


Useful Power Maximization for Wave Energy Converters

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Wave energy converters (WECs) have enormous potential in providing clean renewable energy with high levels of predictability. The geospatial and temporal nature of the wave energy resource makes it particularly attractive in serving coastal communities and cities in a complementary nature with wind and solar generation. With these and other potential benefits, engineers have been working for many years to design machines that effectively produce electricity from ocean waves.

Unfortunately, a large portion of research studies on WECs stop short of considering electrical power. Instead, in many cases, academic research on WEC modeling, control, and experimental testing focused on mechanical power—i.e., the product force (F) or torque (τ) with velocity (\dot{x}). This approach has been justified by the assumption, which is often implicit, that electrical power and mechanical power are monotonically or even linearly related. In fact, based on this assumption, some studies use a single scalar efficiency factor (η) to find electrical power (P_e) based on mechanical power (P_m).

$$P_e(\tau, \dot{x}) = P_m(\tau, \dot{x}) \eta \quad (1)$$

A glance at the efficiency map for an electric generator quickly shows that efficiency varies dramatically with torque and velocity. Thus, (1) should be rewritten as follows.

$$P_e(\tau, \dot{x}) = P_m(\tau, \dot{x}) \eta(\tau, \dot{x}) \quad (2)$$

It is actually quite possible for a trajectory that maximizes absorbed mechanical power to expend electrical power (i.e., *negative efficiency*).

The “black box” efficiency map (η) in (2) can be produced empirically from a test stand or replaced with first-principle-based models. This model should account for both the electric generator and the drive train, which together constitute the power take-off (PTO) system. Similarly, a WEC designed to desalinate water should be designed based not on mechanical power but on the rate at which it produces potable water.

While simplifications are a necessary part of all research—in fact, one could argue that simplification is one of the critical aspects that distinguishes engineering from science—the application of this particular simplification to disregard the more complex relationships between electrical and mechanical power has stunted and perhaps even prevented the development of high-performing WECs. The usage of (1) can work quite well in other application areas where torque and shaft speeds are steady and have relatively small oscillations (e.g., in wind or gas turbines). The wave input forces are *purely* oscillatory (zero mean). Thus, while some PTO designs may incorporate rectification, storage, and smoothing to produce a more constant generator shaft speed, the system must generally be treated as oscillatory and dynamic.

Researchers are increasingly considering and employing complete models in their studies of WECs and focusing on electrical power as the critical metric with which to measure performance. A framework to accomplish this based on using the multi-port network theory to produce composite impedance models to represent the WEC hydrodynamics and PTO was suggested by Bacelli and Coe [1]. In addition to the intuition that can be gained



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from a model of this nature, which might tell a designer where to focus his/her efforts, the framework also facilitates the application of impedance matching control approaches while achieving maximum power transfer in oscillatory systems. Similarly, Blanco et al. [2] considered the sizing of a WEC using a Thévenin equivalent circuit model for combined mechanical and electrical systems.

Baker et al. [3] performed experimental testing on a linear generator and lab-scale WEC in which measurements of both mechanical and electrical power were made. Resistive motor winding losses and mechanical friction losses combined to produce maps of electrical power and PTO efficiency. A numerical study on a WEC with a hydraulic PTO was conducted by Andersen et al. [4], where the authors compared mechanical and electrical power for different control strategies and system pressures. The importance of considering electrical power was well illustrated by the fact that the system producing the highest levels of mechanical power produced relatively low electrical power. In some cases, a hardware-in-the-loop (HIL) experiment can prove to be an effective tool, as shown by Hansen et al. [5], who considered the rigid-body (product of force and velocity) and fluid (product of pressure and flow) powers for a hydraulic PTO system (electrical power was not considered). Hansen et al. [5] reported that the rigid body to fluid conversion step had efficiencies ranging from 85% to −78% (the negative efficiency indicating that absorbed power at the rigid-body stage became expended power at the fluid stage). By modeling the performance of a WEC with a direct-drive electrical generator, Tedeschi et al. [6] similarly found that, in some cases, the “optimal” control strategy (designed to maximize mechanical power absorption) actually expends electrical power on average.

These dramatic results—a controller considered optimal in one way and producing losses in the way that truly matters—are pushing the wave energy research and development community towards a more holistic view of WECs that targets designs for electrical power generation. This progression will greatly benefit the performance and economic viability of WECs.

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