The first testing of iMEC-enabled hardware in uncontrolled conditions was done at Lake Washington. The PTOs were deployed in January 2013 following intensive testing on a hydraulic test stand.

Harnessing Magnetostriction

The next generation wave energy converter?

BY BALAKRISHNAN NAIR AND RAHUL SHENDURE

Wave energy has the potential to meet nearly 10% of global electricity demand (approximately 2,000 TWh/year). Unlike wind or solar energy, wave energy can be forecasted several days in advance and is located close to coastal areas with growing demand. Inventors and organizations around the world have tried to turn this low-frequency, low-amplitude resource into utility-scale electricity for decades. These attempts have universally used power generation technologies with moving parts, resulting in high operating and maintenance costs, as well as low efficiency and the need for large amounts of structural mass, which together drive up capital cost. The levelized cost of energy (LCOE) for wave energy has been estimated to be between 25 and 60 cents/kWh, many times higher than that from conventional sources.

At Oscilla Power, Inc. (OPI), we are developing a patented magnetostrictive wave energy harvester (MWEH) that could enable the disruptively low-cost production of grid-scale electricity from ocean waves. Designed to operate cost effectively across a wide range of wave conditions, the MWEH will be the first use of reverse magnetostriction, a phenomena in which high-magnitude, but low-displacement, mechanical load changes are converted into magnetic flux changes and then electricity (via induction), for large-scale energy production.

While the newly-developed, higher-performing magnetostrictive alloys (such as iron-gallium) are prohibitively expensive for utility-scale power generation applications, iron-aluminum (Fe-Al) alloys can provide the required cost and capacity.

Our iMEC technology platform enables Fe-Al alloys to provide the required performance for power generation. The driving magnetomotive force is provided by permanent magnets, which typically make up less than 1% of the generator mass.

Tension changes on this circuit result in changes in magnetic permeability of the Fe-Al rods, resulting in changes in flux density within the circuit—all with no perceptible relative motion (less than 200 ppm of deformation). Electricity is generated by electromagnetic induction, using copper coils wound around the alloy rods.

The pre-compressed rods never go out of compression during normal operation. During extreme conditions that result in very high tension, safety bolts are engaged that pick up the excess mechanical load. These features are intended to eliminate fatigue-related failures.

Magnetostrictive harvesters have been shown to have greater than 80% mechanical to electrical efficiency, a capability that should enable us to achieve higher efficiencies than have previously been demonstrated for wave energy converters (WEC).

Tension leg platform model

The MWEH's architecture is similar to that of tension leg platforms used in the oil and gas industry. It consists

The MWEH can produce energy from waves with no significant relative motion between or significant dimensional change of its components.

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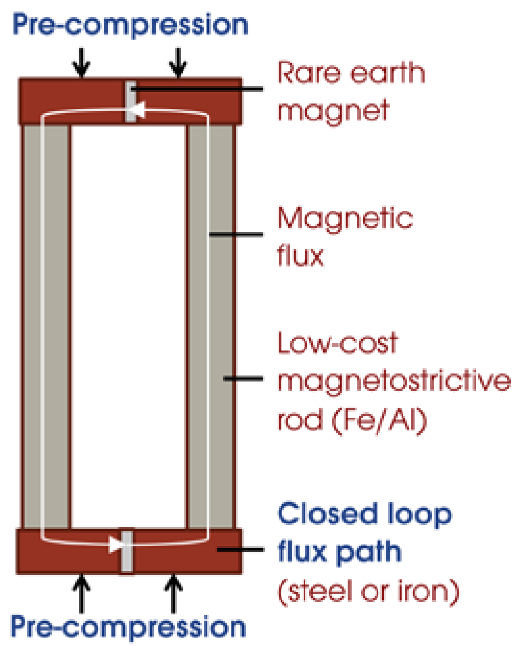
of a partially submerged buoy, anchored to a catenary-moored heave plate by taut tethers. These tethers are largely made up of, or are connected to, discrete, robust power takeoff modules (PTOs), which contain iMEC-enabled generators. Hydrodynamic forces on the buoy cause the line tension of each tether to continuously change, resulting in a high-force, low-displacement mechanical energy input that is converted to electrical energy in the PTOs.

The MWEH has several advantages over other approaches to wave energy generation, giving it the potential to achieve the following.

No moving parts. The MWEH can produce energy from waves with no significant relative motion between or significant dimensional change of its components. This eliminates sub-system (for example, lubrication, bearings, and seals for moving components) costs and will significantly reduce operating and maintenance costs due to the elimination of the need to periodically service or replace components such as joints or bearings.



Conceptual illustration of OPI's magnetic circuit.

Low cost materials. The MWEH's materials set does not include significant quantities of any supply-limited or expensive materials. While small quantities of commercial rare earth magnets are used, these could be replaced by ferrite magnets if their cost or availability becomes an issue.

Low cost manufacturing. All components used in the MWEH's PTO are amenable to low-cost, high-volume, automotive-scale manufacturing. The buoys and anchors have no complex parts.

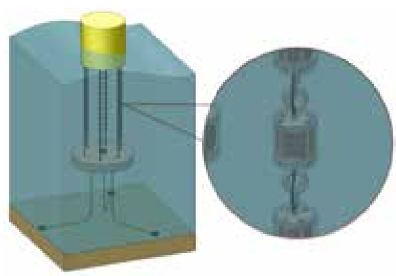
Relative ease of deployment. Standard vessels that do not have to be customized to hold equipment in a specific direction or to deploy devices onto the ocean floor can be used.

High efficiency across the wave spectrum. Operating substantially below the resonant frequency, the MWEH does not experience steep reductions in efficiency on either side of a nominal/rated condition, as is the case with many other WEC technologies that rely on wave motion to move a floating body. While such WEC systems are intrinsically "narrow-band" technologies, the MWEH operates as a wide-band device across the wave spectrum.

Minimal environmental impact. Broadly speaking, the MWEH's impacts should be more manageable than that of other approaches for the following reasons: at least 8 m between individual tethers; EMF leakage below detection limits for marine organisms; anchor design flexibility; customizable above-water buoy profile to minimize its attraction to sea life; and minimal noise due to lack of moving parts.

Technology development

Development of our technology has proceeded along three general thrusts: generator design and optimization, including validation and improvement of our performance model; design and optimization of the PTO and overall system, including the buoy and anchor; and



The architecture of the MWEH is similar to that of tension leg platforms used in the oil and gas industry, consisting of a partially submerged buoy anchored to a catenary-moored heave plate by taut tethers.

deployment of sub-scale systems in wave tanks and open-water environments.

Generator design and optimization. Our key accomplishments in this area include:

- Performance: production of more than one tesla of magnetic flux density change, a level of performance sufficient to achieve the power density and energy generation assumed in our cost model
- Scale up: Core size was successfully scaled up from approximately 2.5 cm to more than 10 cm. To date, the generator testing has validated the accuracy of our predictive models for achievable flux change and power production
- Reliability: Magnetostrictive generators have been successfully subjected to more than 1.5 million load cycles (approximately 2.4% of the number of cycles expected over a 20-year lifetime).

Following an initial decrease of approximately 2.5%, which can be attributed to core and coil heating, power production remained constant.

Design and optimization of the PTO and overall system. We have executed design, prototype testing, and modeling activities to optimize the PTO and overall system. Finite element design engineering was used to maximize load transfer from the tethers to the magnetostrictive generator and to evaluate, along with prototype testing, a variety of sealing methodologies that have been proven in analogous systems.

At the system level, our work has focused on the modeling and simulation of a utility-scale system in central Oregon coast wave conditions. Executed in Orcaflex by naval engineering consultancy Marine Innovation and Technology, these simulations output a time series of tether tensions. When combined with the generator performance model, these outputs can predict power generation as a function of wave conditions and system design. The simulations enabled us to design a system that can survive a 100-year wave.

We worked with Powertech Labs, a subsidiary of Canadian utility BC Hydro, to develop conceptual designs for the power electronics and transmission components of the MWEH system using off-the-shelf hardware. We also have carried out exhaustive design failure modes and effects analysis with external experts to prioritize technical risks associated with the MWEH.

Deployment of sub-scale systems. In 2010, we conducted two rounds of wave tank testing at the University of California at Berkeley's tow tank. In addition to accomplishing preliminary reduction to practice, we were able to demonstrate high correlation between the predicted and actual generator output.

In 2012, Professor Jim Thomson and his team at the Applied Physics Laboratory at the University of Washington designed a mooring system that enabled us to conduct the first testing of iMEC-enabled hardware in uncontrolled conditions at Lake Washington. The

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The MWEH generator testing has validated the accuracy of OPI's predictive models for achievable flux change and power production.

PTOs were deployed in January 2013 following intensive testing on a hydraulic test stand.

During the 3-month deployment, 20 wave events were recorded. Detailed analysis of the hourly average tether load change rate was conducted for the data from a particular storm to validate the dependence on wave height. We also were able to validate a strong correlation between predicted output of the PTOs, calculated using the tether loading, and their actual output. Finally, we validated that power was harnessed across all of the wave frequencies present.

Future plans

As the MWEH has moved from the lab to tank to open water, the technology has performed successfully, with a strong correlation between predicted and actual output. Our ongoing and future technology development activities include generator scale-up, additional prototype deployment, and integration of component technologies to drive additional cost reduction. Prototype systems with will be tested at Isle of Shoals in New Hampshire, together with the University of New Hampshire's Center for Ocean Renewable Energy, in 2013-2014.

Detailed cost modeling suggests that a utility-scale MWEH array using gen 3 generators, located off the central Oregon coast, could produce electricity at less than 10 cents/kWh without incentives and without requiring significant learning curves.

We would like to acknowledge the contributions of Professor Jim Thomson and his team at the Applied Physics Laboratory at the University of Washington to the Lake Washington deployment.

We also would like to acknowledge the following individuals for their contributions to our progress over the past three years: Alison Flatau (University of Maryland); Dominique Roddier and Antoine Peiffer (Marine Innovation and Technology); Joao Cruz and the Wave Energy team at GL Garrad Hassan; Dallas Meggitt (Sound and Sea Technology); and Jahangir Khan (Powertech Labs). **MT**

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LEARN MORE

For further information on wave energy or magnetostriction, check out the following resources.

"A Brief Review of Wave Energy," by T.W. Thorpe, ETSU-R120, AEA Technology for the UK Department of Trade and Industry (1999)

"The Future Potential of Wave Power in the United States," by M. Previsic, RE Vision Consulting for the U.S. Department of Energy (2012)

"A Review of Magnetostrictive Iron–Gallium Alloys," by J. Atulasimha and A.B. Flatau, Smart Materials and Structures (2011)

"Application of the Villari Effect to Electric Power Harvesting," by X. Zhao and D.G. Lord, Journal Of Applied Physics (2006)