Is it a showstopper? Reliability assessment and criticality analysis for Wave Energy Converters

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Abstract

The reliability of wave energy converters (WECs) is a key issue that has to be addressed in order to make them a viable energy option. At this stage of early industrial development the reliability assessment of WECs is a challenging task. In this paper existing reliability methods, namely Reliability Block diagrams, have been applied to a notional configuration. It was found that omnipresent lack of failure rate data makes rather crude adjustments of often generic data necessary which generally lead to rather unfavourable and highly uncertain results. Reliability data is either not available due to sparse field experience or is kept confidential, within different project developments to secure competitive advantages and intellectual property.

In order to foster the progress of the marine energy industry, the reliability of devices must be demonstrated and improved. This requires a joint effort between industry stakeholders to collect, share and disseminate existing failure knowledge and future operational experience.

Keywords: Failure rate adjustment, Marine energy, Reliability assessment, Reliability Block Diagrams

Nomenclature

λ_B = base failure rate
π_E = environmental adjustment factor
π_{FM} = specific failure mode factor
π_{DS} = data source uncertainty factor
π_C = component failure rate
R_{Sys} = system reliability
R_{PT} = reliability power transmission
R_{PTO} = reliability power take-off

1 Introduction

Ocean wave energy is becoming a field of great interest as it offers both sustainable electricity generation and the emergence of a new industry sector. Currently several wave energy devices are proceeding from the prototype stage towards commercial deployment. Whereas prototypes require the demonstration of, e.g. fundamental working principles, conversion efficiency and survivability; commercial deployment is driven by plant-performance indicators like reliability, availability and maintainability which heavily influence cost and revenue. A concise reliability assessment of WECs forms the basis for the commercial case. The necessary long term investments make reliability a key challenge towards developing economically viable wave energy devices.

2 Challenges to Conventional Reliability Analysis

2.1 Traditional Approaches

Reliability analysis is a well-developed statistical tool for predicting performance of installations in many industries. Many of the tools and methods currently in use were developed by the aviation industry, where reliability of components is essential as failures can have extreme consequences in terms of loss of life. The methods developed for the aviation industry [1] have since been translated to the oil and gas industry where, as well as the safety and environmental consequences, equipment failure can have large consequences in terms of lost profits if an installation has to suspend production for any period of time. As the wave energy industry matures, reliability is again of high importance, with the consequence of failures requiring, in many cases, expensive and complex interventions, which must be carried out in an

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inherently harsh environment, even at the prototype stage.

There are several tools used for reliability prediction and lifecycle management with the aim of optimising availability of equipment, and some of these are described briefly below.

2.1.1 Reliability Block Diagrams

Reliability Block Diagrams (RBDs) provide a diagrammatical representation of a system's reliability performance. The development of an RBD requires the definition of success for the system (such as its ability to produce power), followed by a division into blocks of equipment which reflect the logical behaviour of the system. Each block should be statistically independent and as large as possible. Each block then has an associated probabilistic failure rate based upon the arrangement of equipment it represents (considering such aspects as single point failures, redundancy, etc.). By linking all blocks up into a 'success path', it is possible to produce a stochastic representation of the system's probability of failure in a given period of time.

2.1.2 Fault Trees

The fault tree provides a diagrammatic representation of a system's reliability. In this case, the objective is to estimate the probability of a critical fault occurring. Fault trees provide a static picture of the combinations of failures and events that can cause the specified critical fault to occur. Fault tree analysis may be made quantitative by applying probabilities to the failures and events that have to occur to result in the specified event.

2.1.3 Availability Assessment

A standard practice in the performance forecasting industry is to use statistical methods based on discrete event simulation, with the major output of such a method being the total availability of the system over the given timeframe. The methods require that each component or sub-system is assigned a probabilistic distribution representing the statistical description of its time to failure, and another distribution for the time to repair, along with the interval between planned maintenance. The model chooses a value for the time to failure of each component from the distributions and runs the simulation until the first event occurs (either a failure or a planned maintenance), at which time an action is usually required (which could be shutdown for maintenance or maintenance on-line depending on the nature of the failure). The downtime associated with the event is calculated, and the simulation runs to the next event. Once the simulation has been run for the specified lifetime of the system, the total downtime is calculated and a value for the system availability in that time can be produced. This provides a SINGLE estimate of the properties of the system governed by statistical variations and the simulation (model) must therefore be run many times to obtain the statistical distributions for the system response to determine the most likely values, and provide an estimate of uncertainty in the result. The level of uncertainty in the analysis ultimately depends upon the accuracy of the input parameters (failure rates and distributions). It is also possible to run a sensitivity analysis, which indicates the factor(s) that have the largest impact (positive or negative) on the result, and this can be used to target resources in the most cost-effective manner.

2.2 Lack of Data

In mature industries, such as the oil and gas industry, there is a considerable history and experience in the use of specific equipment, and consequentially a large volume of reliability data is available. In some cases this has been collated in databases (such as OREDA [2]), which are consulted by reliability analysts for use in simulations. The production of this database had a considerable influence on the development of the offshore oil and gas industry.

While this data includes several components and sub-systems which are regularly employed in the design of new wave energy converters, there are several problems with the application of these data in reliability analyses for these new systems. The most obvious problem is often the novel use of an existing technology, either with a new duty cycle, or in a new environment. Such changes in the way a component is employed will have a large impact on the time to failure and the critical failure modes of the technology, and the existing failure data may no longer be directly applicable.

A larger, albeit less obvious problem is the requirement for routine maintenance in order to keep the equipment performing as required. Most offshore installations are frequently (if not constantly) manned, and simple regular maintenance routines are employed to prevent large failures from occurring. Data from databases such as OREDA presents failure rates and interventions outside this routine maintenance (i.e. only unplanned interventions), with the implication that use of these data is only accurate on the assumption that routine maintenance is possible on the equipment. For many designs of wave energy converter, because of the necessarily hostile environment into which they will be installed, maintenance may be impossible for a large proportion of the year. This presents a large problem for the supply of this equipment as times between interventions are likely to be significantly greater than for conventional installations.

2.3 IP / Competitive Advantage constraints

A further complication comes with the competitive nature of the industry at this stage. Reliability data gathered by a device developer represents a significant investment by them, but is also seen to provide a competitive advantage over competitors. For this reason, device developers are at present unlikely to be willing to share any data they produce.

There have been similar problems in the offshore oil and gas industry, in terms of presentation of data in a confidential manner. This was overcome in the OREDA project [2] by using a procedure for reporting and presenting reliability data from operators in a manner which does not allow for identification of specific manufacturers, and the processes developed are formalised in the international standard ISO 14224. In the wave energy industry in its present state, the device designs are so specific that it is again likely to be difficult to maintain the anonymity of the device. However, the solutions and procedures to this problem have been developed during the OREDA project as noted above, and the benefit of such collaboration between developers would be to solve a problem which it is extremely difficult (if not impossible) for any one developer to solve on their own due to time and resource constraints, not to mention the problems with small sample sizes.

These issues demonstrate the importance not only of collection of reliability data for the wave energy industry, but also of the collaboration between device developers to provide sufficient data to solve the problems which all developers will face. The experience to develop such a database exists from previous projects, which would allow the data to be processed into a useful form for future reliability assessments.

2.4 Necessity of Crude Adjustments

Many companies currently designing wave energy converters aim to use existing, proven technology as far as possible. However, as described above, the equipment is generally used in a slightly different way to its usual application, either in terms of loading, operating environment or accessibility for maintenance. This necessitates the adjustment of existing reliability data for the new aspect in the design.

This assessment of the level of adjustment can be made by qualitative means by comparing some aspects of the application of the component between the new system and that from which the reliability data was collected (for example, movement from a well controlled, dry environment to a more corrosive environment in the splash zone can be expected to result in an increase in the rate of corrosion, and therefore an increase in the failure rate for the associated failure modes). In some cases, this comparison can be made quantitatively by comparing lifetime loading and duty cycles for the component, and adjusting the frequency of usage-based failure modes based on the difference.

Although there may be some logic behind these methods, it is important to note that they are far from accurate. The effect of the changes in application on the given failure rate is not easily estimable, and will increase the uncertainty in the overall estimation of reliability as the boundaries of the failure rate distributions are moved, a little or a lot depending upon the ‘fit’ of the data to the application. For this reason, it is important to have some means of producing useful reliability data (for similar duty cycles in similar environments) for some critical components used in wave energy converters, for the benefit of device developers.

2.5 Component Testing

The most obvious, and probably most feasible, way of producing reliability data in the near future will be by component lifecycle testing. As discussed in previous papers [3], this may be used to circumvent the problems with investment and competitive advantage for the device developers, as the investment can be made by other stakeholders in the industry. Providing the components for testing are selected correctly (i.e. not specific to any one device) and the data is presented in a confidential manner using the practices developed in projects such as OREDA, it should be possible to begin the production of useful data on failure rates and failure modes. The most efficient way of achieving this initially may be to target components for which data already exists and see how the reliability data should be modified for WECs, providing guidance for other components. This would likely require fewer resources than testing all components to generate reliability data.

The selection of the criteria for which components to test, and the environment and loading for testing, is a complex issue and will require some discussion.

3 Case study

Similarly to the situation of the processing plant industry in the late 1990s, the lack of comprehensive data on equipment failures and load distributions poses the main limitation to reliability assessments [4]. An approach based on the assumption of constant failure rates and crude data adjustments in combination with a sensitivity analysis appears to be the best currently available in order to determine the reliability and identify critical items of WECs. At later stages environmental, operating and maintenance conditions may be revised to evaluate their impact on degradation processes, failure frequencies and repair/replacement times. This case study investigates the reliability of a generic hydraulic WEC, due to the fact that sufficient technical information and failure rate data could be found for this type of device which mainly comprises off-the shelf components. The intention of this study is to indicate the problems that an external agency will have in developing realistic assessments of the reliability of such a system using generic data. It must be stressed, that the analysis does not intend to derive actual reliability figures for any specific device, and serves only to illustrate the problem of reliability prediction for WECs.

3.1 Methodology

In the following, the functional structure of a system is illustrated by Reliability Block Diagrams (RBDs). The considered timeframe is the useful life of the system, i.e. the bottom of the bathtub-curve with assumed constant failure rates. The reasoning for both choices lies in the scarce information for WECs. A more detailed knowledge of the system layout and single functions would be necessary to conduct more sophisticated analytical state-space models (e.g. Markov chains) and system simulations. Operational experience and lifetime data, crucial to consider early failures and wear-out mechanisms are sparse information. Thus, it is difficult to abandon the assumption of constant failure rates which entails a tendency to underestimate failure rates at early stages in product life. This reliability assessment comprises six primary steps:

1. Development of a system block model
2. Collection of component failure rates from reliability databases
3. Adjustment of failure rates towards the expected application / environmental effects
4. Data input to the system model and reliability calculation
5. Data variation
6. Result analysis

3.1.1 System Block Model

The purpose of a WEC system is the generation of electricity utilising the energy of the waves. Despite the different constructions and working principles of WECs, from a functional viewpoint there exist great similarities [5]. Fig.1 shows a generic RBD for a wave energy device (based on [6]). The WEC system comprises four sub-systems, which are common to all devices.

In the case of near shore and offshore devices the moorings warrant the station keeping of the device. The structure provides shelter for the power take-off (PTO) machinery, maintains the system's level of buoyancy and withstands applied loadings. The PTO converts the wave energy input into electricity, which in turn is transmitted to shore via the power transmission sub-system. The transmission sub-system for offshore applications can be further divided into the busbar which provides electrical connection within the device; the transformer increases the voltage level; a circuit breaker which allows the separation of the device from the grid; the umbilical enables data transfer to and from the device and the sea cable conducts the electricity to the shore grid station. The other sub-systems are highly device-specific and depend on both conversion principle (hydraulic; air- or water turbines; linear permanent magnets) and location.

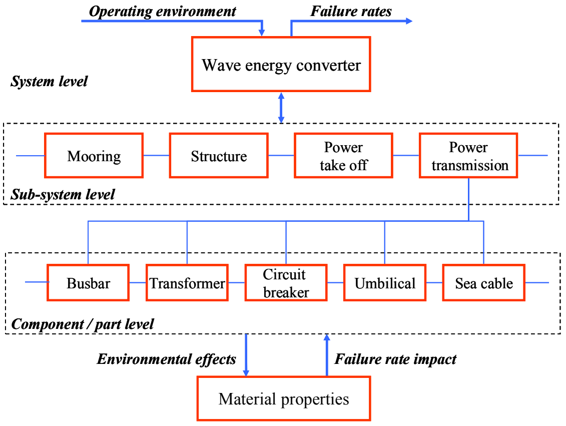


Figure 1: Generic Reliability Block Diagram for wave energy converter

3.1.2 Reliability data and adjustment

The data used for the reliability assessment was collected from various sources and databases [2, 7-11] available in the public domain. An already existing embryonic database compiled by [12] was extended and failure rate adjustments accounting for data sources and environmental loading conditions were used. The base failure rate data adjustment in order to estimate the failure rate of the component λ_C follows the general methodology of [11] and comprises four consecutive steps:

1. Sourcing of base failure rate data λ_B and additional information
2. Environmental factor π_E application;
3. Specific failure mode factor π_{FM}, if applicable
4. Data source uncertainty factor π_{DS}

$$\lambda_C = \lambda_B \cdot \pi_E \cdot \pi_{FM} \cdot \pi_{DS}$$

Equation 1: Base failure rate adjustment

The adjustment of failure rates to account for environmental influences that have not been prevalent during the failure rate collection and the resulting base failure rate is widely used in reliability predictions. The parts stress analysis proposed in [11] involves a simple multiplication of base failure rates with empirical factors.

The difficulty lies in the determination and applicability of those factors towards the wave energy application. The factors in the MIL-HDBK are given for electronic parts and components, where the base failure rate has been established through laboratory experiments. So if, e.g. industry specific failure rates are used for an electric component of a WEC (e.g. circuit breaker) these factors cannot simply be applied. In this case it might be advisable to calculate the difference of distinct environmental conditions, which are then more applicable. Table 1 presents a matrix of factors that can be used to adjust failure rates from various environments towards the environment that will be encountered for WEC applications (highlighted in grey). The stress level in naval conditions is about 10-15 times higher than in benign laboratory conditions

(G_B), between 1.5-2.5 higher than in ground fixed (G_F), and 1-1.5 times higher than in mobile applications. The conversion from a sheltered marine environment N_S to an unsheltered or undersea marine condition, as it might be necessary for the application of OREDA data towards WEC, implies a factor of 1.4-1.6.

				Base failure rate environment						
				G_B	G_F	G_M	N_S	N_U	N_{UU}	N_{SB}
			Factor	0.38	2.50	4.20	4.00	5.70	6.30	4.00
Application environment	**Environment**									
	Ground, benign,	G_B	0.38	1.00	0.15	0.09	0.10	0.07	0.06	0.10
	Ground, fixed	G_F	2.50	6.58	1.00	0.60	0.63	0.44	0.40	0.63
	Ground, mobile	G_M	4.20	11.05	1.68	1.00	1.05	0.74	0.67	1.05
	Naval, sheltered	N_S	4.00	10.53	1.60	0.95	1.00	0.70	0.63	1.00
	Naval, unsheltered	N_U	5.70	15.00	2.28	1.36	1.43	1.00	0.90	1.43
	Naval, undersea	N_{UU}	6.30	16.58	2.52	1.50	1.58	1.11	1.00	1.58
	Naval, submarine	N_{SB}	4.00	10.53	1.60	0.95	1.00	0.70	0.63	1.00

Table 1: Environmental loading adjustment factors for different base failure rate environments [11]

Environmental adjustment factors imply a multitude of unspecified failure causes. A more accurate approach is the application of failure mode specific factors which is applied by the chemical processing industry [13]. For a specific component (e.g. a valve) the failure causes (process medium factors, external environmental factors and location factors) are identified and subsequently quantified, so that particular failure rate influences can be considered (e.g. an adjustment factor of 1.21 for a corrosive atmosphere). The prerequisite to derive cause specific failure rate adjustments is a highly detailed data collection, which specifies the exact failure modes and environmental conditions. This increased effort is often not made for reliability databases because it incurs higher cost and organisational complexity. Nevertheless, it appears to be worthwhile for the wave energy industry to collect more detailed information. More accurate assessments through precise failure rate adjustments could contribute to decrease safety margins and cost.

During the adjustment a double consideration of stressors is likely to occur, but intended. As an example, the environmental factor for a marine environment already implies the failure mode of corrosion. In the case of a component that is particularly susceptible to corrosion this can be accounted for by an additional failure mode factor. Consequently, the adjustment of failure rates is always subject to interpretation and judgement of the analyst. Where double consideration of stressors occurs, the resulting failure rates tend to be more pessimistic.

Data uncertainty of raw failure data that has not been described statistically is usually expressed in terms of confidence intervals [14]. As the original sample is often unknown, the mean failure rates presented in reliability databases cannot be assigned to confidence intervals. Therefore, the following uncertainty bands are assigned to account for different data source qualities, i.e. a modification of upper and lower boundaries [15]

- ± 10% for site- and industry specific data
- ± 30% for generic data sources
- ± 50% for failure rates derived by expert judgment

3.1.3 Reliability calculation

As a next step it is necessary to establish the related time-dependent reliability values which account for the system configuration in order to describe the system behaviour and identify critical components. Stemming from reliability theory, the formulas listed in Table 2 are applicable. In addition to the constant failure rate assumption it is further supposed that the system is not repaired within a 12 month period. One year is usually regarded as the shortest practical maintenance interval for the majority of devices [5], allowing access during larger weather windows in summer. Thus, the yardstick for overall system reliability is a 12 month period.

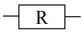
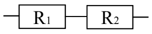
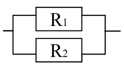
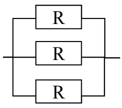
RBD configuration	**Reliability** **no repair, constant failure rate**	**General system reliability** **for n blocks**
	$R = \exp(-\lambda t)$	-
	$R = \exp[-(\lambda_1 + \lambda_2)\, t]$	$R_{System} = \prod_{i=1}^{n} R_i$
 Active	$R = \exp(-\lambda_1 t) + \exp(-\lambda_2 t)$ $-\exp[-(\lambda_1 + \lambda_2)\, t]$	$R_{System} = 1 - \prod_{i=1}^{n} (1 - R_i)$
 Active 1/3	$R = 3\exp(-\lambda t) - 3\exp(-2\lambda t)$ $+\exp(-3\lambda t)$	$R_{System} = 1 - \prod_{i=1}^{n} (1 - R_i)$
Active 2/3	$R = 3\exp(-2\lambda t) - 2\exp(-3\lambda t)$	$R_{System} = 1 - \sum_{i=0}^{m-1} \binom{n}{i} R^i (1-R)^{n-i}$

Table 2: Reliability calculations for different system configurations

3.1.4 Data variation

A sensitivity analysis can be used to investigate the model response towards a parametric or a structural change and allows a determination of the uncertainties that are coupled to the model parameters. In the case of an insensitive model an estimated parameter may be used rather than a highly precise value. Large changes of system behaviour and outcomes for a parameter enable the identification of leverage points [16].

In the present analysis failure rate data was categorised into three data source classes (site/industry specific; generic, expert judgement) in order to assign uncertainty boundaries. These upper and lower failure rate boundaries were used as input values for a single factor sensitivity analysis, which shows the effect of each component on the sub-system failure rate. This variation was then compared against the mean failure rate of the sub-system, allowing the identification of those components which have the highest impact due to high uncertainties and/or high failure rates.

3.2 Reliability assessment for a hydraulic WEC

As discussed earlier, the resulting failure rates of the assessed sub-systems *should not* be taken as an absolute figure, but as a general guiding parameter. In extreme cases component failure rates may vary by an order of magnitude if the upper/lower value or different sources are considered. However, within the sub-system prediction, the relative failure contribution of each component provides a valuable tool in design analysis [14]. The illustrative WEC system can be divided into four different sub-systems:

- *Mooring*: Assuming a slack-moored device.
- *Structure*: A thin-walled 20 mm steel structure is assumed for the main structure.
- *Power take-off system* This subsystem comprises a hydraulic system with parallel units to provide redundancy

Mooring, Structure and Power transmission are assumed to operate in series (Figure 2), i.e. if one of these sub-systems fail, the entire plant fails and is not able to produce electricity. The units for the power take-off operate in parallel in a 'k out of 6' mode. Power production can be maintained, although at reduced level, if individual units fail.

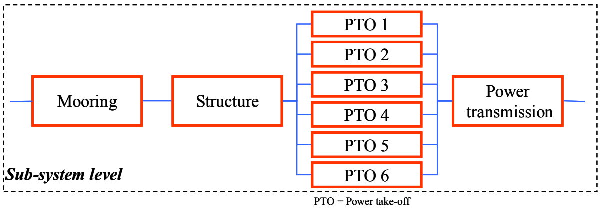


Figure 2: WEC Reliability block diagram sub-system

It must be mentioned, that in this case study, only the reliability is assessed. The ability of the device to survive certain failures would be different, as a mooring failure could lead to a loss of the entire device whereas the failure of a PTO unit would have lower consequences than total loss, e.g. loss of revenue.

3.2.1 Mooring

From a reliability point of view, in the event of a mooring failure, operation would stop in order to repair/replace the damaged mooring. This relates to an in-series RBD configuration of the mooring arrangements.

On a component level three components can be differentiated, the anchor, the mooring cable (or chain) and the attachment to the device. The failure rate database does not provide information about these single components. However, incidents and mooring failures have been continuously monitored for Floating Production Systems (FPSs) in the offshore oil and gas industry. A study by DNV reports that a failure of FPS mooring systems in the North Sea occurs once every 5.4 years [17], which equals a failure rate of $\lambda_{Mooring}$, FPS = 0.185/a.

FPSs are used in the oil and gas industry to receive process and store crude oil at offshore production wells in deep water. Most of these vessels are moored to a central turret within the hull. This allows the FPS to rotate freely around the point of mooring to direct the bow into the prevailing wave, current or wind direction in order to minimise loadings.

As the environmental conditions can be assumed to be very similar, and both systems are designed to be permanently moored the reported failure rate is used throughout this assessment. Nevertheless, there are significant differences in mooring designs for WECs. The required safety factor is higher in the oil industry due to the potential loss of life and risk of large environmental pollution as consequence of failure [18]. These risks are not apparent for unmanned WEC, so the safety factors (and installation cost) could be reduced but would result in higher failure rates. Thus, the stated mooring failure rate is likely to be a lower bound for WECs.

Due to the assessment of reliability rather than survivability and the stated failure rate at sub-system level, the in-series configuration of the three mooring line assemblies with a failure rate of $\lambda_{C,Mooring} = 0.185$/a each is deemed to be appropriate. This results in a failure rate for the entire mooring sub-system of $\lambda_{Mooring} = \Sigma\,(\lambda_{C,Mooring}) = 0.555$/a.

3.2.2 Structure

The structural sub-system can be regarded as in-series configuration of hull, connection joints and seals.

There is no generic structural failure rate information provided in the compiled data base as the structure is highly device and wave-load dependant. However, accident and failure rates for Aframax tankers have been recorded under the EU project 'Pollution Prevention and Control' (EU, 2004) and reported in [19]. Assuming the comparability of single hulled oil tankers and the structural housing of the WEC an indication of expected failure rates can be established. The average structural failure rate which satisfies the constant failure rate assumption was calculated at $\lambda_{SF,\,Aframax} = 0.011$/a. The applied failure rate is decreased by an order of magnitude, due to the smaller area and the less corrosive internal environment. Hence, the non-accidental structural failure rate probability is estimated at $\lambda_{Hull} = \lambda_{SF,\,Aframax} * 0.1 = 0.001$/a.

The failure rate of the joints is extremely difficult to estimate, as information is virtually not available in the public domain neither on design nor on expected loads. A rather crude approximation is obtained through the mechanical linkage of the Circular Sea Clam, a WEC proposed in 1978 as part of the UK's wave energy programme [20]. It consisted of 12 circular connected steel tubes with attached flexible air bags as PTO mechanism. The failure rate of the mechanical linkage reported in [7] is already factored for unprotected shipboard and given as $\lambda_{Joint,\,SC} = 0.63$/a. Assuming six connections for the illustrative device, the suitable fraction of $\lambda_{Joints} = \lambda_{Joint,\,SC} * 0.5 = 0.315$/a, is used as failure rate for the joint connections.

Component	Base failure rate λ_B [1/a]	Source	Adjusting factor	Component Failure rate λ_C [1/a]	Remark
Power take-off					
Hydraulic ram	0.087	[7]	2.8	0.24	Piston & cylinder p = 82 bar, Adjusted for $p \leq 300$ bar (*2), marine unsheltered (*1.4)
Manifold	0.002	[7]	2	0.004	Adjusted for higher p
Accumulator high/low p	0.263	[8]	1.6	0.42	Mean value adjusted for naval sheltered
Hydraulic. Motor	0.107	[8]	1.6	0.17	Geometric mean, adjusted for naval sheltered
Electric Generator	1.588	[2]	1	1.59	Critical failure, mean value
Power Transmission					
415V busbar	0.004	[9]	2.3	0.01	Adjusted for naval unsheltered
Transformer	0.053	[2]	1.4	0.07	Voltage: 441V - 5.5/6.6kV Adjusted for naval unsheltered
Circuit breaker	0.184	[2]	1.4	0.26	Voltage: 441V - 5.5/6.6kV Adjusted for naval unsheltered
Umbilical	0.037	[7]	1	0.04	Dynamic umbilical
Sea cable	0.15	[7]	0.6	0.09	Voltage: 400kV; failure per 10 km length, adjusted for lower capacity

Table 3: Component failure rates power take-off - and power transmission sub-system

A generic failure rate is available for rolling rubber seals $\lambda_{Seal,R} = 0.0364/a$ [7]. It is already adjusted for marine use, but the inverse application of hydraulic rams with significantly higher cycle frequency is not accounted for, so an additional capacity factor (120%) $\pi_{Capacity} = 2$ is applied resulting in: $\lambda_{Seal} = \lambda_{Seal,R} * \pi_{Capacity} \approx 0.07/a$. For the structural sub-system this yields:

$\lambda_{Structure} = \lambda_{Hull} + \lambda_{Joints} + (12 * \lambda_{Seal}) = 1.19/a$

3.2.3 Power take-off

A hydraulic system was chosen for the PTO system. The main subsidiary parts consist of hydraulic ram, manifold, accumulator, hydraulic motor and electric generator (comp. e.g. [21]) and is shown as in-series configuration in Figure 3.

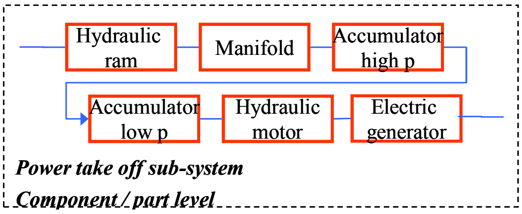


Figure 3: RBD Hydraulic power take-off

Industry specific or at least generic failure rates could be obtained for all components. Table 3 lists the base failure rates, data source, respective adjustment factors and resulting failure rates for the PTO.

As each hydraulic PTO unit is assumed as series of components, the resulting failure rate is determined as sum of the adjusted failure rates from Table 3:

$\lambda_{PTO} = \Sigma \lambda_{C,PTO} = 2.42/a$

3.2.4 Power Transmission

The power transmission system can be regarded as a series configuration of busbar, transformer, circuit breaker, umbilical and sea cable. The busbar runs through the device and bridges the gaps between the steel tubes. Thus, a factor of 2.3 was multiplied to the base failure rate to account for the less sheltered environment.

Even though the failure rates for transformer and circuit breaker come from an industry-specific database [2] they are adjusted by a factor of 1.4, as they are not installed on a stable platform but on a floating device. The specific failure rate for the sea cable (per 10 km cable length) is reduced, as the given capacity (400 kV) is not reached. Table 3 summarises the component failure rates for the power transmission system. Again, the resulting failure rate for the sub-system is easy to calculate: $\lambda_{PT} = \Sigma \lambda_{C,PT} = 0.47/a$

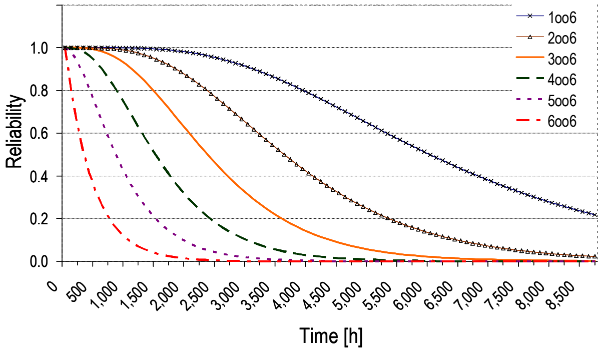


Figure 4: Reliability power take-off sub-system for different generating capacities (noo6)

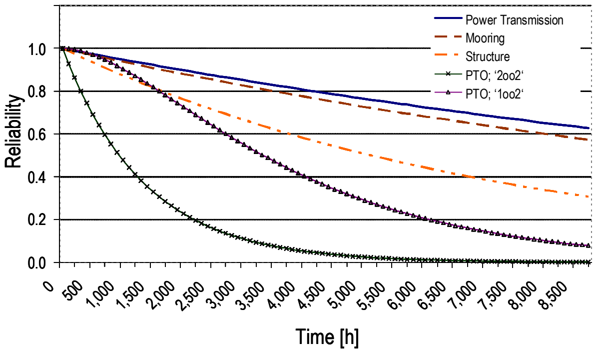


Figure 5: Sub-system reliability

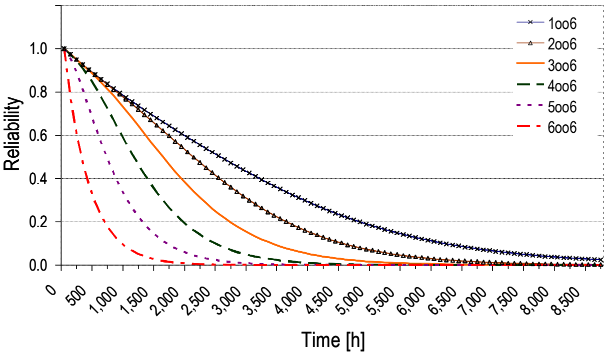


Figure 6: Reliability overall system for different generating capacities (noo6)

Figure 4 highlights the redundancy effect of the six independent PTO units. The reliability for one operational sub-system out of six, i.e. 1oo6 capacity, is very high during the first 2,000 operating hours and decreases to a value $R_{PTO,\ 1oo6}$ (8,760h) = 0.2 after one year. The reliability drops of significantly for higher generating capacities that require more hydraulic sub-systems to be operational, namely $R_{PTO,\ 6oo6}$ (2,000h) = 0.01, which is two orders of magnitude smaller than $R_{PTO,\ 1oo6}$ (2,000h).

3.2.5 Reliability calculations

Referring back to Figure 2, the WEC system is modelled as a combination of series and parallel components. The six PTO units are configured redundant and it can be expected that they exhibit similar failure rates. A calculation with 6 parallel blocks was performed, to determine reliability values for all possible generating capacities between '1 out of 6' (1oo6) and 6oo6. As a next step, the sub-system and overall system reliability were calculated. The appropriate equations are given in Table 2. The results are shown in the following Figure 4 - Figure 6.

The reliability values of the different sub-systems are compared in Figure 5. While power transmission and mooring exhibit reliability values R_{PT} (8,760) ≈ 0.6 after one year of fictitious operating time, the structure- and the PTO module sub-system indicate significantly lower levels of reliability < 0.3 after 12 months. The reliability increase through redundancy is illustrated by the two PTO curves with a series- (2oo2) and a parallel configuration (1oo2) of two units. However, the PTO seems to be the weakest link.

The absolute reliability values of all sub-systems are low, i.e. significantly lower than R = 0.8 and would not be acceptable for a commercial device. These more than conservative values are due to the fact that throughout this analysis utilised failure rates are frequently outdated, subject to high safety factors and adjustments were crude. However, the comparison of the sub-systems shows that in particular the device structure and the power module exhibit low reliability values. This illustrates how even the application of "crude" data can be used to identify those areas where better failure rates estimates should be sought.

Multiplication of the individual sub-system reliabilities yields the overall system reliability (see Figure 6). After 3,000 hours, the reliability for different generating capacities is as follows: $R_{Sys,\ 1oo6}$ (3,000) = 0.43; $R_{Sys,\ 4oo6}$ (3,000) = 0.05; $R_{Sys,\ 6oo6}$ (3,000) = 0.001.

These extremely low values can be explained by the pessimistic failure rate estimates and additional failure rate adjustments. For some failures, e.g. seal leakage, the device could stay operational for additional hours without repair. Nevertheless, these kinds of failures were included, as they make repair activities necessary. Thus, the displayed values could be termed as 'theoretical reliability levels'. The 'practical reliability' would be significantly higher, as e.g. minor failures are accumulated until repair activities are planned. Such a failure differentiation is desirable but requires much more detailed information on both the device design and failure rate circumstances and could not be obtained for this study. These theoretical reliability values underline the need for high quality information, the investigation and improvement of high failure sub-systems and the benefits of redundant configuration to establish high reliability without instantaneous intervention.

3.2.6 Sensitivity analysis

The results of the sensitivity analysis are shown in the tornado chart diagram in Figure 7. They illustrate the degree to which the failure rate prediction is affected by the uncertainty of the individual components. The large bars at the top indicate a significant effect of the particular component on the resulting sub-system failure rate under the given assumptions. The worst/best case is specified as relative figure in relation to the mean failure rate and in absolute terms.

The most critical components in the hydraulic PTO unit are the generator, the accumulator and the hydraulic ram (see Figure 7). The uncertainty range of the generator failure was judged as small (10%) because the data is sourced from the OREDA database. However, it exhibits a high failure rate $\lambda_{Generator}$ = 1.59/a, which accounts for most of the total sub-system failure rate. For the accumulators and the hydraulic rams only generic data was available. The base failure rate of the hydraulic rams was heavily adjusted by a factor of 2.8, due to both the reverse- and marine application.

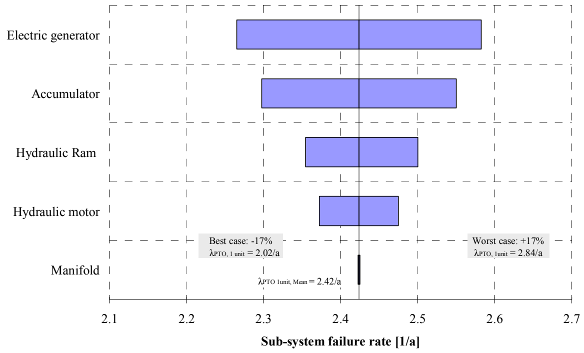


Figure 7: Sensitivity analysis hydraulic power take-off unit

The power transmission sub-system failure rate (λ_{PT} = 0.47/a) is dominated by the circuit breaker as the component with the highest failure rate λ_{CB} = 0.26/a. It must be mentioned, that the sea cable failure is given as specific value per 10 km of length. So if the distance to shore increases to more than 30 km, the sea cable would be the most critical component for the power transmission.

The tornado chart for the mooring sub-system is omitted here as three identical components were assumed. The failure rate was determined for FPS moorings, so the uncertainty range was deemed small (± 10%), resulting in a best/worst case failure rate of $\lambda_{Mooring}$ = 0.50/a - 0.61/a.

Comparing the variation of the analysed sub-systems it is apparent that the failure rate for the structure is subject to the largest uncertainty (± 35%), followed by the hydraulic loop (± 17%), the power transmission (± 11%) and the mooring (± 11%). The reason for this variation mainly lies in the data quality, but also in the absolute level of failure rate. If the uncertainty of those input variables could be reduced, the uncertainty of the overall system failure could be decreased. Two main approaches can be followed to reduce the uncertainty of failure rate predictions [22]:

- More information/better knowledge of the identified input variable (e.g. more detailed failure rate data, precise failure rate adjustment)
- Determine strategies to reduce the effect of the input variable, e.g. introducing redundancy or improve the component's reliability

It is evident, that the sub-systems and components with high failure rates, e.g. the main components of the hydraulic cycle are already designed in parallel configuration in order to decrease the failure consequence for the overall systems. A more detailed investigation of the behaviour, expected failure rates and failure modes of the identified components (in particular seals, hydraulic rams, accumulators, circuit breaker and generator) in the wave energy application could not only improve the reliability prediction but indicate possibilities of reliability improvements. This could be achieved through the deployment of prototypes and first commercial wave farms together with dedicated component testing.

4 Discussion

It must be noted that this case study is an illustrative example and *would not* reflect the performance of an existing device at a later stage in the development process. It might, however reflect the state of confidence for a device at an earlier stage of development, perhaps with some tank testing, but before many operational hours had been achieved at sea or large scale prototyping had been carried out.

There are a number of reasons for the somewhat unfavourable results:

- outdated/pessimistic and often generic failure rate data,
- no repair activities considered within 12 months time,
- crude adjustments.

Beyond these, the assessment of uncertainty of the outcomes was assumed to be only dependant on the data held within the database and did not include a contribution from factors such as the difference in operational loading. As an example one might consider the major components, the source of the data and how suitable it might be:

Moorings: In this case the mooring failure rate was taken from an industry project relevant to FPS moorings. One would consider this data to be very creditable and 'accurate' for the given situation. However, how much should there be adjustment for the mooring of a floating WEC? Recent research to determine the mooring loads for a WEC [23] point to the possibility that, at least for some designs, the dynamic loads and rates could be quite different from those experienced by an FPS and this could conceivably radically alter (reduce) the failure rates from those in the study.

Structure: This case is almost the opposite of that for moorings. The data used was based on quite a radically different type of structure and the data for the structural linkages from a relevant but relatively old study. One could certainly argue that modern engineering design codes and analyses for the marine environment would *reduce* both the failure rates and its uncertainty from those used in this model.

PTO: The power take-off might be seen to fall somewhere in the middle in that there is a large amount of relevant information of the various subcomponents from several different applications. The difficulty here is assigning relevant adjustments to account for the unusual operations of the components.

In order to draw conclusions from already existing failure rate data it is necessary to assess the uncertainty of failure rates regarding the differences of operating environment and loading conditions, i.e. putting the failure rates in the context of the application.

Detailed, device specific, reliability assessments are of course carried out or contracted by the device developers, e.g. [24]. However, the results are not published, making external reliability and availability measures in resource assessments subject to speculation.

The key points to emphasise are that (i) there is a lack of generic data that a developer can apply at an early stage in the development process before the knowledge is built through development (ii) The analysis of any device from an external view will be compromised by lack of suitable data. This necessitates a joint effort of stakeholders in order to advance the development of the marine energy sector.

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