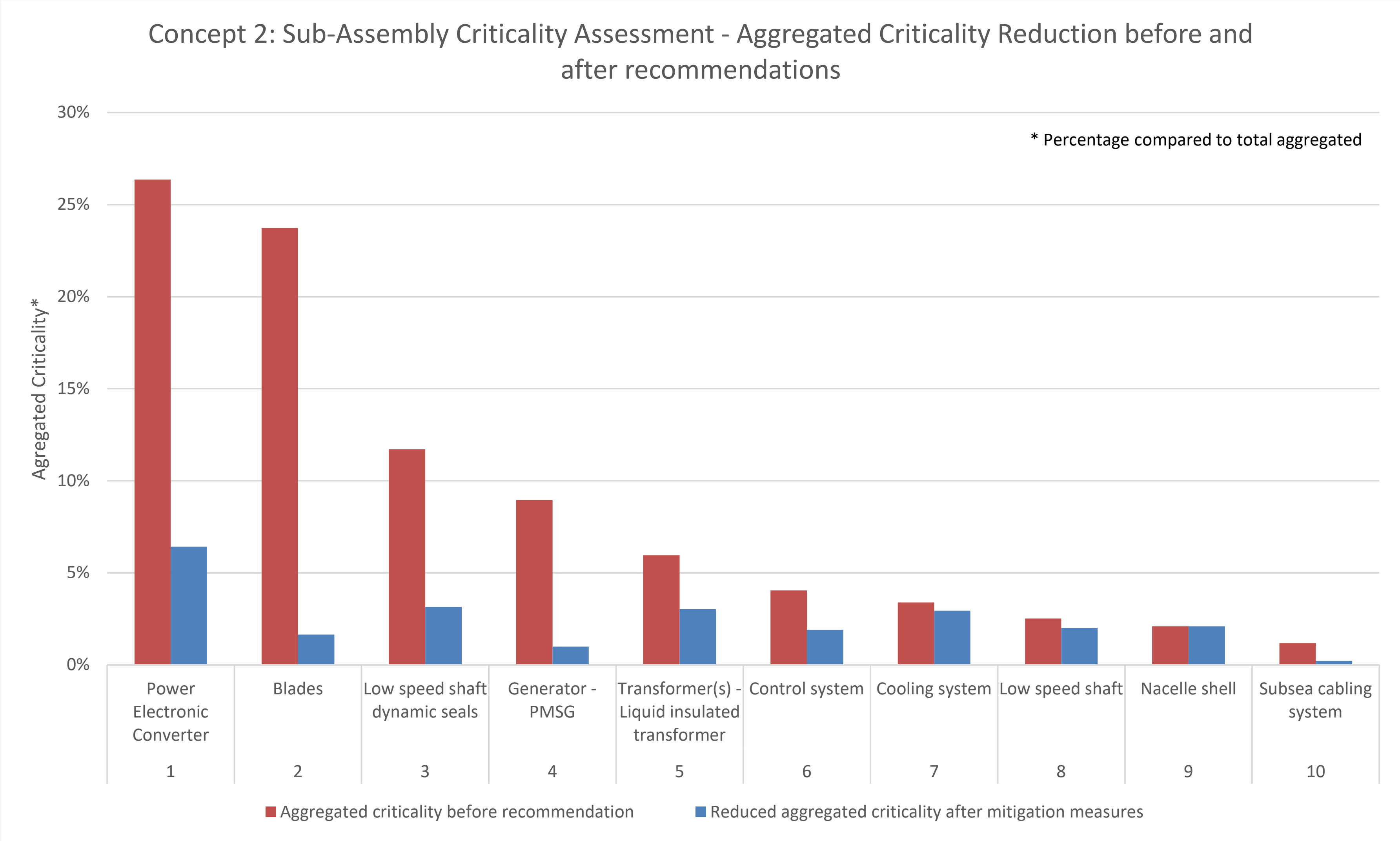

Figure 7-4 - Concept 2 - Aggregated Criticality Assessment Chart– Sub-Assemblies Top 10

7.2.3 Concept 3

a) Assemblies

Table 7.9 - Concept 3 - Aggregated Criticality Assessment – Assemblies

Priority ranking	Assembly	Aggregated criticality before recommendation	Number of failure modes that need to be mitigated by monitoring	Number of failure modes that need to be mitigated by redesign	Number of failure modes that need to be mitigated by redesign and monitoring	Total correction actions needed	Reduced aggregated criticality after mitigation measures
1	Rotor	29%	5	0	7	12	9%
2	Drivetrain	26%	7	2	6	15	14%
3	Electrical system	13%	7	1	0	8	8%
4	Nacelle	9%	1	0	1	2	8%
5	Auxiliaries	8%	1	0	0	1	7%
6	Support Structure, Floater	8%	2	0	1	3	6%
7	Control & Communication system	4%	0	3	0	3	3%
8	Individual Yaw system (Optional, Alternative to Turret)	4%	1	0	1	2	2%
9	Foundation system	0%	0	0	0	0	0%
Total aggregated criticality		0,016	24	6	16	46	58%

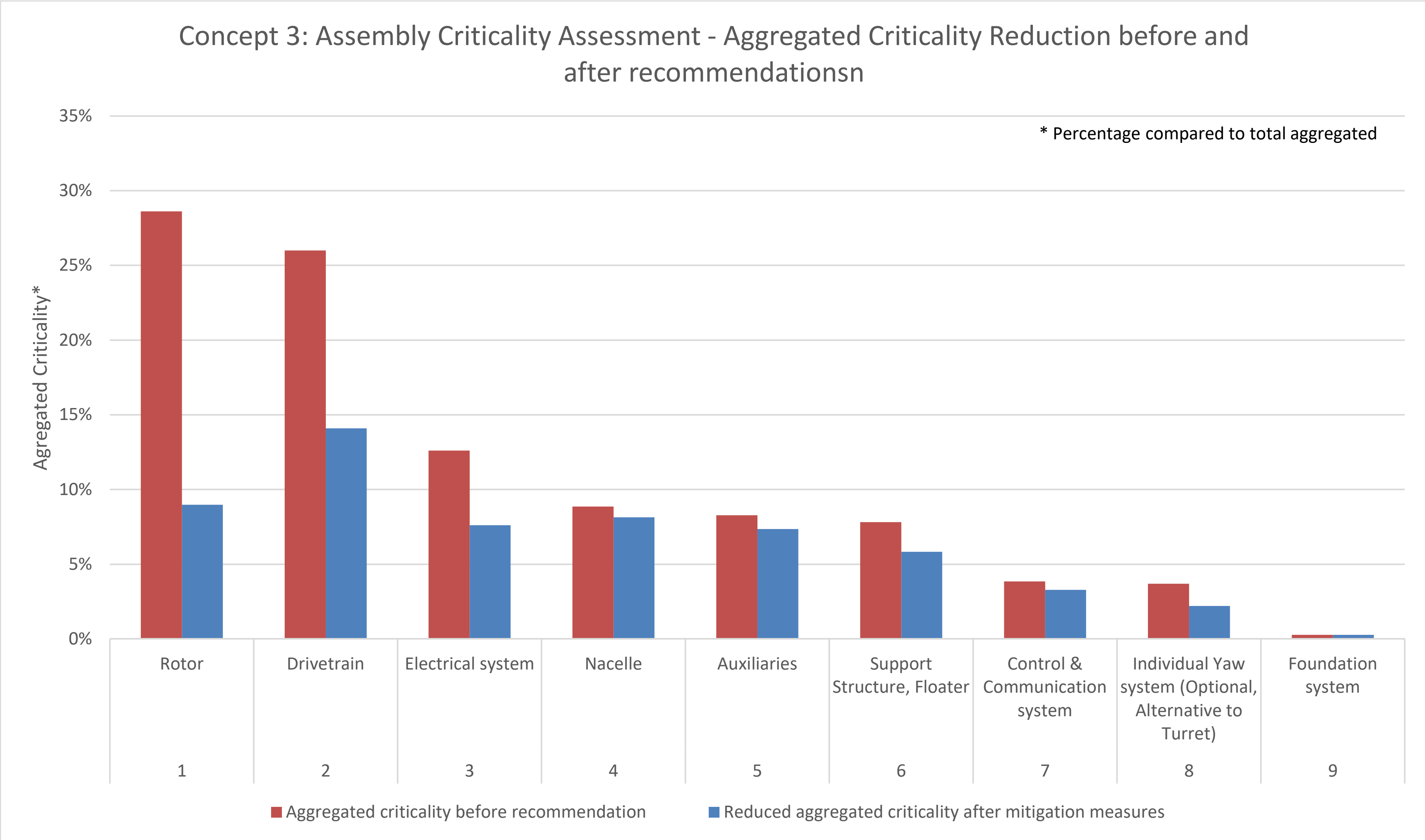

Figure 7-3 - Concept 3 - Aggregated Criticality Assessment Chart– Assemblies

b) Sub-Assemblies

Table 7.10 - Concept 3 - Aggregated Criticality Assessment – Sub-Assemblies Top 10

Priority ranking	Sub-Assembly	Aggregated criticality before recommendation	Number of failure modes that need to be mitigated by monitoring	Number of failure modes that need to be mitigated by redesign	Number of failure modes that need to be mitigated by redesign and monitoring	Total correction actions needed	Reduced aggregated criticality after mitigation measures
1	Blades	15%	4	0	5	9	5%
2	Pitch system	12%	1	0	2	3	2%
3	Low speed shaft dynamic seals	11%	3	1	1	5	6%
4	Low speed shaft	8%	2	1	2	5	4%
5	Generator - Induction Generator	5%	2	0	0	2	3%
6	Power electronic converter	5%	4	0	0	4	3%
7	Interface with foundation	5%	2	0	1	3	3%
8	Braking system	4%	2	0	2	4	2%
9	Nacelle shell	4%	1	0	0	1	3%
10	Ballast (liquid ballast)	3%	1	0	0	1	2%
Total aggregated criticality		71%	22	2	13	37	32%

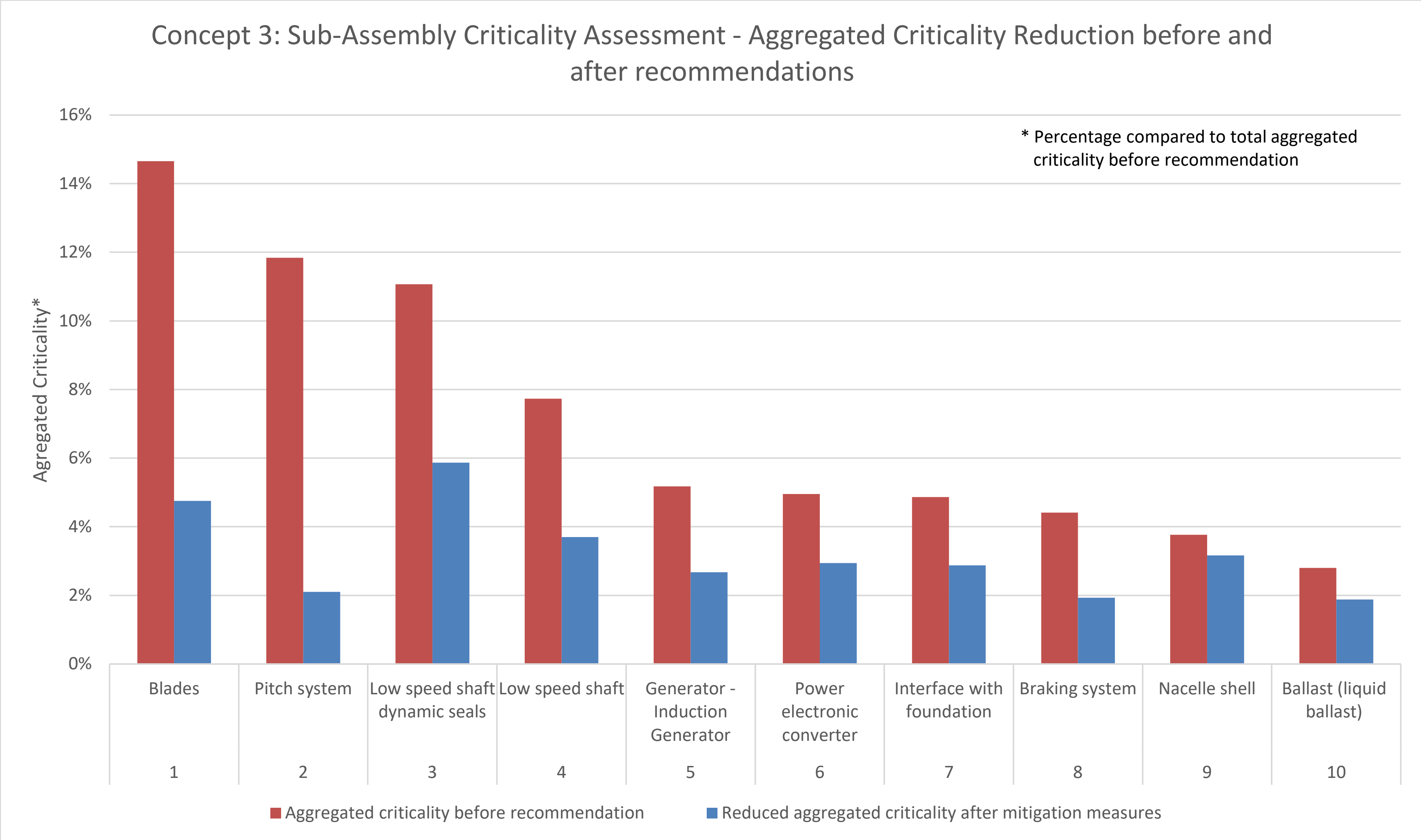

Figure 7-5 - Concept 3 - Aggregated Criticality Assessment Chart– Sub-Assemblies Top 10

7.2.4 Concept 4

a) Assemblies

Table 7.11 - Concept 4 - Aggregated Criticality Assessment – Assemblies

Priority ranking	Assembly	Aggregated criticality before recommendation	Number of failure modes that need to be mitigated by monitoring	Number of failure modes that need to be mitigated by redesign	Number of failure modes that need to be mitigated by redesign and monitoring	Total correction actions needed	Reduced aggregated criticality after mitigation measures
1	Electrical system	28%	3	1	4	8	20%
2	Drivetrain	19%	3	2	1	6	14%
3	Nacelle	15%	0	0	1	1	15%
4	Rotor	14%	2	1	0	3	11%
5	Control & Communication system	7%	0	3	0	3	6%
6	Support structure	7%	0	0	0	0	7%
7	Foundation system	5%	0	0	1	1	2%
8	Auxiliaries	3%	0	0	0	0	3%
9	Tunnel	1%	0	0	0	0	1%
Total aggregated criticality		100%	8	7	7	22	78%

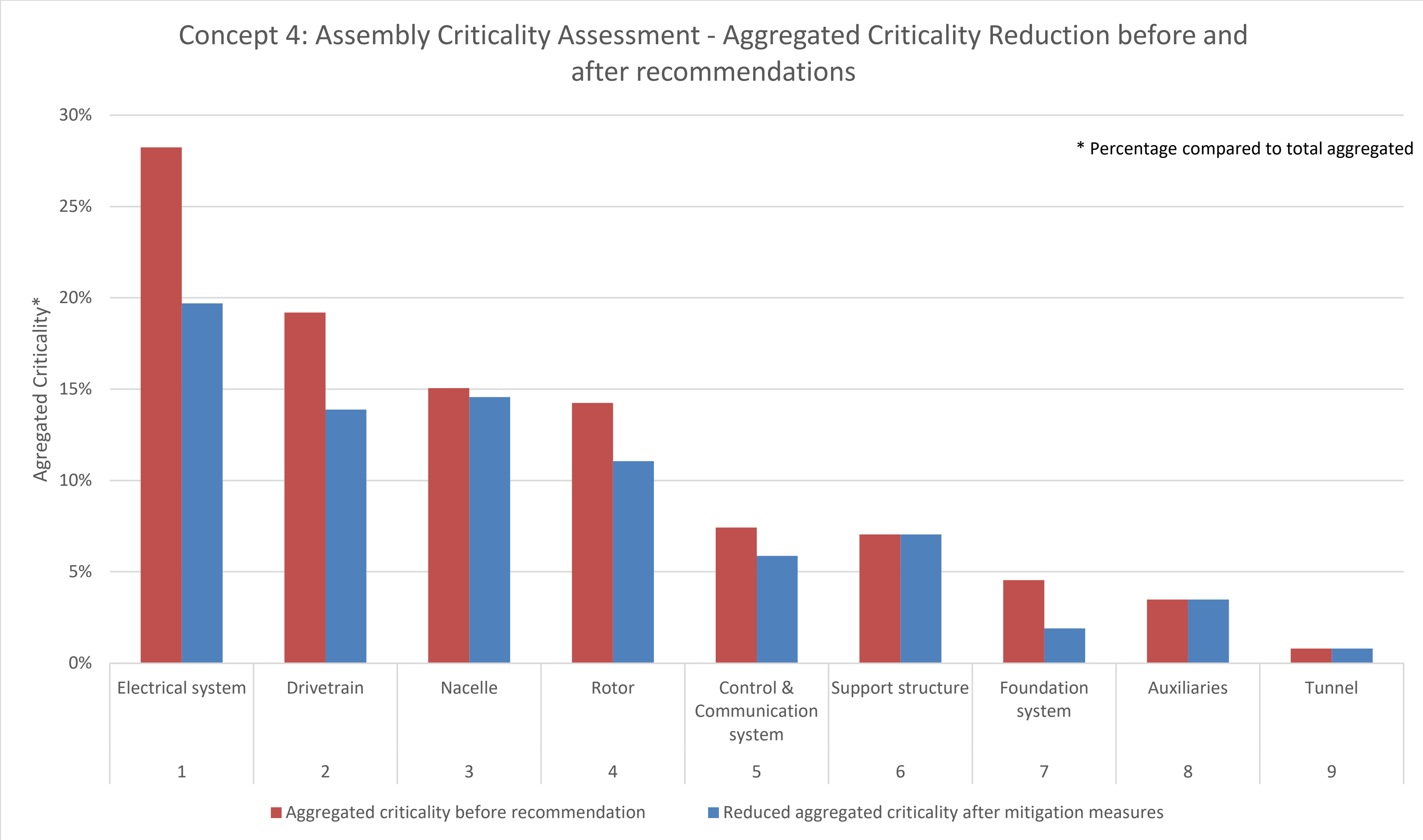

Figure 7-3 - Concept 4 - Aggregated Criticality Assessment Chart– Assemblies

b) Sub-Assemblies

Table 7.12 - Concept 4 - Aggregated Criticality Assessment – Sub-Assemblies Top 10

Priority ranking	Sub-Assembly	Aggregated criticality before recommendation	Number of failure modes that need to be mitigated by monitoring	Number of failure modes that need to be mitigated by redesign	Number of failure modes that need to be mitigated by redesign and monitoring	Total correction actions needed	Reduced aggregated criticality after mitigation measures
1	Low speed shaft	14%	3	2	0	5	9%
2	Blades	12%	2	0	0	2	10%
3	Power electronic converter	11%	1	1	1	3	10%
4	Generator	9%	2	0	0	2	4%
5	Control system	5%	0	3	0	3	3%
6	Suction anchor	5%	0	0	1	1	2%
7	Transformer(s) -Liquid insulated transformer	4%	0	0	1	1	4%
8	Main Structure (including auxiliary equipment)- Fixed	4%	0	0	0	0	4%
9	Nacelle shell	4%	0	0	0	0	4%
10	Access into nacelle (Subsea)	3%	0	0	0	0	3%
Total aggregated criticality		72%	8	6	3	17	53%

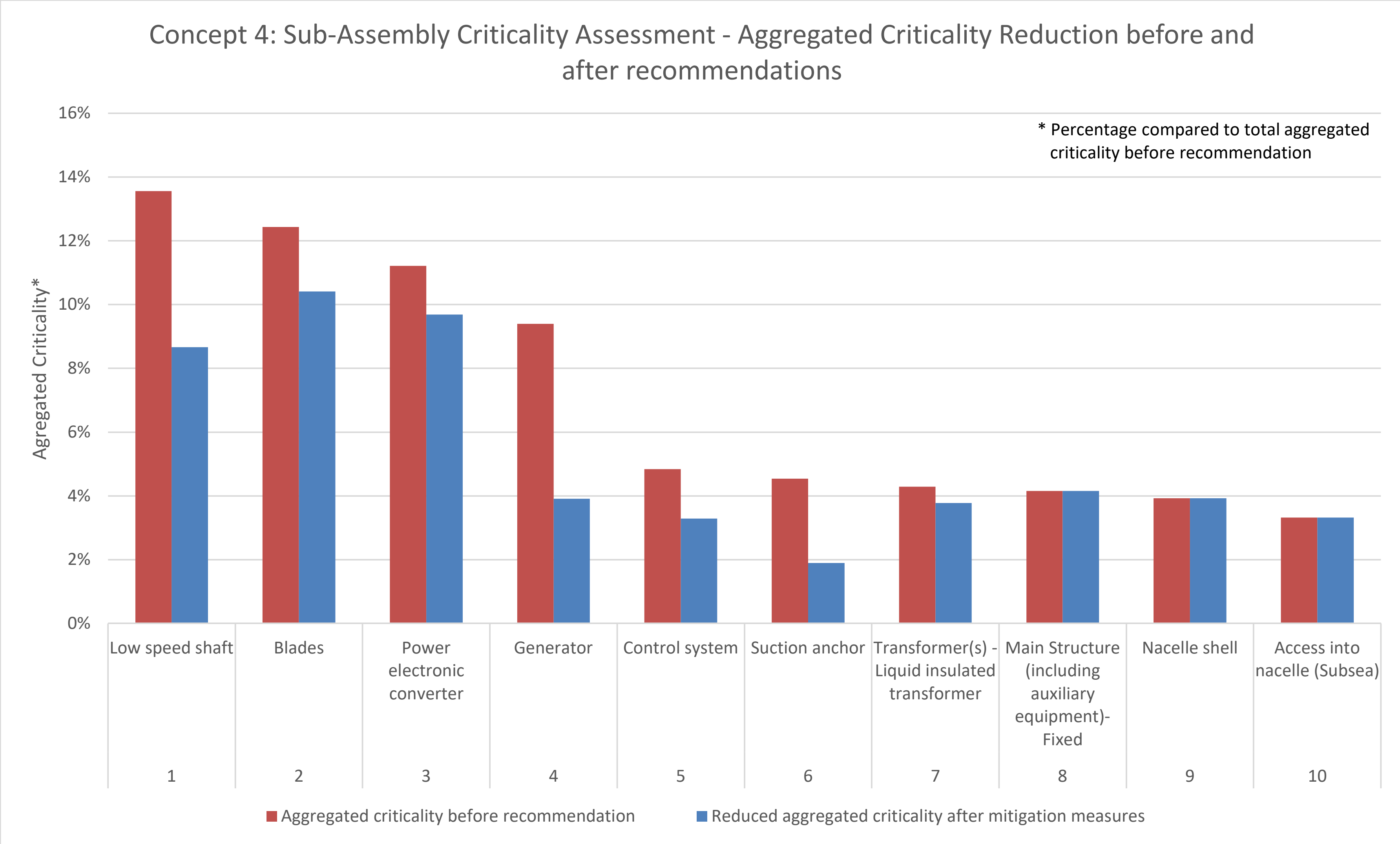

Figure 7-6 - Concept 4 - Aggregated Criticality Assessment Chart– Sub-Assemblies Top 10

7.3 Recommendations

In the following figure, a few particular examples explaining how to apply the methodology exposed for recommendations assessment will be shown. The examples exposed bellow has been extracted from critical failure modes that were obtained for concept 3 (floating multirotor).
As an example of the application of the method to obtain the final results in the aggregated criticality analysis, we can take a closer look into the critical failure modes associated with the blades and pitch system of this third concept.

We can see that from an initial design uses mainly as "In service monitoring", the "Inspection Visit Tools" (IVT) or the evaluation of the "Indirect Detection" (IDE, mainly because of the lack of performance in power production from the expected values, collected through the general SCADA system). In the case of the pitch system is considered to use as common practice a number of sensors, that is the reason why in the preliminary "In service monitoring" there is two examples of "Direct Measurement" (DM).

On the other hand for the initial design controls we can observed a combination of the use of General Design Practices (GDP) combined with a detailed analysis (DTA), mainly consisting in CFD ("Computational Fluid Dynamics") simulations and FEM ("Finite Elements Methods") calculation.
According to the different results obtained in the combination of "RPN", "SxO" and "SxD" we have a recommendation of increasing the level of "Monitoring", increasing the level of design ("Redesign") or even a combination of both:

- **"Monitoring":** The RPN for these failure modes are considered reduced after the implementation of several increases of monitoring levels including:
  - "Model Based Estimation", (MBE), as described in D4.1 [16], this method is under development in the REALTIDE WP3 dealing with "Current to wire model", and in the WP4 related to monitoring that will integrate these models in the monitoring system proposed;
  - "Multiple Integrated detection" (MUID), this technique based in the combination of several sensors from different measurement principles will be developed in WP4 by the REALTIDE Consortium based on the results of the present analysis done in the FMECAs.
- **"Redesign":** The RPN for these failure modes are considered reduced after the implementation of several increases of design levels including:
  - "DTA": Detail analysis of the specific component, for those not considered previously.
  - "Extended Experimental Campaign: Full scale components", (EXPC), this method is under development in the REALTIDE WP5 dealing with "New materials and components", will include among their activities experimental testing of full size instrumented blades, taking into account the expected loads spectra derived from WP2 and WP3 of the REALTIDE project. These solution affects normally to the Occurrence level of the failure modes;
  - "Redundancy, modularity and fast repair solutions" (RND), this technique is based in the reduction of the severity of a failure by a design that includes a redundant solution (it will work even after a failure appears, maybe at reduced performance), the use of modularity, allowing to replace a smaller/less costly component/subcomponent or the use of fuses of any type (electrical fuses or even mechanical ones like a pin or shaft key) very cheap and easy to replace in case of an overload.
- **"Redesign & Monitoring":** .In these cases a combination solution from both sets, previously described are implemented.

Sub-system	Assembly		Failure ID	Production effect Category	Detection / Control Measure	Risk Reduction Measure: Design controls	Risk Reduction Measure: In service monitori	Criticality Assessment: Severity	Criticality Assessment: Occurren ce	Criticality Assessment: Detectab ility	Criticality Assessment: RPN	Criticality Assessment: Crit	Criticality Assessment: SxO	Criticality Assessment: SxD	Recommendation: ¿Actions needed	Recommendation: Mainte nan	Recommendation: Monitorin g	Recommendation: Redesign	Criticality Assesment: Severit y	Criticality Assesment: Occurrenc e	Criticality Assesment: Detectabilit y	Criticality Assesment: RPN	Criticality Assesment: Modifications on RPN	Criticality Assesment: Crit.
ydrodynamic System	Nacelle	Interface with supporting structure	14	1	YES	GDP	IVT	5	5	5	125	High	25	25	Redesign & Monitoring		IVT, DM	GDP, RDN	5	4	4	80	-45	Mediu
	Rotor	Blades	41	2	YES	GDP, DTA	IVT, IDE	4	7	7	196	High	28	28	Redesign & Monitoring		IVT, IDE, MUID	GDP, DTA, EXPC	4	5	4	80	-116	Mediu
			42	2	YES	GDP, DTA	IVT, IDE	4	6	6	144	High	24	24	Redesign & Monitoring		IVT, IDE, MUID	GDP, DTA, EXPC	4	5	4	80	-64	Mediu
			43	2	YES	GDP	IVT, IDE	4	6	6	144	High	24	24	Redesign & Monitoring		IVT, IDE, MUID	GDP, DTA, EXPC	4	5	4	80	-64	Mediu
			44	3	YES	GDP, DTA	IVT, IDE	5	5	5	125	High	25	25	Redesign & Monitoring		IVT, IDE, MUID	GDP, DTA, EXPC	5	4	4	80	-45	Mediu
			45	3	YES	GDP, DTA	IVT, IDE	5	6	5	150	High	30	25	Monitoring		IVT, IDE, MUID	GDP, DTA	5	6	4	120	-30	Mediu
			47	3	YES	GDP, DTA	IVT, IDE	5	5	5	125	High	25	25	Redesign & Monitoring		IVT, IDE, MUID	GDP, DTA, EXPC	5	4	4	80	-45	Mediu
			49	2	YES	GDP, DTA	IVT, IDE	6	8	5	240	High	48	30	Monitoring		IVT, IDE, MBE	GDP, DTA	6	8	2	96	-144	Mediu
			51	2	YES	GDP	IVT, IDE	4	7	5	140	High	28	20	Monitoring		IVT, IDE, MUID	GDP	4	7	4	112	-28	Mediu
			52	2	YES	GDP	IVT, IDE	4	9	5	180	High	36	20	Monitoring		IVT, IDE, MBE	GDP	4	9	3	108	-72	Mediu
		Pitch system	75	3	YES	GDP	IDE, DM	6	7	7	294	High	42	42	Redesign & Monitoring		IDE, DM, MBE	GDP, RDN	6	5	4	120	-174	Mediu
			76	3	YES	GDP	IDE, DM	5	6	6	180	High	30	30	Redesign & Monitoring		IDE, DM, MBE	GDP. DTA	5	4	4	80	-100	Mediu
			77	3	YES	GDP	IVT, IDE	5	7	5	175	High	35	25	Monitoring		IVT, IDE, DM	GDP	5	7	3	105	-70	Mediu
		Yaw locking / brake mechanism																						

Figure 7-7 - Example of FMEA - Floating Tidal Turbine – Rotor

8 CONCLUSIONS

The objectives of the Task 1.1 are to understand the critical components of a generic Tidal Turbine and to propose recommendations in terms of condition monitoring and redesign in order to increase its reliability.
The first step was to define the taxonomy of a generic tidal turbine, i.e., its technical decomposition into systems, assemblies and components. With the diversity of existing Tidal Turbines concepts and components technologies, taxonomy has been defined for 4 generic tidal concepts in order to reflect as much as possible future likely commercial design:

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

The combination of these 4 concepts resulted to a general taxonomy for a generic Tidal Turbine (sections 0 and 4).
Then a reliability methodology based on Failure Modes and Effect Analysis (FMEA) was developed in order to take into consideration the objectives and specificities of RealTide project and to be applicable on a "generic" Tidal Turbine. FMEA is a systematic and comprehensive analysis with the objective to increase the reliability by recommending actions which will mitigate or eliminate the critical failures. This deliverable describes the principles and the definitions to be used during the application of the methodology on a tidal turbine. Certain concepts such as Risk Control Measures and Risk Reduction Measures were categorized taking into consideration what is generally installed or applied on existing tidal turbines or on turbines currently under development. With this categorized definitions, any experienced team work can easily carry out a FMEA study on "generic" tidal devices.

The resulting methodology was then undertaken on the 4 generic tidal concepts with inputs from partners' experience and existing literature.
Many traditional failure modes of components in offshore exists in databases such as the OREDA one (from the O&G sector). In addition, tidal turbine power trains have similarities to wind turbines, so they share a significant number of failure modes that have been identified.

During the FMEA process, an exhaustive list of failure mode and causes was produced for each component of the 4 tidal turbine concepts. This list will be further addressed in Task 1.2 as an input for RAM analysis and also in Task 1.6 for the development of the reliability database.

The analysis identified the most critical failure modes by the use of RPN (Risk Priority Number) concept. For those ones, means of mitigation to increase reliability need to be recommended. RealTide Partners developed a methodology based on the concept of sensitivity that allows selecting what the most relevant recommendations among redesign and/or monitoring activities are to be implemented on the tidal turbines. When the level failure mode criticality is high due to a combination of high severity (S) and low detectability (inverse of D) of the failure mode, then a design recommendation is selected; and when the combination of severity and occurrence of the failure mode is too high, a monitoring recommendation is selected. In case the three factors are high, both redesign and monitoring should be selected as a recommendation.

The recommendations were defined in a general way, giving an indication of what kind of redesign or in service monitoring should be in place complementary to the risk reduction measures already in place in order to reduce the criticality of the failure mode.
The recommendations types that were most often proposed to increase the monitoring level were:

- **MBE. - Model based estimation;**
- **MUID. - Multiple integrated detection.**

The recommendations types that were most often proposed to increase the design level were:

- **DTA. - Detail analysis. CAE (computer aided engineering): FEM, CAD, CFD, etc.;**
- **RDN. - Redundancy;**
- **EXPC - Extended experimental campaign, full scale components.**

The FMEA resulted in a total of 243 recommendations for all of the 4 concepts where 137 are monitoring recommendations and 106 are redesign. Those recommendations will be respectively addressed in WP4 and WP5 for further analysis.
The concept with the highest number of recommendations is the 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, the 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) and its high reliability. 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 is the tidal turbine, the greater is the number of critical failure modes.

In order to compare the criticality of assemblies and sub-assemblies, a methodology consisting in calculating the aggregated criticality at these levels in the taxonomy of the 4 tidal concepts.
This aggregated Criticality Assessment highlighted that the most critical assemblies are:

- **Electrical System;**
- **Rotor; and**
- **Drivetrain;**

which are the most vital assemblies to energy production presenting high costs and time to repair . Although Electrical System is the most critical Assembly when compiling the results of the 4 concepts, this system are less vulnerable in floating thanks to a better access to the tidal turbine, reducing time of repair and then limiting the costs and loss of production in case of failure.
From this 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 should be payed during the further tasks and WP. As the RealTide project activities globally focuses more on Rotors and Drivetrains, the the Electrical System may need to be further studied in a more specific project dedicated to this system.

Finally, these first FMEA versions will be the basis for other WPs especially those with high iteration with the WP1. The FMEA is a dynamic process and, according to the progress of theses WPs, the FMEAs will be subject to adjustments and modifications all along the project.

APPENDIX A - GENERIC TIDAL TURBINE TAXONOMY

Proposed Generic Tidal Turbine Taxonomy								Concepts			
Sub-System	**Assembly**	**Sub-Assembly**	**Sub-Assembly type**	**Component**	**Component type**	**Sub Component**	**Function**	**1**	**2**	**3**	**4**
Hydrodynamic System	**Nacelle**	Nacelle shell	Permanently Closed				Provision of watertight compartment		x		x
			Openable				Transfer PTO and rotor loads to sub-structure	x		x	
		Nacelle joints	Permanent joint (welded)				Hold nacelle parts together Provide water tightness		x		x
			Openable	Static Seals between nacelle segments			Provide water tightness	x		x	
		Interface with supporting structure	Detachable				Transfer loads to yaw mechanism or to support structure (see support structure)	x	x		x
			Non Detachable							x	
		Penetrations	Above water level (for floating type)				Provide water tightness Provide passage to cables and pipes			x	
			Subsea					x	x		x
		Lifting points					Provide attachment points for transport and handling	x	x	x	x
		Seafastening / tug points					Provide attachment points for tugging out of the nacelle (if buoyant nacelle) Provide attachment points to deck of transport ship during transport of nacelle	x			x

Proposed Generic Tidal Turbine Taxonomy								Concepts			
Sub-System	**Assembly**	**Sub-Assembly**	**Sub-Assembly type**	**Component**	**Component type**	**Sub Component**	**Function**	**1**	**2**	**3**	**4**
		Sub-assembly frame					Support drivetrain, transferring loads from components of drivetrain to nacelle (brake, gearbox, generator)	x	x	x	x
		Lifting equipment / reaction points					Allow moving equipment inside the nacelle	x			
		Access into nacelle (hatches)	Above water level (for floating type)				Provide access into nacelle			x	
			Subsea					x	x		x
		Corrosion protection	Material selection				Provide corrosion protection for nacelle	x	x	x	x
			Coating				Provide corrosion protection for nacelle	x	x	x	x
			Impressed current				Provide corrosion protection for nacelle	x	x	x	x
			Corrosion Allowance				Provide corrosion protection for nacelle	x			x
		Other structural elements on the nacelle					Facilitate attachment of subsea cable or other exterior sensors				
	Rotor	Blades	Casting, Hollow, Spar and shell, Monocoque, Other types	Blade shell			Capture energy from current	x	x	x	x
			Free flooded, Semi-flooded, Non-flooded	Blade structural element			Withstand structural loads (normal operating, abnormal, accidental)	x	x	x	x
			Air, Foam	Blade coating			Withstand fatigue loads	x	x	x	x
			Buoyant, Non Buoyant	Blade root			Transfer loads to root connection	x	x	x	x
			Serrated trailing edge, Fluted, fin, etc	Blade hydrodynamic features			Buoyant blades: rise to surface in case of accidental de-attachment Non-buoyant blades: sink to seabed in case of accidental de-attachment	x	x		x

Proposed Generic Tidal Turbine Taxonomy								Concepts			
Sub-System	**Assembly**	**Sub-Assembly**	**Sub-Assembly type**	**Component**	**Component type**	**Sub Component**	**Function**	**1**	**2**	**3**	**4**
		Hub		Hub shell			Transfer loads from blades to main shaft Water/oil tightness (water ingress and oil leak) Resist extreme loads Resist fatigue load Provide housing for the pitch system	x	x	x	
		Front Bulb					Improve hydrodynamic performance	x	x	x	
		Pitch System		Pitch Motor			Provide rotating mechanism power for the pitch	x		x	
				Pitch Actuator	Hydraulic mecanical actuator		Allow pitching of the blades and therefore control of the turbine loading. Provides pitch motion			x	
					Electro mecanical actuator			x			
				Pitching load transfer component (shaft, trunnion, crank ring)			Provide load transfer from actuator/gearbox to the blade	x		x	
				Pitch Bearing (including fixation between pitch and bearing)			Support loads in pitch system Allow blade rotation about pitch axis Transfer axial loads and bending moments to hub Resist ultimate loads Resist fatigue loads	x		x	
				Pitch gearbox (including support)			Transfer motion from pitch actuator to pitching shaft Provide a ratio for power-torque transmission between parts	x		x	

Proposed Generic Tidal Turbine Taxonomy								Concepts			
Sub-System	**Assembly**	**Sub-Assembly**	**Sub-Assembly type**	**Component**	**Component type**	**Sub Component**	**Function**	**1**	**2**	**3**	**4**
				Dynamic seals for blades			Provide water tightness and oil leakage	x		x	
				Electric or hydraulic system (Bateries or hydraulic group)			Provide actuators with power	x		x	
		Corrosion protection	Material selection				Provide corrosion protection for metallic part of the rotor	x	x	x	x
			Coating				Provide corrosion protection for metallic part of the rotor	x	x	x	x
			Impressed current				Provide corrosion protection for metallic part of the rotor				
			Corrosion Allowance				Provide corrosion protection for metallic part of the rotor	x	x	x	x
		Ring					Improve blades strenght / stability				x
	Tunnel	Tunnel					Improve turbine performance by venturing effect				x
	Yaw system	Yaw shaft (trunnion, crank ring)					To transmit mechanical power	x		opt.	
		Yaw Gear					To transmit torque	x		opt.	
		Yawing mechanism power actuator	Hydraulic	Hydraulic power unit			Provide power to the guiding mechanism during deployment, and braking mechanism	x		opt.	
				Yaw locking mechanism and turbine attachment mechanism				x		opt.	
				Guiding mechanism		External power docking station		x		opt.	

Proposed Generic Tidal Turbine Taxonomy								Concepts			
Sub-System	**Assembly**	**Sub-Assembly**	**Sub-Assembly type**	**Component**	**Component type**	**Sub Component**	**Function**	**1**	**2**	**3**	**4**
			Electrical	Yaw locking mechanism and turbine attachment mechanism				x		opt.	
				Guiding mechanism		External power docking station		x		opt.	
		Yaw locking / brake mechanism		Yaw locking (clamp, gears, wedges, pins)			Provide attachment of nacelle onto substructure Prevents unintended separation of turbine form substructure under yawing operations Possible three conditions to be considered: Open ((for connection during installation), Partially engaged (to allow yaw without releasing vertical transference of permanent loads if part of load path for permanent loads) and Closed (to restrain yaw of the nacelle during operation).	x		opt.	

Proposed Generic Tidal Turbine Taxonomy								Concepts			
Sub-System	Assembly	Sub-Assembly	Sub-Assembly type	Component	Component type	Sub Component	Function	1	2	3	4
		Cable and pipe management system		Guiding mechanism			Manage cables and pipes when yawing, prevent entangling, rubbing of cables when yawing Guide cable connections between nacelle and main structure Align connections with sub structure	x		opt.	
				Drag chain			Manage Connection when yawing, prevent entangling, rubbing of cables when yawing	x		opt.	
				Slip ring			Provide contact between conducting surface(s) and brushes	x		opt.	
				Hydraulic connection			Provide connection to substructure/nacelle for hydraulic hoses during installation	x		opt.	
		Yaw load bearing	Rolling				Resist structural loads	x		opt.	
			Plain				Resist fatigue loads Transmit load from upper part of joint to lower part of joint Allow rotation about the yaw axis if relevant, transfer bending moments and axial loads to sub-structure or skirt			opt.	
Reaction System	Foundation system	Foundation fixation	Piles				Transfer loads from sub-structure to seabed, while complying with requirements for ultimate, fatigue and accidental limit states as	x			
			Gravity base						x		
			Suction anchor								x

Proposed Generic Tidal Turbine Taxonomy								Concepts			
Sub-System	Assembly	Sub-Assembly	Sub-Assembly type	Component	Component type	Sub Component	Function	1	2	3	4
			Pretensioned anchor pile				well as serviceability aspects such as displacements and natural period			x	
	Support Structure	Interface with foundation	Interface with foundation (Foundation fixation Piles type)	Grouting (piling solution)			Transfer loads to foundation fixings Resist hydrodynamic loads from substructure	x			
				Grout seal			Keep the grout inside pile / pile sleeve annulus during cure time keep cracked grout between pile and pile sleeve annulus.	x			
				Temporary structure (before grouting)			Provision of: positioning for drilling Guide drilling Guide piling Withstand dynamic environmental loads during drilling, piling, grouting Withstand dynamic loads from the grout while drying stage Support for static loads	x			
			Interface with foundation (Foundation fixation gravity base type)	Gravity base casing			Transfer loads to foundation fixings Resist hydrodynamic loads from substructure		x		
			Interface with foundation (Foundation fixation pretensioned anchor piles type)	Mooring line			Fixing the turbine on the seabed			x	
				Turret			Anchoring point providing free rotational movement for the turbine			x	

Proposed Generic Tidal Turbine Taxonomy								Concepts			
Sub-System	**Assembly**	**Sub-Assembly**	**Sub-Assembly type**	**Component**	**Component type**	**Sub Component**	**Function**	**1**	**2**	**3**	**4**
		Main Structure (including auxiliary equipment)	Fixed				Raise turbine height over seabed Resist hydrodynamic loads on the structure Resist fatigue loads Transfer loads to foundation fixings Provide support to umbilical	x	x		x
			Floating				Resist hydrodynamic loads on the structure Resist fatigue loads Transfer loads to mooring lines			x	
		Installation interface	Bolt eye				Provide installation/Lifting interface	x	x		x
		Interface with turbine support					Provide safe attachment to turbine Resist hydrodynamic loads on the structure Resist fatigue loads Provide support to umbilical Transfer loads to main structure	x	x	x	x
		Corrosion protection	Material selection				To provide corrosion protection for the metallic structural part	x	x	x	x
			Coating				To provide corrosion protection for the metallic structural part	x	x	x	x
			Impressed current				To provide corrosion protection for the metallic structural part	x	x	x	x
			Corrosion Allowance				To provide corrosion protection for the metallic structural part	x	x	x	x
Power take off	**Auxiliaries**	Firefighting System					Various electrical components damage, overheating, fire or even explosion	x		x	

Proposed Generic Tidal Turbine Taxonomy								Concepts			
Sub-System	**Assembly**	**Sub-Assembly**	**Sub-Assembly type**	**Component**	**Component type**	**Sub Component**	**Function**	**1**	**2**	**3**	**4**
		Ballast	Liquid ballast				Allow trimming adjustment of nacelle during deployment Allow buoyancy adjustment of nacelle			x	
			Solid ballast							x	x
		Bilge system					Empty nacelle if water ingress Oil and water separation			x	
		Cooling system		Heatexchanger			Providing cooling mechanism for the electrical components	x	x	x	x
				Cooling Pump			Providing circulation mechanism for the heat exchanger coolant	x	x	x	x
				Coolant			Serving as the cooling working fluid for the electrical system heat management	x	x	x	x
				Cooling system connections			Providing circulation mechanism for the heat exchanger coolant	x	x	x	x
		Air treatment		Compressor			Prevent nacelle interior from condensation and salty environment			x	
				Air Filter				x		x	
				Dehumydifier					x	x	x
		Beacon/Lights					To indicate turbine position to the passing vessels			x	
	Drivetrain	Low speed shaft					Transfer torque from hub to drive train gearbox Transfer torque to generator (if relevant) Resist ultimate loads Resist fatigue loads	x	x	x	x

Proposed Generic Tidal Turbine Taxonomy								Concepts			
Sub-System	**Assembly**	**Sub-Assembly**	**Sub-Assembly type**	**Component**	**Component type**	**Sub Component**	**Function**	**1**	**2**	**3**	**4**
		Low speed shaft bearings					Transfer thrust and bending moments to nacelle	x	x	x	x
		Low speed shaft dynamic seals					Provide water tightness	x	x	x	x
		High speed shaft					Transfer torque from gearbox to generator Resist ultimate loads Resist fatigue loads	x		x	
		High speed shaft bearings					Allow rotation of high speed shaft Resist misalignment induced loads Resist fatigue loads	x		x	
		Gearbox / high speed shaft		Coupling			Step up rotation speed of main shaft and support main shaft through bearings Transmission of torque loads into nacelle	x		x	
				Gears			To transmit torque	x		x	
				Bearing			Transfer thrust and bending moments to nacelle	x		x	
				Shaft			To transmit mechanical power	x		x	
				Casing			To provide enclosure for the gearbox components	x		x	
				Gearbox Lubrication system			Interface between gearbox and sub-frame	x		x	
		Braking system		Low speed brake		Braking disks, pads	Brake the drivetrain from low speed shaft	x	x	x	x
				Generator rear brake (disk)		Braking disks, pads	Brake the drivetrain from generator shaft	x	x		
				Parking / Blocking brake		Braking disks, pads	Keep turbine stopped after braking operation	x	x	x	

Proposed Generic Tidal Turbine Taxonomy								Concepts			
Sub-System	**Assembly**	**Sub-Assembly**	**Sub-Assembly type**	**Component**	**Component type**	**Sub Component**	**Function**	**1**	**2**	**3**	**4**
				Braking actuator	Hydraulic power unit		Provide hydraulic power to braking mechanism	x		x	
					Electrical		Provide electrical power to braking mechanism		x		x
		Couplings	Shrink fit couplings	Key connections			To transmit power	x		x	
			Torsionally elastic couplings					x			
			Tooth couplings								
			Bolted flange couplings								
			Friction flange couplings								
			Torque limiters (Mechanical, hydraulic or magnetic Type)				Provide physical decoupling between shafts Cap transmitted torque along the main drive train	x			
		Shaft Lubrication system					Provide lubrication to the shaft	x	x	x	
	Control & Communication system	Control system		Data acquisition and processing			Detect events or changes from their measured environment and send feedback to the controller	x	x	x	x
				LAN		Network Cable	Transmit data from and to sensors and controller in the turbine	x	x	x	x
						Network Interface Card		x	x	x	x
				Controllers		Software	Provide logic and control system algorithm for the turbine	x	x	x	x
						Hardware					x

Proposed Generic Tidal Turbine Taxonomy								Concepts			
Sub-System	**Assembly**	**Sub-Assembly**	**Sub-Assembly type**	**Component**	**Component type**	**Sub Component**	**Function**	**1**	**2**	**3**	**4**
				Fiber Optic			Transmit data from and to the turbine and shore based command center	x	x	x	x
				Emergency and safety chains			To provide safety mechanism, protect and isolate components failure	x	x	x	x
		Condition monitoring	Condition monitoring system sensors	Transducer			Monitor defined parameters and send information to condition monitoring system	x	x	x	x
				Data acquisition hardware				x	x	x	x
		Systems cabinets	Pitch cabinet				Provide enclosure for pitch control system switches and connectors	x		x	
			Yaw cabinet				Provide enclosure for the yaw system switches and connectors	x			
			Power control cabinet				Provide enclosure for the control system switches and connectors	x	x	x	x
			Auxiliary cabinet				Provide enclosure for the auxilliary control system switches and connectors	x	x	x	x
			Environmental monitoring cabinet				Provide enclosure for the environment monitoring switches and connectors	x	x	x	x

Proposed Generic Tidal Turbine Taxonomy								Concepts			
Sub-System	**Assembly**	**Sub-Assembly**	**Sub-Assembly type**	**Component**	**Component type**	**Sub Component**	**Function**	**1**	**2**	**3**	**4**
			Bus communication interfaces				Provide enclosure for communication PLC control system components	x	x	x	x
	Electrical system	Generator	PMSG	Winding			Transform mechanical power into electrical power		x		x
				Bearings / Bearing housing					x		x
				Magnet					x		x
				Frame					x		x
				Insulator					x		x
			DFIG	Stator Winding				x			
				Rotor Winding				x			
				Bearings / Bearing housing				x			
				Slip Ring / Brush				x			
				Frame				x			
				Insulator				x			
			Induction Generator	Stator Winding						x	
				Rotor Winding						x	
				Bearings / Bearing housing						x	
				Frame						x	
				Insulator						x	
		Power Electronic Converter	Switch IGBT / Switch driver				To regulate voltage, current, and frequency of the electricity output of the turbine	x	x	x	
			DC Bus / Capacitor					x	x	x	x
			DC Choper / Crowbar					x	x	x	x
			Filter					x	x	x	x
			Controller / Sensors					x	x	x	x
			Heat Management					x	x	x	x
		Transformer(s)	Liquid insulated transformer	Winding			To increase the alternating voltages in order to have efficient		x		x
				Insulator					x		x
				Magnetic Core					x		x

Proposed Generic Tidal Turbine Taxonomy								Concepts			
Sub-System	**Assembly**	**Sub-Assembly**	**Sub-Assembly type**	**Component**	**Component type**	**Sub Component**	**Function**	**1**	**2**	**3**	**4**
				Refrigerant			export power transmission		x		x
			Dry type transformer	Winding				x		x	
				Insulator				x		x	
				Magnetic Core				x		x	
		HV switchgear					Feed and protect the tidal turbine electrical system	x	x	x	
		LV switchgear					Feed and protect the tidal turbine electrical system	x	x		
		Power cabling system					Transmit electrical power production	x	x		
		Auxilliary Cabling System and Connector					To transmit auxilliary electrical power	x	x		
		UPS systems		Batteries			Provide back-up power in case of grid loss or internal failure to: - Pitch control and power system - Tidal turbine control system - Converter control system - HV switchgear protection relay - Others	x	x	x	x
		Subsea cabling system					To export generated electrical power to the grid	x	x	x	x
		Dynamic cable					Electrical connection of the power equipment and the grid			x	
		Subsea cable joints	Internal				Connect the subsea cabling systemthe interior of the turbine	x		x	

Proposed Generic Tidal Turbine Taxonomy								Concepts			
Sub-System	Assembly	Sub-Assembly	Sub-Assembly type	Component	Component type	Sub Component	Function	1	2	3	4
			External				To provide secure connection and removal of subsea cable from the tidal turbine		x		x
		Lighting Protection					Provide protection for floating tidal turbine type			x	
		Electrical Protection and Safety					To provide safety mechanism, protect and isolate electrical equipment failure	x	x	x	x

APPENDIX B- FMEA WORKSHEET CONCEPT 1 – COMPLEX BOTTOM FIXED TIDAL TURBINE

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
1	Hydrodynamic System	**Nacelle**	Nacelle shell			Provision of watertight compartment	Structural deficiency - Unacceptable corrosion	Improper material selection	Surface leakage leading to water infiltration into the nacelle	Damaged various internal turbine components
2								Failure of corrosion protection		
3							Structural deficiency - Unacceptable crack/rupture	Improper design - inadequate strength calculation	Surface leakage leading to water infiltration into the nacelle	Damaged various internal turbine components
4								Fabrication error		
5							Structural deficiency - Unacceptable fouling	Improper design - inadequate fouling protection specification	Increase surface roughness	Reduced hydrodinamic profile
6								Fabrication error - inadequate fouling protection application		
7							Structural deficiency - deformation due to impact	Installation error - incident due to careless installation process	Surface leakage leading to water infiltration into the nacelle	Damaged various internal turbine components
8								External cause - Drop object from vessel on the surface		
9			Nacelle joints			Hold nacelle parts together Openable, provide maintenance access for big electrical equipments Provide water tightness	Structural deficiency - Unacceptable corrosion	Fabrication error - inadequate pre and post weld heat treatment	Surface leakage leading to water infiltration into the nacelle	Damaged various internal turbine components
10							Structural deficiency - Cracking, and reduced fatigue strength	Improper design leading to weld defect due to: - Improper weld geometry design - unanticipated service conditions - innappropriately specified weld process parameters - incompatibilities of the materials being welded and the processes employed	Nacelle joint failure below the design load	Water infiltration into the nacelle, leading to damage on various internal turbine components
11								Fabrication error leading to weld defect due to: - Improperly executed welds		
12							External leakage	installation error -improper handling leading to intrusion of contaminants (dirt, dust, etc)	Nacelle seal failure below the design load	Water infiltration into the nacelle, leading to damage on various internal turbine components

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
13							Structural deficiency - nacelle seal early wear	Fabrication error leading to material defect	Nacelle seal failure below the design load	Water infiltration into the nacelle, leading to damage on various internal turbine components
14			Interface with supporting structure			Transfer loads to yaw mechanism or to support structure (see support structure)	Structural deficiency - Unacceptable corrosion	Improper material selection	reduced interface lifetime	reduced turbine operability lifetime
15										
16							Structural deficiency - Unacceptable crack/rupture	Improper design - inadequate strength calculation	interface deformation	Risk of nacelle fall
17								Fabrication error		
18							Structural deficiency - Unacceptable fouling	Improper design - inadequate fouling protection specification	Mismatch interface	Nacelle retrieval or reinsertion problem
19								Fabrication error - inadequate fouling protection application		
20			Penetrations			Provide water tightness Provide passage to cables and pipes	Structural deficiency - Unacceptable corrosion	Improper material selection	Surface leakage leading to water infiltration into the nacelle	Damaged various internal turbine components
21								Failure of corrosion protection		
22							Structural deficiency - Unacceptable crack/rupture	Improper design - inadequate strength calculation	Surface leakage leading to water infiltration into the nacelle	Damaged various internal turbine components
23								Fabrication error		
24			Lifting points			Provide attachment points for transport and handling	Structural deficiency - Unacceptable corrosion	Improper material selection	Lug rupture during nacelle lifting operation	Nacelle and its internals damage due to the impact of the fall
25								Failure of corrosion protection		
26							Structural deficiency - Unacceptable crack/rupture	Improper design - inadequate strength calculation	Lug rupture during nacelle lifting operation	Nacelle and its internals damage due to the impact of the fall
27								Fabrication error		
28			Sub-assembly frame			Support drivetrain, transferring loads from components of drivetrain to nacelle (brake, gearbox, generator)	Structural deficiency - Unacceptable corrosion	Improper material selection	Reduced mechanical strength	Weaken nacelle structural integrity
29								Failure of corrosion protection		
30							Structural deficiency - Unacceptable crack/rupture	Improper design - inadequate strength calculation	nacelle frame deformation	Weaken nacelle structural integrity
31								Fabrication error		

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
32			Access into nacelle (hatches)			Provide access into nacelle	Structural deficiency - Unacceptable corrosion	Improper material selection	Surface leakage leading to water infiltration into the nacelle	Damaged various internal turbine components
33								Failure of corrosion protection		
34							Structural deficiency - Unacceptable crack/rupture	Improper design - inadequate strength calculation	Surface leakage leading to water infiltration into the nacelle	Damaged various internal turbine components
35								Fabrication error		
36							Structural deficiency - Joint rupture / crack	Fabrication error	Surface leakage leading to water infiltration into the nacelle	Damaged various internal turbine components
37			Seafastening / tug points				Structural deficiency - Cracking, and reduced fatigue strength	Improper design due to inadequate configuration, calculation, and innacurate loading cases	Lug rupture during component lifting operation	component damage due to the impact of the fall or possible safety incident
38								Fabrication error leading to material defect		
39							Structural deficiency - early wear	Improper design - inadequate strength calculation	Lug rupture during component lifting operation	component damage due to the impact of the fall or possible safety incident
40								Fabrication error	Lug rupture during component lifting operation	component damage due to the impact of the fall or possible safety incident
41			Corrosion protection	Material selection		Provide corrosion protection for nacelle	Corrosion	Improper design - inadequate material selection	Surface leakage leading to water infiltration into the nacelle	Damaged various internal turbine components

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
42				Coating			Structural deficiency - adhesion failure, Blistering, surface cracking	Improper design - inadequate specification & coating selection	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
43								Fabrication error - Poor surface preparation, coating application, and inspection	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
44							Structural deficiency - excessive marine growth	Improper design - inadequate specification & coating selection	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
45								Fabrication error - Poor surface preparation, coating application, and inspection	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
46							Structural deficiency - erosion	Improper design - inadequate specification & coating selection	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
47								external factor - erosive environment	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
48							Structural deficiency - coating disbonding from metal surface	Fabrication error - Poor surface preparation, coating application, and inspection	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
49				Impressed current			Parameter deviation - insufficient current output	Installation error - improper setting	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
50							Parameter deviation - electrical short	Installation error	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
51							Structural deficiency - early failure	Installation error - improper location distribution	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
52							Structural deficiency - early failure	Improper design - inadequate specification & Anode selection	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
53				Corrosion Allowance			Corrosion	Improper design - inadequate thickness allowance design	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
54		**Rotor**	Blades	Blade shell		Capture energy from current via its hyrodinamics profile	Structural deficiency - Skin or adhesive debonding	Fabrication error - poor quality uniformity	chipped surface, increased roughness, reduced lifetime	Reduced turbine performance
55							Structural deficiency - Adhesive joint failure of leading or trailing edges	Fabrication error - Poor fabrication process and quality control	chipped surface, increased roughness, reduced lifetime	Reduced turbine performance
56							Structural deficiency - crack in gelcoat	Fabrication error - Poor fabrication process and quality control	chipped surface, increased roughness, reduced lifetime	Reduced turbine performance
57							Structural deficiency - Delamination of laminates	Fabrication error - Poor fabrication process and quality control	Damaged blade	Reduced turbine performance or possibly turbine inoperable

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
58							Structural deficiency - individual lamina failure (splitting or cracking)	Fabrication error - Poor fabrication process and quality control	Damaged blade	Reduced turbine performance or possibly turbine inoperable
59							Structural deficiency - increase surface roughness	External factor - fouling/ Marine growth	Reduced blade hydrodinamic properties	Reduced turbine performance
60				Blade structural element		Withstand structural loads (normal operating, abnormal, accidental) Withstand fatigue loads Transfer loads to root connection	Structural deficiency - Sandwich face/core delamination	Fabrication error - Poor fabrication process and quality control	Damaged blade	Reduced turbine performance or possibly turbine inoperable
61							Structural deficiency - Delamination of laminates	Fabrication error - Poor fabrication process and quality control	Damaged blade	Reduced turbine performance or possibly turbine inoperable
62							Structural deficiency - individual lamina failure (splitting or cracking)	Fabrication error - Poor fabrication process and quality control	Damaged blade	Reduced turbine performance or possibly turbine inoperable
63							Structural deficiency - Web fatigue failure	Fabrication error - Poor fabrication process and quality control	Damaged blade	Reduced turbine performance or possibly turbine inoperable
64				Blade coating		Provide protection to the blade against biofouling	Structural deficiency - peeling / wear	Fabrication error - Poor fabrication process and quality control	chipped surface, increased roughness, reduced lifetime	Reduced turbine performance
65							Structural deficiency - biofouling	Fabrication error - inadequate fouling protection application	chipped surface, increased roughness, reduced lifetime	Reduced turbine performance
66				Blade root		Securing the blades to the blade hub	Structural deficiency - Erosion of the sealing of the root	Fabrication error - Poor fabrication process and quality control	Damaged or loss of blade	Reduced turbine performance or possibly turbine inoperable
67							Structural deficiency - Fatigue failure in root connection	Fabrication error - Poor fabrication process and quality control	Damaged or loss of blade	Reduced turbine performance or possibly turbine inoperable
68							Structural deficiency - Fatigue failure in root transition area	Fabrication error - Poor fabrication process and quality control	Damaged or loss of blade	Reduced turbine performance or possibly turbine inoperable
69				Blade hydrodynamic features		Increase energy conversion efficiency of the blades	Structural deficiency - Adhesive joint failure	Fabrication error - Poor fabrication process and quality control	chipped surface, increased roughness, reduced lifetime	Reduced turbine performance
70							Structural deficiency - Skin or adhesive debonding	Fabrication error - Poor fabrication process and quality control	chipped surface, increased roughness, reduced lifetime	Reduced turbine performance
71			Hub	Hub shell		Transfer loads from blades to main shaft	structural deficiency - mechanical failure	Improper material - inadequate material selection	Hub rupture	

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
72						Resist extreme loads Resist fatigue load	(facture, yield, and cracking)	Improper design - inadequate design strength		Reduced turbine performance or possibly turbine inoperable
73								Off design service - unexpected loading conditions		
74								Fabrication error		
75							structural deficiency - unacceptable corrosion	Improper material selection	Hub rupture	Reduced turbine performance or possibly turbine inoperable
76								Failure of corrosion protection		
77							structural deficiency - fatigue failure	Improper material - inadequate material selection	Hub rupture	Reduced turbine performance or possibly turbine inoperable
78								Improper design - inadequate design strength		
79								Off design service - unexpected loading conditions		
80							structural deficiency - Normal wear	Expected wear and tear from normal operating condition	Hub rupture	Reduced turbine performance or possibly turbine inoperable
81							vibration	Installation error - imbalance installation	Reduced hub lifetime	Reduced turbine performance
82			Front Bulb			Improve hydrodynamic performance	Structural deficiency - peeling / wear	Fabrication error - Poor fabrication process and quality control	degradation of front bulb	reduced hydrodynamic performance
83							Structural deficiency - biofouling	Fabrication error - inadequate fouling protection application	degradation of front bulb	reduced hydrodynamic performance

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
84							Structural deficiency - Delamination	Fabrication error - Poor fabrication process and quality control	degradation of front bulb	reduced hydrodynamic performance
85							Structural deficiency - individual lamina failure (splitting or cracking)	Fabrication error - Poor fabrication process and quality control	degradation of front bulb	reduced hydrodynamic performance
86			Pitch System	Pitch Actuator (Electro mecanical actuator)	Piston		Structural deficiency - misalignment	Fabrication error leading to installation defect	degraded performance	Inaccurate pitch control leading to low performance
87							Structural deficiency - sticking	installation error -improper handling leading to intrusion of contaminants (dirt, dust, etc)	degraded performance	Inaccurate pitch control leading to low performance
88							Structural deficiency - early wear	Fabrication error leading to material defect	degraded performance	Inaccurate pitch control leading to low performance
89					Seals		External leakage	installation error -improper handling leading to intrusion of contaminants (dirt, dust, etc)	degraded performance	Inaccurate pitch control leading to low performance
90							Structural deficiency - early wear	Fabrication error leading to material defect	degraded performance	Inaccurate pitch control leading to low performance
91					Mounting		Structural deficiency - misalignment	Fabrication error leading to installation defect	degraded performance	Inaccurate pitch control leading to low performance
92							Vibration	Installation error - imbalance installation	degraded performance	Inaccurate pitch control leading to low performance
93					Motor	Stator	Parameter deviation- coil fail	Fabrication error leading to material defect	degraded performance	Inaccurate pitch control leading to low performance
94							Structural deficiency - insulation deterioration	Fabrication error leading to material defect	short circuit	Loss of pitch control feedback or turbine inoperable
95						Rotor	Parameter deviation- rotor magnet deterioration	Fabrication error leading to material defect	degraded performance	Inaccurate pitch control leading to low performance
96							Structural deficiency - imbalance rotor	Installation error - imbalance installation	degraded performance	Inaccurate pitch control leading to low performance

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
97				Control system			Parameter deviation - drift error	Fabrication error - substandard sensor components	Random deviation of the reading	Inaccurate pitch control leading to low performance
98							Parameter deviation - environmental error	Fabrication error - substandard sensor components	Sensor is more sensitive to properties other than the property being measured	Inaccurate pitch control leading to low performance
99							Structural deficiency - components failure	Fabrication error - substandard sensor components	Loss of ability to control the pitch	Loss of pitch control feedback or turbine inoperable
100		**Yaw system**	Yaw shaft (trunnion, crank ring)	Yaw shaft (trunnion, crank ring)			structural deficiency - mechanical failure (facture, yield, and cracking)	Off design service - unexpected loading conditions	degraded performance	Loss of yaw control, degraded turbine performance
101								Fabrication error leading to material defect	degraded performance	Inaccurate yaw control leading to low performance
102			Yaw Gear	Yaw Gear			Structural deficiency - mechanical failure (surface fatigue, wear, breakage)	Off design service - unexpected loading conditions	Loss of ability to control the yaw	degraded turbine performance
103								Fabrication error leading to material defect	degraded performance	Inaccurate yaw control leading to low performance

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
104								Installation error - (misalignment, lubrication contamination)	degraded performance	Inaccurate yaw control leading to low performance
105			Yawing mechanism power actuator	Hydraulic power unit			Structural deficiency - misalignment	Fabrication error leading to installation defect	degraded performance	Inaccurate yaw control leading to low performance
106							Structural deficiency - sticking	installation error -improper handling leading to intrusion of contaminants (dirt, dust, etc)	degraded performance	Loss of yaw control, degraded turbine performance
107							Structural deficiency - early wear	Fabrication error leading to material defect	degraded performance	Inaccurate yaw control leading to low performance
108							External leakage	installation error -improper handling leading to intrusion of contaminants (dirt, dust, etc)	degraded performance	Inaccurate yaw control leading to low performance
109				Yaw locking mechanism and turbine attachment mechanism			structural deficiency - mechanical failure (facture, yield, and cracking)	Off design service - unexpected loading conditions	Loss of ability to control the yaw	degraded turbine performance
110				Guiding mechanism		External power docking station	structural deficiency - mechanical failure (facture, yield, and cracking)	Off design service - unexpected loading conditions	degraded performance	Inaccurate yaw control leading to low performance
111			Yaw locking / brake mechanism	Yaw locking (clamp, gears, wedges, pins)			structural deficiency - mechanical failure (facture, yield, and cracking)	Off design service - unexpected loading conditions	degraded performance	Inaccurate yaw control leading to low performance
112			Cable and pipe management system	Hydraulic connection			External leakage	installation error -improper handling leading to intrusion of contaminants (dirt, dust, etc)	degraded performance	Inaccurate yaw control leading to low performance

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
113			Yaw load bearing	Yaw load bearing			Structural deficiency - Denting of the bearing raceways and ball	installation error -improper handling leading to intrusion of contaminants (dirt, dust, etc)	degraded performance	Inaccurate yaw control leading to low performance
114							Structural deficiency - Discolored ball tracks and ball, early wear	Lubricant failure	degraded performance	Inaccurate yaw control leading to low performance
115								Installation error - loose or over fits	degraded performance	Inaccurate yaw control leading to low performance
116	Reaction System	**Foundation system**	Foundation fixation			Transfer loads from sub-structure to seabed, while complying with requirements for ultimate, fatigue and accidental limit states as well as serviceability aspects such as displacements and natural period	Structural deficiency - tension failure in pile steel	Off design service - unexpected loading conditions	The foundation and structural part experience Uplitf, tilting or sliding	Reduced turbine operability
117								Soil ageing	The foundation and structural part experience Uplitf, tilting or sliding	Reduced turbine operability
118								Fabrication error leading to material defect	The foundation and structural part experience Uplitf, tilting or sliding	Reduced turbine operability
119								Installation error	The foundation and structural part experience Uplitf, tilting or sliding	Reduced turbine operability
120		**Support Structure**	Interface with foundation	Grouting (piling solution)		Transfer loads to foundation fixings Resist hydrodynamic loads from substructure	Structural deficiency - breakage	Design failure - unsuitable grouted connection design	The foundation and structural part experience Uplitf, tilting or sliding	Reduced turbine operability
121							Structural deficiency - dissolved grouting	Off design service - unexpected loading conditions	The foundation and structural part experience Uplitf, tilting or sliding	Reduced turbine operability
122				Grout seal			Structural deficiency - breakage	Fabrication error leading to material defect	The foundation and structural part experience Uplitf, tilting or sliding	Reduced turbine operability
123				Temporary structure (before grouting)			Structural deficiency - breakage	Design failure - unsuitable grouted connection design	The foundation and structural part experience Uplitf, tilting or sliding	Reduced turbine operability
124			Main Structure (including auxiliary equipment)			Raise turbine height over seabed Resist hydrodynamic loads on the structure Resist fatigue loads Transfer loads to	Structural deficiency - Corrosion	Improper material selection	Cracking on structural parts	Weaken structural integrity
125								Failure of corrosion protection		
126							Structural deficiency - Cracking, and reduced fatigue strength	Improper design leading to weld defect due to: - Improper weld geometry design - unanticipated service conditions	Structural part failure	Unability to withstand operation load leading to risk of nacelle falling

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
						foundation fixings Provide support to umbilical		- innappropriately specified weld process parameters - incompatibilities of the materials being welded and the processes employed		
127								Improper design due to inadequate configuration, calculation, and innacurate loading cases		
128								Improper material selection leading to inadequate strength properties		
129								Fabrication error leading to weld defect due to: - Improperly executed welds		
130							Structural deficiency - Reduced strength due to impact	Installation error - incident due to careless installation process	Structural part failure	Unability to withstand operation load leading to risk of nacelle falling
131								External cause - Drop object from vessel on the surface		
132							Structural deficiency - unacceptable vibration	Installation error leading to unstable support position	Unacceptable operating condition for nacelle's internal components	Reduced turbine operability
133							In-service problems - unacceptable biofouling	Improper design - inadequate fouling protection specification	Reduced support structure lifetime	reduced turbine operability lifetime
134								Fabrication error - inadequate fouling protection application		
135			Installation interface			Provide installation/Lifting interface	Structural deficiency - Unacceptable corrosion	Improper material selection	Reduced interface lifetime	Structural parts decommisioning problem
136								Failure of corrosion protection		
137							Structural deficiency - Unacceptable crack/rupture	Improper design - inadequate strength calculation	Lug rupture during support structure lifting operation	structural parts damage due to the impact of the fall

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
138								Fabrication error		
139			Interface with turbine support				Structural deficiency - Unacceptable corrosion	Improper material selection	reduced interface lifetime	reduced turbine operability lifetime
140								Failure of corrosion protection		
141							Structural deficiency - Unacceptable crack/rupture	Improper design - inadequate strength calculation	interface deformation	Risk of nacelle fall
142								Fabrication error		
143							Structural deficiency - Unacceptable fouling	Improper design - inadequate fouling protection specification	Mismatch interface	Nacelle retrieval or reinsertion problem
144								Fabrication error - inadequate fouling protection application		
145			Corrosion protection	Material selection		Providing corrosion protection for the support structure parts	Corrosion	Improper design - inadequate material selection	Surface leakage leading to water infiltration into the nacelle	Damaged various internal turbine components
146				Coating			Structural deficiency - adhesion failure, Blistering, surface cracking	Improper design - inadequate specification & coating selection	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
147								Fabrication error - Poor surface preparation, coating application, and inspection	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
148							Structural deficiency - excessive marine growth	Improper design - inadequate specification & coating selection	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
149								Fabrication error - Poor surface preparation, coating application, and inspection	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
150							Structural deficiency - erosion	Improper design - inadequate specification & coating selection	Corrosion on protected surface leading to leakage	Damaged various internal turbine components

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
151								external factor - erosive environment	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
152							Structural deficiency - coating disbonding from metal surface	Fabrication error - Poor surface preparation, coating application, and inspection	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
153				Impressed current			Parameter deviation - insufficient current output	Installation error - improper setting	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
154							Parameter deviation - electrical short	Installation error	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
155							Structural deficiency - early failure	Installation error - improper location distribution	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
156							Structural deficiency - early failure	Improper design - inadequate specification & Anode selection	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
157				Corrosion Allowance			Corrosion	Improper design - inadequate thickness allowance design	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
158	**Power take off**	**Auxiliaries**	Fire Fighting System			Provide safety measure in the event of fire hazard	Fail to function on demand	Fabrication error - substandard component leading to Loss of continuity	Electrical fault cannot be localized	Various electrical components damage, overheating, fire or even explosion
159								Installation error		
160			Air treatment	Compressor			Structural deficiency - reduction of internal clearances	Fabrication error leading to material defect	degraded performance	low turbine performance
161							Vibration	Installation error	degraded performance	low turbine performance
162							Structural deficiency - early wearing & accelerated curing	Fabrication error leading to material defect	degraded performance	low turbine performance
163							Structural deficiency - breakdown (breakage, explotion, etc)	Fabrication error leading to material defect	degraded performance	low turbine performance
164							Spurious operation - low flow pulsation	Fabrication error leading to material defect	degraded performance	low turbine performance

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
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165				Air Filter			Contamination	Installation error leading to intrusion of foreign materials	Reduced lifetime of lubricated components	Reduced turbine performance
166			Cooling system	Heatexchanger		Providing cooling mechanism for the electrical components	Insufficient heat transfer	Improper design - inadequate heat exchange characteristics	Low heat transfer	Reduced turbine performance
167							External Leakage	Fabrication error - Improper welding	loos of coolant	Reduced turbine performance or possibly turbine inoperable
168							Plugged / choked	Installation error - presence of contaminants	Coolant circulation problem, Low heat transfer	Reduced turbine performance
169							Structural Deficiency - Unacceptable corrosion	Improper design - inadequate material	Reduced lifetime	Reduced turbine performance
170				Cooling Pump		Providing circulation mechanism for the heat exchanger coolant	External leakage	Installation error - improper fitting	Coolant circulation problem, leading to loss of coolant	Reduced turbine performance or possibly turbine inoperable
171							Structural Deficiency - Unacceptable corrosion	Improper design - inadequate material	Reduced lifetime	Reduced turbine performance
172							Noise / Vibration	Installation error - inbalance impeller	Reduced lifetime	Reduced turbine performance

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
173							Structural deficiency - impeller breakdown	Fabrication error - substandard impeller fabrication	Pump inoperable	Turbine inoperable
174							structural deficiency - accelerated components wear	Fabrication error - compoenents fabrication defect	Reduced lifetime	Reduced turbine performance
175				Coolant		Serving as the cooling working fluid for the electrical system heat management	Parameter deviation - temperature	Improper design - inapropriate coolant selection	Low heat transfer	Reduced turbine performance
176							Contamination	Installation error - presence of contaminants	Coolant circulation problem, Low heat transfer	Reduced turbine performance
177				Cooling system connections		Providing circulation mechanism for the heat exchanger coolant	Structural Deficiency - ageing / erosion	Installation error - presence of contaminants	loos of coolant	Reduced turbine performance or possibly turbine inoperable
178							Leakage	Fabrication error - Improper welding or fitting	loos of coolant	Reduced turbine performance or possibly turbine inoperable
179							Plugged / choked	Installation error - presence of contaminants	Coolant circulation problem, Low heat transfer	Reduced turbine performance
180							Structural Deficiency - Unacceptable corrosion	Improper design - inadequate material	Reduced lifetime	Reduced turbine performance
181			Air treatment	Dehumydifier			Parameter deviation - short lifetime	Installation error - presence of contaminants	Non functioning dehumydifier	Risking internal turbine components lifetime
182		**Drivetrain**	Low speed shaft			Transfer torque from hub to generator Resist ultimate loads Resist fatigue loads	structural deficiency - mechanical failure (facture, yield, and cracking)	Improper material - inadequate material selection	Shaft failure	Turbine inoperable
183								Improper design - inadequate design strength		
184								Off design service - unexpected loading conditions		
185								Fabrication error		
186							structural deficiency - unacceptable corrosion	Improper material selection	Reduced shaft lifetime	Reduced turbine performance or possibly turbine inoperable
187								Failure of corrosion protection		

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
188							structural deficiency - fatigue failure	Improper material - inadequate material selection	Shaft failure	Turbine inoperable
189								Improper design - inadequate design strength		
190								Off design service - unexpected loading conditions		
191							structural deficiency - accelerated wear	Off design service - unexpected loading conditions	Reduced lifetime	Reduced turbine performance
192							vibration	Installation error - imbalance installation	Reduced lifetime	Reduced turbine performance
193			Low speed shaft bearings			Allow rotation of the shaft Resist misalignment induced loads Resist fatigue loads	Structural deficiency - premature fatigue	Improper design - inadequate bearing selection	Heavy ball wear paths, widespread spalling leading to bearing failure	Reduced turbine performance or possibly turbine inoperable
194							Structural deficiency - false brinelling	off-design service - excessive external load	Elliptical wear marks in axial direction at each ball position, leading to accelerated wear process and lower bearing lifetime	Reduced turbine performance
195							Structural deficiency - true brinelling	Installation error -improper handling leading to severe impact and static overload	Indentation in the raceways, leading to bearing vibration and lower bearing lifetime	Reduced turbine performance
196							Structural deficiency - Denting of the bearing raceways and ball	installation error -improper handling leading to intrusion of contaminants (dirt, dust, etc)	Accelerated wear and high vibration	Reduced turbine performance or possibly turbine inoperable
197							corrosion	installation error - exposure to corrosive environment	Rust and abrasive runway or balls surface, leading to accelerated wear process and lower bearing lifetime	Reduced turbine performance or possibly turbine inoperable
198								operation error - exposure to corrosive environment		
199							Vibration	Installation error - bent shafts, intrusion of dirt on shaft or housing support, misaligment	Non parallel ball path on bearing outer raceway, leading to excessive	Reduced turbine performance

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
									vibration and lower bearing lifetime	
200							Structural deficiency - Discolored ball tracks and ball, early wear	Lubricant failure	Accelerated wear leading to Spalling, facture of running surface and subsequent removal of small material	Reduced turbine performance
201								Installation error - loose or over fits		
202							Structural deficiency - early wear and fatigue	Off design service - unexpected loading conditions	Spalling, facture of running surface and subsequent removal of small material	Reduced turbine performance
203			Low speed shaft dynamic seals			Provide water tightness for the nacelle	Dry running	Lubrication failure	seal faces surface damage, Seal failure	Leakage leading to water intrusion damaging various internal turbine components
204							Poor lubrication	Lubrication failure	Small, cracks on the seal faces, presence of noises and vibration, reduced seal lifetime	Leakage leading to water intrusion damaging various internal turbine components
205							Blockage	installation error -improper handling leading to intrusion of contaminants (dirt, dust, etc)	Clogging, and sticking of the O rings, opening of the sealing gap, leading to reduced lifetime of the seal	Reduced turbine performance
206								Operation error - intrusion of sands		
207							Structural deficiency - corrosion	installation error - exposure to corrosive environment	accelerated wear process and lower seal lifetime	Reduced turbine performance
208								operation error - exposure to corrosive environment		
209							Structural deficiency - abnormal wear	Installation error - misalignment	Abnormal wear on O rings, uneven depth of the wear track around seal seating, wear on the seal sleeves, leading to reduced seal lifetime	Reduced turbine performance
210			Gearbox / high speed shaft	Coupling			Structural deficiency - ruptured / cracked flexible element	Design failure - improper coupling selection	Damaged coupling	low turbine performance
211								Installation error due to chemical contamination	Damaged coupling	low turbine performance

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
212							Structural deficiency - split hub	Installation error due to misalignment	Damaged coupling	low turbine performance
213							Structural deficiency - burst hub	Design failure - improper coupling selection	Damaged coupling	Turbine inoperable
214								Off design service - unexpected loading conditions	Damaged coupling	Turbine inoperable
215							Structural deficiency - elongated bolt holes	Off design service - excessive torsional vibration or loading	Damaged coupling	low turbine performance
216							Structural deficiency - accelerated wear and early fatigue	Off design service - unexpected loading conditions	Damaged coupling	low turbine performance
217								Maintenance error - lack of maintenance	Damaged coupling	low turbine performance
218				Gears			Structural deficiency - mechanical failure (surface fatigue, wear, breakage)	Off design service - unexpected loading conditions	Loss of ability to control the yaw	degraded turbine performance
219								Fabrication error leading to material defect	degraded performance	Inaccurate yaw control leading to low performance
220								Installation error - (misalignment, lubrication contamination)	degraded performance	Inaccurate yaw control leading to low performance
221				Bearing			Structural deficiency - premature fatigue	Improper design - inadequate bearing selection	Heavy ball wear paths, widespread spalling leading to bearing failure	Reduced turbine performance or possibly turbine inoperable

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
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222							Structural deficiency - false brinelling	off-design service - excessive external load	Elliptical wear marks in axial direction at each ball position, leading to accelerated wear process and lower bearing lifetime	Reduced turbine performance
223							Structural deficiency - true brinelling	Installation error -improper handling leading to severe impact and static overload	Indentation in the raceways, leading to bearing vibration and lower bearing lifetime	Reduced turbine performance
224							Structural deficiency - Denting of the bearing raceways and ball	installation error -improper handling leading to intrusion of contaminants (dirt, dust, etc)	Accelerated wear and high vibration	Reduced turbine performance or possibly turbine inoperable
225							corrosion	installation error - exposure to corrosive environment	Rust and abrasive runway or balls surface, leading to accelerated wear process and lower bearing lifetime	Reduced turbine performance or possibly turbine inoperable
226								operation error - exposure to corrosive environment		
227							misalignment	Installation error - bent shafts, intrusion of dirt on shaft or housing support	Non parallel ball path on bearing outer raceway, leading to excessive vibration and lower bearing lifetime	Reduced turbine performance

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
228							Structural deficiency - Discolored ball tracks and ball, early wear	Lubricant failure	Accelerated wear leading to Spalling, facture of running surface and subsequent removal of small material	Reduced turbine performance
229								Installation error - loose or over fits		
230							accelerated wear and fatigue	Off design service - unexpected loading conditions	Spalling, facture of running surface and subsequent removal of small material	Reduced turbine performance
231				Shaft			structural deficiency - mechanical failure (facture, yield, and cracking)	Improper material - inadequate material selection	Shaft failure	Turbine inoperable
232								Improper design - inadequate design strength		

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
233								Off design service - unexpected loading conditions		
234								Fabrication error		
235							structural deficiency - unacceptable corrosion	Improper material selection	Reduced shaft lifetime	Reduced turbine performance or possibly turbine inoperable
236								Failure of corrosion protection		
237							structural deficiency - fatigue failure	Improper material - inadequate material selection	Shaft failure	Turbine inoperable
238								Improper design - inadequate design strength		
239								Off design service - unexpected loading conditions		
240							structural deficiency - accelerated wear	Off design service - unexpected loading conditions	Reduced lifetime	Reduced turbine performance
241							vibration	Installation error - imbalance installation	Reduced lifetime	Reduced turbine performance
242				Casing			structural deficiency - mechanical failure (facture, yield, and cracking)	Improper material - inadequate material selection	Reduced lifetime	Reduced turbine performance
243								Improper design - inadequate design strength	Reduced lifetime	Reduced turbine performance
244								Corrosion	Reduced lifetime	Reduced turbine performance
245				Gearbox Lubrication system			Parameter deviation - high/low temperature	External factor - ambient temperature too high / too low	Reduced lifetime of lubricated components	Reduced turbine performance
246							Parameter deviation - high moisture	Installation error leading to intrusion of water	Reduced lifetime of lubricated components	Reduced turbine performance
247							Parameter deviation - viscosity	External factor - ambient temperature too high / too low	Reduced lifetime of lubricated components	Reduced turbine performance
248							Contamination	Installation error leading to intrusion of foreign materials	Reduced lifetime of lubricated components	Reduced turbine performance
249			Couplings				structural deficiency - worn flexing element or shaft bushings	Installation error - excessive misaligment	Reduced lifetime	Reduced turbine performance
250							structural deficiency - fatigue or rupture elastomeric flexing element	Off design service - unexpected loading conditions	Reduced lifetime	Reduced turbine performance
251							vibration	Installation error - excessive misaligment	Reduced lifetime	Reduced turbine performance

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
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252			Braking system	Low speed brake		Providing stopping mechanism for the turbine				
253				Generator rear brake (disk)		Providing stopping mechanism for the turbine	Fracture	Design error - inproper brake selection	Brake facture during operation	Loss ability to control the turbine
254							Accelerated wear	Installation error - contaminant presence	reduced brake lifetime	reduced turbine performance
255				Parking / Blocking brake		Maintaining turbine on parking position				
256				Braking actuator (electrical)		Provide electrical power to braking mechanism	Blockage	Water intrusion		
257			Shaft Lubrication system			Provide lubrication to the shaft	Parameter deviation - high/low temperature	External factor - ambient temperature too high / too low	Reduced lifetime of lubricated components	Reduced turbine performance
258							Parameter deviation - high moisture	Installation error leading to intrusion of water	Reduced lifetime of lubricated components	Reduced turbine performance
259							Parameter deviation - viscosity	External factor - ambient temperature too high / too low	Reduced lifetime of lubricated components	Reduced turbine performance

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
260							Contamination	Installation error leading to intrusion of foreign materials	Reduced lifetime of lubricated components	Reduced turbine performance
261		**Control & Communication system**	Control system	Control sensors		Detect events or changes from their measured environment and send feedback to the controller	Parameter deviation - nonlinearity / sensor bias	Fabrication error - substandard sensor components	Sensor sensitivity is not constant over the measured range.	Inaccurate turbine operation leading to low performance
262								Installation error - presence of contaminants or moisture inside the sensors components		
263							Parameter deviation - drift error	Fabrication error - substandard sensor components	Output signal slowly changes independent of the measured property	Inaccurate turbine operation leading to low performance
264								Installation error - presence of contaminants or moisture inside the sensors components		
265							Parameter deviation - noise error	Fabrication error - substandard sensor components	Random deviation of the reading	Inaccurate turbine operation leading to low performance
266								Installation error - presence of contaminants or moisture inside the sensors components		
267							Parameter deviation - environmental error	Fabrication error - substandard sensor components	Sensor is more sensitive to properties other than the property being measured	Inaccurate turbine operation leading to low performance
268								Installation error - presence of contaminants or moisture inside the sensors components		
269							Spurious Stop	Fabrication error - substandard sensor components	Loss of ability to measure	Loss of control feedback, leading to low performance or turbine inoperable
270				LAN	Network cable	Transmit data from and to sensors and controller in the turbine	Spurious Stop	Open circuit (wire breakage or connector disconnected) due to vibration	Loss of communication	Loss of control, leading to turbine inoperable
271								Short circuit due to pinched cable		

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
272							Loss of part of data package	Installation error - Jitter due to vibration on loose contact	Interrupted control & communication	Inaccurate or delayed turbine operation leading to low performance
273					Network interface card	Providing interface to the controller	Spurious Stop	Fabrication error - PCB failure	Loss of ability to measure	Loss of control feedback, leading to low performance or turbine inoperable
274							Signal interference	fabrication error - Component with low noise resistance threshold	Interrupted control & communication	Inaccurate or delayed turbine operation leading to low performance
275				Controllers	Software	Provide logic control system for the turbine	Unauthorized access	Hackin and Operator error	Loss of ability to control	Loss of control feedback, leading to turbine inoperable
276							Delayed operation	Design error - resource starvation due to improper software engineering	Reduced performance of the controller	Inaccurate or delayed turbine operation leading to low performance
277							Spurious operation	Design error - improper software engineering	Unexpected response/behaviour	Inaccurate or delayed turbine operation leading to low performance
278					Hardware	Provide logic control system for the turbine	spurious stop	CPU Failure - High leakage current, output stuck, short circuit	Unexpected response/behaviour	Loss of control feedback, leading to low performance or turbine inoperable
279								Memory Failure - Data bit loss, short circuit, slow transfer of data	Unexpected response/behaviour	Loss of control feedback, leading to low performance or turbine inoperable
280				Fiber Optic		Transmit data from and to the turbine and shore based command center	Faulty signal	Fabrication error leading to Facet damage	Reduced performance of data transmission	Loss of control feedback, leading to low performance or turbine inoperable
281							Faulty signal	Fabrication error due to Photo oxidation, contact degradation, crystal grow-in defects leading to Laser wear out	Reduced performance of data transmission	Loss of control feedback, leading to low performance or turbine inoperable
282							Faulty signal	Fabrication error - Power from laser reflect back leading to Laser instability	Reduced performance of data transmission	Loss of control feedback, leading to low performance or turbine inoperable
283							Faulty signal	Normal wear - deterioration of solder leading to whisker formation	Reduced performance of data transmission	Loss of control feedback, leading to low performance or turbine inoperable
284							Faulty signal	Fabrication error - substandard quality control , non-radiative center leading to	Reduced performance of data transmission	Loss of control feedback, leading to low performance or turbine inoperable

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
285							No signal	Normal wear - fatigue due to microcracks leading to cable & jacket fracture	Loss of data transmission	Loss of control feedback, leading to low performance or turbine inoperable
286				Emergency and safety chains		To provide safety mechanism, protect and isolate components failure	Fail to function on demand	Fabrication error - substandard component leading to Loss of continuity	Fault cannot be localized	Various electrical components damage, overheating, fire or even explosion
287								Installation error		
288			Condition monitoring	Condition monitoring sensors		Monitor defined parameters and send information to condition monitoring system	Parameter deviation - nonlinearity / sensor bias	Fabrication error - substandard sensor components	Sensor sensitivity is not constant over the measured range.	Inaccurate turbine operation leading to low performance
289								Installation error - presence of contaminants or moisture inside the sensors components		
290							Parameter deviation - drift error	Fabrication error - substandard sensor components	Output signal slowly changes independent of the measured property	Inaccurate turbine operation leading to low performance
291								Installation error - presence of contaminants or moisture inside the sensors components		
292							Parameter deviation - noise error	Fabrication error - substandard sensor components	Random deviation of the sensor reading	Inaccurate turbine operation leading to low performance
293								Installation error - presence of contaminants or moisture inside the sensors components		
294							Parameter deviation - environmental error	Fabrication error - substandard sensor components	Sensor is more sensitive to properties other than the property being measured	Inaccurate turbine operation leading to low performance
295								Installation error - presence of contaminants or moisture inside the sensors components		
296							Structural deficiency - components failure	Fabrication error - substandard sensor components	Total loss of sensor ability to measure	Loss of control feedback, leading to low performance or turbine inoperable
297				Data acquisition hardware		Monitor defined parameters and send information to condition monitoring system	Fail to function on demand	Fabrication error - substandard electronic component or software leading to failure to transmit or receive data	Total or partial loss of sensor ability to measure	Loss of control feedback, leading to low performance or turbine inoperable
298			Systems cabinets	Power control cabinet		Send feedback from drive train drive train to PLC controller transmit orders from PLC controller to brake/locking mechanism, drive train	Overheating	Installation error - poor cooling	Loss of control and feedback	Turbine inoperable
299							Signal interference	Installation error - poor cabling / connection management	Loss of control and feedback	Turbine inoperable

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
300				Auxiliary cabinet		Send feedback from auxiliary systems to PLC controller	Overheating	Installation error - poor cooling	Loss of control and feedback	Turbine inoperable
301							Signal interference	Installation error - poor cabling / connection management	Loss of control and feedback	Turbine inoperable
302				Environmental monitoring cabinet		Transmit from environmental condition sensors to PLC controller	Overheating	Installation error - poor cooling	Loss of environment data feedback	Reduced turbine control accuracy
303							Signal interference	Installation error - poor cabling / connection management	Loss of environment data feedback	Reduced turbine control accuracy
304				Bus communication interfaces		Allow communication between cabinets and PLC control system Allow communication with shore	Overheating	Installation error - poor cooling	Loss of control and feedback	Turbine inoperable
305							Signal interference	Installation error - poor cabling / connection management	Loss of control and feedback	Turbine inoperable
306		**Electrical system**	Generator	Stator Winding			structural deficiency - core fault	Fabrication error leading to material defect due to inadequate insulation, incorrect core construction, or introduction of foreign bodies	overheated generator leading to catastrophic runaway	Turbine inoperable
307								Cooling failure	overheated generator leading to catastrophic runaway	Turbine inoperable
308							Vibration	Fabrication error leading to material defect due to inadequate support	Inbalance generator rotation	turbine damage and inoperable
309							Structural deficiency - loss of magnetic wedges	Installation error leading to poor wedges installation	grounding failure and mechanical damage to the coils	turbine damage and inoperable
310							corrosion	installation error - exposure to corrosive environment	Rust and abrasive runway or balls surface, leading to accelerated wear process and lower bearing lifetime	Reduced turbine performance or possibly turbine inoperable
311				Rotor Winding			Vibration	Installation error leading to imbalance rotor	Inbalance generator rotation	turbine damage and inoperable
312							structural deficiency - winding overstress	Design defect leading to improper material (coil lad insulation method)	distortion, loosening or displacement of the windings leading to decreasing performance of the transformer	reduced performance or possibly turbine inoperable

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
313								Fabrication error leading to loose end winding banding tapes	distortion, loosening or displacement of the windings leading to decreasing performance of the transformer	reduced performance or possibly turbine inoperable
314								off design service - surge due to voltage irregularities	distortion, loosening or displacement of the windings leading to decreasing performance of the transformer	reduced performance or possibly turbine inoperable
315							structural deficiency - rotor lead damage	off design service - peak voltage spikes from converter	Stronger bearing harmonic current and flashover leading to leads damage	Turbine inoperable
316							corrosion	installation error - exposure to corrosive environment	Rust and abrasive runway or balls surface, leading to accelerated wear process and lower bearing lifetime	Reduced turbine performance or possibly turbine inoperable
317				Bearings / Bearing housing			Structural deficiency - premature fatigue	Improper design - inadequate bearing selection	Heavy ball wear paths, widespread spalling leading to bearing failure	Reduced turbine performance or possibly turbine inoperable
318							corrosion	installation error - exposure to corrosive environment	Rust and abrasive runway or balls surface, leading to accelerated wear process and lower bearing lifetime	Reduced turbine performance or possibly turbine inoperable
319								operation error - exposure to corrosive environment		
320							Structural deficiency - Denting of the bearing raceways and ball	installation error -improper handling leading to intrusion of contaminants (dirt, dust, etc)	Accelerated wear and high vibration	Reduced turbine performance or possibly turbine inoperable
321				Slip Ring / Brush			structural deficiency - sticking	Fabrication error leading to moisture intrusion	brushes dust damage insulation winding	Reduced turbine performance or possibly turbine inoperable
322							structural deficiency - Loosening	installation error	brushes dust damage insulation winding	Reduced turbine performance or possibly turbine inoperable
323							structural deficiency - early wearing	Fabrication error leading to material defect	brushes dust damage insulation winding	Reduced turbine performance or possibly turbine inoperable
324							corrosion	installation error - exposure to corrosive environment	Rust and abrasive runway or balls surface, leading to accelerated wear process and lower bearing lifetime	Reduced turbine performance or possibly turbine inoperable

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
325				Frame			structural deficiency - deformation	design error leading to unanticipated magnetic pull of the field flux on the core	Damaged frame	Excessive vibration, reduced turbine performance or possibly turbine inoperable
326							corrosion	installation error - exposure to corrosive environment	Rust and abrasive runway or balls surface, leading to accelerated wear process and lower bearing lifetime	Reduced turbine performance or possibly turbine inoperable
327				Insulator			Loss of isolation - early ageing	Fabrication error leading to material defect	Damage insulation leading to generator damage	Turbine inoperable
328							Loss of isolation - overheating / burst	Off-design service - peak voltage spikes	Damage insulation leading to generator damage	Turbine inoperable
329							Loss of isolation - overheating / burst	Fabrication error leading to moisture intrusion	Damage insulation leading to generator damage	Turbine inoperable
330			Power Electronic Converter	Switch / Switch driver			Parameter deviation - overheating	Installation error due to loose connections	Complete thermal failure of the connection or the nearby insulation	Turbine inoperable
331							Loss of isolation - insulation breakdown	Installation error due to poor insulation	Short circuit leading to damaged components	Turbine inoperable
332							Corrosion	Installation error leading to water intrusion or immersion	Short circuit leading to damaged components or longterm insulation damage	Turbine inoperable
333							Structural deficiency - burst	Installation error due to inproper switch breaker racking	short circuit, arcing ground fault leading to fire or explosion	Turbine inoperable
334				DC Bus / Capacitor						
335				IGBT			Spurious stop	Fabrication error - substandard components leading to Electrical overstress (EOS) or Electrostatic discharge	Potential fire for converter and surrounding electrical components	Turbine inoperable
336								Off design service - Voltage overload leading to Electrical overstress (EOS)	Potential fire for converter and surrounding electrical components	Turbine inoperable
337							Fail to start on demand	Installation error - unexpected condensation after certain inoperation period	Failure to start	Turbine inoperable
338							Corrosion	Installation error - salt intrusion	Reduced lifetime	reduced performance

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
339							Parameters degradation - unacceptable vibration	Installation error - loose fitting	Frretting corrosion on interface of contacting materials undergoing slight, cyclic relative motion,leading to reduced lifetime	reduced performance
340							Parameter degradation - thermal ageing	Fabrication error - substandard components	Appearance of weld fatigue in the form of creep, voids, cracks and delamination leads to reduced heat dissipation.	reduced performance
341							Parameter degradation - thermomechanical fatigue	Fabrication error - substandard components	Bond wire lift off, leading to reduced thermal dissipation	reduced performance
342				DC Choper / Crowbar		Converts fixed DC input to a variable DC output voltage	Spurious stop	installation error - insufficient gap between the bar leading to potential short circuit	Occurrence of fire or explosion	Turbine inoperable
343				Filter		Eliminate electrical noise	Capacitor tank rupture	Off design service - Voltage overload	Occurrence of fire or explosion	Turbine inoperable
344							Spurious stop	Fabrication defect leading to substandard components	Electricity signal unfiltered	Reduced turbine performance
345				Heat Management		to Dissipate heat from the converter	Insufficient heat transfer	Fabrication error - substandard components leading to Parameter degradation - thermal ageing	Cooling grease thermal ageing, leading to overheat igbt and reduced lifetime	reduced performance
346			Transformer(s) - Liquid insulated transformer	Winding		To increase the alternating voltages in order to have efficient export power transmission	Winding distortion	Fabrication error - Substandard components leading to winding distortion	distortion, loosening or displacement of the windings leading to decreasing performance of the transformer	reduced performance or possibly turbine inoperable
347							Loss of isolation	Operation error - Lack of maintenance leading to accelerated tear and wear	Thermal losses creates hotspots in the winding, leading to tear and wear and reduced lifetime	reduced performance
348				Insulator			Insufficient efficiency	Fabrication error - Substandard components	Dielectric breakdown leading to short circuit	reduced performance or possibly turbine inoperable
349							Bushing failure	Vibration	Dielectric breakdown leading to short circuit	reduced performance or possibly turbine inoperable
350								Off design service - voltage overload		
351								Installation error - water intrusion		

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
352				Magnetic Core			Parameter deviation - overheating	fabrication error - substandard core laminiation	Eddy current induces core overheating, leading to damage on other components	reduced performance or possibly turbine inoperable
353				Refrigerant			Leakage	Fabrication error - substandard components	Low heat transfer, heat build up inside the transformer, leading to gas pressure build up, which may result in transformer to blow	reduced performance or possibly turbine inoperable
354			HV switchgear			To control, protect and isolate electrical equipment.	Fail to function on demand - Fuse/circuit breaker unable to isolate electrical equipment	Installation error - loose connection	Thermal failure of the connection	Turbine inoperable
355							Breakdown - Insulation	Installation error - substandard insulation	Dielectric breakdown leading to short circuit a,d switchgear failure	Turbine inoperable
356			LV switchgear			To control, protect and isolate electrical equipment.	Fail to function on demand - Fuse/circuit breaker unable to isolate electrical equipment	Installation error - loose connection	Thermal failure of the connection	Turbine inoperable
357							Breakdown - Insulation	Installation error - substandard insulation	Dielectric breakdown leading to short circuit a,d switchgear failure	Turbine inoperable
358			Power cabling system			Transmit electrical power production	Spurious Stop	Fabrication error - substandard component leading to Loss of continuity	Cable core cannot absorb the mechanical load, hence transfer the load to the copper conductor, leading to breakage under tensile load	Reduced performance or possibly turbine inoperable
359								Installation error - cable overbending leading to loss of continuity		
360							Breakdown - Insulation	Fabrication error - substandard component	Flash over, leading to fire or explosion	Reduced performance or possibly turbine inoperable
361								Installation error - cable overbending		
362							Faulty transmission	Fabrication error - substandard component leading to Shielding losses	EMC interference	Reduced performance
363			Auxilliary Cabling System and Connector			To transmit auxilliary electrical power	Spurious Stop	Fabrication error - substandard component leading to Loss of continuity	Cable core cannot absorb the mechanical load, hence transfer the load to the	Reduced performance or possibly turbine inoperable

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
364								Installation error - cable overbending leading to loss of continuity	copper conductor, leading to breakage under tensile load	
365							Breakdown - Insulation	Fabrication error - substandard component	Flash over, leading to fire or explosion	Reduced performance or possibly turbine inoperable
366								Installation error - cable overbending		
367							Faulty transmission	Fabrication error - substandard component leading to Shielding losses	EMC interference	Reduced performance
368			UPS systems			To provide backup auxilliary electrical power	Fail to start on demand	External factor - Low lifespan due to high ambient temperature	Backup power failure	Loss of auxilliary electricity supply for turbine control and monitoring system
369							Breakdown	O & M error - due to improper overcharging voltage leading to thermal runaway	Risk of UPS fire and explosion	Loss of auxilliary electricity supply for turbine control and monitoring system and damage to surrounding components
370			Subsea cabling system			To export generated electrical power to the shore	Structural deficiency	installation error - vessel maneuver induce over torsional load on the umbilical leading to Torsional failure	bird-caging or necking of armor wire and or helical component.	delayed turbine operation
371			Subsea cable joints			To provide secure connection and removal of subsea cabl from the tidal turbine	Structural deficiency	Fabrication error - substandard component	Loss of connection	Inability to transmit generated electrical power
372								Installation error - Excessive flexing at the junction between the cable and connector		
373							Faulty transmission	Fabrication error - substandard component leading to Shielding losses	Reduced power transmittal performance	Reduced export power quality
374			Electrical Protection and Safety			To provide safety mechanism, protect and isolate electrical equipment failure	Fail to function on demand	Fabrication error - substandard component leading to Loss of continuity	Electrical fault cannot be localized	Various electrical components damage, overheating, fire or even explosion
375								Installation error		

APPENDIX C- FMEA WORKSHEET CONCEPT 2 – SIMPLE BOTTOM FIXED TIDAL TURBINE

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
1	Hydrodynamic System	Nacelle	Nacelle shell			Provision of watertight compartment	Structural deficiency - Unacceptable corrosion	Improper material selection	Surface leakage leading to water infiltration into the nacelle	Damaged various internal turbine components
2								Failure of corrosion protection		
3							Structural deficiency - Unacceptable crack/rupture	Improper design - inadequate strength calculation	Surface leakage leading to water infiltration into the nacelle	Damaged various internal turbine components
4								Fabrication error		
5							Structural deficiency - Unacceptable fouling	Improper design - inadequate fouling protection specification	Increase surface roughness	Reduced hydrodinamic profile
6								Fabrication error - inadequate fouling protection application		
7							Structural deficiency - deformation due to impact	Installation error - incident due to careless installation process	Surface leakage leading to water infiltration into the nacelle	Damaged various internal turbine components
8								External cause - Drop object from vessel on the surface		
9			Nacelle joints			Hold nacelle parts together Provide water tightness	Structural deficiency - Unacceptable corrosion	Fabrication error - inadequate pre and post weld heat treatment	Surface leakage leading to water infiltration into the nacelle	Damaged various internal turbine components
10							Structural deficiency - Cracking, and reduced fatigue strength	Improper design leading to weld defect due to: - Improper weld geometry design - unanticipated service conditions - innappropriately specified weld process parameters - incompatibilities of the materials being welded and the processes employed	Nacelle joint failure below the design load	Water infiltration into the nacelle, leading to damage on various internal turbine components
11								Fabrication error leading to weld defect due to: - Improperly executed welds		
12			Interface with supporting structure			Transfer loads to yaw mechanism or to support structure (see support structure)	Structural deficiency - Unacceptable corrosion	Improper material selection	reduced interface lifetime	reduced turbine operability lifetime
13										
14							Structural deficiency - Unacceptable crack/rupture	Improper design - inadequate strength calculation	interface deformation	Risk of nacelle fall
15								Fabrication error		

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
16							Structural deficiency - Unacceptable fouling	Improper design - inadequate fouling protection specification	Mismatch interface	Nacelle retrieval or reinsertion problem
17								Fabrication error - inadequate fouling protection application		
18			Penetrations			Provide water tightness Provide passage to cables and pipes	Structural deficiency - Unacceptable corrosion	Improper material selection	Surface leakage leading to water infiltration into the nacelle	Damaged various internal turbine components
19								Failure of corrosion protection		
20							Structural deficiency - Unacceptable crack/rupture	Improper design - inadequate strength calculation	Surface leakage leading to water infiltration into the nacelle	Damaged various internal turbine components
21								Fabrication error		
22			Lifting points			Provide attachment points for transport and handling	Structural deficiency - Unacceptable corrosion	Improper material selection	Lug rupture during nacelle lifting operation	Nacelle and its internals damage due to the impact of the fall
23								Failure of corrosion protection		
24							Structural deficiency - Unacceptable crack/rupture	Improper design - inadequate strength calculation	Lug rupture during nacelle lifting operation	Nacelle and its internals damage due to the impact of the fall
25								Fabrication error		
26			Sub-assembly frame			Support drivetrain, transferring loads from components of drivetrain to nacelle (brake, gearbox, generator)	Structural deficiency - Unacceptable corrosion	Improper material selection	Reduced mechanical strength	Weaken nacelle structural integrity
27								Failure of corrosion protection		
28							Structural deficiency - Unacceptable crack/rupture	Improper design - inadequate strength calculation	nacelle frame deformation	Weaken nacelle structural integrity
29								Fabrication error		
30			Access into nacelle (hatches)			Provide access into nacelle	Structural deficiency - Unacceptable corrosion	Improper material selection	Surface leakage leading to water infiltration into the nacelle	Damaged various internal turbine components
31								Failure of corrosion protection		
32							Structural deficiency - Unacceptable crack/rupture	Improper design - inadequate strength calculation	Surface leakage leading to water infiltration into the nacelle	Damaged various internal turbine components
33								Fabrication error		
34							Structural deficiency - Joint rupture / crack	Fabrication error	Surface leakage leading to water infiltration into the nacelle	Damaged various internal turbine components
35			Corrosion protection	Material selection		Provide corrosion protection for nacelle	Corrosion	Improper design - inadequate material selection	Surface leakage leading to water infiltration into the nacelle	Damaged various internal turbine components
36				Coating			Structural deficiency - adhesion failure, Blistering, surface cracking	Improper design - inadequate specification & coating selection	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
37								Fabrication error - Poor surface preparation, coating application, and inspection	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
38							Structural deficiency - excessive marine growth	Improper design - inadequate specification & coating selection	Corrosion on protected surface leading to leakage	Damaged various internal turbine components

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
39								Fabrication error - Poor surface preparation, coating application, and inspection	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
40							Structural deficiency - erosion	Improper design - inadequate specification & coating selection	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
41								external factor - erosive environment	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
42							Structural deficiency - coating disbonding from metal surface	Fabrication error - Poor surface preparation, coating application, and inspection	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
43				Impressed current			Parameter deviation - insufficient current output	Installation error - improper setting	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
44							Parameter deviation - electrical short	Installation error	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
45							Structural deficiency - early failure	Installation error - improper location distribution	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
46							Structural deficiency - early failure	Improper design - inadequate specification & Anode selection	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
47				Corrosion Allowance			Corrosion	Improper design - inadequate thickness allowance design	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
48		**Rotor**	Blades	Blade shell		Capture energy from current via its hyrodinamics profile	Structural deficiency - Skin or adhesive debonding	Fabrication error - poor quality uniformity	chipped surface, increased roughness, reduced lifetime	Reduced turbine performance
49							Structural deficiency - Adhesive joint failure of leading or trailing edges	Fabrication error - Poor fabrication process and quality control	chipped surface, increased roughness, reduced lifetime	Reduced turbine performance
50							Structural deficiency - crack in gelcoat	Fabrication error - Poor fabrication process and quality control	chipped surface, increased roughness, reduced lifetime	Reduced turbine performance
51							Structural deficiency - Delamination of laminates	Fabrication error - Poor fabrication process and quality control	Damaged blade	Reduced turbine performance or possibly turbine inoperable
52							Structural deficiency - individual lamina failure (splitting or cracking)	Fabrication error - Poor fabrication process and quality control	Damaged blade	Reduced turbine performance or possibly turbine inoperable
53							Structural deficiency - increase surface roughness	External factor - fouling/ Marine growth	Reduced blade hydrodinamic properties	Reduced turbine performance
54				Blade structural element		Withstand structural loads (normal operating, abnormal,	Structural deficiency - Sandwich face/core delamination	Fabrication error - Poor fabrication process and quality control	Damaged blade	Reduced turbine performance or possibly turbine inoperable

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
55						accidental) Withstand fatigue loads Transfer loads to root connection	Structural deficiency - Delamination of laminates	Fabrication error - Poor fabrication process and quality control	Damaged blade	Reduced turbine performance or possibly turbine inoperable
56							Structural deficiency - individual lamina failure (splitting or cracking)	Fabrication error - Poor fabrication process and quality control	Damaged blade	Reduced turbine performance or possibly turbine inoperable
57							Structural deficiency - Web fatigue failure	Fabrication error - Poor fabrication process and quality control	Damaged blade	Reduced turbine performance or possibly turbine inoperable
58				Blade coating		Provide protection to the blade against biofouling	Structural deficiency - peeling / wear	Fabrication error - Poor fabrication process and quality control	chipped surface, increased roughness, reduced lifetime	Reduced turbine performance
59							Structural deficiency - biofouling	Fabrication error - inadequate fouling protection application	chipped surface, increased roughness, reduced lifetime	Reduced turbine performance
60				Blade root		Securing the blades to the blade hub	Structural deficiency - Erosion of the sealing of the root	Fabrication error - Poor fabrication process and quality control	Damaged or loss of blade	Reduced turbine performance or possibly turbine inoperable
61							Structural deficiency - Fatigue failure in root connection	Fabrication error - Poor fabrication process and quality control	Damaged or loss of blade	Reduced turbine performance or possibly turbine inoperable
62							Structural deficiency - Fatigue failure in root transition area	Fabrication error - Poor fabrication process and quality control	Damaged or loss of blade	Reduced turbine performance or possibly turbine inoperable
63				Blade hydrodynamic features		Increase energy conversion efficiency of the blades	Structural deficiency - Adhesive joint failure	Fabrication error - Poor fabrication process and quality control	chipped surface, increased roughness, reduced lifetime	Reduced turbine performance
64							Structural deficiency - Skin or adhesive debonding	Fabrication error - Poor fabrication process and quality control	chipped surface, increased roughness, reduced lifetime	Reduced turbine performance
65			Hub	Hub shell		Transfer loads from blades to main shaft Resist extreme loads Resist fatigue load	structural deficiency - mechanical failure (facture, yield, and cracking)	Improper material - inadequate material selection	Hub rupture	Reduced turbine performance or possibly turbine inoperable
66								Improper design - inadequate design strength		
67								Off design service - unexpected loading conditions		
68								Fabrication error		
69							structural deficiency - unacceptable corrosion	Improper material selection	Hub rupture	Reduced turbine performance or possibly turbine inoperable
70								Failure of corrosion protection		
71							structural deficiency - fatigue failure	Improper material - inadequate material selection	Hub rupture	Reduced turbine performance or possibly turbine inoperable

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
72								Improper design - inadequate design strength		
73								Off design service - unexpected loading conditions		
74							structural deficiency - Normal wear	Expected wear and tear from normal operating condition	Hub rupture	Reduced turbine performance or possibly turbine inoperable
75							vibration	Installation error - imbalance installation	Reduced hub lifetime	Reduced turbine performance
76			Front Bulb			Improve hydrodynamic performance	Structural deficiency - peeling / wear	Fabrication error - Poor fabrication process and quality control	degradation of front bulb	reduced hydrodynamic performance
77							Structural deficiency - biofouling	Fabrication error - inadequate fouling protection application	degradation of front bulb	reduced hydrodynamic performance
78							Structural deficiency - Delamination	Fabrication error - Poor fabrication process and quality control	degradation of front bulb	reduced hydrodynamic performance
79							Structural deficiency - individual lamina failure (splitting or cracking)	Fabrication error - Poor fabrication process and quality control	degradation of front bulb	reduced hydrodynamic performance
80			Corrosion protection	Material selection		Provide corrosion protection for metallic part of the rotor	Corrosion	Improper design - inadequate material selection	Surface leakage leading to water infiltration into the nacelle	Damaged various internal turbine components
81				Coating			Structural deficiency - adhesion failure, Blistering, surface cracking	Improper design - inadequate specification & coating selection	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
82								Fabrication error - Poor surface preparation, coating application, and inspection	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
83							Structural deficiency - excessive marine growth	Improper design - inadequate specification & coating selection	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
84								Fabrication error - Poor surface preparation, coating application, and inspection	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
85							Structural deficiency - erosion	Improper design - inadequate specification & coating selection	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
86								external factor - erosive environment	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
87							Structural deficiency - coating disbonding from metal surface	Fabrication error - Poor surface preparation, coating application, and inspection	Corrosion on protected surface leading to leakage	Damaged various internal turbine components

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect – Local Effect	Failure Effect – System Effect
88				Impressed current			Parameter deviation - insufficient current output	Installation error - improper setting	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
89							Parameter deviation - electrical short	Installation error	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
90							Structural deficiency - early failure	Installation error - improper location distribution	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
91							Structural deficiency - early failure	Improper design - inadequate specification & Anode selection	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
92				Corrosion Allowance			Corrosion	Improper design - inadequate thickness allowance design	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
93	Reaction System	**Foundation system**	Gravity base			Transfer loads from sub-structure to seabed, while complying with requirements for ultimate, fatigue and accidental limit states as well as serviceability aspects such as displacements and natural period	In service problem- loss of stability	Expected loading - cyclic loading due to wave, current and soil condition	The foundation and structural part experience Uplitf, tilting or sliding	Reduced turbine operability
94							Structural deficiency - Cracking	Installation error - incident due to careless installation process	fondation cracking	Weaken structural integrity
95		**Support Structure**	Interface with foundation			Transfer loads to foundation fixings Resist hydrodynamic loads from substructure	Structural deficiency - Unacceptable corrosion	Improper material selection	reduced interface lifetime	reduced turbine operability lifetime
96										
97							Structural deficiency - Unacceptable crack/rupture	Improper design - inadequate strength calculation	interface deformation	Risk of nacelle fall
98								Fabrication error		
99							Structural deficiency - Unacceptable fouling	Improper design - inadequate fouling protection specification	Mismatch interface	Nacelle retrieval or reinsertion problem
100								Fabrication error - inadequate fouling protection application		
101			Main Structure (including auxiliary equipment)			Raise turbine height over seabed Resist hydrodynamic loads on the structure Resist fatigue loads Transfer loads to foundation fixings Provide support to umbilical	Structural deficiency - Corrosion	Improper material selection	Cracking on structural parts	Weaken structural integrity
102								Failure of corrosion protection		
103							Structural deficiency - Cracking, and reduced fatigue strength	Improper design leading to weld defect due to: - Improper weld geometry design - unanticipated service conditions - innappropriately specified weld process parameters - incompatibilities of the materials being welded and the processes employed	Structural part failure	Unability to withstand operation load leading to risk of nacelle falling

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
104								Improper design due to inadequate configuration, calculation, and innacurate loading cases		
105								Improper material selection leading to inadequate strength properties		
106								Fabrication error leading to weld defect due to: - Improperly executed welds		
107							Structural deficiency - Reduced strength due to impact	Installation error - incident due to careless installation process	Structural part failure	Unability to withstand operation load leading to risk of nacelle falling
108								External cause - Drop object from vessel on the surface		
109							Structural deficiency - unacceptable vibration	Installation error leading to unstable support position	Unacceptable operating condition for nacelle's internal components	Reduced turbine operability
110							In-service problems - unacceptable biofouling	Improper design - inadequate fouling protection specification	Reduced support structure lifetime	reduced turbine operability lifetime
111								Fabrication error - inadequate fouling protection application		
112			Installation interface			Provide installation/Lifting interface	Structural deficiency - Unacceptable corrosion	Improper material selection	Reduced interface lifetime	Structural parts decommisioning problem
113								Failure of corrosion protection		
114							Structural deficiency - Unacceptable crack/rupture	Improper design - inadequate strength calculation	Lug rupture during support structure lifting operation	structural parts damage due to the impact of the fall
115								Fabrication error		
116			Interface with turbine support				Structural deficiency - Unacceptable corrosion	Improper material selection	reduced interface lifetime	reduced turbine operability lifetime
117								Failure of corrosion protection		
118							Structural deficiency - Unacceptable crack/rupture	Improper design - inadequate strength calculation	interface deformation	Risk of nacelle fall
119								Fabrication error		
120							Structural deficiency - Unacceptable fouling	Improper design - inadequate fouling protection specification	Mismatch interface	Nacelle retrieval or reinsertion problem
121								Fabrication error - inadequate fouling protection application		
122			Corrosion protection	Material selection		Providing corrosion protection for the support structure parts	Corrosion	Improper design - inadequate material selection	Surface leakage leading to water infiltration into the nacelle	Damaged various internal turbine components
123				Coating				Improper design - inadequate specification & coating selection	Corrosion on protected surface leading to leakage	Damaged various internal turbine components

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
124							Structural deficiency - adhesion failure, Blistering, surface cracking	Fabrication error - Poor surface preparation, coating application, and inspection	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
125							Structural deficiency - excessive marine growth	Improper design - inadequate specification & coating selection	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
126								Fabrication error - Poor surface preparation, coating application, and inspection	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
127							Structural deficiency - erosion	Improper design - inadequate specification & coating selection	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
128								external factor - erosive environment	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
129							Structural deficiency - coating disbonding from metal surface	Fabrication error - Poor surface preparation, coating application, and inspection	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
130				Impressed current			Parameter deviation - insufficient current output	Installation error - improper setting	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
131							Parameter deviation - electrical short	Installation error	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
132							Structural deficiency - early failure	Installation error - improper location distribution	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
133							Structural deficiency - early failure	Improper design - inadequate specification & Anode selection	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
134				Corrosion Allowance			Corrosion	Improper design - inadequate thickness allowance design	Corrosion on protected surface leading to leakage	Damaged various internal turbine components
135		**Auxiliaries**	Cooling system	Heatexchanger		Providing cooling mechanism for the electrical components	Insufficient heat transfer	Improper design - inadequate heat exchange characteristics	Low heat transfer	Reduced turbine performance
136							External Leakage	Fabrication error - Improper welding	loos of coolant	Reduced turbine performance or possibly turbine inoperable
137							Plugged / choked	Installation error - presence of contaminants	Coolant circulation problem, Low heat transfer	Reduced turbine performance
138							Structural Deficiency - Unacceptable corrosion	Improper design - inadequate material	Reduced lifetime	Reduced turbine performance
139				Cooling Pump		Providing circulation mechanism for the heat exchanger coolant	External leakage	Installation error - improper fitting	Coolant circulation problem, leading to loss of coolant	Reduced turbine performance or possibly turbine inoperable
140							Structural Deficiency - Unacceptable corrosion	Improper design - inadequate material	Reduced lifetime	Reduced turbine performance
141							Noise / Vibration	Installation error - inbalance impeller	Reduced lifetime	Reduced turbine performance

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
142							Structural deficiency - impeller breakdown	Fabrication error - substandard impeller fabrication	Pump inoperable	Turbine inoperable
143							structural deficiency - accelerated components wear	Fabrication error - compoenents fabrication defect	Reduced lifetime	Reduced turbine performance
144				Coolant		Serving as the cooling working fluid for the electrical system heat management	Parameter deviation - temperature	Improper design - inapropriate coolant selection	Low heat transfer	Reduced turbine performance
145							Contamination	Installation error - presence of contaminants	Coolant circulation problem, Low heat transfer	Reduced turbine performance
146				Cooling system connections		Providing circulation mechanism for the heat exchanger coolant	Structural Deficiency - ageing / erosion	Installation error - presence of contaminants	loos of coolant	Reduced turbine performance or possibly turbine inoperable
147							Leakage	Fabrication error - Improper welding or fitting	loos of coolant	Reduced turbine performance or possibly turbine inoperable
148							Plugged / choked	Installation error - presence of contaminants	Coolant circulation problem, Low heat transfer	Reduced turbine performance
149							Structural Deficiency - Unacceptable corrosion	Improper design - inadequate material	Reduced lifetime	Reduced turbine performance
150			Air treatment	Dehumydifier			Parameter deviation - short lifetime	Installation error - presence of contaminants	Non functioning dehumydifier	Risking internal turbine components lifetime
151		Drivetrain	Low speed shaft			Transfer torque from hub to generator Resist ultimate loads Resist fatigue loads	structural deficiency - mechanical failure (facture, yield, and cracking)	Improper material - inadequate material selection	Shaft failure	Turbine inoperable
152								Improper design - inadequate design strength		
153								Off design service - unexpected loading conditions		
154								Fabrication error		
155							structural deficiency - unacceptable corrosion	Improper material selection	Reduced shaft lifetime	Reduced turbine performance or possibly turbine inoperable
156								Failure of corrosion protection		
157							structural deficiency - fatigue failure	Improper material - inadequate material selection	Shaft failure	Turbine inoperable
158								Improper design - inadequate design strength		
159								Off design service - unexpected loading conditions		
160							structural deficiency - accelerated wear	Off design service - unexpected loading conditions	Reduced lifetime	Reduced turbine performance
161							vibration	Installation error - imbalance installation	Reduced lifetime	Reduced turbine performance

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
162			Low speed shaft bearings			Allow rotation of the shaft Resist misalignment induced loads Resist fatigue loads	Structural deficiency - premature fatigue	Improper design - inadequate bearing selection	Heavy ball wear paths, widespread spalling leading to bearing failure	Reduced turbine performance or possibly turbine inoperable
163							Structural deficiency - false brinelling	off-design service - excessive external load	Elliptical wear marks in axial direction at each ball position, leading to accelerated wear process and lower bearing lifetime	Reduced turbine performance
164							Structural deficiency - true brinelling	Installation error -improper handling leading to severe impact and static overload	Indentation in the raceways, leading to bearing vibration and lower bearing lifetime	Reduced turbine performance
165							Structural deficiency - Denting of the bearing raceways and ball	installation error -improper handling leading to intrusion of contaminants (dirt, dust, etc)	Accelerated wear and high vibration	Reduced turbine performance or possibly turbine inoperable
166							corrosion	installation error - exposure to corrosive environment	Rust and abrasive runway or balls surface, leading to accelerated wear process and lower bearing lifetime	Reduced turbine performance or possibly turbine inoperable
167								operation error - exposure to corrosive environment		
168							Vibration	Installation error - bent shafts, intrusion of dirt on shaft or housing support, misaligment	Non parallel ball path on bearing outer raceway, leading to excessive vibration and lower bearing lifetime	Reduced turbine performance
169							Structural deficiency - Discolored ball tracks and ball, early wear	Lubricant failure	Accelerated wear leading to Spalling, facture of running surface and subsequent removal of small material	Reduced turbine performance
170								Installation error - loose or over fits		
171							Structural deficiency - early wear and fatigue	Off design service - unexpected loading conditions	Spalling, facture of running surface and subsequent removal of small material	Reduced turbine performance
172			Low speed shaft dynamic seals			Provide water tightness for the nacelle	Dry running	Lubrication failure	seal faces surface damage, Seal failure	Leakage leading to water intrusion damaging various internal turbine components
173							Poor lubrication	Lubrication failure	Small, cracks on the seal faces, presence of noises and vibration, reduced seal lifetime	Leakage leading to water intrusion damaging various internal turbine components
174							Blockage	installation error -improper handling leading to intrusion of contaminants (dirt, dust, etc)	Clogging, and sticking of the O rings, opening of the sealing	Reduced turbine performance

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect: Local Effect	Failure Effect: System Effect
175								Operation error - intrusion of sands	gap, leading to reduced lifetime of the seal	
176							Structural deficiency - corrosion	installation error - exposure to corrosive environment	accelerated wear process and lower seal lifetime	Reduced turbine performance
177								operation error - exposure to corrosive environment		
178							Structural deficiency - abnormal wear	Installation error - misalignment	Abnormal wear on O rings, uneven depth of the wear track around seal seating, wear on the seal sleeves, leading to reduced seal lifetime	Reduced turbine performance
179			Braking system	Low speed brake		Providing stopping mechanism for the turbine				
180				Generator rear brake (disk)		Providing stopping mechanism for the turbine	Facture	Design error - inproper brake selection	Brake facture during operation	Loss ability to control the turbine
181							Accelerated wear	Installation error - contaminant presence	reduced brake lifetime	reduced turbine performance
182				Parking / Blocking brake		Maintaining turbine on parking position				
183				Braking actuator (electrical)		Provide electrical power to braking mechanism				
184			Shaft Lubrication system			Provide lubrication to the shaft	Parameter deviation - high/low temperature	External factor - ambient temperature too high / too low	Reduced lifetime of lubricated components	Reduced turbine performance
185							Parameter deviation - high moisture	Installation error leading to intrusion of water	Reduced lifetime of lubricated components	Reduced turbine performance
186							Parameter deviation - viscosity	External factor - ambient temperature too high / too low	Reduced lifetime of lubricated components	Reduced turbine performance
187							Contamination	Installation error leading to intrusion of foreign materials	Reduced lifetime of lubricated components	Reduced turbine performance
188		**Control & Communication system**	Control system	Control sensors		Detect events or changes from their measured environment and send feedback to the controller	Parameter deviation - nonlinearity / sensor bias	Fabrication error - substandard sensor components	Sensor sensitivity is not constant over the measured range.	Inaccurate turbine operation leading to low performance
189								Installation error - presence of contaminants or moisture inside the sensors components		
190							Parameter deviation - drift error	Fabrication error - substandard sensor components	Output signal slowly changes independent of the measured property	Inaccurate turbine operation leading to low performance
191								Installation error - presence of contaminants or moisture inside the sensors components		

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
192							Parameter deviation - noise error	Fabrication error - substandard sensor components	Random deviation of the reading	Inaccurate turbine operation leading to low performance
193								Installation error - presence of contaminants or moisture inside the sensors components		
194							Parameter deviation - environmental error	Fabrication error - substandard sensor components	Sensor is more sensitive to properties other than the property being measured	Inaccurate turbine operation leading to low performance
195								Installation error - presence of contaminants or moisture inside the sensors components		
196							Spurious Stop	Fabrication error - substandard sensor components	Loss of ability to measure	Loss of control feedback, leading to low performance or turbine inoperable
197				LAN	Network cable	Transmit data from and to sensors and controller in the turbine	Spurious Stop	Open circuit (wire breakage or connector disconnected) due to vibration	Loss of communication	Loss of control, leading to turbine inoperable
198								Short circuit due to pinched cable		
199							Loss of part of data package	Installation error - Jitter due to vibration on loose contact	Interrupted control & communication	Inaccurate or delayed turbine operation leading to low performance
200					Network interface card	Providing interface to the controller	Spurious Stop	Fabrication error - PCB failure	Loss of ability to measure	Loss of control feedback, leading to low performance or turbine inoperable
201							Signal interference	fabrication error - Component with low noise resistance threshold	Interrupted control & communication	Inaccurate or delayed turbine operation leading to low performance
202				Controllers	Software	Provide logic control system for the turbine	Unauthorized access	Hackin and Operator error	Loss of ability to control	Loss of control feedback, leading to turbine inoperable
203							Delayed operation	Design error - resource starvation due to improper software engineering	Reduced performance of the controller	Inaccurate or delayed turbine operation leading to low performance
204							Spurious operation	Design error - improper software engineering	Unexpected response/behaviour	Inaccurate or delayed turbine operation leading to low performance
205					Hardware	Provide logic control system for the turbine	spurious stop	CPU Failure - High leakage current, output stuck, short circuit	Unexpected response/behaviour	Loss of control feedback, leading to low performance or turbine inoperable
206								Memory Failure - Data bit loss, short circuit, slow transfer of data	Unexpected response/behaviour	Loss of control feedback, leading to low performance or turbine inoperable

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
207				Fiber Optic		Transmit data from and to the turbine and shore based command center	Faulty signal	Fabrication error leading to Facet damage	Reduced performance of data transmission	Loss of control feedback, leading to low performance or turbine inoperable
208							Faulty signal	Fabrication error due to Photo oxidation, contact degradation, crystal grow-in defects leading to Laser wear out	Reduced performance of data transmission	Loss of control feedback, leading to low performance or turbine inoperable
209							Faulty signal	Fabrication error - Power from laser reflect back leading to Laser instability	Reduced performance of data transmission	Loss of control feedback, leading to low performance or turbine inoperable
210							Faulty signal	Normal wear - deterioration of solder leading to whisker formation	Reduced performance of data transmission	Loss of control feedback, leading to low performance or turbine inoperable
211							Faulty signal	Fabrication error - substandard quality control , non-radiative center leading to	Reduced performance of data transmission	Loss of control feedback, leading to low performance or turbine inoperable
212							No signal	Normal wear - fatigue due to microcracks leading to cable & jacket fracture	Loss of data transmission	Loss of control feedback, leading to low performance or turbine inoperable
213				Emergency and safety chains		To provide safety mechanism, protect and isolate components failure	Fail to function on demand	Fabrication error - substandard component leading to Loss of continuity	Fault cannot be localized	Various electrical components damage, overheating, fire or even explosion
214								Installation error		
215			Condition monitoring	Condition monitoring sensors		Monitor defined parameters and send information to condition monitoring system	Parameter deviation - nonlinearity / sensor bias	Fabrication error - substandard sensor components	Sensor sensitivity is not constant over the measured range.	Inaccurate turbine operation leading to low performance
216								Installation error - presence of contaminants or moisture inside the sensors components		
217							Parameter deviation - drift error	Fabrication error - substandard sensor components	Output signal slowly changes independent of the measured property	Inaccurate turbine operation leading to low performance
218								Installation error - presence of contaminants or moisture inside the sensors components		
219							Parameter deviation - noise error	Fabrication error - substandard sensor components	Random deviation of the sensor reading	Inaccurate turbine operation leading to low performance
220								Installation error - presence of contaminants or moisture inside the sensors components		
221							Parameter deviation - environmental error	Fabrication error - substandard sensor components		Inaccurate turbine operation leading to low performance

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
222								Installation error - presence of contaminants or moisture inside the sensors components	Sensor is more sensitive to properties other than the property being measured	
223							Structural deficiency - components failure	Fabrication error - substandard sensor components	Total loss of sensor ability to measure	Loss of control feedback, leading to low performance or turbine inoperable
224				Data acquisition hardware		Monitor defined parameters and send information to condition monitoring system	Fail to function on demand	Fabrication error - substandard electronic component or software leading to failure to transmit or receive data	Total or partial loss of sensor ability to measure	Loss of control feedback, leading to low performance or turbine inoperable
225			Systems cabinets	Power control cabinet		Send feedback from drive train drive train to PLC controller transmit orders from PLC controller to brake/locking mechanism, drive train	Overheating	Installation error - poor cooling	Loss of control and feedback	Turbine inoperable
226							Signal interference	Installation error - poor cabling / connection management	Loss of control and feedback	Turbine inoperable
227				Auxiliary cabinet		Send feedback from auxiliary systems to PLC controller	Overheating	Installation error - poor cooling	Loss of control and feedback	Turbine inoperable
228							Signal interference	Installation error - poor cabling / connection management	Loss of control and feedback	Turbine inoperable
229				Environmental monitoring cabinet		Transmit from environmental condition sensors to PLC controller	Overheating	Installation error - poor cooling	Loss of environment data feedback	Reduced turbine control accuracy
230							Signal interference	Installation error - poor cabling / connection management	Loss of environment data feedback	Reduced turbine control accuracy
231				Bus communication interfaces		Allow communication between cabinets and PLC control system Allow communication with shore	Overheating	Installation error - poor cooling	Loss of control and feedback	Turbine inoperable
232							Signal interference	Installation error - poor cabling / connection management	Loss of control and feedback	Turbine inoperable
233		**Electrical system**	Generator - PMSG	Winding		Transform mechanical power into electrical power	Winding distortion	Fabrication error - Substandard components leading to winding distortion	distortion, loosening or displacement of the windings leading to decreasing performance of the transformer	reduced performance or possibly turbine inoperable

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
234				Frame			Structural deficiency - interlaminar breakdown (laminated steel core plates are electrically connected)	Fabrication error - construction deffect: - Burrs on the coreplate -Inadequate insulation of the coreplate - Incorrect construction of the core - Introduction of foreign bodies	Core is electrically interconnected, overheated, and buckled leading to catastrophic runaway breakdown (melting)	Generator damaged, turbine inoperable
235								Off-design service - overheating, current overload, or overfluxing incident		
236								Operation error: - Pole slipping - Foreign bodies shorting coreplates due to wear and tear during operation		
237				Insulator			Insufficient efficiency	expected operation load: mechanical stress caused by vibration and switching pulses, and stress caused by the different thermal expansion coefficients of the materials involved	Sectors short circuit creating flash and burned, leading to generator failure	Turbine inoperable
238								Accelerated thermal aging due to fabrication error such as loose bar wedging, defects in the insulation such as delamination, cracks, voids, and wrinkled damaged layer	Vibration induced abrasion of the slot corona protection by the sharp edges of the laminated stator core, leading to partial discharge	Generator damaged, turbine inoperable
239			Power Electronic Converter	DC Bus / Capacitor						
240				IGBT			Spurious stop	Fabrication error - substandard components leading to Electrical overstress (EOS) or Electrostatic discharge	Potential fire for converter and surrounding electrical components	Turbine inoperable
241								Off design service - Voltage overload leading to Electrical overstress (EOS)	Potential fire for converter and surrounding electrical components	Turbine inoperable
242							Fail to start on demand	Installation error - unexpected condensation after certain inoperation period	Failure to start	Turbine inoperable

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
243							Corrosion	Installation error - salt intrusion	Reduced lifetime	reduced performance
244							Parameters degradation - unacceptable vibration	Installation error - loose fitting	Frretting corrosion on interface of contacting materials undergoing slight, cyclic relative motion,leading to reduced lifetime	reduced performance
245							Parameter degradation - thermal ageing	Fabrication error - substandard components	Appearance of weld fatigue in the form of creep, voids, cracks and delamination leads to reduced heat dissipation.	reduced performance
246							Parameter degradation - thermomechanical fatigue	Fabrication error - substandard components	Bond wire lift off, leading to reduced thermal dissipation	reduced performance
247				DC Choper / Crowbar		Converts fixed DC input to a variable DC output voltage	Spurious stop	installation error - insufficient gap between the bar leading to potential short circuit	Occurrence of fire or explosion	Turbine inoperable
248				Filter		Eliminate electrical noise	Capacitor tank rupture	Off design service - Voltage overload	Occurrence of fire or explosion	Turbine inoperable
249							Spurious stop	Fabrication defect leading to substandard components	Electricity signal unfiltered	Reduced turbine performance
250				Heat Management		to Dissipate heat from the converter	Insufficient heat transfer	Fabrication error - substandard components leading to Parameter degradation - thermal ageing	Cooling grease thermal ageing, leading to overheat igbt and reduced lifetime	reduced performance
251			Transformer(s) - Liquid insulated transformer	Winding		To increase the alternating voltages in order to have efficient export power transmission	Winding distortion	Fabrication error - Substandard components leading to winding distortion	distortion, loosening or displacement of the windings leading to decreasing performance of the transformer	reduced performance or possibly turbine inoperable
252							Loss of isolation	Operation error - Lack of maintenance leading to accelerated tear and wear	Thermal losses creates hotspots in the winding, leading to tear and wear and reduced lifetime	reduced performance
253				Insulator			Insufficient efficiency	Fabrication error - Substandard components	Dielectric breakdown leading to short circuit	reduced performance or possibly turbine inoperable
254							Bushing failure	Vibration	Dielectric breakdown leading to short circuit	reduced performance or possibly turbine inoperable
255								Off design service - voltage overload		

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
256								Installation error - water intrusion		
257				Magnetic Core			Parameter deviation - overheating	fabrication error - substandard core laminiation	Eddy current induces core overheating, leading to damage on other components	reduced performance or possibly turbine inoperable
258				Refrigerant			Leakage	Fabrication error - substandard components	Low heat transfer, heat build up inside the transformer, leading to gas pressure build up, which may result in transformer to blow	reduced performance or possibly turbine inoperable
259			HV switchgear			To control, protect and isolate electrical equipment.	Fail to function on demand - Fuse/circuit breaker unable to isolate electrical equipment	Installation error - loose connection	Thermal failure of the connection	Turbine inoperable
260							Breakdown - Insulation	Installation error - substandard insulation	Dielectric breakdown leading to short circuit a,d switchgear failure	Turbine inoperable
261			LV switchgear			To control, protect and isolate electrical equipment.	Fail to function on demand - Fuse/circuit breaker unable to isolate electrical equipment	Installation error - loose connection	Thermal failure of the connection	Turbine inoperable
262							Breakdown - Insulation	Installation error - substandard insulation	Dielectric breakdown leading to short circuit a,d switchgear failure	Turbine inoperable
263			Power cabling system			Transmit electrical power production	Spurious Stop	Fabrication error - substandard component leading to Loss of continuity	Cable core cannot absorb the mechanical load, hence transfer the load to the copper conductor, leading to breakage under tensile load	Reduced performance or possibly turbine inoperable
264								Installation error - cable overbending leading to loss of continuity		
265							Breakdown - Insulation	Fabrication error - substandard component	Flash over, leading to fire or explosion	Reduced performance or possibly turbine inoperable
266								Installation error - cable overbending		
267							Faulty transmission	Fabrication error - substandard component leading to Shielding losses	EMC interference	Reduced performance

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
268			Auxilliary Cabling System and Connector			To transmit auxilliary electrical power	Spurious Stop	Fabrication error - substandard component leading to Loss of continuity	Cable core cannot absorb the mechanical load, hence transfer the load to the copper conductor, leading to breakage under tensile load	Reduced performance or possibly turbine inoperable
269								Installation error - cable overbending leading to loss of continuity		
270							Breakdown - Insulation	Fabrication error - substandard component	Flash over, leading to fire or explosion	Reduced performance or possibly turbine inoperable
271								Installation error - cable overbending		
272							Faulty transmission	Fabrication error - substandard component leading to Shielding losses	EMC interference	Reduced performance
273			UPS systems			To provide backup auxilliary electrical power	Fail to start on demand	External factor - Low lifespan due to high ambient temperature	Backup power failure	Loss of auxilliary electricity supply for turbine control and monitoring system
274							Breakdown	O & M error - due to improper overcharging voltage leading to thermal runaway	Risk of UPS fire and explosion	Loss of auxilliary electricity supply for turbine control and monitoring system and damage to surrounding components
275			Subsea cabling system			To export generated electrical power to the shore	Structural deficiency	installation error - vessel maneuver induce over torsional load on the umbilical leading to Torsional failure	bird-caging or necking of armor wire and or helical component.	delayed turbine operation
276			Subsea cable joints			To provide secure connection and removal of subsea cabl from the tidal turbine	Structural deficiency	Fabrication error - substandard component	Loss of connection	Inability to transmit generated electrical power
277								Installation error - Excessive flexing at the junction between the cable and connector		
278							Faulty transmission	Fabrication error - substandard component leading to Shielding losses	Reduced power transmittal performance	Reduced export power quality
279			Electrical Protection and Safety			To provide safety mechanism, protect and isolate electrical equipment failure	Fail to function on demand	Fabrication error - substandard component leading to Loss of continuity	Electrical fault cannot be localized	Various electrical components damage, overheating, fire or even explosion
280								Installation error		

APPENDIX D- FMEA WORKSHEET CONCEPT 3 – FLOATING MULTI ROTOR TIDAL TURBINE

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
1	Hydrodynamic System	Nacelle	Nacelle shell			Provision of watertight compartment Transfer PTO and rotor loads to sub-structure	Structural deficiency - Unacceptable corrosion	Improper material selection	Surface leakage leading to water infiltration into the nacelle	Damaged various internal turbine components
2								Failure of corrosion protection		
3							Structural deficiency - Unacceptable crack/rupture	Improper design - inadequate strength calculation	Surface leakage leading to water infiltration into the nacelle	Damaged various internal turbine components
4								Fabrication error		
5								Impact		
6							Structural deficiency - Unacceptable fouling	Improper design - inadequate fouling protection specification	Increase surface roughness	Reduced hydrodynamic profile
7								Fabrication error - inadequate fouling protection application		
8							Structural deficiency - deformation due to impact (no leakage)	Installation error - incident due to careless installation process	Surface leakage leading to water infiltration into the nacelle	Damaged various internal turbine components
9								External cause - Drop object from vessel on the surface		

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
10							External leakage	Nacelle shell not closed properly	Leakage leading to water infiltration into the nacelle	Damaged various internal turbine components
11			Nacelle joints			Provide water tightness	Structural deficiency - Unacceptable corrosion	Improper design	Surface leakage leading to water infiltration into the nacelle	Damaged various internal turbine components
12							Structural deficiency - Cracking, and reduced fatigue strength	Improper design	Nacelle joint failure below the design load	Water infiltration into the nacelle, potentially leading to damage on various internal turbine components
13								Improper assembly		
14			Interface with supporting structure			Transfer loads to yaw mechanism or to support structure (see support structure)	Structural deficiency - Unacceptable corrosion	Improper material selection	reduced interface lifetime	reduced turbine operability lifetime
15							Structural deficiency - Unacceptable crack/rupture	Improper design - inadequate strength calculation	interface deformation	Risk of nacelle fall
16								Fabrication error		
17							Structural deficiency - Unacceptable fouling	Improper design - inadequate fouling protection specification	Mismatch between surfaces when closing the nacelle	It may potentially leads to water infiltration into the nacelle damaging several internal components
18								Fabrication error - inadequate fouling protection application		
19			Penetrations			Provide attachment points for transport and handling	Structural deficiency - Unacceptable corrosion	Improper material selection	Surface leakage leading to water infiltration into the nacelle	Damaged various internal turbine components
20								Failure of corrosion protection		
21							Structural deficiency - Unacceptable crack/rupture	Improper design - inadequate strength calculation	Surface leakage leading to water infiltration into the nacelle	Damaged various internal turbine components
22								Fabrication error		
23							Accidental deformation/cracking during assembly/installation	Improper manipulation producing cracks in penetrations tubing	Surface leakage leading to water infiltration into the nacelle	Damaged various internal turbine components
24			Lifting points			Provide attachment points for transport and handling	Structural deficiency - Unacceptable corrosion	Improper material selection	Lug rupture during nacelle lifting operation	Nacelle and its internals damage due to the impact of the fall
25								Failure of corrosion protection		
26							Structural deficiency - Unacceptable crack/rupture	Improper design - inadequate strength calculation	Lug rupture during nacelle lifting operation	Nacelle and its internals damage due to the impact of the fall
27								Fabrication error		
28			Sub-assembly frame			Support drivetrain, transferring loads from components of drivetrain to nacelle (brake, gearbox, generator)	Structural deficiency - Unacceptable corrosion	Improper material selection	Reduced mechanical strength	Weaken nacelle structural integrity
29								Failure of corrosion protection		
30							Structural deficiency - Unacceptable crack/rupture	Improper design - inadequate strength calculation	nacelle frame deformation	Weaken nacelle structural integrity
31								Fabrication error		
32			Access into nacelle (above sea water)			Provide access into nacelle	Structural deficiency - Unacceptable corrosion	Improper material selection	Surface leakage leading to water infiltration into the nacelle	Damaged various internal turbine components
33								Failure of corrosion protection		
34							Structural deficiency - Unacceptable crack/rupture	Improper design - inadequate strength calculation	Surface leakage leading to water infiltration into the nacelle	Damaged various internal turbine components
35								Fabrication error		

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
36							Water ingress	Joint rupture	Hatches detachment	Damaged various internal turbine components
37			Corrosion protection	Material selection		Provide corrosion protection for nacelle	Accelerated corrosion, leakages, structural weakness	Improper material selection	Corrosion, leakage	Reduction on nacelle life
38				Coating				Mismanipulation, impact		
39				Impressed current				Electronic failure		
40				Corrosion Allowance				Miscalculation		
41		**Rotor**	Blades	Blade shell		Transfer loads from blades to main shaft Water/oil tightness (water ingress and oil leak) Resist extreme loads Resist fatigue load Provide housing for the pitch system	Structural deficiency - Skin or adhesive debonding	Fabrication error - poor quality uniformity	chipped surface, increased roughness, reduced lifetime	Reduced turbine performance
42							Structural deficiency - Adhesive joint failure of leading or trailing edges	Poor quality uniformity due to a fabrication error, impacts or erosion	chipped surface, increased roughness, reduced lifetime	Reduced turbine performance
43							Structural deficiency - crack in gelcoat	Poor quality uniformity due to a fabrication error, impacts or erosion	chipped surface, increased roughness, reduced lifetime	Reduced turbine performance
44							Structural deficiency - Delamination of laminates	Poor quality uniformity due to a fabrication error, impacts or erosion	Damaged blade	Reduced turbine performance or possibly turbine inoperable
45							Structural deficiency - individual lamina failure (splitting or cracking)	Poor quality uniformity due to a fabrication error, impacts or erosion	Damaged blade	Reduced turbine performance or possibly turbine inoperable
46				Blade structural element			Structural deficiency - Sandwich face/core delamination	Fabrication error - Poor fabrication process and quality control	Damaged blade	Reduced turbine performance or possibly turbine inoperable
47							Structural deficiency - Delamination of laminates	Fabrication error - Poor fabrication process and quality control	Damaged blade	Reduced turbine performance or possibly turbine inoperable
48							Structural deficiency - individual lamina failure (splitting or cracking)	Fabrication error - Poor fabrication process and quality control	Damaged blade	Reduced turbine performance or possibly turbine inoperable
49							Structural deficiency	Understimated loaded, due to external and control originated efforts	Damaged blade	Reduced turbine performance or possibly turbine inoperable
50							Structural deficiency - Web fatigue failure	Fabrication error - Poor fabrication process and quality control	Damaged blade	Reduced turbine performance or possibly turbine inoperable
51				Blade coating			Structural deficiency - peeling / wear	Fabrication error - Poor fabrication process and quality control	chipped surface, increased roughness, reduced lifetime	Reduced turbine performance

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
52							Abnormal output- low speed	Fouling/Marine growth	chipped surface, increased roughness, reduced lifetime	Reduced turbine performance
53				Blade root			Structural deficiency - Erosion of the sealing of the root	Fabrication error - Poor fabrication process and quality control	Damaged or loss of blade	Reduced turbine performance or possibly turbine inoperable
54							Structural deficiency - Fatigue failure in root connection	Fabrication error - Poor fabrication process and quality control	Damaged or loss of blade	Reduced turbine performance or possibly turbine inoperable
55							Structural deficiency - Fatigue failure in root transition area	Fabrication error - Poor fabrication process and quality control	Damaged or loss of blade	Reduced turbine performance or possibly turbine inoperable
56				Blade hydrodynamic features			Structural deficiency - Adhesive joint failure	Fabrication error - Poor fabrication process and quality control	chipped surface, increased roughness, reduced lifetime	Reduced turbine performance
57							Structural deficiency - Skin or adhesive debonding	Fabrication error - Poor fabrication process and quality control	chipped surface, increased roughness, reduced lifetime	Reduced turbine performance
58			Hub	Hub shell		Transfer loads from blades to main shaftWater/oil tightness (water ingress and oil leak)Resist extreme loadsResist fatigue loadProvide housing for the pitch system	structural deficiency - mechanical failure (fracture, yield, and cracking)	Improper material - inadequate material selection	Hub rupture	Reduced turbine performance or possibly turbine inoperable
59								Improper design - inadequate design strength		
60								Off design service - unexpected loading conditions		
61								Fabrication error		
62							structural deficiency - unacceptable corrosion	Improper material selection	Hub rupture	Reduced turbine performance or possibly turbine inoperable
63								Failure of corrosion protection		
64							structural deficiency - fatigue failure	Improper material - inadequate material selection	Hub rupture	Reduced turbine performance or possibly turbine inoperable
65								Improper design - inadequate design strength		
66								Off design service - unexpected loading conditions		
67							structural deficiency - Normal wear	Expected wear and tear from normal operating condition	Hub rupture	Reduced turbine performance or possibly turbine inoperable
68							vibration	Installation error - imbalance installation	Reduced hub lifetime	Reduced turbine performance
69			Front Bulb			Improve hydrodynamic performance	Structural deficiency - peeling / wear	Fabrication error - Poor fabrication process and quality control	Damage to pitch system	reduced hydrodynamic performance
70							Structural deficiency - biofouling	Fabrication error - inadequate fouling protection application	Damage to pitch system	reduced hydrodynamic performance

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
71							Structural deficiency - Delamination	Fabrication error - Poor fabrication process and quality control	Damage to pitch system	reduced hydrodynamic performance
72							Structural deficiency - individual lamina failure (splitting or cracking)	Fabrication error - Poor fabrication process and quality control	Damage to pitch system	reduced hydrodynamic performance
73			Pitch system	Pitch actuator (Electro-mechanical)		Allow pitching of the blades and therefore control of the turbine loading. Provides pitch motion	Blades can move freely in pitch axis	Broken motor	Loss or limitation of pitch control	Reduced turbine performance or possibly turbine inoperable
74				Pitching load transfer component (shaft, trunnion, crank ring)		Allow pitching of the blades and therefore control of the turbine loading. Provides pitch motion	Blades can move freely in pitch axis	Overload, pitch clogging, fatigue or corrosion	Loss or limitation of pitch control	Reduced turbine performance or possibly turbine inoperable
75				Pitch bearing		Support loads in pitch system Allow blade rotation about pitch axis Transfer axial loads and bending moments to hub Resist ultimate loads Resist fatigue loads	Pitch blocked	Bearing failure due to overload or an external agent	Loss or limitation of pitch control	Reduced turbine performance. Rotor overload. Risk of blade breakage.
76				Pitch gear		Transfer motion from pitch actuator to pitching shaft Provide a ratio for power-torque transmission between parts	Blades can move freely in pitch axis	Fracture in pitch gear	Loss or limitation of pitch control	Reduced turbine performance or possibly turbine inoperable
77				Dynamic seals for blades		Provide water tightness and oil leakage	Water ingress into the pitch system	Corrosion, overload, fracture or fatigue	Loss or limitation of pitch control	Reduced turbine performance or possibly turbine inoperable
78				Electric system		Provide actuators with power	Asymmetry in the blades position	Electronic failure	Loss or limitation of pitch control	Reduced turbine performance or possibly turbine inoperable

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
79							Asymmetry in the blades position	Battery failure	Loss or limitation of pitch control	Reduced turbine performance or possibly turbine inoperable
80							Asymmetry in the blades position	Slip ring failure	Loss or limitation of pitch control	Reduced turbine performance or possibly turbine inoperable
81							Asymmetry in the blades position	Cabling failure	Loss or limitation of pitch control	Reduced turbine performance or possibly turbine inoperable
82			Corrosion protection	Material selection		Provide corrosion protection for metallic part of the rotor	Accelerated corrosion, leakages, structural weakness	Improper material selection	Corrosion, leakage	Reduction on rotor life
83				Coating				Mismanipulation, impact		
84				Impressed current				Electronic failure		
85				Corrosion Allowance				Miscalculation		
86		**Individual Yaw system (Optional, Alternative to Turret)**	Yaw locking / brake mechanism			Provide attachment of nacelle onto substructure Prevents unintended separation of turbine form substructure under yawing operations Possible three conditions to be considered: Open ((for connection during installation), Partially engaged (to allow yaw without releasing vertical transference of permanent loads if part of load path for permanent loads) and Closed (to restrain yaw of the nacelle during operation).	Turbine can move freely in yaw axis	Excessive brake pad wear	Turbine is partially fixed	Reduced turbine performance or possibly turbine inoperable
87								Hydraulic failure	Turbine is partially fixed	Reduced turbine performance or possibly turbine inoperable

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
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88			Cable and pipe management system	Guiding mechanism		Manage cables and pipes when yawing, prevent entangling, rubbing of cables when yawing Guide cable connections between nacelle and main structure Align connections with sub structure	Cable not protected, potential short circuit	Colapsing of tube protecting the cable	Cable damaged	Reduced turbine performance or possibly turbine inoperable
89				Drag chain		Manage Connection when yawing, prevent entangling, rubbing of cables when yawing	Tangled chains	Out of plane bending	Chain shortened	Reduced performance (deasligned)
90				Slip ring		Provide contact between conducting surface(s) and brushes	Current leakages	Lack of isolation, arcs	Electrical arcs	Power losses
91							Excesive wear	Material loss, non proper brush selection, electrical arcs	Heating	Reduced turbine performance,Power losses
92			Yaw load bearing (plain)			Resist structural loads Resist fatigue loads Transmit load from upper part of joint to lower part of joint Allow rotation about the yaw axis if relevant, transfer bending moments and axial loads to sub-structure or skirt	Turbine does not orientate properly	Excessive bearing wear	Partial loss of yaw orientation	Reduced turbine performance or possibly turbine inoperable
93								Extreme loads	Partial loss of yaw orientation	Reduced turbine performance or possibly turbine inoperable
94	Reaction System	**Foundation system**	Pretensioned anchor pile			Transfer loads from sub-structure to seabed, while complying with requirements for ultimate, fatigue and accidental limit states as well as	In service problem- loss of stability	Expected loading - cyclic loading due to wave, current and soil condition	The foundation and structural part experience Uplift, tilting or sliding	Tidal turbine free movement lead to potential damage to other component of tidal turbine and reduced performance
95							Structural deficiency - Cracking	Installation error - incident due to careless installation process	foundation cracking	Tidal turbine anchor lost lead to Tidal turbine total lost

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
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						serviceability aspects such as displacements and natural period				
96		Support Structure, Floater	Interface with foundation	Mooring line		Fixing the turbine on the seabed	Mooring line fracture	Cables wear, fatigue, impact with vessels or heavy storm	Large displacement of the device. Overload of the remaining mooring lines, electrical cable damaged	Turbine shutdown
97							Displacement greater than expected	Metocean extreme conditions, snags, entanglements	Instability or abnormal working	Reduced stability lead to potential vibration and damage to component. Performance limited
98				Turret (Optional, Alternative to Individual Yaw)		Anchoring point providing free rotational movement for the turbine	Loose or detachment of one mooring line	Exceedance of load-carrying capacity by extreme metoceanic conditions, design error, weld defect, corrosion, fatigue...	Large displacement of the device. Overload of the remaining mooring lines, electrical cable damaged	Turbine shutdown
99							Loose or detachment of more than one mooring line	Exceedance of load-carrying capacity by extreme metoceanic conditions, design error, weld defect, corrosion, fatigue...	Large displacement of the device. Overload of the remaining mooring lines, electrical cable damaged	Turbine shutdown. High risk of loosing the entire device
100							Noise, squeakings. The platform has problems to stabilize	Bearings failure	The platform does not face current correctly	Other components may be damaged
101							Device blocked	Bearing failure, asymmetrical bearing wear, bearing seizure	The platform does not orientate	Total or partial loss or power
102			Main Structure (including auxiliary equipment)-Floating			Resist hydrodynamic loads on the structure Resist fatigue loads Transfer loads to mooring lines	Structural deficiency - Corrosion	Improper material selection	Cracking on structural parts	Weaken structural integrity
103								Failure of corrosion protection		
104							Structural deficiency - Cracking, and reduced fatigue strength	Improper design leading to weld defect due to: - Improper weld geometry design - unanticipated service conditions - inappropriately specified weld process parameters - incompatibilities of the materials being welded and the processes employed	Structural part failure	Inability to withstand operation load leading to risk of nacelle falling

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
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105								Improper design due to inadequate configuration, calculation, and inaccurate loading cases		
106								Improper material selection leading to inadequate strength properties		
107								Fabrication error leading to weld defect due to: - Improperly executed welds		
108							Structural deficiency - Reduced strength due to impact	Installation error - incident due to careless installation process	Structural part failure	Inability to withstand operation load leading to risk of nacelle falling
109								External cause - Drop object from vessel on the surface		
110							Structural deficiency - unacceptable vibration	Installation error leading to unstable support position	Unacceptable operating condition for nacelle's internal components	Reduced turbine operability
111							In-service problems - unacceptable biofouling	Improper design - inadequate fouling protection specification	Reduced support structure lifetime	reduced turbine operability lifetime
112								Fabrication error - inadequate fouling protection application		
113			Interface with turbine support			Provide safe attachment to turbine Resist hydrodynamic loads on the structure Resist fatigue loads Provide support to umbilical Transfer loads to main structure	Structural deficiency - Unacceptable corrosion	Improper material selection	Reduced interface lifetime	Reduced turbine operability lifetime
114								Failure of corrosion protection		
115							Structural deficiency - Unacceptable crack/rupture	Improper design - inadequate strength calculation	Interface deformation	Risk of nacelle fall
116								Fabrication error		
117							Structural deficiency - Unacceptable fouling	Improper design - inadequate fouling protection specification	Mismatch interface	Nacelle retrieval or reinsertion problem
118								Fabrication error - inadequate fouling protection application		
119			Corrosion protection	Material selection		To provide corrosion protection for the metallic structural part	Accelerated corrosion, leakages, structural weakness	Improper material selection	Corrosion, leakage	Reduction on support structure life
120				Coating				Mismanipulation, impact		
121				Impressed current				Electronic failure		
122				Corrosion Allowance				Miscalculation		

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
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123	Power take off	Auxiliaries	Firefighting System			Various electrical components damage, overheating, fire or even explosion	CO2 does not flow	Valve broken, bottle leakage, electrical failure	Unavailable firefighting system in case of emergency	The device integrity is seriously compromised in case of fire
124							Lack of pressure	Valve broken, bottle leakage, electrical failure	Fire extinction cannot be performed in optimal condition	It may compromise the extintion time and therefore the integrity of some componets in case of fire
125			Cabinets			Provide enclosure for the auxilliary control system switches and connectors	Lack of command on auxiliary systems	Electrical failure	Missfunction of pumps or heat removal systems	Ballast and/or bilge levels (draft and attitude), humidity or temperature level out of specs
126			Ballast (solid ballast)			Allow trimming adjustment of nacelle during deployment Allow buoyancy adjustment of nacelle	Loss of ballast material	External break	Loss of stability	Risk of device loss
127			Ballast (liquid ballast)			Allow trimming adjustment of nacelle during deployment Allow buoyancy adjustment of nacelle	Mechanical failure (noise, vibrations or squeakings)	Insufficient lubrication, components fails: Shaft, impeller, bearings, valves, pipes...	Mechanical components may be damaged	The stabilization of the platform cannot be performed properly. Max Power limitation
128							Electric failure	Breakage of cables or connectors	Pumps stop working	The stabilization of the platform cannot be performed properly. Max Power limitation
129							The device is not stabilized	Tank fissures, sealing defects, or valve failures, electrical failure, pipes obstruction, hydraulic system leakages, pumps failure	It may compromise the stability of the platform. Floodage of the device. Overload on drivetrain.	The stabilization of the platform cannot be performed properly. Max Power limitation
130							Pressure/flow loss	Pump cavitation due to clogging/obstruction of the aspiration circuit	Damage on impellers	The stabilization of the platform cannot be performed properly. Max Power limitation
131							Abnormal operation	Tank fissures, sealing defects, or valve failures, electrical failure, pipes obstruction, hydraulic system leakages, pumps failure	It may compromise the stability of the platform. Floodage of the device. Overload on drivetrain.	The stabilization of the platform cannot be performed properly. Max Power limitation

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
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132			Bilge system			Empty nacelle if water ingress Oil and water separation	Bilge floodage	Leakage, bilge pumps failure, level sensor failure	Dirty water filtration in surrounding locations	Other components may be damaged
133							Unacceptable corrosion	Improper maintenance, design failure	Structural damage	Other components may be damaged
134							Pressure/flow loss	Pump cavitation due to clogging/obstruction of the aspiration circuit	Damage on impellers	Overflooding, draft affected
135			Cooling system	Heatexchanger		Providing cooling mechanism for the electrical components	Insufficient heat transfer	Improper design - inadequate heat exchange characteristics	Low heat transfer	Reduced turbine performance
136							External leakage	Fabrication error - Improper welding	Loos of coolant	Reduced turbine performance or possibly turbine inoperable
137							Internal leakage	Improper assembly during fabrication, aging or erosion	Low heat transfer	Reduced turbine performance
138							Plugged / choked	Installation error - presence of contaminants	Coolant circulation problem, Low heat transfer	Reduced turbine performance
139							Structural Deficiency - Unacceptable corrosion	Improper design - inadequate material	Reduced lifetime	Reduced turbine performance
140				Cooling Pump		Providing circulation mechanism for the heat exchanger coolant	External leakage	Installation error - improper fitting	Coolant circulation problem, leading to loss of coolant	Reduced turbine performance or possibly turbine inoperable
141							Structural Deficiency - Unacceptable corrosion	Improper design - inadequate material	Reduced lifetime	Reduced turbine performance
142							Unacceptable vibration & noise	Installation error - unbalance impeller	Reduced lifetime	Reduced turbine performance
143							Structural deficiency - impeller breakdown	Fabrication error - substandard impeller fabrication	Pump inoperable	Turbine inoperable
144							structural deficiency - accelerated components wear	Fabrication error - components fabrication defect	Reduced lifetime	Reduced turbine performance
145				Coolant		Serving as the cooling working fluid for the electrical system heat management	Parameter deviation - Monitored variables (temperature) exceeding tolerance	Improper design - inappropriate coolant selection	Low heat transfer	Reduced turbine performance
146							Contamination	Installation error - presence of contaminants	Coolant circulation problem, Low heat transfer	Reduced turbine performance
147				Cooling system connections		Providing circulation mechanism for the	External leakage	Fabrication error - Improper welding or fitting	Loss of coolant	Reduced turbine performance or possibly turbine inoperable
148							Plugged / choked	Installation error - presence of contaminants	Coolant circulation problem, Low heat transfer	Reduced turbine performance

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
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149						heat exchanger coolant	Structural Deficiency - Unacceptable corrosion	Improper design - inadequate material	Reduced lifetime	Reduced turbine performance
150			Air treatment	Air filter		Prevent nacelle interior from condensation and salty environment	Limited air entrance	Filter obstruction	Overheating of the atmosphere	Reduced turbine performance or limited operation time
151				Dehumydifier			Humidity excess in the atmosphere	Sensor failure	Electrical or electronic components may be damaged due to shortcircuit or corrosion	Reduced turbine performance or possibly turbine inoperable
152								Compresor breakage	Electrical or electronic components may be damaged due to shortcircuit or corrosion	Reduced turbine performance or possibly turbine inoperable
153			Beacon/Lights			To indicate turbine position to the passing vessels	Light does not work	Hits, power supply problems	The device cannot be seen on the sea	It may compromise the security of the device
154							Poor lighting	Lights in bad conditions	The device cannot be identified properly on the sea	It may compromise the security of the device
155								Power supply problems	The device cannot be identified properly on the sea	It may compromise the security of the device
156								Excess of dirt	The device cannot be identified properly on the sea	It may compromise the security of the device
157							Total or partial beacon loss	Hits, extreme metocean conditions	The device cannot be identified properly on the sea	It may compromise the security of the device
158		**Drivetrain**	Low speed shaft			Transfer torque from hub to drive train gearbox Transfer torque to generator (if relevant) Resist ultimate loads Resist fatigue loads	structural deficiency - mechanical failure (fracture, yield, and cracking)	Improper material - inadequate material selection	Shaft failure	Turbine inoperable
159								Improper design - inadequate design strength		
160								Off design service - unexpected loading conditions		
161								Fabrication error		
162							structural deficiency - unacceptable corrosion	Improper material selection	Reduced shaft lifetime	Reduced turbine performance or possibly turbine inoperable
163								Failure of corrosion protection		
164							structural deficiency - fatigue failure	Improper material - inadequate material selection	Shaft failure	Turbine inoperable
165								Improper design - inadequate design strength		
166								Off design service - unexpected loading conditions		
167							structural deficiency - accelerated wear	Off design service - unexpected loading conditions	Reduced lifetime	Reduced turbine performance
168							vibration	Installation error - imbalance installation	Reduced lifetime	Reduced turbine performance
169			Low speed shaft bearings			Transfer thrust and bending moments to nacelle	Structural deficiency - premature fatigue	Improper design - inadequate bearing selection	Heavy ball wear paths, widespread spalling leading to bearing failure	Reduced turbine performance or possibly turbine inoperable

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
170							Structural deficiency - false brinelling	off-design service - excessive external load	Elliptical wear marks in axial direction at each ball position, leading to accelerated wear process and lower bearing lifetime	Reduced turbine performance
171							Structural deficiency - true brinelling	Installation error -improper handling leading to severe impact and static overload	Indentation in the raceways, leading to bearing vibration and lower bearing lifetime	Reduced turbine performance
172							Structural deficiency - Denting of the bearing raceways and ball	installation error -improper handling leading to intrusion of contaminants (dirt, dust, etc.)	Accelerated wear and high vibration	Reduced turbine performance or possibly turbine inoperable
173							corrosion	installation error - exposure to corrosive environment	Rust and abrasive runway or balls surface, leading to accelerated wear process and lower bearing lifetime	Reduced turbine performance or possibly turbine inoperable
174								operation error - exposure to corrosive environment		
175							misalignment	Installation error - bent shafts, intrusion of dirt on shaft or housing support	Non parallel ball path on bearing outer raceway, leading to excessive vibration and lower bearing lifetime	Reduced turbine performance
176							Structural deficiency - Discoloured ball tracks and ball, early wear	Lubricant failure	Accelerated wear leading to Spalling, facture of running surface and subsequent removal of small material	Reduced turbine performance
177								Installation error - loose or over fits		
178							accelerated wear and fatigue	Off design service - unexpected loading conditions	Spalling, facture of running surface and subsequent removal of small material	Reduced turbine performance
179			Low speed shaft dynamic seals			Provide water tightness	Dry running	Lubrication failure	Seal faces surface damage, Seal failure	Leakage leading to water intrusion damaging various internal turbine components
180							Poor lubrication	Lubrication failure	Small, cracks on the seal faces, presence of noises and vibration, reduced seal lifetime	Leakage leading to water intrusion damaging various internal turbine components

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
181							Particle deposits	installation error -improper handling leading to intrusion of contaminants (dirt, dust, etc.)	Clogging, and sticking of the O rings, opening of the sealing gap, leading to reduced lifetime of the seal	Reduced turbine performance
182								Operation error - intrusion of sands		
183							Structural deficiency -corrosion	installation error - exposure to corrosive environment	accelerated wear process and lower seal lifetime	Reduced turbine performance
184								operation error - exposure to corrosive environment		
185							Structural deficiency - abnormal wear	Installation error - misalignment	Abnormal wear on O rings, uneven depth of the wear track around seal seating, wear on the seal sleeves, leading to reduced seal lifetime	Reduced turbine performance
186			High speed shaft			Transfer torque from gearbox to generator Resist ultimate loads Resist fatigue loads	Vibrations or noise	Bent shaft	Damaged shaft	Inoperable turbine. Vibrations can damage other components.
187							Turbine stops working	Shaft breakage	Loss of the transmision due to shaft breakage	Inoperable turbine. Vibrations can damage other components.
188			High speed shaft bearings			Allow rotation of high speed shaft Resist misalignment induced loads Resist fatigue loads	Vibrations, noise or squeakings.	Misalignment	Damaged shaft	Reduced turbine performance or possibly turbine inoperable
189								False Brinelling	Damaged shaft	Reduced turbine performance or possibly turbine inoperable
190								Poor lubrication	Damaged shaft	Reduced turbine performance or possibly turbine inoperable
191							Turbine stops working	Bearing breakage	Loss of the transmision due to bearing breakage	Turbine inoperable
192			Gearbox / high speed shaft	Coupling		Step up rotation speed of main shaft and support main shaft through bearings Transmission of torque loads into nacelle	Vibrations, noise or squeakings.	Excessive coupling wear	Gearbox not working in optimal conditions	Reduced turbine performance

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
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193				Gears		To transmit torque	Vibrations, noise or squeakings.	Excessive gear wear	Damaged gearbox	Reduced turbine performance or possibly turbine inoperable
194				Gears		To transmit torque	Turbine stops working	Gear breakage	Gearbox blockage	Inoperable turbine
195				Bearing		Transfer thrust and bending moments to nacelle	Vibrations, noise or squeakings.	Excesive bearing wear	Gearbox not working in optimal conditions	Reduced turbine performance
196				Bearing		Transfer thrust and bending moments to nacelle	Turbine stops working	Bearing breakage	Gearbox blockage	Inoperable turbine
197				Shaft		To transmit mechanical power	Turbine stops working	Shaft breakage	Gearbox blockage	Inoperable turbine
198				Casing		To provide enclosure for the gearbox components	structural deficiency - mechanical failure (fracture, yield, and cracking)	Vibrations, improper component selection	Aditionasl vibrations	Other components may be damaged
199				Gearbox lubrication system		Interface between gearbox and sub-frame	Vibrations, noise or squeakings.	Poor lubrication	Damaged gearbox	Reduced turbine performance or possibly turbine inoperable
200			Braking system	Low speed brake		Brake the drivetrain from low speed shaft	Inadequate shaft braking	Pads wear, brake fluid in bad conditions, lack of pressure	The turbine does not stop in safe conditions	It may compromise the security of the device
201			Braking system	Low speed brake		Brake the drivetrain from low speed shaft	The brake does not act	Pads /Brake disk breakage	The turbine does not stop in safe conditions	It may compromise the security of the device
202			Braking system	Low speed brake		Brake the drivetrain from low speed shaft	The brake does not act	Hydraulic system failure	The turbine does not stop in safe conditions	It may compromise the security of the device
203			Braking system	Parking / Blocking brake		Keep turbine stopped after braking operation	Inadequate low speed shaft fixing	Pads wear, brake fluid in bad conditions, lack of pressure, hydraulic failure	O&M working cannot be carried out safely	Risk for people
204			Braking system	Braking actuator-Hydraulic power unit		Provide hydraulic power to braking mechanism	Inadequate low speed shaft fixing	Lack of pressure in the hydraulic circuit due to: Leakage, valve failure or pump failure	The turbine does not stop in safe conditions. O&M working cannot be carried out safely	Risk for people
205			Couplings	Key connections		To transmit power	Breakage of the key connection	Non optimal working conditions: fatigue or overload due to abrupt starts and stops.	Shaft unattached	Total loss of power
206			Shaft lubrication system			Provide lubrication to the shaft	Vibrations, noise or squeakings.	Lubricant in bad conditions	Overheating, shaft damage	Abnormal functioning of the global system. Loss of power.
207		**Control & Communication system**	Control system	Data acquisition and processing		Detect events or changes from their measured environment and send feedback to the controller	Parameter deviation - nonlinearity / sensor bias	Fabrication error - substandard sensor components	Sensor sensitivity is not constant over the measured range.	Inaccurate turbine operation leading to low performance
208		**Control & Communication system**	Control system	Data acquisition and processing		Detect events or changes from their measured environment and send feedback to the controller	Parameter deviation - nonlinearity / sensor bias	Installation error - presence of contaminants or moisture inside the sensors components	Sensor sensitivity is not constant over the measured range.	Inaccurate turbine operation leading to low performance

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
209							Parameter deviation - drift error	Fabrication error - substandard sensor components	Output signal slowly changes independent of the measured property	Inaccurate turbine operation leading to low performance
210								Installation error - presence of contaminants or moisture inside the sensors components		
211							Parameter deviation - noise error	Fabrication error - substandard sensor components	Random deviation of the reading	Inaccurate turbine operation leading to low performance
212								Installation error - presence of contaminants or moisture inside the sensors components		
213							Parameter deviation - environmental error	Fabrication error - substandard sensor components	Sensor is more sensitive to properties other than the property being measured	Inaccurate turbine operation leading to low performance
214								Installation error - presence of contaminants or moisture inside the sensors components		
215							Structural deficiency - components failure	Fabrication error - substandard sensor components	Loss of ability to measure	Loss of control feedback, leading to low performance or turbine inoperable
216				LAN	Network cable	Transmit data from and to sensors and controller in the turbine	Complete data transfer failure	Open circuit (wire breakage or connector disconnected) due to vibration	Loss of communication	Loss of control, leading to turbine inoperable
217								Short circuit due to pinched cable		
218							Loss of part of data package	Installation error - Jitter due to vibration on loose contact	Interrupted control & communication	Inaccurate or delayed turbine operation leading to low performance
219					Network interface card		Complete data transfer failure	Fabrication error - PCB failure	Loss of ability to measure	Loss of control feedback, leading to low performance or turbine inoperable
220							Signal interference	fabrication error - Component with low noise resistance threshold	Interrupted control & communication	Inaccurate or delayed turbine operation leading to low performance
221				Controllers	Software	Provide logic and control system algorithm for the turbine	Unauthorized access	Hacking	Loss of ability to control	Loss of control feedback, leading to turbine inoperable
222							Buffer overflow	Design error - resource starvation due to improper software engineering	Reduced performance of the controller	Inaccurate or delayed turbine operation leading to low performance
223							Race condition	Design error - improper software engineering	Unexpected response/behaviour	Inaccurate or delayed turbine operation leading to low performance

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
224					Hardware		CPU Failure - High leakage current, output stuck, short circuit	fabrication error - Component with substandard quality	Unexpected response/behaviour	Loss of control feedback, leading to low performance or turbine inoperable
225							Memory Failure - Data bit loss, short circuit, slow transfer of data	fabrication error - Component with substandard quality	Unexpected response/behaviour	Loss of control feedback, leading to low performance or turbine inoperable
226				Fiber Optic		Transmit data from and to the turbine and shore based command center	Facet damage	Fabrication error - Pulse width / optical power density	Reduced performance of data transmission	Loss of control feedback, leading to low performance or turbine inoperable
227							Laser wear out	Fabrication error Photo oxidation, contact degradation, crystal grow-in defects	Reduced performance of data transmission	Loss of control feedback, leading to low performance or turbine inoperable
228							Laser instability due to reflections	Fabrication error - Power from laser reflect back	Reduced performance of data transmission	Loss of control feedback, leading to low performance or turbine inoperable
229							Whisker formation	Normal wear - deterioration of solder	Reduced performance of data transmission	Loss of control feedback, leading to low performance or turbine inoperable
230							Dark line defects	Fabrication error - substandard quality control , non-radiative center	Reduced performance of data transmission	Loss of control feedback, leading to low performance or turbine inoperable
231							Structural deficiency - cable & jacket fracture	Normal wear - fatigue due to microcracks	Loss of data transmission	Loss of control feedback, leading to low performance or turbine inoperable
232				System / component protection sensors		To provide safety mechanism, protect and isolate components failure	Electrical failure	Breakage of electronic components	It can affect the power electronic	Loss of control feedback, leading to low performance or turbine inoperable
233			Condition monitoring	Condition monitoring sensors		Monitor defined parameters and send information to condition monitoring system	Parameter deviation - nonlinearity / sensor bias	Fabrication error - substandard sensor components	Sensor sensitivity is not constant over the measured range.	Inaccurate turbine operation leading to low performance
234								Installation error - presence of contaminants or moisture inside the sensors components		
235							Parameter deviation - drift error	Fabrication error - substandard sensor components	Output signal slowly changes independent of the measured property	Inaccurate turbine operation leading to low performance
236								Installation error - presence of contaminants or moisture inside the sensors components		
237							Parameter deviation - noise error	Fabrication error - substandard sensor components	Random deviation of the sensor reading	Inaccurate turbine operation leading to low performance
238								Installation error - presence of contaminants or moisture inside the sensors components		

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
239							Parameter deviation - environmental error	Fabrication error - substandard sensor components	Sensor is more sensitive to properties other than the property being measured	Inaccurate turbine operation leading to low performance
240								Installation error - presence of contaminants or moisture inside the sensors components		
241							Structural deficiency - components failure	Fabrication error - substandard sensor components	Total loss of sensor ability to measure	Loss of control feedback, leading to low performance or turbine inoperable
242				Data acquisition hardware			Failure to transmit or receive data	Fabrication error - substandard electronic component or software	Unable to receive condition monitoring data	Unable to monitoring equipment condition
243			Systems cabinets	Power control cabinet		Provide enclosure for the control system switches and connectors	Malfunctioning of one or more control components	Overheating, humidity, electrical failure, overload, isolation failure	Subsystems control loss	Turbine inoperative or power derrating
244				Auxiliary cabinet		Provide enclosure for the auxilliary control system switches and connectors	Malfunctioning of one or more control components	Overheating, humidity, electrical failure, overload, isolation failure	Auxiliaries subsystems control loss	Partial or total loss of power
245				Environmental monitoring cabinet		Provide enclosure for the environment monitoring switches and connectors	Environmental data is not sent correctly	Overheating, humidity, electrical failure, overload, isolation failure	Environmental data is not sent correctly lead to device operate in safe mode	Potential escalation in case other failure. Non-compliance with the legal obligations
246				Bus communication interfaces		Provide enclosure for communication PLC control system components	Not all data is sent correctly	Overheating, humidity, electrical failure, overload, isolation failure	Cabinets communication unavailable and loss of tidal turbine information from shore	Loss of turbine performance, potential loss of efficiency. Non-planned corrective maintenance operation
247							Loss of isolation	Overtemperature, manufacturing defect	Current leakages or short circuits leading to less stator performance and reliability. Harmonic generation.	Generator loss of function, Turbine inoperative

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
248				Pitch cabinet		Provide enclosure for pitch control system switches and connectors	Loss of pitch control	Overheating, humidity, electrical failure, overload, isolation failure	Loss of pitch angle control	Assuming that pitch gear is reversible, loss of power
249		Electrical system	Generator -Induction Generator	Stator winding		Transform mechanical power into electrical power	Magnetic wedge loss	Overtemperature, vibration, manufacturing defect	Less stator performance and reliability. Harmonic generation.	Partial loss of electrical production
250							Loss of isolation	Overtemperature, manufacturing defect	Current leakages or short circuits leading to less stator performance and reliability. Harmonic generation.	Generator loss of function, Turbine inoperative
251							Brushes failure	Improper grade, improper seating, improper ring material, environmental issues	Generator does not commute	Loss of electrical production
252							High brush wear	Design defect, improper cleaning during maintenance	Generator does not commute properly	Loss of electrical production
253				Rotor winding			Loss of isolation	Overtemperature, manufacturing defect	Less rotor performance and reliability. Harmonic generation.	Partial loss of electrical production
254				Bearings / Bearing housing			Vibration, noise or squeakings	Misalignment	Damaged shaft	Reduced turbine performance or possibly turbine inoperable
255								False Brinelling	Damaged shaft	Reduced turbine performance or possibly turbine inoperable
256								Poor lubrication	Damaged shaft	Reduced turbine performance or possibly turbine inoperable
257				Silent blocks			Vibrations greater than expected	Excessive wear, improper design	It may cause instabilities on the turbine	Risk of damaging other components
258				Frame			Structural deficiency - cracks or large deformations	Fatigue, corrosion or Improper design	It may cause instabilities on the turbine	Risk of damaging other components
259				Insulator			Operation deficiency: Overcurrent	Cracks due to overheating	Leakage or short circuit in the wiring	Turbine stop
260			Power electronic converter	DC Bus / Capacitor		To regulate voltage, current, and frequency of the electricity output of the turbine	The device cannot be controlled properly	Capacitor breakage	Element damaged	Partial or total loss of power, harmonics generation
261							Unstable operation	Capacitor breakage	Element damaged	Partial or total loss of power, harmonics generation
262				IGBT			Electrical overstress (EOS)	Fabrication error - substandard components	Occurrence of fire or explosion	Turbine inoperable

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
263								Off design service - Voltage overload		
264							Electrostatic discharge	Fabrication error - substandard components	Occurrence of fire or explosion	Turbine inoperable
265								Off design service - Voltage overload	Element damaged	Partial or total loss of power
266							Parameters degradation - condensation	Installation error - unexpected condensation after certain inoperation period	Failure to start	Turbine inoperable
267							Corrosion	Installation error - salt intrusion	Reduced lifetime	reduced performance
268							Parameters degradation - unacceptable vibration	Installation error - loose fitting	Fretting corrosion on interface of contacting materials undergoing slight, cyclic relative motion, leading to reduced lifetime	reduced performance
269							Parameter degradation - thermal ageing	Fabrication error - substandard components	Appearance of weld fatigue in the form of creep, voids, cracks and delamination leads to reduced heat dissipation.	reduced performance
270							Parameter degradation - thermomechanical fatigue	Fabrication error - substandard components	Bond wire lift off, leading to reduced thermal dissipation	reduced performance
271				DC Choper / Crowbar			Short circuit	installation error - insufficient gap between the bar	Occurrence of fire or explosion	Turbine inoperable
272				Filter			Capacitor tank rupture	Off design service - Voltage overload	EMI switching noise not eliminate	Turbine electric power quality impact
273				Controller / Sensors			Controller does not respond	Programming defect, power supply problem, incorrect operation conditions.	Control tasks are not properly performed	Turbine inoperable
274				Heat Management			Parameter degradation - thermal ageing	Fabrication error - substandard components	Overheating of power electronic converte	Turbine inoperable

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
275			Transformer(s) - Dry type transformer	Winding		To increase the alternating voltages in order to have efficient export power transmission	Winding distortion	Fabrication error - Substandard components	distortion, loosening or displacement of the windings leading to decreasing performance of the transformer	reduced performance or possibly turbine inoperable
276							Accelerated tear and wear	Operation error - Lack of maintenance	Thermal losses creates hotspots in the winding, leading to tear and wear and reduced lifetime	reduced performance
277				Insulator			Short circuit	Fabrication error - Substandard components	Dielectric breakdown leading to short circuit	reduced performance or possibly turbine inoperable
278							Bushing failure	Vibration	Dielectric breakdown leading to short circuit	reduced performance or possibly turbine inoperable
279								Off design service - voltage overload		
280								Installation error - water intrusion		
281				Magnetic Core			Parameter deviation - overheating	fabrication error - substandard core laminiation, short circuit or ventilation failure	Eddy current induces core overheating, leading to damage on other components	reduced performance or possibly turbine inoperable
282			HV switchgear			Feed and protect the tidal turbine electrical system	Faulty connection	Installation error - loose connection	Increase resistance at localized point, leading to increased heat, possibly it escalate until complete thermal failure of the connection	Turbine inoperable
283							Insulation breakdown	Installation error - substandard insulation	Dielectric breakdown leading to short circuit	Turbine inoperable
284			UPS systems	Batteries		Provide back-up power in case of grid loss or internal failure to: - Pitch control and power system - Tidal turbine control system - Converter control system - HV switchgear protection relay - Others	Backup power supply failure	Overtemperature, overvoltage, shortcircuit	No power supply in emergency conditions	Inoperable turbine in emergency case

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
285			Dynamic cable			Electrical connection of the power equipment and the grid	Large displacement	Hits or extreme metoceanic conditions	Tugging and breakage risk	Loss of power
286							Breakage	Hits or extreme metoceanic conditions	Very expensive repair	Turbine inoperable
287			Subsea cable joints			Connect the subsea cabling system the interior of the turbine	Blockage	Corrosion, clogging, deformation	Risk of cable detachment	reduced performance or possibly turbine inoperable
288			Lighting Protection			Provide protection for floating tidal turbine type	Lighting rod breakage	Extreme sea conditions	Element damaged	Lack of lightning protection, damage to tidal turbine.
289							High earthing resistance	Electrical connection to cathodic protection in bad conditions	Element damaged	Lack of lightning protection, damage to tidal turbine.
290			Electrical Protection and Safety			To provide safety mechanism, protect and isolate electrical equipment failure	No acting protection	Manufacturing defect	Cables damaged	Risk of damaging other components, risk for people
291								Constant overtemperature working conditions	Cables damaged	Risk of damaging other components, risk for people

APPENDIX E- FMEA WORKSHEET CONCEPT 4 – CROSS FLOW TIDAL TURBINE

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
1	Hydrodynamic System	Nacelle	Nacelle shell			Provision of watertight compartment Transfer PTO and rotor loads to sub-structure	Structural deficiency - Unacceptable corrosion	Improper material selection	Surface leakage leading to water infiltration into the nacelle	Damaged various internal turbine components
2								Failure of corrosion protection		
3							Structural deficiency - Unacceptable crack/rupture	Improper design - inadequate strength calculation	Surface leakage leading to water infiltration into the nacelle	Damaged various internal turbine components
4								Fabrication error		
5								Impact		
6							Structural deficiency - Unacceptable fouling	Improper design - inadequate fouling protection specification	Increase surface roughness	Reduced hydrodinamic profile
7								Fabrication error - inadequate fouling protection application		
8							Structural deficiency - deformation due to impact (no leakage)	Installation error - incident due to careless installation process	Surface leakage leading to water infiltration into the nacelle	Damaged various internal turbine components
9								External cause - Drop object from vessel on the surface		
10			Nacelle joints			Hold nacelle parts together Provide water tightness	Structural deficiency - Unacceptable corrosion	Fabrication error - inadequate pre and post weld heat treatment	Surface leakage leading to water infiltration into the nacelle	Damaged various internal turbine components
11							Structural deficiency - Cracking, and reduced fatigue strength	Improper design leading to weld defect due to: - Improper weld geometry design - unanticipated service conditions - innappropriately specified weld process parameters - incompatibilities of the materials being welded and the processes employed	Nacelle joint failure below the design load	Water infiltration into the nacelle, leading to damage on various internal turbine components
12								Fabrication error leading to weld defect due to: - Improperly executed welds		

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
13			Interface with supporting structure			Transfer loads to yaw mechanism or to support structure (see support structure)	Structural deficiency - Unacceptable corrosion	Improper material selection	reduced interface lifetime	reduced turbine operability lifetime
14							Structural deficiency - Unacceptable crack/rupture	Improper design - inadequate strength calculation	interface deformation	Risk of nacelle fall
15								Fabrication error		
16							Structural deficiency - Unacceptable fouling	Improper design - inadequate fouling protection specification	Mismatch interface	Nacelle retrieval or reinsertion problem
17								Fabrication error - inadequate fouling protection application		
18			Penetrations			Provide water tightness Provide passage to cables and pipes	Structural deficiency - Unacceptable corrosion	Improper material selection	Surface leakage leading to water infiltration into the nacelle	Damaged various internal turbine components
19								Failure of corrosion protection		
20							Structural deficiency - Unacceptable crack/rupture	Improper design - inadequate strength calculation	Surface leakage leading to water infiltration into the nacelle	Damaged various internal turbine components
21								Fabrication error		
22							Accidental deformation/cracking during assembly/installation	Improper manipulation producing cracks in penetrations tubing	Surface leakage leading to water infiltration into the nacelle	Damaged various internal turbine components
23			Lifting points			Provide attachment points for transport and handling	Structural deficiency - Unacceptable corrosion	Improper material selection	Lug rupture during nacelle lifting operation	Nacelle and its internals damage due to the impact of the fall
24								Failure of corrosion protection		
25							Structural deficiency - Unacceptable crack/rupture	Improper design - inadequate strength calculation	Lug rupture during nacelle lifting operation	Nacelle and its internals damage due to the impact of the fall
26								Fabrication error		
27			Seafastening/tug points			Provide attachment points for tugging out of the nacelle (if buoyant nacelle) Provide attachment points to deck of transport ship during transport of nacelle	Structural deficiency - Unacceptable corrosion	Improper design - inadequate strength calculation	Tug point breakage	The tug operations cannot be performed
28							Structural deficiency - Unacceptable crack/rupture	Fabrication error	Tug point breakage	The tug operations cannot be performed

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
29			Sub-assembly frame			Support drivetrain, transferring loads from components of drivetrain to nacelle (brake, gearbox, generator)	Structural deficiency - Unacceptable corrosion	Improper material selection	Reduced mechanical strength	Weaken nacelle structural integrity
30								Failure of corrosion protection		
31							Structural deficiency - Unacceptable crack/rupture	Improper design - inadequate strength calculation	nacelle frame deformation	Weaken nacelle structural integrity
32								Fabrication error		
33			Access into nacelle (Subsea)			Provide access into nacelle	Structural deficiency - Unacceptable corrosion	Improper material selection	Surface leakage leading to water infiltration into the nacelle	Damaged various internal turbine components
34								Failure of corrosion protection		
35							Structural deficiency - Unacceptable crack/rupture	Improper design - inadequate strength calculation	Surface leakage leading to water infiltration into the nacelle	Damaged various internal turbine components
36								Fabrication error		
37							Water ingress	Joint rupture	Hatches detachment	Damaged various internal turbine components
38			Corrosion protection	Material selection		Provide corrosion protection for nacelle	Accelerated corrosion, leakages, structural weakness	Improper material selection	Corrosion, leakage	Reduction on nacelle life
39				Coating				Mismanipulation, impact		
40				Impressed current				Electronic failure		

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
41				Corrosion Allowance				Miscalculation		
42		Rotor	Blades	Blade shell		Capture energy from current Withstand structural loads (normal operating, abnormal, accidental) Withstand fatigue loads Transfer loads to root connection Buoyant blades: rise to surface in case of accidental de-attachment Non-buoyant blades: sink to seabed in case of accidental de-attachment	Structural deficiency - Skin or adhesive debonding	Fabrication error - poor quality uniformity	chipped surface, increased roughness, reduced lifetime	Reduced turbine performance
43							Structural deficiency - Adhesive joint failure of leading or trailing edges	Poor quality uniformity due to a fabrication error, impacts or erosion	chipped surface, increased roughness, reduced lifetime	Reduced turbine performance
44							Structural deficiency - crack in gelcoat	Poor quality uniformity due to a fabrication error, impacts or erosion	chipped surface, increased roughness, reduced lifetime	Reduced turbine performance
45							Structural deficiency - Delamination of laminates	Poor quality uniformity due to a fabrication error, impacts or erosion	Damaged blade	Reduced turbine performance or possibly turbine inoperable
46							Structural deficiency - individual lamina failure (splitting or cracking)	Poor quality uniformity due to a fabrication error, impacts or erosion	Damaged blade	Reduced turbine performance or possibly turbine inoperable
47				Blade structural element			Structural deficiency - Sandwich face/core delamination	Fabrication error - Poor fabrication process and quality control	Damaged blade	Reduced turbine performance or possibly turbine inoperable
48							Structural deficiency - Delamination of laminates	Fabrication error - Poor fabrication process and quality control	Damaged blade	Reduced turbine performance or possibly turbine inoperable
49							Structural deficiency - individual lamina failure (splitting or cracking)	Fabrication error - Poor fabrication process and quality control	Damaged blade	Reduced turbine performance or possibly turbine inoperable
50							Structural deficiency - Web fatigue failure	Fabrication error - Poor fabrication process and quality control	Damaged blade	Reduced turbine performance or possibly turbine inoperable
51				Blade coating			Structural deficiency - peeling / wear	Fabrication error - Poor fabrication process and quality control	chipped surface, increased roughness, reduced lifetime	Reduced turbine performance

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
52							Abnormal output- low speed	Fouling/Marine growth	chipped surface, increased roughness, reduced lifetime	Reduced turbine performance
53				Blade root			Structural deficiency - Erosion of the sealing of the root	Fabrication error - Poor fabrication process and quality control	Damaged or loss of blade	Reduced turbine performance or possibly turbine inoperable
54							Structural deficiency - Fatigue failure in root connection	Fabrication error - Poor fabrication process and quality control	Damaged or loss of blade	Reduced turbine performance or possibly turbine inoperable
55							Structural deficiency - Fatigue failure in root transition area	Fabrication error - Poor fabrication process and quality control	Damaged or loss of blade	Reduced turbine performance or possibly turbine inoperable
56				Blade hydrodynamic features			Structural deficiency - Adhesive joint failure	Fabrication error - Poor fabrication process and quality control	chipped surface, increased roughness, reduced lifetime	Reduced turbine performance
57							Structural deficiency - Skin or adhesive debonding	Fabrication error - Poor fabrication process and quality control	chipped surface, increased roughness, reduced lifetime	Reduced turbine performance
58			Corrosion protection	Material selection		Provide corrosion protection for metallic part of the rotor	Accelerated corrosion, leakages, structural weakness	Improper material selection	Corrosion, leakage	Reduction on rotor life
59				Coating				Mismanipulation, impact		
60				Impressed current				Electronic failure		
61				Corrosion Allowance				Miscalculation		
62			Ring			Improve blades strenght / stability	Structural deficiency- Ring breakage	Vibrations, cracks, fatigue, excesive corrosion or impacts	Lack of blades stability. Vibrations	Partial loss of power. Risk of blades breakage
63		**Tunnel**	Tunnel			Improve turbine performance by venturing effect	Structural deficiency- Partial Tunnel detachment	Vibrations, cracks, fatigue, excesive corrosion or impacts	Reduced hydrodynamic performance	Partial loss of power. It may damage the blades
64							Structural deficiency- Total funnel detachment	Vibrations, cracks, fatigue, excesive corrosion or impacts	Reduced hydrodynamic performance	Partial or total loss of power. It may damage the blades
65	**Reaction System**	**Foundation system**	Suction anchor			Transfer loads from sub-structure to seabed, while complying with requirements for ultimate, fatigue and	Slack anchor	Expected loading - cyclic loading due to wave, current and soil condition	Loss of water tighteness due to suction anchor structure deficiency or suction valve failure	Tidal turbine free movement lead to potential damage to other component of tidal turbine and reduced performance

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
66						accidental limit states as well as serviceability aspects such as displacements and natural period	Structural deficiency - Cracking	Installation error - incident due to careless installation process	Foundation cracking	Tidal turbine anchor lost lead to Tidal turbine total lost
67		**Support structure**	Main Structure (including auxiliary equipment)-Fixed			Raise turbine height over seabed Resist hydrodynamic loads on the structure Resist fatigue loads Transfer loads to foundation fixings Provide support to umbilical	Structural deficiency - Corrosion	Improper material selection	Cracking on structural parts	Weaken structural integrity
68								Failure of corrosion protection		
69							Structural deficiency - Cracking, and reduced fatigue strength	Improper design leading to weld defect due to: - Improper weld geometry design - unanticipated service conditions - innappropriately specified weld process parameters - incompatibilities of the materials being welded and the processes employed	Structural part failure	Unability to withstand operation load leading to risk of nacelle falling
70								Improper design due to inadequate configuration, calculation, and innacurate loading cases		
71								Improper material selection leading to inadequate strength properties		
72								Fabrication error leading to weld defect due to: - Improperly executed welds		
73							Structural deficiency - Reduced strength due to impact	Installation error - incident due to careless installation process	Structural part failure	Unability to withstand operation load leading to risk of nacelle falling
74								External cause - Drop object from vessel on the surface		
75							Structural deficiency - unacceptable vibration	Installation error leading to unstable support position	Unacceptable operating condition for nacelle's internal components	Reduced turbine operability
76							In-service problems - unacceptable biofouling	Improper design - inadequate fouling protection specification	Reduced support structure lifetime	reduced turbine operability lifetime

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
77								Fabrication error - inadequate fouling protection application		
78			Installation interface (Bolt eye)			Provide installation/Lifting interface	Structural deficiency-Breakage	off-design service - excessive external load, improper material selection/sizing, corrosion	Unatachement of the lifting sling	It may compromise the integrity of the device
79			Interface with turbine support			Provide safe attachment to turbine Resist hydrodynamic loads on the structure Resist fatigue loads Provide support to umbilical Transfer loads to main structure	Structural deficiency - Unacceptable corrosion	Improper material selection	Reduced interface lifetime	Reduced turbine operability lifetime
80								Failure of corrosion protection		
81							Structural deficiency - Unacceptable crack/rupture	Improper design - inadequate strength calculation	Interface deformation	Risk of nacelle fall
82								Fabrication error		
83							Structural deficiency - Unacceptable fouling	Improper design - inadequate fouling protection specification	Mismatch interface	Nacelle retrieval or reinsertion problem
84								Fabrication error - inadequate fouling protection application		
85			Corrosion protection	Material selection		To provide corrosion protection for the metallic structural part	Accelerated corrosion, leakages, structural weakness	Improper material selection	Corrosion, leakage	Reduction on support structure life
86				Coating				Mismanipulation, impact		
87				Impressed current				Electronic failure		
88				Corrosion Allowance				Miscalculation		

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
89	Power take off	Auxiliaries	Ballast (solid ballast)			Allow trimming adjustment of nacelle during deployment Allow buoyancy adjustment of nacelle	Loss of ballast material	External break	Loss of stability	Risk of device loss
90	Power take off	Auxiliaries	Cooling system	Heatexchanger		Providing cooling mechanism for the electrical components	Insufficient heat transfer	Improper design - inadequate heat exchange characteristics	Low heat transfer	Reduced turbine performance
91	Power take off	Auxiliaries	Cooling system	Heatexchanger		Providing cooling mechanism for the electrical components	External leakage	Fabrication error - Improper welding	loos of coolant	Reduced turbine performance or possibly turbine inoperable
92	Power take off	Auxiliaries	Cooling system	Heatexchanger		Providing cooling mechanism for the electrical components	Internal leakage	Improper assembly during fabrication, aging or erosion	Low heat transfer	Reduced turbine performance
93	Power take off	Auxiliaries	Cooling system	Heatexchanger		Providing cooling mechanism for the electrical components	Plugged / choked	Installation error - presence of contaminants	Coolant circulation problem, Low heat transfer	Reduced turbine performance
94	Power take off	Auxiliaries	Cooling system	Heatexchanger		Providing cooling mechanism for the electrical components	Structural Deficiency - Unacceptable corrosion	Improper design - inadequate material	Reduced lifetime	Reduced turbine performance

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
95				Cooling Pump		Providing circulation mechanism for the heat exchanger coolant	External leakage	Installation error - improper fitting	Coolant circulation problem, leading to loss of coolant	Reduced turbine performance or possibly turbine inoperable
96							Structural Deficiency - Unacceptable corrosion	Improper design - inadequate material	Reduced lifetime	Reduced turbine performance
97							Unacceptable vibration & noise	Installation error - inbalance impeller	Reduced lifetime	Reduced turbine performance
98							Structural deficiency - impeller breakdown	Fabrication error - substandard impeller fabrication	Pump inoperable	Turbine inoperable
99							structural deficiency - accelerated components wear	Fabrication error - compoeents fabrication defect	Reduced lifetime	Reduced turbine performance
100				Coolant		Serving as the cooling working fluid for the electrical system heat management	Parameter deviation - Monitored variables (temperature) exceeding tolerance	Improper design - inapropriate coolant selection	Low heat transfer	Reduced turbine performance

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
101							Contamination	Installation error - presence of contaminants	Coolant circulation problem, Low heat transfer	Reduced turbine performance
102				Cooling system connections		Providing circulation mechanism for the heat exchanger coolant	External leakage	Fabrication error - Improper welding or fitting	loos of coolant	Reduced turbine performance or possibly turbine inoperable
103							Plugged / choked	Installation error - presence of contaminants	Coolant circulation problem, Low heat transfer	Reduced turbine performance
104							Structural Deficiency - Unacceptable corrosion	Improper design - inadequate material	Reduced lifetime	Reduced turbine performance
105			Air treatment	Dehumydier		Prevent nacelle interior from condensation and salty environment	Humidity excess in the atmosphere	Sensor failure	Electrical components may be damaged	Reduced turbine performance or possibly turbine inoperable
106								Motor breakage	Electrical components may be damaged	Reduced turbine performance or possibly turbine inoperable
107		**Drivetrain**	Low speed shaft			Transfer torque from hub to drive train gearbox Transfer torque to generator (if relevant) Resist ultimate loads Resist fatigue loads	structural deficiency - mechanical failure (facture, yield, and cracking)	Improper material - inadequate material selection	Shaft failure	Turbine inoperable
108								Improper design - inadequate design strength		
109								Off design service - unexpected loading conditions		

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
110								Fabrication error		
111							structural deficiency - unacceptable corrosion	Improper material selection	Reduced shaft lifetime	Reduced turbine performance or possibly turbine inoperable
112								Failure of corrosion protection		
113							structural deficiency - fatigue failure	Improper material - inadequate material selection	Shaft failure	Turbine inoperable
114								Improper design - inadequate design strength		
115								Off design service - unexpected loading conditions		
116							structural deficiency - accelerated wear	Off design service - unexpected loading conditions	Reduced lifetime	Reduced turbine performance
117							vibration	Installation error - imbalance installation	Reduced lifetime	Reduced turbine performance
118			Low speed shaft bearings			Transfer thrust and bending moments to nacelle	Structural deficiency - premature fatigue	Improper design - inadequate bearing selection	Heavy ball wear paths, widespread spalling leading to bearing failure	Reduced turbine performance or possibly turbine inoperable
119							Structural deficiency - false brinelling	off-design service - excessive external load	Elliptical wear marks in axial direction at each ball position, leading to accelerated wear process and lower bearing lifetime	Reduced turbine performance
120							Structural deficiency - true brinelling	Installation error -improper handling leading to severe impact and static overload	Indentation in the raceways, leading to bearing vibration and lower bearing lifetime	Reduced turbine performance

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
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121							Structural deficiency - Denting of the bearing raceways and ball	installation error -improper handling leading to intrusion of contaminants (dirt, dust, etc)	Accelerated wear and high vibration	Reduced turbine performance or possibly turbine inoperable
122							corrosion	installation error - exposure to corrosive environment	Rust and abrasive runway or balls surface, leading to accelerated wear process and lower bearing lifetime	Reduced turbine performance or possibly turbine inoperable
123								operation error - exposure to corrosive environment		
124							misalignment	Installation error - bent shafts, intrusion of dirt on shaft or housing support	Non parallel ball path on bearing outer raceway, leading to excessive vibration and lower bearing lifetime	Reduced turbine performance
125							Structural deficiency - Discolored ball tracks and ball, early wear	Lubricant failure	Accelerated wear leading to Spalling, facture of running surface and subsequent removal of small material	Reduced turbine performance
126								Installation error - loose or over fits		
127							accelerated wear and fatigue	Off design service - unexpected loading conditions	Spalling, facture of running surface and subsequent removal of small material	Reduced turbine performance

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
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128			Low speed shaft dynamic seals			Provide water tightness	Dry running	Lubrication failure	seal faces surface damage, Seal failure	Leakage leading to water intrusion damaging various internal turbine components
129							Poor lubrication	Lubrication failure	Small, cracks on the seal faces, presence of noises and vibration, reduced seal lifetime	Leakage leading to water intrusion damaging various internal turbine components
130							Particle deposits	installation error -improper handling leading to intrusion of contaminants (dirt, dust, etc)	Clogging, and sticking of the O rings, opening of the sealing gap, leading to reduced lifetime of the seal	Reduced turbine performance
131								Operation error - intrusion of sands		

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
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132							Structural deficiency - corrosion	installation error - exposure to corrosive environment	accelerated wear process and lower seal lifetime	Reduced turbine performance
133								operation error - exposure to corrosive environment		
134							Structural deficiency - abnormal wear	Installation error - misalignment	Abnormal wear on O rings, uneven depth of the wear track around seal seating, wear on the seal sleeves, leading to reduced seal lifetime	Reduced turbine performance
135			Braking system	Low speed brake (electrical)		Brake the drivetrain from low speed shaft	Inadequate shaft braking	Wear of primary/secondary shoes, magnet failure due to electric failure	The turbine does not stop in safe conditions	Survival operation: Loss of power. It may compromise the security of the device
136							Permanent braking	Electrical or control failure	The turbine does not stop in safe conditions	Total loss of power. It may compromise the security of the device
137				Electrical power unit		Provide electrical power to braking mechanism	Fail to function on demand	Power supply problem	The turbine does not stop in safe conditions	Total loss of power. It may compromise the security of the device

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
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138		**Control & Communication system**	Control system	Data acquisition and processing		Detect events or changes from their measured environment and send feedback to the controller	Parameter deviation - nonlinearity / sensor bias	Fabrication error - substandard sensor components	Sensor sensitivity is not constant over the measured range.	Inaccurate turbine operation leading to low performance
139								Installation error - presence of contaminants or moisture inside the sensors components		
140							Parameter deviation - drift error	Fabrication error - substandard sensor components	Output signal slowly changes independent of the measured property	Inaccurate turbine operation leading to low performance
141								Installation error - presence of contaminants or moisture inside the sensors components		
142							Parameter deviation - noise error	Fabrication error - substandard sensor components	Random deviation of the reading	Inaccurate turbine operation leading to low performance
143								Installation error - presence of contaminants or moisture inside the sensors components		
144							Parameter deviation - environmental error	Fabrication error - substandard sensor components	Sensor is more sensitive to properties other than the property being measured	Inaccurate turbine operation leading to low performance
145								Installation error - presence of contaminants or moisture inside the sensors components		
146							Structural deficiency - components failure	Fabrication error - substandard sensor components	Loss of ability to measure	Loss of control feedback, leading to low performance or turbine inoperable

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
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147				LAN	Network cable	Network Cable	Complete data transfer failure	Open circuit (wire breakage or connector disconnected) due to vibration	Loss of communication	Loss of control, leading to turbine inoperable
148								Short circuit due to pinched cable		
149							Loss of part of data package	Installation error - Jitter due to vibration on loose contact	Interrupted control & communication	Inaccurate or delayed turbine operation leading to low performance
150					Network interface card		Complete data transfer failure	Fabrication error - PCB failure	Loss of ability to measure	Loss of control feedback, leading to low performance or turbine inoperable
151							Signal interference	fabrication error - Component with low noise resistance threshold	Interrupted control & communication	Inaccurate or delayed turbine operation leading to low performance
152				Controllers	Software	Provide logic and control system algorithm for the turbine	Unauthorized access	Hacking	Loss of ability to control	Loss of control feedback, leading to turbine inoperable
153							Buffer overflow	Design error - resource starvation due to improper software engineering	Reduced performance of the controller	Inaccurate or delayed turbine operation leading to low performance
154							Race condition	Design error - improper software engineering	Unexpected response/behaviour	Inaccurate or delayed turbine operation leading to low performance
155					Hardware		CPU Failure - High leakage current, output stuck, short circuit	fabrication error - Component with substandard quality	Unexpected response/behaviour	Loss of control feedback, leading to low performance or turbine inoperable

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
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156							Memory Failure - Data bit loss, short circuit, slow transfer of data	fabrication error - Component with substandard quality	Unexpected response/behaviour	Loss of control feedback, leading to low performance or turbine inoperable
157				Fiber Optic		Transmit data from and to the turbine and shore based command center	Facet damage	Fabrication error - Pulse width / optical power density	Reduced performance of data transmission	Loss of control feedback, leading to low performance or turbine inoperable
158							Laser wear out	Fabrication error Photo oxidation, contact degradation, crystal grow-in defects	Reduced performance of data transmission	Loss of control feedback, leading to low performance or turbine inoperable
159							Laser instability due to reflections	Fabrication error - Power from laser reflect back	Reduced performance of data transmission	Loss of control feedback, leading to low performance or turbine inoperable
160							Whisker formation	Normal wear - deterioration of solder	Reduced performance of data transmission	Loss of control feedback, leading to low performance or turbine inoperable
161							Dark line defects	Fabrication error - substandard quality control , non-radiative center	Reduced performance of data transmission	Loss of control feedback, leading to low performance or turbine inoperable
162							Structural deficiency - cable & jacket fracture	Normal wear - fatigue due to microcracks	Loss of data transmission	Loss of control feedback, leading to low performance or turbine inoperable
163				System / component protection sensors		To provide safety mechanism, protect and isolate components failure	Electrical failure	Breakage of electronic components	It can affect the power electronic	Loss of control feedback, leading to low performance or turbine inoperable

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
164			Condition monitoring	Condition monitoring sensors		Monitor defined parameters and send information to condition monitoring system	Parameter deviation - nonlinearity / sensor bias	Fabrication error - substandard sensor components	Sensor sensitivity is not constant over the measured range.	Inaccurate turbine operation leading to low performance
165								Installation error - presence of contaminants or moisture inside the sensors components		
166							Parameter deviation - drift error	Fabrication error - substandard sensor components	Output signal slowly changes independent of the measured property	Inaccurate turbine operation leading to low performance
167								Installation error - presence of contaminants or moisture inside the sensors components		
168							Parameter deviation - noise error	Fabrication error - substandard sensor components	Random deviation of the sensor reading	Inaccurate turbine operation leading to low performance
169								Installation error - presence of contaminants or moisture inside the sensors components		
170							Parameter deviation - environmental error	Fabrication error - substandard sensor components	Sensor is more sensitive to properties other than the property being measured	Inaccurate turbine operation leading to low performance
171								Installation error - presence of contaminants or moisture inside the sensors components		

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
172							Structural deficiency - components failure	Fabrication error - substandard sensor components	Total loss of sensor ability to measure	Loss of control feedback, leading to low performance or turbine inoperable
173				Data acquisition hardware			Failure to transmit or receive data	Fabrication error - substandard electronic component or software	Unable to receive condition monitoring data	Unable to monitoring equipment condition
174			Systems cabinets	Power control cabinet		Provide enclosure for the control system switches and connectors	Malfuctioning of one or more control components	Overheating, humidity, electrical failure, overload, isolation failure	Subsystems control loss	Turbine inoperative or power derrating
175			Systems cabinets	Auxiliary cabinet		Provide enclosure for the auxilliary control system switches and connectors	Malfuctioning of one or more control components	Overheating, humidity, electrical failure, overload, isolation failure	Auxiliaries subsystems control loss	Partial or total loss of power
176			Systems cabinets	Environmental monitoring cabinet		Provide enclosure for the environment monitoring switches and connectors	Environmental data is not sent correctly	Overheating, humidity, electrical failure, overload, isolation failure	Environmental data is not sent correctly lead to device operate in safe mode	Potential escalation in case other failure. Non-compliance with the legal obligations
177			Systems cabinets	Bus communication interfaces		Provide enclosure for communication PLC control system components	Not all data is sent correctly	Overheating, humidity, electrical failure, overload, isolation failure	Cabinets communication unavailable and loss of tidal turbine information from shore	Non-planned corrective maintenance operation
178		**Electrical system**	Generator	Winding		Transform mechanical power into electrical power	Loss of isolation	Overtemperature, manufacturing defect	Current leakages or short circuits leading to less stator performance and reliability. Harmonic generation.	Generator loss of function, Turbine inoperative
179		**Electrical system**	Generator	Bearings / Bearing housing		Transform mechanical power into electrical power	Vibration, noise or squeakings	Missaligment	Damaged shaft	Reduced turbine performance or possibly turbine inoperable
180		**Electrical system**	Generator	Bearings / Bearing housing		Transform mechanical power into electrical power	Vibration, noise or squeakings	False Brinelling	Damaged shaft	Reduced turbine performance or possibly turbine inoperable
181		**Electrical system**	Generator	Bearings / Bearing housing		Transform mechanical power into electrical power	Vibration, noise or squeakings	Poor lubrication	Damaged shaft	Reduced turbine performance or possibly turbine inoperable
182		**Electrical system**	Generator	Silent Blocks		Transform mechanical power into electrical power	Vibrations greater than expected	Excesive wear, improper design	It may cause instabilities on the turbine	Risk of damaging other components
183		**Electrical system**	Generator	Magnet		Transform mechanical power into electrical power	Magnet damaged	Manufacturing defect	Loss of the generator	Turbine inoperable
184		**Electrical system**	Generator	Magnet		Transform mechanical power into electrical power	Magnet damaged	Overspeed	Loss of the generator	Turbine inoperable

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
									Local Effect	System Effect
185							Magnetic wedge loss	Overtemperature, vibration, manufacturing defect	Less rotor performance and reliability.	Partial loss of electrical production
186				Frame			Structural deficiency - cracks or large deformations	Fatigue, corrosion or Improper design	It may cause instabilities on the turbine	Risk of damaging other components
187				Insulator			Operation deficiency: Overcurrent	Cracks due to overheating	Leakage or short circuit in the wiring	Turbine stop
188			Power electronic converter	DC Bus / Capacitor		To regulate voltage, current, and frequency of the electricity output of the turbine	The device cannot be controled properly	Capacitor breakage	Lack of command on the device	Partial or total loss of power
189							Unstable operation	Capacitor breakage	Lack of command on the device	Partial or total loss of power
190				IGBT			Electrical overstress (EOS)	Fabrication error - substandard components	Occurrence of fire or explosion	Turbine inoperable

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
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191								Off design service - Voltage overload		
192							Electrostatic discharge	Fabrication error - substandard components	Occurrence of fire or explosion	Turbine inoperable
193								Off design service - Voltage overload		
194							Parameters degradation - condensation	Installation error - unexpected condensation after certain inoperation period	Failure to start	Turbine inoperable
195							Corrosion	Installation error - salt intrusion	Reduced lifetime	reduced performance
196							Parameters degradation - unacceptable vibration	Installation error - loose fitting	Frretting corrosion on interface of contacting materials undergoing slight, cyclic relative motion,leading to reduced lifetime	reduced performance

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
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197							Parameter degradation - thermal ageing	Fabrication error - substandard components	Appearance of weld fatigue in the form of creep, voids, cracks and delamination leads to reduced heat dissipation.	reduced performance
198							Parameter degradation - thermomechanical fatigue	Fabrication error - substandard components	Bond wire lift off, leading to reduced thermal dissipation	reduced performance
199				DC Choper / Crowbar			Short circuit	installation error - insufficient gap between the bar	Occurrence of fire or explosion	Turbine inoperable
200				Filter			Capacitor tank rupture	Off design service - Voltage overload	EMI switching noise not eliminate	Turbine electric power quality impact
201				Controller / Sensors			Controller does not respond	Programming defect, power supply problem, incorrect opeation conditions.	Control tasks are not properly performed	Turbine inoperable

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
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202				Heat Management			Parameter degradation - thermal ageing	Fabrication error - substandard components	Overheating of power electronic converter	Turbine inoperable
203			Transformer(s) - Liquid insulated transformer	Winding		To increase the alternating voltages in order to have efficient export power transmission	Winding distortion	Fabrication error - Substandard components	distortion, loosening or displacement of the windings leading to decreasing performance of the transformer	reduced performance or possibly turbine inoperable
204							Accelerated tear and wear	Operation error - Lack of maintenance	Thermal losses creates hotspots in the winding, leading to tear and wear and reduced lifetime	reduced performance
205				Insulator			Short circuit	Fabrication error - Substandard components	Dielectric breakdown leading to short circuit	reduced performance or possibly turbine inoperable
206							Bushing failure	Vibration	Dielectric breakdown leading to short circuit	reduced performance or possibly turbine inoperable
207								Off design service - voltage overload		
208								Installation error - water intrusion		
209				Magnetic Core			Parameter deviation - overheating	fabrication error - substandard core laminiation, short circuit or ventilation failure	Eddy current induces core overheating, leading to damage on other components	reduced performance or possibly turbine inoperable

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
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210				Refrigerant			Loss of coolant	Leakage, improper maintenance	Overtemperature	total or partial loss of power
211			UPS systems	Batteries		Provide back-up power in case of grid loss or internal failure to: - Pitch control and power system - Tidal turbine control system - Converter control system - HV switchgear protection relay - Others	Backup power supply failure	Overtemperature, overvoltage, shortcircuit	No power supply in emergency conditions	Inoperable turbine in emergency case
212			Subsea cabling system			To export generated electrical power to the grid	Torsional failure	installation error - vessel maneuver induce over torsional load on the umbilical	bird-caging or necking of armor wire and or helical component.	delayed turbine operation
213							Breakage	installation error, hits, cuts	Total or partial loss of the electical safety components	Total loss of power

Failure ID	Sub-system	Assembly	Sub-Assembly	Components	Sub-Components	Function	Failure Mode	Root Cause	Failure Effect	
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214			Subsea cable joints- External			To provide secure connection and removal of subsea cable from the tidal turbine	Wrong connection	Improper installation	Total or partial loss of the electrical safety components	Total loss of power
215			Electrical Protection and Safety			To provide safety mechanism, protect and isolate electrical equipment failure	No acting protection	Manufacturing defect	Cables damaged	Risk of damaging other components, risk for people
216								Constant overtemperature working conditions	Cables damaged	Risk of damaging other components, risk for people