System approach to reliability engineering - case: wave energy converter

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Wave power is a promising technology for producing renewable energy. Several types of wave energy converters (WECs) have recently been developed and introduced as technical solutions for capturing the energy of ocean waves. One of the WEC types is an Oscillating Wave Surge Converter (OWSC) that extracts energy from wave surges and the movement of water within them. Reliable operation and high system availability of WECs are key aspects to achieve the levelized cost of energy (LCOE) targets. Systematic reliability engineering methods can offer valuable support for the design and evaluation of highly automated multi-technical WEC systems. Analytical and simulation-based methods such as Failure Mode, Effects and Criticality Analysis (FMECA), Reliability Block Diagrams (RBDs) and Life Cycle Cost (LCC) calculations can be utilized in from early conceptual design phase. The system approach aims to guide the work to right system hierarchy level and to enable the use of available but partly uncertain information for system models, analyses and simulations. The research on reliability engineering methodology in VTT is related to concept development and system design of an OWSC and especially its power take of system (PTO) in an ongoing EU funded research project ‘MegaRoller’. Our results confirm that reliability-engineering efforts should be considered as an interconnected and iterative process, and the system approach helps to look at things at the appropriate level and accuracy.

Keywords: ocean energy, wave energy converter, system design, reliability, maintainability, life cycle costs.

1. Introduction

Wave power represents a considerable opportunity for clean renewable energy supply. Despite its attractive characteristics (renewable, environmentally friendly, abundant and widely available, around-the-clock generation, more predictable than wind or solar energy), wave power entails significant challenges that have so far prevented it from becoming a mainstream energy source. These system level challenges are related to construction, operation and maintenance, wave-energy farm optimization, lifecycle costs, return on investments, environmental issues, socio-economic issues, and authority permits for operations. Reliable operation and high system availability of WECs are key aspects to achieve the targets set for the levelized cost of energy (LCOE).

Wave energy systems use various methods to capture the energy of the waves depending on their type (point absorber buoys, surface attenuators, oscillating water columns or overtopping device) (Figure 1). Oscillating wave surge converters (OWSCs) is a class of wave energy technology that uses bottom-hinged plates oscillating in pitch following the surge movement of the water particles in the nearshore zone (10m-25m water depth) and designed to absorb wave energy through horizontal motion of the prime mover.

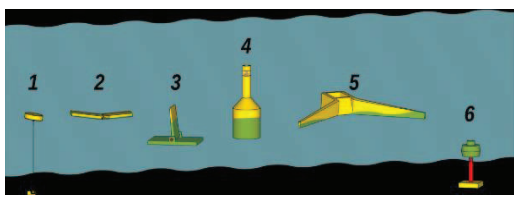

Figure 1. WEC concepts (Wikiwand).

The power take-off (PTO) is the core component that converts wave-induced oscillations from mechanical energy to electricity. Efficiency and reliability are two key challenges for PTOs because waves generate slow and irregular oscillations, which requires processing of large alternating forces in order to extract power (Pecher & Kofoed, 2017).

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1.1 *Research on reliability aspects in WECs*

Reliability of WECs has been studied already in the 1970s and 80s (Wolfram, 2006), but most advances in WEC technologies have emerged only during the past decade. Due to the nature of wave energy as a relatively new field of study in engineering, there is only a limited number of research references available regarding the reliability aspects of WEC devices. A major part of the available research focuses on fatigue-related phenomena on the mechanical structures, caused by the varying loads imposed by different sea states (Ambühl et al., 2015; Ransley, 2015), as well as survivability of the WEC device in the extreme maritime conditions, such as during storms (Coe & Neary, 2014).

So far, significantly smaller focus seems to have been placed on the power take-off (PTO) systems of WECs, with very limited references available (Henderson, 2006). While the PTO can mostly consist of well-known components, the unusual operating conditions are likely to affect the reliability performance of these established components as well (Wolfram, 2006). In addition, as typical for most new technologies, available studies mostly focus on technical aspects of reliability. However, some studies have also been published towards understanding the economic implications of WEC system reliability and, for example, the related maintenance strategies (McAuliffe et al., 2015; Heikkilä et al., 2019).

It should also be noted that different WEC devices operate with a very wide range of operational principles, and may have drastically different reliability characteristics depending on the design goals, operating conditions, and reliability performance requirements set to the device. Because of the large number of different WEC types, most available studies focus on specific WEC systems, mostly with rather different characteristics from the OWSC type design of the MegaRoller concept introduced in this paper. For example, Ambühl (2015) has extensively reviewed two types of WECs, both of which are floating devices (in contrast to the submerged MegaRoller). Similarly, Cretu et al. (2016), Mueller et al. (2016) and Thies (2012) have all studied different types of WECs. These studies apply varying methods for failure identification (including e.g. FMEA) and probabilistic methods, such as reliability block diagrams (RBD) and Bayesian statistics for reliability prediction.

As a common finding in these studies, it is apparent that a high level of uncertainty is characteristic for reliability assessments of WECs due to the lack of reliability data from previous installations and due to the wide range of new WEC technologies and installation sites. Previous research also suggests that because of the uncertainties related to WEC reliability data, information from other domains with similar characteristics should be incorporated whenever relevant. This is because other offshore domains, such as wind energy or oil and gas sector, share some characteristics related to reliability requirements and environmental conditions with WECs. They also have a longer tradition with publicly available reliability related data. Research in these fields can support reliability prediction, but also more comprehensive techno-economic studies.

1.2 *Objectives*

In this paper, we present an outline of a system approach for reliability engineering to support the design of an innovative OWSC system. The system approach aims to guide the reliability engineering work to right system hierarchy level and to enable the use of available but partly uncertain information for system models, analyses and simulations. In this paper, we discuss the evaluation of system concepts, and cost comparisons of various design options from system availability point of view. We also discuss system failures and system maintainability issues from two different viewpoints: wave energy farm versus single WEC.

1.3 *MegaRoller project*

Our current work on reliability engineering is related to concept development and system design of an OWSC in an EU funded research project 'MegaRoller'. https://www.sintef.no/MegaRoller

The project aims to develop a 1MW power take-off system (PTO) for wave energy converters. It will work with oscillating wave surge converters (OWSCs), which use bottom-hinged panels to follow the surge movement of water in the nearshore area at a depth of 10-25m.

Figure 2. A concept image of the MegaRoller OWSC device, consisting of a panel that oscillates with the waves and power take-off systems to harness the energy (MegaRoller, 2017)

The objective of the project is to create expertise in the area of PTO design and control systems and to develop innovative concepts and solutions to reduce the levelized cost of energy (LCOE) to below $150 per MWh for the next generation of OWSC devices. The project also aims to increase the knowledge of how wave energy can be used and integrated to the grid in various business cases.

The MegaRoller project is an EU-funded research & innovation action for 2018-2021. Hydroll coordinates the project and the project partners are AW-Energy, ABB, Hydman, K2 Management, WavEC, SINTEF, IiB, LIN and VTT.

2. System approach to reliability engineering

In machinery design, reliability engineering is typically started from analysing component failures according to the system breakdown structure that describes the component level design. This means that in this point the whole machinery system is already designed to detail level although it is well known that the most appropriate way to affect the system reliability characteristics is to focus on the beginning of the system development in conceptual design phase.

The system approach to reliability engineering in this context means the mindset and procedures to guide the reliability engineering work to right system hierarchy level and to enable the use of available but partly uncertain information for system modelling, system analyses and simulations. Our research in this field aims to develop and apply system approach for reliability engineering of highly automated multi-technical systems following the Systems Engineering (SE) principles. The main research questions in our study are:

- How to evaluate system reliability characteristics and cost implications at different stages of WEC development process and how to validate the final design?
- How to support decision-making in finding cost-effective solutions that fulfil the reliability and maintainability requirements?

In general, the systems-engineering principles are said to be scalable plans of actions including company-specific applications of life cycle and systems-engineering processes, decisions on system architecture, and requirement specifications and management. In this context, systems engineering efforts can be utilised for the development of the entire wave energy park as well as a single WEC.

The main characteristics of systems engineering can by summarised by listing them as systematic and extensive requirement specifications and management, systematic verification of design solutions and validation of implementations, and breaking down of system design problems into manageable sub-problems (Granholm, 2013).

Reliability engineering should be understood as one of the systems analysis and control efforts in the iterative systems engineering process. It emphasizes dependability aspects in the lifecycle management of a product (Figure 3). The general purpose of systems-analysis efforts is to resolve conflicts identified in systems-engineering tasks, to manage risks throughout the systems engineering efforts, and to support the overall process to end up with balanced requirements and design solutions (ISO IEC 26702:2007).

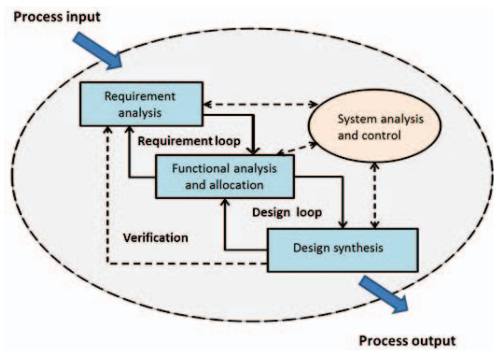

Figure 3. A simplified flowchart of the systems-engineering problem-solving process, according to the DoD's DAU (2001).

Based on our experience in other fields of industry we have a strong view that systematic reliability engineering methods can offer valuable support for the design and evaluation of highly automated multi-technical WEC systems. The system approach we are studying and developing for reliability engineering is based on the Top-Down approach (INCOSE, 2015) starting from the evaluation of alternative conceptual designs. The reliability engineering work should then continue supporting the system design in various system development phases. Although the information in early conceptual design phases is inadequate and includes uncertainties, it is important to bring up system reliability related aspects, assess risks and allocate system reliability requirements.

The reliability engineering methodology in this approach consists of well-known methods that are commonly used to support industrial product design to ensure that customer expectations for reliability are met throughout the life of the product with low overall life-cycle costs.

The methods we are studying and applying in the MegaRoller project are:

- Potential Problem Analysis (PPA) for the identification of system availability risks of an wave energy park and a single OWSC (MegaRoller device)
- Functional modelling of the PTO using Functional Block Diagrams (FBD)
- Failure Mode, Effects and Criticality Analysis (FMECA) of the PTO,
- Reliability modelling using Reliability Block Diagrams (RBDs) and simulation of selected subsystems of the PTO,
- Life Cycle Cost (LCC) modelling and calculations of the OWSC (MegaRoller device)

In the following chapters, we describe shortly the methods and discuss experiences of their implementation in this context.

3. Identification of availability risks in a wave energy park

It is probable that the WECs will not be used as single units, but as parts of a wave energy park. The energy park consists of several WECs connected together forming a large power plant. To ensure consistent and reliable energy production the site-specific availability risks must be identified and taken into account. For example, harsh sea conditions of the installation site might cause some limitations to the production and the distance between the energy park and the docks to where the WECs are towed for periodic maintenance affects the productivity of the site.

WECs will be standardized products like offshore wind turbines nowadays. Tailoring will increase production costs and makes the product support more complicated. By identifying the wave loads and reliability risks caused by the site-specific conditions the maintenance program and the supporting functions related to maintenance can be adjusted in site-specific manner to ensure that the overall system availability requirements will be fulfilled.

There are numerous risk analysis methods that can be used for identifying the site-specific risks. In our approach, we use Potential Problem Analysis (PPA) (Suokas and Rouhiainen 1993). The PPA method is a qualitative risk identification, analysis and criticality assessment method based on expert knowledge and expert evaluation. It has been widely applied in process industry and in manufacturing industry.

4. Functional modelling and FMECA

FMECA is a standardized reliability analysis method. A general description of FMECA process is presented in IEC 60812 standard "Failure modes and effects analysis" (IEC 60812, 2018). FMECA can be used in various ways dealing with different level of details. A generic FMECA process is illustrated in Figure 4.

According to the previous experiences from industrial applications, it is advisable to utilize FMECA on at least two system levels: on functional and on component level. On functional level, it is possible to analyze large technical systems in a reasonably short time. In the functional level analysis, the failure modes must be kept at functional level. For example, a function will not be executed or a function is being executed incorrectly. Technical aspects come up as possible causes of the functional problems.

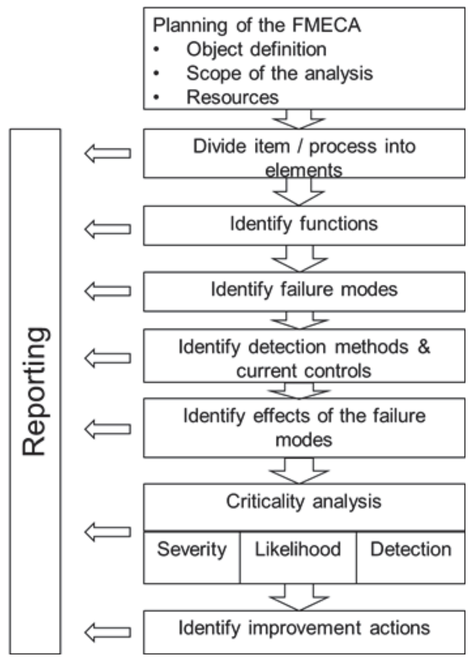

Figure 4. Generic FMECA process according to the IEC 60812 (2018).

For conducting FMECA in a functional level, a functional description of the system under study is the starting point. In the case of WEC devices, the functions can be described following the energy flow - from ocean waves through the WEC's energy transformation systems all the way to electric power generation and grid connection. The system functional description describes the functions, their connections and the equipment that are required to perform the functions. In our approach, the functional descriptions are made by using Functional Block Diagrams (FBDs) according to the Structured Analysis and Design Technique (SADT) (Marca and McGowan, 1987). A basic block of SADT is illustrated in Figure 5.

If the functional level FMECA shows that some functional failure modes are critical for the system performance, it is well justified to continue analysis with component level FMECA. In the component level FMECA, the modules or parts are analyzed in details. This way the most critical component and their connections are identified. By this two-stage FMECA process, it is possible to allocate expert resources appropriately and to target the reliability improvement measures cost-effectively to the most critical components. FMECA results are also essential information when building a maintenance program according to Reliability Centered Maintenance (RCM) principles (IEC 60300-3-11, 2009).

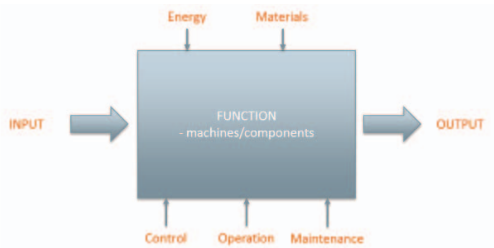

Figure 5. A basic block of functional description.

It is useful for the overall system development process to start FMECA process on functional level in early phases of the project. In the early phase, the alternations and modifications to the design are much cheaper to conduct comparing to the situation later where some of the critical components are already ordered or the manufacturing process of parts has begun.

5. Reliability modelling and simulation

System reliability predictions can be performed using various methods. In our approach, we apply a reliability modelling and simulation method utilizing reliability block diagrams (RBD). A RBD describes a system as a combination of interconnected blocks, each representing a defined part of the system, typically a component or a group of components. Each block is assigned with a function describing the block's reliability performance over time (Čepin 2011). Several commercial software packages are available for performing RBD calculations.

The RBD method is flexible and can be applied in different phases of design and on different levels of detail. For WEC design, it can be applied throughout the system development process. In concept design phase, some rough reliability estimations can be made based on a RBD model from the very early stages of development. For example, this can be used to support comparison studies between fundamental design choices, such as comparison between hydraulic or electric power transmission alternatives. Reliability modelling can also be used to allocate reliability requirements between different subsystems, and to identify clear bottlenecks in the system concept related to reliability, as well as maintainability and availability. In addition to examining individual WEC devices, modelling can be also done on a level of a WEC farm consisting of multiple units.

In the system design phase, the reliability model should be updated as the system design proceeds. This allows more detailed reliability estimations and further evaluation of design alternatives. FMECA results can be used to direct the modelling activities so that the identified most critical parts of the system are examined and simulated at the highest level of detail. An important output of the reliability simulations is the identification of components and subsystems, which have high uncertainty in their reliability performance. This information can be used to indicate which parts of the system still require modifications to ensure sufficient reliability and which part require most thorough testing activities. After system modifications, the model must be further elaborated to represent the actual design.

Being mathematical models, RBDs are representations of data. The quality of models is always dependent of the amount and quality of data available. Thus, interesting research tasks considering WECs are to define the reliability distributions for different system components, and to study uncertainties associated with new product development project in a challenging environment. A perfect reliability calculation can never be achieved, but a number of data sources can be utilized to provide a credible estimation of system reliability. These data sources include:

- Data provided by component manufacturers, as a large part of a WEC device can consist of off-the-shelf components.
- General reliability data sources, such as industry guidelines and handbooks, especially ones related to offshore industries.
- Analytical results regarding component lifetimes (only for major tailor-made system components).
- Relevant experiences from previous installations and tests.

6. LCC modelling and estimation

Life cycle costing (LCC) is the process of performing an economic analysis to assess the cost of an item over a portion, or all, of its life cycle in order to make decisions that will minimize the total cost of ownership while still meeting stakeholder requirements (IEC 60300-3-3, 2017). The objective of the life cycle costing in the case of the wave energy system is to define all the costs that the novel technology generates during its entire life cycle. As the lifetime of a wave energy system could be upward of several decades, operating and maintenance costs can end up being several times higher than the original acquisition price. For example, predictability of the remaining useful lifetime of the PTO components plays an important role in achieving the goals for reducing the need for periodic maintenance as well as downtime due to failures and negative environmental impacts. By taking into account life cycle costs, decision makers have a better opportunity of optimizing the total cost of ownership and achieving better profitability in the long term.

In our approach, the standard IEC 60300-3-3: 2017 forms the basis for the Life Cycle Costing methodology. Our aim is to combine economic assessment and technical reliability assessment to be able to give input for the optimization of operational efficiency and reliability and minimizing life cycle costs WEC concepts.

The main costs related to wave energy system are capital costs (acquisition, installation etc.), operating and monitoring (remote operation cost, scheduled inspection, consumables etc.) maintenance (scheduled annual maintenance cost, service maintenance cost and unavailability cost etc.) and other costs. The cost breakdown structure developed for the MegaRoller project is illustrated in Figure 6. It should also be considered that e.g., societal and environmental risks are generating impacts not only to companies, but also to all stakeholders in a value network (Räikkönen et al. 2019). In all, harnessing the value of the WEC concept is about balancing out values emerging from different domains: environmental, technological, economic, business and societal (Dalton et al. 2015).

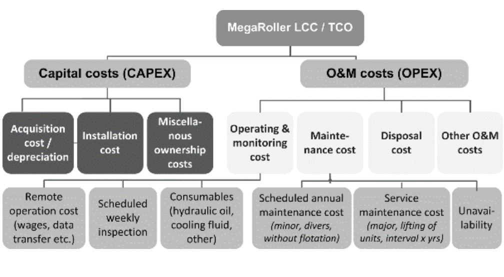

Figure 6. MegaRoller cost breakdown structure (CBS).

The LCC model and related tool that is developed in the MegaRoller -project is a practical framework for conducting the life cycle cost analysis of the wave energy system to support design and asset management of the entire system. The framework provides a loose coupling between LCC and FMECA analysis by incorporating the results of a FMECA into life cycle cost analysis. Figure 7 presents the information used to quantify failures in one of the tool's modules. Categorization and assessment of failure risks and risk related costs helps to calculate potential cost savings achieved by failure risk reduction. The failure costs include both unplanned maintenance costs (spare parts and work) and unavailability costs. Probability is calculated based on the risk frequency (risks realized during the life cycle). Annual cost savings are calculated by multiplying the occurrence and the cost and dividing this by the lifetime (years).

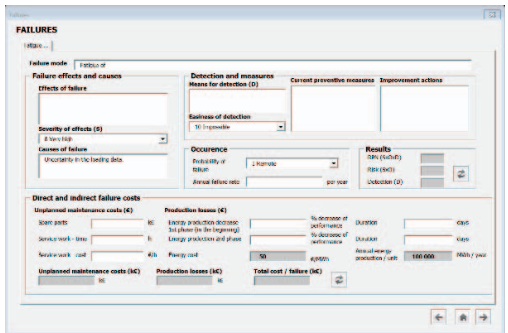

Figure 7. MegaRoller LCC tool: Failures –user interface.

The proposed framework provides practitioners with the opportunity to adopt a proactive approach to assess LCC for various wave energy system alternatives. The framework itself includes many steps and consists of structuring the decision situation and the investment in question, setting the boundaries and framing conditions for the assessment. The essential part of the framework is the definition of the cost structure and assessment of costs, along with, finally, synthesis to reach an overall ranking of different WEC design options. The total life cycle cost, discounted life cycle cost as well as annual cost and discounted cumulative cost are calculated as result indicators of LCC.

Analyzing the life cycle costs of different WEC concepts is not a simple task. The first challenge is to establish a structure, which includes all relevant cost elements, factors and their effect on total life cycle cost of the WEC concept. Another challenge concerns the availability of data for costs. Especially, as the analysis is done in the early phases of a life cycle, uncertainty related to costs is high. Thus, a tool supporting the LCC analysis could be of help and the LCC demo tool that is developed in the MegaRoller project strives to tackle the aforementioned challenges.

7. Discussion

In this paper, we have described a system approach, practical methods and related tools for reliability engineering to support the design and evaluation of WEC systems. The approach aims to improve the system level reliability engineering practices applicable for the development of highly automated multi-technical WEC devices. The approach described consists of the following elements:

- System description and functional modelling for the identification of the key system functionalities
- Failure Modes, Effect and Criticality Analysis (FMECA) in functional and component levels to find the most critical failure modes
- Reliability modelling using Reliability Block Diagram (RBD) and simulations to identify reliability critical components and subsystems and to evaluate design alternatives
- Life Cycle Costing (LCC) modelling and estimation of the WEC in several system development phases in connection with failure impact evaluation

Based on our experiences in the MegaRoller research project and experiences in other fields of industry we can say that systematic reliability engineering methods can offer valuable support for the design and evaluation of highly automated multi-technical WEC systems.

Reliability engineering work should not be considered as separate activities, but rather a process of interconnected efforts that complement each other and brings together technical, economical, operational and maintenance views.

In the case of WECs, maintenance is one of the biggest components in the life cycle costs. Therefore, the maintenance program development is essential from early phases of the system development to fulfill the overall LCC targets in the final WEC implementation and operating lifetime. With function-level FMECA, it is possible to identify the subsystems that are the main drivers in the maintenance program development.

Regarding the identification and valuation of preventive and unplanned corrective maintenance costs and unavailability, there is a clear linkage between LCC and reliability modelling. As the lifetime of a WEC could be 20 years or more, operating and maintenance costs can end up being several times higher than the original acquisition price (Heikkilä et al., 2019).

The approach we have been developing enhances the transparency of decision-making and contributes to the more comprehensive use of available information affecting the cost effectiveness of different design alternatives and their impacts across the entire life cycle of the system.

As with any qualitative analysis and evaluation methodology, the limitations of the approach must be taken into account when interpreting the results. It may e.g. not cover all the important aspects of linking failures and risks with economic factors. However, the research has already proved clearly that the indirect costs such as the cost of unavailability must be taken into account when calculating the life cycle cost of wave energy systems. For example, the lifting and flotation of the system from the seabed is very costly. In the next phases of the MegaRoller project, the method and related tool will be further evaluated and tested. It is expected that in most cases, a different set of cost categories and decision criteria will be used without any changes needed in the overall structure of the assessment procedure. Our aim is to develop the approach in the project and get experiences how it works and how it should be further developed.

It should be noted that the approach is not linear, but instead, all the analyses should be updated as the system development advances. A major focus in our approach is on the integration of the above-mention methods within the system development process.

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