

TiPTORS Design for Reliability Tool

Phase 1 Specification

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1 Introduction

The diverse range of technology concepts in tidal energy converters characterises this early stage of the tidal sector. However, in the last few years some technologies have been progressing faster towards the very first multiple deployments and commercialisation. The Horizontal Axis Tidal Turbine (HATT) is one of the more dominant configurations being developed. However, even within this “narrow” classification, the technology developers have chosen different design solutions and strategies. The differences are largely influenced by the different approaches taken to minimise the Levelised Cost of Energy (LCoE). Maintenance costs are a significant cost driver over the lifetime of an installed unit and therefore reliability is going to be a key factor.

This report proposes a methodology to be followed for the development of a simulation tool for the purpose of analysing the reliability of power train components. Reliability is a complex problem and has multiple influencing factors and interrelationships and therefore the proposed approach is broken down into discrete processes. These are outlined in Section 3.2 and shown diagrammatically in Figure 1.

The simulation tool will enable an improvement of reliability throughout the design process by simulating the reliability of tidal turbine powertrain systems and components. An example case is presented within this report, providing guidance on the how this may be achieved and demonstrating the feasibility of the approach.

DNV GL is capturing the knowledge and guidance accumulated during the process and plan to publish a freely available Recommended Practice to feed this back into the industry and align with certification. The proposed table of contents for the Recommended Practice is appended to this document in Appendix V.

2 Abbreviations

CAPEX	Capital Expenditure
FMECA	Failure Modes, Effects and Criticality Analysis
FT	Fault Tree
HATT	Horizontal Axis Tidal Turbine
HSS	High Speed Shaft
LCoE	Levelised Cost of Energy
MTBF	Mean Time Between Failures
NREL	National Renewable Energy Laboratory
OPEX	Operational Expenditure
OREDA	Offshore Reliability Data
PDAE	Partial Differential Algebraic Equation
P&ID	Piping and Instrumentation Diagram
PTO	Power take off
RBD	Reliability Block Diagram
RMS	Root Mean Square
RP	Recommended Practise
TiPTORS	Tidal Power Take Off Reliability Simulation
TQ	Technology Qualification

3 Outline of Methodology

3.1 Introduction

The status for reliability assessment of tidal turbines is as discussed in the General Industry Practice and Design Parameters, reference [1]. The conclusion reached is that reliability data is available but this is not specific to the tidal turbine industry. The simulation tool to be developed is to allow a higher level of accuracy in predicting reliability than is currently possible using only surrogate data from other industries. A set of requirements and an approach are proposed. These will form a framework for developing a simulation tool to improve reliability during the powertrain design cycle. An example case study is presented in section 11.

3.2 Process

Seven key steps to developing a tool that would be able to provide critical information on the reliability impact of design decisions have been identified. These are:

- Agree an industry applied taxonomy defining systems, sub-systems assemblies and components for a generic tidal turbine. It is recommended that an adoption and adaptation of the wind taxonomy is used. This is becoming standardised for wind and many systems and components are common between wind and tidal.
- Collect annual rate of failure data from a surrogate industry (i.e. the Reliawind project, Offshore Reliability Data (OREDA) data).
- Undertaking a Failure Modes, Effects and Criticality Analysis (FMECA) based on generic powertrain configurations which focus on reliability issues (to determine critical areas to focus on in the absence of tidal turbine specific reliability data).
- Identifying Key Indicators that impact reliability. These shall be identified from the FMECA for a generic tidal turbine and the simulation tool will have the capacity to model the changes to key indicators as part of the design improvement process.
- Incorporation of knowledge on physics of failure for critical components. The main source of data for this is the work by US Military. See references [4] and [5].
- Develop systems engineering model that is able to feedback changes to key indicators
- Link changes to the design that impact reliability to the drivetrain specific cost model

An overview of the development of the model is shown in Figure 1.

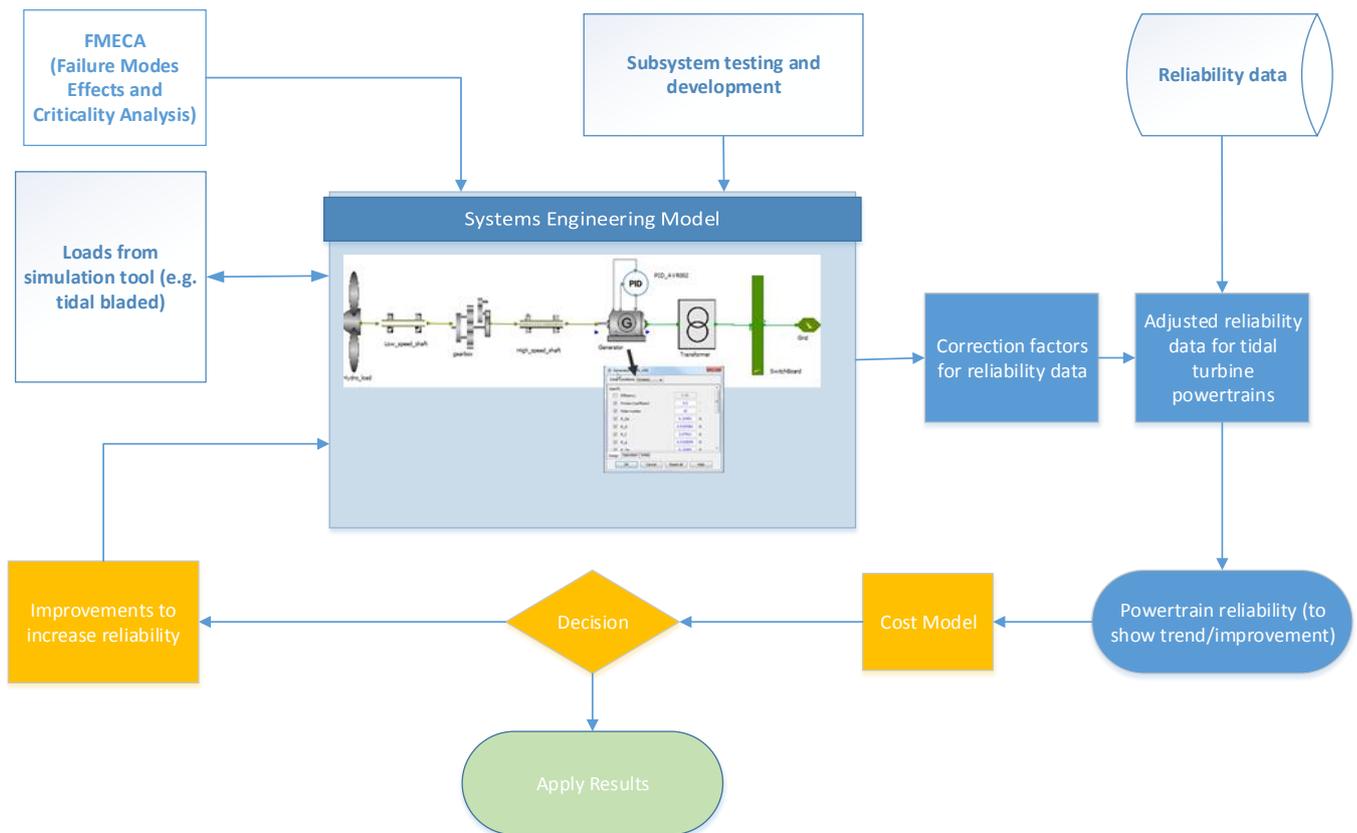


Figure 1: Processes for the development of a Reliability Tool

3.3 Input from Phase 1

3.3.1 Taxonomy

There is already a basic taxonomy for a tidal turbine that has been developed and this is discussed in section 4 which builds on the approach set out in reference [2]. However in order to carry out a thorough FMECA and as the project develops ensure consistency in reporting across different design configurations this will be developed in more detail. For example when we need to analyse a ‘generator failure’ this could be windings, shaft, bearings, terminals, casing etc. and the taxonomy must be fit for purpose to enable this to be identified. The benefits of this for the project will continue through to the testing to be carried out in Phase 2 where failures need to be reported from multiple sources. We will take input from the work done on reliability reporting in wind but it is expected to be significant tidal specific inputs to the taxonomy report.

An alternative to developing a new tidal turbine taxonomy would be to apply the VGB taxonomy for wind as described in ‘RDS-PP – Application Guideline; Part 32: Wind Power Plants’

3.3.2 Databases

The availability of data is discussed in detail in report [1]. The availability of the data is a concern as it will have commercial value to the owner. Data from wind especially will enable the project to deliver usable benchmarked results significantly sooner to the industry. Access to a

detailed wind turbine reliability database is considered critical for the baseline data to be used in the simulation tool. This should provide annual failure rates for common powertrain components.

3.3.3 FMECA for Reliability

The focus of this project is on reliability impacts and therefore the process for undertaking a FMECA shall be targeted towards specific failure modes. Starting from the generic taxonomy developed as a baseline a FMECA shall be carried out at a level appropriate to the aims of this project and the level of detail made available by turbine developers. The FMECA process is outlined in more detail in section 6 and FMECA Guide Tool report [3]. The FMECA is an important step in deriving the 'key indicators' which will direct the focus of the research work packages in the Tidal Power Take Off Reliability Simulation (TiPTORS) program.

3.3.4 Key Indicators Influencing Reliability

Following the process detailed in the FMECA guide tool [3] will determine a set of 'key indicators' as described in section 7. These have been derived through the FMECA process as the influencing factors on failure mechanisms. A variation in a key indicator would therefore impact the reliability of a component.

3.3.5 Research Physics of Failure

Development of the physics of failure correlations to key indicators is described in section 0. A significant amount of work has historically been undertaken on physics of failure to enable an estimation of the effect of changes to key indicators. A core reference for this is the work carried out in the US by the military see references [4] and [5]. This can form a basis for the initial development of the simulation tool but further research will be needed as part of the TiPTORS programme to confirm the accuracy and improve the predictive ability. This will link the key indicators derived in the FMECA to the parameters derived from the system modelling approach allowing the design improvements for reliability to be assessed quantitatively.

3.3.6 Building a Systems Engineering Model

Without vast amounts of data from installed turbines with different configurations to assess how design modifications impact reliability a simulation model can be used to generate data. The comparative costs and ease of experimentation make the benefits obvious; however the accuracy of the output needs to be established. This will be a key requirement for the simulation tool.

3.3.7 Closing the Loop with the Cost Model

Design changes will inevitably have an impact on cost and there will often be a trade-off between higher CAPEX and/or OPEX costs and reliability. The final decision on making the change to improve reliability should be informed by a life cycle cost for the turbine and so integrating a cost model into the process is the final step of the development. Cost data are

commercially sensitive so an approach to how a cost model could be built is discussed in section 10.

4 Taxonomy

4.1 Introduction

Horizontal axial tidal turbines are integrated systems where mechanical, electrical, control subsystems and components are coupled together. The taxonomic breakdown of the turbine's power take-off (PTO) system into subsystems and components forms the basis for the reliability simulation tool. Particularly:

- The powertrain FMECA can be developed following a component by component basis as dictated by the taxonomic breakdown.
- The powertrain systems engineering (simulation) model will have, in most cases, a one-to-one correspondence with the turbine subsystems and components, as the latter are defined by the taxonomic breakdown.

4.2 Taxonomic Breakdown

By following a top-down approach (starting from the powertrain system, dividing this to the "first level" of components and so on) the level of detail in the taxonomy, i.e. which will be the smallest non-dividable units of the system, depends on:

The level of the FMECA analysis it is going to support

For example at phase 1 of the TiPTORS project (as well as at the initial phase of a Technology Qualification (TQ) (see reference [6]) or a design process) a high level FMECA with component failure modes grouped together; in such a case the ontologies of the taxonomy should take this into account.

The amount of system design information available

The basic information required for defining the ontologies in the taxonomy would be contained in the Piping and Instrumentation Diagrams (P&ID's), system drawings and functional descriptions of the system, its components and subsystems. The availability of such system specification data is related to the phase of the project where the FMECA is applied. E.g. in early phases of a technology qualification process, depicted in Figure 2, not much information may be available in order to dig down to much detail. Consequently, this affects the detail of the taxonomic breakdown.

The required first principles and controls for capturing correctly the system behaviour in the systems engineering model

According to the phase of the project, this may or may not include failure modes. Although it might be argued that the breakdown of a system to many levels of subsequent subcomponents may lead to a simulation model with increased simulation capabilities; there is always the

caveat of developing too complex models requiring information that is not easily obtainable. To that context, care must be taken so that the taxonomic breakdown will contain only the absolutely necessary detail.

The availability of reliability data for the system

In order to utilise reliability data available in databases, the database taxonomy should be taken into account; the system breakdown should be compatible to the database taxonomy.

4.3 Taxonomy Development

Through phases 1 and 2 of the project an iterative process for the taxonomic breakdown is to be followed. During phase 1 a generic taxonomy has been identified. This approach enables the analysts to initially identify the key areas of interest and then scrutinise the critical components and operations for reliability by enhancing the taxonomy in these areas and performing separate FMECAs for these components and subsystems during development phase 2. During phase 2, the systems engineering model will be correspondingly enhanced so as to incorporate the most recent taxonomy and results from the FMECA

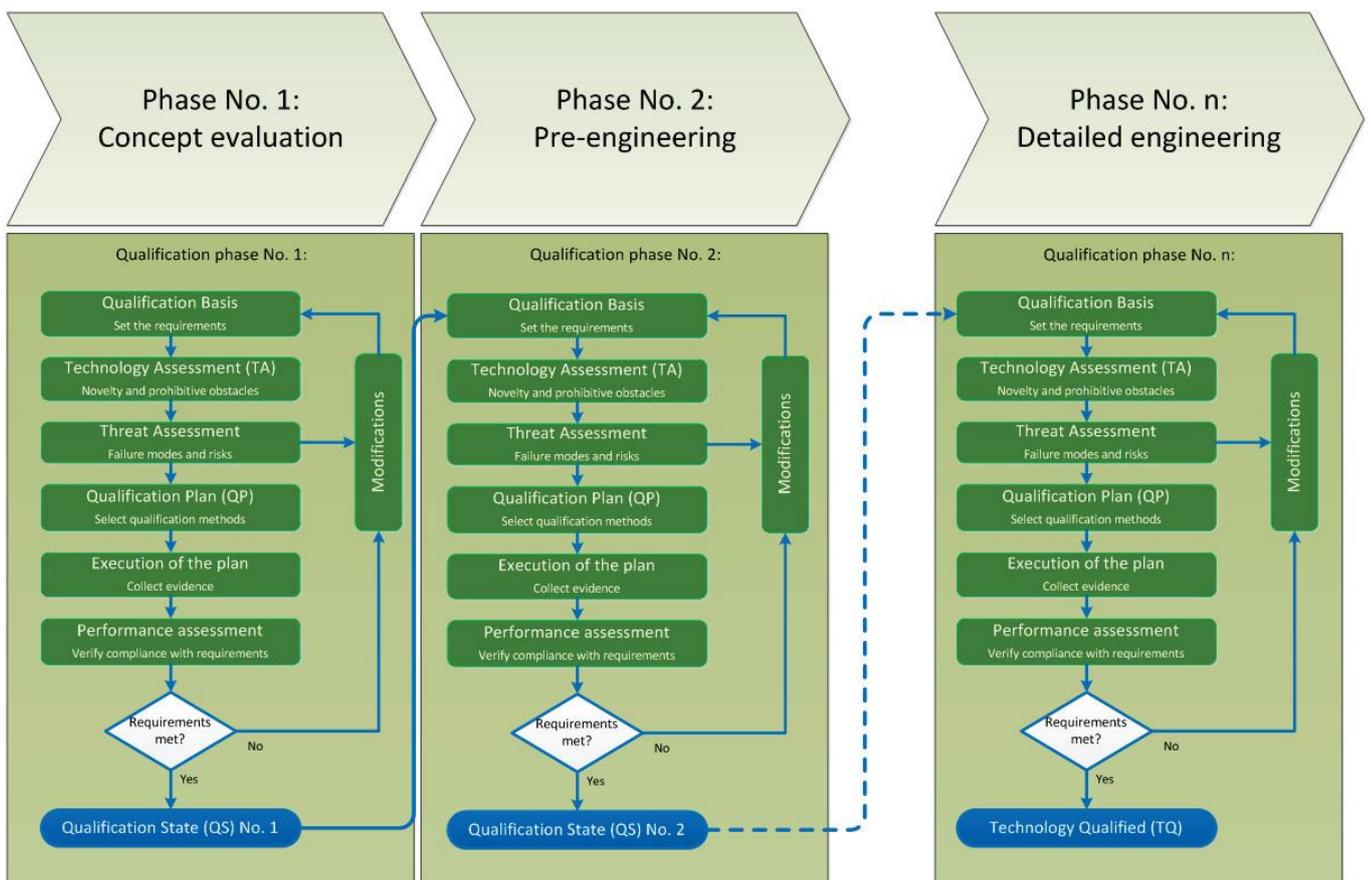


Figure 2: Diagram depicting a TQ program process. The Threat Assessment stages (during the various phases of the overall process) include FMECAs in order to identify failure modes and risks.

The PTO system, depicted in Figure 3 in blue, is subdivided into the following subsystems:

No	Subsystem
6.	Pitch System
7.	Yaw System
8.	Powertrain
9.	Seals
10.	Bearings
11.	Auxiliary subsystems
12.	Electrical system
13.	Control system

Table 1: Subsystem breakdown of tidal turbine PTO

The subsequent breakdown of the above subsystems that is used in phase 1 can be found in Appendix I (updated from the deliverable report **RD.15/78801.1**). By following the previously presented PTO taxonomic breakdown a high level FMECA was prepared for phase 1. The methodology followed in order to derive a complete FMECA during phase 2 is presented in the FMECA Guide Tool [3].

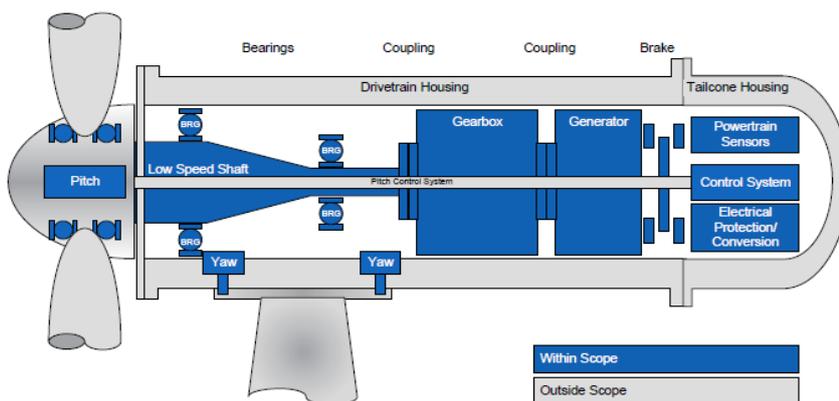


Figure 3: Axial tidal power turbine showing PTO machinery system and controls.

Based on the latest outcomes of phase 1, the project team has identified the need of creating an initial case-study that will exemplify the methodology to be followed during the subsequent phases of the project. Although the case-study will be limited to certain subcomponents and to a relatively small number of failure modes this will not reduce their demonstrating capabilities since the main steps of the methodology will be presented. The synthesis of the case-study will be based on pre-existing models and will follow the taxonomic breakdown of phase 1.

5 Reliability Database

5.1 Introduction

Databases for wind reliability (Reliawind [7], National Renewable Energy Laboratory (NREL)) and offshore (OREDA, [8]) have been collated and are used in their respective industries to improve reliability. The most applicable databases are those from wind, particularly offshore where some similarly harsh environmental conditions will be faced by the turbine. However unlike the OREDA database these are not publically available. The background to available data is discussed in reference [1].

5.2 Database Foundation

Although not available publically the information contained in the wind reliability databases is key to success and it is expected that full or partial access can be accessed in order to gain specific insights. Some of the data publically available such as in Figure 4 taken from the Reliawind data show how useful this can be in defining the critical areas for further research. The databases can provide a foundation of data giving a benchmark which the reliability simulation compared against. If we are able to drill down to component failure modes then we can also begin to confirm the reliability physics of failure methodology.

5.3 Key Input

From Figure 4 which is an extract of reference [7] we can already see that the Frequency converter, Pitch system, yaw system and gearbox make up over 50% of turbine downtime. As tidal turbines share many of the same structures and configurations it is not unreasonable to assume a similar breakdown of reliability downtime would apply, although even less failure critical components are important considering the longer maintenance intervals in tidal compared to wind as well as the higher cost of intervention.

With a breakdown to component level, with annual failure rates, the TiPTORS project can begin to develop and apply the factors that will make the results tidal turbine specific.

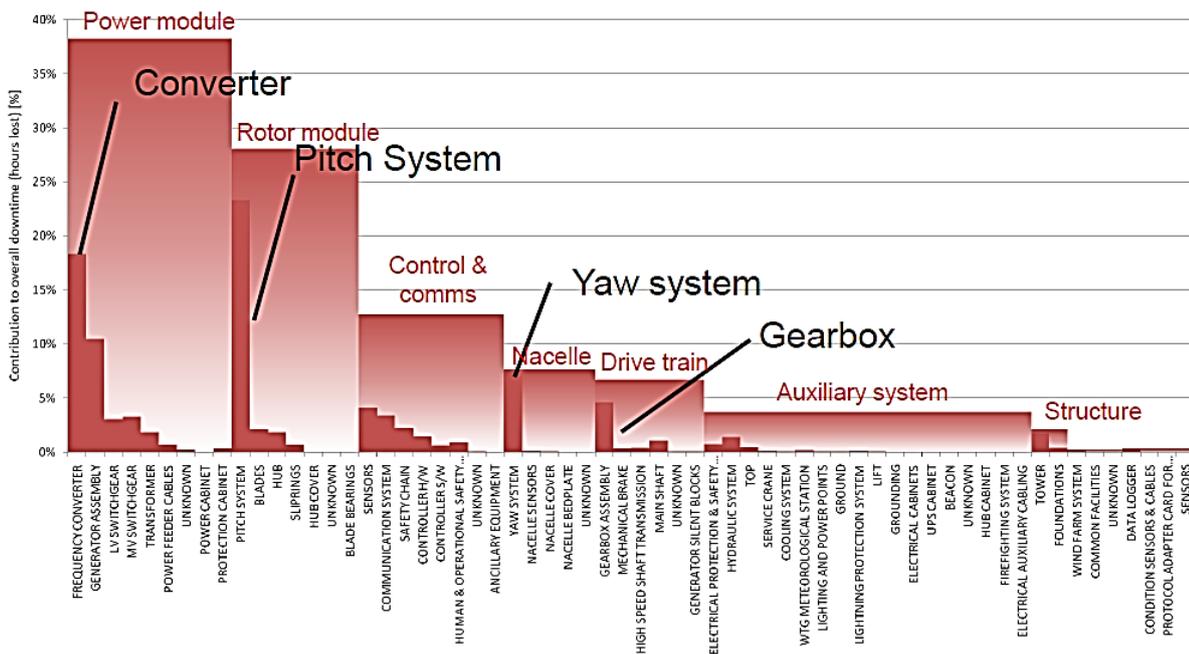


Figure 4: Normalised downtime of sub-systems and assemblies for wind turbines in the Reliawind database [7].

In time it is expected that tidal will develop their own database of reliability data from deployments but it will take time to build up the operational hours to provide statistically significant results. The instinct for many developers is not to share this data as the knowledge is a market differentiator. For this reason there needs to be a process for collating anonymising and sharing data that benefits the industry but is sensitive to the developers concerns.

6 FMECA

6.1 Introduction

Guidance on how to complete FMECA according to principles agreed for the TiPTORS project are contained in the updated FMECA Guide Tool [3]. The TiPTORS team has introduced two elements into the FMECA to enable the translation into the simulation tool. These are;

- The key indicators which are defined as the process variables which will influence reliability. In the judgement of the team, Key Indicators will be the measurable parameters informing the condition of component which influence the performance at the material / environmental level of the component
- Prevention controls are those that help reduce the likelihood that a failure mode or cause will occur (i.e. affect the occurrence value).

6.2 Example FMECA

The bottom up (component) approach taken for the TiPTORS program was applied to a sample of components and the low speed shaft; generator and frequency converters were assessed. This helped define the approach now documented in the FMECA Guide tool [3]. The examples are included in Appendix III

6.3 Use of FMECA

Defining key indicators will be done through the FMECA process and therefore to start the system engineering model an initial FMECA of the power take off should be completed. It is therefore an important part of the process although it is completed outside of the systems engineering model and is considered an input (see Figure 1).

7 Key Indicators

7.1 Introduction

For each failure mode and associated failure mechanisms (relevant to those reflected from reliability databases) the parameters that are influential in the increase or decrease of the occurrence of failure (associated mainly with degradation aspects, not accidental or abnormal transient conditions) are to be identified through the FMECA process. These parameters are defined as 'key indicators' within this project and are to be used to adjust reliability data available from other industries. The set of parameters are likely to be limited as they are related to physical events such as vibration, temperature, stress levels, stress ranges, humidity, speed and accelerations that are also possible to be monitored (and normally used for health and operating parameters). They can be either external (ambient inside nacelle for example) or result of processes taking into account tolerances, acceleration, wear, etc.

7.2 Reliability Simulation

The key indicators will be the output from the system engineering model. The simulations should be restricted to steady-state conditions as the objective is to look into the degradation during operation. This assumes that the extreme cases, transient cases and faults that are related to a relatively low probability of occurrence are assessed and designed in order to provide sufficient strength without exceeding operational restrictions and parameters (i.e. not important to degradation aspects and not initiating defects that will lead to early failures). The same is applicable for accidental events, when it is assumed that following an accidental event, an inspection will be required and the system brought up to 'as-new' condition.

Another important aspect is to consider the influence of the permanence of the key indicators levels during operation (i.e. time). This is to capture the postponement of maintenance activities for longer than usual and identified / assumed in existing reliability databases (for example, using mean time between failures (MTBF) as a parameter to identify normal maintenance intervals likely to be required or manufacturer's maintenance specification).

In the cases where no information is available, the risk associated to the failure mode is high and the degree of novelty is also high, physics of failure may be used to define the time to failure. In this case, time to failure would directly reflect the reliability.

7.3 Using Key Indicators

The simulations will output the key indicator values which are then used to assess the impact on reliability. Knowledge of how these influence reliability will be taken from research, component supplier's data and further testing. This is the area that most work will be required in phase 2 to pull all the information together to provide an integrated reliability simulation tool.

8 Systems Engineering Model

8.1 Objectives and Specification

The objectives of the systems engineering model are:

- Assessment of PTO system under various conditions of operation in the entire loading envelope of the system
- Development and synthesis of a PTO model capable to represent both non-failed and failed system states
- Development and synthesis of a PTO model capable to include physics of failure and/or empirically based component degradation models for critical reliability components
- Mathematical modelling (i.e. through model's process variables) and quantitative estimation of the key reliability indicators (temperatures, pressures, stresses, etc.) at various system positions
- Assessment of multiple PTO configurations, improved designs and innovations allowing reliability comparisons between designs. The PTO model should be capable to be refined to the level of accuracy necessary to the study required
- Soft-sensing for support of condition monitoring
- Development of a library of reconfigurable components for PTO modelling

The approach that will be followed for the development of the systems engineering model includes the followings steps:

- Use of PTO's taxonomic breakdown, each component model that comprises the simulation model should have an one-to-one correspondence with the taxonomy ontologies
- Identification of physical phenomena (physical process description), first principles, collection and post-processing of empirical/experimental data required for representing the system's operation is adequate for the purposes of the project detail
- Derivation of mathematical equations (through first principles, or empirical/knowledge-based techniques) for nominal (i.e. not in failed states) component operation
- Derivation of mathematical equations accounting for failure mode simulation and their mechanisms (degradation, physics of failure). This should be done in accordance to the failure modes identified from the complete FMECA (phase 2). Since many different possible failure modes co-exist, a prioritisation according to the risk number (FMECA) should be made

- Computer code implementation/ reconfiguration of models and enhancement in case of utilisation of pre-existing models
- Synthesis of the PTO overall system model
- System model/ component model validation (including physics of failure).

From the aforementioned steps, the 3rd, 4th and 5th bullets refer to the case where there is no already existing library of component models that could be directly used for the synthesis of the overall system model.

The model specifications are listed below:

- Steady-state and transient modelling capabilities
- Multi-configurable component models. So as to easily synthesise and customise model to represent specific PTO architectures
- Multilevel modelling approach: component models of various different levels of detail can be coupled one to another and interchanged, according to the specific needs of each one of the simulated scenarios
- Links with external hydrodynamic calculation codes (e.g. Tidal Bladed [9]). Capture of hydrodynamic and machinery dynamics effects.
- Capability to perform stochastic simulations, references [10-13] for (i) the estimation of reliability measures due to failure events and (ii) for taking into account epistemic uncertainties related to model parameters, measurement signals and environmental conditions (see Appendix IV).

The simulation platform will be based on DNV GL's already established modelling and simulation tools [9, 14].

8.2 Mathematical Modelling

8.2.1 Introduction

Based on the component physical process description a mathematical model for each component is created. As discussed earlier, this model can be a phenomenological model based on first principles, or it can be based on detailed physical models or even correlations from experimental data (if available). A general description of the model component mathematical equations reads:

$$\frac{d\vec{Y}}{dt} = \vec{F} \left(\vec{Y}(t), \frac{d\vec{Y}}{dx_i}(t), \vec{u}(t), \vec{b}(t), t \right) \quad \text{Eq. 1}$$

$$\vec{H}\left(\vec{Y}(t), \frac{d\vec{Y}}{dx_i}(t), \vec{u}(t), \vec{b}(t), t\right) = 0 \quad \text{Eq. 2}$$

where t is the time, $\vec{Y} = (Y_1, \dots, Y_{N_Y})$, $\vec{u} = (u_1, \dots, u_{N_u})$ and $\vec{b} = (b_1, \dots, b_{N_b})$ are the vectors of differential variables, algebraic variables and parameters, respectively. The vectors \vec{Y} and \vec{u} consist the process variables of the system. \vec{F} and \vec{H} are vector functions. The partial derivative base vector \vec{x} , is an appropriate distribution domain, usually expressing geometry dimensions (e.g. length, width, radius, etc.). The partial differential algebraic equation (PDAE) system is completed by the necessary initial and boundary conditions.

In a more generic manner, Eqs. 1 and 2 may represent, apart from a component model, a control strategy scheme or even a physics of failure and degradation model that could be coupled with a component model; the latter is particularly of large importance within the TiPTORS project.

As in any model-based systems engineering approach, the overall PTO system model will be synthesized from coupling the component models. Hence, connectivity rules between component models, expressed in the form of algebraic equations of the process variables, must be used. Therefore, the physical models of the framework can be divided in two broad sets: a) individual component mathematical models, and b) connectivity equations between components. A general form of the connectivity equation reads:

$$C_j(\vec{X}_{outlet}) = C_{j+1}(\vec{X}_{inlet}) \quad \text{Eq. 3}$$

where C_j and C_{j+1} is the first and the second component, respectively, in a two component connection, see Figure 5. With \vec{X} are the process variables that are propagated to the next component. Eq. 3 is actually an equality of variables between inlets and outlets of different components. The following types of connectivity equations are to be used: a) fluid flow (e.g. in cooling network component models), b) mechanical (shaft) (e.g. in powertrain component models), c) electrical (e.g. between generator and switchboard models) and d) control signal connections.

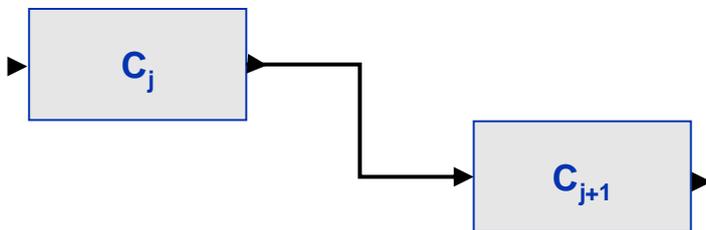


Figure 5: Connectivity between two components, C_j and C_{j+1}

8.2.2 Example of Component Mathematical Model and Connectivity Equations

In order to exemplify the discussion made in paragraph 8.2, a synchronous generator is used as an example. As mentioned in paragraph 8.2, various levels of modelling detail should be

supported by a customisable library of component models. In Figure 6, two different typical synchronous electrical generator modelling approaches are presented: (i) a simple look-up table model correlating mechanical power input and generator efficiency and (ii) a detailed PDAE model (d-q-0 model). The analyst may choose one of these two models based on what is the scope of the simulations, namely if steady-state analysis producing lumped electrical power and root mean square (RMS) current and voltage values is enough (look-up model) or if a more detailed (e.g. including stator, rotor windings) steady-state or even transient analysis is required (d-q-0 model). The simulation platform should be capable to support all modelling approaches.

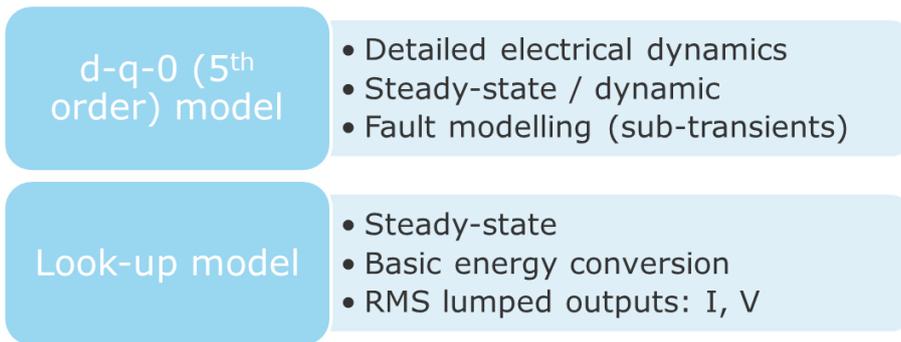


Figure 6: Two examples of typical electrical generator mathematical models

The synchronous generator PDAE model is modelled according to the two axis theory, reference [15] (d-q-0 model). The model's state Eqs. 1 & 2 are presented below. The voltage balance for the dq-frame is given by the following differential equations [15, 16]:

$$\dot{\psi}_d = u_d + R_d \cdot i_d + \psi_q \cdot \omega_r \cdot \frac{p}{2} \quad \text{Eq. 4}$$

$$\dot{\psi}_q = u_q + R_q \cdot i_q - \psi_d \cdot \omega_r \cdot \frac{p}{2} \quad \text{Eq. 5}$$

$$\dot{\psi}_f = u_f - R_f \cdot i_f \quad \text{Eq. 6}$$

$$\dot{\psi}_D = -R_D \cdot i_D \quad \text{Eq. 7}$$

$$\dot{\psi}_Q = -R_Q \cdot i_Q \quad \text{Eq. 8}$$

the flux linkages are given by:

$$\psi_d = -L_d \cdot i_d + L_{df} \cdot i_f + L_{dD} \cdot i_D \quad \text{Eq. 9}$$

$$\psi_q = -L_q \cdot i_q + L_{qQ} \cdot i_Q \quad \text{Eq. 10}$$

$$\psi_f = -L_{df} \cdot i_d + L_f \cdot i_f + L_{fD} \cdot i_D \quad \text{Eq. 11}$$

$$\psi_D = -L_{dD} \cdot i_d + L_{fd} \cdot i_f + L_D \cdot i_D \tag{Eq. 12}$$

$$\psi_d = -L_d \cdot i_d + L_{df} \cdot i_f + L_{dD} \cdot i_D \tag{Eq. 13}$$

Where $\omega_r = \omega_{el} / (p/2)$. The Eq. 6 & Eq. 11 represent the voltage balance and flux linkage in the field windings, in fact a permanent-magnet synchronous machine can be readily analysed by using the above equations simply by assuming that the machine is excited by a field current of constant value, making sure to calculate the various machine inductances based on the effective permeability of the permanent-magnet rotor, [15].

Moreover, in Figure 7, the connectivity between an electrical generator and a frequency converter is presented along with the process variables that are propagated from the one component to the other. In this case, the chosen process variables that are included in the connectivity equations are the RMS current and voltage values, the electrical frequency and the power factor. These process variables may change according to the modelling needs and are an essential part of each component model specification.

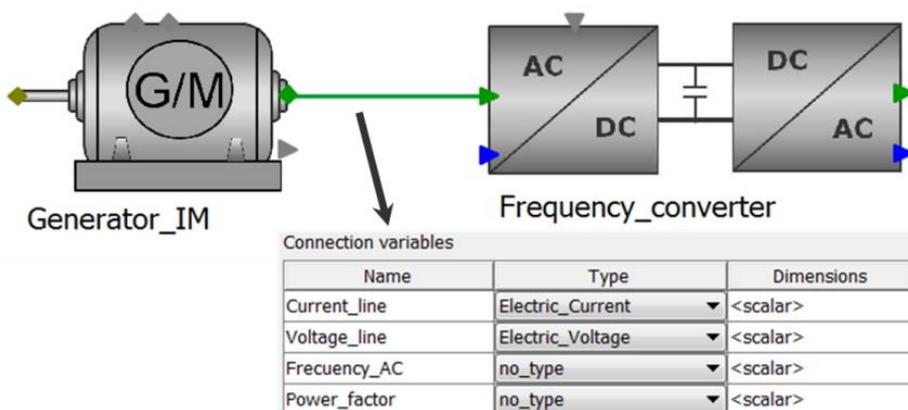


Figure 7: Electrical connectivity between a generator and a fully rated frequency converter

Nomenclature

Symbols

- i Current, (A)
- L_d d-winding self-inductance, (H)
- L_D D-winding self-inductance, (H)
- L_{dD} d- and D-winding mutual inductance, (H)
- L_{df} d- and field-winding mutual inductance, (H)
- L_f Field-winding inductance, (H)
- L_{fD} Field and D-winding mutual inductance, (H)
- L_q q-winding self-inductance, (H)
- L_Q Q-winding self-inductance, (H)
- L_{qQ} q- and Q-winding mutual inductance, (H)
- p Number of poles, (-)
- u Voltage, (V)
- ψ Flux linkage, (Wb t)
- ω_{el} Electric angular velocity, (rad/s)
- ω_r Shaft's angular velocity, (rad/s)

Subscripts

Nomenclature**Symbols**

<i>D</i>	D- amortisseur winding
<i>d</i>	d-winding
<i>el</i>	Electrical
<i>f</i>	Field-winding
<i>Q</i>	Q- amortisseur winding
<i>q</i>	q-winding

9 Physics of Failure

9.1 Introduction

According to the specifications of paragraph 8.1, the systems engineering model should be capable to calculate the system's key reliability indicators. Initially, by using the values of these indicators the analysts will be enabled to qualitatively estimate the impact on the reliability that the various operating conditions, loading conditions, system design and configurations may have. Furthermore, if a quantitative answer regarding the system reliability level is required, physics of failure models will be employed. These models will be coupled with the system's component models and based on the variation in key indicators will provide the probability of a failure event occurrence due to the failure mechanisms related to the various key indicators.

9.2 Failure Mode Models

The failure mode models can be divided into the following subcategories: (a) simple lumped first principle models enhanced with empirical information as used in the US military handbooks [4, 5], (b) high fidelity detailed physical models (usually also including some form of empirical information) and (c) pure empirical-based models that will use results from experiments conducted in phases 2 and 3 of TiPTORS or from other sources (if applicable).

A starting point in order to correlate the impact that the level of the key indicators may have to the reliability of the component could be the utilisation of the mathematical equations found in engineering handbooks, [4, 5]. Later on based on the experimental results from phases 2 & 3 the failure of physics models will be enhanced or even substituted with more detailed ones. The approach that will be followed for the development of the physics of failure models includes the followings steps:

- Identification of physical phenomena, first principles, collection and post-processing of empirical/experimental data.
- Derivation of mathematical equations (through first principles, or empirical/knowledge-based techniques) for the failure mechanisms.
- Computer code implementation and compatibility with PTO system model.
- Model validation.

9.3 Failure Mechanisms

As mentioned in the previous paragraph, the identification of the various failure mechanisms is a key aspect of the overall process, consequently this has been initiated already from phase 1. In Appendix II a collection of some of the most significant drivetrain failure mechanisms (as

identified during the FMECA workshop in DNV GL premises in London, 16-17 April 2015) are listed. In

Table 2 a list of gearbox (main part of the drivetrain, see taxonomy) failure modes and the corresponding failure mechanisms are listed according to report reference [5]. Moreover, in

Table 3 a list of gearbox failure events with the corresponding mechanisms based on NREL tests [17] is given.

FAILURE MODE	FAILURE CAUSE	FAILURE EFFECT
Pitting	Cyclic contact stress transmitted through lubrication film	Tooth surface damage
Root fillet cracking; Tooth end cracks	Tooth bending fatigue	Surface contact fatigue and tooth failure
Tooth shear	Fracture	Tooth failure
Scuffing	Lubrication breakdown	Wear and eventual tooth failure
Plastic deformation	Loading and surface yielding	Surface damage resulting in vibration, noise and eventual failure
Spalling	Fatigue	Mating surface deterioration, welding, galling, eventual tooth failure
Tooth bending fatigue	Surface contact fatigue	Tooth failure
Contact fatigue	Surface contact fatigue	Tooth failure
Thermal fatigue	Incorrect heat treatment	Tooth failure
Abrasive wear	Contaminants in the gear mesh area or lubrication system	Tooth scoring, eventual gear vibration, noise

Table 2: Gearbox failure modes and mechanisms

Qty	Location	Code	Description
1	bearing	5.4.3	Hertzian Fatigue, Micropitting, Edgte of Raceway
1	bearing	6.1.1	Wear, Adhesion, Mild
3	bearing	6.1.3	Wear, Adhesion, Severe (Scuffing)
4	bearing	6.2.1	Wear, Abrasion, Two-body
10	bearing	6.2.2	Wear, Abrasion, Three-body
1	bearing	6.2.3	Wear, Abrasion, Polishing
14	bearing	8.1.1	Cracking, Roller and Ring Cracks, Hardening Cracks
2	bearing	8.1.2	Cracking, Roller and Ring Cracks, Grinding Cracks
1	gear	3.1	Overload, Fracture, Brittle
1	gear	4.1	Bending Fatigue, Low Cycle
2	gear	5.3	Hertzian Fatigue, Subcase Fatigue
6	gear	6.4	Wear, Fretting-Corrosion
2	gear	4.2.1	Bending Fatigue, High Cycle, Root Fillet Cracks
3	gear	4.2.2	Bending Fatigue, High Cycle, Profile Cracks
2	gear	6.1.1	Wear, Adhesion, Mild
1	gear	6.2.2	Wear, Abrasion, Moderate
4	gear		not found

Table 3: Summary of Failure Database Incidents

10 Cost Model

10.1 Introduction

The cost model starts from the overall LCoE for an array with general parameters and targets that are assumed / considered vital for the necessary positive result. For TiPTORS, it is required that the focus is on the drivetrain and this part has to be detailed enough to capture the impact of changes on the drivetrain that may result from the simulations to achieve improved reliability (from change of configuration of systems to change on level of tolerances or surface finishing, for example).

10.2 Impact on Overall Cost

A breakdown of CAPEX for the supply and installation of tidal turbines is not publically available to give precise figures for the cost of the PTO. As this data is commercially sensitive for the turbine developers only high level estimates are published. From the JRC ETRI 2014 report [18] this shows the CAPEX for an installed turbine estimated as €10.7million/MW reducing to €4.4million/MW by 2020. The figure below shows that the mechanical and electrical equipment supply is over half of the CAPEX cost. Although the proportion directly related to the PTO is not shown in the report it can be assumed that this equates to a bulk of the costs in these segments. Therefore it will be critical for all turbine developers to minimise PTO costs while at the same time meeting their reliability and availability targets.

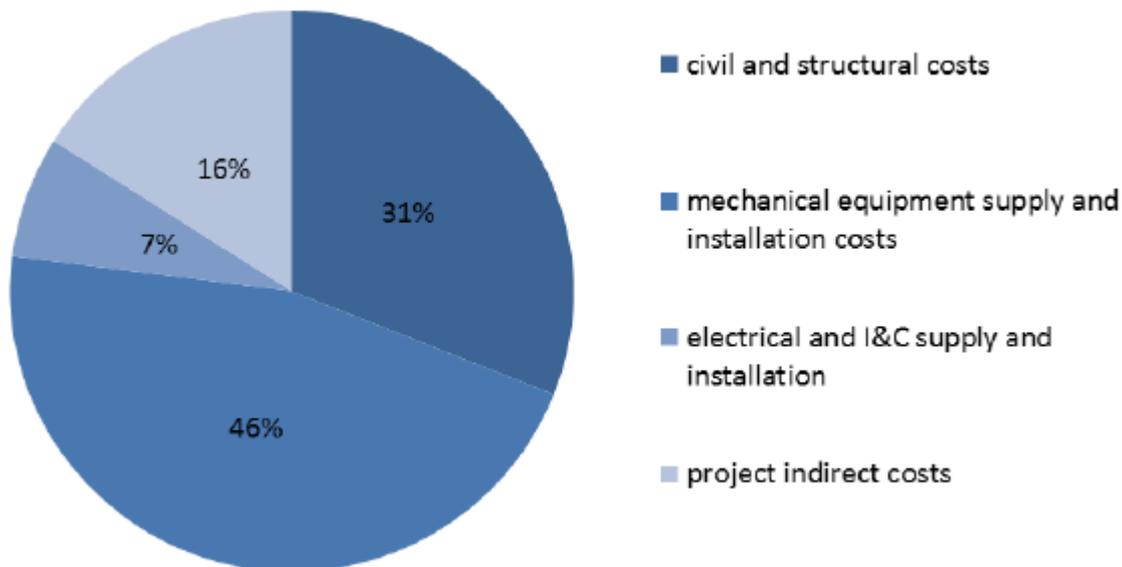


Figure 8 CAPEX breakdown for tidal power (source: ETRI 2014, [18])

10.3 Reliability Design

The impact on drivetrain costs due to modifications for increased reliability is an important constraint on the extent that reliability improvements can be implemented. In efforts to design more reliable systems there will be associated changes to the costs of the component, subsystem or assembly and often additional testing and commissioning costs related to the increasing level of complexity or refinement (e.g. the need for tighter tolerances means higher grade components and more accurate assembly and testing).

The first step in creating the cost model should be to determine the level of refinement needed in the cost assessment of the drivetrain. This should be done considering the contribution of the different systems, subsystems and components on the overall cost of the drivetrain and their importance in the overall contribution of the LCoE. This could be carried out at an early stage with a limited amount of information available. It would be necessary to perform a qualitative assessment on the impact of both the component costs and assembly and commissioning costs related to complexity parameters.

It is recognised that the cost model should provide the means to include the information above (and where possible suggest some indicative relative increase in costs for manufacturing and assembly) rather than provide actual values, as this is likely to be variable from manufacturer to manufacturer, country to country and affected by scale and annual variations on supply and demand. The framework / tool should be established defining the important aspects to consider and the impact of the aspects discussed above in the final cost of the drivetrain. The cost model should also allow the user to establish the acceptable margin of cost variation for a given increase in reliability.

The cost model should take the input from the reliability simulation tool in terms of the overall reliability (revenue) and its impact on the maintenance intervals (OPEX) that will affect the overall LCoE and define new acceptance criteria.

11 Demonstration Case Study

11.1 Introduction

The items discussed in this report will form the basis for the reliability simulation tool. However it is clear that there is a significant amount of information needed to complete the task. Initially Phase 1 was envisaged as a purely scoping exercise.

It has become clear through the work done on the TiPTORS program to date that to develop a demonstration case study (demonstrator) during phase 1 will be the most direct way to start producing value from the project and develop the detailed scope of the work packages required in phase 2.

11.2 Preliminary Work

The development of the demonstration case study undertaken in phase 1 given the limitations of time, budget and most critically information will only be possible at a high level. However this effort will be a proof of concept approach and will develop a framework where the further research completed as part of phase 2 can fit. Phase 2 will be a complex project to manage and coordinate and with multiple partners all responsible for their individual contribution their needs to be a way to control the process. By having a pre-existing package that can be presented as a vision of the final result and a structure for the work packages to feed into will ensure that there are no gaps and a successful result. The demonstrator would be produced only to provide output to the project deliverables.

The case study is presented in Appendix IV.

12 References

1. Report 1.1.4,5,6,8,9 General Industry Practice and Design Parameters - PP124801-WP1.1.5-001, 2015.
2. RD15-78801.1_System Architecture HATT_20150306.
3. RD15-104101-1_FMECA Guide Tool_20150320.
4. *Military Handbook Reliability Prediction of Electronic Equipment*, 1991, Department of Defense.
5. *Handbook of Reliability Prediction Procedures for Mechanical Equipment*, L.T.S. Naval Surface Warfare Center, Editor 2011, NSWC: West Bethesda, Maryland 20817-5700.
6. *Recommended practice: Technology qualification*, 2013, Det Norske Veritas.
7. al., M.W.e., ed. *Measuring Wind Turbine Reliability – Results of the Reliawind Project*.
8. *OREDA: Offshore Reliability Data*. 5 ed, ed. SINTEF 2009: Published by the OREDA Partshipants.
9. DNVGL. *Tidal bladed*. 2015; Available from: <https://renewableenergysoftwareportal.dnvgl.com/Home/ProductDownloads?ProductID=2>.
10. Lewis, E.E. and F. Böhm, *Monte Carlo simulation of Markov unreliability models*. Nuclear Eng. And Design, 1984. **77**(49-62).
11. Rao, K.D., et al., *Dynamic fault tree analysis using Monte Carlo simulation in probabilistic safety assessment*. Reliability Eng. and System Safety, 2009. **94**: p. 872-883.
12. Labeau, P.E., *Probabilistic Dynamics: Estimation of generalized unreliability through efficient Monte-Carlo simulation*. Ann. Nucl. Energy, 1996. **23**(No. 17): p. 1355-1369.
13. Smidts, C., *Probabilistic Dynamics: a comparison between continuous event trees and discrete event tree model*. Reliability Eng. and System Safety, 1994. **44**: p. 189-206.
14. Dimopoulos, G.G., et al., *A general-purpose process modelling framework for marine energy systems*. Energy Conversion and Management 2014. **86 (2014)** p. 325–339.
15. Fitzgerald, A.E., C. Kingsley, and S.D. Umans, *Electric Machinery*. 6 ed 2003: McGraw-Hill.
16. Kakalis, N., et al., *COSSMOS: Model development and implementation III*, 2011, Det Norske Veritas.
17. Link, H., et al., *Gearbox Reliability Collaborative Project Report: Findings from Phase 1 and Phase 2 Testing*, 2011, NREL.
18. *Joint Research Centre of the European Commission: Energy Technology Reference Indicator projections for 2010-2050 (ETRI 2014)*.
19. Dimopoulos, G.G. and N.M.P. Kakalis. *An integrated modelling framework for the design, operation and control of marine energy systems*. In *26th CIMAC World Congress*. 2010. Bergen, Norway.
20. Billinton, R. and R. Allan, *Reliability Evaluation of Engineering Systems: Concepts and Techniques*. Advanced Publishing Program 1985, London: Pitman.
21. Villemeur, A., *Reliability, Availability, Maintainability and Safety Assessment: Methods and Techniques Vol. 1*. 1992: John Wiley & Sons.

22. Rausand, M. and A. Høyland, *System Reliability Theory: Models, Statistical Methods and Applications*. 2nd ed: John Wiley & Sons.
23. Walker, M. and Y. Papadopoulos, *Qualitative temporal analysis: Towards a full implementation of the Fault Tree Handbook*. Control Engineering Practice, 2009. **17**: p. 115-1125.
24. Manno, G., A. S. Zymaris, et al., *Dynamic reliability of three nonlinear aging components with different failure modes characteristics.*, in *ESREL 2013 2013*: Amsterdam.
25. Mercurio, D., et al., *Identification and classification of dynamic event tree scenarios via possibilistic clustering: Application to a steam generator tube rupture event.* . Accident Analysis and Prevention, 2009. **41**: p. 1180–1191.
26. Zymaris, A.S., G. Manno, et al., *Model-based reliability methods: Automatic Fault Tree generation from process modelling, internal report*. 2012, Det Norske Veritas.
27. Babykina, G., et al., *Reliability assessment for complex systems operating in dynamic environment.* . Advances in Safety, Reliability & Risk Management, 2012(ISBN 978-0-415-68379-1.).
28. Distefano, S., F. Longo, and K.S. Trivedi, *Investigating dynamic reliability and availability through state–space models.* . Computers and Mathematics with Applications 64 (2012) 3701–3716. , 2012.
29. Siu, N., *Risk assessment for dynamic systems: An overview*. Reliability Eng. and System Safety, 1994. **43**: p. 43-73.
30. Devooght, J., *Dynamic reliability*. Adv. in Nuclear Science and Technology, 1997. **25**.
31. Marseguerra, M., et al., *A concept paper on dynamic reliability via Monte Carlo simulation*. Mathematics and Computers in Simulation, 1998. **47**: p. 371-382.
32. Labeau, P.E., *A Monte-Carlo estimation of the marginal distributions in a problem of probabilistic dynamics*. Reliability Eng. and System Safety, 1996. **52**: p. 65-75.

Appendix I

The initial taxonomic breakdown used during phase 1 is tabulated in the tables below.

6	PITCH SYSTEM
6.1	Rotating mechanism
6.1.1	Pitch actuator
6.1.1.1	Hydraulic-mechanical actuator
6.1.1.2	Electro-mechanical actuator
6.1.1.2.1	Pitch gearbox
6.1.1.2.2	Pitch gearbox support
6.1.2	Pitching Load transfer component (shaft, trunnion, crank ring)
6.2	Power
6.2.1	Hydraulic power unit
6.2.2	Electrical
6.2.2.1	Grid (see electrical system)
6.2.2.2	Turbine Generator (see electrical system)
6.2.2.3	Back-up system (see electrical system)
6.3	Connection rotor and power and controls system
6.3.1	Electrical
6.3.2	Mechanical
6.3.3	Hydraulic
6.4	Structural load bearing
6.4.1	Bearings (see bearings in rotating mechanism)
6.4.2	Root connection (see root connection in blades)
6.5	Control system (see control systems section)
6.6	Seals (see seals systems section)
7	YAW SYSTEM
7.1	Rotating mechanism
7.1.1	Yaw shaft (trunnion, crank ring)
7.1.2	Yaw drive
7.1.2.1	Electro-mechanical actuator
7.1.2.1.1	Yaw Gearbox
7.1.2.2	Hydraulic-mechanical actuator
7.1.2.3	Thruster
7.2	Power
7.2.1	Yawing mechanism
7.2.1.1	Hydraulic power unit
7.2.1.2	Electrical
7.2.1.2.1	Grid (see electrical system)
7.2.1.2.2	Turbine Generator (see electrical system)
7.2.2	Yaw locking mechanism and turbine attachment mechanism
7.2.2.1	Hydraulic power unit
7.2.2.2	Electrical
7.2.3	Guiding mechanism
7.2.3.1	External power docking station (sealed plate)
7.2.3.1.1	Electrical
7.2.3.1.2	Hydraulic
7.3	Control (see yaw control in Control systems)
7.4	Structural locking mechanism
7.4.1	Yaw locking (clamp, gears, wedges, pins)
7.5	Cable and pipes management system
7.5.1	Guiding mechanism
7.5.1.1	Active components
7.5.1.1.1	Rotating mechanism

7.5.1.1.1.1	Hydraulic-mechanical actuator
7.5.1.1.2	Ramming mechanism
7.5.1.1.2.1	Hydraulic-mechanical actuator
7.5.1.1.2.2	Electro-mechanical actuator
7.5.1.3	Passive components
7.5.1.3.1	Alignment pins
7.5.2	Drag chain
7.5.3	Slip ring
7.5.4	Wetmate connection to subsea cable
7.5.5	Hydraulic connection
7.6	Structural load bearing (yaw)
7.7	Control system (see control systems section)

8	DRIVETRAIN
8.1	Low speed shaft
8.2	Low speed shaft bearings (see bearings)
8.3	Gearbox
8.3.1	Bespoke design
8.3.2	Derived from wind turbine
8.3.3	Gearbox fixation to sub assembly frame
8.4	High speed shaft
8.5	Braking system
8.5.1	Low speed shaft brake
8.5.2	High speed shaft brake
8.5.3	Generator rear brake (disk)
8.5.4	Resistor bank
8.5.5	Electric brake (generator counter-torque)
8.5.6	Brake fixation to sub assembly frame
8.5.7	Parking brake
8.5.8	Braking disks
8.5.9	Braking pads
	Braking pads
8.5.10	Power
8.5.10.1	Hydraulic power unit
8.5.10.2	Electrical
8.5.10.2.1	Grid (see electrical system)
8.5.10.2.2	Turbine Generator (see electrical system)
8.6	Rope cutter
8.7	Corrosion protection (see corrosion protection)
8.8	Torque limiter
8.8.1	Mechanical torque limiter
8.8.2	Magnetic torque limiter
8.9	Couplings
8.9.1	Shrink fit couplings
8.9.2	Key connections
8.9.3	Torsionally elastic couplings
8.9.4	Tooth couplings
8.9.5	Bolted flange couplings
8.9.6	Friction flange couplings
8.10	Lubrication system (bearings etc.)
8.11	Control system (see control systems section)

9	SEALS
9.1	Static
9.1.1	Seals between nacelle segments
9.1.2	Seal between hub and low speed shaft
9.2	Dynamic
9.2.1	Low speed shaft seals
9.2.2	Hub seals for blades

10	BEARINGS
10.1	Pitch bearings
10.1.1	Rolling
10.1.2	Plain
10.2	Low speed shaft bearings
10.2.1	Rolling
10.2.2	Plain
10.3	High speed shaft bearings Not in the shaft
10.4	Yaw bearings
10.4.1	Rolling
10.4.2	Plain

11	AUXILARY SYSTEM
11.1	Ballast
11.1.1	Liquid ballast
11.1.2	Solid ballast
11.2	Bilge system
11.3	Cooling system
11.4	Heaters and de-humidifying
11.5	Control system (see control systems section)
11.6	Lubrication system (see drivetrain section)

12	ELECTRICAL SYSTEM
12.1	Generator
12.2	Frequency converter
12.2.1	Sub-sea integral within turbine
12.2.2	Sub-sea external to turbine
12.2.3	Shore based
12.2.4	Surface piercing platform
12.2.5	Sub-sea array frequency converters
12.2.6	Shore based array frequency converters
12.3	Transformer(s)
12.3.1	Liquid insulated transformer
12.3.2	Dry type transformer
12.3.3	Sub-sea integral within turbine
12.3.4	Sub-sea external to turbine
12.3.5	Shore based
12.3.6	Surface piercing platform
12.3.7	Sub-sea array transformers
12.3.8	Shore based array transformers
12.4	GIS HV switchgear
12.4.1	Sub-sea integral within turbine
12.4.2	Sub-sea external to turbine
12.4.3	Shore based
12.4.4	Surface piercing platform
12.4.5	Sub-sea array switchgear
12.4.6	Shore based array switchgear
12.5	Power cabling system
12.6	LV switchgears
12.6.1	Sub-sea integral within turbine
12.6.2	Sub-sea external to turbine
12.6.3	Shore based
12.6.4	Surface piercing platform
12.5.5	Sub-sea array switchgear

12.5.6	Shore based array switchgear
12.6	UPS systems
12.6.1	Batteries
12.6.2	Premagnetisation/Charge circuit
12.7	Subsea cabling system
12.8	Subsea cable joints
12.8.1	Internal
12.8.2	External
12.9	Control system (see control systems section)

13	CONTROL SYSTEM
13.1	Control and safety strategy
13.1.1	Pitch
13.1.1.1	Allows individual pitch control
13.1.1.2	Collective pitch control
13.1.2	Stall
13.1.3	Over-speed
13.2	Control system
13.2.1	HATT Supervision Control and Data Acquisition
13.2.2	Emergency and safety chains
13.3	Sensors
13.3.1	Control sensors
13.3.2	System/component protection sensors
13.3.3	Condition monitoring system sensors
13.3.4	Vibration monitoring
13.3.5	CCTV
13.4	Systems cabinets
13.4.1	Pitch cabinet
13.4.2	Yaw cabinet
13.4.3	Power control cabinet
13.4.4	Auxiliary cabinet
13.4.5	Environmental monitoring cabinet
13.4.6	Bus communication interfaces

Appendix II

Drivetrain failure mechanisms

- 1 Ageing of hydraulic fluid
 - 2 Ageing of lubrication oil
 - 3 Alteration of friction surface (if friction type)
 - 4 Bending moment and axial forces
 - 5 Control fault
 - 6 Corrosion
 - 7 Creep
 - 8 Deformation of braking discs due to corrosion / material degradation
 - 9 Distortion due to temperature fluctuation
 - 10 Excessive vibration
 - 11 Fatigue
 - 11.1 Fatigue due to alternative nature of wave loading
 - 11.2 Fatigue due to dynamic stresses
 - 11.3 Fatigue due to misalignment / eccentricities
-

Appendix III

Example FMECA output

Component	Function	Tech. Class	Novelty	Failure mode	Failure mechanism or cause	Key Indicator	Prevention Controls	Detection in Operation	Consequence	Current Controls	Risk Ranking			Comments	Recommended Actions
											Cons	Prob	Risk		
Low speed shaft	Transfer torque from hub to drive train gearbox Transfer torque to generator (if relevant) Resist ultimate loads Resist fatigue loads	2	Loading Maintenance intervals	Structural failure	Bending moment and axial forces transmitted by rotor exceed capacity	Strain	Material specification Initial shaft modelling Calculations Heat treatment Hydrodynamic load modelling	Strain sensor	Loss of power production Possible loss of hub/rotor System shutdown Retrieval needed	Feathering of the blades before loading reaches strength capacity	5	2	Med		Detailed site-specific met-ocean data is a way of reducing uncertainty and therefore probability of failure Increasing load factor can reduce probability of failure
Low speed shaft	Transfer torque from hub to drive train gearbox Transfer torque to generator (if relevant) Resist ultimate loads Resist fatigue loads	2	Loading Maintenance intervals	Structural failure	Fatigue due to dynamic stresses on shaft (bending, torsion, axial)	Strain Vibrations	Material specification Initial shaft modelling Calculations Heat treatment Hydrodynamic load modelling	Determination of number and intensity of cycles through low speed shaft strain monitoring			5	3	High		Detailed site-specific met-ocean data is a way of reducing uncertainty and therefore probability of failure Increasing DFF can reduce probability of failure
Low speed shaft	Transfer torque from hub to drive train gearbox Transfer torque to generator (if relevant) Resist ultimate loads Resist fatigue loads	2	Loading Maintenance intervals	Structural failure	Wear due to excessive / inadequate contact with bearings	Vibration	Manufacturers fit Geometric tolerancing Surface finish Alignment	Visual inspection during maintenance			5	2	Med		Increasing safety margins is a way of reducing consequence
Low speed shaft	Transfer torque from hub to drive train gearbox Transfer torque to generator (if relevant) Resist ultimate loads Resist fatigue loads	2	Loading Maintenance intervals	Structural failure	Fatigue due to misalignment	Vibration	Geometric tolerance No load run test Bearing positioning	Nacelle vibration sensor		Testing of system prior to deployment	5	3	High		Redundancy of vibration sensor allows increased detection capacity and therefore reduces consequence by allowing faster response Monitoring of vibration is to be considered to allow early detecting and therefore to reduce probability class
Low speed shaft	Transfer torque from hub to drive train gearbox Transfer torque to generator (if relevant) Resist ultimate loads Resist fatigue loads	2	Loading Maintenance intervals	Structural failure	Accidental impact	Strain	ALS robustness	Low speed shaft strain sensor			5	1	Med		Definition of accidental scenarios and considering corresponding load cases in the design of the system is a way to reduce consequence class

Component	Function	Tech. Class	Novelty	Failure mode	Failure mechanism or cause	Key Indicator	Prevention Controls	Detection in Operation	Consequence	Current Controls	Risk Ranking			Comments	Recommended Actions
											Cons	Prob	Risk		
Low speed shaft	Transfer torque from hub to drive train gearbox Transfer torque to generator (if relevant) Resist ultimate loads Resist fatigue loads	3	Loading Maintenance intervals	Structural failure	Blade not feathered during high flow speeds	Strain	Control systems specification Commissioning tests Control system functional/bench tests	Control system sensors/alarms indicating alignment of blades Strain gauges			5	2	Med	This item is to capture the impact of failure to control blades in high flows	
Low speed shaft	Transfer torque from hub to drive train gearbox Transfer torque to generator (if relevant) Resist ultimate loads Resist fatigue loads	2	Loading Maintenance intervals	Structural failure	Corrosion due to inadequate protection or consumed anodes (Fretting Corrosion)	Salinity Temperature Humidity	Material specification Corrosion protection Environment control	Visual inspection during maintenance		Corrosion protection	5	3	High	Corrosion protection to be considered with sufficient margin to cover the design life and conditions inside the nacelle Special care should be given to electrical continuity of protection, in particular in areas nearing low speed shaft seal	

Appendix IV

A variable-speed variable-pitch architecture with a fully rated frequency converter is modelled in DNVGL COSSMOS [14, 19]. The rated power is 1.6MW. For the needs of this specific example, the flowsheet model of Figure 9 follows the taxonomic breakdown presented in the Appendix I including the main drivetrain and electrical components as can be found in Table 4

- The gearbox has one planetary and two parallel stages with a total step-up ratio equal to 100.
- The generator is an induction (690V) machine.
- The converter (sub-sea integral within turbine design) is rated for 1.6MW and performs the electrical power conversion into fixed frequency and voltage for the electrical grid connection.
- The power transformer (sub-sea integral within turbine design) steps-up the 690V to 6600V for the grid connection. The LV side (step-down from 6600V to LV turbine system) is not taken into account in this model.

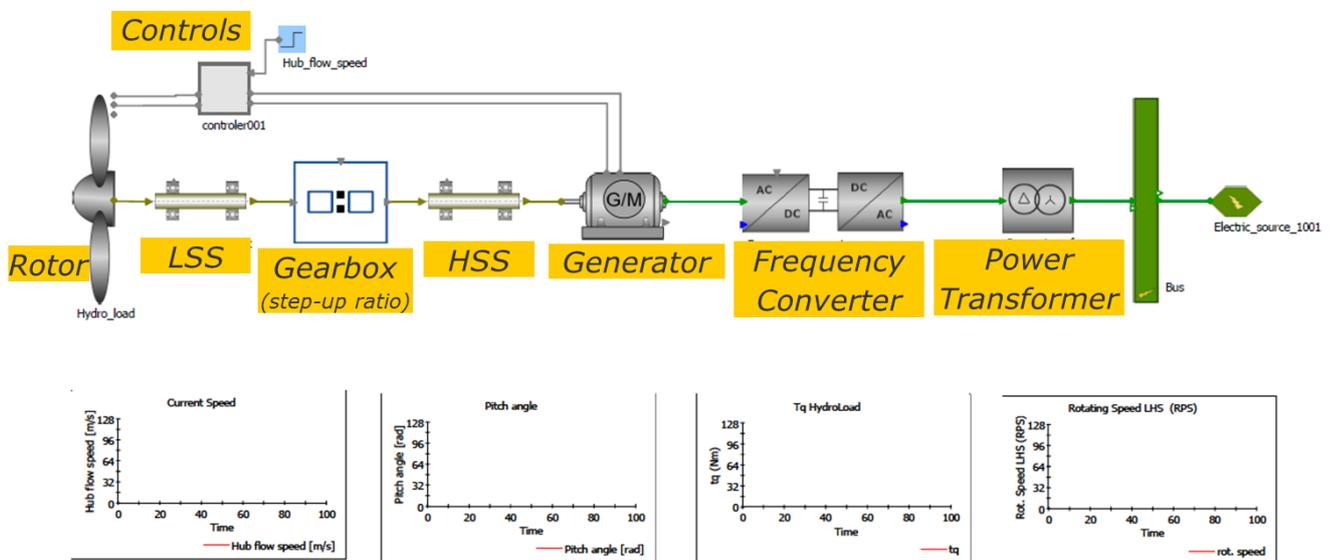


Figure 9: Systems engineering model of tidal PTO

8.1	Low speed shaft
8.3	Gearbox
8.3.1	Carrier
8.3.2/3/4	Planet1/2/3
8.3.5/6/7/8	Gear1/2/3/4
8.3.9	Ring
8.3.10	Sun
8.4	High speed shaft
12.1	Generator
12.2	Frequency Converter
12.2.1	Sub-sea integral within turbine
12.3	Transformer
12.3.3	Sub-sea integral within turbine
12.4	GIS HV switchgear
12.4.1	Sub-sea integral within turbine

Table 4: Main Drivetrain & Electrical Components

The scope of this simplified example is to demonstrate a design for reliability methodology under various operating conditions in the entire loading envelope of the system. The reliability of the gearbox gear wheels was chosen to be studied. The model input is the sea water flow speeds at the turbine hub height, which in this case is a varying in time operating input profile. In Figure 10 an example of such a profile (timeseries) is given for a period of 1000h. The reliability simulations often require periods of simulations of the order of thousands hours, meaning that fast transients such as electrical dynamics are not taken into account. Moreover for this demonstration example no drivetrain vibrations are considered.

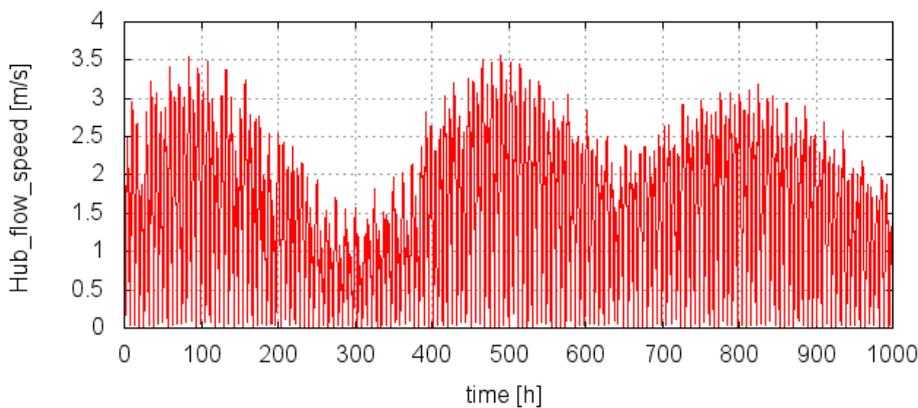


Figure 10: Timeseries of hub flow speed [m/s], indicative values

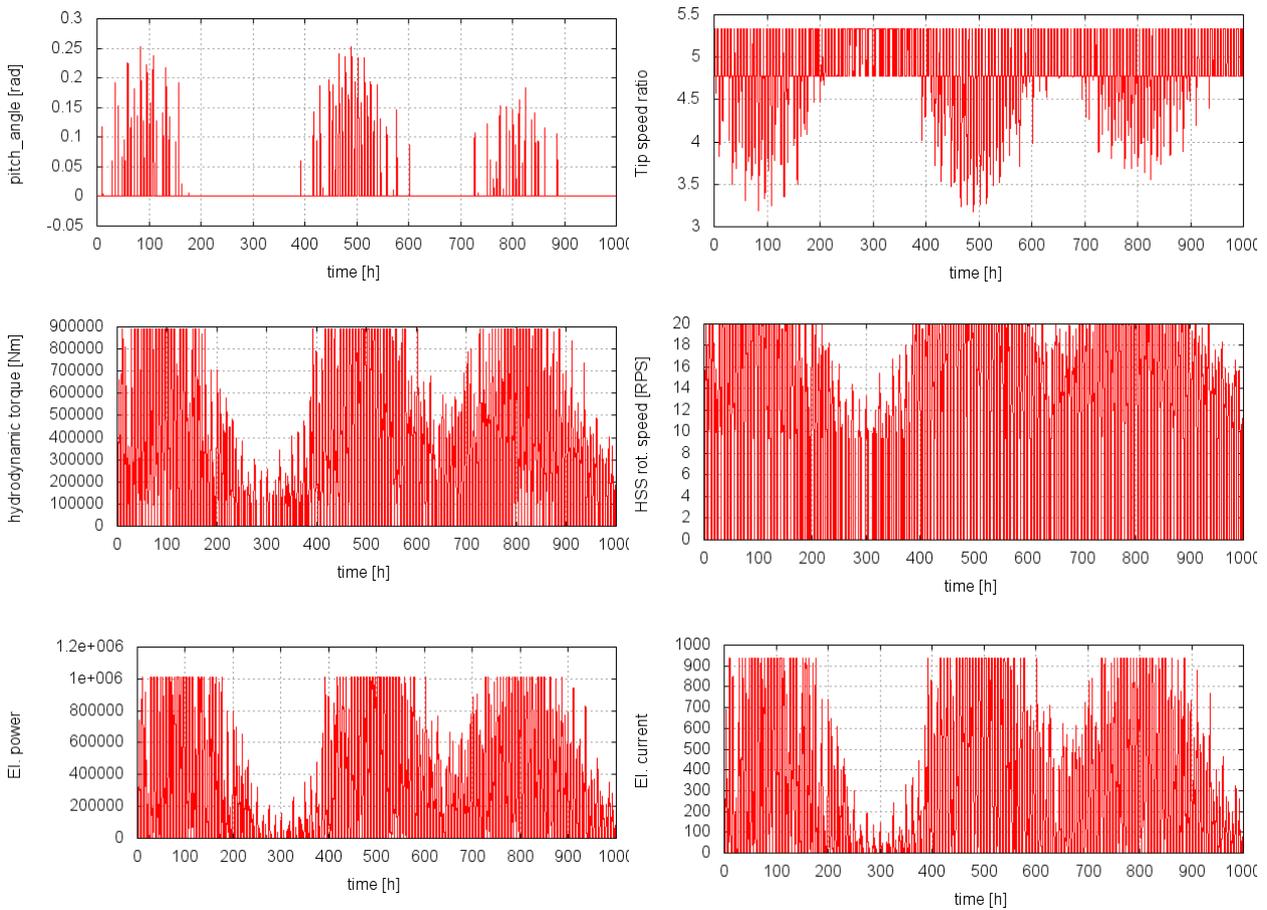


Figure 11: Top-left: pitch angle [values corresponding to speeds below cut-off are neglected for viewing reasons]; Top-right: tip speed ratio [values corresponding to speeds below cut-off are neglected for viewing reasons]; Middle-left: hydrodynamic torque; Middle-right: High Speed Shaft (HSS) rotating speed; Bottom-left: Electrical power from generator; Bottom-right: Electrical current produced from generator

The hydrodynamic information is provided to the model through a look-up table where the rotor power coefficient is tabulated for different tip speed ratios and pitch angles. This information have been produced by performing steady state simulation runs in Tidal Bladed [9].

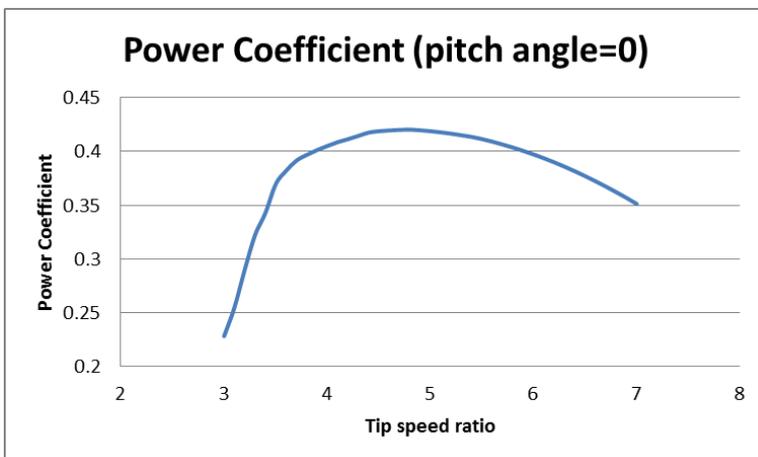


Figure 12: Rotor power coefficient curve for zero pitch angle

For the purposes of the reliability evaluation a more detailed gearbox model should be included. The latter shall take into account the specifics of the gearbox assembly and basic geometries (see Figure 14). Moreover the model should be capable of estimating the reliability key indicators related to the gearbox. The updated flowsheet model can be seen in Figure 13.

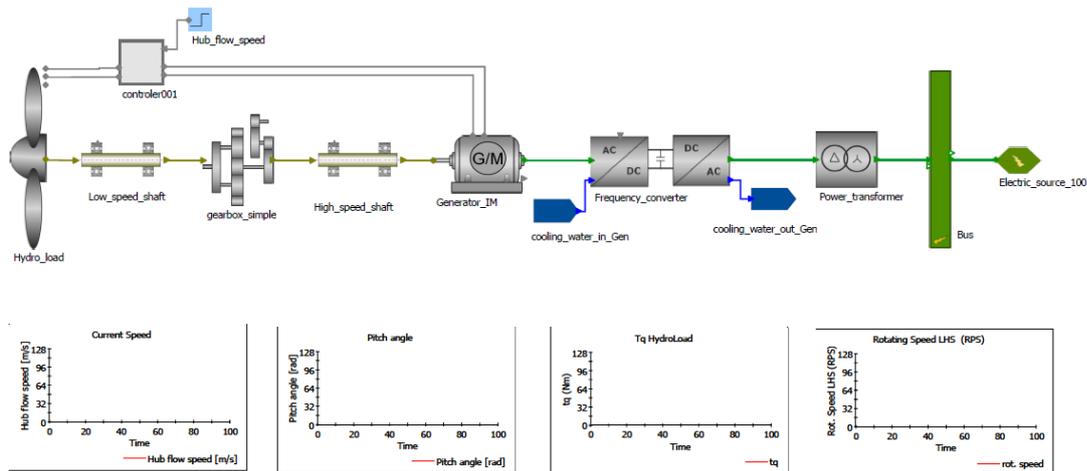


Figure 13: Systems engineering model of tidal PTO

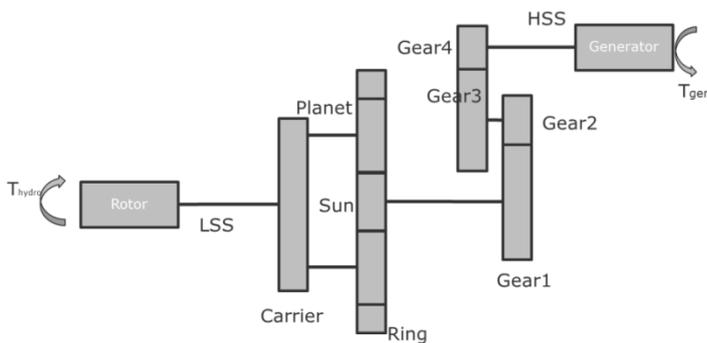


Figure 14: Epicyclic gearbox with two parallel stages

For the purposes of this demonstration example, the gearbox is assumed to be comprised solely of the gearwheels of Figure 14. The key failure indicators (paragraph 7) for this particular equipment are the gear load, gear speed, the temperature (that affects also the lubricant viscosity) and possible misalignment. According to reference [5] the failure rate of each gear, λ_G , could be estimated by Eq. 14:

$$\lambda_G = \lambda_{G,B} \cdot C_{GS} \cdot C_{GP} \cdot C_{GA} \cdot C_{GL} \cdot C_{GT} \cdot C_{GV} \tag{Eq. 14}$$

Where λ_G is the failure rate [failures/operating hours], $\lambda_{G,B}$ is the base failure rate as provided by the manufacturer for specific operating conditions. The correction multiplying factors $C_{G?}$ correspond to corrections that take into account the deviation of the key indicators from the designed operating conditions:

- C_{GS} : Gear speed

- C_{GP} : Load
- C_{GA} : Misalignment
- C_{GL} : Lubricant (viscosity)
- C_{GT} : Temperature
- C_{GV} : AGMA service factor

The gear speed multiplying factor can be calculated by, reference [5]:

$$C_{GS} = k + \left(\frac{v_0}{v_d}\right)^{0.7} \tag{Eq. 15}$$

Where v_0 is the operating speed and v_d is the design speed, k is a constant (=1)

The gear loading multiplying factor can be calculated by:

$$C_{GP} = \left(\frac{L_0/L_D}{k}\right)^{4.69} \tag{Eq. 16}$$

Where L_0 is the operating load and L_d is the design load, k is a constant (=1)

The failure probability (unreliability) at a time t is given by the Eq. 17:

$$P_F(t) = 1 - \exp\left[-\int_0^t \lambda_G(\tau) d\tau\right] \tag{Eq. 17}$$

The failure model described by Eq. 14-Eq. 17, is programmed in a generic and reconfigurable way and it can be inserted in the overall flowsheet PTO model when life-time reliability calculations of the gearbox constituents are required. In Figure 15 the failure probability, estimated by Eq. 17, of two gears that are parts of the gearbox assembly is presented.



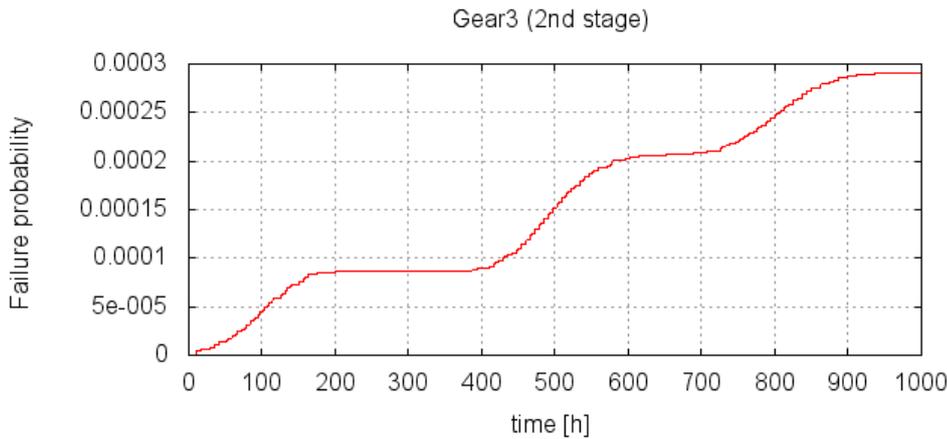


Figure 15: Failure probability of gear1 (1st stage) and gear2 (2nd stage) during operating time [h]

After adjusting/determining the individual component failure rates, the next step (Figure 1) is to estimate the reliability metrics for the PTO system and/or its subsystems of interest (in this example, a subsystem of interest could have been the gearbox assembly). Based on the taxonomy of Table 4, the gearbox Reliability Block Diagram (RBD) [20, 21] has a simple series form (Figure 16). This can be also expressed in the form of a Fault Tree (FT) [21, 22] where the gearbox failure event is the top event and the basic events are the gearbox assembly subcomponent failures (Figure 17). For such a simple case both graphs (RBD and FT) can be solve following logical decision rules that give:

$$R_{(8.3)} = \prod_{i=1}^{10} R_{(8.3.i)} \tag{Eq. 18}$$

$$\begin{aligned}
 P_{F(8.3)} &= P[F_{(8.3.1)} + F_{(8.3.2)} + \dots + F_{(8.3.10)}] \tag{Eq. 19} \\
 &= \sum_{i=1}^{10} P[F_{(8.3.i)}] - \sum_{j=2}^{10} \sum_{i=1}^{j-1} P[F_{(8.3.i)} \cdot F_{(8.3.j)}] \\
 &+ \sum_{j=3}^{10} \sum_{k=2}^{j-1} \sum_{i=1}^{k-1} P[F_{(8.3.i)} \cdot F_{(8.3.j)} \cdot F_{(8.3.k)}] - \dots \\
 &+ (-1)^m P[F_{(8.3.i)} \cdot F_{(8.3.j)} \cdot \dots \cdot F_{(8.3.10)}] = 1 - R_{(8.3)}
 \end{aligned}$$

where $R_{(8.3)}$ is the gearbox reliability (the subscript 8.3 refers to the taxonomy number of the component, (see Table 4), correspondingly $R_{(8.3.?)}$ and $F_{(8.3.?)}$ are the reliability and the failure probabilities for the subcomponents with taxonomic numbers 8.3.?. Moreover, it is $P[A \cdot B] = P[A] \cdot P[B]$ and $P[A + B] = P[A] + P[B] - P[A]P[B]$.

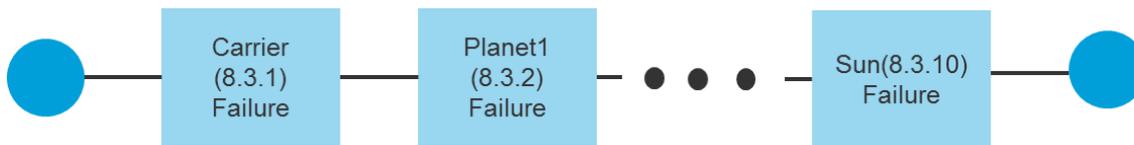


Figure 16: RBD of the gearbox

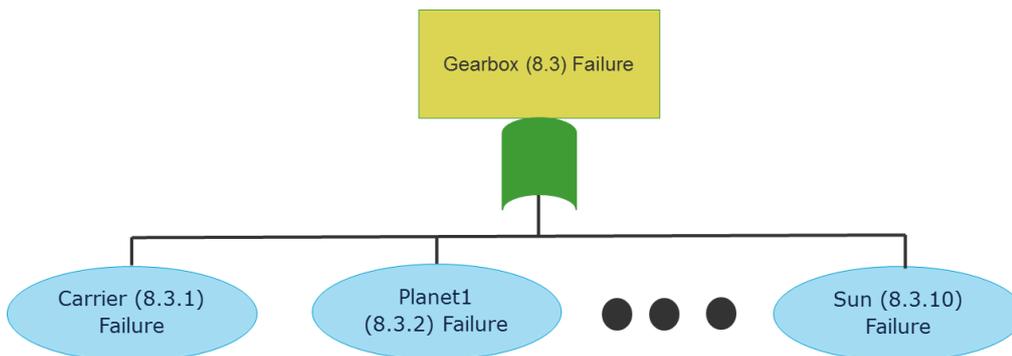


Figure 17: Gearbox FT

Although in this simple case an analytical solution is easy to obtain, when it comes to more complex cases (especially in fault tolerant systems as the tidal turbine PTOs) and more complex system fault logics (e.g. as in Dynamic Fault-Trees [11, 23]) the use of stochastic simulations such as Monte-Carlo and Discrete Event Simulation techniques [10][11] may be required. A key contributing factor to the need of employment of such approaches is the fact that the component failure rates are depending on the physical process of the system. This means that both the physical process (deterministic system state equations, paragraph 8.2) and the stochastic events (in here, the failure events) are interrelated and have to be solved concurrently.

Approaches capable of doing this are a subject of recent research in systems reliability [24-28] and have their origins in the nuclear industry. In the relevant literature this approach is mentioned as “Dynamic probabilistic risk assessment, DPRA”, [29] or more generally “Probabilistic dynamics”, [12, 13] or “Dynamic reliability”, [30, 31]. Although a formal Markovian mathematical framework is established (that also incorporates the physical behaviour), namely the Chapman-Kolmogorov equations [12, 30], the direct solution of these equations is a computationally demanding task even for simple systems and therefore biased and analogue Monte-Carlo simulation techniques [10, 12, 32] are usually employed. Moreover, by employing stochastic simulation techniques the epistemic uncertainties related to model parameters, measurements and environmental factors can be quantitatively assessed.

With this simple example the following aspects of the proposed methodology have been highlighted:

- The value of the Systems Engineering approach: the combined effect the system components (including controls) is taken into account in order to estimate the operating parameters of the system and the reliability key indicators.
- Assessment of PTO system reliability under various conditions of operation in the entire loading envelope of the system.
- Development and synthesis of a PTO model capable to include physics of failure and/or empirically based component degradation models for critical reliability components.
- Mathematical modelling (i.e. through model's process variables) and quantitative estimation of the key reliability indicators (temperatures, pressures, stresses, etc.) at various system conditions.
- Soft-sensing for support of condition monitoring: gear load (force) values cannot be directly measured, but can be produced by utilising in a combined manner signal measurements and simulations.
- Development of a library of reconfigurable components models for the PTO system analysis including physics of failure.

Appendix V

The Recommended Practice (RP) - Design for Reliability of Power Take-Off will be developed as the experience and knowledge is validated and consolidated throughout TiPTORS Phases 2 and 3. The preliminary Table of Contents offers a view of the aspects to be covered in the RP and the level of detail required. This table of contents also offers an understanding of the tasks to be performed during the next phases.

1. Introduction
 - 1.1 General
 - 1.2 Scope and Limitations
 - 1.3 Definitions
 - 1.4 Symbols
 - 1.5 PTO Description
 - 1.5.1 PTO taxonomy
 - 1.6 Methodology
 - 1.6.1 Design for Reliability
 - 1.6.2 Modelling Philosophy
 - 1.6.3 Reliability and Costs
 - 1.6.4 Use of Surrogate Data
 - 1.6.5 Use of Physics of Failure
 - 1.7 Reliability Processes
 - 1.7.1 Reliability methodologies
2. Reliability Data
 - 2.1 Taxonomy and Boundaries
 - 2.2 Contents
 - 2.2.1 Limitations and Applicability
 - 2.2.2 Key indicators
 - 2.3 Establishment of Database
 - 2.4 Selection of data
 - 2.5 Modification of Surrogate Databases
 - 2.5.1 Identification of Key Indicators
 - 2.5.2 Operational Differences
 - 2.5.3 Methodology for Adjustments of Reliability Data
 - 2.5.4 Uncertainties
3. Failure Modes
 - 3.1 Application of FMECA
 - 3.2 Identification of Failures Mechanisms and Criticality
 - 3.3 Relation between Failure Modes, Mechanisms and Reliability Information
 - 3.4 Detection and Key Indicators
4. Physics of Failure
 - 4.1 General
 - 4.2 Description of main Physics of Failure
 - 4.3 Modelling Considerations
 - 4.4 Uncertainties
 - 4.5 Estimation of Reliability
5. Simulation

- 5.1 Load Cases
 - 5.1.1 General Considerations
 - 5.1.2 Design Philosophy and Selection of Load Cases
 - 5.1.3 Steady State
 - 5.1.4 Transient Conditions
 - 5.1.5 Accidental Scenarios
 - 5.1.6 Loading Interfacing with PTO Model
 - 5.1.7 Loading Resolution
- 5.2 Physics of Failure
- 5.3 Modelling of PTO
 - 5.3.1 Pitch System
 - 5.3.2 Low Speed Shaft
 - 5.3.3 Main Bearings
 - 5.3.4 Gears
 - 5.3.5 Couplings
 - 5.3.6 Generator
 - 5.3.7 HV Switchgear
 - 5.3.8 Inverter
 - 5.3.9 LV Switchgear
 - 5.3.10 Yaw System
 - 5.3.11 Control Systems
 - 5.3.12 UPS
 - 5.3.13 Cooling System
 - 5.3.14 Bilge System
 - 5.3.15 Lubrication System
 - 5.3.16 PTO Support
- 5.4 Selection of Key Indicators
- 5.5 Effect of Maintenance (Degradation with Time)
- 5.6 Sensitivity Studies
- 5.7 Processing of Results

- 6. Technologies for assessing Reliability
 - 6.1 General
 - 6.2 Representation of PTO
 - 6.3 Reliability Assignment
 - 6.4 Processing of Results

- 7. Cost Model
 - 7.1 General
 - 7.2 Modelling
 - 7.2.1 Overall Boundaries
 - 7.2.2 Initial Costs
 - 7.2.3 Consideration of Serial Production
 - 7.2.4 PTO Representation
 - 7.2.5 Utilisation of reliability data and stochastic analyses
 - 7.2.6 Sensitivity
 - 7.2.7 Acceptance Margins
 - 7.3 Processing of Results

- 8. Simulation Verification
 - 8.1 Calibration against Measurements
 - 8.2 Monitoring Requirements
 - 8.3 Variability of Measurements

- 8.4 Costs Model Variability
- 8.5 Definition of Actions

- 9. Condition Monitoring
 - 9.1 Sensors & sensor reliability
 - 9.2 PTO Condition Monitoring scheme
 - 9.3 In-service update of failure models and reliability models
 - 9.4 Continuous system inspection and state identification
 - 9.5 Development of reliability database
 - 9.6 Soft-sensing

- 10. References

- 11. Commentary

- 12. Examples

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