Review of Wave Energy Converter Power Take-Off Systems, Testing Practices, and Evaluation Metrics

Preprint

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REVIEW OF WAVE ENERGY CONVERTER POWER TAKE-OFF SYSTEMS, TESTING PRACTICES, AND EVALUATION METRICS

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ABSTRACT

While the field of wave energy has been the subject of numerical simulation, scale model testing, and precommercial project testing for decades, wave energy technologies remain in the early stages of development and must continue to prove themselves as a promising modern renewable energy field. One of the difficulties that wave energy systems have been struggling to overcome is the design of highly efficient energy conversion systems that can convert the mechanical power derived from the oscillation of wave-activated bodies into another useful product. Often the power take-off (PTO) is defined as the single unit responsible for converting mechanical power into another usable form, such as electricity, pressurized fluid, compressed air, or others. The PTO—and the entire power conversion chain—is of great importance, as it not only affects how efficiently wave power is converted into electricity, but it also contributes to the mass, size, structural dynamics, and levelized cost of energy of the wave energy converter (WEC). Because there is no industrial standard device or devices for wave energy conversion in the marine energy industry, PTO system designs are highly variable. The majority of current WEC PTO systems incorporate a mechanical or hydraulic drive train, power generator, and an electrical control system. The challenge of WEC PTO designs is designing a mechanical-to-electrical component that can efficiently convert irregular, bidirectional, low-frequency, and low-alternating-velocity wave motions. While gross average power levels can be predicted in advance, the variable wave elevation input has to be converted into smooth electrical output and hence usually necessitates some type of energy storage system, such as battery storage, accumulators, super capacitors, etc., or other means of compensation such as an array of devices. One of the primary challenges for wave energy converter systems is the fluctuating nature of wave resources, which require WEC components to be designed to handle loads (i.e., torques, forces, and powers) that are many times greater than the average load. This approach requires a much greater PTO capacity than the average power output and often leads to a higher cost. In addition, supporting mechanical coupling and or gearing can be added to the power conversion chain to help alleviate difficulties with the transmission and control of fluctuating large loads with low frequencies (indicative of wave forcing) into smaller loads at higher frequencies (optimal for conventional electrical machine design). But these additions can quickly increase the complexity of the power conversion chain, which could result in a greater number of failure modes and increased maintenance costs; therefore, it is important to balance complexity and ruggedness. All of the previous points demonstrate how the PTO influences WEC dynamics, reliability, performance, and cost, which are critical design factors. This paper further explores these topics by providing a review of the state-of-the-art PTO systems currently under development, how these novel PTO systems are tested and derisked prior to commercial deployment, the evaluation metrics historically used to differentiate PTO designs, and how PTO systems can be improved to support the development of wave energy systems focused on control co-design.

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INTRODUCTION

The United States, like many other countries, has a significant wave energy resource close to human population centers that to date has been too costly to commercially exploit. Presently, the levelized cost of energy (LCOE) of prototype wave energy converters (WECs) is driven by very high structural costs, which are primarily caused by the inability to control peak loads and the lower-than-desired power production levels driven by the available power take-off (PTO) systems. The PTO systems are responsible for converting mechanical power into another usable form, such as electricity or compressed air, and for the corresponding PTO control strategy. The majority of today's WEC control strategies have focused on maximizing annual energy production by manipulating the output force/torque of the PTO unit [1]. Therefore, there are currently no commercial WEC devices providing power to the U.S. electricity grid, and WEC technologies are still considered to be in early-stage development.

As shown in the U.S. Department of Energy Reference Model Project [2], the PTO cost component of WEC designs is expected to account for approximately 10% of the LCOE [3], when accounting for economies of scale. However, the PTO contribution to the LCOE could easily be up to 20% or greater for WEC prototypes or precommercial pilot demonstrations with approximately 5–10 units. Therefore, improving PTO power performance and reducing PTO component costs can lead to a dramatic improvement in final LCOE estimates. Other renewable energy technologies have industry standards for energy conversion devices, but there is no standard WEC design for marine energy. Therefore, the PTO system and supporting power conversion chain (PCC) designs remain quite diverse [4]. The PCC is the remaining balance of systems component required to convert the WEC motion to PTO motion, exporting generated power to the grid or energy storage, or other necessary hardware.

Most WEC PCC systems consist of four main components: 1) mechanical or hydraulic drivetrain, 2) power generator, 3) export power electronics, 4) and electrical control system. A significant challenge facing WEC PCC designs is surviving and efficiently converting irregular, bidirectional, low-frequency, and high-force (or torque) ocean waves into electricity or other products. The nature of the fluctuating wave elevation has to date required WEC components to handle loads that are many times greater than the yearly average load [5]. In order to survive, or handle, the peak forces and power spikes, many developers have been required to overdesign the PTO capacity, which comes at a higher cost, especially when the increased capacity is only utilized over a fraction of the year. Furthermore, given that random wave elevation generates a variable input to the PTO, the output power will also be variable and must be conditioned before it can be exported to the grid or other electrical load. Therefore, WEC designers attempt to smooth the electrical output using some type of energy storage system, such as battery storage, accumulators, or supercapacitors, or other means of compensation such as a staggered array of devices.

WEC researchers continue to work at designing and incorporating supporting mechanical and electrical couplings to improve the conversion of large, low-frequency wave loads into smaller, higher-frequency loads more appropriate for conventional electrical machine design. However, these additions increase the PCC complexity by increasing the number of failure modes [6], which could lead to catastrophic failures or more frequent maintenance visits, both of which can quickly increase operational costs. Therefore, WEC system designers aim to increase power generation per unit cost of a PTO and PCC while reducing the number of failure modes. Depending on the WEC design, the PTO may represent a critical failure path in which loading is concentrated in the WEC structure. In response to these concerns, some WEC researchers and developers have been advocating and pursuing WEC designs with a distributed PTO network—multiple smaller units such as SBM's S3 WEC [7] rather than a single large unit.

The previous points demonstrate how the PTO and the entire PCC influence WEC mass, structural dynamics, reliability, performance, and cost, which are all critical design factors [8]. The remainder of this paper is dedicated to an exploration of the challenges and potential solutions for next-generation PTOs. This paper begins by reviewing WEC optimal control theory, which puts into perspective the unique demands for WEC PTOs to maximize power. Next, it reviews state-of-the-art PTO systems under development to inform the reader of past and present efforts in the PTO and PCC design space. Then, the paper discusses the evaluation metrics historically used to differentiate between PTO designs and how they can be used to support control co-design focused development of wave energy systems. The paper ends with a discussion on how novel PTO systems are tested and derisked prior to commercial deployment.

REVIEW OF OPTIMAL CONTROL FOR WAVE ENERGY CONVERTERS

Wave power extraction algorithms have shown that optimizing the amount of wave harvested power requires the PTO to periodically transfer power to the float requiring four-quadrant control of the PTO that is often termed "reactive control" [9, 10]. The goal is to match the float natural frequency with the incident wave frequency by using the PTO to provide a spring force related to the WEC or PTO displacement that can artificially shift the natural frequency of the body response. These two conditions can be demonstrated from the general one-degree-of-freedom equation of motion for a WEC, as shown by the following expressions:

$$\frac{i\omega\xi_j}{A} = \frac{X_j}{[B_{jj}+B_g]+i\left[-\frac{K_{jj}+K_g}{\omega}+\omega\left(M_{jj}+\mu_{jj}\right)\right]} \quad (1)$$

$$Z_{jj} = B_{jj} + i\left(\omega\left(M_{jj} + \mu_{jj}\right) - \frac{K_{jj}}{\omega}\right) , \tag{2}$$

$$Z_g = B_g - i\frac{K_g}{\omega} , \tag{3}$$

$$\angle Z_g = \arctan\left(\frac{-K_g}{\omega B_g}\right) , \tag{4}$$

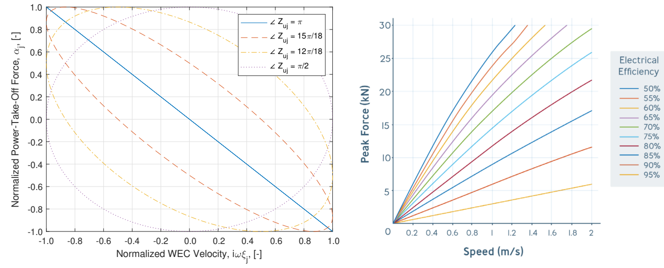
$$\frac{i\omega\xi_j}{A} = \frac{X_j}{Z_{jj} + Z_g} , \tag{5}$$

where $i\omega\xi_j$ is the jth degree-of-freedom complex velocity amplitude, A is the wave amplitude, X_j is the wave-excition force per wave amplitude, K_{jj} is the linear spring coefficient in the jth degree of freedom, K_g is the PTO-restoring coefficient, M_{jj} is the mass or moment of inertia in the jth degree-of-freedom, μ_{jj} is the radiation added moment of inertia or added mass in the jth degree of freedom, ω is the wave angular frequency, B_{jj} is the radiation wave damping in the jth degree of freedom, B_g is the PTO-damping coefficient, Z_{jj} is hydrodynamic impedence in the jth degree-of-freedom, and Z_g is PTO impedence. Following the expression given by Eqn. (5), the optimal control implementation requires the following relationship:

$$Z_g = Z_{jj}^{*} = \Re\left\{Z_{jj}\right\} - i\Im\left\{Z_{jj}\right\} \tag{6}$$

where $\Re$ denotes the real part and $\Im$ denotes the imaginary part. Equation (6) demonstrates that the PTO force feedback loop may require a nonzero spring coefficient to induce an artificial resonance such that the WEC velocity is in phase with the wave-excitation force. However, the cost of implementing the WEC optimal control can be costly if PTO efficiency is not taken into account [11, 12]. As shown in Figure 1a, the phase angle between the PTO spring and damping coefficients, $\angle Z_g$, can result in a linear or circular trace between the PTO force and velocity. Under passive control (also known as resistive control where $Z_g = |Z_{jj}|$), the PTO resistive force is linearly proportional to the speed of the PTO and provides the linear trace. The application of WEC optimal control, as one moves away from the floating body natural frequency, can require large PTO spring coefficients that dominate the PTO damping coefficient, leading to a phase angle that approaches $\pi/2$, which represents the circular velocity-to-force trace in Figure 1 where the largest PTO force demands occur when the velocity is zero. Analytically there is no issue with this implementation; however, when reviewing the sample velocity-to-force efficiency map in Figure 1b, one can see that for high force and low velocity, the efficiency can drop well below 50% electrical efficiency, which will likely negate the power gains from implementing WEC optimal control. Therefore, care needs to be taken when determining the PTO and control algorithm pair for a given WEC system.

The PTO should not be optimized once a control strategy is



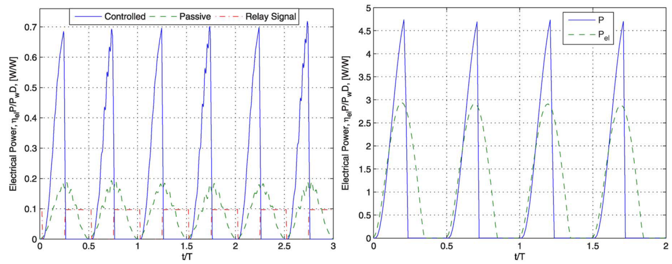
(a) PTO Velocity-to-Force Phase Map (Taken from [12])

(b) PTO Velocity-to-Force Efficiency Map (Taken from [11])

FIGURE 1. (A) PLOT OF THE CHANGING RELATIONSHIP BETWEEN VELOCITY AND FORCE WITH CHANGING PHASE ANGLE AND (B) PTO EFFICIENCY MAP BETWEEN PTO FORCE AND VELOCITY FOR THE TRIDENT POWER-POD PTO.

selected, but rather an iterative solution can be obtained by varying the control strategy to understand how the optimized PTO requirements change and to match those characteristics to known PTO architectures [13]. The influence of the control strategy on the structural fatigue also needs to be considered, as careful design of the control strategy is imperative to ensure cost-effective electrical converters [8, 14].

Another pair of commonly known control strategies that do not require bidirectional energy flow is declutching [15] and latching [16]. These control strategies attempt to speed up or slow down the WEC velocity to better align with the wave-excitation force phase in hopes of improving power production. These control strategies do not require the PTO to act as a motor during any portion of the wave cycle, but they require either decoupling the PTO force from the WEC or providing a large restraining force to fix the WEC in position for a given time duration. Such control requirements increase the demands on the PTO, which can lead to additional costs from meeting PTO force demands or additional storage and power electronics to smooth out the peaks in power generation. Figure 2 shows an example time signal between passive and declutching control in which one can see that the peak in power in the declutching-controlled WEC is three times that of the passive controller and is only active for half the wave cycle. Furthermore, the work referenced in Figure 2 demonstrates that the optimum PTO force profile will be affected by the PTO efficiency map, which, after including a PTO efficiency map in the model predictive controller, moved the optimal solution from declutching to a more passive control force profile, as the larger PTO force values generated had lower mechanical-to-electrical conversion efficiency. The reader is directed to [18] for a comparison of additional control strategies for WECs.



(a) DECLUTCHING VERSUS RESISTIVE PTO CONTROL.

(b) DECLUTCHING CONTROL WITH AND WITHOUT EFFICIENCY CONSIDERATIONS.

FIGURE 2. (A) COMPARISON OF THE PASSIVE AND CONTROLLED TIME HISTORIES OF ELECTRICAL POWER OUTPUT AT THE CONTROLLED STEADY STATE IN REGULAR WAVE EXCITATION. (B) COMPARISON OF TIME HISTORIES FROM NONLINEAR MODEL PREDICTIVE CONTROL SIMULATIONS WITH AND WITHOUT ELECTRICAL EFFICIENCY CONSIDERATIONS. IN THE LEGEND, *P* DENOTES MAXIMIZATION OF THE MECHANICAL ABSORBED POWER WHILE P_{EL} DENOTES MAXIMIZATION OF ELECTRICAL POWER (ADOPTED FROM [17]).

REVIEW OF POWER TAKE-OFF SYSTEMS

As discussed in [20], original equipment manufacturers have several options when attempting to identify a suitable PTO solution:

- Hydraulics
  - Nonbiodegradable hydraulic fluid (closed circuit)
  - Seawater hydraulic fluid (open circuit) most common with desalination
- Direct-drive electrical generators
  - Rotary
  - Linear
- Mechanical transmissions
  - Direct mechanical drive systems coupling the motion directly to the generator
  - Several energy conversions are necessary, potentially decreasing overall efficiency
- Electroactive polymers
- Triboelectric nanogenerators (TENGs)

The high-level PCCs for the different PTO solutions are illustrated in Figure 3 through the electrical output stage; however, there will likely need to be additional power electronics added to the right side of Figure 3 to convert the wild AC (varying frequency and voltage) to grid-acceptable AC (fixed voltage and frequency).

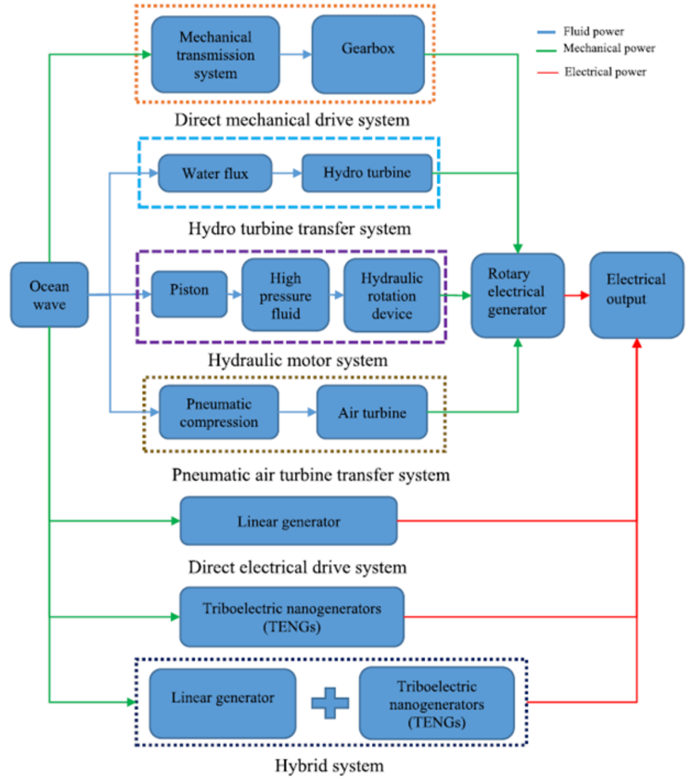


FIGURE 3. WORKING PRINCIPLES OF VARIOUS PTOS AND SUPPORTING PCCS (ADOPTED FROM [19]).

Hydraulic Systems

Hydraulic systems are often well suited to absorb energy when dealing with large forces at low frequencies. The forces generated by hydraulics are considerably greater than those from electrical machines. A common component of hydraulic systems used in oscillating systems is a double-acting hydraulic piston pump, which can convert linear or rotational WEC motion into pressurized fluid that is moved throughout the hydraulic circuit. The oscillating nature of most WECs generally leads to the bidirectional fluid between the terminals of the double-acting hydraulic piston. The bidirectional fluid flow is often rectified through a set of check valves that convert the pressurized fluid into unidirectional flow [21]. The rectified unidirectional flow can then be used to drive a unidirectional high-speed-rotation electrical machine. Traditional hydrostatic transmissions tend to use coupled variable displacement pumps and motors, which have an ideal operating point and a peak efficiency of around 80%. When operating outside ideal conditions, efficiency can quickly drop to where the part-load losses (including coulomb and viscous friction, leakage, and compressibility) are significant [22]. Often, the device will spend most of the time operating at a fraction of the PTO rating, and therefore the system may need to be designed with the highest part-load efficiency possible. The hydraulic circuit itself does not convert the mechanical power to electricity; moreover, electricity may not always be the output quantity of interest. For example, with desalination systems, high-pressure hydraulic fluid is the quantity of interest [23]. If electricity is the desired output, then hydraulic circuits need to be connected to a generator for the mechanical-to-electrical conversion process, which is then connected to an inverter (approximately 95% efficient) for grid connection and the use of variable speed control. To avoid over-sizing a motor/generator couple, an energy overflow system could be added such that if the cylinder flow exceeds motor capacity, the primary and overflow PTOs can be combined in a common line and power an extra electrical machine. A consequence of using a hydraulic system is that there will be pipe and hose losses, which can be difficult to model and, depending on the amount of piping in the system, can be a significant power loss that reduces the wave-to-wire efficiency [24]. Despite the best efforts of the hydraulic circuit designer, the motor will leak fluid and it will often be necessary to include a charge/booster pump (with hydraulic reservoir) to complete flushing for cooling and filtering. However, seals will inevitably break down over time, which can increase the maintenance costs of the power conversion chain.

Direct-Drive Systems

The term "direct-drive" indicates the transmission of wave energy directly to the PTO without the use of pneumatics, hydraulic systems, or linkages. The reduced friction and number of energy conversion steps are often cited as leading to improvements in the wave-to-wire efficiency of direct-drive PTO systems. Traditional power stations use synchronous generators that operate at nearly constant speeds that match the local grid frequency. Derived from proven applications in wind turbines, asynchronous rotary direct-drive generators could be a favorable solution that makes transmission technologies obsolete. These systems generally offer high efficiency but at large costs for rare earth materials used in the composition of the permanent magnets. Depending on the conversion system, generators used for wave energy may have to cope with variable speed; four generator types are identified and contrasted in [25].

Rather than rotary generators, several past and current WEC developers are considering using linear generators in which the dominant WEC oscillation mode is translational. Linear generators can have large up-front costs, with the two main components being the field-producing magnets and the armature coils [26]. The development of these linear designs requires care in the design of bearing systems that maintain alignment of the rotor (moving component) with the stator (generally fixed or close to stationary component). The benefit of a linear generator is that there are fewer intermediate conversion steps compared to a conventional hydraulic circuit. However, the frequency of oscillation is much smaller than conventional electrical machine design and requires continued research into slow-speed electrical machines [22]. One of the first wave energy developers attempting to use a linear generator design was the Archimedes Wave Swing [27]. Their modified version took third place in the U.S. Department of Energy's Wave Energy Prize [28]. Linear generators have often been connected with heaving one- or two-body point absorbers, such as those from developers Seabased [29] and Ocean Power Technologies [30], as heave motion is the dominant oscillation mode that can be paired with a linearly driven PTO. Linear permanent magnet generators exhibit high part-load effectiveness, but designs are not yet fully optimized because linear generators have a low power-to-weight ratio and require a large and heavy support structure.

Whether a rotary or linear design is used, most electrical machines will require a power converter to covert the variable output from the linear or rotary generator into a fixed voltage and frequency for grid connection. Often, this consists of two back-to-back voltage source inverters connected via a DC link. The generator side of the inverter allows rectification and control of the generator currents, whereas the grid-side inverter allows control of the DC link voltage and real power flow into the grid [31].

Electroactive Polymers

Over the past decade there has been emerging research focused on dielectric elastomer generators, which are constructed by coating a dielectric elastomer membrane with electrodes. The mechanical energy from the wave deforms the membrane, reducing the capacitance and thereby increasing the electrical potentials of charges residing in the electrodes. Although promising simulations and scaled experimental results have been reported [7,32,33], the technology is still far from mature. Efficient manufacturing of reliable electroactive polymer (EAP) actuators as well as force control and overload prevention using EAP actuators are required before the technology can become competitive with other current WEC designs. The leading technology developer of EAP WECs is currently SBM Offshore, who are developing their S3 WEC [7]. The European PolyWEC project developed a poly-oscillating water column (poly-OWC); rather than use an air turbine, the top of the OWC uses a polymer coated with dielectric elastomers to convert the undulating surface into electricity [32].

Triboelectric Nanogenerators

TENGs are very new entrants into the WEC PTO domain. This working principle was first proposed in 2012 based on the coupling of triboelectrification and electrostatic induction, which are theorized to have the specific merits of high power density, high efficiency, low weight, and low manufacturing costs [34]. However, this technology has not been proven in the ocean environment, and the cost to scale to the kilowatt level is unknown, as no prototype of such scale has been built. The TENG PTO may find more success in applications focused on Powering the Blue Economy™ [35], where power requirements are on the level of watts.

OTHER PCC SUSBSYSTEM CONSIDERATIONS

The previous section described the components directly responsible for converting the kinetic energy from an oscillating WEC into other useful energy. However, these power converters are often coupled with other supporting mechanical and electrical hardware to successfully transmit power from the waves to the grid or other electrical load.

Power Electronics

As discussed in the introduction, the WEC and connected PTO are oscillated by a variable amplitude and frequency input that, without power smoothing, will generate an electrical output that will need to be rectified to meet the requirements of the local grid. To achieve this, the PCC will likely require power electronics to convert the generated electricity into a form that is suitable for delivery to the target electrical load. Today, most power electronics available for WEC developers are taken from the wind and solar industries and have been made to work; however, given the greater variability in the electrical output signal of WEC systems, there are opportunities to improve the power electronics to suit the unique needs of WEC systems.

Gearboxes

As discussed in the section about direct-drive systems, although the WEC motion can be coupled directly to the electrical machine input shaft, the oscillating frequency of the incident waves is much lower than the optimal range for most conventional electrical machines. In an attempt to multiply the input shaft speed of the electrical machine, a mechanical transmission system, such as a gearbox, is used to drive the electrical machine closer to the optimal speed and torque profile needed for the electrical machine to work in its best efficiency regime [36].

Mechanical Motion Rectifiers

Mechanical motion rectifiers have been proposed to convert irregular oscillatory wave motion to unidirectional rotation. Generally, these subsystems in the PCC consist of two one-way gears placed along a drive shaft that convert the bidirectional motion of the WEC oscillations into the unidirectional motion of the drive shaft, which would be connected to the input shaft of the electrical machine [37]. The intent of converting the stroke in either oscillation direction to unidirectional motion is to raise the mean input shaft speed of the electrical machine. The goal of the mechanical motion rectifier is to keep the input shaft speed of the electrical machine from crossing zero, where the electrical-to-mechanical efficiency is known to be extremely poor.

Seals

Generally only a necessity of hydraulic systems (although also present if a drive shaft is exposed to water and the internal compartment must be water tight), seals are required to prevent hydraulic fluid from leaking and continuing to flow in the desired direction in the hydraulic circuit. Uncertainty around a seal's lifetime can make it difficult to develop maintenance intervals greater than 1 year of continuous operation because of the seal material's fatigue and corrosion properties [22]. If one were to assume an average wave period of 10 s during a given year, a seal would experience more than 3 million cycles, during which time any misalignment or internal friction could quickly wear away the seal material and thereby increase the chance of leakage, which would drop the pressure within the hydraulic circuit. Seal design is difficult and often relies on operational knowledge to help determine which seals are best suited for a given environment and loading profile.

End Stops

Issues with end stops arise from the oscillating interface exceeding its designed travel. The high forces and kinetic energy of moving components in extreme conditions cannot be suddenly absorbed upon reaching the end of the designed travel, potentially damaging components of the PCC. High-stroke actuators could be used as a mitigation, but they have high mass and therefore high expense, and their maximum stroke capability would not be exploited most of the time. [22]. End-stop-related issues tend to be of greater concern with linear hydraulic cylinders and generators, as the direction of motion cannot be extended indefinitely, and therefore other mechanical means need to be applied to limit the stroke. For example, the stroke could be limited through the use of nonlinear springs or mechanical linkages that decrease the influence of WEC motion on the PTO drive (reverse gearing ratio) as the PTO moves within a specified distance from the end stop. The use of rotary-based PTOs can potentially avoid end stop issues, as they may rotate around the shaft axis indefinitely. Popular with several current WEC developers is the use of a winch mechanism that drives a rotary pump or generator—examples include WaveSub [38], CalWave [39], and OscillaPower [40].

ENERGY STORAGE SYSTEMS

In an effort to smooth out the oscillatory power output from the wave system, several energy storage systems have been and continued to be explored in the wave energy converter space. Given that the peak-to-average power ratio for a given sea state can exceed 20–30, it is desirable to collect and store the large power spikes (refer to Figure 2a) to then be exported to the grid or other load at the desired voltage and frequency.

Flywheels

These PCC subsystems attempt to add a large, often rotating, inertia between the WEC drive shaft and the input shaft of an electrical machine. Often connected through a one-way clutch, the WEC motion will work to spin up the large rotating inertia, which will continue spinning in one direction even if the WEC motion is small or halted for a brief period. Although a fairly simple mechanical system, the need for a large rotating inertia adds extra mass and space to the WEC structure, which may be more difficult to obtain in practice than in theory.

Accumulators

Hydraulic systems can include several hydraulic gas accumulators that can store the energy from peak loads and smooth the wave energy conversion from the motor. However, the required accumulator volume to decrease this peak-to-average power ratio may comprise a majority of the available hull volume of the WEC, which presents a design challenge when also designing the WEC for all the other balance of systems components.

Batteries

For short-term onboard storage, several developers are considering the use of batteries to store power that can be used to smooth the power output during lulls in wave elevation. Battery technologies are well-known, but given the highly cyclic wave environment, there is a risk that the battery life could be depleted quickly.

Supercapacitors

Supercapacitors are also known as electric double-layer capacitors, ultracapacitors, and electrochemical double-layer capacitors. While supercapacitors cannot compete with batteries in terms of energy density, their much longer cycle life, power density, operational temperature range, and ability to fully discharge make them an energy storage system option to be considered [41] to complement battery storage for improved system performance and battery lifetime. Supercapacitors may also provide short-term energy storage that can be used to drive the PTO (i.e., drive energy back to the PTO rather than to the grid). This is a potential avenue that developers can take to satisfy the four-quadrant power flow required to implement more complex WEC control strategies.

DISCUSSION ON PTO EVALUATION METRICS

There are a wide variety of needs for evaluation metrics to compare the performance of various PTO designs. In most cases, the two most important evaluation metrics for any PTO are the final power output and costs (both capital and operational expenditures); however, in the early design phases a developer often does not have sufficient details to calculate these values. Therefore, stand-in evaluation metrics can be developed that act as indirect performance and cost metrics to assist in the optimization of the WEC and PCC.

Power Peak-to-Average Ratio

This metric describes the individual PTO and/or device control capability to reduce peak-to-average power during the generation/power absorption cycle for different time scales (e.g., second to second, minute to minute, sea state to sea state). The power peak-to-average ratio can be calculated from numerical or experimental time series from the following expression:

$$PPAR_{PTO} = \frac{\underset{[T_0\ \ T_1]}{\max} P_{PTO}(t)\,(P_{PTO}(t)>0)}{\frac{1}{T_1-T_0}\int_{T_0}^{T_1} P_{PTO}(t)\,(P_{PTO}(t)>0)\,dt}$$

$$\text{where } \begin{cases} P_{PTO}(t)>0 & =1 \\ P_{PTO}(t)<0 & =0 \end{cases} \tag{7}$$

where $P_{PTO}(t)$ is the instantaneous power generation of the PTO. The variables T_0 and T_1 are the start and end instances of the time history of interest and indicate that these statistics could be calculated over minutes or hours. PTO power absorption is defined as positive power while the PTO power consumption is defined as negative power. Baseline targets to improve can be found in literature, such as ratios of 15:1 up to 30:1 for annual average energy production compared to rated power [5]. As discussed in Section *Review of Optimal Control for Wave Energy Converters*, optimal control may require the PTO to reverse the energy flow and drive the WEC as a motor for a duration equal to the wave cycle. This power consumption cycle can have substantial peaks in the instantaneous power input, which could exceed the peaks during the generation cycle. Therefore, another metric could be added that examines the performance time signals during the consumption stage, or an absolute value could be placed in the numerator of Eqn. (7) to account for both absorption and consumption peaks.

Force (or Torque) Peak-to-Average Ratio

This metric describes the capability of the PTO and/or device control to reduce peak force (or torque) to average force (or torque) during the power generation cycle. The force peak-to-average ratio can be calculated from numerical or experimental time series from the following expression:

$$FPAR_{PTO} = \frac{\max\limits_{[T_0 \;\; T_1]} F_{PTO}(t)\,(P_{PTO}(t) > 0)}{\frac{1}{T_1 - T_0}\int_{T_0}^{T_1} F_{PTO}(t)\,(P_{PTO}(t) > 0)\,dt}$$
$$\text{where } \begin{cases} P_{PTO}(t) > 0 & = 1 \\ P_{PTO}(t) < 0 & = 0 \end{cases} \tag{8}$$

where $F_{PTO}(t)$ is the instantaneous PTO force (or torque) observed during the power generation cycle. The maximum instantaneous peak value is used for the calculation of this metric, whereas other approaches use a statistical value in which a 95% exceedance threshold is used to define the maximum, as the peak of a single wave elevation can be strongly dependent on the chosen phase realization. This metric is important because any increase in annual energy production must be balanced against the growth in WEC structural and PTO loads that can significantly outpace the growth in energy capture [44]. The oscillatory nature of waves means that PTOs and PCCs will need to be designed to handle the cyclic fatigue loads over the WEC lifetime. A wave energy converter will most likely be designed for a 25-year life span, over which time it will experience about 10^9 wave fatigue loading cycles (about the same cycle count as a wind turbine), so the ability to reduce peak loads will reduce the root-mean-square loads and accumulated fatigue damage.

PTO Displacement Peak-to-Average Ratio

This metric describes the ratio between the peak displacement, or extension from equilibrium, to average displacement of the PTO during all operations of the PTO unit. The displacement peak-to-average ratio can be calculated from numerical or experimental time series from the following expression:

$$XPAR_{PTO} = \frac{\max\limits_{[T_0 \;\; T_1]} |x_{PTO}(t)|}{\frac{1}{T_1 - T_0}\int_{T_0}^{T_1} |x_{PTO}(t)|\,dt} \tag{9}$$

where $x_{PTO}(t)$ is the instantaneous PTO displacement (linear or rotational) observed during operation. The ratio is a measure of how much of the total PTO stroke is effectively used. Small ratios indicate a good usage of the designed (available) PTO stroke. Although Eqn. (9) is a performance metric, the impact on the LCOE will depend on the marginal cost of additional PTO stroke and how that improves the power production potential of the WEC.

Aggregating Metrics into a Single Holistic Metric

The metrics listed above are not exhaustive, and many other metrics could be added, reported, and debated in future work [42]. However, researchers and developers working on PTO designs cannot look at metrics individually but should consider all proposed metrics to give a more holistic review of the PCC, control algorithm, and other WEC design considerations (such as the Technology Performance Levels (TPLs) proposed in [43]). For example, in the Wave Energy Converter Control Competition (WECCCOMP) [45], an evaluation criterion, EC, was developed that combined five different evaluation metrics as follows:

$$EC = \frac{\text{avg}\,(P)}{2 + \frac{|f|_{98}}{F_{max}} + \frac{|z|_{98}}{Z_{max}} + \frac{\text{avg}|P|}{|P|_{98}}} \tag{10}$$

where $avg(P)$ is the average electrical output from the PTO, for which [45] assumed a mechanical-to-electrical efficiency of 70%, $|f|_{98}$ is the 98th percentile of the absolute motor force time history, F_{max} is the motor force constraint on the PTO, $|z|_{98}$ is the 98th percentile of the absolute motor displacement time history, Z_{max} is the motor displacement constraint on the PTO, $avg|P|$ is the mean absolute electrical power, and $|P|_{98}$ is the 98th percentile of the absolute power time history. The goal of WECCCOMP was to maximize the EC, which acted as a first-order benefit-to-cost ratio; however, this evaluation metric could have placed different weights for the PTO force, displacement, or maximum power requirement depending on the additional costs one would expect for selecting or developing a PTO with additional capacity.

SCALED TESTING OF POWER TAKE-OFFS AND POWER CONVERSION CHAINS

After attempting to match geometric and dynamic similitude, most experimentalists will find it difficult to purchase or build a laboratory-scale PTO system that is representative of the full-scale PTO design. At laboratory scale, frictional forces can dominate, especially when wave amplitudes are at the centimeter scale, and coil resistances within electrical machines increase, reducing conversion efficiency. A PTO system, with supporting PCC, can be tested at larger scales; however, the costs of building and testing also significantly increase with scale [4]. Therefore, during small-scale WEC testing, developers and researchers typically use a simplified PTO model, often a passive damping implementation, and report the mechanical power input to the PTO and PCC. The development time for designing a model-scale PTO can in itself be a significant research exercise and is another reason why many WEC developers choose to simplify their PTO systems [46].

Review of WEC Scaling Laws

Small-scale models of WECs and PTOs should represent, as accurately as possible, the real-scale physics. In most scaling exercises a dimensional analysis is carried out to make sure the appropriate dimensionless numbers are matched to represent the dominant physics that describe the operational principles of a given design. To maintain full similitude between the laboratory model and the corresponding full-scale design, geometrical, kinematic, and dynamic similitudes must be fulfilled. However, it is well known in ship model testing that it is extremely difficult, if not impossible, to match both the Froude and Reynolds numbers. Often, given that floating body system dynamics are dominated by gravitational waves, experimentalists focus on matching the Froude number and acknowledge that viscous effects may not be matched as accurately [19]. Another concern with small-scale PTO modeling is that the mechanical power scales to the 3.5 power, which means that a 1:10 scale decreases power by approximately 3,162, and very quickly a device generating approximately 1 kW at full scale will be generating less than a watt at model scale. Therefore, care must be taken when scaling up experimental results because of the uncertainty of such a small measured quantity and because the amplification in scaling could potentially greatly distort the expected PTO performance. In general, the scale of wave tank tests must be significantly smaller than what a subscale PTO system should be, as the WEC model must fit within the size constraints of most wave tanks. As mentioned previously, most WEC developers will utilize a simplified mechanical PTO to represent the lumped parameter performance of the PTO (i.e., a simplified spring-damper system) in an effort to verify proof of concept and build confidence in their hydrodynamic model. Once confidence is established in the WEC hydrodynamic model based on validation against experimental data, a developer can consider completing larger scaled tests of their proposed PTO where the WEC hydrodynamics are a simulated component that allow for hardware-in-the-loop testing.

PTO Simulators

Rather than scaling a PTO design from full to model scale, a PTO simulator is included in the model-scale experiment to generate a desired mechanical force (or torque) based on the WEC response. The PTO simulators allow for experimental flexibility, as the online control algorithm can determine the mechanical force the scaled PTO device would experience, and thus several control strategies can be tested on the same test article [45]. An example of such a PTO simulator can be an electric motor working as an active damper with a feedback control loop [47]. Given that model-scale wave tank tests are designed to verify proof of concept, the need to have a fully representative PTO unit is generally of less importance, and the ability to evaluate the response of the device under different PTO loading conditions, such as linear or coulomb damping, is prioritized so the developer can determine the most promising control strategies to further explore as they scale up tests.

Laboratory Bench Testing

In order to reduce uncertainty and minimize risk associated with a new or even modified PTO unit, developers and researchers should test their devices in a dry laboratory setting. The laboratory bench test setup generally consists of four main elements: the generating system itself (representing the PTO), a motor drive system (used to mimic the driving forces or torques the PTO and PCC encounter), a supporting structure with couplings, and a data acquisition system to record measured responses from electronic sensors [48]. The drive motor can be programmed with any custom time-history profiles that would allow designers to implement system identification tests of both linear and nonlinear dynamics [49] of their PTO and PCC to develop reduced-order models that can be used for controller design or implemented in numerical models. Furthermore, the laboratory testing provides an opportunity where system faults can be implemented to observe how the PTO and PCC would respond. The measured data can then be used with machine condition monitoring techniques to assist in identifying potential faults when deployed at sea and develop fault-tolerant control algorithms that maximize performance and minimize damage as the WEC system awaits potential maintenance [50]. These research efforts should be explored in order to minimize WEC downtime when deployed in the open ocean where retrieval and maintenance costs of a failed PTO unit will be easily an order of magnitude higher than if the issue was identified in the laboratory. The reader is also encouraged to review the International Electrotechnical Commission 62600-103 document on guidelines for the early-stage development of WECs [51], which has been written by the international community to provide the accepted best practices in scaled prototype testing to allow test results to be certified and accepted internationally.

CONCLUSIONS

An efficient, near maintenance-free, and reliable PTO system is fundamental to reach the goal of cost-effectiveness for wave energy conversion. However, at this time there continues to be a wide range of PTO concepts being pursued across the WEC community. The marine energy community should expect that there will be eventual technology convergence for PTOs along with WEC convergence, which should attract original equipment manufacturers to engage with WEC developers to fine-tune the PTO designs. The hope would then be that manufacturers would commit to building out the supply chain infrastructure to assist in driving the costs of the leading PTO technologies down such that mass scale production can be achieved. This report has focused on the PTO development of grid-connected WECs, but the requirements and design-drivers for the optimal PTO could change if a developer chose to target the markets that fall under the Powering the Blue Economy initiative. Regardless, the information presented in this report has demonstrated that WEC hydrodynamics and PTO dynamics are inherently coupled, and optimizing the two separately will almost always lead to a suboptimal system [52]. For example, a WEC might be hydrodynamically optimized to offer the greatest transfer of the wave dynamics to mechanical motion, but if the PTO cannot provide the required force (or torque) profile to maximize, the benefits of WEC size or operation will be lost. Therefore, the constraints and operational characteristics of the PTO and supporting PCC should be included as early as possible in the design process to leverage co-design principles in the development of WEC systems.

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