Ocean Wave Energy Overview and Research at Oregon State University

(Invited Paper)

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***Abstract*—The solutions to today's energy challenges need to be explored through alternative, renewable and clean energy sources to enable a diverse national energy resource plan. An extremely abundant and promising source of energy exists in the world's oceans. Ocean energy exists in the forms of wave, tidal, marine currents, thermal (temperature gradient) and salinity. Among these forms, significant opportunities and benefits have been identified in the area of ocean wave energy extraction, i.e., harnessing the motion of the ocean waves, and converting that motion into electrical energy. This paper presents the fundamentals of ocean wave energy, and also a summary of the wave energy research being conducted at Oregon State University. This paper is intended to serve as an introduction to wave energy for scientists and engineers, particularly those with a wind energy background.**

I. Introduction

Significant opportunities and benefits have been identified in the area of ocean wave energy extraction, i.e., harnessing the motion of the ocean waves, and converting that motion into electrical energy. Wave energy is in actuality a concentrated form of solar energy in that it is the uneven heating of the Earth's surface that creates the winds, and it is the wind that generates the waves. With the west to east traveling global winds, it is the west coasts of land masses that see the greatest wave energy potential, and those potentials increase toward the Earth's poles.

Waves have several advantages over other forms of renewable energy such as wind and solar, in that the waves are more available (seasonal, but more constant) and more predictable with better demand matching. Wave energy also offers higher energy densities, enabling devices to extract more power from a smaller volume at consequent lower costs and reduced visual impact.

The Electric Power Research Institute (EPRI) has estimated that the wave energy resource potential that could be credibly harnessed in the U.S. is equivalent to the nation's existing hydro power resource (about 6.5% of the total U.S. electricity supply). These estimates correspond to 260 TWh/yr, or an average power of 30,000 MW. Considering that 50% of the U.S. population lives within 50 miles of the coastline, wave energy presents a promising addition to the nation's renewable energy portfolio, by providing power where it is needed [1].

Ocean wave energy technologies are in the preliminary stages of development, where wind turbines were approximately 15-20 years ago, with several topologies developing, and no clearly superior engineering solutions yet established. Fortunately, several factors such as advanced technologies and materials, and lessons learned from other renewable industries, offer encouraging predictions that the "catch-up" time for wave energy can be accelerated.

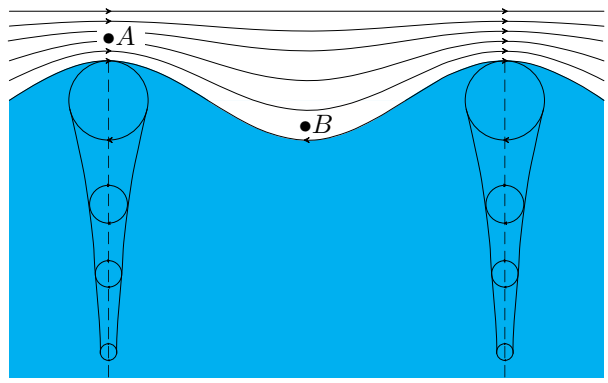

Fig. 1. Wave creation

Since 1998, Oregon State University (OSU) in Corvallis, OR, has been developing a leading wave energy program to educate students who are motivated to responsibly develop renewable energy resources. Innovative wave energy technologies are being explored in the university environment, where professors work with students on advanced degrees.

II. Ocean Wave Physics

A. Wave Creation

Ocean waves are created by the wind. As the air flows over an open ocean wave, as shown in Fig. 1, the air moves faster at the wave crests (point A) than in the troughs (point B). By the Bernoulli principle, this produces a pressure differential that tends to increase the elevation difference between the crest and trough. The area over the ocean in which a particular set of waves is developed depends on the size of the pressure fronts involved. This area is called a "fetch."

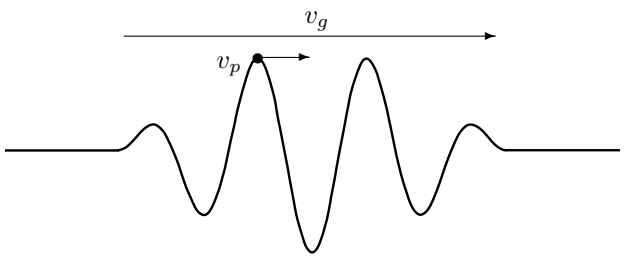

Fig. 2. Phase velocity and group velocity

Waves developed in a fetch can travel great distances with little attenuation. For example, the waves at any given time on the West Coast of the U.S. are a combination of large swells produced over the open ocean that have traveled for hours or days to reach the shore, and smaller "chop" waves from local wind.

B. Wave Velocity

There are two measures of wave velocity: the phase velocity and the group velocity. The phase velocity is the distance per time from the peak of a wave to the following peak. If a person were traveling next to the wave in a boat, the phase velocity is the speed the boat would need to travel at for the wave to appear stationary in the boater's reference frame. The phase velocity is

$$v_p = \sqrt{\frac{g\lambda}{2\pi}}. \tag{1}$$

Where g is the acceleration of gravity and λ is the wavelength.

The group velocity is less intuitive. It can be described as the velocity of a packet of waves. For water waves, the group velocity is half of the phase velocity [2].

$$v_g = v_p/2 \tag{2}$$

This is shown in Fig 2. For illustration, consider when a stone is dropped in the center of a body of still water, the waves that an observer sees radiating outward from the point of contact are a packet of a waves traveling at the group velocity. If one looks closely, it can be observed that waves are being created at the back of the packet and traveling to the front of the packet where they disappear. These waves within the packet are traveling at the phase velocity, which is twice the group velocity. The importance of this distinction is that the energy transmitted by the water moves at the *group velocity*, not the phase velocity.

Using (1), a typical Oregon wave of 100 meter wavelength travels at approximately 12 m/s (or 25 mph).

C. Wave Power

In the previous section it is stated that the energy in water travels at the group velocity, which is a function of wavelength. To calculate the power transmission, the energy per longitudinal unit of length in the wave is required. Then a simple product of energy per length and energy transmission velocity will yield energy flux, or power delivered.

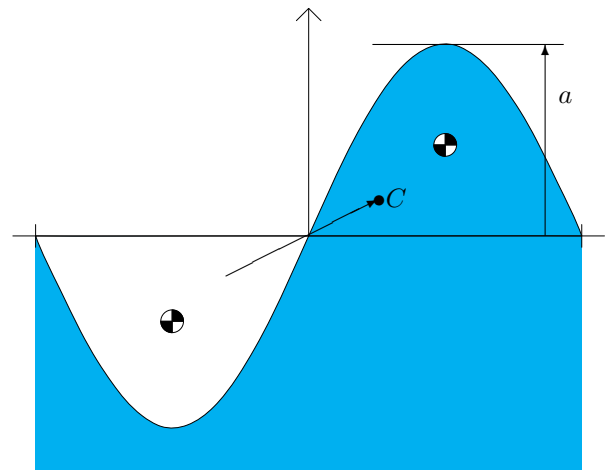

Fig. 3. Energy per wavelength

$$P = J_\lambda \cdot v_g \tag{3}$$

To calculate the energy per wavelength, J_λ, it is necessary to integrate along the wavelength for the energy required to have moved each differential particle of water from a point in the trough to its symmetric location in the crest, as shown with water particle "C" in Fig. 3. This gives the total amount of potential energy in one wavelength, per unit of crest length (into the page). Then by using the equipartition of energy, the potential energy is equal to the kinetic energy, and is thus one half of the total energy [2]. The result is

$$J_\lambda = \frac{1}{2}\rho g a^2 \quad [J/m], \tag{4}$$

where ρ is the density of water, approximately 1025 kg/m^3, and a is the wave amplitude. The power per unit length into the page (i.e., per meter crest length, mcl) is then given as

$$P_{wave,mcl} = \frac{1}{4}\rho g a^2 \sqrt{g\lambda/(2\pi)} \quad [P/m]. \tag{5}$$

This equation can be expressed in terms of the wave period, T.

$$\lambda = v_p T \tag{6}$$

$$P_{wave,mcl} = \frac{1}{4}\frac{\rho g^2 a^2 T}{2\pi} = \frac{\rho g^2 H^2 T}{32\pi} \quad [P/m] \tag{7}$$

Note that the *wave height* H is historically defined as trough to crest, and is equal to $2a$. The salient features of (5) and (7) to note is that the wave power is proportional to the wave height squared, proportional to the square root of wavelength and linearly proportional to the wave period.

III. Wave Resource and Power Extraction

A. Wave Energy Converter Types

There are four general categories of ocean wave energy converters (WEC): oscillating water column (OWC), attenuator, overtopping, and point absorber.

1) Oscillating water column (OWC): The OWC operates on the principle of air compression and decompression. An inverted chamber is placed in the water such that waves cause the "floor" of the chamber to rise and fall, therefore compressing and decompressing the air in the chamber. A turbine is placed at a small opening in the chamber to capture energy from the air as it rushes in an out. Examples: Oceanlinx, Wavegen, Ocean Energy.

2) Attenuator: Attenuators are usually devices with rectangular aspect ratios that can be oriented perpendicular or colinear with the wave front. For example, an energy absorbing structure on a jetty would be an attenuator. One of the largest commercial devices, the Pelamis, is an example of an attenuator design that is oriented perpendicular to the wave, spanning more than a wavelength. Examples: Pelamis Wave Power, Wavestar.

3) Overtopping: Overtopping devices are effectively low-head hydro systems. Large arms, either on the shore or on a floating structure, channel waves toward a central collection basin. As the waves are focused on the basin, the volume of water rises up and spills over a retaining wall to fill the basin. This creates a small elevation differential with surrounding water level that can be exploited via a standard low-head hydro turbine. Examples: Wave Dragon, Wave Plane, WAVEnergy.

4) Point absorber: Point absorbers, often simply called a "buoy," are single, relatively small devices (compared individually to the other WEC types). They are typically (though not necessarily) cylindrical in shape and constrained to one major degree of motion, usually up-and-down (i.e., "heave"). They are generally significantly smaller in diameter than a wavelength. Examples: Columbia Power Technologies, Ocean Power Technologies, Wavebob, Archimedes Wave Swing, Fred Olsen, Finavera.

B. Wave Probabilities and Capacity Factor

For wind energy, the wind frequency distribution and the wind energy converter (i.e., wind turbine) power curve can be defined as a function of wind speed. These two concepts also apply to wave energy, but with an additional dimension. The wave frequency distribution and wave energy converter power curves can be defined as functions of *both* wave period and wave height.

An example wave frequency distribution for a location off of the coast of Oregon is given in Fig. 4. The wave height is typically given as $H_{1/3}$, which is called the "significant" wave height, and is equal to the mean of the largest one third of the waves. The figure shows for this particular location that the most common wave is approximately 2.5 meters in height (crest-trough) and has a period of approximately 10 seconds. Note that there is a positive correlation between wave height and period. As the wave power is proportional to the square of the wave height, and linearly proportional to the period, this approximates a cubic relationship to the input (similar to wind power.)

The power curve for a particular device can also be given as a function of wave height and wave period. The capacity factor can be calculated by integrating the product of the two surfaces, the same procedure as for wind turbine capacity factor.

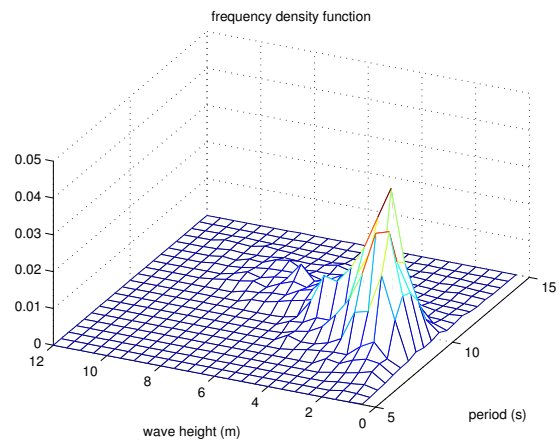

Fig. 4. Wave probability

$$CF = P_{ave}/P_{rated} \tag{8}$$

$$P_{ave} = \int\int P_{WEC}(H,T) \cdot f(H,T)\, dH\, dT \tag{9}$$

Where $P_{WEC}(H,T)$ is the wave energy converter power curve and $f(H,T)$ is the probability distribution.

As the wave energy industry is still young, there are not many examples of verified power curves. In some few cases it is given by the manufacturer from simulation and calculations [3]. It is currently anticipated that, like the wind industry, the curves will have four regions: (1) low power cut-out, (2) maximum power capture, (3) power shedding, and (4) high power cut-out. Power shedding may be achieved by a number of ways, including changing the physical structure of the system to change its resonant frequency, or by changing the generator operation to "detune" the WEC. Optimal power control and detuning is covered in Section IV.

C. Capture Width

Capture width is in some ways analogous to the notion of coefficient of power. It is defined as "at a given frequency...the ratio of the total mean power absorbed by the body to the mean power per unit crest wave width of the incident wave train" [4]. Capture width (sometimes also called "absorption width") is a measure of the WEC size and conversion ability.

$$CW = P/P_{wave,mcl} \quad [m] \tag{10}$$

Where P is the generator output in the current wave climate described by $P_{wave,mcl}$. For example, if a WEC has a capture width of 2 meters in a 30 kW/mcl wave climate, then it will output 60 kW in that climate. This can be accomplished with a small device with a high conversion efficiency, or a large device with a lower conversion efficiency.

For an axisymmetric WEC constrained to a single degree of motion (e.g., a cylindrical buoy limited to straight up-and-down movement), the theoretical maximum of CW is $\lambda/(2\pi)$ [5].

Relative capture width is a measure of the energy capture and is defined as the capture width divided by the device width. For the previous example, if the WEC in question had a width of 4 meters, then $RCW = 2/4 = 0.5$. Interestingly, the RCW can be greater than 1, meaning it is theoretically possible for a device to capture more energy than exists in the wave energy incident across the WEC width. This is due to three-dimensional effects and the nature of constructive and destructive wave interactions shortly beyond the physical reach of the WEC [4].

IV. Optimal Control

A. Linear Monochromatic

Much fundamental work on optimal control theory and energy extraction for wave energy has been done by Johannes Falnes, Kjell Budal, Stephan Salter, David Evans and others [5]–[7].

Ocean waves of significant size are non-linear. However, as is often the case with control design problems, it is useful to find a means of linearizing within the region of operation. This can be done by assuming the wave energy converter generator (i.e., power take-off) to be equivalent to a spring-mass-damper system, in which the generator produces an opposing force proportional to acceleration, velocity, and position. To simplify this analysis, we will restrict the system to one degree of motion (e.g., heave).

The wave action can be approximated by using a linearization of the Morison wave equations [5], [8]. This linearization can be summarized as

$$F_e = A\ddot{z}_w + C\dot{z}_w + kz_w. \tag{11}$$

Where F_e is the excitation force from the wave, A is the added mass, C is the viscous damping, k is the hydrostatic stiffness, and z_w is the elevation of the water at the device (i.e., the wave profile as a function of time). The added mass is a concept introduced to include the water surrounding a submerged body that moves with the body, effectively increasing its mass in terms of the force required to accelerate it.

The equation of motion can be written simply as

$$F_e - F_{gen} = (A+m)\ddot{z}_b + C\dot{z}_b + kz_b. \tag{12}$$

Where F_{gen} is the force produced by the electrical generator, m is the mass of the device, and z_b is the elevation of the wave energy conversion device.

Making another assumption that the wave climate is monochromatic (i.e., one frequency, steady state sinusoidal), (12) can be written in phasor form

$$\begin{aligned} \hat{F}_e - \hat{F}_{gen} &= (j\omega(A+m) + C + k/(j\omega)) \cdot j\omega\hat{Z}_b \quad (13) \\ &= (j\omega(A+m) + C + k/(j\omega)) \cdot \hat{V}_b. \quad (14) \end{aligned}$$

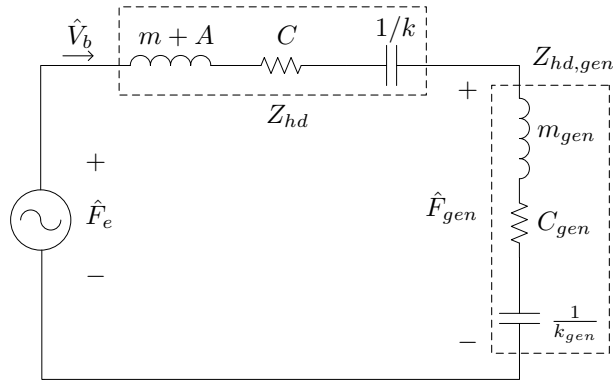

Fig. 5. Linearized hydrodynamics equivalent circuit

As stated above, assuming F_{gen} to be a function of acceleration, velocity, and position

$$\hat{F}_{gen} = (j\omega m_{gen} + C_{gen} + k_{gen}/(j\omega)) \cdot \hat{V}_b, \tag{15}$$

the average generator power is

$$P_{gen} = C_{gen}\hat{V}_b\hat{V}_b^* = C_{gen}|\hat{V}_b|^2. \tag{16}$$

These equations can be arranged to be analogous to the circuit shown in Fig. 5, where "voltage" is force, and "current" is buoy velocity. The real power in the hydrodynamic impedance, Z_{hd}, is power radiated back to the sea, and the real power in the generator *hydrodynamic* impedance, $Z_{hd,gen}$, is power into the electrical generator.

Controlling power extraction by the generator becomes an impedance matching problem, with the optimal power extraction when $m_{gen} = -(m+A)$, $C_{gen} = C$, and $k_{gen} = -k$.

$$F_{gen,opt} = -(A+m)\ddot{z}_b + C\dot{z}_b - kz_b \tag{17}$$

In other words, through proper control of the generator it is possible to adjust the resonant frequency of the system to match the dominant wave frequency, ω. In this case, the power absorbed by the generator is one half of the incoming power. The remaining one half is radiated back to the sea. Therefore it is shown that the maximum power capture by a point absorber (i.e., axisymetric buoy) operating in a single degree of motion is 0.5. If the wave energy converter is allowed to move back and forth (i.e., surge) in addition to up and down (i.e., heave), there is an additional set of equations for the other degree of motion, and the theoretical limit is 1.

Also note that for $m_{gen} \neq 0$ or $k_{gen} \neq 0$ there is a component of the generator force that is out of phase with the velocity. This is reactive power. In the case of wave energy, the period for the position, velocity, and acceleration is at least several seconds, and often 10 or more seconds. Therefore, the reactive power requirement for optimal control can be quite severe, requiring enough energy storage to sink and source the reactive component of the generator power for several seconds. A suboptimal control method that does not require reactive power is

$$F_{gen,opt} = C_{gen}\dot{z}_b \tag{18}$$

where

$$C_{gen} = |j\omega(A+m) + C + k/(j\omega)| \quad (19)$$
$$= \sqrt{C^2 + (\omega(A+m) - k/\omega)^2} \quad (20)$$

B. Latching

Another form of important WEC control is known as "latching" or "phase control." For a point absorber, when the WEC is near the top of its stroke, the buoy is held (latched) at the top until the wave has fallen away. The buoy is then released and travels quickly to the bottom of its stroke, where it is latched until the wave has come up, then released. The buoy then quickly travels up to the top of its stroke and the cycle is repeated. Latching is non-linear means of creating high velocities, and ensuring the force and velocity to be largely in phase [5], [6].

V. General Resource Characteristics

Wave energy has some unique characteristics:

- Due to global wind cells and weather patterns, the wave resource is much stronger on the west coast of the continents and stronger toward the poles. In the U.S., Alaska, Oregon, Washington, California, and Hawaii have the largest wave resource.
- Compared to wind energy, wave energy is characterized by less hour-to-hour variation, and a generally higher availability.
- Wave power has a very high power density, with an Oregon yearly average of $30\ kW/mcl$.
- There is also a strong seasonal variation, with larger waves in the winter than the summer. For Oregon, the winter waves average around $50\ kW/mcl$ and the summer waves $10\ kW/mcl$.
- Waves have a long forecasting horizon. As calculated above, a typical Oregon wave might travel at approximately 12 m/s. If a wave environment is detected several hundred miles offshore by a measurement buoy network, it can give perhaps 10 or more hours of forecast time before the waves arrive at the shore. In fact, it has been shown that it may be possible to accurately forecast up to *two days* in advance [9].
- WECs can be shore-based or floating. Generally the resource is larger several kilometers offshore in 50 or more meters of water, before the swells start to become breakers and dissipate their energy and the effects of the ocean floor start to cause highly nonlinear behavior.
- The viewshed impact is not expected to be signficant. Most of the devices from major technology developers have a visual profile similar to a medium sized fishing vessel.
- The power output from a single device without energy storage will be a pulse output with power peaking when the device is experiencing the largest velocity and wave force (i.e., twice per wave period). Energy storage may be required to smooth the output, although significant spacial aggregation effects for many WECs in a park should greatly smooth the output and reduce or eliminate the need for energy storage.

VI. Activities at Oregon State University

A. Foundational Research

Oregon State University is one of the global leaders in academic wave energy research, initiating in the program in 1998. The wave energy technology efforts have been focused on direct-drive conversion technologies, in which the force and velocity in the wave is converted to electricity as directly as possible without using intermediate state of hydraulics or pneumatics. OSU's efforts have also included building strong support at the state and federal levels, in addition to building essential collaborations with the industries, utilities, and the ocean community.

B. 2007

In 2007, the first ocean testing of a direct-drive wave energy converter was conducted off of the coast of Newport, OR, in October, as shown in Fig. 6. The test was in approximately 40 meters of water, approximately 2.5 kilometers from the shore. This design was a point absorber, approximately 3.3 meters tall and 1.2 meters wide. A cutaway diagram is shown in Fig. 7. The principle of operation is that the central cylinder, called the "spar," houses a bobbin-wound three-phase armature. The spar is moored such that it does not have a significant heave response (i.e., up and down). The outside cylinder is called the "float" and on its interior surface facing the spar contains an array of 960 magnets [10]. The waves move the float and magnets up and down relative to the spar, and by Faraday's law voltage is directly induced in the armature. This is an example of a "direct drive" design as there is a direct coupling to the incoming force and velocity to electrical generation, without using intermediate hydraulics of pneumatics.

This test primarily focused on hydrodynamic performance and the effectiveness of the sliding surface between the spar and float. The primary observations were that the towing and deployment procedure all went well, but improvements needed to be made to the sliding surface.

C. 2008

In the following year the design was improved and renamed as the "L10", for "Linear 10 kW." This work was a collaborative effort with Columbia Power Technologies (CPT) and the Navy. The generator used in the L10 is the same as in the 2007 model, but the spar and float structure was completely redesigned, as shown in Fig. 8. The float was changed to a more "saucer"-like profile, while the spar was extended with a pressurized ballast chamber to give control over freeboard. The sliding surface between the spar and float was also improved.

Testing was conducted for five days in September 2008 off Newport, OR. Figure 9 shows the system during the test producing power. An on-board relay can route the generator power out through the power take-off cable, or to the large halogen light mounted on top of the spar. The light functions

Fig. 6. Oct. 2007 testing

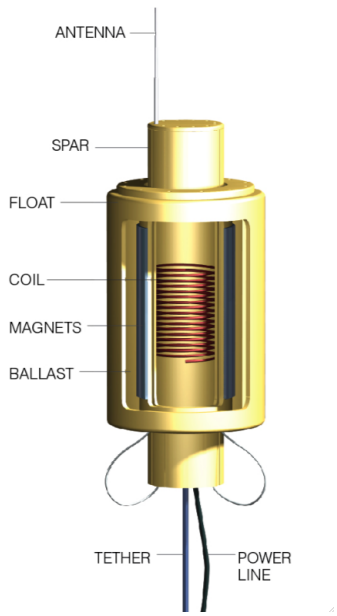

Fig. 7. 2007 1 kW WEC (Image courtesy of the New York Times)

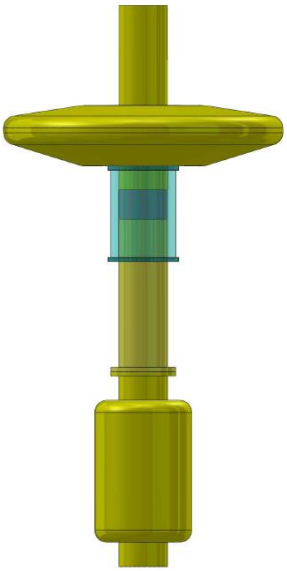

Fig. 8. 2008 10 kW L10 WEC

Fig. 9. September 2008 testing

as a load, and gives an easy to spot visual indication of the generator performance.

This test was extremely successful with the deployment, mooring, hydrodynamic, and generator performance all matching or exceeding expectations. The generator was loaded with an active loading system, called the Power Analysis and Data Acquisition system (PADA) [11]. The PADA is a marine proof three-phase rectifier with a buck converter to a load off the internal DC bus. The current drawn from the generator can be controlled by proper control of the buck converter duty ratio. Figure 10 shows the L10 current and voltage output with the PADA set to regulate the per phase generator current output to $10\ A$ peak per phase output. Figure 11 shows the L10 power output over 1 minute with the phase currents controlled to $6\ A$ peak per phase output.

D. Current and Future Work

Currently Oregon State University is continuing to conduct collaborative research with CPT toward a full-scale WEC. In addition, OSU researchers are very active in the newly created Northwest National Marine Renewable Energy Center.

E. The Northwest National Marine Renewable Energy Center

Since 2004, Oregon State University (OSU) has made strong efforts to establish a National Marine Renewable Energy Center, which has now been awarded by the USDOE (in September 2008). Through the USDOE Water Power Program, a Northwest National Marine Renewable Energy Center (NNMREC) is being established, led by OSU, in collaboration with the University of Washington (with their tidal work), and the National Renewable Energy Lab (NREL). The NNMREC will help move the generation of energy from waves, ocean

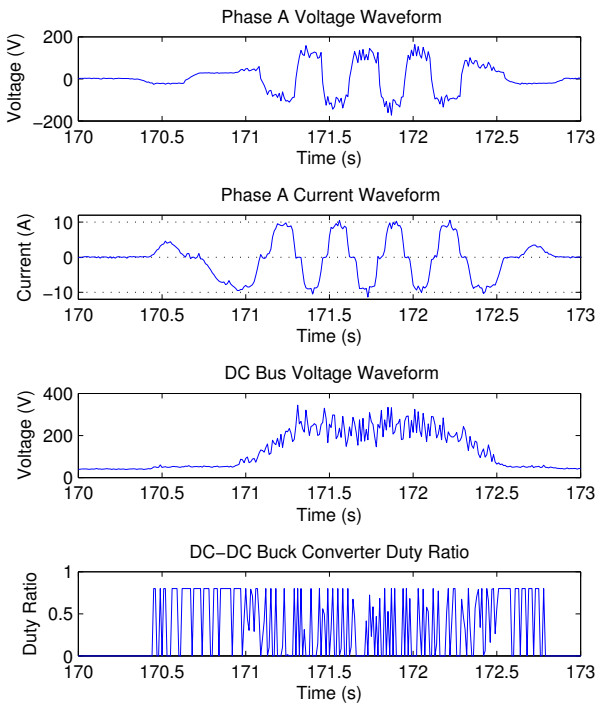

Fig. 10. L10 and PADA voltage and current with 10 A commanded current

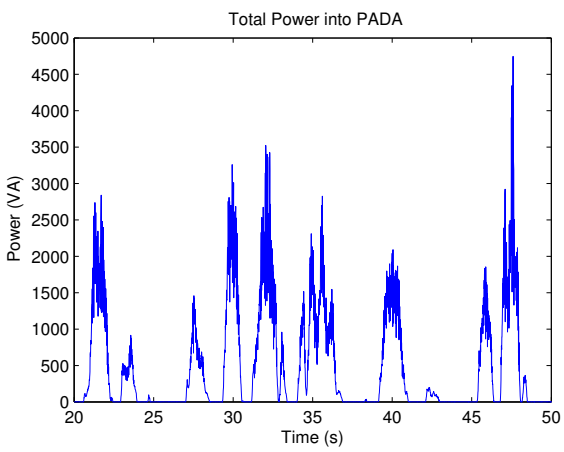

Fig. 11. L10 power with 6 A commanded current

currents and tides from the laboratory to an integral part of the nation's alternative energy future. The NNMREC will build a mobile (non-grid connected) floating "test berth" to test and demonstrate wave energy technologies off the Oregon Coast near Newport, as well as perform extensive environmental impact studies, modeling, community outreach and other initiatives.

The following topic areas will be addressed by the NNMREC:

- Development of facilities to serve as an integrated, standardized test Center for U.S. and international developers of wave and tidal energy.
- Evaluation of potential environmental and ecosystem impacts, focusing on the compatibility of marine energy technologies in areas with sensitive environments and existing users.
- Device and array modeling and optimization for effective deployment of wave and tidal energy technologies.
- Improved forecasting of the wave energy resource.
- Increased reliability and survivability of marine energy systems.
- Educational outreach and engagement about marine renewable energy and the NNMREC.

Results of key findings and research programs will be disseminated to all stakeholders and interested parties through workshops, conferences, publications, and an on-line portal.

VII. Conclusion

This paper presents a broad overview of ocean wave energy and the research activities at Oregon State University. Ocean wave energy is a significant resource for the western U.S. states, and can play an important role in establishing sustainable energy independence. Field test results have been encouraging, and even larger and improved designs are currently under development.

Acknowledgment

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