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Authored	E. Hammagren, K. O’Hearn, M. Ondusko		
Reviewed	M. Ondusko		
Version Approved	Erik Hammagren Digitally signed by Erik Hammagren DN: O=Columbia Power, CN=Erik Hammagren, E=ehammagren@columbiapwr.com Reason: I am the author of this document Location: Date: 2020-05-11 09:39:06 Foxit PhantomPDF Version: 9.1.0		
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1 INTRODUCTION

The SeaRAY is a deployable power system for maritime sensors, monitoring equipment, communications, unmanned underwater vehicles, and other similar payloads. This Project is to design, deliver, and test a prototype low-power Wave Energy Converter (WEC) that lowers the total cost of ownership and provides robust, new capabilities for customers in the maritime environment. This report includes a description of readiness and how the design developed over the BP1 timeframe. This document serves as the System Design and Integration Plan for Budget Period 1 (BP1) and is Deliverable 4.11 of the DOE contract for project DE-EE0008627.

2 PRE PROJECT-CONCEPT

The original scope of this project was to design, deliver, and test a prototype WEC that generates an average of 244 Watts. The WEC was to be paired with a simple mooring and gravity anchor. The prototype is to be transported in and deployed from a standard 20 ft shipping container. The entire system can be handled by a small vessel commonly available to educational research departments. The WEC was to be an inexpensive device that would be a predecessor system for a larger-scale, more powerful WEC. C·Power wanted to make a versatile device that could be deployed in multiple locations with varying degrees of sea states to maximize the number of consumers that one device could satisfy.

C·Power designed and built a small successfully deployed prototype prior known as the WEBS (Wave Energy Buoy that Self-deploys) in support of the Defense And Research Projects Agency's (DARPA) Tactical Undersea Network Architectures (TUNA) project. This previous project was selected as a point of reference and starting place. WEBS was a non-moored system comprised of two major bodies: the WEC and the heave plate. The WEC consisted of a nacelle and two floats. One of the floats was fixed to the nacelle and the other was connected to two Power Take Off (PTO) units to generate electricity. The Drive float actuated both PTO drivetrains which transferred the rotational motion into a gearbox and generator. The Heave Plate restricted the heave motion of the nacelle allowing the wave swell to move the drive float. A spring was used to provide a restoring force to the floats in the trough of the wave. WEBS was only to be deployed occasionally in calm sea states and thus required a limited design life.

C·Power's initial assumption was the target industry would be comprised of sea state monitoring and environmental research of the seafloor. This would only require a small energy storage system and a sensor package that would transmit data in bursts. Use cases would be in locations where solar was not an option due to the environment and/or risk of theft or vandalism. Research has identified ready markets for energy provisions in watt and kilowatt scales.

3 FINAL DESIGN

The industry guidance was the major driver on the SeaRAY project. Market research showed an interest in offshore, low-maintenance power sources from 10W to 3kW. The target areas of interest were expanded to include the North Sea and areas in the tropics. This original concept design was enhanced to accommodate more energetic sea states capturing more power than the original goal.

Market research also identified low-power, remote applications the low-power WEC could complement quite well, significantly reducing the need for crewed vessels to run the day to day operations. With this market research, the WEC rating was increased to a 1 kW average power device. A seafloor garage with integrated power storage receives the captured power and redistributes it to various possible payloads. The final design is described in the following document:

- *DE-EE0008627 4.5 Final Design Review PD v1.0 03-10-2020.pdf*

3.1 **0100** *Hull*

The hull was designed to accommodate the highly energetic sea states off the coast of Oregon maintaining the capability of power capture in the less energetic environment of Kaneohe Bay, Hawaii. Sea state data was used from both PACwave North (near Newport, OR) and the Wave Energy Test Site (WETS-in Kaneohe Bay, HI) to model the WEC reactions for use in the development of the WEC's outside body dimensions and weights. Operational and 100-year return seas were used for both sites. Both environments were accommodated with a smaller, more robust final-design structure reducing mass and surface expression relative to the concept design.

The floats arms of the concept design were of equal length with the forward, wave-ward float driving two generators, while the aft was fixed to the nacelle and reacted the torque applied to the nacelle by the forward drive float. This design was not feasible in the higher energy seas. The simulations showed the floats colliding at speeds as high as 8 m/s creating possible fatigue failure. After multiple attempts to mitigate the speed and frequency of the float collisions, the design was altered to a nested float arrangement with each float driving a PTO. The revision increased the aft float width and arm length allowing it to overtop the nacelle and forward float to avoid float collision.

The nesting floats require the aft float arms to be too long to be transported in a standard shipping container; a project goal enabling rapid deployment. This issue was addressed by adding a hinged float arm. The arm allows shipment in a standard container and may be quickly extended and secured on site prior to deployment.

Initial simulations of the nesting float design showed a performance reduction. The forward float would occasionally over top the WEC and aft side position. With both floats on the same side there was no reaction force to the drive floats, eliminating power being generated. However, if each float drove only one of the two PTOs with the yoke providing the reaction torque, the performance was only slightly reduced when the floats were nested, but increased during normal orientations. The floats were modified, repositioned, and ballasted so the offset of the center of gravity and center of buoyancy caused each float to return to its nominal operating position passively.

These are high level design constraints from performance modeling to reduce loads and increase power:

- Floats

Specific gravity close to 0.5 optimizes performance.

Specific gravity high reduces lower mooring peak tension as it reduces total WEC reserve buoyancy.

Specific gravity low to reduces peak PTO speed when WEC is fully submerged during extreme seas.

Center of gravity lower and closer to nacelle than center of buoyancy provides bias in float motion to stay at its designed still water position.

- Nacelle

Specific gravity as low as possible to provides upper mooring pre-tension.

Specific gravity higher than floats to reduces peak PTO speed in extreme seas.

Center of gravity as low as possible to reduces peak PTO speed in extreme seas.

The combined nacelle reserve buoyancy and upper mooring pre-tension must be close to 0 but positive for both performance and ease of the float return motion requirements. However reserve buoyancy must be high enough to accommodate the bio-growth over the deployment.

A Yoke long to provide enough restoring torque, in addition to plates at yoke to damp nacelle pitch motion, improve performance when floats flipped during extreme seas.

- Heave plate

As heavy as nacelle design constraints allow.

Center of gravity as low as possible to improves stability.

3.2 0200 PTO

The initial concept design utilized one PTO connected to the forward float. The gearbox ratio was selected to optimize the generator input rotational speed. Higher efficiency is obtained with speed but voltage also increases. A second PTO was introduced to keep the peak speed within generator voltage limits while increasing power output to project targets. The PTOs were later decoupled in conjunction with the rotating aft float; each float actuating one PTO.

Modeling included numerous runs at different generator damping. As the wave drives the float the generator is commanded a torque based on how fast the float is moving and voltage limit. Damping optimizes the float motion to sea state to maximize power harvesting. The WEC will select a damping value from a look up table based on forecasted conditions.

During peak accelerations, the inertia of the generator exceeds rate torque of the gearbox. A torque limiter, a coupler that disengages when torque between the two shafts exceeds a threshold, was determined to be a crucial part of the drive train. The torque limiter on the SeaRAY protects the PTO from higher than design torque in these conditions. During the brief instances, the torque will spike, and the torque limiter will slip, not allowing the torque to travel through the gearbox and damage any components. The torque limiter then reengages when the float speed is low enough for the torque to be below the threshold. These devices are an important safety mechanisms in various industries.

The torque limiter is purposefully disengage the float from the PTO when speeds become too high and the voltage generated exceeds design parameters. When the Supervisor Control and Data Acquisition (SCADA) system detects via encoders that the speed is approaching critical, the generator will be commanded to apply a torque the exceeds the torque limiter threshold. This will then disengage the generator from the float which will slow from its own inertia.

3.3 0300 Electric Plant

The electric plant is comprised of a 3 phase ac generator, and ac to DC intermediate bus, power conditioning, a burn resistor, WEC power storage for hotel loads, and DC transmission to the seafloor battery. These components take the noisy ac power from the generator terminals, convert to DC, condition the power for use from other devices, burn off excess power that cannot be used or sent to the garage for storage to power end use payloads.

The electric plant has interfaces to most systems, establishing design constraints for the Electric Plant. The PTO topology chosen drove the input voltage range for all the power electronics limiting the selection of the motor used as a generator. The input power values generated from the hull determines sizing of many of the components. The relatively low median input voltages, compared to the peak, required high efficiency components to keep the power production high. The damping values that were found to optimize the performance of the WEC define the range of components used to command that torque.

3.4 0400 SCADA

The National Renewable Energy Laboratory (NREL) was chosen as a partner to design and build the SCADA system for SeaRAY. From a different existing DOE projects, NREL has a developed a system that is easily adapted to various energy converters. This system is comprised of the sensors throughout the WEC, communication throughout the WEC and onto the internet, and the decision-making code for PTO and emergency system control.

3.5 0500 and 0600 Auxiliary and Outfit and Furnishings

The auxiliary and outfit and furnishing systems use Commercial Off-The-Shelf (COTS) marine components. Onboard emergency system includes fire detection, flooding detection, access alarms, and condition communications. The bilge system is designed to remove water from the hull compartments. The surveillance system includes a Global Positioning Satellite (GPS) antenna, an Inertial Measurement Unit (IMU), and an internal and external camera system.

3.6 0700 Mooring/Umbilical

The mooring/umbilical's mechanical properties are split in two functional groupings: the upper connected between the heave plate and the WEC, and the lower connection between the heave plate and the garage. The upper connection is stiff in tension to maintain a high load between the heave plate and the WEC to create the interaction necessary for optimal performance. The upper section is EOM's stretch hose in parallel with a nylon bridle. The lower connection requires a soft cable which lowers the load capacity requirement for all sea states. The soft cable allows the WEC to travel a further distance which allows the energy to be dissipated over a larger distance, thus lowering the peak load. The solution for the lower section is EOM's stretch hose.

EOM's stretch hose has previously only incorporated an ethernet cable to data transfer. An ethernet cable's data rate was deemed insufficient to support the payloads the SeaRAY is intended to support. A fiber optic cable is the preferred data transfer technology. EOM is currently building and testing a prototype cable that has an integrated fiber line.

3.7 0750 Seafloor Garage

The seafloor garage is a system that was added to the scope of this project. The initial function was to only be an anchor. From the market research, a garage that could store power on the seafloor and transfer it to various payloads, opening a wide array of potential use cases for remote power. The garage is being designed to include 25-50 kWh of energy storage and an electrical distribution unit. The garage will also anchor the WEC.

The garage was originally intended to include a dock for ROVs and AUVs and well as their tether management systems. It was determined that multiple seafloor touchdown points to accommodate marine operations and component modularity was a better alternative to the all in one design.

4 READINESS

4.1 0100 Hull

The hull thicknesses and additional structural reinforcement have been sized with DNV-GL standards. The loading between the bodies was taken from the hydrodynamic modeling and post-processed with an Excel spreadsheet to determine minimum thicknesses and sizes. This sizing is being refined by Malin, conducting a Finite Element Analysis (FEA) model to optimize the structure. Those results will then be used to create fabrication drawings.

4.2 0200 PTO

The PTO components are COTS and have been specified from the basic loading, torque and speed determined in the modeling.

4.3 0300 Electric Plant

The layout, function and requirements of the components that make up the electric plant have been specified and to which parts are being selected or designed if a COTS item cannot be adapted. C·Power has been in discussion with Vicor to contract the work required for this system.

4.4 0400 SCADA

Utilizing NREL's SCADA system significantly reduced the amount of design time required for the system. C·Power is utilizing the existing hardware and software that has been developed under another DOE project. The sensors, signals, user interaction, motor and PE interface, and alert levels have been identified. Component selection, functional programming and human interface programming is ongoing.

4.5 0500 and 0600 Auxiliary and Outfit and Furnishings

These systems consist of COTS components which have been specified.

4.6 0700 Mooring/Umbilical

The mooring/umbilical design has been specified to comprise 4 nylon lines to create a bridle tension system between the WEC and the heave plate along with a stretch hose for power and communications. The lower section, between the heave plate and garage, is a single stretch hose to continue the communication and power transfer to the garage. The mooring model from EOM has been validated against C·Power's model for system loading. The fiber optic cable inside the stretch hose is being bench tested for optical losses and attenuation. That bench tested is expected to conclude in early June of 2020.

4.7 0750 Seafloor Garage

The use cases for the garage have been set. The use cases determine the amount and availability requires of power that payloads can utilize. The battery sizing is being optimized for incoming power generated on the WEC as well as the outgoing power to the subsea payloads. C·Power is working with EC-OG to modify their existing Halo product to meet the requirements for this project.

5 GLOSSARY

BP	Budget Period
C·Power	Columbia Power Technologies Inc.
COTS	Commercial Off the Shelf
DOE	Department of Energy
EDR	Engineering Design Requirements
FMECA	Failure Modes, Effects and Criticality Assessment
ICD	Interface Control Document
PTO	Power Take Off
SCADA	Supervisory Control and Data Acquisition
SOW	Scope of Work
V&V	Verification and Validation
WEC	Wave Energy Converter