MARMOK-Oscillating Water Column (OWC)

Final Technical Report

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Pages: 43

ABBREVIATIONS

AAPP	Annual Average Pneumatic Power
AHT	Anchor Handling Tugs
ALS	Accidental Limit State
BiMEP	Biscay Marine Energy Platform
CFD	Computer Fluid Dynamics
COG	Center of Gravity
DLC	Design Load Case
DOE	Department of Energy
DOF	Degree of Freedom
FEM	Finite Element Method
FLS	Fatigue Limit State
FOA	Funding Opportunity Announcement
GM	Metacentric height
GZ	Righting stability lever arm
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Organization for Standardization
LC	Load Case
LCOE	Levelized Cost of Energy
MBL	Minimum Breaking Load
NEC	National Electrical Code (NFPA 70)
NEMA	National Electrical Manufacturer's Association
NESC	National Electrical Safety Code
NFPA	National Fire Protection Association
NREL	National Renewable Energy Laboratory
OTRC	Offshore Technology Research Center
OWC	Oscillating Water Column
PTO	Power Take Off
PWS	PacWave-South
SF	Safety Factor
NREL	Sandia National Laboratory
SOPO	Statement of Project Objectives
SS	Sea State
ULS	Ultimate Limit State
UPS	Uninterruptible Power Supply
WAMIT	Wave Analysis Massachusetts Institute of Technology
WEC	Wave Energy Converter

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

The main objective of the MARMOK-OWC project is to advance future commercial viability of floating Oscillating Water Column (OWC) technology by performing a detailed Wave Energy Converter (WEC) design that is:

- Specifically designed for PacWave-South (PWS) site wave climate to maximize energy production;
- Optimized in terms of initial investment and operational costs for a two-year deployment in this site;
- Capable of ensuring device survivability and operability/maintainability along defined design life;
- Designed to be connected to the electrical grid by means of an umbilical cable that connects to a subsea connector, and capable of delivering power to the grid according to the relevant power quality standards;
- Capable of producing more than 220.000 kWh/year (or equivalent 25kW annual average electrical power) output; and
- Designed according to IEEE 1547 and IEC TS 62600 technical standards.

This project is built on IDOM's extensive knowledge and experience with wave energy harvesting technology development, demonstrated by the successful design, manufacturing, deployment and testing of the MARMOK-A-5 (see Figure 0-1) full-scale low-power prototype deployed in the Biscay Marine Energy Platform (BIMEP) test site (Spain). This prototype (grid-connected and rated 30kW), was deployed in October 2016 and has survived three years of operation in open waters under real-sea conditions. As such, IDOM's wave energy technology has been successfully tested to TRL 6-7 stage. This previous deployment experience will be referenced throughout this document when relevant.

Figure 0-1: MARMOK-A-5 full-scale low-power prototype deployed offshore

This report summarizes the work conducted by IDOM within DE-FOA-0002080 which has led to a ready-to-build design of a commercial size WEC optimized for PWS site conditions. In the following figure the resulting design can be found with a rated power of 300kW.

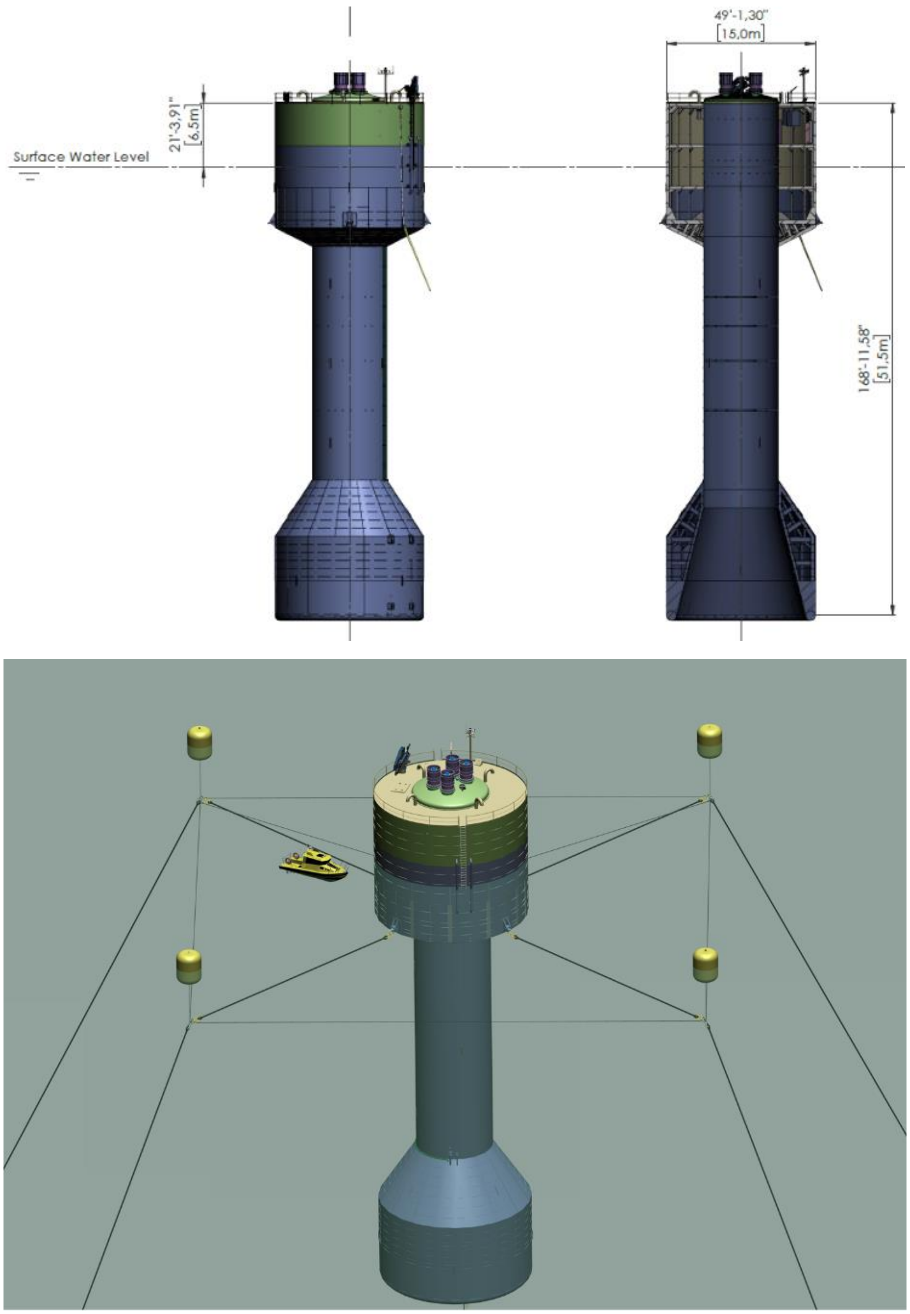


Figure 0-2: MARMOK-A-15 prototype overview, main dimensions (top), connected to the mooring system (bottom)

In addition to the WEC design, a summary of the main lessons learned during this project are also included at the end of this report.

1 MARMOK-OWC TECHNOLOGY GENERAL DESCRIPTION

The present WEC follows the OWC working principle. The basic device concept can be described as a spar element holding a cylindrical water column in the interior. These two bodies, the device structure and the internal water column, are coupled by the PTO and designed to be excited by the incoming waves, each with different resonance periods, so that relative movement between the two bodies is enhanced. An air chamber is contained in the upper side of the water column, whose compression and decompression is forced to pass through self-rectifying air turbines. These turbines are directly coupled to electric generators which are controlled by power electronics. The generated power is transmitted to shore by a subsea cable. The structure has a ballast tank on its submerged section, facilitating the towing process during installation/deinstallation by pumping air into the ballast tank or filling the ballast tank with sea water. The Spar type OWC is a simple yet powerful concept, with no moving parts except the air turbines. All critical elements (PTO included) are protected from sea water.

The system is secured to a shared mooring configuration which further facilitates device deployment in arrays achieving a significant reduction in costs and better utilization of the sea surface compared to the individually moored WECs. Figure 1-1 shows a single MARMOK-OWC device and an array deployment of multiple devices.

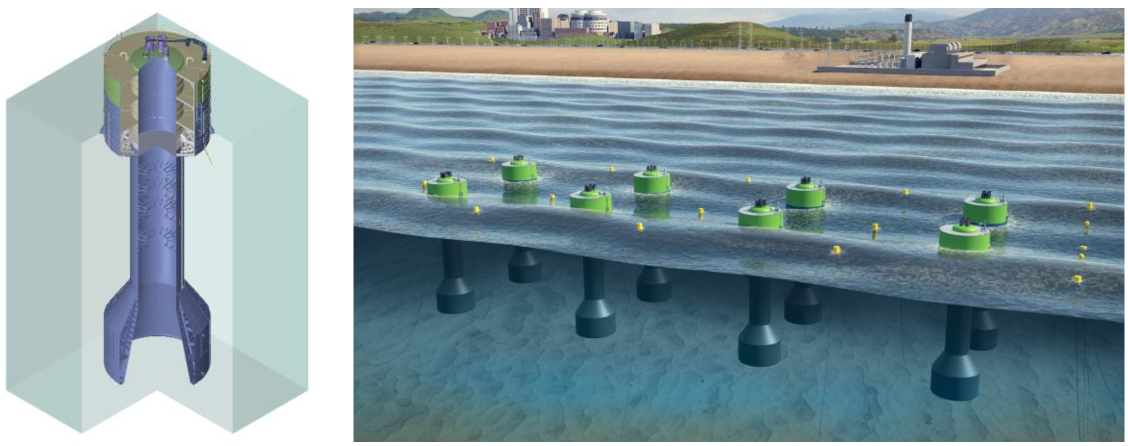


Figure 1-1: Sketch of the MARMOK-OWC device (left) and array deployment (right).

2 WEC GEOMETRY OPTIMIZATION

2.1 METHODOLOGY DESCRIPTION

The geometry proposed in this project was selected to fit PWS conditions. A geometric optimization process was performed to maximize absorbed power to WEC cost ratio, taking into account certain hydrodynamic, manufacturing and maneuverability criteria.

The geometry has been parameterized with the nomenclature of the dimensions reported in Figure 2-1 (left), whereas in Figure 2-1 (right), the nomenclature of the WEC parts are presented.

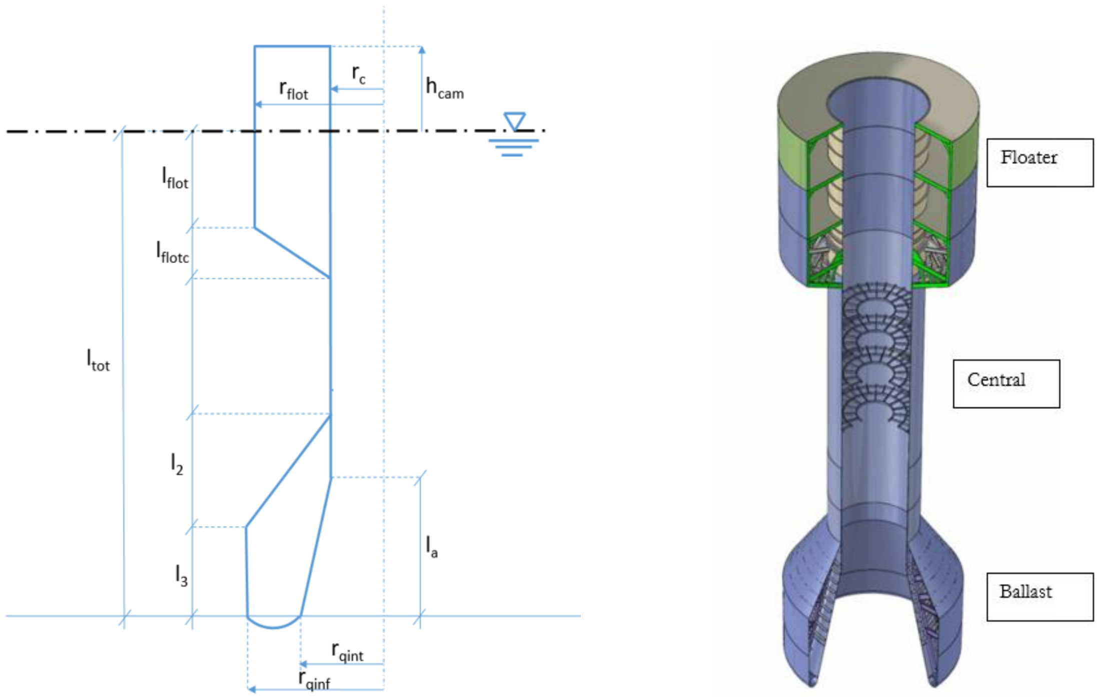


Figure 2-1: Geometry parametrization

A numerical model has been developed in the frequency domain to obtain practical evaluations of the power performance potential of each geometry under PWS site wave conditions.

A simplified structural design model has been developed, which for a given geometry estimates the structure cost using simplified load cases based on IEC standard and extreme environmental conditions from PWS.

In addition, a device transportability check that excludes non-compliant geometries was used. For this purpose, depending on the weight of steel determined by the structural model, the minimum ballast tank volume is determined to ensure that the device can float in a horizontal position during transportation.

Finally, the geometry of the device was adjusted to take into consideration the device's dynamic stability under operating conditions, based on a non-linear hydrodynamic model.

A summary of the calculation process performed is shown in Figure 2-2.

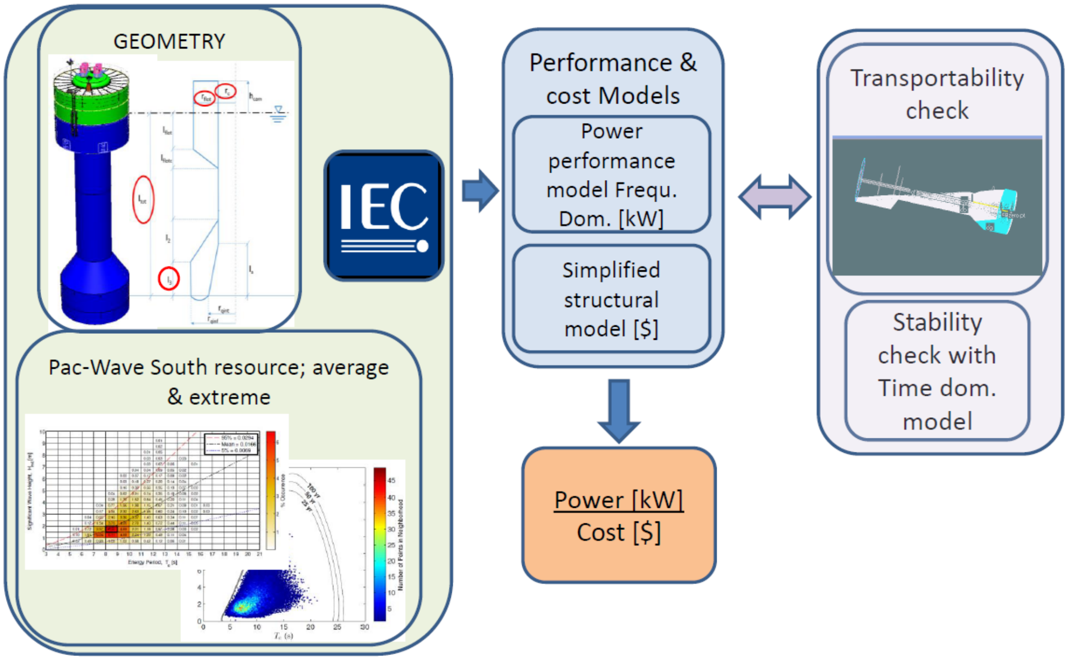


Figure 2-2 Optimization methodology description

In the next section, the criteria used in the optimization are explained in detail.

In addition to these calculations, for the main dimensions selected, a more detailed analysis on the conical shapes influence in the power performance was performed by Sandia National Laboratories through a CFD model. Optimal transition angles and shapes were incorporated in the final design of the WEC.

2.2 GEOMETRY OPTIMIZATION CRITERIA

Three main criteria were taken into account to select the optimal geometry looking at the Extracted Power (EP) to cost ratio (EP/cost) maximization, transportability and dynamic stability for the different geometries considered.

2.2.1 Criterion 1: *EP/Cost* Ratio Maximization

The EP is represented by the Annual Average Pneumatic Power (AAPP) that the device is able to capture, according to the annual average PWS wave source. The AAPP is a value which depends on the hydrodynamic interaction between the two bodies involved in the system, the buoy and the OWC, and therefore on the PTO damping established between them. The PTO damping provided was numerically optimized in order to maximize the AAPP for each sea state.

The cost will depend on structural calculations for each geometry considered in the optimization process. For this objective, a simplified structural calculation model was developed. In summary, this model estimates the hull thickness, the number of stiffeners (both primary and secondary) as well as their thicknesses in order to resist survival loads, minimizing the structure cost. For the cost calculation, the following aspects have been taken into account:

- Required quantity of steel.

- Type and length of welding, which quantifies the structure's complexity and allows to estimate the manufacturing cost.

These calculations determine the AAPP/cost ratio.

2.2.2 Criterion 2: Transportability

Transportability sets the minimum size of the ballast tank. The minimum volume required of the ballast tank is calculated for each geometry, under which the device is not maneuverable anymore.

A simplified transportability condition has been implemented in the simplified structural design model, whereas a more detailed hydrostatic stability characterization for the final selected geometry has been reported under operating and transportation conditions using a stability analysis software.

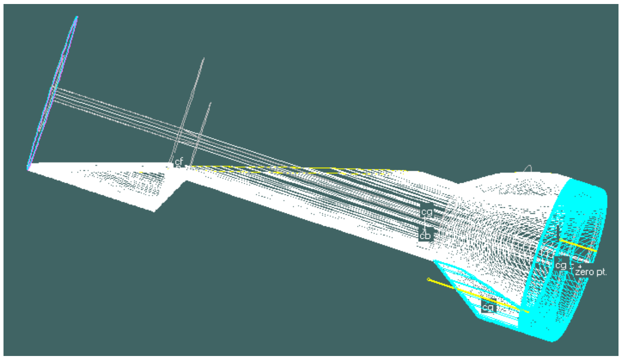


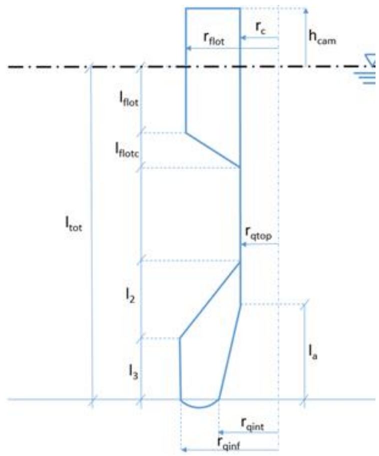
Figure 2-3: Equilibrium configuration in transportability position

2.2.3 Criterion 4: Dynamic Stability

This criterion allows the AAPP to be preserved, attenuating the heave-pitch coupling (common coupling of spar type floating platforms); basically, to allow large heave motion amplitudes while minimizing pitch angles. Since it is a non-linear phenomenon, a time-domain analysis is conducted with a hydrodynamic model developed. It is a criterion which is used to optimize the floater design after having preselected an optimum geometry obtained by the three previous criteria described above.

2.3 CONCLUSION ON THE GEOMETRY OPTIMIZATION

Based on the optimization process conducted, the main final geometric parameters obtained are presented in Figure 2-4. To reference the external diameter of 15m, the device is called MARMOK-A-15.



r_flot [m]	7.5
r_c [m]	3.75
l_3 [m]	8.0
l_tot [m]	45.0
rq inf [m]	7.5
hcam [m]	6.5
Displacement [tonnes]	1948

Figure 2-4: Optimized geometry's WEC for Pac Wave South site

3 STRUCTURAL DESIGN

3.1 MARMOK-A-15 FINAL DESIGN

3.1.1 General Configuration

The structure can be described as a spar element made of steel A572 Gr. 50 with a draft of 45m holding a cylindrical water column in its interior. A conical shape at the inner bottom section provides a soft expansion and contraction of the water column, and therefore reducing energy losses.

The structure assembly under evaluation can be considered in three main parts: a floater, a ballast and a central cylinder (see Figure 3-1). Each of them is explained here:

The **floater** is located on the upper part of the WEC linked to the central cylinder and has two main functions. First, the floater is responsible for the buoyancy/stability of the whole structure. Second, all the electrical components are installed inside and protected from sea water in watertight interior compartments. The air turbines are located on top of the floater, in a dedicated cover plate to close the air chamber.

The **Ballast tank**, located on the lower part of the structure and also attached to the central cylinder. Its main role is to maintain the structure in a vertical position. Permanent ballast is included at the bottom section of the tank adding the necessary weight to achieve the total displacement. Additionally, variable ballast is included to allow switching between the transportation mode (horizontal position) and the operating mode (vertical position).

The **Central cylinder**'s main functions are holding the water column and transmitting forces and moments from the floater to the ballast tank. It consists of a simple tube without external stiffeners. Internal stiffeners (spiders shape) are added to prevent bulking failure mode.

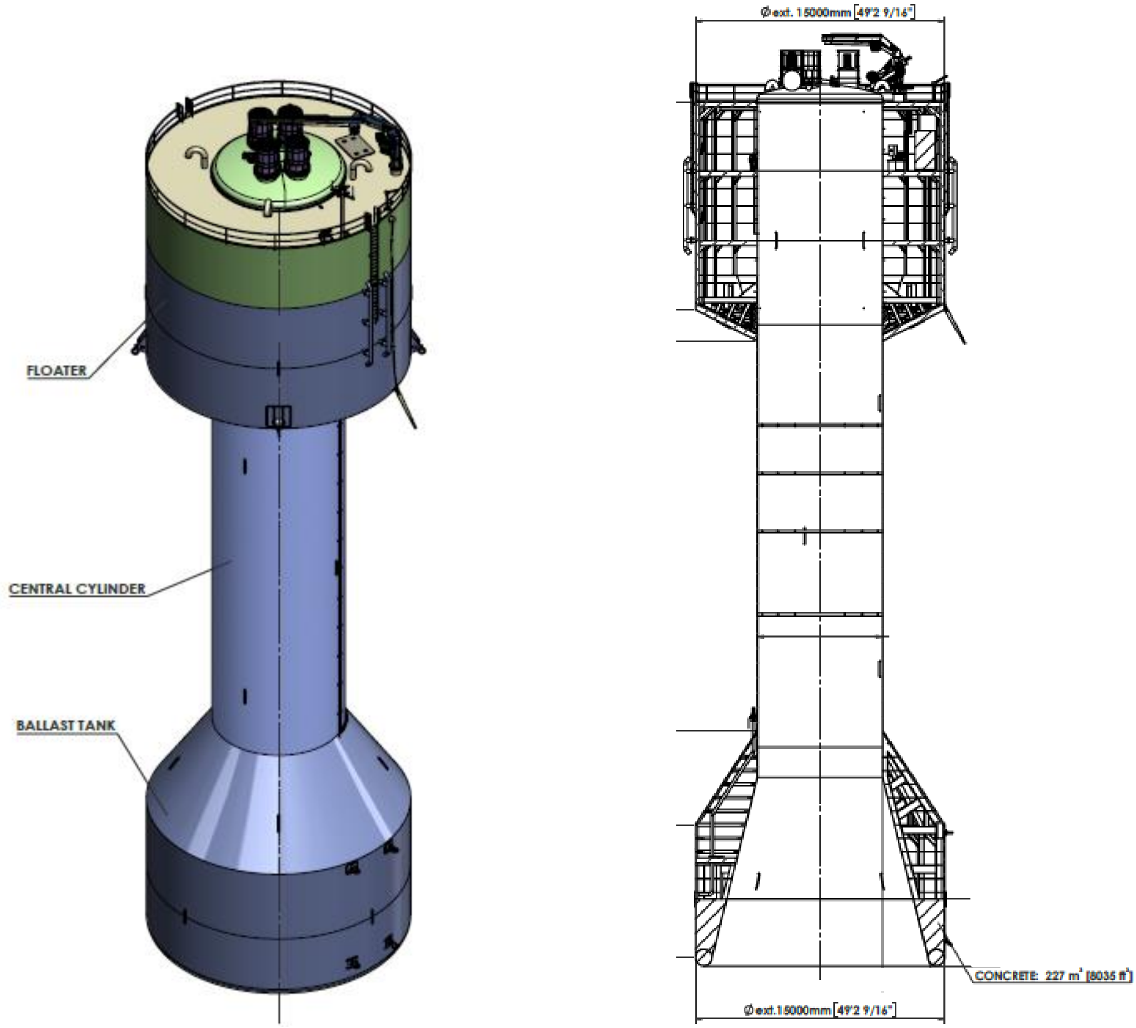


Figure 3-1:Structural overview of MARMOK-A-15 device

Table 3-1 summarizes the final buoy mass balance, showing how the total displacement is divided into steel, permanent ballast made of concrete and variable ballast composed by sea water. The remaining weight (Rest) is composed by the PTO-turbine, coating system, electrical/mechanical equipment, etc.

Physical Property	Value
Mass Steel [t]	626.6
Rest [t]	30.0
Mass Concrete [t]	546.1
Mass Water [t]	745.3

Table 3-1: MARMOK-A-15 weight distribution

3.1.2 Corrosion Control

One of the most important degradation mechanisms that the WEC will face during its lifecycle is the corrosion of the steel. The following systems are established to avoid corrosion:

- Coating scheme;
- Sacrificial anodes, welded onto the wetted surface.

Applicable standards have been followed to determine the number and positions of the sacrificial anodes.

3.2 DESIGN METHODOLOGY

The design methodology defines the general design principles to validate the structure, highlighting the following ones:

- withstand loads liable to occur during all temporary, operating and damaged conditions, if required
- maintain acceptable safety for personnel and environment
- have adequate durability against degradation during the design life of the structure.

The methodology applied is called LRFD methodology (Load and Resistance Factor Design), which consists of obtaining the target safety level as close as possible by applying load and resistance factors to characteristic reference values of basic variables. This procedure is extensively described in paragraph 5.11 from Standard [1] *(IEC TS 62600-2 ED2. Part 2: Design requirements for marine energy system)*. By means of these factors the loads acting on the structure and the resistance of the structure or resistance of the structural materials can be obtained from equations (3-1) and (3-2) respectively.

$$F_d = \gamma_f x F_k \tag{3-1}$$

$$f_d = \frac{f_k}{\gamma_m} \tag{3-2}$$

Where:

- F_d: design value for loads acting on the WEC for the given design load case;
- γ_f: partial safety factor for loads;
- F_k: characteristic value for the load;.
- f_d: design values for material properties;
- f_k: partial safety factors for material properties;
- γ_m: characteristic values of material properties.

The safety magnitude of a structural element is considered to be satisfactory if the design load effect (F_d) does not exceed the design resistance (f_d). Equation (3-3) defines a limit state that must not be reached.

$$F_d \geq f_d \tag{3-3}$$

3.2.1 Limit States and Failure Modes

A limit state is as a condition beyond which a structure or a part thereof exceeds a specified design requirement. IEC standard [1] distinguishes 4 limit states:

- Ultimate limit state (ULS), corresponding to the ultimate resistance for carrying loads.
- Fatigue limit state (FLS), related to the possibility of failure due to the effect of cyclic loading.
- Accidental limit state (ALS), corresponding to damage to components due to an accidental event or operational failure.

- Serviceability limit state (SLS), defined as the state of design beyond which a structural system loses operationally its serviceability for the actual service load that the structure is subjected to.

For each limit sate, the failure modes to be analyzed are:

1. ULS/ALS
    a. Strength: loss of structural resistance (excessive yielding);
    b. Buckling: resistance to buckle, mainly, in slender areas under high compressive stress.
2. FLS: crack initiation under cyclic loading;
3. SLS: in this case different failure modes may occur: deformations that affect structural function, resonances,…..

To develop the design, the failure modes under the limit states are evaluated as it is explained hereunder.

3.3 DESIGN LOADS

The current section presents a development of the design loads to be applied under each of the load cases selected. For the definition of this design loads the characteristic loads, load factors and the interaction of the WEC with environmental loads have been considered. The analyses of each of these factors are presented in the subsections of the current section.

3.3.1 Characteristic Loads

Table 3-2 (Table 3 from [1]) describes the loads needed to be considered for the design.

Environmental (see DNV-RP-C205 for additional guidance)	Hydrostatic	The result of still water pressure acting on the immersed surfaces of a body can be statically analyzed.
	Hydrodynamic	Dynamic loads that are caused by water flow and its interaction with the immersed body depend on the water kinematics, water density, dynamic viscosity, water depth, the shape of the immersed structure, and hydro-elastic effects.
	Wave	The interaction of waves with the MEC shall be analyzed using a relevant wave theory to calculate wave kinematics parameters, such as water particle velocities and accelerations at MEC components. For submerged components of the MEC, periodic pressure variations from passing waves shall be considered.
	Breaking wave	Breaking wave impact loads can lead to dynamic magnification, depending on the duration of the impact relative to the natural period of the structure. In the case where a MEC is installed close to the shoreline, fatigue loading due to breaking waves shall be considered. Since the analysis of breaking wave loads contains many uncertainties, model tests are recommended for the evaluation of the loads.
	Wave slamming	Wave slamming is the result of passing wave interaction with MEC components, usually normal to the surface of the structure.
	Green water	Green water is a term used to describe the overtopping of a body of seawater during severe wave conditions. Structural members exposed to green water shall be designed to withstand appropriate design head pressures.
	Currents	Currents represent water flowing around a structure that produce variable pressures and flow paths. Currents may contain turbulence, which can impose significant loading on the MEC. Cavitation can also impose additional loads on the structure and shall be considered. Dynamic loads that are caused by currents and their interaction with immersed bodies depend on the water kinematics, water density, dynamic viscosity, water depth, the shape of the immersed structure, and hydro-elastic effects.
	Vortex shedding	Vortex shedding creates oscillating loads behind a non-streamlined shape determined by the geometry of the structure and the velocity of the currents and waves.
	Aerodynamic	The quasi-static and dynamic loads that are caused by the interaction of airflow with the MEC's components above the water surface are determined by average wind speed, turbulence intensity, density of the air and the aerodynamic shape of the MEC's components above the water surface and their interactive effects, including aero-elastic effects.
	Seismic	Seismic loads include direct loads generated by seabed movements and fluid loads caused by the seismically induced fluid motions, such as tsunamis.
	Topside icing	Topside icing can cause stability and structural issues caused by icing of the structure above the waterline.
	Ice	Fast sea or river ice cover and/or dynamic loading caused by wind and current induced motion of ice floes can cause significant impact or fatigue loading.
Operational (see ISO 19901-6)	Construction	Unique construction loads occur during fabrication, assembly, transportation and installation of the MEC.
	Actuation	Actuation loads occur during normal operation and control of the MEC. The interaction of the MEC control system with the motion of the structure shall be considered in the control system design and load analysis.
	Maintenance	Unique loads can occur during maintenance work, such as locking of rotational components.
	Gravitational and inertial	Gravitational and inertial loads are caused by gravity, vibration, rotation and seismic activity.
	Vessel impact	Vessel impact force is determined by vessel size, mass, speed, and incident angle.
	Debris impact	Damage can occur from floating debris, such as fishing nets and plastic waste that may include large entrained masses, such as floating logs, chemical debris and fuel slicks.

Table 3-2: Characteristic loads from [1].

3.3.2 Load Factors

The load and material factors used for the design depend on the limit states and design categories according to [1]. Under ALS, SLS and FLS limit states the load factors are 1.0 , whereas the load factors under ULS are shown in the Table 3-3 (Table 6 from[1]):

Load category	Unfavourable loads				Favourable loads[c]
	Design category				All design categories
	Normal (N)	Extreme (E)	Abnormal (A)	Transport/erection (T)	
Environmental	1,35	1,35	1,1	1,5	0,9
Operational	1,35/1,5[b]	1,35	1,1	1,5	0,9
Gravity	1.1/1.35[a]	1,1/1,35[a]	1,1	1,35	0,9
Other inertial forces	1,35	1,35	1,1	1,35	0,9

a For masses not being determined by weighing.

b For MECs working within ±5 % of whole-body or component structural resonance [see Annex B].

c Pre-tension and gravity loads that significantly relieve the total load response are considered favourable loads.

Table 3-3: Load factors under ULS from [1]

3.3.3 Combination of Environmental Conditions

The combination among different environmental loads must be considered for the total load effect. The guidelines given in [1] are followed with 5 different combinations to consider under ULS.

Environmental combination ID	Environmental event and return period (years) to define characteristic value of corresponding load effect					
	Waves	Current	Water level	Wind	Ice	Dominating event
1	50	5	50	5	–	Ground swell
2	5	50	50	5	–	Sea currents
3	–	5	NWLR	5	50	Sea ice
4	50	5	50	50	–	Wind swell
5	-	50	50	5	-	River current

Table 3-4: Combination of uncorrelated extreme events [1].

4 MOORING SYSTEM

The mooring system design has been carried out in order to assure the floating structure stays stationary in place. In addition, other issues related to the structure offset as well as the required footprint and total lines' mass, which influence the umbilical cable design and the mooring costs respectively, have been considered.

The preliminary mooring design was conducted in two main steps, an initial quasi-static sensitivity analysis and then a dynamic analysis, both subject to the assumed governing environmental conditions. In this section, the design steps followed are presented as well as the final mooring details and supporting calculations.

4.1 MOORING CONFIGURATION

The mooring design has been based on the same configuration as the one used during the deployment of the low power MARMOK-A-5 device. This system is based on a catenary anchored rectangular cell, kept afloat through four small buoys, placed at each corner. The floating WEC is placed inside the mentioned cell and connected to the corners thereof.

The mooring configuration consist of three main subsystems: four catenary lines, a floating cell and buoy-cell connecting lines. Consequently, the following main components of the mooring system have been identified in this phase:

4. Catenary lines:
    a. Anchor;
    b. Chain section;
    c. Polyester section;
5. Floating cell:
    a. Cell lines;
    b. Cell buoys;
6. Buoy-Cell connecting lines

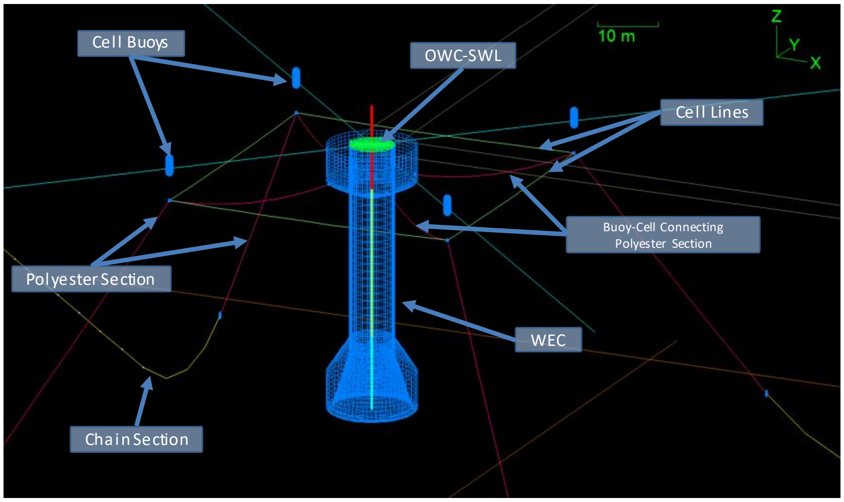


Figure 4-1: Mooring configuration linked to the floating WEC. Main components identified pointed out

This mooring configuration decouples the heaving motion in operational conditions while assuring that the floater remains secure in extreme conditions. In addition, it enables connecting additional units so multiunit devices can be deployed together.

4.2 ENVIRONMENTAL CONDITIONS

The mooring design shall withstand extreme environmental conditions combining wave, current and wind loads. Waves were considered through the corresponding sea state, exerting time varying forces on the structure and mooring system. Currents were considered as a constant force based on the mean current speed. Direct influence of wind on the structure was not considered since the exposed surface of the structure to atmospheric air is relatively low compared to the submerged structural area. The recommended return periods in [2] (*IEC TS 62600-10 Edition 1.0 2015-03. Part 10: Assessment of mooring system for marine energy converters (MECs), 2015*) and [3] (*IEC TS 62600-10 ED2 (114/390/DTS). Part 10: Assessment of mooring system for marine energy converters (MECs), 2020*) for waves and current were used, being the combination of 50 years for waves and 5 years for current the most demanding for this WEC.

During the preliminary design a limited number of environmental conditions were simulated while, for the final design, a more complete set of conditions were evaluated as it is explained in the following subsections.

4.3 DESIGN METHODOLOGY

During the preliminary phase of the mooring system design, a sensitivity analysis has been developed using a quasistatic model to preselect a limited number of mooring designs to be further analyzed in a fully coupled time domain dynamic model. The main design parameters which have been investigated are the chain diameter and length, as well as system pretension and horizontal stiffness.

Once the preliminary design was determined, it was tested in the laboratory testing campaign and, based on the obtained results, it has been refined. This lead to the final design which has been more extensively analyzed under a variety of environmental conditions and limit states to ensure it complies with applicable IEC standard [2],[3].

4.3.1 Preliminary design

Initially a quasi-static analysis has been used for the preliminary design, allowing a large number of quick analyses so that sensitivity analysis can be performed. The sensitivity analysis sets tendencies of the mooring system in terms of offset of the WEC and the related cost.

An initial static characterization of the mooring system was carried out so the different combinations of lines' mass, pretension and axial stiffness were evaluated with reduced computational cost. The characterization was performed for the two main environmental conditions directions, i.e. aligned with a line and centered between lines, as shown in Figure 4-2.

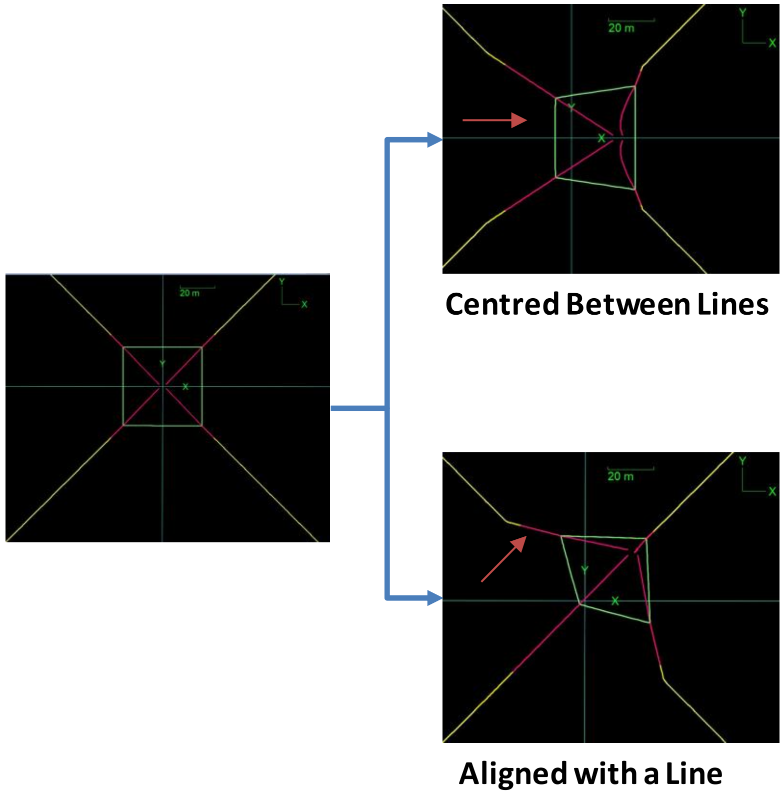


Figure 4-2: Mooring characterization, environmental conditions directions considered.

The mooring static characterization consists of moving the floating device horizontally and storing a set of non-dimensional curves providing information about the restoring force of the whole mooring system, as well as about the suspended line length and line tension of the most loaded line.

4.3.2 Final design

Based on the preliminary design developed, an extended number of environmental conditions were simulated to refine mooring system parameters leading to several system modifications. Additionally, numerical model details were updated with more refined characteristics for all components such as cell buoys size and weight as well as polyester ropes stiffness.

The criteria which have been followed to determine mooring system details are listed below:

- Chain diameter and grade have been selected to withstand maximum loads calculated from governing load cases applying the corresponding safety factor specified by the IEC standard.
- Chain length has been selected to maintain the same system pretension which has been set during the preliminary design.
- Anchor positions have been set in order to avoid any vertical uplift force.
- Anchor size has been selected to ensure the maximum horizontal loads they receive are under their ultimate holding capacity while applying the applicable safety factor stated by the IEC standard.
- Polyester ropes' diameter has been selected to reach at least same chain´s MBL

- Polyester ropes length in the catenary lines has been maximized while avoiding any contact of the rope with the seabed.
- Cell lines steel wire cables diameter have been selected to withstand maximum estimated loads with the applicable safety factor
- For all accessories (shackles, links…) the MBL has been selected to be equal or larger than the one from the elements that they connect.

Applying all these criteria, the final mooring system was achieved. The resulting mooring system design can be seen in the following figure:

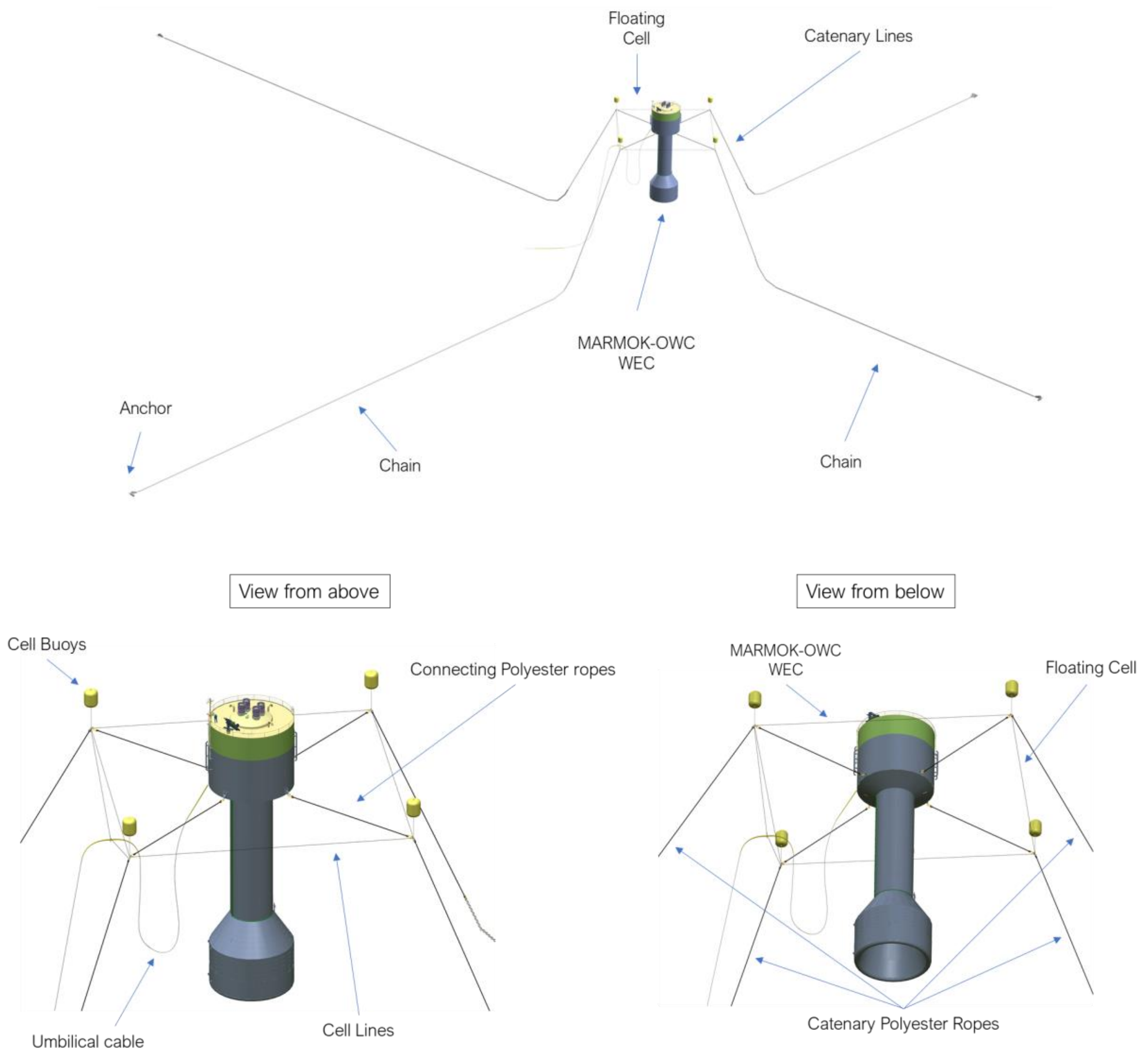


Figure 4-3: Mooring system final design description

4.4 UMBILICAL CABLE ROUTING DESIGN

Related to the design of the mooring system, a routing and sizing of the umbilical cable was conducted. A set of design load cases were extracted from the environmental conditions of PWS, looking for the most demanding conditions while analysing different alternatives, such as hanging the cable from the mooring system, connection locations to the WEC (different azimuth angles) and lazy wave depth.

Once the dynamic cable's connection position was defined, the next step was to define the cable itself. Once again, the better way to study several options optimizing computation and simulation time was pursued, which resulted in the conduction of a set of sensitivity analyses focusing on the tension and bending radius of the cable in the worst design load cases.

The sensitivity analyses carried out consisted of looking for a design which stayed within the limits in terms of maximum cable tension and minimum bending radius while avoiding clashing against the WEC. The main design parameter where the bend stiffener position, cable sections lengths as well as cable to WEC connection location.

Additionally, it was necessary to design the lazy wave's stiffeners, including the depth value in which it would be more appropriate to be installed, according to the technical criteria described (best performance in terms of tensions and curvatures) and to O&M criteria (trying not to install the lazy wave too deep to facilitate the maintenance operations).

Finally it was decided that the best alternative was connecting the cable to the mooring system to minimize its motions with a connection point located in the West direction as it was observed in Figure 4-3.

5 POWER TAKE OFF SYSTEM AND ITS CONTROL STRATEGY

For the design of the power take off system, a detailed analysis of its main components has been performed; the air turbine and the electric generator.

5.1 PTO design

The PTO system can be considered as a combination of a certain number of air turbine-electric generator sets that work in parallel, so several alternatives can be pursued depending on the size and number of these sets. An initial study of these alternatives was conducted considering a different number of air turbine-electric generator sets varying the size of the turbine and the rated power of the generator to maximize the AAEP.

Once the sets were sized, a detailed aerodynamic development of a Wells turbine was conducted in collaboration with Sandia National Laboratories (SNL) and Penn State University, aiming at an improvement of the baseline Wells turbine designed by IDOM. During this development the effect of the increase of the number of blades, and consequently the solidity, and the introduction of guide vanes were evaluated among other characteristics. A coupled development was performed combining analytical aerodynamic analysis and CFD simulations.

Regarding the electric generator, a comparison between a squirrel cage induction machine and a permanent magnets synchronous generator was conducted by means of simplified numerical models developed in collaboration with National Renewable Energy Laboratory (NREL). Together with this set, a series valve was selected to allow turbines switch off for survival conditions.

The optimization resulted in a set of 4 Wells turbine with 75kW electric generator each, leading to a rated power of 300kW.

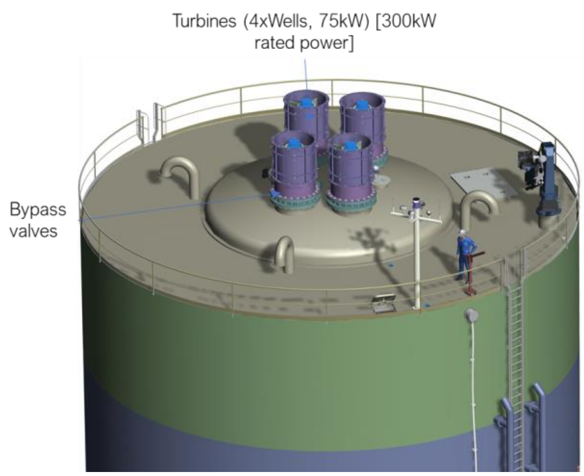


Figure 5-1: PTO configuration

5.2 Control strategy

Besides the design of the physical components, a control strategy for the operation of the PTO was developed. There are many different parameters that considerably affect the performance of a WEC

and therefore influence the electric power generation. The average yearly generation is to be maximized while keeping other relevant variables under control, such as avoiding excessive power peaks (which would force use of bigger and more expensive power electronics and electrical components) or not overcoming certain torque and velocity limits. In this type of WEC, the main parameter to be controlled is the rotational speed of the turbine, which can follow different control laws optimized to maximize power performance while ensuring certain constraints are satisfied. The optimization problem is finally defined as the process of finding the design variable vector that, without violating the preestablished design constraints, maximizes the value of the objective function. In this case, these are:

- Objective function:

  The control strategy is designed to maximize the annual average electric power generation which is the objective function of the optimization process.

- Constraints:

  Due to environmental conditions and structural design specifications, some existing invariant constraints are taken into account, like the exciting forces that come from the PWS data obtained for different sea states, or the limit in maximum electric peak power, which should not exceed a specific threshold. The optimization then will be limited to a precise operating design conditions.

- Variables:

  The vector of design variables, $\boldsymbol{x}$, is composed by the values of the six parameters that define the control law curve where the torque is defined as a function of the turbine rotational speed.

The process is conducted by means of a time domain model in MATLAB/Simulink.

For the development of the most appropriate control strategy different control variables have been analyzed, plus the frequency of varying the control strategy on an attempt to maximize the extracted electric power, starting from baseline control strategies, in which static control laws are implemented, to advanced control strategies, in which an optimization process is followed and the control law is frequently modified. Within the scope of this project a baseline control strategy has been designed where constant control parameters are applied, and a more advance Model Predictive Control strategy has been defined, where the control parameters are adapted in real time based on the incoming waves measured by a wave rider buoy located in the vicinity of the WEC.

6 CONTROL ARCHITECHTURE & INSTRUMENTATION

6.1 INSTRUMENTATION; HARDWARE

In this section, the hardware and instrumentation related to the MARMOK-A-15 software is given. Each of the choices has been taken considering the application, the location, and the compliance with the high quality of the instrumentation needed.

The installation requires that the instrumentation fulfills with the following requirements:

- The safety and automation systems will be designed as independent systems.
- **Standards**: Systems, components and signals will be standardized to the largest extent possible.
- **Redundancy** shall be implemented where necessary in order to ensure safe operation of the device. This redundancy shall be simple even in case of failure or malfunction.
- **Degree of protection**: it must be specified by manufacturers that the components are applicable for marine environments. In the case the instrumentation does not fulfill it, a box or a cabinet with the required degree of protection must be provided.
- **Recognized quality**: all the instrumentation must be supplied obeying a recognized quality from manufacturers. To the extent possible, they should provide quality certificates for their products.
- **Experience**: Taking into account previous experience in this type of projects, if components/suppliers from previous projects are applicable, they have been selected for this one.
- **Control system:** PLC has been selected with specific characteristics:
    - Distributed architecture: The X67 system allows the connection of several independent input and output modules. They also have an IP67 degree of protection.
- **Functionality**: hardware elements must achieve their purpose in a direct, simple and practical way.

6.2 SOFTWARE

To this end, the following principles have been applied in order to obtain clean, modular, scalable and easy-to-maintain programming:

- **Clean**: Program the desired functionalities, including their program structure, specific variable types and nomenclature of functions and variables.
- **Modular**: Enable software scalability through structuring and sorting tools for folders, files and programming units.
- **Scalable**: Using object oriented programming (OOP) with the objective of easily increase or decrease the number of devices, pumps, fans.... .
- **Easy to maintain**: Being structured in objects, it is possible to perform unit testing and thus facilitate the maintenance of the code.
    - Using object oriented programming it is also possible to perform modifications in a fast and safe way, which allows for easy maintenance.
- Failure of any of the safety or automation systems should initiate an alarm at the monitoring station and the notification of the corresponding responsible parties.

All these principles can be fulfilled with object-oriented programming, therefore this type of programming has been selected.

The software that controls the different functions and components of the MARMOK-A-15 is implemented in the Local Control System (LCS).

7 ELECTRICAL SYSTEM

The electrical system of the MARMOK-A-15 has been designed to achieve 4 main goals while complying with local codes and international standards (Such as NEC, NEMA, NFPA, IEC [4] , IEEE [5], etc.) to the maximum extent possible. These goals are:

1. Coupling with the grid at PacWave South
2. Facilitate power generation of the MARMOK A-15 OWC
3. Power transmission from the MARMOK A-15 to shore grid
4. Maintain operability of the MARMOK systems on board

7.1 POWER TRANSMISSION SYSTEM

This system has the main purpose to transmit power back to shore. The following activities have been done during the design of this system:

Firstly, load flow studies has been done using Electrical Transient Analyzer Program (ETAP) commercial software to determine a suitable transmission voltage and visualize the voltage deviation at different generation scenario and transmission voltage levels. To achieve it, a model of the MARMOK electrical system has been built within ETAP.

By using this model, 4 transmission voltages (12.47kV, 13.8kV, 23kV, 34,5kV, all according to ANSI 84.1) have been studied with 3 Generation scenarios (Peak generation, nominal generation & zero generation).

Secondly, selection and sourcing of the following components have been done:

- Medium Voltage (MV) Submarine Cable
- MV Switchgear
- Main Step-Up Transformer

7.2 POWER DISTRIBUTION SYSTEM

This system has the main purpose of distributing power within the WEC for transmission and to supply onboard consumers. Selection and configuration of the Main Distribution Switch panel has been completed for this system. The switch panel is the interface of coupling with the grid, the PTO system and the auxiliary system on the MARMOK.

7.3 AUXILIARY SYSTEMS

This system has the main purpose to power all auxiliary loads crucial for MARMOK operation. Selection and modification of the following components have been done:

- 480V Auxiliary Panelboard
- 120V Auxiliary Panelboard and 10kVA single-phase dry-type transformer, powering bilge system, ventilation, space heaters and control panel
- Uninterruptible Power Supply (UPS) System, 3kVA charger and rectifier with 40+ hours of Lithium-ion iron phosphate batteries considering the loads from essential equipment such as

PLC, 4G Router, network switch, GPS, and a single actuation of boarding valves, turbine series valves and ventilation valves (to close all but the boarding valve which is opened).
- Lighting System, NEMA 4X LED for normal and emergency scenarios

Additional design effort has been made for maintaining a suitable operating environment for electrical equipment and ensuring survivability of the MARMOK, such as:

- Lightning Protection System and risk assessment has been performed and deemed not necessary according to NFPA 780
- Cabling and routing, achieved with wet proof cablings and wall-mounted cableways with defined routing codes.

8 AUXILIARY SYSTEMS

Besides the main subsystems of the device, several ancillary subsystems have been designed to ensure the correct function of the overall device. The experience gathered during the previous deployment of the MARMOK-A-5 has driven the design of most of these subsystems.

A **ventilation system** has been designed for the floater compartments, not only for avoiding the overheating of the electronics, but also for ensuring the suitability of the environment for the technicians during maintenance operations.

The same compartments are equipped with several pumps conforming the **bilge system** of the buoy to remove any possible water leakage into the floater.

A **fire suppression system** has been implemented in the buoy to avoid any detrimental consequence the unlikely and localized potential fires could provoke.

Looking into the ease of the maintenance operations, an **onboard crane** has been selected to be installed in the main deck of the buoy, which will enable simple maintenance operations to be conducted without the need of specialized vessels.

Finally, a **boarding valve** has been designed for facilitating the boarding of maintenance personnel to the buoy from an external vessel.

Besides this main auxiliary system, several safety elements are included in the design, such as a boat landing, boarding ladders and handrails.

9 TANK TESTING CAMPAIGN

An extensive tank testing campaign of the designed device was conducted from July to September 2021 at the Offshore Technology Research Center (OTRC) in College Station, Texas.

The objective of this campaign concerned the experimental assessment of the WEC focused on numerical model validation and refinement, as well as power performance assessment. This was achieved through the following partial objectives:

- Full hydrodynamic characterization of the moored device for numerical models validation under operational sea states:
  - Loads and motion characterization of the device
  - Static characterization of the mooring system
  - Power performance prediction
- Loads and motions measurement under extreme sea conditions to compare against numerical models which are used for structural and mooring design

For this testing campaign, the applicable IEC standard [6] has been followed to the largest extent possible during test preparation, execution and data postprocessing. According to the standard these tests correspond to a Stage 2.

9.1 TEST MODEL AND PLAN

For this testing campaign, a 1:28 model was fabricated with an equivalent mooring system to account for the depth differences between the tank and PacWave-South test site.

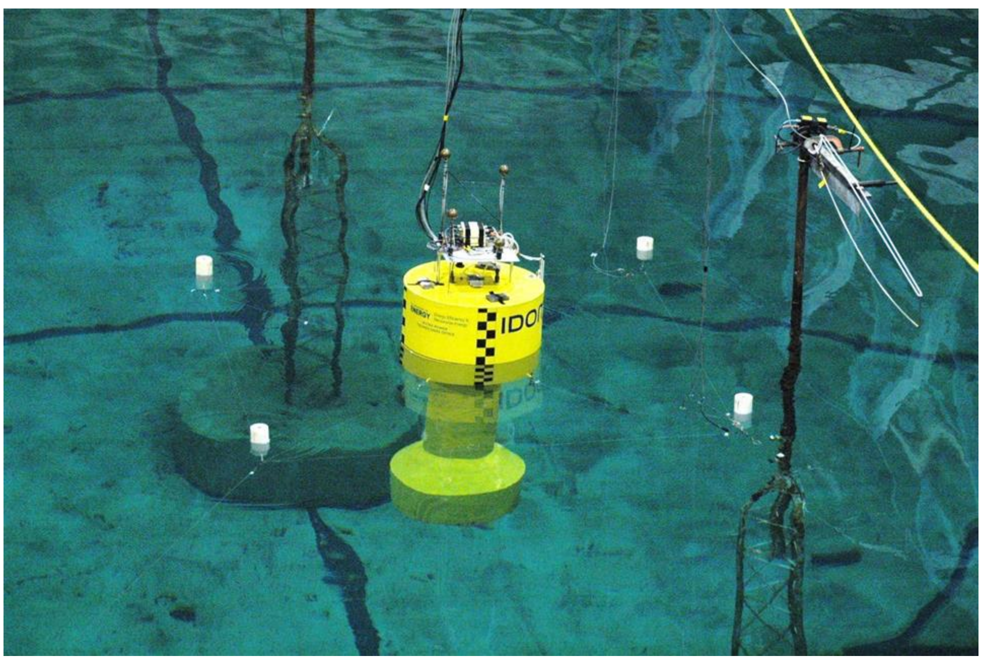


Figure 9-1: WEC and mooring system deployed and instrumented

During this testing campaign several tests were conducted, stating quantification of the natural periods and damping coefficients of the device by means of decay tests, and the corroboration of mooring

properties with static offset tests. A combination of regular waves and white noise tests was also performed for the hydrodynamic characterization of the buoy. A PacWave South representative operational sea states set was tested for the assessment of the power performance of the device plus the calibration of the power performance estimation models. The suitability of the design against PacWave South extreme conditions was also tested, successfully enduring the demanding extreme sea states that can occur in the location. Finally a tow test was conducted for the assessment of the horizontal drag of the device.

9.2 MAIN CONCLUSIONS

The primary conclusion that were obtained from the testing campaign was that the device presents the expected behavior in both operation and extreme conditions.

Regarding operational conditions, the main focus was put on power performance measurement, which has been demonstrated to be aligned with the expectations in all the tested wave heights and periods which cover the full design range. When looking into the dynamics of the WEC, no unexpected behavior was found.

Regarding survival conditions, buoy dynamics were measured and they were found to be aligned with the expected values.

On the power performance, after calibration, a high level of agreement was obtained, reaching an average annual error of -1.12% with respect to numerical models results. Regarding the buoys dynamics, alignment of values was found in the main degrees of freedom.

The main lessons learned of this testing campaign are presented in section 12.1.

10 MARINE OPERATIONS AND O&M PLAN

During this project the main marine operations required for the MARMOK-A-15 deployment and operation at PacWave-South were analysed. The main objectives of this task were:

- Identify the system design adaptations required to ensure the system can be installed, operated, and maintained
- Identify the means required to develop these operations (cranes, vessels…)

As a summary, in this section the main means required for the main marine operations are presented:

1. Preinstallation of the anchors and mooring system
    a. One Anchor Handling Tugs (AHT)
2. Preinstallation of the umbilical cable
    a. One Multicat DP support boat (aprox. Size 42m length, 12m beam)
3. At port lifting operation to place device in water and ballasting
    a. Two land-based cranes
4. Horizontal towing out
    a. One tugboat, possibly two on port
5. Ballasting at installation site
    a. One tugboat
    b. One small boat with divers support
6. Hooking up the preinstalled mooring system and umbilical cable connection
    a. One tugboat
    b. One Multicat DP support boat
    c. One small boat with divers support
7. Operation & Maintenance
    a. One small personnel transfer boat with boat landing protection and 2m x 2m deck space
8. Decommissioning and deinstallation (including de-ballasting)
    a. The same as in the installation and commissioning, plus a compressor to remove water ballast.

During this project the main preventive maintenance operations have been identified based on the experience operating the previous prototype MARMOK-A-5.

A periodicity has been established for each preventive task being 6 months for some of them. This periodicity shall be understood as a task to be performed twice per year: first, after winter season as soon as the environmental conditions permit access to the buoy and second as preparation for the winter, taking advantage of any appropriate weather window.

The maintenance tasks have been divided into 4 areas:

- Buoy External area;
- Buoy Internal area;
- External submerged area 6m below MSL (depth <6m);
- External submerged area 6m above MSL (depth >6m).

11 NATIONAL LABS TECHNICAL ASSISTANCE

During this project NREL and SNL have provided technical assistance in several design tasks as it is summarized in this section.

- *Improved air turbine aerodynamic design:* This task was performed in collaboration with SNL and Penn State University. An iterative multi-fidelity numerical modeling approach was used consisting of a 1D analysis of scaling relationships and design variables (torque, thrust, solidity) to identify optimal concept and configuration, then a 2D analysis using turbomachinery design tools to target desired aerodynamic operating conditions and define rotor and guide vane blade geometries and finally a 3D analysis using CFD modeling of blade designs to determine turbine performance. The workflow used can be seen in the following figure:

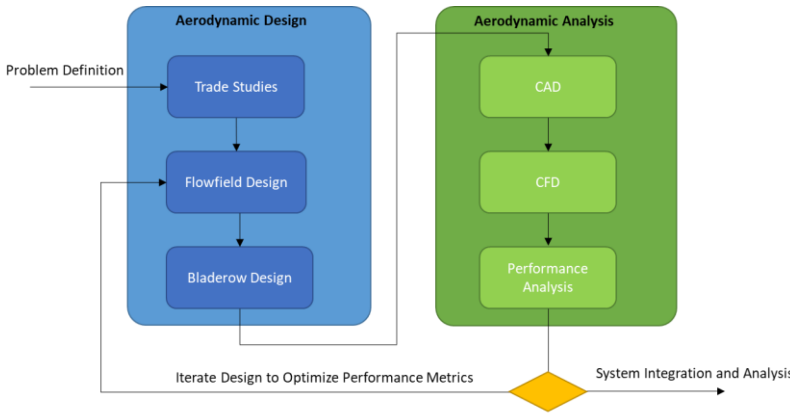


Figure 11-1: Workflow used in the iterative multi-fidelity numerical modeling approach used to design and improve the performance of the Wells turbine for use within the MARMOK-OWC.

An example of the outputs obtained from the CFD simulations can be seen in the following figure:

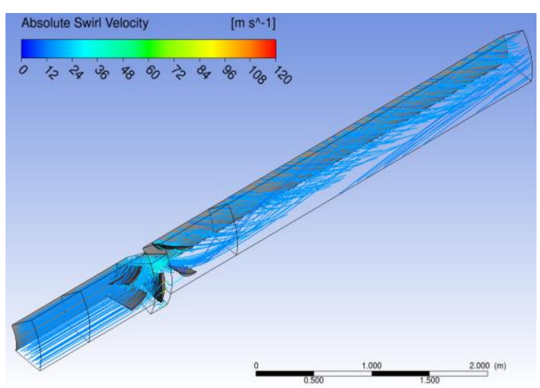


Figure 11-2: CFD output of one of the configurations analyzed, 7 rotor blades and 15 stator guide vanes.

- *PTO electric generator type selection:* This task was developed in collaboration with NREL. Simplified models for both Permanent Magnet Synchronous Generator (PMG) and a Squirrel

Cage Induction Generator (SCIG) were developed to compare their conversion efficiency. An example of the efficiency curves obtained can be seen in the following figure.

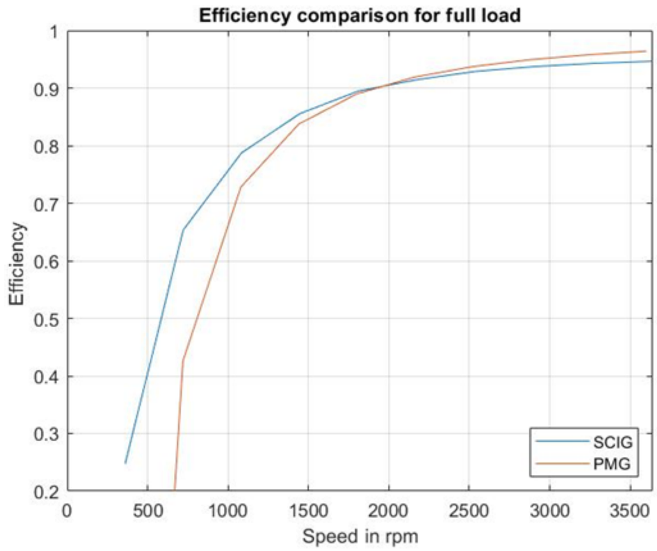


Figure 11-3: Efficiency curves obtained through the simplified models developed.

Comparison was made for half and full loads, showing similar behaviour for full load, while PMG provides less power at half load but achieves better efficiency at peak load. Consequently, the simplicity and robustness of the SCIG was prioritised and it was selected as the preferred typology for this project.

- *CFD model to determine second order drag forces and extreme loads:* This task was performed in collaboration with SNL. Firstly a CFD model was developed to perform forced oscillations in heave and determining the drag losses for different geometries. It helped to optimise the buoy geometry, both external and internal conical shapes. A screenshot of the model developed can be seen in the following figure:

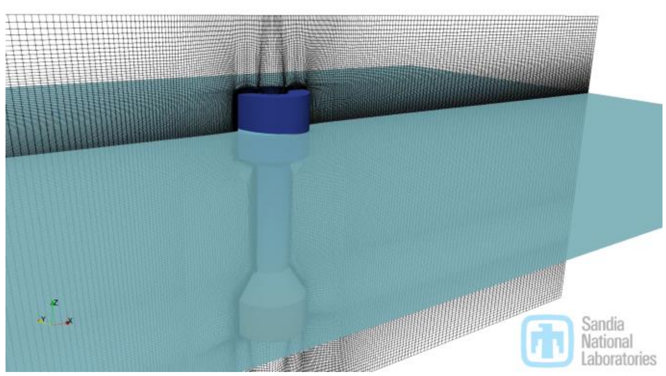


Figure 11-4: CFD model developed to perform forced oscillations in heave and optimize hull shape.

Secondly, same model was used to measure hull pressure distribution when subjected to extreme regular waves. It was used to confirm the assumptions employed in the structural design of the hull and ballast tank stay in the conservative side.

- *Environmental conditions extended characterization:* This task was performed in collaboration with SNL. Based on the raw data available on both waves and currents [8], SNL made a detailed analysis of the extreme conditions including the incoming direction in the analysis. This helped to optimise the mooring system design. The results obtained are shown in the following figures.

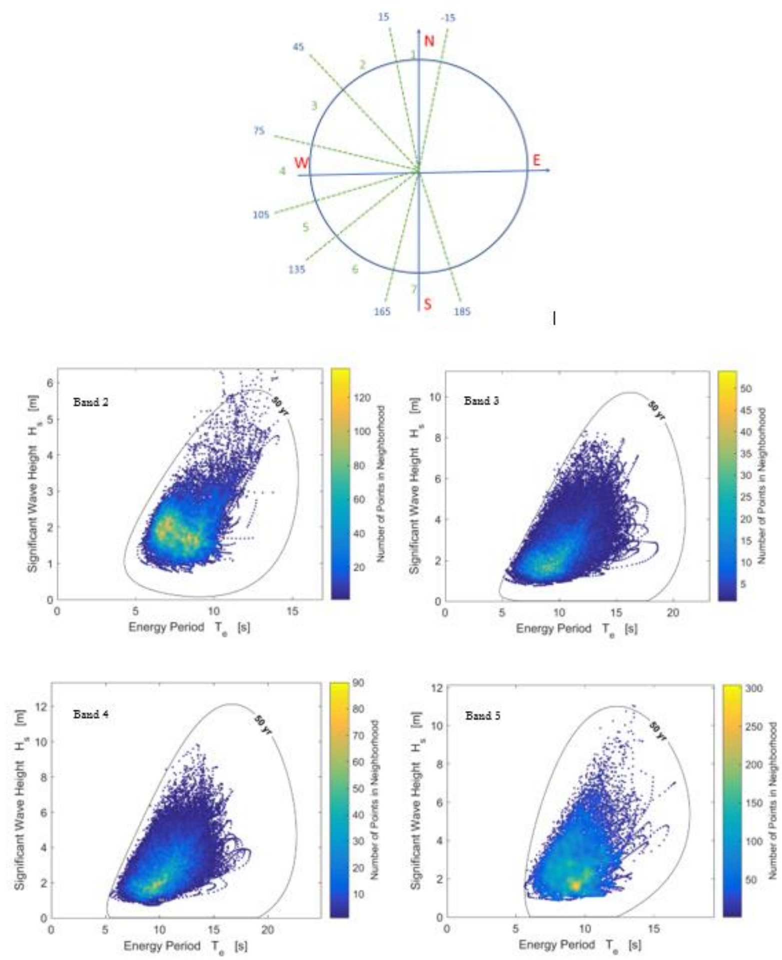


Figure 11-5: Defined directional bins (On the top) and 50 year environmental contours for different wave propagation directions.

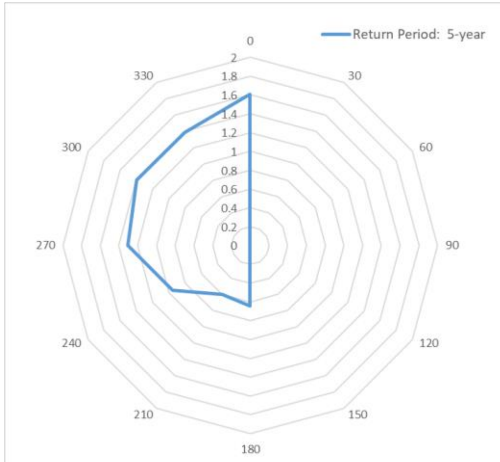


Figure 11-6: Directional current velocity rose distribution at PWS for 5-year return period

- *Mooring design in array configuration:* This task was developed in collaboration with NREL. One of the main cost reduction pathways when analysing this technology is reducing mooring system cost for array deployments by sharing mooring system components. The main objective of this task was the investigation of variation of mooring cost as WEC farm size increases. NREL's mooring dynamics simulation tool, MoorDyn, was determined to be able to model large WEC array mooring systems at a relatively low computational cost without running into significant numerical issues. Several WEC layouts were analysed for increasing number of WECs in each cluster, developing a preliminary mooring system design and estimating a cost. Some examples of the layouts analysed can be seen in the following figure:

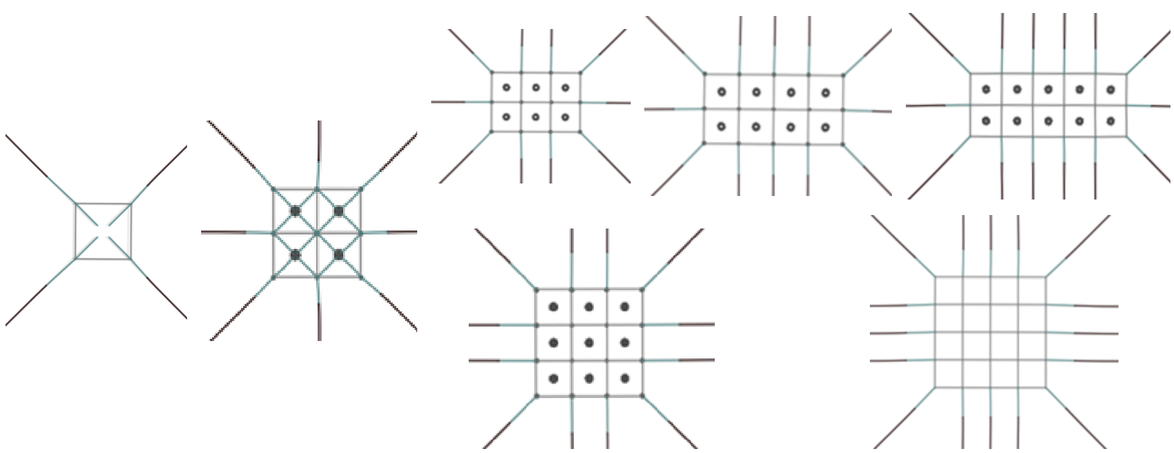


Figure 11-7: WEC Array Layouts Considered in Task ($\boldsymbol{2xN}$ on top, $\boldsymbol{NxN}$ on bottom)

Results showed promising cost savings (reaching a 60% reduction) when increasing the number of devices as it can be seen in the following figure:

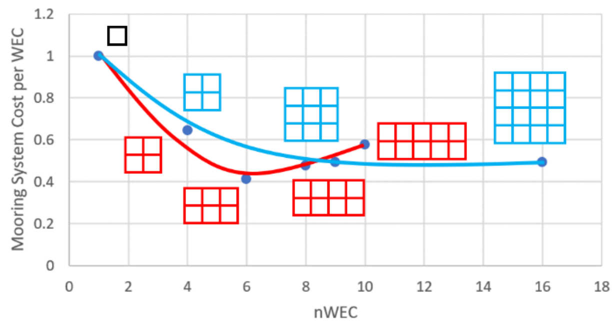


Figure 11-8: Normalized mooring system cost per WEC

12 MAIN LESSONS LEARNED

In this section the main lessons learned during the execution of this project are presented. These are mainly related to the laboratory testing campaign and the standards incorporation in the design. Additionally other learnings derived from the execution of the project are presented.

12.1 LABORATORY TESTING CAMPAIGN

Regarding the testing campaign the main lessons learned are listed below:

- Fabrication of this type of spar types buoys with low center of gravity may become challenging compared to the more traditional model fabrication techniques and it has to be explored as soon as possible.
- Consider instrumentation weight in the model design as soon as possible because it may add a significant weight (specially for old versions of motion tracking systems).
- Watertightness of model instrumentation has to be clearly specified and inspected before starting running extreme sea states due to submergence events will occur.
- Check before starting the testing campaign if any sensor has a significant drift to either reduce it by changing sensor or be prepared to eliminate it during the data postprocessing.
- For extreme tests, cable routing into the model has to be carefully designed to avoid clashing with instrumentation .
- White noise tests provide an efficient way of calculating system RAOs, but they are subjected to filtering process parameters so regular waves should not be avoided.

12.2 STANDARDS INCORPORATION

Regarding the incorporation of the standards in the design, the following outcomes may be outlined per subsystem:

<u>Structural design:</u>

The structural design has been performed following IEC guidelines and when lack of detailed rules and guidelines was found, other standards have been used to complement, particularly Det Norske Veritas (DNV) standards.

The necessary contents without accurate guidelines within IEC standards found are:

- The characteristics loads calculation and definition, which are carried out following standard DNV-RP-C205, which is also mentioned within IEC standard.
- The failure mode assessments. The analysis methodology followed along the report is based on FEM, not finding accurate guidelines within IEC standard. Thus,
    - Standard DNV-RP-C208 are applied for strength and buckling failure modes for the hull. DNVGL-OS-C101 may support some issues in the assessments;
    - Standard DNV-OS-E301 is applied for padeyes (design solution for the connexion with the mooring system) and surrounding structure;
    - Standard DNV-RP-C203 standard is applied for the fatigue failure mode;

- Standard DNVGL-ST-0437 is applied for impact loads, which occur during vessel approach for maintenance, equipment installation or replacement;
- Standard DNV-RU-SHIP-3Ch4 is applied for towing operation;
- Standard DNV-OS-H205 for lifting operation.

Mooring design:

For the mooring design IEC TS 62600-10 Edition 1.0 2015 [2] has been used, where applicable safety factors are stated. However, it has been found that limited guidelines on the environmental conditions to be considered are reported. Consequently, to properly build the design load cases, a draft of the second edition has been used [3] which has been found sufficient to develop the mooring system design.

This standard has also been employed for the design of the umbilical cable routing, using same considerations for extreme environmental conditions selection, safety factors and design load cases definition.

Testing campaign

For the test plan definition TS 62600-103 edition 1.0 has been followed to the largest extent possible, also considering some inputs from the draft version of the edition 2. This testing campaign, due to the scale and objectives, corresponds to the Stage 2 of the standard, so Stage 2 associated criteria have been followed for testing environment characterization, power performance estimations, kinematics and dynamics in operational and survival conditions. It has affected the number of frequencies determined in the regular tests and test duration in regular wave and irregular wave tests. On the laboratory requirements side, data acquisition (DAQ) requirements have been shared with the laboratory and they have followed them to the largest extent possible considering the DAQ hardware available in the laboratory and the normal procedures based on their testing experience. So it has been found challenging to fully comply with all DAQ requirements without affecting the DAQ design already in place, which was not subjected to be modified. For the reporting of the results, this standard has also been successfully considered.

Electrical design

IEEE 1547-2018 is the main standard for any grid connected device in the US. During the design phase of this WEC, the grid-tied inverter selected was considered partially compliant with IEEE 1547-2018. For further assuring standard compliance, the settings of the inverter must be tunned during testing phase with the fabricated prototype prior to deployment. UL1741 listed (Compliant through testing against IEEE 1547.1-2020) inverters are available in the market, selecting these devices would benefit standard compliance of the overall WEC.

Regarding the IEC TS 62600-30 standard, it focuses mainly on power quality characteristics, providing extensive procedures and requirements for testing measurements. During the design process, certain hardware was included in the design to facilitate testing. Ultimately, testing has to be made with a fabricated prototype or dynamic numeric simulation model to test against compliance. Fortunately, power quality issues are covered by IEEE 1547-2018 as one of the clauses.

12.3 OTHERS

Additionally, other lessons have been learned during the execution of this project. These can be listed as follows:

- The importance of having detailed environmental conditions characterization has been found to be key when optimizing mooring system design. Particularly, having the wave environmental

contours per propagation direction and the extreme current velocity directional distribution has contributed to develop a more detailed load cases table. It has led to a significant mooring system optimization compared to using omnidirectional contours which require assuming most severe conditions coming from same direction.

- On the structural design, for the floater design, the assumption of having the buoy fixed when subjected to extreme environmental conditions has been confirmed to be in the conservative side when comparing it with the pressure distribution obtained in the testing campaign where the buoy was free floating connected to the mooring system. Similarly, the assumption of having an axisymmetric pressure distribution for the hull design has been found to be conservative compared to the analysis performed through CFD simulations by Sandia National Laboratory.
- This FOA required a manufacturability review of the design by a third party company. Doing this during the design stage has been found to be very interesting to allow design modifications which eventually lead to an optimized (and cheaper) manufacturing process. Some examples of the comments received during the review are listed below:
    - Recommended using shell sections size compatible with typical US steel manufacturers outputs;
    - Using standard profiles for the stiffeners may imply a significant cost reduction;
    - In areas with no weight constraints, using thicker plates with less number of stiffeners may lead to cheaper configurations.
- Due to the severe environmental conditions of PacWave-South site (not only waves but also currents), the umbilical cable routing design has been found to be more challenging than originally expected. So it is recommended that this design is considered as early as possible in the WEC design process, particularly in high energetic deployment sites.
- It is key to consider installation and O&M strategies as early as possible in the design process. Specialized vessels availability may be an issue is some deployments sites which may influence the WEC design, marine operations design and eventually their viability. For example, this WEC design included a crane on deck to allow turbines substitution using a standard vessel and the turbine number was decided looking into the weight of each turbogenerator set to allow easier substitutions offshore.

13 CONCLUSIONS AND NEXT STEPS

In this report, the final WEC design developed under the award DE-EE0008952, as part of the Funding DE-FOA-0002080, has been presented. As requested by the FOA, the design has been specifically designed for PacWave-South conditions and optimized to maximize captured power to cost ratio. The survivability of the system has been demonstrated under the expected extreme conditions for a 2 year design lifetime, as well as its operability and maintainability. The MARMOK-A-15 has been designed to be connected to the electrical grid and it has demonstrated to be capable of delivering +25kW of annual average electric power. Additionally, the design process has been conducted according to the applicable IEC and IEEE standards. During the project, a laboratory testing campaign of a scaled prototype was conducted to calibrate numerical models, which have been used for the power performance estimation, and the structural and mooring designs.

The design has started with a thorough analysis of the environmental conditions for the site, both the average and extreme conditions. Then the geometry optimization has been presented with the objective of maximizing the captured power to structure cost ratio.

For the selected geometry the detailed structural design has been developed leading to 626t of steel required to withstand extreme environmental conditions. On the mooring system design, a 4 catenary line system with mixed chain and polyester ropes, employing drag anchors has been developed. Related to the mooring system, the umbilical cable routing design has been developed to ensure cable integrity under extreme conditions. For these systems the design methodology has been presented.

The PTO system design of a coupled air turbine and electric generator has been developed. Different control strategies have been analyzed and compared, leading to two preselected strategies, a simple baseline control strategy as well as an advanced Model Predictive Control strategy.

The control architecture and instrumentation required to operate the WEC have been defined showing a preselection of the main components. This includes the hardware required as well as the software definition to ensure a safe and efficient operation of the system. The electrical design of the system has also been developed to transmit the power generated to shore and manage the auxiliary systems required. The latter have been defined and design choices justified.

To ensure the operability and maintainability of the system the main marine operations have been analyzed and have identified the means required. A preliminary maintenance plan has been developed.

In addition to the prototype design, several performance metrics have been estimated as requested by the FOA (i.e. LCOE, peak to average ratio and capture width). Particularly, the LCOE has been calculated not only for the single device but also for a small and medium size array, aligned with the next steps identified in the technology development path.

Finally within this project, a technology commercialization plan has been developed, identifying next development stages and focusing on the closest potential markets, i.e. the niche markets such as the isolated power systems/communities, aquaculture and offshore oil & gas.

Regarding the next steps after this project, the most immediate one would be the fabrication and testing of this commercial size prototype at PacWave-South. The main objective would be the demonstration of the full power technology in a real offshore environment advancing the technology from the current TRL 6-7 to TRL 8.

In parallel to this potential deployment, R&D efforts will be focused on the power performance improvement, mainly looking into the PTO design and control strategies optimization while maintaining the high robustness and maintainability already demonstrated for this technology. In addition to this, long term cost reduction pathways will be investigated such as the cost saving derived from array deployments as well as the use of alternative materials such as concrete.

14 REFERENCES

[1] IEC TC 114: MARINE ENERGY – WAVE, TIDAL AND OTHER WATER CURRENT CONVERTERS. IEC TS 62600-2 ED2. Part 2: Design requirements for marine energy system, 2019.

[2] IEC TC 114: MARINE ENERGY – WAVE, TIDAL AND OTHER WATER CURRENT CONVERTERS. IEC TS 62600-10 Edition 1.0 2015-03. Part 10: Assessment of mooring system for marine energy converters (MECs), 2015.

[3] IEC TC 114: MARINE ENERGY – WAVE, TIDAL AND OTHER WATER CURRENT CONVERTERS. IEC TS 62600-10 ED2 (114/390/DTS). Part 10: Assessment of mooring system for marine energy converters (MECs), 2020.

[4] IEC TC 114: MARINE ENERGY – WAVE, TIDAL AND OTHER WATER CURRENT CONVERTERS. IEC TS 62600-30 ED1. Part 30: Electrical power quality requirements, 2018.

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